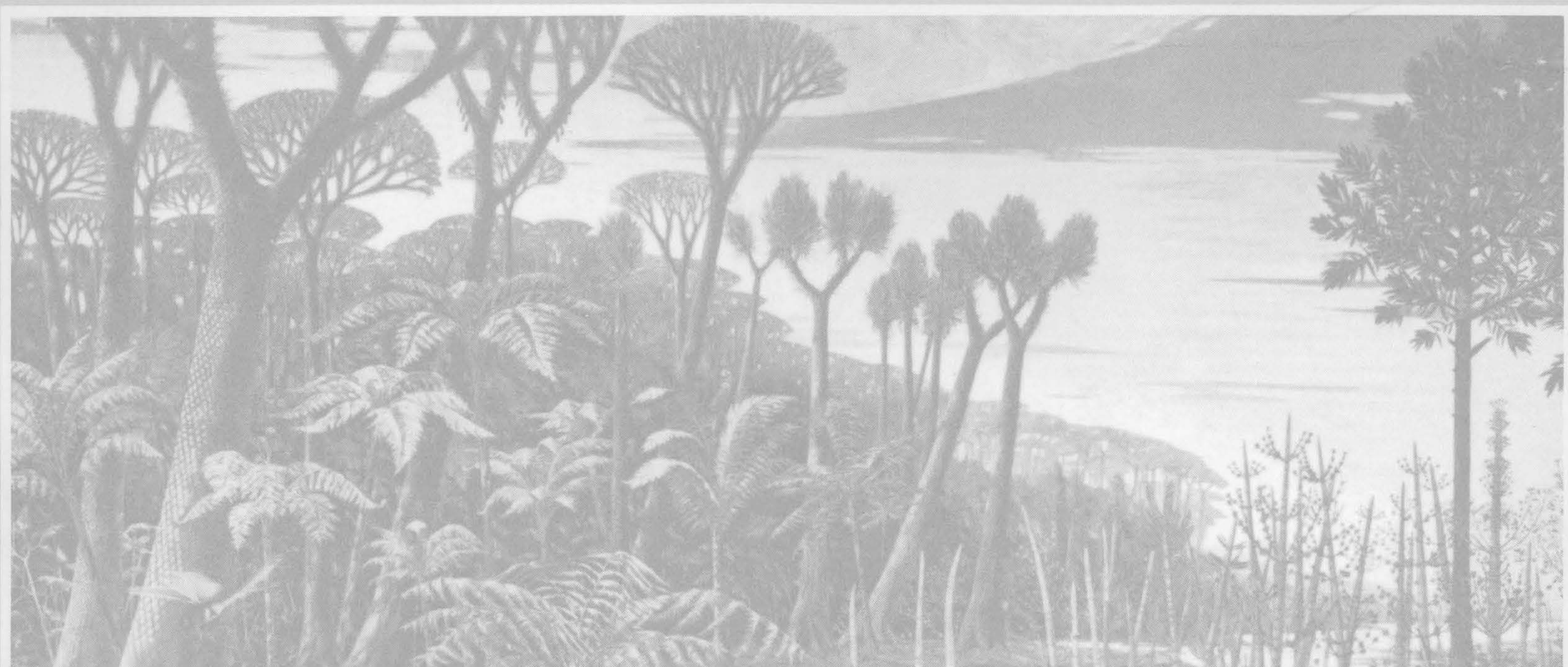
The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States



GEOLOGICAL SURVEY PROFESSIONAL PAPER 1110–A–L

ON THE COVER

Swamp-forest landscape at time of coal formation: lepidodendrons (left), sigillarias (in the center), calamites, and cordaites (right), in addition to tree ferns and other ferns. Near the base of the largest *Lepidodendron* (left) is a large dragonfly (70-cm wingspread). (Reproduced from frontispiece in Kukuk, Paul (1938), "Geologie des Niederrheinisch-Westfälischen Steinkohlengebietes" by permission of Springer-Verlag, New York, Inc.)

The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—

A. Massachusetts, Rhode Island, and Maine, by James W. Skehan, S.J., Daniel P. Murray, J. Christopher Hepburn, Marland P. Billings, Paul C. Lyons, and Robert G. Doyle

B. Pennsylvania and New York, by William E. Edmunds, Thomas M. Berg, William D. Sevon, Robert C. Piotrowski, Louis Heyman, and Lawrence V. Rickard

C. Virginia, by Kenneth J. Englund

D. West Virginia and Maryland, by Thomas Arkle, Jr., Dennis R. Beissell, Richard E. Larese, Edward B. Nuhfer, Douglas G. Patchen, Richard A. Smosna, William H. Gillespie, Richard Lund, Warren Norton, and Herman W. Pfefferkorn

E. Ohio, by Horace R. Collins

F. Kentucky, by Charles L. Rice, Edward G. Sable, Garland R. Dever, Jr., and Thomas M. Kehn

G. Tennessee, by Robert C. Milici, Garrett Briggs, Larry M. Knox, Preston D. Sitterly, and Anthony T. Statler

H. Georgia, by William A. Thomas and Howard R. Cramer

I. Alabama and Mississippi
   Mississippian stratigraphy of Alabama, by William A. Thomas
   Pennsylvanian stratigraphy of Alabama, by Everett Smith
   Carboniferous outcrops of Mississippi, by Alvin R. Bicker, Jr.

J. Michigan, by Garland D. Ells

K. Indiana, by Henry H. Gray

L. Illinois, by Elwood Atherton and James E. Palmer

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1110–A–L

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H. William Menard, *Director*

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FOREWORD

The year 1979 is not only the Centennial of the U.S. Geological Survey—it is also the year for the quadrennial meeting of the International Congress on Carboniferous Stratigraphy and Geology, which meets in the United States for its ninth session. This session is the first time that the major international congress, first organized in 1927, has met outside Europe. For this reason it is particularly appropriate that the Carboniferous Congress closely consider the Mississippian and Pennsylvanian Systems; American usage of these terms does not conform with the more traditional European usage of the term "Carboniferous."

In the spring of 1976, shortly after accepting the invitation to meet in the United States, the Permanent Committee for the Congress requested that a summary of American Carboniferous geology be prepared. The Geological Survey had already prepared Professional Paper 853, "Paleotectonic Investigations of the Pennsylvanian System in the United States," and was preparing Professional Paper 1010, "Paleotectonic Investigations of the Mississippian System in the United States." These major works emphasize geologic structures and draw heavily on subsurface data. The Permanent Committee also hoped for a report that would emphasize surface outcrops and provide more information on historical development, economic products, and other matters not considered in detail in Professional Papers 853 and 1010.

Because the U.S. Geological Survey did not possess all the information necessary to prepare such a work, the Chief Geologist turned to the Association of American State Geologists. An enthusiastic agreement was reached that those States in which Mississippian or Pennsylvanian rocks are exposed would provide the requested summaries; each State Geologist would be responsible for the preparation of the chapter on his State. In some States, the State Geologist himself became the sole author or wrote in conjunction with his colleagues; in others, the work was done by those in academic or commercial fields. A few State Geologists invited individuals within the U.S. Geological Survey to prepare the summaries for their States.

Although the authors followed guidelines closely, a diversity in outlook and approach may be found among these papers, for each has its own unique geographic view. In general, the papers conform to U.S. Geological Survey format. Most geologists have given measurements in metric units, following current practice; several authors, however, have used both metric and inch-pound measurements in indicating thickness of strata, isopach intervals, and similar data.

This series of contributions differs from typical U.S. Geological Survey stratigraphic studies in that these manuscripts have not been examined by the Geologic Names Committee of the Survey. This committee is charged with insuring consistent usage of formational and other stratigraphic names in U.S. Geological Survey publications. Because the names in these papers on the Carboniferous are those used by the State agencies, it would have been inappropriate for the Geologic Names Committee to take any action.

The Geological Survey has had a long tradition of warm cooperation with the State geological agencies. Cooperative projects are well known and mutually appreciated. The Carboniferous Congress has provided yet another opportunity for State and Federal scientific cooperation. This series of reports has incorporated much new geologic information and for many years will aid man's wise utilization of the resources of the Earth.

H. William Menard
Director, U.S. Geological Survey

CONTENTS

The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—Massachusetts, Rhode Island, and Maine

By JAMES W. SKEHAN, S.J., DANIEL P. MURRAY,
J. CHRISTOPHER HEPBURN, MARLAND P. BILLINGS,
PAUL C. LYONS, *and* ROBERT G. DOYLE

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1110-A

Prepared in cooperation with the Massachusetts Department of Public Works, the Massachusetts Department of Environmental Quality Engineering, Office of the State Geologist, and the Maine Geological Survey, Department of Conservation

Historical review and summary of areal, stratigraphic, structural, and economic geology of Mississippian and Pennsylvanian rocks in Massachusetts, Rhode Island, and Maine

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1979

CONTENTS

ILLUSTRATIONS

[Plate follows references cited]

TABLE

THE MISSISSIPPIAN AND PENNSYLVANIAN (CARBONIFEROUS) SYSTEMS IN THE UNITED STATES— MASSACHUSETTS, RHODE ISLAND, AND MAINE

By JAMES W. SKEHAN, S.J.,[1] DANIEL P. MURRAY,[1]
J. CHRISTOPHER HEPBURN,[2] MARLAND P. BILLINGS,[3]
PAUL C. LYONS, and ROBERT G. DOYLE[4]

ABSTRACT

In New England, deposits known or inferred to be of Carboniferous age are present in five basins in Massachusetts and Rhode Island and in several additional isolated localities in Massachusetts and eastern Maine. Rocks near Worcester, Mass., and in the Narragansett and Norfolk Basins are dated as Pennsylvanian on the basis of plant megafossils. Deposits of the Boston, Woonsocket, and North Scituate Basins and the Harvard Conglomerate at Pin Hill, Harvard, Mass., are of uncertain age but may be Carboniferous. Rocks within a series of graben blocks in eastern Maine are inferred to be Carboniferous.

The Narragansett Basin, Massachusetts and Rhode Island, is a structural depression and topographic lowland occupying 2,460 km². Rocks dated by plant megafossils as Early to Late Pennsylvanian unconformably overlie a Cambrian or Precambrian basement; the Precambrian basement consists primarily of 600-million- to 650-million-year-old granitic rocks cutting older volcanic, volcaniclastic, and plutonic rocks. The Middle to Upper Pensylvanian rocks are coal, sandstone, conglomerate, siltstone, and shale. Distribution of lithologies and sedimentary structures in the approximately 3,700-m-thick section indicate that most of the sedimentary rocks of the five formations that compose the section were deposited in a fluvial environment.

Anthracite and semianthracite are found widely, in seams as much as 8 m thick, in the 1,700-km² part of the basin that has undergone lower greenschist-facies metamorphism. These coals have very low sulfur contents; have moderate to high contents of ash, which is dominantly secondary quartz; and yield 13,000 to 14,700 BTU's per ton.

The Narragansett Basin is characterized by a rich megaflora consisting of 300 nominal species from approximately 140 floral localities. Nearly all are confined to the Rhode Island Formation and range from Alleghenian to Conemaughian (Westphalian C to Stephanian A) or younger.

Most rocks in the Narragansett Basin are in the lower greenschist facies; however, in southern Rhode Island, the regional metamorphic grade increases in a short distance to upper amphibolite facies and, in at least an indirect way, is associated with the late syntectonic to posttectonic Narragansett Pier Granite of Permian age. The larger, Massachusetts, part of the basin is faulted and mildly folded. In contrast, the southern, Rhode Island, section of the basin is moderately to intensely deformed and is characterized by several generations of folds and faults.

The Norfolk Basin contains two formations of Pennsylvanian age, the Wamsutta Formation and the Pondville Conglomerate; these formations are also present in the adjacent Narragansett Basin. In the Norfolk Basin, these rocks are present in a syncline overturned to the southeast and are in part bounded by thrust faults. Plant fossils from the Pondville suggest a Pottsvillian age, probably equivalent to the Westphalian B of Maritime Canada and Europe.

The Woonsocket and North Scituate Basins contain clastic sedimentary rocks long correlated with those of the Narragansett Basin; however, they may be much older. The beds dip generally to the east, are polydeformed, and are in the upper greenschist facies of metamorphism.

Two small patches of nonmarine phyllite are present near Worcester, Mass. Phyllite encloses a 2-m-thick lens of meta-anthracite at the "Worcester Coal Mine." To the south, at the second outcrop area, a similar phyllite is interbedded with coarse stretched-pebble conglomerate, granule conglomerate, and arkose. The metamorphic grade is just below the almandine isograd. On the basis of plant fossils, the rocks are assigned an Early to Middle Pennsylvanian age. The Harvard Conglomerate, an isolated deposit northeast of Worcester, has been considered Pennsylvanian. However, the unit is unfossiliferous, and the field relationships have been debated.

The bedrock in and near the Boston Basin may be assigned to five map units: (1) "basement," Precambrian, possibly including some Paleozoic; (2) Blue Hills-Quincy and Nahant areas, Lower and Middle Cambrian sedimentary rocks and Ordovician(?) igneous rocks; (3) Mattapan and Lynn Volcanic Complexes, possibly as old as Precambrian or as young as Pennsylvanian; (4) Boston Bay Group, having a maximum thickness of 5,700 m and consisting of the Cambridge Argillite and the Roxbury Conglomerate, which is a southerly lithofacies of the lower part of the Cambridge

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Argillite; and (5) Triassic(?) diabases. A diamictite (tillite) is present at the top of the Roxbury Conglomerate.

Because supposed fossils collected from the Boston Bay Group may be inorganic, the age of the group is still in doubt. On lithologic and tectonic grounds, the group is considered to be Pennsylvanian, but other ages have been proposed.

The strata of the Boston Bay Group are thrown into a series of folds, most of which plunge eastward. Five longitudinal faults, some of which dip steeply, are present. One transverse fault strikes north. The deformation was late Paleozoic.

Similarities in ages, lithologies, stratigraphy, and structure of the Narragansett and Norfolk Basins and of the deposits at Worcester suggest that their origins are related and that all these deposits may have been part of a single fluviatile, nonmarine basin. The ages of the Boston, Woonsocket, and North Scituate Basins are uncertain. These three basins are dissimilar enough from the other basins and have lithologies and stratigraphy, in part at least, similar enough to fossiliferous Cambrian rocks to suggest that they may be much older than Carboniferous. All five basins and the deposits at Worcester were deformed by folding and faulting in the Alleghanian orogeny.

Sedimentary rocks inferred to be of Carboniferous age have been mapped in eastern Maine within a series of graben blocks related to segments of the 320-km-long Norumbega fault system. The rocks have been tentatively separated into two members, arkosic and nonarkosic. The unit consists of multicolored bedded and nonbedded siltstone, sandstone, arkose, and polymictic conglomerate. No fossils or economic minerals have been reported.

INTRODUCTION

Deposits of the Narragansett Basin, Massachusetts and Rhode Island, deposits of the Norfolk Basin, Massachusetts, and deposits near Worcester, Mass., are dated as Pennsylvanian on the basis of plant megafossils. Deposits of the Boston, Woonsocket, and North Scituate Basins and the Harvard Conglomerate at Pin Hill, Harvard, Mass., are of uncertain age but may be Carboniferous. Sedimentary rocks within a series of graben blocks in eastern Maine are inferred to be Carboniferous. The area in southeastern New England occupied by deposits known or inferred to be Carboniferous is shown in figure 1.

The stratigraphic nomenclature used in this paper has not been reviewed by the Geologic Names Committee of the U.S. Geological Survey. The nomenclature used here conforms with the current usage of the Massachusetts Department of Public Works; the Massachusetts Department of Environmental Quality Engineering Office, of the State Geologist; and the Maine Geological Survey, Department of Conservation.

ACKNOWLEDGMENTS

Research in the Narragansett Basin was supported largely by NSF (National Science Foundation) Grant No. AER7602147 and U.S. Bureau of Mines Contract No. J0188022; that in the Norfolk Basin was supported by NSF Grant No. AER 7602147.

We wish to acknowledge the excellent spirit of cooperation among the authors of the several parts of this chapter. We are also grateful to members of the Narragansett Basin Project who have assisted in various phases of the field and laboratory studies, particularly Frederick Adinolfi, Robert Bouchard, Gregory Gintoff, Jay Jones, Daniel Logue, Anne O'Connell, Jonathan Raben, James W. Ring, S.J., Peter Rushworth, and Tarin Smith and to Joanne Tucker, Sally Sargent, and Bruce Withey who assisted in the preparation of the manuscript and illustrations.

P. C. Lyons wishes to acknowledge Clifford G. Grant, who collected the plant specimens illustrated on plate 1, and Paul Jappe, who photographed them. The identification of *Neuropteris rarinervis* (pl. 1, fig. Q) was made by W. C. Darrah.

No review of the Carboniferous geology of New England would be complete without mentioning the late Alonzo W. Quinn, who was the driving force behind the systematic mapping and related studies in the Narragansett Basin and other parts of New England during the last several decades. We wish to dedicate these papers to this geologist, one of the dedicated pioneers of regional geologic studies in New England and one who gave substantial moral support to the Narragansett Basin Project from the beginning and who followed its progress with interest and encouragement.

We thank William R. Barton, Joseph Pecoraro, and Joseph Sinnott for their encouragement to the senior author to undertake the Narragansett Basin Project and for their assistance, as well as that of very many people, especially the Hon Margaret M. Heckler who supported the project from the beginning, Thomas P. O'Neill III, Lt. Governor of Massachusetts, and the entire New England Congressional delegation. Additionally, we acknowledge Russell Dutcher, Lincoln R. Page, Nicholas Rast, and especially Irving Sacks for valuable assistance at many stages of the project and all the many others too numerous to mention who have contributed in important ways.

NARRAGANSETT BASIN OF MASSACHUSETTS AND RHODE ISLAND

By JAMES W. SKEHAN, S.J., and DANIEL P. MURRAY

The Narragansett Basin is a structural depression and topographic lowland occupying 2,460 km^2. Rocks

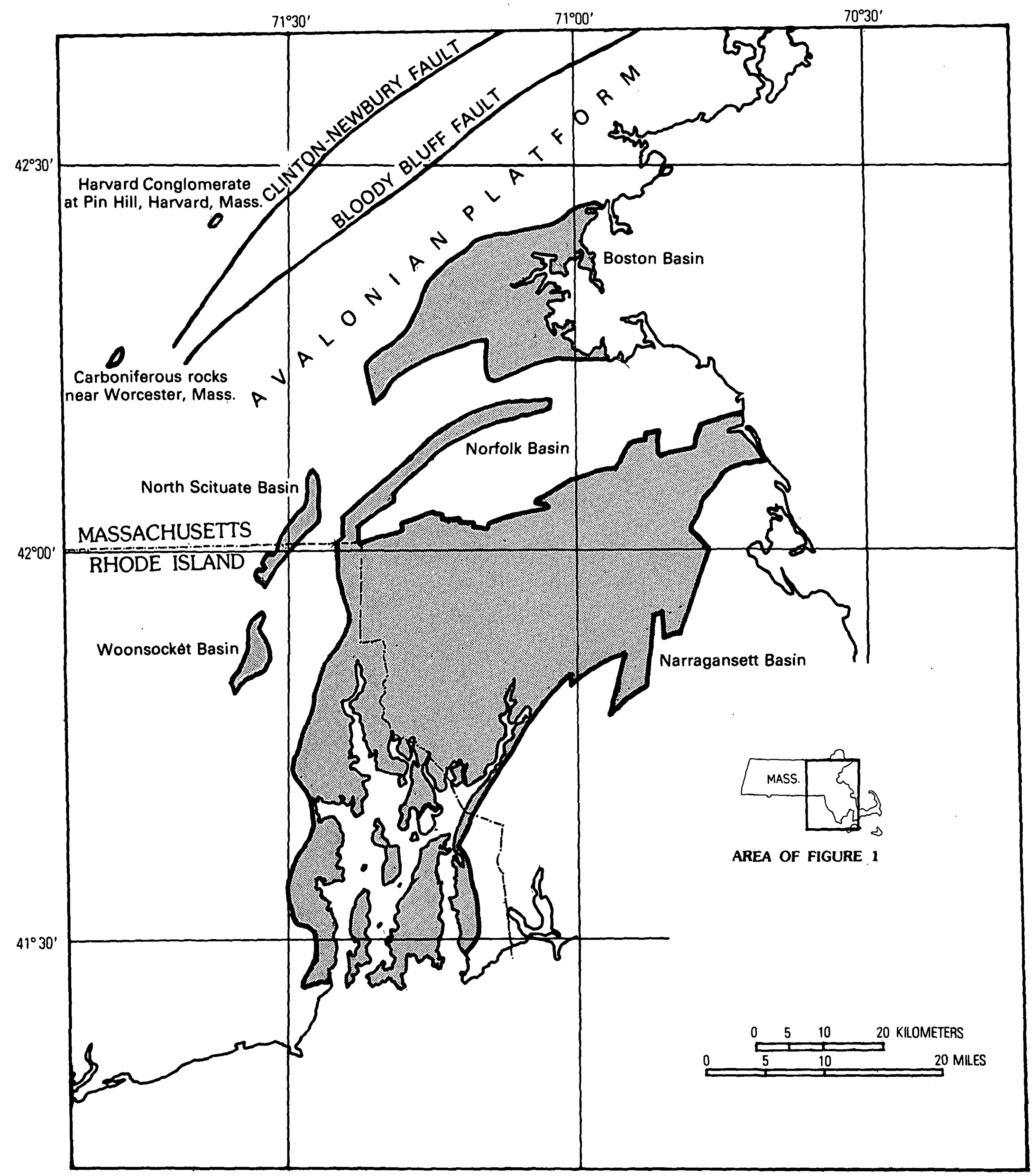


FIGURE 1.—Area of southeastern New England occupied by deposits known or inferred to be Carboniferous.

dated by plant megafossils as Early to Late Pennsylvanian unconformably overlie a Cambrian or Precambrian basement; the Precambrian basement consists primarily of 600-million- to 650-million-year-old granitic rocks (Naylor, 1975) cutting older volcanic, volcaniclastic, and plutonic rocks. The Middle to Upper Pennsylvanian rocks (fig. 2) are coal, sandstone, conglomerate, siltstone, and shale. Distribution of lithologies and sedimentary structures indicate that most of the sedimentary rocks were deposited in a fluviatile environment. Most of these rocks are in the lower greenschist facies; however, in southern Rhode Island, the regional metamorphic grade increases in a short distance to upper amphibolite facies and, in at least an indirect way, is associated with the late syntectonic to posttectonic Narragansett Pier Granite of Permian age. The larger, Massachusetts, part of the basin is faulted and mildly folded. In contrast, the southern, Rhode Island, section of the basin is moderately to intensely deformed and is characterized by several generations of folds and faults.

The first detailed survey of the Narragansett Basin was by Shaler, Woodworth, and Foerste (1899). More recently, Quinn and Oliver (1962), Mutch (1968), and Skehan and Murray (1978) provided comprehensive reviews of the geology of this basin and of the many previous reports on it. All Rhode Island has been mapped at the scale of 1:24,000, and these data are available as published or open-file reports. This work is summarized on the geologic map of Rhode Island (Quinn, 1971). Lyons (1977) has mapped the Massachusetts part of the basin in reconnaissance at this scale; his maps are available at the scale of 1:31,250 (Lyons, 1977).

BASIN CONFIGURATION

Recent mapping has resulted in several significant changes in our ideas of the shape of the Narragansett Basin (fig. 2): (1) Discovery of a trilobite fauna having Acado-Baltic affinities indicates that phyllites on Conanicut Island that were previously mapped as Carboniferous are Middle Cambrian marine metasediments (Skehan, Murray, Palmer, and Smith, 1977). (2) The Narragansett Basin may extend to the northeast at least as far as the present coastline (Lyons, 1977, p. 17); moreover, the basin may continue some distance beneath the sea north of Cape Cod Bay. (3) New floral ages (Brown and others, 1978) confirm the previously assumed Pennsylvanian age for the clastic metasedimentary rocks along the southwest margin of Narragansett Bay. (4) Observations on distribution of glacial erratics relative to bedrock indicate that Pennsylvanian deposits of the Narragansett and Norfolk Basins are separated by no more than 1 km near the northeastern corner of Rhode Island, suggesting that the two basins were formerly connected. Recent geophysical studies off southern New England (McMaster and Collins, 1978, p. 15) suggest that the basin extends 16–22 km south-southwest of Narragansett Bay.

Contacts between Pennsylvanian sedimentary rocks and basement rocks along the basin margin and within the basin are exposed in only a few localities. In some exposures, the contact is an unfaulted unconformity; in others, the Pennsylvanian rocks are in contact with basement rocks as a result of faulting (Quinn, 1971; Skehan and others, 1976; Lyons, 1977).

A relatively simple geometry has been assumed for the basement-cover configuration (Shaler and others, 1899, fig. 8). High-angle normal and low-angle thrust faults are thought to define the irregular contact in places. A schematic structural profile of the southern Narragansett Basin is shown in figure 3.

STRATIGRAPHIC RELATIONSHIPS

Five formations, now referred to collectively as the Narragansett Bay Group (new name), are recognized in the Narragansett Basin, the Pondville Conglomerate, the Wamsutta Formation, the Rhode Island Formation, the Dighton Conglomerate, and the Purgatory Conglomerate. All these consist of clastic terrigenous sedimentary rocks. Lack of outcrop coupled with rapid facies changes and structural complexities has prevented the construction of a detailed stratigraphy for the Narragansett Basin. The stratigraphic sequence of these units is the same as that presented by Mutch (1968, fig. 2), except for the age assignment of the Purgatory Conglomerate, which may be correlative with the Dighton Conglomerate. A previously estimated total thickness (Shaler and others, 1899) of 3,700 m for these formations was highly speculative; however, it is consistent with stratigraphic sections determined recently from depth to basement under the Narragansett Basin computed from gravity observations (Peter Sherman, written commun., 1978). The lithologic characteristics and ages of these formations are summarized in table 1.

Pondville Conglomerate.—The type locality for the Pondville Conglomerate is in the Norfolk Basin at Pondville Station, Mass. (Shaler and others, 1899, p. 134–139), where it consists of coarse conglom-

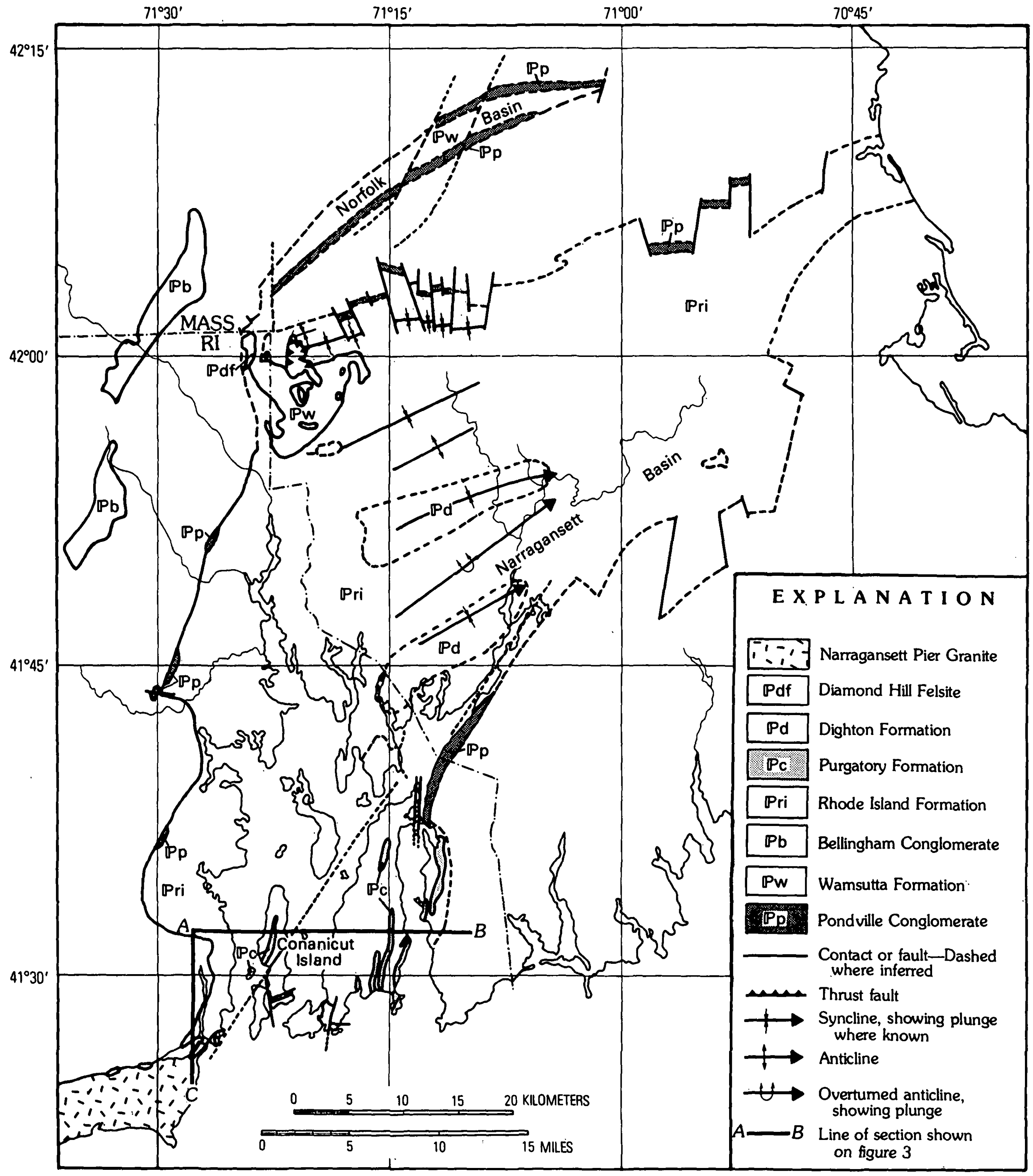


FIGURE 2.—Geologic map of the Narragansett, Norfolk, North Scituate, and Woonsocket Basins, Massachusetts and Rhode Island. Locations of structural profiles (figs. 3, 5) are shown. The complex fold patterns of the southern part of the Narragansett Basin are not shown.

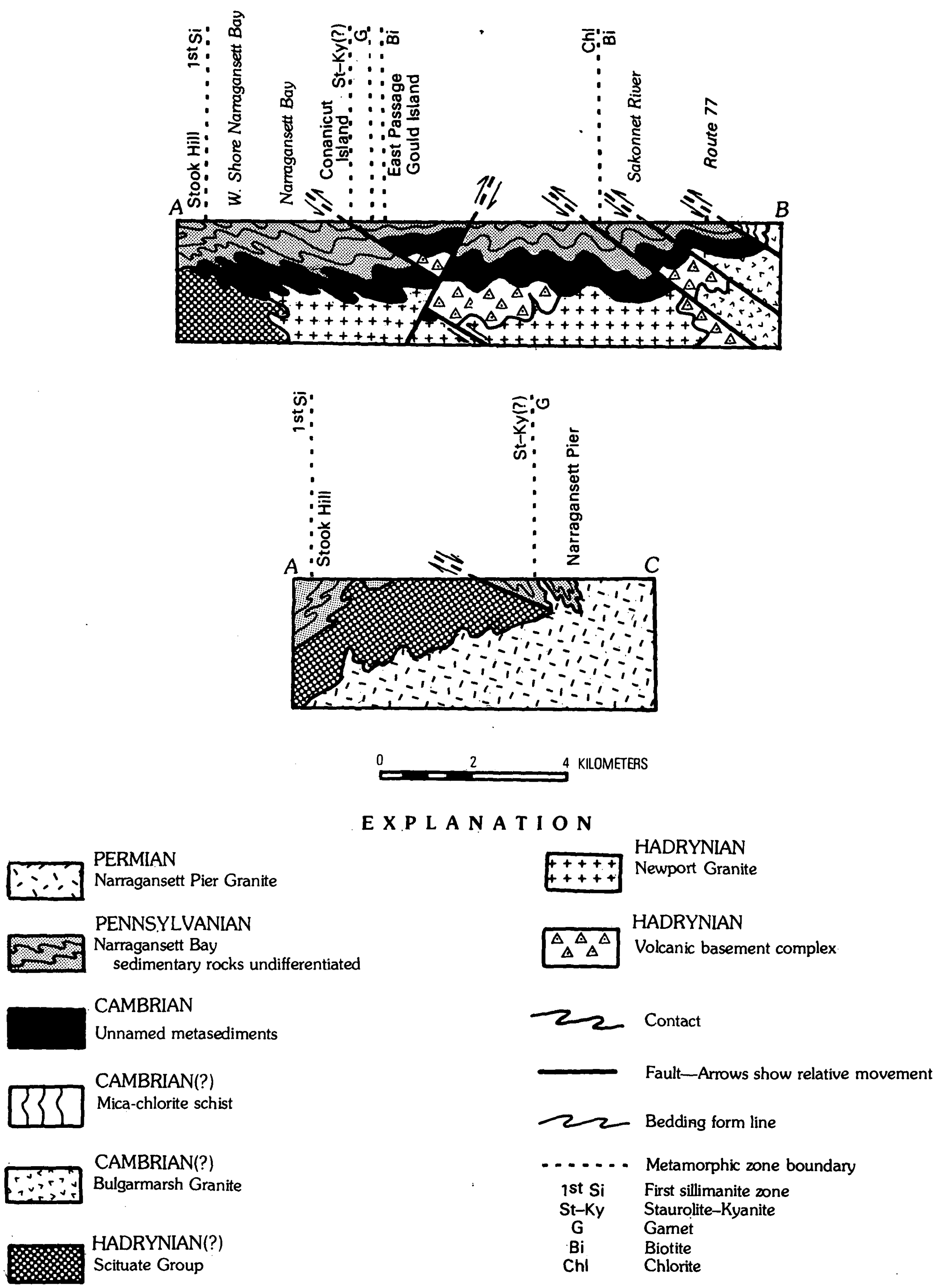


FIGURE 3.—Schematic structural profile across the southern Narragansett Basin.

TABLE 1.—*Description of stratigraphic units in the Narragansett and Norfolk Basins*

Stratigraphic unit	Lithology	Sedimentary and other distinguishing features	Approximate thickness	Age	References [1]
Purgatory Conglomerate.	Coarse-grained to very coarse grained conglomerate, interbedded with thin sandstone and magnetite-rich sandstone lenses; clasts in conglomerate are almost entirely quartzite, but several varieties of quartzite are present.		>30 m (>100 ft)	No Pennsylvanian floro yet known, but coal pebble is present; several distintive lower Paleozoic faunas are present in quartzite clasts.	Mosher and Wood, 1976.
Dighton Conglomerate.	Gray conglomerate consisting primarily of rounded quartzite cobbles to boulders and containing subordinate rounded granite cobbles and slate pebbles; very little sand matrix; lenses of medium sandstone form less than 20 percent of the unit.	The sandstone lenses are faintly cross-bedded and coarser both upward and downward into adjacent conglomerate.	<300–450 m (<1,000–1,500 ft)	Small isolated amounts of allochthonous? nondiagnostic plant debris.	Skehan and others, 1976.
Rhode Island Conglomerate.	Gray sandstone and siltstone and lesser amounts of gray to black shale, gray conglomerate, and coal 10 m (30 ft) thick. Quartz forms the major components of the sandstone (Mutch, 1968, fig. 5) and conglomerate.	Both fining- and coarsening-upward sequences are present; paleocurrents have been defined only locally; conglomerate is relatively less abundant than in Dighton.	<3,000 m (<10,000 ft)	Westphalian C and D and Stephanian.	Skehan and Murray, 1978; Lyons and Chase, 1976.

TABLE 1.—*Description of stratigraphic units in the Narragansett and Norfolk Basins*—Con.

Stratigraphic unit	Lithology	Sedimentary and other distinguishing features	Approximate thickness	Age	References [1]
Wamsutta Formation.	Interbedded red coarse-grained conglomerate, lithic graywacke, sandstone, and shale; conglomerate layers contain felsite clasts <1.2 m (4 ft); a few lenses of limestone, one rhyolite flow, and several sheets of basalt are present.	Crossbedding and interfingering of layers is characteristic.	300 m (1,000 ft)	Partly equivalent to the Rhode Island Formation as the red layers interfinger with gray and black; contains a few plant fossils.	Lidback, 1977.
Pondville Conglomerate.	At type locality (Pondville Station, Mass.): interbedded red and green slate, siltstone, arkose, and quartzite-pebble conglomerate; elsewhere may also include gray to greenish coarse conglomerate, most pebbles being quartzite, but some being granite or schist; abundant sandy matrix; and dark-gray granule conglomerate containing pebbles of smoky quartz 5 mm (0.2 in.) in diameter irregularly bedded with sandstone and lithic graywacke.	Generally, a basal conglomerate is absent, and the first-deposited beds are siltstone or arkosic sandstone; however, sandstone and shale of the Wamsutta Formation or Rhode Island Formation may lie directly on older rocks; clasts 15–60 cm (6–25 in.) in diameter.	0–150 m (0–500 ft)	Westphalian A or B.	

[1] These references are in addition to Quinn and Oliver (1962), Mutch (1968), and Quinn (1971), which contain information on all these stratigraphic units.

erate resting unconformably upon pre-Devonian rocks. The conglomerate grades vertically into gray sandstone that grades into Wamsutta redbeds.

However, in the Narragansett Basin, the Pondville consists of discontinuous arkosic beds and, to a lesser extent, conglomerate (Mutch, 1968) resting unconformably upon basement rocks that are at least locally deeply weathered. Its absence along most parts of the basin margin may be due to faulting or nondeposition. Moreover, where present, it grades upward into either the Wamsutta Formation, as in the northwest part of the basin, or directly into the Rhode Island Formation, as in southern Narragansett Bay. Finally, we agree with Mutch (1968, p. 180–181) that in the Narragansett and Norfolk Basins, this unit contains many lithologies (see table 1), but we are continuing the traditional use of the name Pondville Conglomerate rather than using the name Pondville Formation.

Wamsutta Formation.—The type locality of the Wamsutta Formation is at Wamsutta Mills, North Attleboro, Mass. (Shaler and others, 1899, p. 144). This unit consists of conglomeratic to arkosic redbeds (table 1). Unlike the Wamsutta in the Norfolk Basin, the Wamsutta in the Narragansett Basin contains a significant amount of volcanic deposits. The Wamsutta Formation interfingers with gray and black sandstones and shales of the Rhode Island Formation. Mutch (1968, p. 187–188) has described the Wamsutta in detail.

Rhode Island Formation.—The Rhode Island Formation was originally called the Rhode Island Coal Measures (Shaler and others, 1899, p. 134, 159). The evolution of the name and a description of the rocks that compose the formation were given by Mutch (1968, p. 183) and Quinn (1971, p. 39–41). The lithologic characteristics are summarized in table 1.

The Rhode Island Formation consists largely of gray sandstone and siltstone and contains lesser amounts of gray to black shale, gray conglomerate, and coal (table 1). Calcareous rocks are confined to the southwestern metamorphosed part of the basin where they are now represented as amphibolite.

This formation constitutes most of the basin; however, because of stratigraphic complexity and lack of outcrops, it is not well understood. Ongoing work in the basin by the staff of Weston Observatory, Department of Geology and Geophysics, Boston College, is concentrated on the Rhode Island Formation (Weston Observatory Staff, 1977). These studies involve mapping of outcrops and a geophysical and drilling program whose purpose is to delineate the coal resources of the basin. Early results of these studies, including detailed logs of 3,100 m of drill core, have provided preliminary information on sedimentary cycles and the paleoenvironment of the Rhode Island Formation (Skehan and others, 1976. p. 449–458; Skehan and Murray, 1978).

Dighton Conglomerate.—The type locality of the Dighton Conglomerate is in Dighton, Mass. (Shaler and others, 1899, p. 184–187). The Dighton consists, for the most part, of cobble conglomerate in the cores of three poorly defined synclines (fig. 2 and table 1).

Purgatory Conglomerate.—The type locality for the Purgatory Conglomerate is Purgatory Chasm in southern Narragansett Bay. Clasts in the Purgatory are cobble- to boulder-sized quartzite. This formation is confined to the southeastern part of the basin where it is everywhere deformed into a stretched-pebble conglomerate (table 1). In the past it has been correlated either with the Dighton (Emerson, 1917, p. 55) or with the lower part of the Rhode Island Formation (Quinn and Oliver, 1962, p. 67). The recent discovery by John Peck (oral commun., 1978) of a well-rounded coal pebble in the Purgatory, although not diagnostic, favors a higher stratigraphic position rather than a lower one. We believe that now no compelling structural or stratigraphic evidence exists for correlating the Purgatory with the lower part of the Rhode Island Formation; results of ongoing studies show that the Purgatory Conglomerate may be near the top of the stratigraphic column (Sharon Mosher, written commun., 1977; Skehan and Murray, 1978). Thus, on the basis of recent structural data and lithologic similarities, we believe that the Purgatory is probably correlative with the Dighton Conglomerate.

COAL DEPOSITS

The Narragansett Basin supported the limited intermittent mining of anthracite from 1808 until 1959. Studies of this coal were reviewed by Toenges and others (1948) and Quinn and Glass (1958). Because of energy shortages in New England and renewed interest in coal, these coal deposits are being reevaluated in a study that relies heavily upon moderately deep continuously cored boreholes (Skehan and Murray, 1978). This section summarizes the results to date of studies of the coal drilled during this program.

As outcrops of coal-bearing rocks are very scarce in the virtually unmetamorphosed part of the Narragansett Basin, only approximately 25 coal occurrences have been recorded (fig. 4); most of these are prospects or small abandoned mines, and more than half of these places were mined. The largest mine was at Portsmouth, R.I., and yielded more than 1 million short tons (Harry Chase, written commun., 1978).

The locations of completed drill holes, chosen primarily to sample these coal occurrences, are shown in figure 4. The coal is anthracite and semianthracite, not meta-anthracite as previously reported. A complete description of the chemical and physical properties of the coal is contained in Skehan and Murray (1978).

Coal seams sampled during drilling are as much as 10 m thick and commonly are internally folded and brecciated. The coal has an very low sulfur content and is moderate- to high-ash anthracite yielding 13,000–14,700 BTU's per ton (as determined from dry samples free of mineral matter). Megascopically, the coal has a dull graphitic appearance and is friable.

Vitrinites are textured and untextured and show mosaic structures in some samples and have reflectance values in the range of normal anthracite; organic inert components have unusually low reflectances. Mineral matter includes quartz, sericitized feldspar, chlorite, illite or muscovite, calcite, pyrite, marcasite, chalcopyrite, sphalerite, and rutile. Petrographically, three types of coal are seen: (1) normal anthracite similar to Pennsylvania anthracite; (2) brecciated anthracite having graphitic carbon coating on surfaces of voids and cracks and common annealing textures; (3) natural coke having graphitic coating similar to type 2. In both types 2 and 3, the secondary carbon acts as a cementing agent.

These coals are interpreted to have undergone coalification to low-volatile bituminous and semianthracite rank. These two ranks were then deformed to produce natural coke and brecciated anthracite, respectively; voids may have formed where coal migrated to low-pressure areas. The deformation also released methane that was subsequently thermally cracked to produce a carbon-rich gas phase. Upon cooling, carbon precipitated out to give the graphitic coating now seen, (Ralph Gray, written and oral communs., 1978). This model for the evolution of the coals correlates well with the known tectonic and metamorphic history of the Narragansett Basin and can also explain many of the previously confusing physical and chemical analyses of the coals.

STRUCTURAL GEOLOGY

The Narragansett Basin is characterized by two structural domains separated approximately along the State boundary between Massachusetts and Rhode Island. In Massachusetts, the deformation was relatively mild, being characterized by northeast- to east-northeast-trending folds (fig. 2) having axial planes dipping moderately to steeply to the northwest. In Rhone Island, the deformation was more intense and is characterized by mainly north-trending folds. It is not yet clear whether this change in trend is accomplished abruptly near the head of the Narragansett Bay, approximately along the Rhode Island-Massachusetts border, or gradually along an arcuate path whose axial region is the area noted above. The southern part of the basin is characterized by folds overturned to the west and associated east-dipping cleavage. The northern part of the basin, like the northern part of the Norfolk Basin (fig. 2), appears to be characterized by less intensely deformed folds that are overturned to the southeast and by associated northwest-dipping cleavage. The rocks of the southern part of the basin are lightly overprinted by structures that are dominant in the northern part of the basin. The Carboniferous rocks of the Narragansett Basin show fewer magnetic lineaments than the rest of southern New England west of the basin (Barosh and others, 1977). Those present are extensions of magnetic lineaments in older basement rocks.

Pennsylvanian rocks at several widely separated localities, such as the Hanover, Mass., and Middletown, R.I., areas, rest unconformably on older rocks of Late Precambrian and Cambrian age. At several other widely separated localities, Precambrian and Cambrian rocks are in fault contact with Pennsylvanian rocks. Whether the Pennsylvanian rocks were for the most part deposited on an extensively eroded land surface or in separate faulted basins is not yet known.

Southern Narragansett Basin.—Mapping by Mosher and Wood (1976) and Skehan and Murray (1978) has shown that the dominant structural features of the southern part of the Narragansett Basin are asymmetric westward-verging folds having east-dipping axial-plane cleavage. Closely associated east-dipping, west-directed thrust faults displace Pennsylvanian rocks. Superimposed on these earlier formed structures is a less conspicuous cleavage commonly associated with westward-dipping, high-angle reverse faults (Skehan, Belt, and Rast, 1977; Mosher and Wood, written commun., 1977; Skehan and Murray, 1978). Late normal faults cut earlier structures (Quinn, 1971, pl. 1).

A stretched-pebble conglomerate containing extraordinarily elongated pebbles is present in many different localities in the southern Narragansett

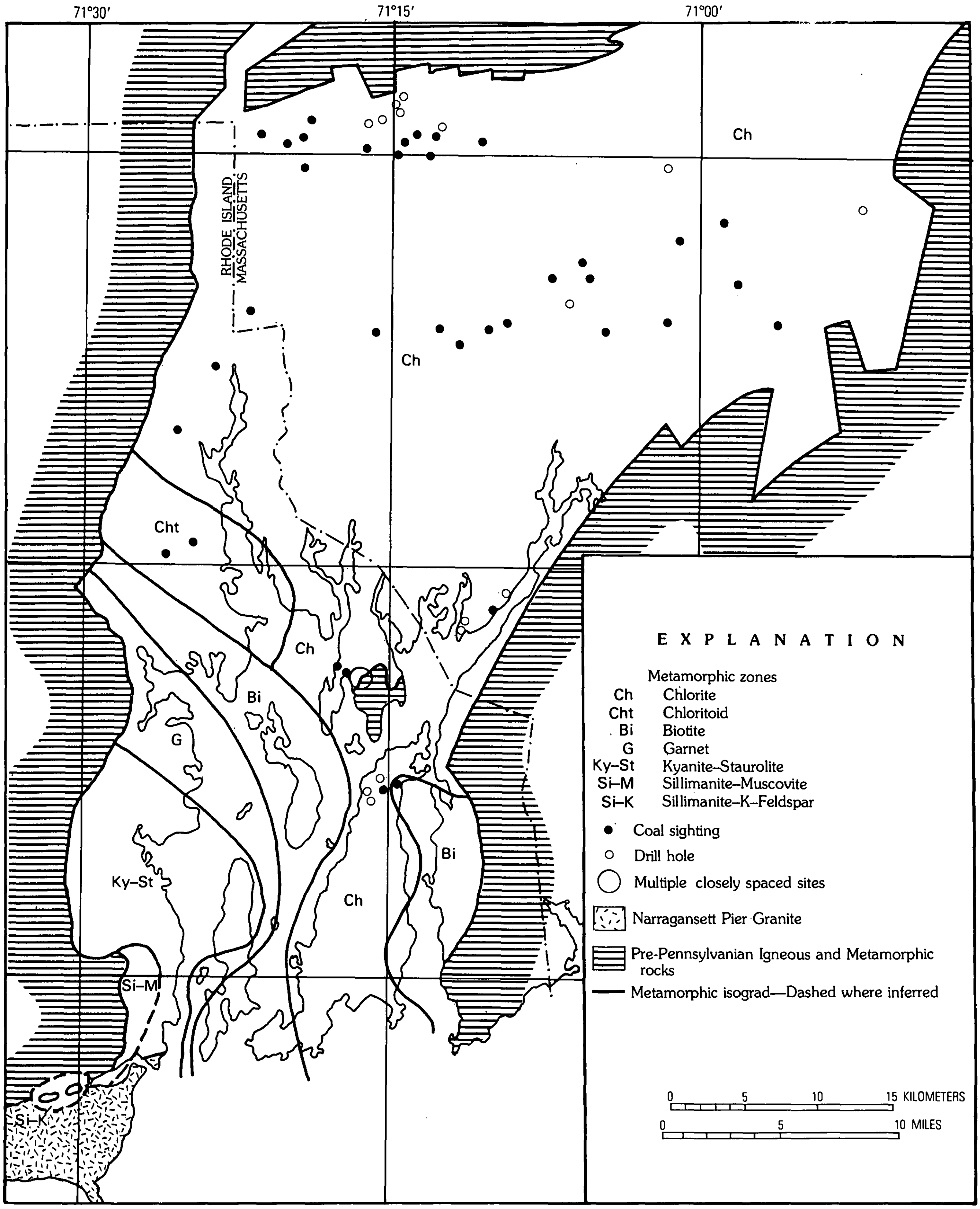


FIGURE 4.—Metamorphic zones and locations of drill holes and coal sightings in the Narragansett Basin.

Basin. A classic location is at Purgatory Chasm, Aquidneck Island, Rhode Island, the type locality of the Purgatory Conglomerate. The longest axis is typically parallel to the primary fold axis.

Northern Narragansett Basin.—The regional folding pattern in the northern part of the Narragansett Basin is defined chiefly by reconnaissance mapping of the Dighton Conglomerate in the east-northeast-trending Great Meadow and Dighton synclines (Shaler and others, 1899; Lyons, 1977). The intensity of metamorphism and deformation effects in the north are far less than in the south.

Faults.—Faults of several orientations and relative ages have been recognized and mapped in a preliminary and reconnaissance fashion (Shaler and others, 1899; Quinn, 1971; Skehan and others, 1976; and Lyons, 1977). Figure 2 shows a number of such faults.

West-directed, east-dipping thrusts, interpreted as early, are succeeded by west-dipping high-angle reverse faults. These compressional faults are considered to be of Alleghanian age. Preliminary mapping by ourselves and by Lyons (1977) suggests that the southeastern margin of the basin may be controlled by such a fault, although its angle of dip is not yet known. The northeasern part of the basin may be a thrust cut by later normal faults (fig. 2).

At the Masslite Quarry, Plainville, Mass., southeast-dipping thrust faults, cut by later north-striking normal faults, are recognized. This sequence of faults suggests that the Pennsylvanian rocks of the Narragansett Basin may have been thrust northwestward over the basement and later displaced by normal faults. An 865-foot NX-cored hole near the quarry shows that the Pennsylvanian sedimentary rocks are unconformable on the basement; therefore, the above-mentioned thrust faults are in the cover rocks.

The northern margin of the basin (fig. 2) and the eastern third of the southern margin are assumed to be offset by normal faults that strike generally within 20° of north. Quinn (1971) mapped a horst block near the southeastern margin of the basin as being bound by north-striking faults and as exposing basement rocks of the Metacom Granite. The granite is cut by a series of closely spaced east-dipping older thrusts. The western margin of the basin at Diamond Hill is marked by a generally north-striking silicified fault zone (Quinn, 1971), similar in orientation to that in Bristol, R. I. (fig. 2).

Faults striking generally northwest or northeast may be more numerous than previously recognized; offset on the northeast-striking faults may be more important than offset on the northwest-striking faults. Evidence for the existence and orientation of the northwest-striking faults in the southern part of the basin consists of (1) various combinations of topographic and drainage alinements that in some places are associated with subparallel orientation of structural elements in the bedrock, (2) offsets of basin margins, and (3) steplike offsets of shorelines. Because these faults have limited demonstrated continuity, they have not been shown in figure 2.

METAMORPHISM

The Narragansett Basin has undergone a Barrovian regional metamorphism that increases in intensity to the southwest as shown in figure 4. The metamorphic gradient is neither uniform nor simple. All the Massachusetts part of the basin and part of the Rhode Island part of the basin are in the chlorite zone, on the basis of mineral assemblages and coal rank. The thermal maximum of this regional metamorphism is roughly centered about the contact between the Narragansett Pier Granite and Pennsylvanian metasediments. However, in detail, it appears that (1) the isograds are oblique to structural trends but are truncated by the granite, and (2) the thermal maximum is actually displaced somewhat to the north of the granite. Our ongoing studies of the southwestern part of the basin suggest that the peraluminous Narragansett Pier Granite is anatectic in origin and thus may be one of the results of the metamorphism and not the cause.

Radiometric dates on muscovite and biotite from the kyanite-staurolite zone indicate a Permian age for the metamorphism (Hurley and others, 1960). Moreover, sillimanite-bearing mineral assemblages in eastern Connecticut may represent the western extension of the Alleghanian metamorphism recorded in Rhode Island (Murray and others, 1978).

Our studies also suggest that sedimentary rocks in the southwestern part of the basin record three episodes of metamorphism: (1) an early greenschist facies of dynamothermal metamorphism; (2) a later period of static prograde Barrovian facies series that peaked at the second sillimanite isograd; and (3) a youngest, localized greenschist facies of dynamothermal retrograde metamorphism.

Because of the availability of thousands of meters of drill core from Massachusetts and northern Rhode Island and abundant sea cliff exposures, roadcuts, and drill core from construction sites in the southwestern part of the basin, we have begun a study of the effects of progressive metamorphism and deformation on coal and associated rock under a wide range of conditions (D. Murray, J. Rehmer, and J. C. Hepburn, unpub. data, 1978). Because of the sensitivity of coal to changes in temperature, pressure, and other factors, study of this area promises to yield valuable insights into regional metamorphic processes.

IGNEOUS ACTIVITY

Both extrusive and intrusive igneous rocks are present within or adjacent to the Narragansett Basin. The former are limited to felsic and mafic flows within the Wamsutta Formation in the Attleboro area. Moreover, the Wamsutta contains a relatively high percentage of volcanic detritus, implying the presence of abundant volcanoes during its formation (Mutch, 1968).

The subsolvus Narragansett Pier Granite intrudes the southwest margin of the Narragansett Basin. Away from the contact with the sedimentary rocks, this pink granite contains abundant biotite and subordinate muscovite. Near the Pennsylvanian sedimentary rocks, the granite is white, and muscovite plus garnet are common (Kocis and others, 1977, 1978). Recently obtained paleontologic dates from xenoliths within the granite (Brown and others, 1978) and radiometric dates from monazites (Kocis and others, 1978) confirm the previously assumed Permian age for the granite.

Other Permian plutonic events are probably represented by pegmatites found throughout southern New England (Zartman and others, 1970) and by the granite in southern New Hampshire (J. B. Lyons, oral commun., 1978).

AGE RELATIONSHIPS

Radiometric dates coupled with the abundant floral dates allow a precise definition of the Alleghanian orogeny as recorded in the Narragansett Basin. Floral dates indicate that deposition of sediments began in early Pottsvillian (Westphalian B) time and persisted at least through Conemaughian (Stephanian A) time. Moreover, at least several hundred meters of Rhode Island Formation plus the Dighton Conglomerate lie stratigraphically above the Stephanian A (or younger) dated rocks. This stratigraphic succession suggests that deposition probably continued well into Conemaughian (Stephanian A) time and possibly into early Monongahelan (Stephanian B) time (280 million years ago).

Mutch (1968, p. 198) summarized radiometric data collected through the mid-1960's. Most of these ages should be used with caution because they are either (1) anomalously old (because of older inherited ages in detrital material) or (2) anomalously young (because of migration of radiogenic material). Of the ages listed in Mutch's review, the Rb/Sr biotite and K/Ar whole-rock ages of Hurley and others (1960) are probably the most useful. These, as well as other ages, were obtained by them from biotite-staurolite-garnet schist on Conanicut Island, southern Narragansett Bay, and indicate that the major progressive metamorphism took place 260 ± 13 m.y. (million years) ago. The somewhat younger (≈230 m.y.–250 m.y.) K/Ar biotite ages also given may represent ages of cooling or uplift.

Recently, the Narragansett Pier Granite was dated at 276 m.y. on the basis of U-Pb ages on monazites (Kocis and others, 1978). Dikes of the Westerly Granite, a homogeneous peraluminous granite, cut the western part of the Narragansett Pier Granite and have been dated at 240 m.y. (Hurley and others, 1960). This also may represent a cooling age, rather than the age of a much younger intrusion.

Taken together, the age relationships suggest that deposition of sediments began in Upper Pottsvillian (Westphalian B) and continued at least through Conemaughian time (Stephanian A). The deposits were buried, deformed, and metamorphosed by 260 m.y. ago.. The intrusions of the granites were virtually contemporaneous at 276 m.y. ago. K/Ar ages in the range of 230 my. to 250 m.y. may record uplift or cooling.

NORFOLK BASIN OF MASSACHUSETTS

By Daniel P. Murray and James W. Skehan, S.J.

The Norfolk Basin is a northeast-trending basin that extends from the northwest margin of the Narragansett Basin toward the Boston Basin (fig. 2). The Norfolk and Narragansett Basins are now separated by about 1 km but were probably connected prior to the formation of the present erosion surface and therefore are shown as one basin in figure 2. Most of the Norfolk Basin is within the Norwood and Blue Hills quadrangles, which were mapped by Chute (1964, 1966, 1969). The sedimentology of one of the major outcrops in this basin was the subject of a detailed study by Stanley (1968).

Stratigraphic relationships.—The Pennsylvanian rocks of the Norfolk Basin consist of two units, the Pondville Conglomerate and the Wamsutta Formation. The Pondville is subdivided into a lower boulder conglomerate member and an upper member of gray coarse sandstone to pebble conglomerate. On the basis of plant megafossils, the upper member has been dated as late Pottsvillian (Lyons and others, 1976). The upper member grades upward into the Wamsutta which, except for the absence of volcanic deposits, is similar to the formation as exposed in the Narragansett Basin. A subaerial paleoenvironment had been previously assumed for the Wamsutta on the basis of the red color and presence of mud cracks (Stanley, 1968). However, the redness of deposits is no longer considered sufficient to indicate a subaerial origin (Van Houten, 1973), and the cracks are reinterpreted by the authors to be dewatering structures. The Wamsutta is thought to represent outwash or sheet deposits on flood plains that formed adjacent to alluvial fans (now seen as the coarser grained Pondville Conglomerate).

Structure and metamorphism.—The dominant structural feature of the Norfolk Basin is a northeast-trending syncline overturned to the southeast; this mainly defines the shape of the basin. Several high-angle north-striking faults also cut the basin (Lyons, 1977, Map B–24). However, the displacement on them is not great. The Pennsylvanian rocks are in part bounded by thrust faults. A schematic structural profile across the Norfolk Basin is shown in figure 5. The entire basin is in the lower greenschist facies.

WOONSOCKET AND NORTH SCITUATE BASINS OF MASSACHUSETTS AND RHODE ISLAND

By JAMES W. SKEHAN, S.J., and DANIEL P. MURRAY

The rocks of the Woonsocket and North Scituate Basins (fig. 1) have long been correlated with rocks at Bellingham, Mass. (Mansfield, 1906, p. 99), referred to as Bellingham Conglomerate (Hall, 1963, p. 53). The rocks of these basins consist of gray to green conglomerate, sandstone, lithic graywacke, and phyllite, all irregularly interbedded (Quinn, 1971, p. 42). In the Woonsocket Basin, the dominant quartzite pebbles are elongate, but in the North Scituate Basin, pebbles are less elongate, conglomerate is less abundant, and sand-size grains are predominant (Quinn, 1971, p. 42).

Structure and metamorphism.—Two alternate interpretations of the structure of these basins are presently permissible: (1) On the basis of a general easterly dip and discordance of the basin rocks with the structure of the older rocks, the eastern borders may be a fault (Richmond, 1952); or (2) the basins may be large infolded synclines, overturned to the northwest. These garnetiferous rocks are in the upper greenschist facies.

On the basis of preliminary structural studies by Hall (1963, p. 53), two and probably three phases of deformation are recognized. The first phase of folding warped bedding around northeast-plunging axes (B1) and caused the formation of an east-dipping axial-plane schistosity; a mica lineation, quartz rods, and stretched pebbles are all parallel to the fold axes. The second phase warped the axial-plane schistosity of B1 folds in an east-northeast direction and caused the formation of a new schistosity and a "crinkle" lineation due to intersection of the two schistosities. A third phase apparently folded the first schistosity as well as the pebbles and warped the crinkle lineation.

Age.—The rocks of the Woonsocket and North Scituate basins may be correlative with those of the Narragansett Basin. We suggest the alternative pos-

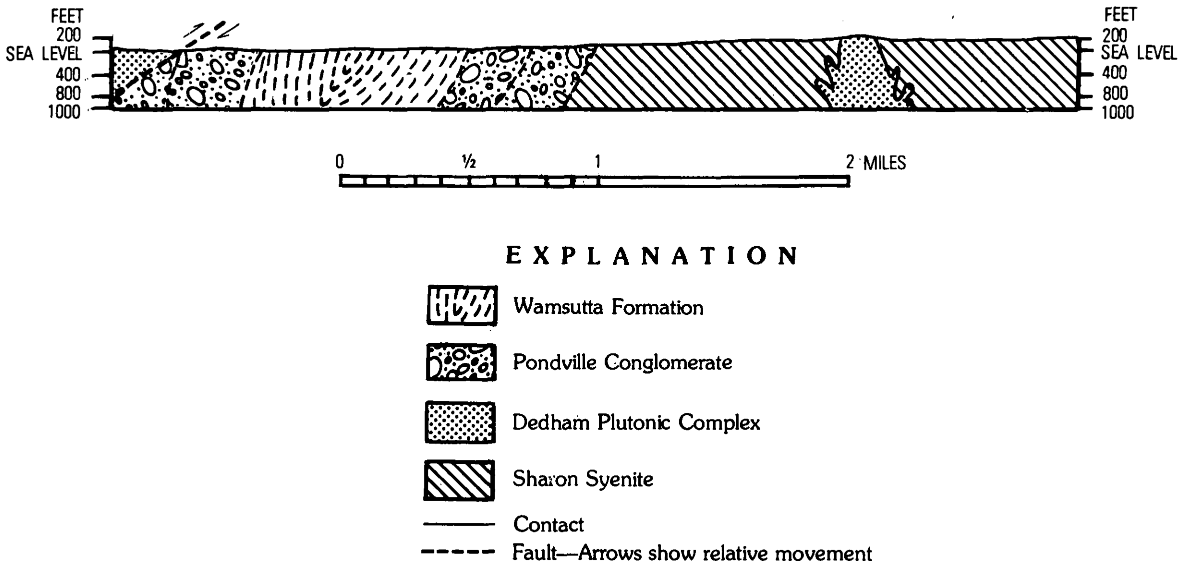


FIGURE 5.—Schematic structural profile across the Norfolk Basin.

sibility that they may be much older. Because these two basins may be virtually in the same structural position as the Boston Basin with respect to the authenticated Carboniferous basins, an understanding of the age of any of these basins' sedimentary rocks may apply to the others.

DEPOSITS NEAR WORCESTER, MASS.

By J. CHRISTOPHER HEPBURN

Two small patches of nonmarine Carboniferous rocks near the city of Worcester in east-central Massachusetts are shown by one symbol in figure 1. Pennsylvanian-age plant fossils have been identified from the northern outcrop area.

Lithology.—Gray to dark-gray, very carbonaceous slate or phyllite is the predominant rock in the northern outcrop area (fig. 6). One 2-m-thick lens of very impure, shiny, black meta-anthracite is present within the phyllite at the site of the long-abandoned "Worcester Coal Mine." A similar phyllite is also present in the poorly exposed southern outcrop area (fig. 6) where it is interbedded with coarse stretched-pebble, polymict conglomerate, feldspathic granule conglomerate, and arkose. The clasts in the conglomerate are in a shaly matrix.

Structure and metamorphism.—The Carboniferous rocks of the Worcester area are moderately to steeply dipping, and the finer grained rocks show a secondary slip cleavage. Electron-microprobe analysis of small garnet porphyroblasts in the phyllite show them to have appreciable MnO (as much as 9.1 weight percent). Thus, the grade of metamorphism is somewhat below that for the normal almandine isograd.

Age.—The "Worcester Coal Mine" has long been of geological interest and has been visited by such luminaries as E. Hitchock, Lyell, and Agassiz. Fossils were first found in 1883 supposedly in response to a remark by Agassiz of "Where are the fossils?" (Perry and Emerson, 1903, p. 18). Grew, Mamay, and Barghoorn, in the most recent summary of the plant fossils, indicate that they "are clearly of Carboniferous age and most likely of the Pennsylvanian Period" (1970, p. 122) and that they most likely can be assigned a Pottsville age. However, P. C. Lyons (in Grew, 1976, p. 395) suggested that the flora is Alleghenian (Westphalian C) in age, that is, younger than Pottsville (fig. 10).

The granite-pebble conglomerate in the southern outcrop area contains clasts of the adjacent blue-quartz-bearing Millstone Hill Granite which has been dated at 345±15 m.y. (Zartman and others, 1965). Therefore, the conglomerate containing this granite must be of Carboniferous age.

Correlation.—Because no readily observable structural or metamorphic breaks exist between these poorly exposed Pennsylvanian rocks and the surrounding rocks, Emerson (1917), in his summary of Massachusetts geology, assigned a Carboniferous age to many of the rocks in central Massachusetts. Recent detailed mapping in the Worcester area (Grew, 1973; Hepburn, 1976; J. C. Hepburn and E. S. Grew, unpub. data, 1977) has shown that the Pennsylvanian deposits are restricted to two small, largely fault-bounded basins. The nomenclature of the Pennsylvanian rocks of the Worcester area is in a state of flux at present. The Worcester Phyllite in the original formational designations (Emerson, 1917; Perry and Emerson, 1903) included both Pennsylvanian and what are now believed to be pre-Pennsylvanian rocks. Probably, the name Worcester Phyllite will be restricted to the pre-Pennsylvanian rocks (Hepburn, 1976) and a new designation will be given to the Pennsylvanian rocks. Whether the conglomeratic units in the Pennsylvanian of the Worcester area are similar in age to, and can be correlated with, the Harvard Conglomerate to the northeast is still not clear.

The Pennsylvanian rocks of the Worcester area probably once were continuous with rocks of similar age in the Narragansett and Norfolk Basins and likely were deposited under similar conditions.

Harvard Conglomerate at Pin Hill.—An isolated deposit of the Harvard Conglomerate at Pin Hill in Harvard, Mass. (fig. 1), has been considered Pennsylvanian in age (Emerson, 1917; Thompson and Robinson, 1976). However, the unit is unfossiliferous, and the field relationships have been debated.

BOSTON BASIN, MASSACHUSETTS

By MARLAND P. BILLINGS

The Boston Basin is a lithologic-tectonic unit that trends east-northeast, is 50 km long, and is 25 km wide (fig. 7). The basin is also a topographic lowland, bounded on the north by the Fells Upland and on the south by the Blue Hills and Sharon Upland (LaForge, 1932, p. 8). On the east, the Boston Basin is submerged by Boston Harbor and Boston Bay, but on the southwest, it merges imperceptibly with the Needham Upland.

The most recent summaries of the bedrock geology by Billings (1976a, b) and other pertinent articles are in Lyons and Brownlow (1976) and New England Intercollegiate Geological Conference (1976).

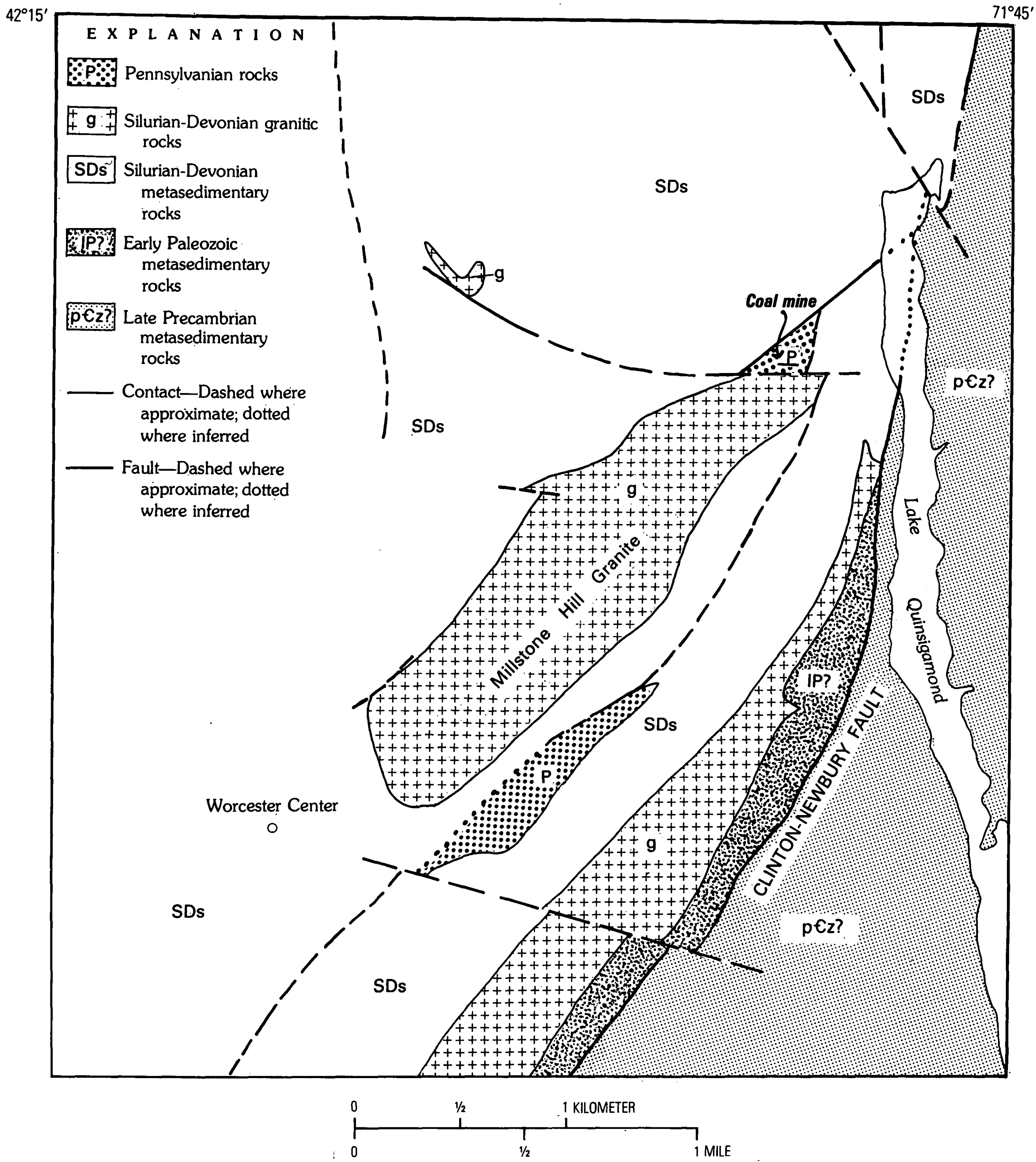


FIGURE 6.—Geologic map of the Worcester area, Massachusetts.

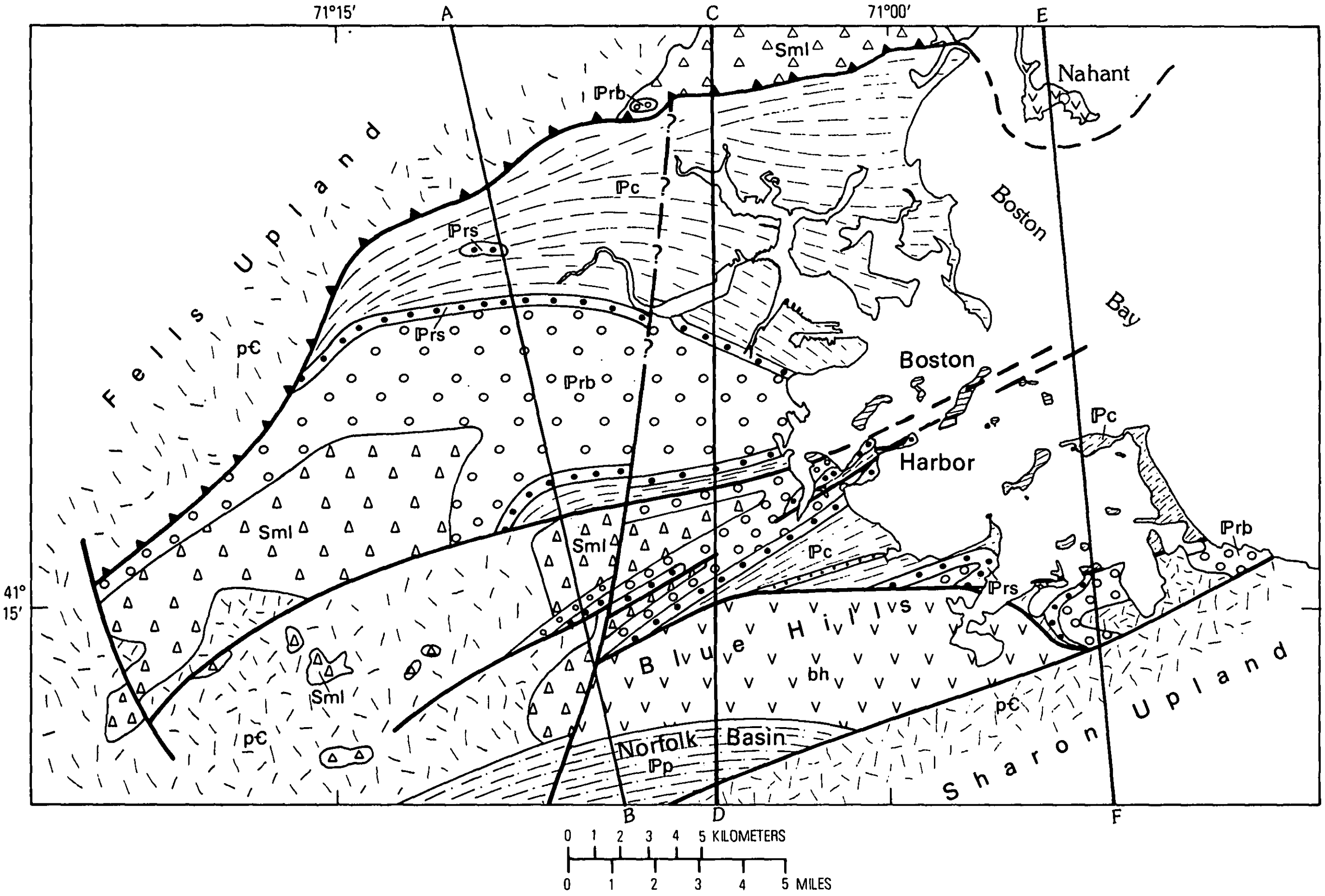


FIGURE 7.—Geologic map of the Boston Basin, Massachusetts. Structural profiles along lines AB, CD, and EF are shown in figure 8. Symbols are shown on p. A18.

LITHOLOGY

In this paper, the rocks will be described as belonging to the following units: (1) "basement," (2) Mattapan and Lynn Volcanic Complexes, (3) Boston Bay Group, and (4) rocks of the Blue Hills-Quincy and Nahant areas. The Triassic(?) diabase is not shown and is not discussed in figure 7.

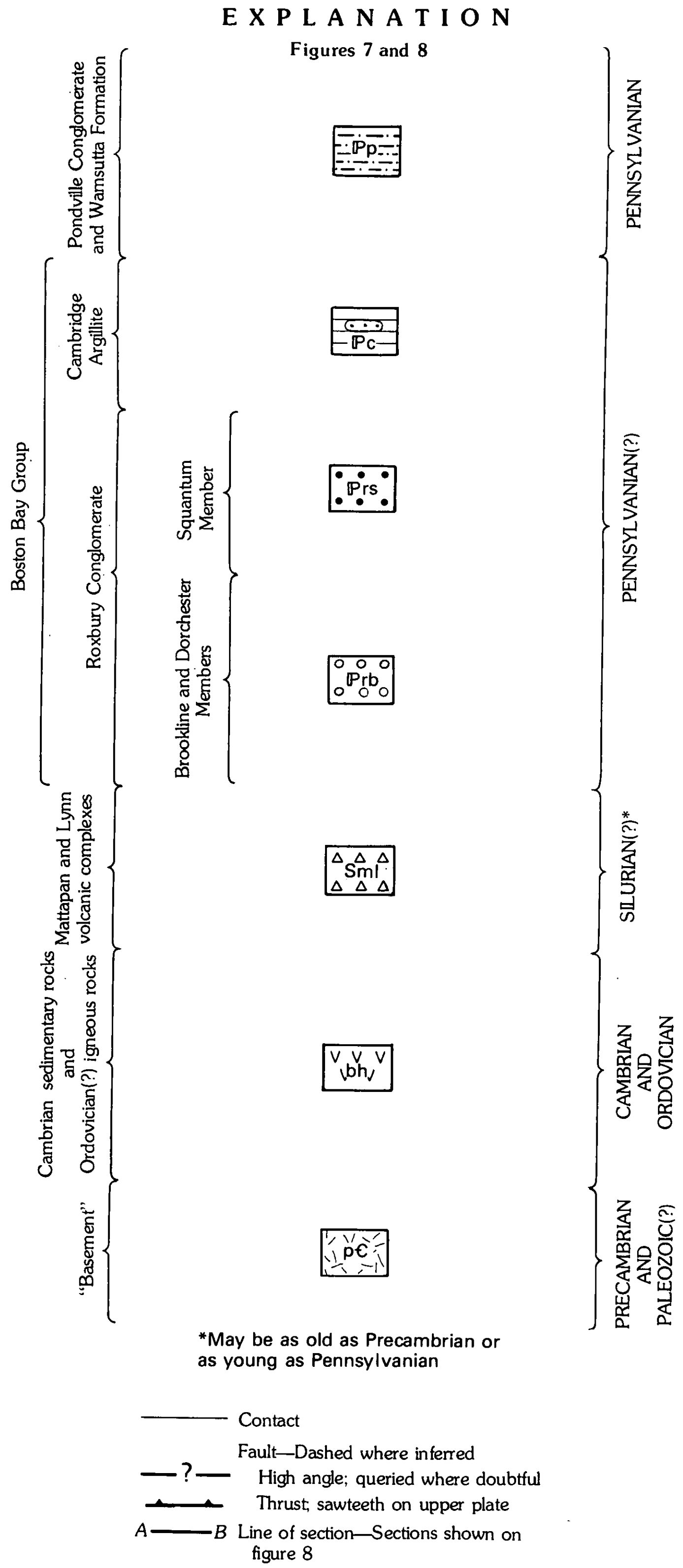
"BASEMENT"

A description of "basement" rocks is beyond the scope of the present paper. The reader is referred to Emerson (1917), LaForge (1932), Bell and Alvord (1976), Castle and others (1976), and Nelson (1975). Within the limits of figure 7, many or all rocks in the "basement" are Precambrian; some may be Paleozoic.

MATTAPAN AND LYNN VOLCANIC COMPLEXES

The Mattapan and Lynn Volcanic Complexes are chiefly hard dense white, pink, and red rhyolites, often called felsite locally. The less abundant melaphyres are dark green to light green and are composed largely of such secondary minerals as albite, hornblende, and epidote. Some trachytes and andesites are present (Emerson, 1917, p. 204). Pyroclastic rocks include crystal tuff, lapilli tuff, breccia, and lahars (Nelson, 1975). Although much of the material in the Lynn and Mattapan Volcanic Complexes appears to have been erupted on the surface as flows, ashfalls, and ashflows, it has long been known that many bodies occupy vents and dikes in the older rocks, such as the Dedham Granodiorite.

The Mattapan is 600 m thick in Hyde Park (Billings, 1929, p. 104); data given by Nelson (1975) indicate that it is at least 760 m thick in Dover and Natick. But in places, as in Hingham and Nantasket, the formation is absent. In 1929, I (Billings, 1929, p. 104) thought that an angular unconformity separated the Mattapan from the overlying Roxbury.



These volcanic complexes are younger than the Dedham Granodiorite, which is 608±17 m.y. or latest Precambrian (Dowse, 1950; Kovach and others, 1977). Moreover, the pronounced unconformity between the volcanic complexes and the Dedham (LaForge, 1932, p. 31) indicates deep erosion after the emplacement of the Dedham and the eruption of the volcanic complexes. R. E. Zartman has recently obtained a zircon age of 580 m.y. from a rhyolite in the Mattapan Volcanic Complex (E-an Zen, written commun., 1977). Such ages are questionable (Higgins and others, 1977), especially for a rock that is present in vents. LaForge (1932, p. 33) said that the Lynn "is cut by the Quincy granite type." Zartman and Marvin (1971) dated the Quincy as 437±32 m.y. (latest Ordovician).

If the Mattapan can be correlated with the volcanic rocks in the Blue Hills, as Chute (1969) assumed, then it is latest Ordovician. The radiometric dates are consistent with assigning the Mattapan and Lynn Volcanic Complexes to the Cambrian or Ordovician.

The Newbury Volcanic Complex is dated by fossils as latest Silurian and possibly earliest Devonian (Shride, 1976, p. 147). This complex can be traced to within 13 km of the Lynn Volcanic Complex. The Newbury and Lynn are lithologically similar. On the basis of dubious paleontological evidence, Pollard (1965) suggested that the Mattapan is Mississippian. Rhyolite and melaphyre similar to those in the Mattapan and Lynn Volcanic Complexes are present in the Alleghenian (Pennsylvanian) Wamsutta Formation of the Narragansett Basin (Emerson, 1917). The possibility that the Mattapan and Lynn may be as old as Precambrian or as young as Pennsylvanian is adopted in figure 7.

BOSTON BAY GROUP

Perhaps the most striking new interpretation of rocks in the Boston Basin is that the Roxbury Conglomerate is a southerly facies of the lower part of the Cambridge Argillite. The rocks of the Boston Bay Group are relatively unmetamorphosed, although some chlorite is present. The maximum thickness of 5,700 m is found in the northern half of the basin, but toward the south, the known thickness is only 1,600 m. The group is probably Pennsylvanian, although many geologists would accept a much older age. An excellent concise tabular summary of the lithology is given in Rehmer and Roy (1976, p. 72).

ROXBURY CONGLOMERATE

The Roxbury Conglomerate is a complex assemblage of nonmarine conglomerate, shale, sandstone, quartzite, arkose, melaphyre, and diamictite. Most of the rocks, except the diamictite, are present throughout the formation. The division into members is based on the relative abundance of the various lithologic types. From bottom to top the three members are: Brookline, Dorchester, and Squantum. The compositions and distinctive features of these members were described by Billings (1976a) and by Bailey, Newman, and Genes (1976). The Brookline Member ranges from 300 to 1,310 m in thickness. The Dorchester Member ranges from 84 to 485 m in thickness. Its top is usually defined by the distinctive diamictite of the Squantum Member which many geologists consider to be a tillite (Rehmer and Roy, 1976; Bailey and others, 1976; Wolfe, 1976). The Squantum ranges from 19 to 122 m in thickness.

CAMBRIDGE ARGILLITE

In the southern part of the Boston Basin, where the Cambridge Argillite is above the Squantum Member of the Roxbury Conglomerate, the Cambridge is 2,500 m thick. In the northern part of the basin, where the lower part of the formation is interpreted as a facies equivalent of the Roxbury Conglomerate, the Cambridge is 5,700 m thick. The "Milton Quartzite" (Billings, 1929, 1976a) is a white sericitic quartzite that is 150 m thick and that lies 850 m above the Squantum Member.

LITHOFACIES IN THE BOSTON BAY GROUP

The facies relationship shown in figure 8 is based largely on observations in the City Tunnel Extension (Billings and Tierney, 1964). The axis of the Charles River syncline coincides in this diagram with the northern limit of the Squantum Member. In the south limb of the syncline, the Squantum and Dorchester Members, as well as the upper part of the Brookline Member, are exposed. But where these units should appear on the north limb, they are replaced by the Cambridge Argillite. Moreover, on the south limb, many beds of gray argillite, similar to those in the Cambridge Argillite, are present in the Dorchester Member. Details are given in Billings and Tierney (1964, fig. 9).

AGE OF THE BOSTON BAY GROUP

For 77 years, the age of the Boston Bay Group has been based on supposed fossils found by Burr and Burke (1900) in the Roxbury Conglomerate.

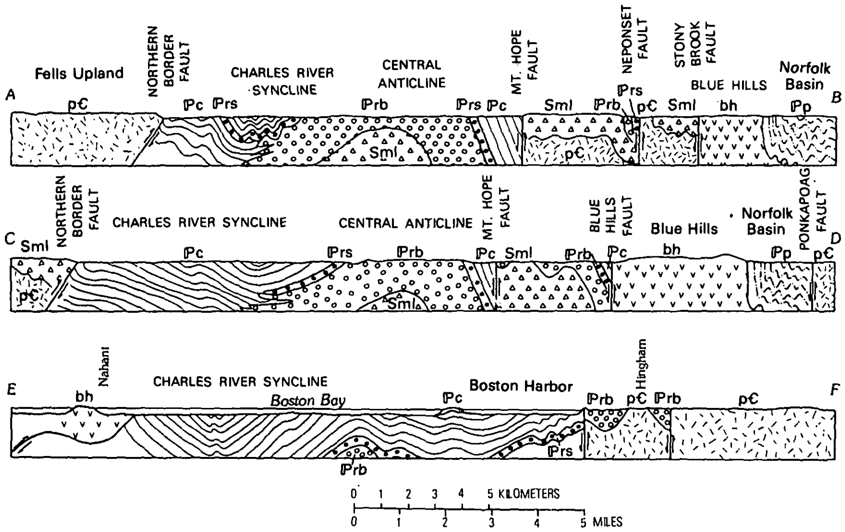


FIGURE 8.—Structural profiles across the Boston Basin along lines AB, CD, and EF shown in figure 7. Symbols are the same as those used in figure 7.

LaForge (1932, p. 38) said: "Except for a few short pieces of tree trunks, of which not even the genus can be certainly determined and which may be either Devonian or Carboniferous, no fossils have been found in these rocks." These specimens were lost for many decades, but one of them was found about 20 years ago in the Harvard paleobotanical collections. Rahm (1962, p. 329) said: "According to Professor Elso Barghoorn (personal communication) the specimens are either *Callixylon* or *Cordaites*, genera which together span a period from the Upper Devonian to the Permian." Professor Barghoorn (oral commun., 1977) has recently concluded that the specimen is inorganic. Bailey and Newman (1978) also consider the specimen to be inorganic, but their proposed mechanism for such an origin is not satisfactory. Under the circumstances, reliable paleobotanical evidence for dating the Boston Bay Group is lacking.

The Roxbury Conglomerate is younger than the Dedham Granodiorite and the Mattapan Volcanic Complex, as many of the clasts in the Roxbury were derived from the Dedham and Mattapan. If, as I believed earlier (Billings, 1929), the Mattapan and Lynn Volcanic Complexes are unconformable beneath the Boston Bay Group, their age tells us only that the Boston Bay Group is younger. However, I agree that the evidence for an unconformity should be restudied.

The most compelling argument on the age of the Boston Bay Group is based on the extensive conglomerate in the Boston Bay Group. In the Narragansett and Norfolk Basins, the only paleontologically dated conglomerate of the kind found in the Roxbury Formation are Pennsylvanian, thus, it seems that tectonic conditions favorable for deposition of "molasse" existed in eastern New England only in the Pennsylvanian.

BLUE HILLS-QUINCY AND NAHANT AREAS

The Blue Hills-Quincy area (fig. 6) contains Lower and Middle Cambrian sedimentary rocks and four mappable igneous units: (1) a volcanic complex (Mattapan Volcanic Complex?), (2) "rhombenporphyry," (3) Blue Hills granite porphyry, and (4) Quincy Granite (Billings, 1976a). The Nahant area contains Lower Cambrian sedimentary rocks and the Nahant Gabbro (Billings, 1976a).

STRUCTURE

A more complete discussion of the geological structure of the Boston Basin has been presented previously (Billings, 1976a, b). Many of the structural features are apparent from the geological map (fig. 7) and structural sections (fig. 8). In order to be more objective, in figure 7 the longitudinal faults in the southern part of the basin are shown as steep (essentially vertical) faults without any indication of their genesis. But I still believe that they are thrusts, originally dipping south, that have been rotated to their present attitude.

Age of Deformation.—The deformation in the Boston Basin is presumed to be the same age as that in the Norfolk and Narragansett Basins, that is, post-Pennsylvanian and older than the Triassic Medford Dike.

BIOSTRATIGRAPHY OF THE PENNSYLVANIAN OF MASSACHUSETTS AND RHODE ISLAND

By Paul C. Lyons

The Narragansett Basin has a rich megaflora consisting of about 300 nominal species, nearly all of which are from the Rhode Island Formation; 31 of these were considered new species or genera by previous workers. The uppermost formation, the Dighton Conglomerate, does not have a known florule. Animal fossils, principally insects and amphibian tracks, have been found, but these are of little stratigraphic importance because of the scarcity of discoveries. Microfloral remains have not been found in the coal or adjacent strata of the Rhode Island Formation. Because structural complexities and facies changes in many parts of the Narragansett Basin interrupt the continuity of the beds, a floral zonation scheme is essential for clarification of the physical stratigraphy.

HISTORY OF BIOSTRATIGRAPHY OF THE NARRAGANSETT BASIN

Some of the earliest contributions to American paleobotany were based on specimens collected during coal mining operations in the Narragansett Basin (Brongniart, 1828–1838; Jackson, 1840; E. Hitchcock, 1841; Teschemacher, 1847). No attempt, however, was made to relate the megaflora to the physical stratigraphy until C. H. Hitchcock (1861) correlated the floral assemblages identified by Lesquereux with the stratigraphic section exposed in the vicinity of Newport, R.I. This first correlation of biologic and rock data was documented by Lyons and Darrah (1977) who concluded that the assemblage in the upper part of the Newport section was of Stephanian age and referable to the Aquidneck shales of Foerste (in Shaler and others, 1899).

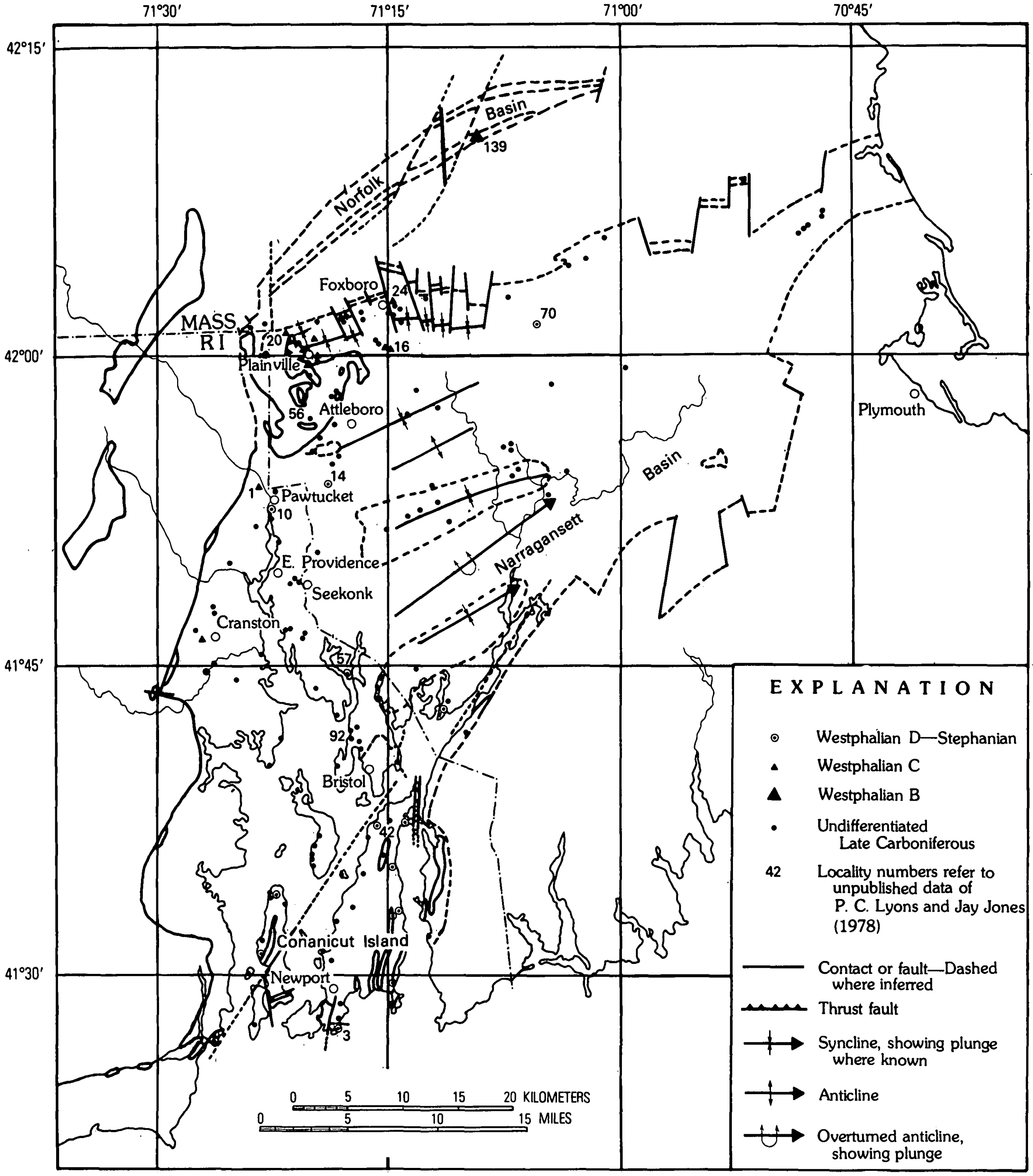


FIGURE 9.—Floral localities in the Narragansett and Norfolk Basins.

The Aquidneck shales are here referred to the upper part of the Rhode Island Formation.

Brongniart's (1828–1838, p. 303) specimens of *Pecopteris arguta* Brong. (=*P. feminaeformis* Schloth.) apparently came from the roof shales of the coal beds mined at Portsmouth, R.I. (fig. 9, loc. 42). The Portsmouth coals were assigned to the Aquidneck shales (Shaler and others, 1899). Coal mining began here in 1809, and these coal beds yielded approximately 2 million tons of coal by the end of the century. A similar amount of coal is still unmined (H. B. Chase, oral commun., 1977).

Further contributions to the flora of the coal-bearing Rhode Island Formation were made later in the 19th century (Jackson, 1851; Lesquereux, 1880–84, 1884, 1889; Clark, 1884; Fuller, 1897; Providence Franklin Society, 1887; Shaler and others, 1899). These authors provided lists of species but little analysis of the stratigraphic positions of these floras.

Weston (1917) and Round (1920) presented many photographs and sketches of the flora of the Narragansett Basin. Weston's thesis (1917) contained little stratigraphic or locality data. Round's thesis (1920) provided generalized locality information indicating that her work was based mainly on specimens derived from the lower part of the Rhode Island Formation, including the Pawtucket (fig. 9, loc. 10) and Valley Falls coal beds (fig. 9, loc. 1). She concluded that the flora examined was similar to that in the Lower Allegheny. Later, Round (1921, 1922a, b) reported taxonomic data on selected species or genera in the basin and correlated (1924, 1927) the flora with those in New Brunswick, Canada, and Henry County, Mo.

During the 1930's, Darrah and his students collected specimens from Perrin's Crossing in Seekonk, Mass., (fig. 9, loc. 14). The variety of pecopterid species reported by Darrah (1969) and the presence of *Sphenophyllum oblongifolium* in these collections are evidence of a Late Pennsylvanian (roughly Stephanian) age for the beds exposed near Perrin's Crossing. A stratigraphic section of these beds assigned to the upper part of the Rhode Island Formation is given in Lyons and Chase (1976). Darrah (1969) noted the absence of the *Neuropteris scheuchzeri-Neuropteris ovata* association from this florule and from the Mount Hope coal beds, that is, the coals mined at Portsmouth, R.I. (fig. 9, loc. 42). Knox (1944) reported an important florule from the Wamsutta Formation (fig. 9, loc. 56) in the same area in Attleboro where amphibian tracks were discovered by Woodworth (1894). Knox (1944) did not provide photographs or taxonomic notes, but he listed species or genera from the Wamsutta that are also found in the lower part of the Rhode Island Formation. These taxa include *Neuropteris* cf. *rarinervis*, *Asterophyllites (Calamocladus) equisetiformis*, and *Sphenopteris* species; only one *Pecopteris* sp. was found in the Wamsutta. He concluded that the Wamsutta assemblage was similar to that in the Lower Allegheny and equivalent to that in the lower part of the Rhode Island Formation.

Other florules assignable to the lower part of the Rhode Island Formation were reported by Lyons (1969, 1971) from Foxboro (fig. 9, loc. 24), by Oleksyshyn (1976) from Plainville (fig. 9, loc. 20), and by Lyons and Chase (1976) from these two localities and from Mansfield (fig. 9, loc. 16). Lyons and Darrah (1978) have documented a younger floral zone within the Rhode Island Formation at Easton, Mass. (fig. 9, loc. 70). This assemblage consists of 40 species and is dominated by pecopterids: *Pecopteris arborescens* (pl. 1, figs. A, E), very common; *P. lamuriana* (pl. 1, fig. F) and *P.* cf. *lamuriana* (pl. 1, fig. H), common; *P.* aff. *hemitelioides* (pl. 1, figs. D, G); *P. unita* (pl. 1, fig. C); and other pecopterids (pl. 1, figs. B, I). *Odontopteris* cf. *reichiana* (pl. 1, fig. L), *Neuropteris rarinervis* (pl. 1, fig. Q), and *Sphenophyllum oblongifolium* are sparingly represented. Other species in this assemblage are shown on plate 1, figures J, K, M, N, O, and P. Lyons and Darrah (1978) concluded that the assemblage was transitional between the Middle and Late Pennsylvanian epochs and is similar to that in rocks of the Upper Allegheny and Lower Conemaugh. A comparable flora (Lyons, unpub. data) is found at Barrington, R.I. (fig. 9, loc. 57).

Important new collections made in connection with the Narragansett Basin Project are from Bristol, R.I. (fig. 9, loc. 92), and the northern part of Conanicut Island, Rhode Island. These florules have not yet been documented but are probably younger than the Easton florule as evidenced by the abundance of *Odontopteris* specimens. *Sphenophyllum oblongifolium* and several *Odontopteris* and *Pecopteris* species reported by Lesquereux (1889) to be present at Pawtucket, R.I. (fig. 9, loc. 10), probably are the youngest reported florule from the Narragansett Basin. The flora from these three localities and the floras from Newport (fig. 9, loc. 3) and Portsmouth, R.I. (fig. 9, loc. 42), and from Seekonk, Mass. (fig. 9), are all considered to be of Late Pennsylvanian age.

A florule from Canton, Mass. (fig. 9, loc. 139), dominated by *Neuropteris obliqua*, *Calamites cisti*, *Cordaites pricipalis*, and a few seeds in the upper member of the Pondville Conglomerate in the Norfolk Basin was reported by Lyons Tiffney, and Cameron (1976). An important discovery in this assemblage was a species probably belonging to *Lonchopteris*, a genus not known in North America west of New England. The authors concluded that the assemblage was similar in other respects, however, to that in the Upper Pottsville rocks of the Southern Anthracite field, Pennsylvania (White, 1900; Wood and others, 1969).

FLORAL ZONATION

A summary of the floral zones here recognized in the Pennsylvanian rocks of New England is given in figure 10. The florule from the Pondville Conglomerate does not readily compare with any floral zones of Read and Mamay (1964). However, this florule is in the zone of *Lonchopteris* assigned by Jongmans (1952) to Westphalian B and, therefore, is presumably equivalent to floral zone 5 or 6 of Read and Mamay (1964). On the basis of work by Grew, Mamay, and Barghoorn (1970), the florule from the "coal mine" at Worcester, Mass. (fig. 6), is presumably referable to floral zone 4. However, I have identified a probable *Neuropteris scheuchzeri* in this assemblage and, therefore, refer it to floral zone 9.

The lower part of the Wamsutta Formation and the lower member of the Pondville Conglomerate do not have known florules; however, the lower part of the Wamsutta is believed to be in floral zones 5 or 6, and the lower member of the Pondville is believed to be in floral zone 5. A florule has not been identified in the Dighton Conglomerate, but, if one is identified, it probably will be assignable to floral zone 11 or 12 of Read and Mamay (1964).

FAUNA OF THE NARRAGANSETT BASIN

Summaries of the fauna found in the Narragansett Basin are in Shaler, Woodworth, and Foerste (1899), Quinn and Oliver (1962), and Willard and Cleaves (1930).

Scudder (1893) described an entirely new insect fauna from Rhode Island. Although consisting almost entirely of wings, it included a spider, 11 (nine new) species of cockroaches, and two other species of insects. In 1895, he designated one of the two cockroaches that were not specifically identified in 1893 as a new species and added a new species of cockroach from East Providence. The fauna was collected principally at localities near Pawtucket, Silver Spring (East Providence), Cranston, Bristol, and East Providence, R.I.; it was apparently derived from the lower part of the Rhode Island

TIME-STRATIGRAPHIC UNITS		FLORAL ZONES OF READ AND MAMAY (1964)	ROCK-STRATIGRAPHIC UNITS					NEW ENGLAND		
			CENTRAL APPALACHIANS				NEW ENGLAND			
NORTH AMERICA	EUROPE		CENTRAL AND WESTERN PENNSYLVANIA	EASTERN PENNSYLVANIA		WEST VIRGINIA	MASSACHUSETTS RHODE ISLAND	FLORAL LOCALITY	FIGURE 9 LOCALITY NUMBER	REFERENCE
LATE PENNSYLVANIAN	Stephanian B(?) or C(?)	11 or 12	Waynesburg Formation				Dighton Conglomerate			This report
			Monongahela Formation				Rhode Island Formation (upper part)	Pawtucket, RI	10	Lesquereux (1889)
	Stephanian A and B	11	Conemaugh Formation (upper part)					Portsmouth, RI	42	Darrah (1969)
	Cantabrian							Seekonk, MA	14	
	Westphalian D	10	Conemaugh Formation (lower part)				Rhode Island Formation (middle part)	Easton, MA	70	Lyons and Darrah (1978)
MIDDLE PENNSYLVANIAN	late Westphalian C	9	Allegheny Formation (upper part)	LLEWELLYN FORMATION			Rhode Island Formation (lower part)	Foxboro, MA	24	Lyons (1969)
								Mansfield, MA	16	Lyons and Chase (1976)
	middle Westphalian C	8						Worcester "coal mine", MA	(see figure 6)	Grew and others (1970)
	early Westphalian C	7	Allegheny Formation (lower part)					Plainville, MA	20	Oleksyshyn (1976)
								Valley Falls, RI	1	Round (1920)
	late Westphalian B (?)	6 or 7	– – – – – –	Sharp Mountain Member	POTTSVILLE FORMATION	Kanawha Formation	Wamsutta Formation (upper part)	Attleboro, MA	56	Knox (1944)
EARLY PENNSYLVANIAN	Westphalian A or B	5 or 6		Schuylkill Member		New River Formation	Wamsutta Formation (lower part)	Canton, MA	1	This report
	Westphalian A-Namurian C(?)	5(?)					Pondville Conglomerate (upper member)			Lyons and others (1976)
	Namurian B	4		Tumbling Run Member		Pocahontas Formation	Pondville Conglomerate (lower member)		139	This report

FIGURE 10.—Pennsylvanian stratigraphic correlation chart.

Formation (Shaler and others, 1899, p. 203). Packard (1889) reported that the lower part of the Rhode Island Formation in Pawtucket yielded several other species of cockroaches of two genera; a spider; *Spirorbis*, a tube of an annelid worm; and a presumed track of a gastropod.

Willard and Cleaves (1930) summarized discoveries of seven species of amphibian footprints: four from Plainville, Mass., and one each from Seekonk (Perrin's Crossing) and South Attleboro, Mass., and East Providence, R.I. Six were new species. Six were from the Rhode Island Formation, and one was from the Wamsutta Formation in South Attleboro. Lyons and Chase (1976) noted possible amphibian skin from Plainville, Mass., and a burrow from Foxboro, Mass.

PALEOGEOGRAPHIC IMPLICATIONS OF PALEONTOLOGIC DATA

Scudder (1895) noted that none of the 193 species of North American (including Nova Scotia and Cape Breton) cockroach was known from Europe and that five of the 14 genera found in America are absent from Europe. These faunal data may indicate that North America and western Europe were somewhat isolated during Early and Middle Pennsylvanian times. However, the presence of *Lonchopteris* in New England, Maritime Canada, and western Europe indicates that North America and Europe were connected during these times. The absence of *Lonchopteris* from areas west of New England probably indicates a Pennsylvanian barrier between New England and the central Appalachians.

Willard and Cleaves (1930) observed that the amphibian footprints of the Narragansett Basin have a closer affinity to the genera identified in Nova Scotia than to the genera described for the central Appalachians. This affinity to Nova Scotian amphibian genera, together with floral data presented by Round (1924) and Lyons (1971), strongly supports a paleogeographic connection between New England and Maritime Canada (Lyons, 1976) during Middle Pennsylvanian time.

ROCKS OF MAINE INFERRED TO BE CARBONIFEROUS

By Robert G. Doyle

Some sedimentary rocks in parts of Hancock and Washington Counties, Maine, are inferred to be of Carboniferous age. These rocks are not fossiliferous; the assignment of this age is based upon (1) proximity to similar rocks that are known to be Carboniferous and that crop out approximately 56 km to the east in the Province of New Brunswick (Larrabee, 1963); (2) lithologic character and the lack of any metamorphic imprint, the latter requiring a post-Acadian age; and (3) identification of a syntectonic granitic source for the conglomeratic granite pebbles within the unit.

LOCATION AND GEOLOGIC SETTING

The rocks inferred to be of Carboniferous age are present in a graben bounded by subparallel segments (fig. 11) of the Norumbega fault system. The

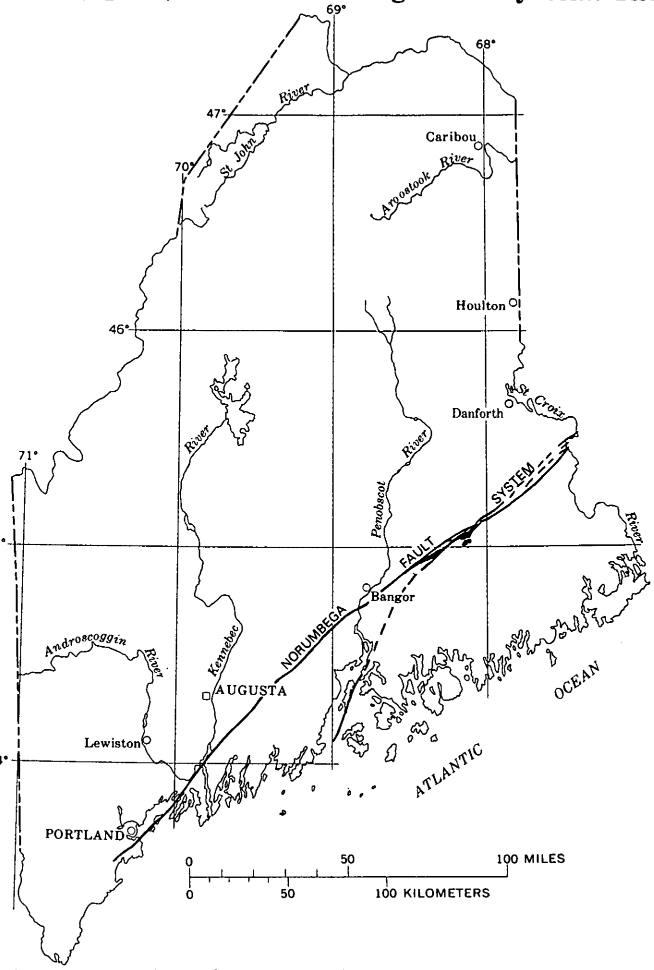


FIGURE 11.—Locations of Maine rocks inferred to be Carboniferous.

Norumbega fault system is a major structure extending 320 km north-northeast from Portland, Maine, on the south-central Atlantic coast to the Maine-New Brunswick line 16 km south of Danforth, Maine. Exposures of the unit are present on the northwest shore of Great Pond and in Alligator Stream which flows into Great Pond (Great Pond, Maine, U.S. Geological Survey 15-minute quadrangle). The unit is bounded on the southeast by silicic metavolcanic and metavolcaniclastic rocks of presumed Ordovician age (Larrabee and others, 1965), and on the north by the quartzite member of the Kellyland Formation of Silurian age (Larrabee and others, 1965; Ludman, 1975). Metasedimentary and plutonic rocks of Siluro-Devonian age (Hussey and others, 1967) are present in the area near the fault-bounded blocks of the unit inferred to be Carboniferous.

DESCRIPTION OF THE UNIT INFERRED TO BE CARBONIFEROUS

Rocks of the unit inferred to be Carboniferous were described by Larrabee, Spencer, and Swift (1965) and Stoeser (1966). The present writer uses the description provided by Stoeser. The unit is separated into two members, the siltstone arkose member and the nonarkosic conglomerate member.

Nonarkosic conglomerate member.—The nonarkosic conglomerate member consists of a red silt/sand matrix enclosing clasts of green and red micaceous quartzite, siltstone, and shale and a small percentage of weathered granitic clasts. The source of the clasts is the siltstone arkose member. The nonarkosic conglomerate member is estimated to be 30 m thick.

Siltstone arkose member.—The siltstone arkose member consists of reddish-brown to purple interbedded arkosic conglomerate, arkosic sandstone, and red siltstone. The source of clasts found in this member is presumed to be nearby Acadian or Late Acadian orogenic plutons of mid-Devonian age. This member is estimated to be 520 m thick.

Economic deposits.—No evidence exists of any economic materials within the unit. Carbonaceous material is absent.

EVOLUTION OF CARBONIFEROUS TERRANES IN NEW ENGLAND

By JAMES W. SKEHAN, S.J., and DANIEL P. MURRAY

PALEOENVIRONMENT AND PALEOGEOGRAPHY

The generally similar ages, lithologies, stratigraphy, and structure of the deposits in the Narragansett and Norfolk Basins and of the deposits at and near Worcester (fig. 1) suggest that their origins are related and that they may have been laid down in a single basin (Quinn and Oliver, 1962). Large-scale faulting, deep erosion, and limited studies of the sediments over the Avalonian terrane in which these basins are situated permit only a general reconstruction of the paleoenvironment and paleogeography.

The ages of the Boston, Woonsocket, and North Scituate Basins are uncertain. All three basins have geologic features similar to those of the Pennsylvanian basins and are close enough to them to have been correlated with them. On the other hand, striking dissimilarities in lithology and stratigraphy exist between these three basins and the fossiliferous Pennsylvanian basins. For example, C. A. Kaye (oral commun., 1977) has noted that the Cambridge Argillite of the Boston Basin may be the equivalent of the Middle Cambrian trilobite-bearing Braintree Argillite. Moreover, structures in the Roxbury Conglomerate that were previously assumed to be plant fossils have been shown to be sandstone pipes (Bailey and Newman, 1978). The recent discovery of Middle Cambrian trilobites (Skehan, Murray, Palmer, and Smith, 1977) in southern Narragansett Bay in rocks previously mapped as Carboniferous underscores the plausibilty of Kaye's suggestion.

The fossiliferous Cambrian rocks in the southern Narragansett Bay were considered by Dale (1884) to be a southern marine facies of an otherwise fluvial basin. The Pennsylvanian deposits of the Norfolk and Narragansett Basins are thought to have been deposited in an upper fluvial environment because (1) the Narragansett and Norfolk Basins do not contain any marine fossils, (2) the Narragansett Basin coal has extraordinarily low sulfur and trace-element contents (Jack Medlin, unpub. data, 1977), and (3) coarse conglomerates are widespread throughout several parts of the Pennsylvanian section in both basins.

The deposits of the Narragansett and Norfolk Basins, moreover, contain a great variety of sedimentary structures, including graded bedding, crossbedding, scour and fill, mud cracks, loadcasts, raindrop impressions (Chute, 1940; Quinn and Oliver, 1962; Stanley, 1968), and sandstone dikes (Lyons, 1969). These features, together with the paleontological evidence, indicate that the known Pennsylvanian rocks were deposited in a fluvial nonmarine environment and were exposed to air (Lyons and others, 1976, p. 193–194). Thus, we envision, for that part of the Carboniferous represented by the known Pennsylvanian deposits and by the deposits considered to be possibly Carboniferous, a region of high relief following the late Acadian episodes in which previously formed nappe structures in central New England (west of this Carboniferous terrane) were domed.

STRUCTURAL EVOLUTION OF THE NARRAGANSETT BASIN

The following sequence, from oldest to youngest, of structural events represents a working model for the deformational history of the Narragansett Basin.

In Rhode Island:

1. Northeast-trending isoclinal overturned to recumbent folds formed with associated east-dipping to subhorizontal cleavage and northwest-directed thrust faults.
2. A milder episode of folding was associated with northwest-dipping cleavage and southeast-directed northwest-dipping thrusts.
3. Cleavage was gently warped, and kink bands formed.

In Massachusetts:

1. Open folds trending east-northeast and having northwest-dipping cleavage formed in most of the Massachusetts part of the basin.
2. Possible southeast-directed thrusting may have emplaced the Blake Hill thrust sheet in Plainville and possibly other thrust sheets not yet well defined. This episode may have been contemporaneous with event 2 (listed above) of Rhode Island.

Several episodes of normal faulting took place following these compressional phases of deformation. Faults formed include:

1. Northwest-striking faults, such as the Portsmouth Abbey fault (William R. Barton, oral commun., 1975), that had significant left-lateral strike motion; such faults are detected by drilling (Skehan and others, 1976).
2. Northeast- and northwest-striking faults.
3. North-striking faults.

STRUCTURAL EVOLUTION OF SOUTHEASTERN NEW ENGLAND

In southeastern New England, the basins known or thought to be Carboniferous have been deformed by folds and faults that are north trending in the south and are east-northeast trending in the north. This post-Conemaugh (post-Stephanian A) deformation was characterized by northwest-dipping southeast-moving thrusts and highangle reverse faults over most of the Avalonian platform. The southern part of the platform is dominantly characterized by southeast-dipping, northwest-directed thrusts that are cut by later northwest-dipping, southeast-directed thrusts.

TIMING AND CAUSES OF THE ALLEGHANIAN OROGENY

A complex structural history is recorded in the pre-Carboniferous and Carboniferous rocks of the Avalonian terrane of New England. The following two-stage working hypothesis is presented to explain the known data.

1. The Acadian orogeny represents the collision of the Eur-Asian and North American plates; the Avalonian terrane formed the leading edge of of the Eur-Asian plate and was sutured to the North American plate approximately along the zone between the Clinton-Newbury and the Bloody Bluff fault zones (fig. 1). This suturing defines the final closure of the Proto-Atlantic Ocean (Iapetus).
2. Closure of the Hercynian Ocean began in late Paleozoic times and resulted in the collision of Gondwana with Laurasia. This event is recorded as the Alleghanian orogeny in eastern North America and the Variscan-Hercynian orogeny in northwest Europe.

Whether the Avalonian plate was overridden by the North American plate or vice versa, the Clinton-Newbury and Bloody Bluff fault zones (fig. 1) may define the suture and mark the northwestern and southeastern boundaries of underplating. Thus, the faults on these plates initially formed during the Acadian; however, their present geometry (such as the east-directed, west-dipping, high-angle reverse faults in the northern part of the Avalonian platform) was defined during the Alleghanian orogeny. Here the Alleghanian (Variscan) orogeny was a major orogenic event consisting of the following elements: (1) isoclinal folding and refolding associated with thrusting; (2) upper amphibolite facies Barrovian regional metamorphism; and (3) intrusion of probably anatectic granites.

The Alleghanian orogeny may either represent: (1) subsequent interactions between the Eur-Asian and North American plates or (2) the collision of the South American parts of Gondwana with Laurasia. The latter interpretation is a logical extension of Irving's (1977) data.

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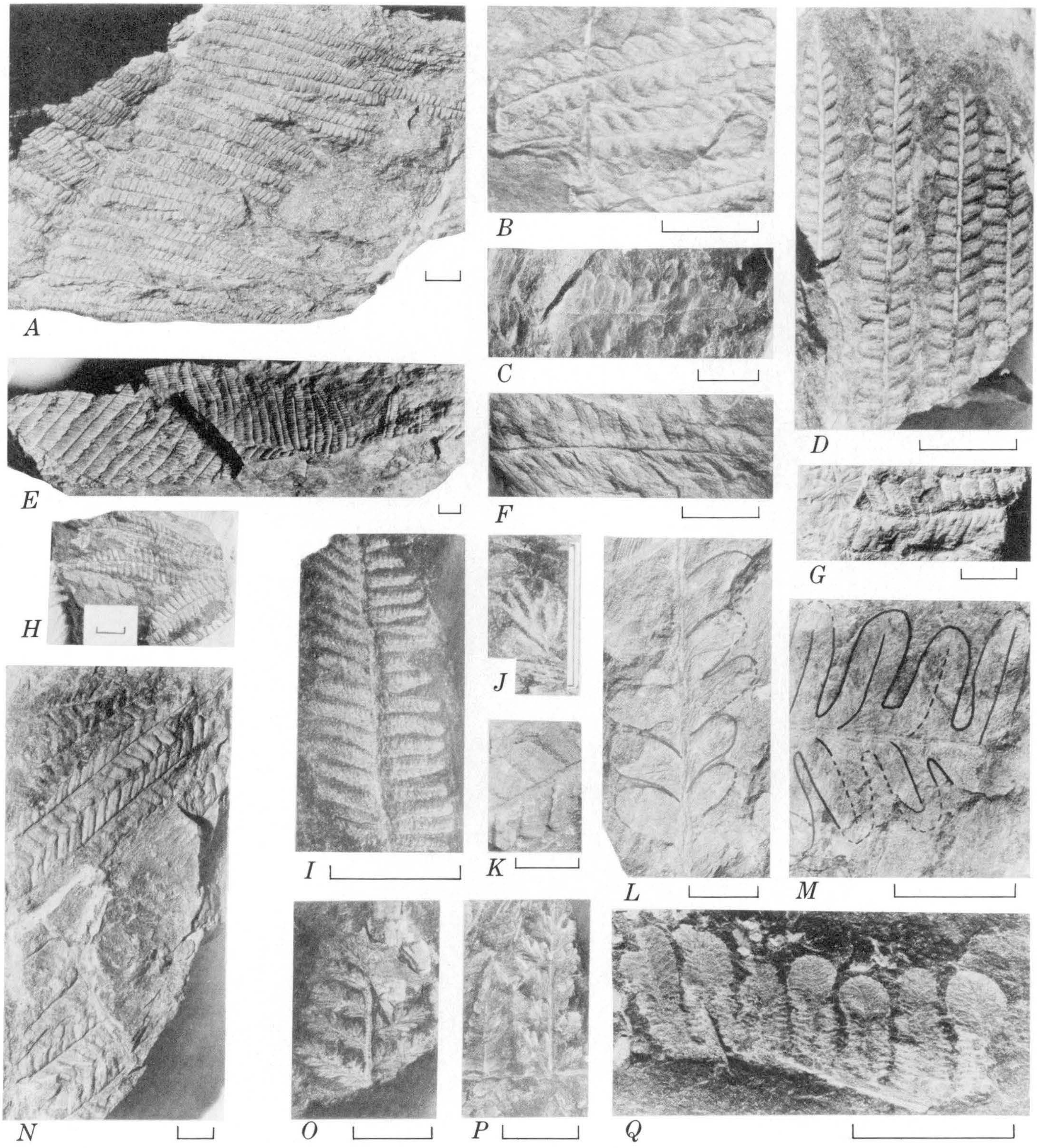
PLATE 1

A contact photograph of the plate in this report is available, at cost, from U.S. Geological Survey Library, Federal Center, Denver, Colorado 80225

PLATE 1

[All specimens are from Easton, Mass. E number is original specimen number; HU number is Harvard University, Paleobotanical Collections, specimen number. Line scale equals 1 cm.]

Figure A. *Pecopteris arborescens* Schlotheim, E-232a, HU-45708.
B. *Pecopteris* sp., E-116, HU-45709.
C. *Pecopteris unita* Brongniart, E-216, HU-45710.
D. *Pecopteris* aff. *hemitelioides* Brongniart, E-97, HU-45711.
E. *Pecopteris arborescens* Schlotheim, E-120, HU-45712.
F. *Pecopteris lamuriana* Heer, E-110, HU-45713.
G. *Pecopteris* aff. *hemitelioides* Brongniart, E-113, HU-45714.
H. *Pecopteris* cf. *lamuriana* Heer, E-141, HU-45715.
I. *Pecopteris lepidorachis*(?) Brongniart, E-132, HU-45716.
J. *Eremopteris* cf. *lincolniana* D. White, E-202a, HU-45717.
K. *Alethopteris*(?) sp., E-195a, HU-45718.
L. *Odontopteris* cf. *reichiana* Gutbier, E-194, HU-45719, pinnules outlined for clarity.
M. *Alethopteris*(?) (Brongniart) Goeppert, E-143, HU-45720, pinna and medial veins outlined for clarity.
N. *Neuropteris obliqua*(?) Brongniart, E-243a, HU-45721.
O. *Eremopteris missouriensis* Lesquereux, E-74, HU-45722.
P. *Sphenopteris* aff. *subalata* Geinitz, E-204, HU-45723.
Q. *Neuropteris rarinervis* Bunbury, E-47, HU-45724.



PECOPTERIS, *EREMOPTERIS*, *ALETHOPTERIS*(?), *ODONTOPTERIS*, *NEUROPTERIS*, AND *SPHENOPTERIS*

The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States— Pennsylvania and New York

By WILLIAM E. EDMUNDS, THOMAS M. BERG, WILLIAM D. SEVON, ROBERT C. PIOTROWSKI, LOUIS HEYMAN, *and* LAWRENCE V. RICKARD

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Prepared in cooperation with the Pennsylvania Geological Survey and the New York State Museum— Geological Survey

Historical review and summary of areal, stratigraphic, structural, and economic geology of Mississippian and Pennsylvanian rocks in Pennsylvania and southwestern New York

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CONTENTS

ILLUSTRATIONS

TABLES

THE MISSISSIPPIAN AND PENNSYLVANIAN (CARBONIFEROUS) SYSTEMS IN THE UNITED STATES — PENNSYLVANIA AND NEW YORK

By WILLIAM E. EDMUNDS,[1] THOMAS M. BERG,[2] WILLIAM D. SEVON,[2]
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ABSTRACT

The Mississippian and Pennsylvanian rocks of Pennsylvania and New York constitute a dominantly clastic sequence 700 to 3,200 m (2,300 to 10,500 ft) thick. Deposited during the late stages of formation of the Appalachian geosyncline, most Mississippian and Pennsylvanian sediments issued from the Acadian orogenic highlands to the southeast along the presumed impact zone of the North American and African continental plates. Less sediment came from the rim of the North American craton to the north and the older Taconic orogenic highlands to the northeast. Paleomagnetic studies suggest that the Pennsylvania-New York area was slightly south of the equator during Mississippian and Pennsylvanian time; examination of the fossil flora indicates a mostly subtropical climate.

Of the seven alternating clastic and carbonate sequences that make up the Appalachian Paleozoic, the Mississippian-Pennsylvanian includes parts of the last two clastic sequences and a thin representative of the last intervening carbonate sequence. These three primary Paleozoic units may be divided into eight major lithologic groupings, which are described herein under 15 principal formations or groups. Two widespread disconformities exist from upper middle Mississippian through lower Middle Pennsylvanian across New York and northern Pennsylvania and possibly beyond.

Biostratigraphic zonation of the Carboniferous of Pennsylvania and New York has not been accomplished yet. The marine Mississippian strata of northwestern Pennsylvania have an abundant fossil invertebrate suite, but most research has been directed toward locating the Devonian-Mississippian boundary. Various avenues of paleozoological research are yet to be followed in both the Mississippian and Pennsylvanian, in order to establish true biozones and correlations with the midcontinent.

The Mississippian has been divided into three and the Pennsylvanian into nine presumably time-sequential botanical biostratigraphic zones.

The Devonian-Mississippian boundary within the marine section of northwestern Pennsylvania is fairly well located; the Mississippian-Pennsylvanian boundary is accurately located where disconformable. Elsewhere, these two boundaries are only approximate. The Pennsylvanian-Permian boundary is controversial. Epoch boundaries, except the Desmoinesian and, locally, the Missourian, are indistinct.

The depositional history of the Mississippian-Pennsylvanian consisted of the following events in chronological order: (1) Late Devonian and Early Mississippian marine transgression; (2) Early Mississippian stable, delta-dominated coast; (3) early middle Mississippian formation of elongate braided alluvial-deltaic sand plain; (4) late middle Mississippian initiation of Mauch Chunk delta in southeast Pennsylvania and epeirogenic uplift of northern Pennsylvania and New York; a shallow marine invasion from the southwest was interposed between the delta and upwarped area; (5) Late Mississippian and Early Pennsylvanian prograding of Mauch Chunk delta and continued erosion in northern Pennsylvania and New York; (6) Early Pennsylvanian alluvial plain established across all of Pennsylvania; (7) Middle Pennsylvanian marine influence in western Pennsylvania established shallow-marine—delta-plain—alluvial-plain conditions from west to east; (8) Middle Pennsylvanian westward prograding of depositional environment, limiting Pennsylvania to nonmarine deltaic and alluvial conditions; (9) middle Late Pennsylvanian marine incursions into Pennsylvania; (10) reduction of depositional environment to shallow estuary remote from marine conditions during Late Pennsylvanian; (11) Late Pennsylvanian-Permian coastal-plain lacustrine environment, apparently severed from marine connection.

In Pennsylvania, recoverable coal resources more than 61 cm thick amount to approximately 30 billion metric tons. Coal heat value ranges from 8,200 to 8,800 calories per gram (14,700 to 15,800 Btu per pound) on a dry, ash-free basis. Pennsylvania coal production in 1976 was 85.6 million metric tons.

Oil and gas production from Mississippian and Pennsylvanian rocks is small. Raw materials for a wide variety of ceramic products are available from Pennsylvanian and some Mississippian units.

INTRODUCTION

The Carboniferous of Pennsylvania and New York is an overwhelmingly clastic sequence containing subordinate amounts of limestone and coal. Strata of Mississippian and Pennsylvanian age underlie approximately 45 percent of Pennsylvania but extend into New York only as small outliers aggregating a few square kilometers (fig. 1). Where

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[2] Pennsylvania Geological Survey, Harrisburg, Pa. 17120.
[3] Pennsylvania Geological Survey, Pittsburgh, Pa. 15222.
[4] New York State Museum—Geological Survey, Albany, N.Y. 12224.

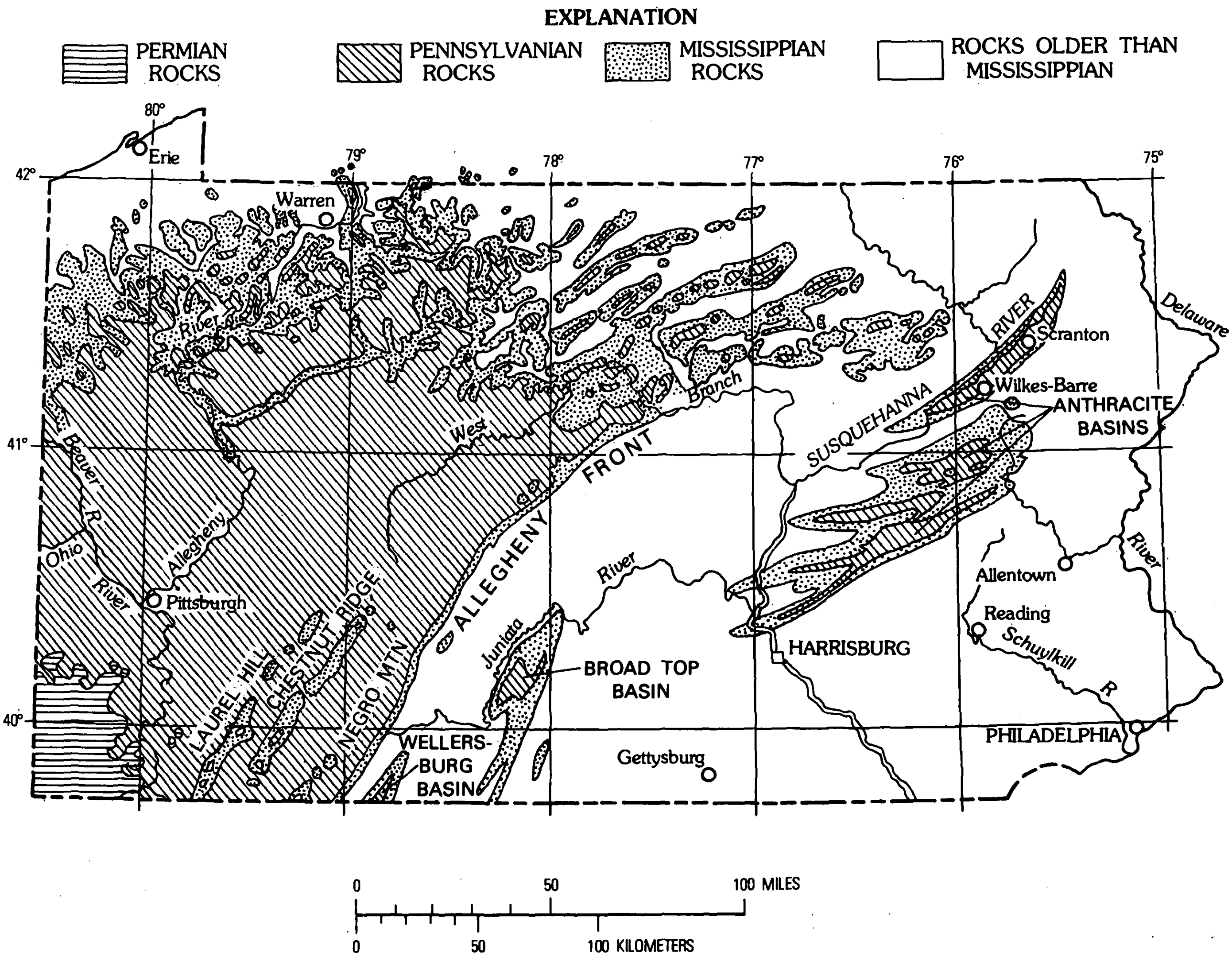

FIGURE 1.—Outcrop of Mississippian and Pennsylvanian rocks in Pennsylvania and New York.

uninterrupted by unconformities, the Mississippian and Pennsylvanian together constitute about 25 percent of the total Paleozoic.

The demonstrable thickness of combined Mississippian and Pennsylvanian rocks ranges from about 700 m (2,300 ft) in southwestern Pennsylvania to 3,000–3,200 m (10,000–10,500 ft) at the Schuylkill River Gap in the Southern Anthracite field. Both a smaller minimum and larger maximum can be inferred in other areas but cannot be demonstrated directly, as the section is incomplete. As an example, in the area around Olean, N.Y., basal Pennsylvanian rocks rest disconformably upon the uppermost Devonian; a reconstructed Pennsylvanian probably would not exceed 450 m (1,500 ft).

The Mississippian and Pennsylvanian sequence contains two widespread resistant sandstone intervals which are prominent ridge and scarp formers across much of Pennsylvania. The lower of these two intervals is the Mississippian Pocono-Burgoon sandstone and conglomerate; the higher is the sandstone and conglomerate of the Pennsylvanian Pottsville Formation. Individually or jointly, the Burgoon-Pocono and the Pottsville sustain the high ridges surrounding the four anthacite basins and the Broad Top and Wellersburg basins. They also form the lip of the Allegheny Front escarpment and the cores of Laurel Hill, Chestnut Ridge, and Negro Mountain.

Mississippian and Lower Pennsylvanian rocks are best exposed along the Allegheny Front; around the Wellersburg, Broad Top, and the four anthracite basins; along the West Branch of the Susquehanna

River and the upper reaches of the Allegheny River and their tributaries; and on the flanks of Laurel Hill and Chestnut Ridge. The Middle and Upper Pennsylvanian sequence is fairly well exposed along the Monongahela, Allegheny, and Ohio Rivers and their major tributaries; the headwaters of the West Branch of the Susquehanna River; and in many major excavations in the Pittsburgh metropolitan area. Many good exposures of various parts of the section are found along the major Interstate Highways such as I-70, I-76 (Pennsylvania Turnpike), I-79, I-80, and I-81. Excellent exposures of the Mississippian occur in the Lehigh River gorge near Jim Thorpe, and excellent exposures of both Mississippian and Pennsylvanian strata are to be found in the vicinity of Pottsville.

The stratigraphic nomenclature used in this paper has not been reviewed by the Geologic Names Committee of the U.S. Geological Survey. The nomenclature used here conforms with the current usage of the Pennsylvania Geological Survey and the New York State Museum—Geological Survey.

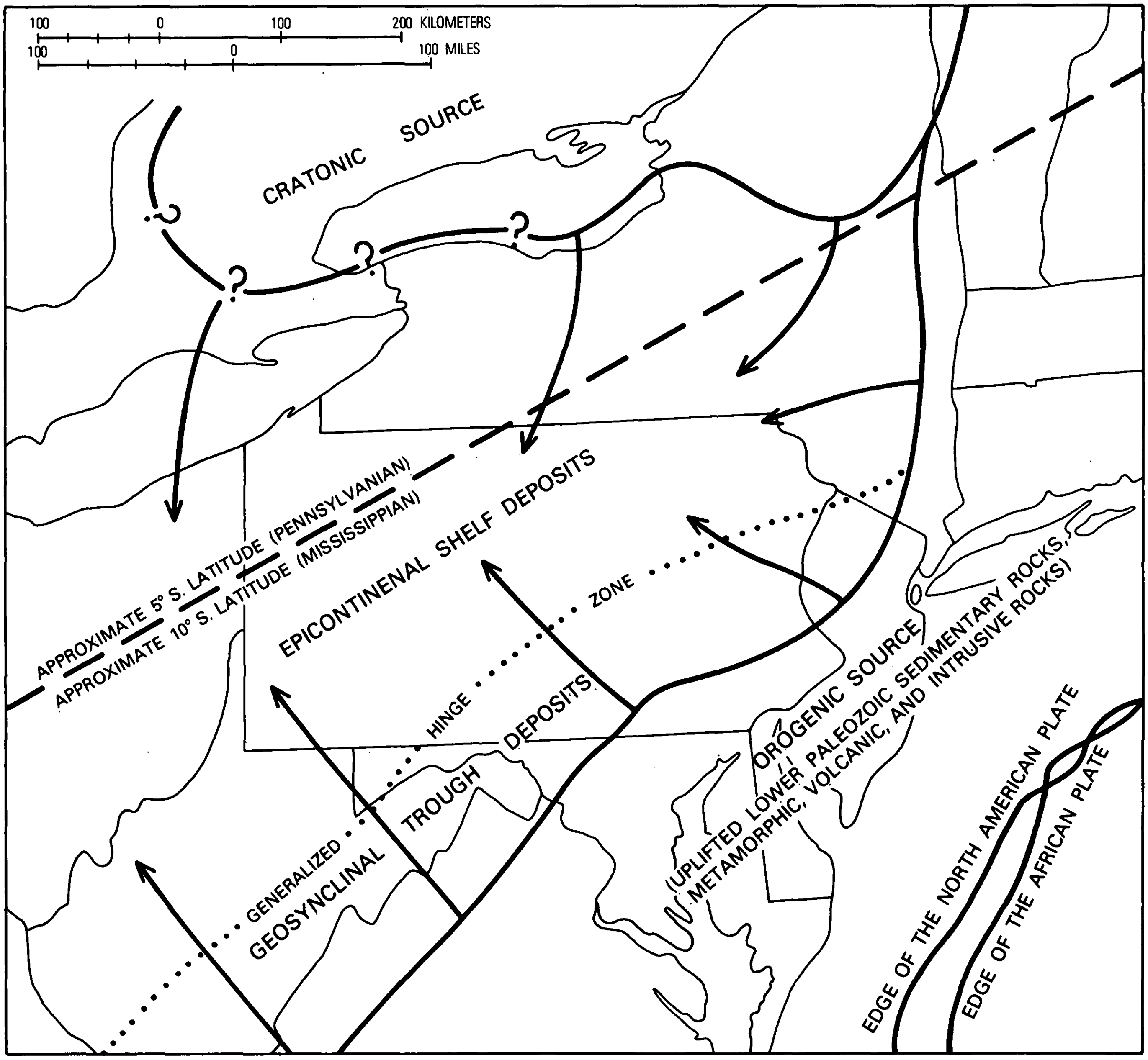

FIGURE 2.—Generalized paleogeography of the Mississippian-Pennsylvanian depositional basin and source areas.

GENERAL GEOLOGIC SETTING

THE APPALACHIAN GEOSYNCLINE

Mississippian and Pennsylvanian rocks were deposited during the late stages of formation of the Appalachian geosyncline. Dietz (1972) postulated that the Appalachian geosyncline formed along the eastern edge of the North American continental plate when this plate initially separated from the northwest African plate during the late Precambrian, thus opening the proto-Atlantic epicontinental seaway.

During the Ordovician Period, the North American and African plates began to close again, crumpling the outer edge of the Appalachian geosyncline. By Mississippian time, the two plates were virtually in contact (Hurley, 1968; Schopf, 1975, p. 26), and large volumes of sediment were being carried westward from the orogenic mountains upthrust along the continental margin toward the cratonic core of North America (fig. 2).
These sediments along with a smaller volume issuing from the craton formed the Appalachian exogeosyncline of Kay (1951, p. 17 and pl. 5) and the continental-shelf deposits.

From Silurian time onward, the geosyncline apparently was sealed off at the northern end in eastern New York where the Taconic orogenic mountains were driven against the Adirondack cratonic high. The eastern orogenic source extended southwestward from the Taconic uplift area through the present location of Philadelphia and Baltimore and beyond.

Mountain building associated with the impact of the two continental plates was intermittent. After the Late Ordovician Taconic culmination, the Acadian orogeny, during Middle to Late Devonian time, produced the sediments of the Upper Devonian Catskill delta. Effects of Acadian mountain building continued, but with diminishing intensity, into the middle Mississippian.

A third orogeny produced the Mauch Chunk delta during middle to Late Mississippian and culminated in the Early Pennsylvanian, when the Pottsville sandstone and conglomerate spread westward. Approximately contemporaneously with this continental-margin orogeny, epeirogenic upwarping along the craton margin uplifted central and western New York and northern Pennsylvania to the point at which further deposition ceased and some erosion of Lower Mississippian units took place.

Continued collision of the continental margins in the late part of the Permian Period—the Appalachian Revolution—produced the massive folding that terminated formation of the classic Appalachian geosyncline. Triassic sediments were deposited in the narrow fault-block basins formed during separation of the North American and African plates.

It should be noted that many workers believe that Appalachian geosynclinal development and deformation resulted from causes other than the movement of continental plates described above.

CLIMATE

Paleomagnetic studies of rocks of Mississippian and Pennsylvanian age (Turner and Tarling, 1975), suggest that Pennsylvania and New York lay slightly south of the equator at that time (fig. 2). Examination of the Mississippian-Pennsylvanian flora by White (1913) and by Köppen and Wegener (1924) indicated a subtropical setting, although probably not as intensely hot as a low-elevation equatorial setting today would imply. Camp (1956) concluded that Pennsylvania and New York lay near the equator in an area that generally received abundant year-round rainfall.

White (1913, p. 74) considered the Mississippian flora to be rather impoverished and stunted, a fact suggesting that climatic conditions were less than ideal. He further noted that the striking evolution of new plant forms in the Early Pennsylvanian suggests optimum temperature and rainfall conditions. White believed that Middle Pennsylvanian vegetation was somewhat less lush and that a drier period prevailed during late Middle and early Late Pennsylvanian. Latest Pennsylvanian floras reflect a return to a substantially better climate.

LITHOSTRATIGRAPHY

GENERAL

The most basic or first-order subdivisions of the Paleozoic sedimentary rocks of the Appalachian geosyncline are the seven alternating clastic and carbonate sequences shown in figure 3. The Mississippian and Pennsylvanian of Pennsylvania span part of the upper two clastic divisions (Devonian-Mississippian and Mississippian-Permian) and include a thin representative of the intervening Mississippian carbonate rocks. These first-order stratigraphic units can be further divided into major second-order lithologic groupings as shown in figure 4.

The Devonian-Mississippian second-order units of figure 4 are derived conceptually from the "magnafacies" of Caster (1934). The "marine black shale" is, in essence, Caster's Cleveland Magnafacies. The

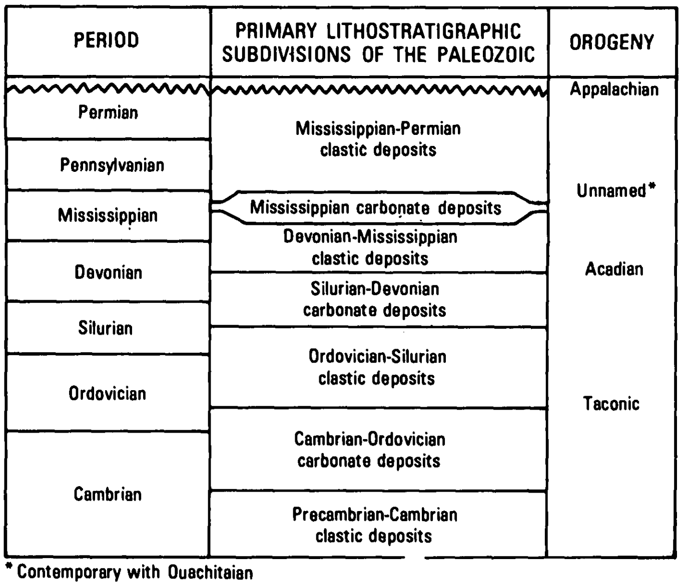

FIGURE 3.—Primary lithostratigraphic subdivisions of the Paleozoic.

"marine fine-grained clastic rocks" and "marine mixed clastic rocks" of figure 4 are equivalent to Caster's Chagrin and Big Bend Magnafacies. The "red, nonmarine mixed clastic rocks" are Caster's Catskill Magnafacies. The "nonred, nonmarine mixed clastic rocks" of figure 4 are equivalent, to the best of our understanding, to Caster's Tioga Magnafacies. The "light gray, nonmarine sandstone and conglomerate" is in essence, Caster's Pocono Magnafacies.

The present lithostratigraphic nomenclature has evolved slowly through the efforts of scores of workers during the past 140 years. The formal terminology used in this report (fig. 5) is that used in the 1979 edition of the Geologic Map of Pennsylvania (Berg and others, 1979). The roots of most groups and formations shown in figure 5 (if not their precise definition and name) were established during the 19th and early 20th centuries. Only the Huntley Mountain, Spechty Kopf, Casselman, and Glenshaw Formations are conceptually of recent origin.

All units are strictly lithostratigraphic and are not intended to have any inherent biostratigraphic or chronostratigraphic connotation. The relationship between the formal stratigraphic terms given in figure 5 and the first- and second-order Paleozoic subdivisions given in figures 3 and 4 are summarized in figure 6.

All Mississippian units are defined by their bulk lithologic character and are distinguished from contiguous units by fairly distinct lithologic differences. Most units reflect more or less discrete depositional environments. As can be seen in figure 6, there is a high degree of conformity and little overlap between Mississippian nomenclature and the second-order lithologic subdivisions of the upper Paleozoic of Pennsylvania.

In contrast, most Pennsylvanian units are not defined by any bulk lithologic homogeneity but are instead intervals bounded by key beds that are as-

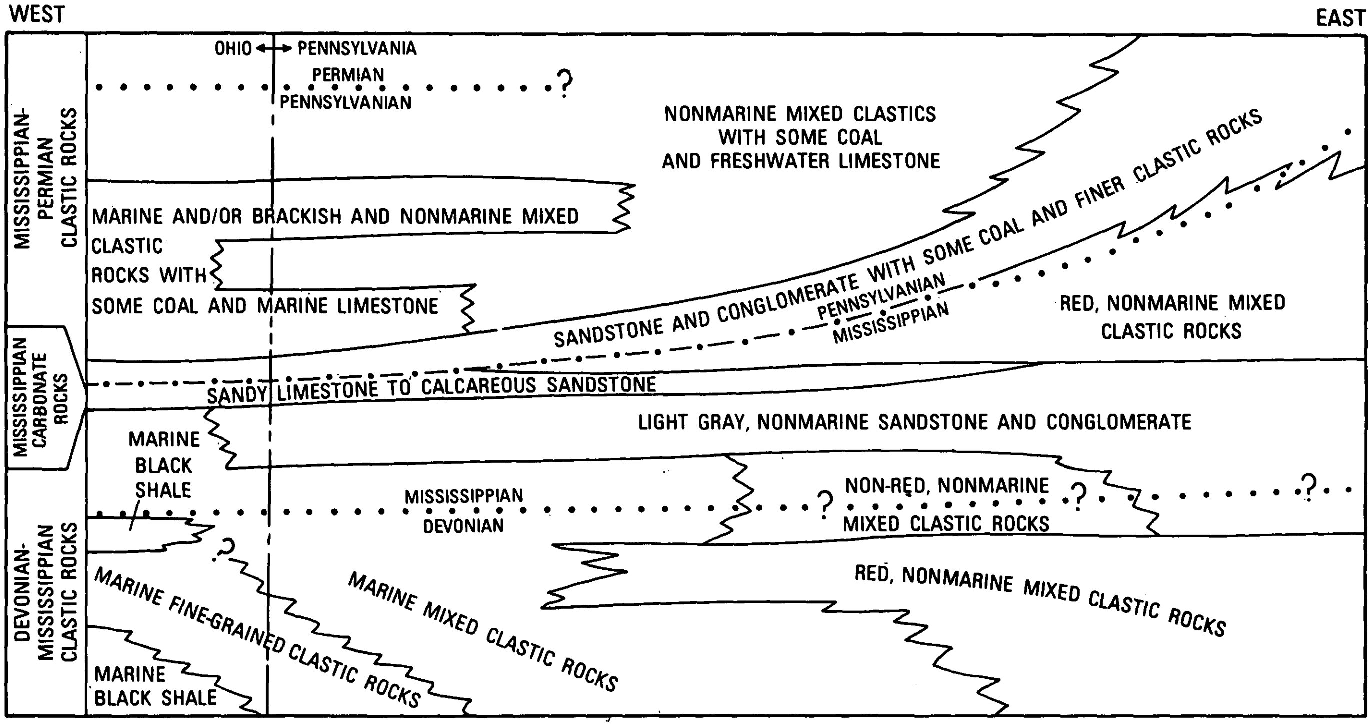

FIGURE 4.—Diagrammatic cross section showing the relation of second-order to first-order middle and late Paleozoic lithologic subdivisions.

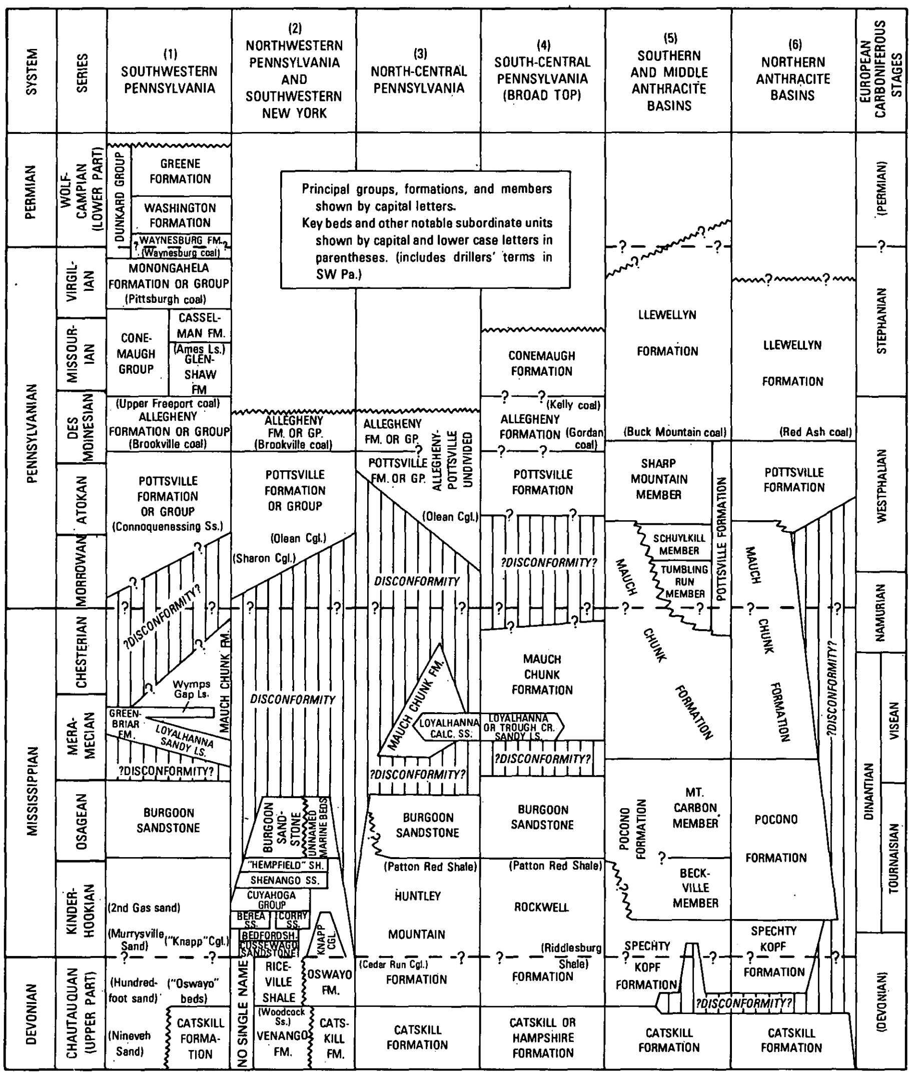

FIGURE 5.—Correlation chart of Mississippian and Pennsylvanian rocks in Pennsylvania and New York.

sumed (sometimes fallaciously) to be both distinctive and widely continuous. Aside from the lower Pottsville sandstone and conglomerate, there is no dominant lithologic distinctiveness to any substantial part of the Pennsylvanian. All is a more or less heterogeneous mixture of sandstone, shale, claystone, limestone, and coal. Such differences as do exist are subtle variations in proportion, such as a change from 4 or 5 percent coal within the Allegheny Group to 1 or 2 percent in the Conemaugh Group. For this reason, there is a large amount of overlap between the nomenclature and the second-order divisions in figure 6.

Most of the unit-defining key beds are coal, and, with one exception, all generally fail to meet the strict requirements of widespread continuity and distinctiveness expected of a key bed. Boundaries of most Pennsylvanian units are projected on interval, on sequence among a multiplicity of overlapping local beds and lenses, and on the above-mentioned subtle variations in lithologic proportion. Pennsylvanian lithostratigraphic subdivision will not easily stand rigorous application of the standard rules of stratigraphic nomenclature.

Stratigraphic relationships among the Mississippian and Pennsylvanian units given in figure 5 across Pennsylvania are shown in the panel diagrams of figures 7 through 10.

RICEVILLE-OSWAYO THROUGH "HEMPFIELD" SEQUENCE

(Figure 5, column 2)

The Riceville-Oswayo through "Hempfield" sequence in northwestern Pennsylvania spans the Devonian-Mississippian boundary and is a mixture of fine-grained sandstone, siltstone, and shale, contain-

FIRST-ORDER LITHOLOGIC DIVISIONS OF THE APPALACHIAN PALEOZOIC (FIGURE 3)	SECOND-ORDER LITHOLOGIC DIVISIONS OF THE APPALACHIAN PALEOZOIC IN PENNSYLVANIA (FIGURE 4)	LITHOSTRATIGRAPHIC NOMENCLATURE (FIGURE 5)
Mississippian-Permian clastic rocks (lower part)	Nonmarine mixed clastic deposits with some coal and fresh-water limestone.	Dunkard Group (Permian) Monongahela Group or Formation Casselman Formation Conemaugh Group (S. central Pa.) Upper Allegheny Group (SW. and NW. Pa.) Allegheny Group (N. central and S. central Pa.) Upper Pottsville Group (N. central and S. central Pa.)
	Marine and/or brackish and nonmarine mixed clastic deposits with some coal and marine limestone	Glenshaw Formation (SW. Pa.) Lower Allegheny Group (SW. and NW. Pa.) Upper Pottsville Formation or Group (SW. and NW. Pa.)
	Sandstone and conglomerate with some coal and finer clastic deposits	Llewellyn Formation Lower Pottsville Formation or Group (western and central Pa. and SW. N.Y.) Pottsville Formation (eastern Pa.)
Mississippian carbonate rocks	Limestone to calcareous sandstone	Greenbriar Formation Loyalhanna Formation Wymps Gap Member of Mauch Chunk Formation
Devonian-Mississippian clastic rocks (upper part)	Red, nonmarine mixed clastic deposits (Mississippian)	Mauch Chunk Formation
	Light gray, nonmarine sandstone and conglomerate	Burgoon Sandstone Pocono Formation Spechty Kopf Formation (in part)
	Non-red, nonmarine mixed clastic deposits	Rockwell Formation Huntley Mountain Formation Spechty Kopf Formation (in part)
	Marine mixed clastic deposits	Unnamed marine equivalents of Burgoon Sandstone Riceville-Oswayo through "Hempfield" sequence Venango Formation (Devonian)
	Red nonmarine mixed clastic deposits (Devonian)	Catskill (Hampshire) Formation (Devonian)
	Marine fine grained clastic deposits	Not represented in figure 5
	Marine black shale	Not represented in figure 5

FIGURE 6.—The relation of first-order and second-order Paleozoic lithologic subdivisions to stratigraphic nomenclature.

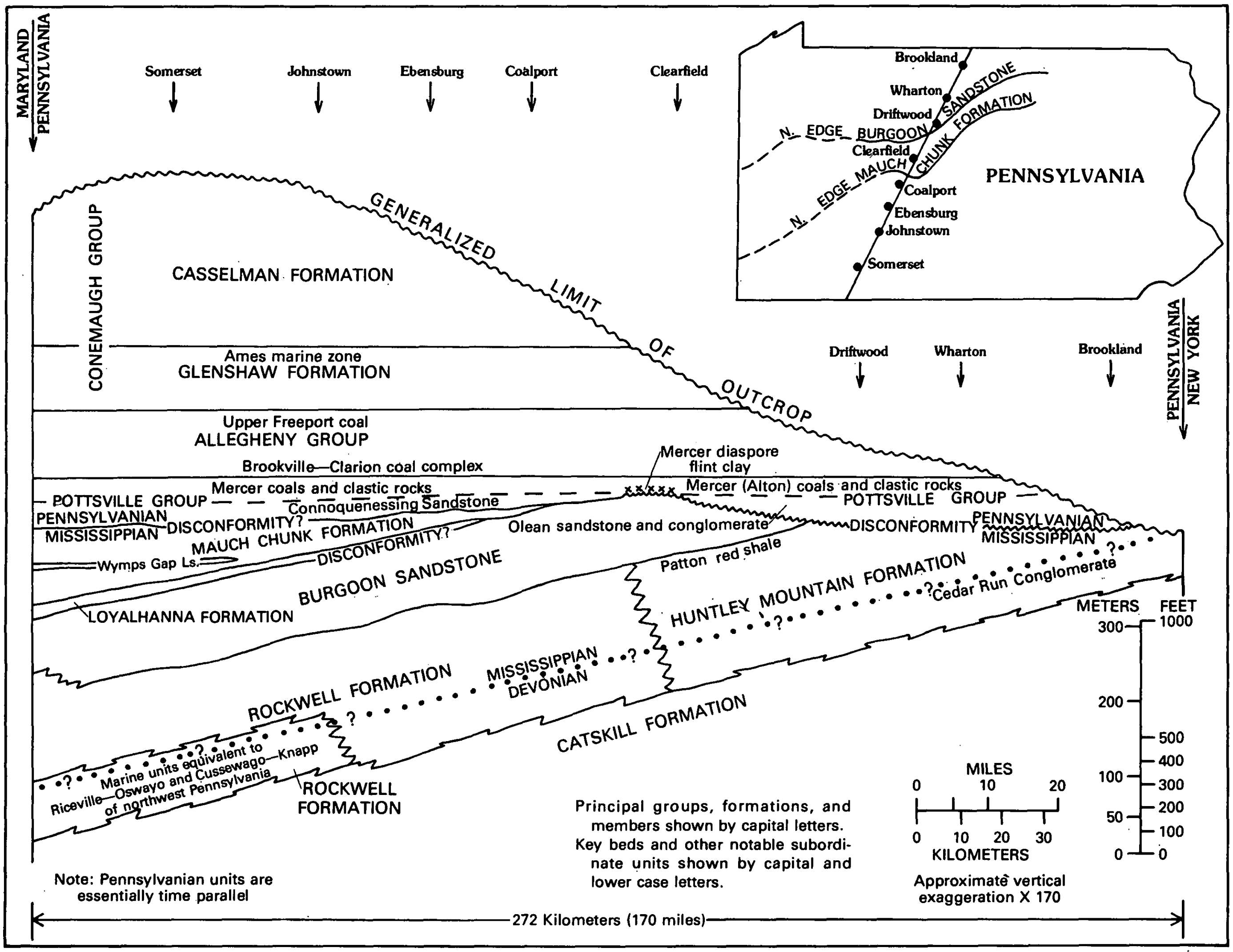

FIGURE 7.—Generalized stratigraphic cross section of Mississippian and Pennsylvanian rocks from Somerset County, Pa., to Cattaraugus County, N.Y.

ing occasional zones of flat-pebble conglomerate. Sandstones and intervening finer grained units have been named individually, but the entire sequence has no collective name. As long as individual units persist, this system of individual names works well. When, however, a component (usually one of the sandstones) disappears laterally, the nomenclature breaks down, resulting in the nameless gaps appearing in figure 5, column 2 bottom. The name "Hempfield" for the shale sequence overlying the Shenango Sandstone proposed by Caster (1934) is flawed by an erroneous type section, based on a miscorrelation in which the shale cited actually underlies the Shenango Sandstone rather than overlying it as Caster intended (Kimmel and Schiner, 1970). Kimmel and Schiner (1970) chose to correct the error by incorporating the shale overlying the Shenango Sandstone into an extended Shenango Formation as an unnamed upper member. It would be preferable to retain the name "Shenango" for the sandstone alone and to formally name the shale above the Shenango Sandstone. The informal term "Hempfield" is used in this report when the unit in question is discussed.

Shale and siltstone in this sequence are generally dark gray to medium dark gray, weathering to light olive gray or olive gray. Some shale is also grayish red to grayish brown. Sandstone is medium light gray to olive gray and has planar bedding and small- to medium-scale crossbedding. These rocks frequently have an abundant and diverse marine invertebrate fauna, extensive bioturbation, numerous trace fossils, some fish remains, and rare plant frag-

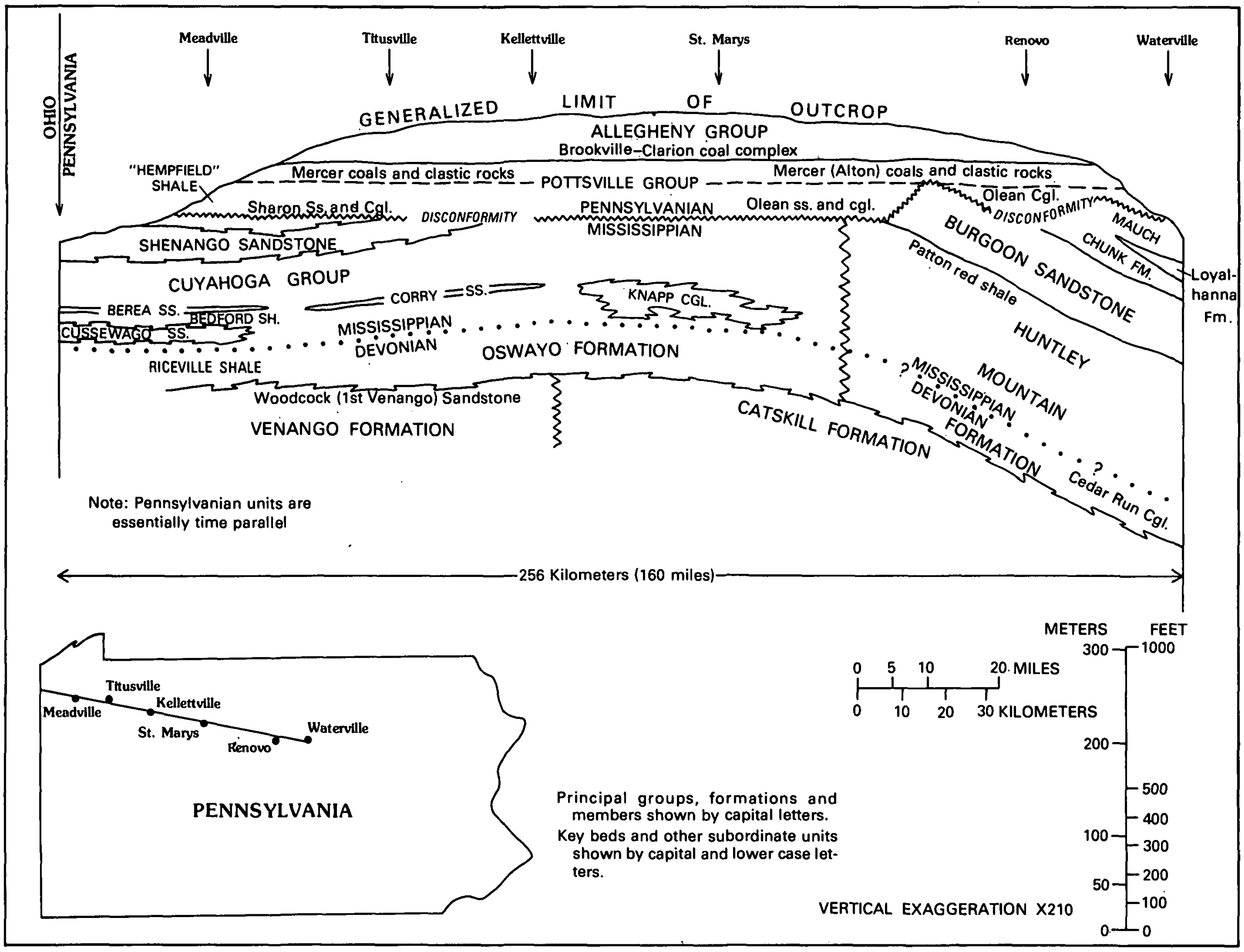

FIGURE 8.—Generalized stratigraphic cross section of Mississippian and Pennsylvanian rocks from Lycoming County, through Crawford County, Pa.

ments. Where completely present, the Riceville-Oswayo through "Hempfield" is about 180 to 215 m (600 to 700 ft) thick.

The "unnamed marine clastics" which are laterally equivalent to the Burgoon Sandstone (fig. 5, column 2) are also, logically, an upward continuation of Riceville-Oswayo through "Hempfield" sequence. Only recently recognized, these post-"Hempfield" marine rocks are exposed at the surface in limited areas in northern Armstrong and northwest Indiana Counties. They probably continue in the subsurface westward to Ohio, where a similar relationship is noted between the Logan (Burgoon) Sandstone and laterally equivalent marine beds.

The transgressive marine Riceville-Oswayo through "Hempfield" sequence that overlies the regressive marine Venango Formation and prograding nonmarine Catskill Formation is the facies equivalent of the dominantly nonmarine Huntley Mountain and Rockwell Formations. The sub-Burgoon section in the subsurface of southwestern Pennsylvania (fig. 5, column 1) is essentially a continuation of the general Riceville-Oswayo through "Hempfield" marine interval.

This sequence, along with the unnamed marine equivalents of the Burgoon, is approximately correlative with the Waverly Group of Ohio.

ROCKWELL, HUNTLEY MOUNTAIN, AND SPECHTY KOPF FORMATIONS
(Figure 5, columns 3–6)

The Rockwell Formation, Huntley Mountain Formation (Berg and Edmunds, 1979), and, in most areas, the Spechty Kopf Formation are a dominantly

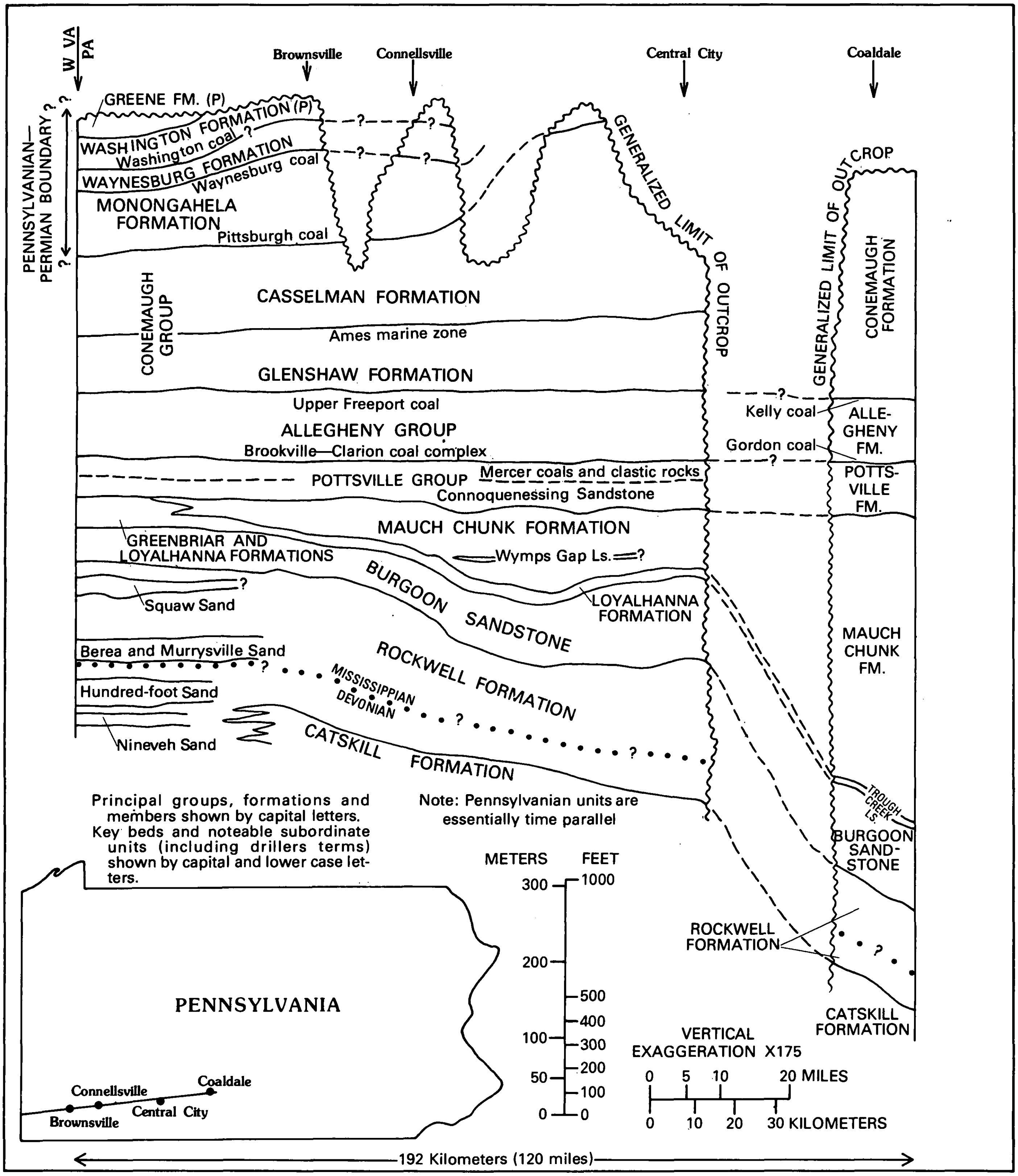

FIGURE 9.—Generalized stratigraphic cross section of Mississippian and Pennsylvanian rocks from Bedford County, through Washington County, Pa.

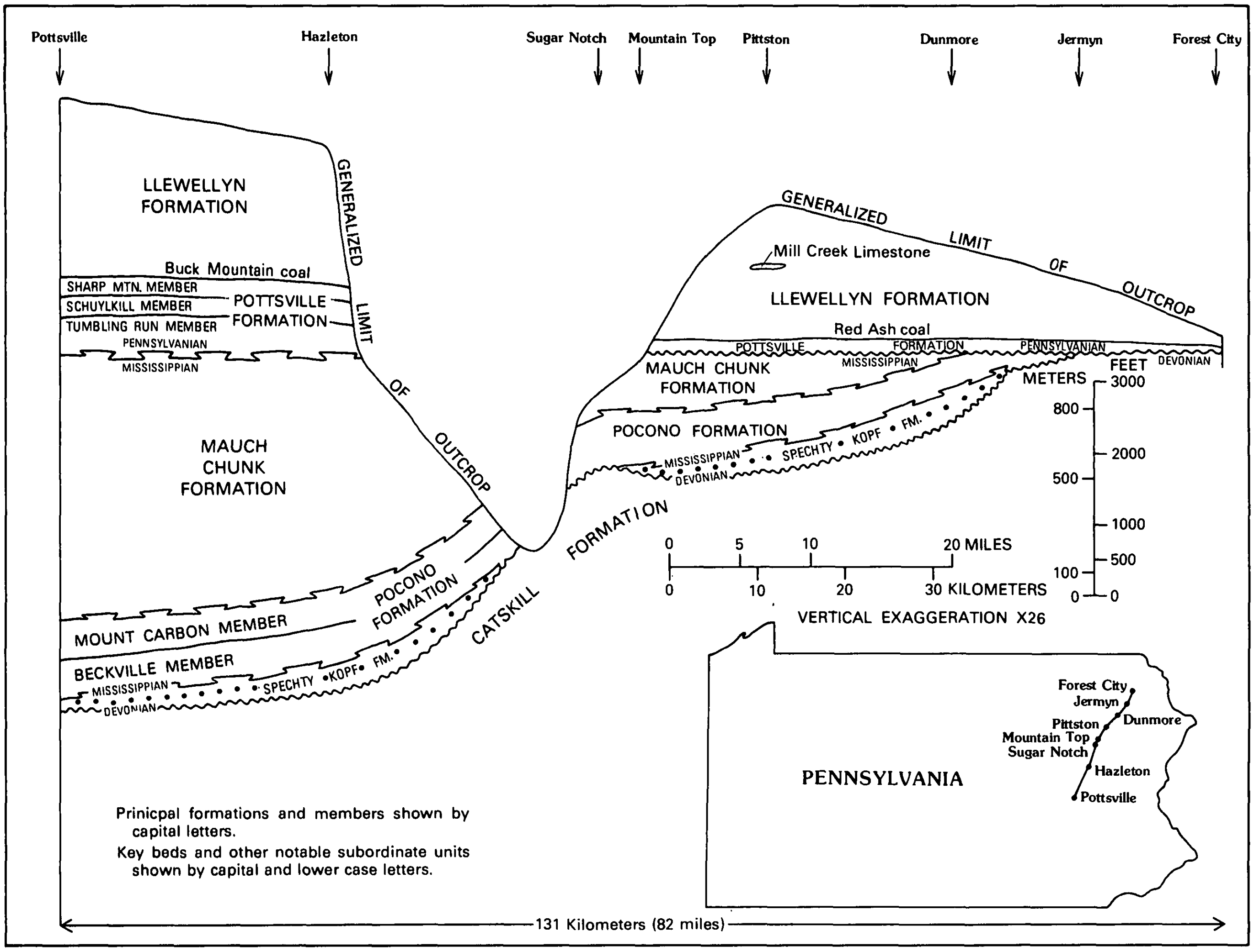

FIGURE 10.—Generalized stratigraphic cross section of Mississippian and Pennsylvanian rocks from Schuylkill County to Susquehanna County, Pa.

nonmarine mixture of sandstone, siltstone, and shale.

All three units are lateral equivalents of one another and of the lower part of the Pocono Sandstone of northeastern Pennsylvania as well. In its type area around the western end of the Southern Anthracite field, the Spechty Kopf is almost entirely sandstone and lithologically is a continuation of the overlying Pocono. Elsewhere, the Spechty Kopf is the nonmarine mixture mentioned above and is generally rather similar to the Rockwell Formation, except for the lack of red beds.

The Rockwell and Huntley Mountain are dominantly nonmarine facies equivalents of the Riceville-Oswayo through "Hempfield" marine sequence of northwestern Pennsylvania; they interfinger with marine beds along their western margin. A few marine units, such as the Cedar Run conglomerate bed of the Huntley Mountain and the Riddlesburg shale member of the Rockwell represent strong, but brief, eastward marine transgressions.

There is some indication that the Huntley Mountain thickens in north-central Pennsylvania, replacing the Burgoon Sandstone by facies change in much the same way that the Burgoon is replaced by marine facies equivalents in northwestern Pennsylvania. In western Maryland, the Rockwell seems to replace the Burgoon in a similar way.

The sandstone, siltstone, and shale of these formations are generally various shades of gray or greenish gray. Plant fossils are sometimes present. The Rockwell and Huntley Mountain contain scattered grayish-red shale and some thin beds or lenses of flat pebble conglomerate. The Spechty Kopf and Rockwell locally contain notable occurrences of diamictite, which may be glacial or glaciofluvial deposits (Sevon 1973).

The Huntley Mountain is distinguished from the Rockwell and Spechty Kopf by its overall greenish or olive cast and by much thin flaggy sandstone. The Huntley Mountain has more lithic affinity to the underlying Catskill Formation, whereas the Spechty Kopf and Rockwell appear to have more lithic affinity to the overlying Pocono Formation. The distinctiveness of the Huntley Mountain Formation is believed to stem from differences in provenance and basin characteristics. The sediment source for the Spechty Kopf and Rockwell was the "new" orogenic belt to the southeast (Pelletier, 1958), whereas the Huntley Mountain may have been derived partly from the old Taconic Highlands to the northeast and possibly the craton to the north as well. In addition, the Huntley Mountain was deposited in the more restricted northeastern end of the Appalachian basin.

The Rockwell, Huntley Mountain, and Spechty Kopf Formations are generally 180 to 250 m (600 to 800 ft) thick. Where they apparently replace the Burgoon Sandstone laterally, the Huntley Mountain and Rockwell may expand to 300 m (1,000 ft).

POCONO, BURGOON, AND SPECHTY KOPF FORMATIONS
(Figure 5, all columns)

The Pocono and Burgoon Formations and, in its type area around the western end of the Southern Anthracite field, the Spechty Kopf Formation are dominantly medium- to coarse-grained, medium-light to very light gray sandstone often containing quartz pebble conglomerate zones. No red beds are present, but subordinate dark shale and siltstone are found. The Pocono is as much as 500 m (1,650 ft) thick and the Burgoon as much as 110 m (360 ft). Plant fossils are common, especially in the finer grained lenses, but no marine invertebrate fossils are found.

The Burgoon appears to be the westward extension of the upper part of the Pocono. Around its depositional margins, the Pocono-Burgoon appears to grade laterally into upward extensions of subjacent units: the Huntley Mountain Formation in north-central Pennsylvania; the lower Mississippian marine clastic rocks of northwestern Pennsylvania and Ohio; and the Rockwell Formation in western Maryland and northern West Virginia.

LOYALHANNA AND GREENBRIER FORMATIONS
(Figure 5, columns 1, 3, and 4)

The Loyalhanna Formation is a thin tongue, less than 30 m (100 ft) thick, of the middle Mississippian Greenbrier Group limestone extending across southwestern and central Pennsylvania. The Loyalhanna grades from a sandy limestone in the south to a calcareous sandstone in the north, in most places strikingly crossbedded. A second thin Greenbrier tongue, the Wymps Gap Limestone Member of the Mauch Chunk Formation, is present throughout much of southwest-central Pennsylvania. The Loyalhanna and Wymps Gap merge in southwestern Pennsylvania to form the subsurface Greenbrier Formation, which in turn is traceable into part of the thick Greenbrier carbonate sequence of West Virginia (Adams, 1970).

The Loyalhanna lies directly and possibly disconformably upon the upper surface of the Burgoon Sandstone except in part of north-central Pennsylvania, where an early wedge of the Mauch Chunk Formation intervenes (Wells, 1974).

MAUCH CHUNK FORMATION
(Figure 5, columns 1, 3–6)

The Mauch Chunk Formation is composed of grayish-red shale and siltstone and some light-gray to yellowish-gray sandstone. It is almost entirely nonmarine, containing some plant fossils and fish fragments. Maximum thickness is uncertain but probably is in the 2,450- to 2,750-m (8,000- to 9,000-ft) range.

The lower part of the Mauch Chunk is a facies equivalent of the Greenbrier-Loyalhanna. In southwestern Pennsylvania, the basal Mauch Chunk wedges out between the underlying Loyalhanna and the Wymps Gap Limestone Member of the Mauch Chunk, which converge to form the Greenbrier Limestone of southwesternmost Pennsylvania. In part of north-central Pennsylvania, a tongue of Mauch Chunk red beds underlies the Loyalhanna facies.

The upper Mauch Chunk is also a facies equivalent of the basal Pottsville in the area of the Southern Anthracite field where the two units are interbedded. Whether the Pottsville-Mauch Chunk contact is conformable or disconformable elsewhere has caused considerable controversy, which is discussed in the following section.

The Mauch Chunk is absent because of nondeposition or erosion, or both, throughout northwestern Pennsylvania and adjacent New York, as well as extreme southwestern and northeastern Pennsylvania.

It undergoes considerable facies changes from southwest to northeast before it is cut out erosionally along the margins of the Northern Anthracite field.

MAJOR DISCONFORMITIES IN THE MISSISSIPPIAN AND PENNSYLVANIAN SYSTEMS
(Figure 5, columns 1, 4, and 6)

The formation of two widespread disconformities during the Mississippian and Pennsylvanian Periods has been hypothesized for Pennsylvania and New York. The earlier of these disconformities is believed to have formed on top of the Burgoon Sandstone before deposition of the Loyalhanna Limestone during Meramecian and, perhaps, early Chesterian time (Reger, 1927). The second disconformity, between the basal Pottsville and the underlying Mississippian and uppermost Devonian strata, formed from late Chesterian through early Atokan time.

The existence of the Burgoon-Loyalhanna disconformity is largely based upon the presumed relative ages of the Loyalhanna-Greenbrier (late Meramecian, on the basis of marine invertebrates) and the Burgoon (presumed Osagean at the latest, on the basis of plant fossils). However, the reality of this disconformity is questionable. The contact between the two is sharp but otherwise remarkably uniform. The age of the Loyalhanna is probably fairly reliable, but control on the terminal age of the Burgoon is very weak. We postulate later in this report that the Burgoon Sandstone was deposited on a vast anastomosing alluvial sand plain, which by Meramecian time was depositionally static. If so, the relation between the Burgoon and Loyalhanna is simply that of a transgressive marine unit encroaching on a foundering alluvial plain. However, at the same time, it appears that epeirogenic uplift was beginning in northern Pennsylvania and New York inducing mild erosion of the Lower Mississippian sediments and restricting the northwestward encroachment of the Loyalhanna. The northern source of the sand fraction of the Loyalhanna is believed to be an erosional escarpment of the Burgoon.

The sub-Pottsville disconformity was originally proposed by I. C. White (1891) to explain the absence of certain floral assemblages from the presumed time-sequential Mississippian-Pennsylvanian paleobotanical zonation system. The disconformity was also proposed to explain the northwestward thinning of the Pennsylvanian Pottsville and the progressive northwestward loss of the Mississippian Mauch Chunk Formation and subjacent Mississippian strata.

Only in the Southern Anthracite field (fig. 5, column 5), and in southeastern West Virginia, where the complete floral sequence is present, were the Mauch Chunk (or equivalent in West Virginia) and Pottsville believed to be conformable. North and west from these limited conformable areas, successively older Mississippian strata were believed to have been truncated by erosion during Early Pennsylvanian time. After erosion, Pennsylvanian Pottsville units were deposited in onlap fashion, so that the basal Pennsylvanian became progressively younger to the northwest. In the extreme case in New York, the Lower Pennsylvanian Olean conglomerate rests disconformably upon the uppermost Devonian Oswayo Formation.

There seems to be little doubt that in places where the Pottsville rests upon units older than the Mauch Chunk, a disconformity is required. In at least part of northern Pennsylvania and New York, erosion probably continued from the Meramecian Epoch into the Morrowan or, possibly, the Atokan Epoch. To what extent erosion was continuous during this span of time depends entirely upon how far north Mauch Chunk sediments encroached before being eroded back to their present limit. The lower beds of the Mauch Chunk (excluding the pre-Loyalhanna tongue in north-central Pennsylvania) now extend only a short distance beyond the northern limit of the Loyalhanna. Around its present margin, the Mauch Chunk apears to have been uplifted and eroded back by the Late Mississippian to Early Pennsylvanian epeirogenic activity, but how far this beveling cut the Mauch Chunk back from its original maximum encroachment is unknown. Nor is it clear how far to the southeast this erosional disconformity continues upon the upper surface of the Mauch Chunk.

According to White's classical concept, the disconformity should exist where the lowest Pennsylvanian floral zone disappears. If this concept is true, the disconformity would extend across the entire State, except for the Southern Anthracite field. However, physical observation of the Mauch Chunk-Pottsville contact in other areas has produced doubts about any substantial disconformable break (Ferm and Cavaroc, 1969; Ferm, 1974). Glass and others (1977, p. 14) have suggested that some of the Lower Pennsylvanian floral zones are biofacies equivalents of the Upper Mississippian zone related to the Mauch Chunk Formation. This possibility has been rejected by most paleobotanists on the basis of phylogenetic comparisons between floral suites of the zones involved. It is also possible that the interrelationships between the floral assemblages and the lithostratigraphic units may have been oversimplified, resulting in the misplacing of a lithostratigraphic boundary on a biostratigraphic basis.

POTTSVILLE GROUP
(Figure 5, columns 1–6)

The Pottsville is dominantly sandstone, conglomerate, and siltstone, and has subordinate amounts of coal, shale, and limestone. Thickness of the group is 215 to 460 m (800 to 1,500 ft) in the Southern and Middle Anthracite fields, but only 15 to 85 m (50 to 250 ft) elsewhere in Pennsylvania.

The Pottsville is entirely nonmarine except in western Pennsylvania, where some marine limestone and shale are present in the upper part. Plant fossils are common throughout.

The lower Pottsville is a facies equivalent of the uppermost Mauch Chunk in the area of the Southern Anthracite field and may or may not be conformable with most of the Mauch Chunk elsewhere (see preceding section on "Major Disconformities"). The Pottsville rests disconformably on lower units down to the Upper Devonian Oswayo in northwestern Pennsylvania and southwestern New York, and the Upper Devonian Catskill Formation at the northern end of the Northern Anthracite field.

The Pottsville is thinnest (15 to 40 m, 50 to 130 ft) where it lies directly upon the eroded Burgoon Sandstone, which apparently produced an Early Pennsylvanian topographic high. The unusual Mercer high-alumina flint clays occur at this disconformable Burgoon-Pottsville contact and at a similar contact between the Pottsville and a resistant sandstone in the lowermost part of the Mauch Chunk Formation.

The Pottsville in northwestern and north-central Pennsylvania was derived from the reworking of earlier Paleozoic sediments in New York uplifted around the rim of the North American craton (Fuller, 1955). The source of the remaining Pottsville was the orogenic highlands to the southeast (Meckel, 1967).

LLEWELLYN FORMATION
(Figure 5, columns 5 and 6)

The Llewellyn Formation is a mixture of interbedded conglomerate, sandstone, siltstone, claystone, and coal. The Llewellyn is the lateral equivalent of the Allegheny and Conemaugh Groups of western Pennsylvania, and possibly the Monongahela Group and part of the Dunkard Group as well. In general, the Llewellyn is much coarser grained than the equivalent rocks to the west. Maximum remaining thickness is 1,070 m (3,500 ft). The entire sequence is nonmarine, except for the thin Mill Creek limestone bed in the Northern Anthracite field (Chow, 1951). Plant fossils are common.

ALLEGHENY, CONEMAUGH, AND MONONGAHELA GROUPS
(Figure 5, columns 1–4)

The Allegheny, Conemaugh, and Monongahela Groups are a sequence composed of many beds of sandstone, siltstone, claystone, coal, and limestone. Except locally, no rock type is dominant throughout any substantial part of the section. Subtle differences are found in the proportion of the various rock types as well as changes in secondary characteristics, such as color and presence or absence of marine fossils.

The establishment of these three groups along with the overlying Permian(?) Dunkard Group arose from early recognition that parts of the total post-Pottsville sequence frequently contained mineable coal beds, whereas others did not. The Allegheny and Monongahela have mineable coals and were originally called the "Lower Productive" and "Upper Productive," respectively, whereas the Conemaugh and Dunkard, which contain thin seams, were the "Lower Barren" and "Upper Barren." In effect, these units were defined by a slight change in a secondary characteristic (thickness) of a volumetrically minor lithologic constituent (coal).

Whatever its economic virtue, the use of "coal mineability" as the defining characteristic for formal geologic units was vague and impossible to apply consistently. Recognizing this difficulty, and faced with a lithologically heterogeneous section, 19th century geologists turned to key beds to provide boundary markers for the Allegheny, Conemaugh, and Monongahela Groups. To retain the concept that the Allegheny and Monongahela Groups contained most of the mineable coals, the key beds selected were the lowest and highest coal beds in each unit.

Inasmuch as a key bed must be a single identifiable widespread unit, it has been accepted, more or less on faith, that coal seams do indeed have these necessary characteristics. In reality, only the Pittsburgh coal (the base of the Monongahela Group) has the true continuity expected of a key bed. In practice, the other boundaries of the four groups are correlated generally on the basis of vertical spacing, and by reference to the relative position of a multiplicity of other beds recognized throughout the sequence. Any coal conveniently close to the expected key-bed boundary is used as such, so long as it persists. For obvious reasons, the code of stratigraphic nomenclature (American Commission on Stratigraphic Nomenclature, 1970) cannot be rigously applied to these units.

The Allegheny Group from the base of the Brookville coal to the top of the Upper Freeport coal is persistently about 80 to 100 m (270 to 320 ft) thick. The lower half contains some marine or brackish water units and no freshwater limestone. The upper half is entirely nonmarine and contains freshwater limestone. The Allegheny Group has no redbeds.

The Conemaugh Group lies between the top of the Upper Freeport coal and the base of the Pittsburgh coal; it is divided into two formations at the top of the Ames marine zone. The lower formation (Glenshaw) contains four widespread marine zones. The upper formation (Casselman) is entirely nonmarine except for a limited brackish-water zone in the lower part. The Conemaugh Group ranges from less than 170 m (550 ft) in Washington County, to more than 275 m (900 ft) in Somerset County. It contains scattered redbeds and nonmarine limestones throughout; several marine limestone units occur in the Glenshaw Formation.

The Monongahela Group extends from the base of the Pittsburgh coal to the top of the Waynesburg coal, and is 85–115 m (275–375 ft) thick in Pennsylvania, increasing from west to east. It is entirely nonmarine, contains abundant freshwater limestone, and has no redbeds.

BIOSTRATIGRAPHY

Marine units containing the principal faunal suites are largely confined to the Devonian-Mississippian Riceville-Oswayo through "Hempfield" sequence; the Mississippian Loyalhanna-Greenbrier sequence; and the Pennsylvanian lower Allegheny Group and Glenshaw Formation. Marine units are mostly limited to western Pennsylvania. (See figs. 4 and 5.) Except for a few thin marine tongues, all the remaining Mississippian and Pennsylvanian is nonmarine, and the associated fauna is sparse and poorly understood.

Fossil plants are common in the Pennsylvanian sequence, and the interrelations between the Pennsylvanian flora and fauna are fairly well understood. Plant fossils occur sporadically throughout the nonmarine Mississippian sequence but only rarely in close association with any marine fauna.

PALEOZOOLOGY

In 1948, Cooper (p. 256) commented on the paleontologic aspects of the Mississippian System in the central and northern Appalachians: "The stratigraphic work upon which the succession was divided into formations was almost entirely of a physical character, and it has been carried on in a near-vacuum of systematic paleontology. Thus many regional correlations are inaccurate." In 1979, that statement regarding the Mississippian of Pennsylvania is still valid. A similar but less harsh commentary is applicable to the present status of paleozoologcal research in the Pennsylvanian System of this part of the Appalachian region.

Although adequate paleontological studies of the Mississippian are lacking, the singularly important contributions on this subject by Caster (1930, 1934) and Chadwick (1935) should be recognized. Caster's documentation of Late Devonian and Mississippian invertebrates of northwestern Pennsylvania, along with his pioneering formulation of facies concepts still stands today as the standard biostratigraphic reference for that area.

Because of the complex facies patterns and lateral intergradations discussed by Caster (1934) and herein under "Lithostratigraphy," and because of the necessarily voluminous systematic paleontology yet to be accomplished, a biostratigraphic zonation of the Lower Mississippian marine sequence has not been established. Considerable effort has been directed at establishing the position of the Mississippian-Devonian boundary (Caster, 1934; Chadwick, 1935; Holland, 1958), and consideration has been given to the possibility that many faunal elements may overlap and approximate a gradation (Caster and others, 1935). Caster's invertebrate faunal lists (1934) tell little of actual abundances of the various taxa, but some inferences can be made regarding diversity changes from Devonian to Mississippian. In the Mississippian, there appear to be significant diversity increases amongst strophomenid and spiriferid brachiopods, along with increases of diversity amongst archaeogastropods, particularly the trochinids.

Holland (1958) described 47 species, subspecies, and morphological variants of brachiopods in the Oswayo and Knapp Formations. He concluded that only two species crossed the Oswayo-Knapp boundary (1958, p. 71) in the Bradford-Warren area. The systemic boundary is there placed at the horizon having the greatest number of new brachiopod forms. Chief among these brachiopods are the genera *Dictyoclostus* and *Syringothyris*. Holland (1958, p. 71) admitted that facies may be a controlling factor in the distribution of brachiopods across the Devonian-Mississippian boundary. This points up the requirement that detailed paleobiogeographic and paleoecologic studies should go hand-in-hand with systematic descriptions of the fossils. Williams (1903) long ago emphasized the importance of understanding the shifting of faunas with depositional environments. His examples were drawn from the Upper Devonian of northern Pennsylvania and southern New York. The principles he articulated are equally applicable to the Devonian-Mississippian sequence of northwestern Pennsylvania today.

Sass (1960) affirmed the Kinderhookian age of the Corry Sandstone in Pennsylvania and pointed out that correlation with the Berea Sandstone to the west is based on stratigraphic position rather than faunal evidence. He suggested (1960, p. 296) that the lower member of the Corry may well correlate with the upper part of the Bedford Shale of Ohio but that systematic studies of Bedford faunas are still needed. Sass also recognized the influence of environments on the invertebrates, citing the more common rugose brachiopod species in the eastern part of the Corry as evidence of more nearshore conditions (1960, p. 295). On the basis of paleobotanical evidence, conodont zonation, and regional lithostratigraphic correlations, deWitt (1970) concluded that the basal Bedford shale may be very Late Devonian in Ohio and Kentucky but that the remaining Bedford Shale and Berea Sandstone are Early Mississippian.

In southwestern Pennsylvania, emphasis has also been placed on locating the Mississippian-Devonian boundary rather than on biostratigraphic zonation. Laird (1941, 1942) listed invertebrates collected from the Devonian and Mississippian strata exposed in the anticlinal inliers of Fayette County. He said (1941, p. 18) that the occurrence of certain species of *Syringothyris*, *Eumetria*, *Leptodesma*, and *Palaeoneilo* mark the base of the Mississippian. The disappearance of certain species of what is now *Cyrtospirifer* ("*Spirifer disjunctus*" gens) marks the upper limit of the Devonian System.

In 1943, Busch (p. 154) examined invertebrates in a shale interval in the upper part of the Shenango Formation in the Oil City 15-minute quadrangle in northwestern Pennsylvania. He concluded, on the basis of comparison with invertebrates of the Mississippi Valley, that the interval could be assigned to a series no older than middle Meramecian. Weller and others (1948, p. 160) questioned Busch's identifications and seriously questioned his correlation. They mentioned that strata overlying the Cuyahoga in Ohio are not known to be younger than uppermost Osagean. Szmuc (1970, p. 47) considers the Shenango fauna in northeastern Ohio to bear a close affinity to that of the eastern part of the Meadville Formation (Cuyahoga Group).

Other than what has been accomplished by Chadwick and by Caster and his students at Cincinnati, and what was done before the turn of the century by the Second Pennsylvania Survey, very little work has been directed toward the paleozoology of the Lower Mississippian of Pennsylvania. Recent work on trace fossils in the Devonian and Mississipian of northwestern Pennsylvania by Gutschick and Lamborn (1975) points to a whole new avenue of biostratigraphic analysis. Another avenue may be opened through conodont studies.

The Upper Mississippian (Meramecian through Chesterian) is represented in Pennsylvania mainly by the Mauch Chunk Formation, which is dominantly nonmarine and rarely bears an invertebrate fauna. In the southwestern part of the State, where the Greenbrier limestones intertongue with the Mauch Chunk redbeds, some paleozoological insights have been obtained. Benson (1934) identified some brachiopods from a Greenbrier tongue near Uniontown, Pa., and concluded that the brachiopod fauna is similar to those of the Greenbrier Formation of West Virginia and the Ste. Genevieve Limestone of Kentucky. Haney (1963, p. 198–199) described the Greenbrier fauna of Pennsylvania as a principally brachiopod-crinoid assemblage closely related to the fauna of the Batesville Sandstone of Arkansas. He regards the Greenbrier fauna as a late Meramecian to early Chestrian assemblage.

In his study of the Mauch Group in northwestern West Virginia, Busanus (1974, 1976) identified an assemblage characterized by pelmatozoans and articulate brachiopods from the Wymps Gap Limestone tongue of the Greenbrier. Because most of the forms identified in the Mauch Chunk-Greenbrier transition are relatively long ranging, Busanus (oral commun., 1978) does not believe that an Elviran (Late Chesterian) age for that part of the section can be refined.

The Wymps Gap Limestone in Somerset County, Pa., as delineated by Flint (1965, p. 48), is somewhat above the base of the Chesterian Series. Another limestone called the "Deer Valley" directly overlies the Loyalhanna Limestone and is considered as basal Chesterian, but Flint (1965, p. 49) recommended further stratigraphic and paleontologic studies.

The Mississippian-Pennsylvanian boundary is marked by a clear unconformity over a large part of Pennsylvania, as has been discussed under "Lithostratigraphy" above. Where the Mauch Chunk and Pottsville are interbedded, the systemic boundary is picked with varying degrees of confidence by paleobotanical methods. Some potential for paleozoological definition of the Mississippian-Pennsylvanian boundary in Pennsylvania may be found in the detailed study of freshwater arthropods and bivalves, but to date, no such research has been done.

Raymond (1911, p. 95–96) presented a list of invertebrates found in the Vanport marine zone of the Pennsylvanian Allegheny Group, along with invertebrates in five marine zones of the Conemaugh Group. His list was preliminary, and no accurate biostratigraphic correlations could be made from it. Williams (1960) identified a large fauna from the Pottsville and Allegheny Groups of western Pennsylvania and established the beginnings of proper paleozoological zonation within those groups. He (Williams, 1960, p. 911) explained the necessary paleoecological and paleoenvironmental evaluations that are a prerequisite to accurate zonation and correlation.

The Glenshaw Formation of the Conemaugh Group is characterized by several marine "zones," which may be genuine fossiliferous limestone beds or which may grade laterally to highly fossiliferous, carbonaceous, calcareous siltstone. The best known and most widespread of these units are the Brush Creek, the Cambridge (Pine Creek), and the Ames. The Ames marine zone is used as a key bed to mark the top of the Glenshaw Formation. Over much of their extent, these marine units may be true biostromes. Invertebrate faunal diversity appears to be greater in these marine zones than at any other horizon within the Mississippian or Pennsylvanian. Seaman (1940, 1941, 1942) listed a large number of invertebrates from these three marine zones and pointed out some minor differences between the three suites, but he did not attempt to erect biozones or to establish correlations with the midcontinent. Chow (1951) documented the occurrence of a marine zone in the Llewellyn Formation called the Mill Creek Limestone; correlation with the Ames of western Pennsylvania is based on interval and faunal content. Further studies on the Glenshaw marine units have been carried out by Lintz (1958), Murphy (1970), Rollins and Donahue (1971), Shaak (1972), and Donahue and Rollins (1974). The thrust of recent research and investigation with regard to the Glenshaw marine intervals has been more to recognize and define fossil invertebrate communities and their ecosystem dynamics through time and in relation to sedimentation cycles (Shaak, 1972; Rollins and Donahue, 1975). Paleontological zonation by invertebrates in this part of the Carboniferous will be contingent upon the success of these paleoecological investigations.

The upper part of the Conemaugh Group, the Casselman Formation, is for the most part nonmarine, and relatively little paleozoological information has been derived from these rocks. The overlying nonmarine Monongahela Group has to date also yielded relatively little paleozoological data. Durden (1969) has provided an important avenue for zonation and correlation through his research on blattoid insects in these nonmarine strata, as well as in the underlying Allegheny and Pottsville Groups and the laterally equivalent Llewellyn Formation.

Fossil vertebrates (fish) have been collected by various workers from all of the Carboniferous of Pennsylvania, but the most serious research on this topic has been carried out by Lund (1970). Continued detailed studies of fossil fishes may well provide a basis for zonation of the upper Conemaugh and Monongahela Group.

PALEOBOTANY

The floral biostratigraphy of Pennsylvania was investigated with considerable energy in the late 19th and early 20th centuries, but interest has dwindled since, so that only a few poorly supported workers continue, intermittently, to pursue the subject. The most authorative summary of the floral biostratigraphy of the entire Mississippian-Pennsylvanian was given in Read and Mamay (1964). Darrah (1969) produced an extensive review of the Late Pennsylvanian flora. The floral biostratigraphic sequence shown in figure 11 is based mostly on Read and Mamay (1964).

The 12 Mississippian and Pennsylvanian floral zones shown in figure 11 are considered biostratigraphically and chronologically sequential. At no single place in Pennsylvania, however, is the complete sequence found. The absence of zones 7 and 8 in the Southern and Middle Anthracite fields is probably a matter of nonpreservation or locally unsuitable growth environment, rather than a missing stratigraphic section. (See Wood and others, 1969, p. 79.

North and northwest from the Southern Anthracite field, Lower Pennsylvanian floral zones 4, 5, 6, and 7 disappear, as do Mississippian zones 3 and 2. This expanding gap in the floral sequence was explained by White (1891) as the result of widespread erosion at the end of the Mississippian, which successively removed the Mississippian sequence toward the northwest. Subsequently, onlapping sediments of the Lower Pennsylvanian Pottsville sequence advanced slowly across this erosion surface. The lowest Pottsville becomes progressively younger toward the northwest, and the older Pennsylvanian

FLORAL ZONE (READ AND MAMAY, 1964)	DOMINANT CHARACTERISTIC FLORAL SPECIES (READ and MAMAY, 1964)	PENNSYLVANIA EXCEPT SOUTHERN and MIDDLE ANTHRACITE FIELDS	SOUTHERN AND MIDDLE ANTHRACITE FIELDS	SERIES	SYSTEM
13	*Callipteris* spp.	Dunkard Group	Possibly present in uppermost Llewellyn Formation	Wolfcampian	Permian
				?	?
12	*Danaeites* spp.	Upper Monongahela Group	Possibly present in upper Llewellyn Formation.	Virgilian	Pennsylvanian
11	*Lescuropteris* spp.	Lower Monongahela Group and Casselman Formation of Conemaugh Group	Possibly present in upper Llewellyn Formation	Missourian	
10	*Neuropteris flexuosa* and *Pecopteris* spp.	Glenshaw Formation of Conemaugh Group and upper Allegheny Group	Lower Llewellyn Formation		
9	*Neuropteris rarinervis*	Lower Allegheny Formation	Upper Sharp Mountain Member of Pottsville Formation and possibly lowermost Llewellyn Formation	Des Moinesian	
8	*Neuropteris tenuifolia*	Upper Pottsville Formation (Mercer)	Not known. Presumed equivalent to middle Sharp Mountain Member of Pottsville Formation		
7	*Megalopteris* spp.	Middle Pottsville Formation (Connoquenessing)	Not known. Presumed equivalent to lower Sharp Mountain Member of Pottsville Formation	Atokan	
6	*Neuropteris tennesseeana* and *Mariopteris pygmaea*	Lowest Pottsville Formation in NW. Pa. (Sharon). Absent elsewhere by disconformity (nondeposition) and/or biofacies with zone 3	Schuylkill Member of Pottsville Formation	Morrowan	
5	*Mariopteris pottsvillea* and *Aneimites* spp.	Absent by disconformity (nondeposition) and/or biofacies with zone 3	Upper Tumbling Run Member of Pottsville Formation		
				?	?
4	*Neuropteris pocahontas* and *Mariopteris evemopteroides*	Absent by disconformity (nondeposition) and/or biofacies with zone 3	Lower Tumbling Run Member of Pottsville Formation	?	?
				?	?
3	*Fryopsis* spp. and *Sphenopteridium* spp.	Mauch Chunk Formation. Absent in SW. Pa. (marine facies) and northern Pa. (Disconformable nondeposition and erosion)	Mauch Chunk Formation	Chesterian	Mississippian
				Meramecian	
2	*Triphyllopteris* spp.	Burgoon and upper Pocono Formations. Absent in northern Pa. by disconformable nondeposition and erosion	Upper Pocono Formation	Osagean	
1	*Adiantites* spp.	Upper Huntley Mountain, upper Rockwell, and lower Pocono Formations	Upper Spechty Kopf and lower Pocono Formations	Kinderhookian	

FIGURE 11.—Mississippian and Pennsylvanian floral zones.

floral zones disappear. See the section on "Major Disconformities of the Mississippian-Pennsylvanian" for additional discussion of this subject.

CHRONOSTRATIGRAPHY

The time boundaries of the Mississippian and Pennsylvanian Periods and their subordinate epochs (fig. 5) are placed entirely by reference to the biostratigraphy of the rock sequence. No supplementary physical data, such as radioactive dating, are available.

Of the three period boundaries involved, only the Devonian-Mississippian boundary in the marine section of northwestern Pennsylvania, and the boundary marked by the disconformity between the Pennsylvanian Pottsville and Lower Mississippian Burgoon (or older strata) are located with some reasonable precision. The extension of the Devonian-Mississippian boundary eastward into the dominantly nonmarine Huntley Mountain, Rockwell, and Spechty Kopf Formations is primarily based upon interval and some general control from the plant fossils.

The Pennsylvanian-Mississippian boundary in the Southern Anthracite area, where the Pottsville reaches maximum thickness, may be placed arbitrarily at the base of that unit. Because, however, the upper Mauch Chunk is the lateral facies equivalent of at least part of the Pottsville, the period boundary must pass into the Mauch Chunk at some point. Because there is some doubt as to what extent the Pottsville-Mauch Chunk contact is conformable or disconformable elsewhere, the position of the Pennsylvanian-Mississippian boundary is obscure.

The least clear of the three period boundaries is that between the Pennsylvanian and Permian. The problem is inordinately complex. The most exhaustive examination of the location of the Pennsylvanian-Permian boundary is in "The Age of the Dunkard" (Barlow, 1975), a symposium in which 23 paleobotanical and paleozoological specialists discuss the problem. Opinions range from placing the Permian-Pennsylvanian boundary as low stratigraphically as the Casselman Formation of the Conemaugh Group, to above the uppermost occurrence of the Dunkard. Much simplified, the problem centers about whether or not the first occurrence of the Permian index fossil, *Callipteris conferta* in the Appalachians corresponds chronologically with its first occurrence in the Permian standard section in central Europe.

The epoch boundaries within the Carboniferous of Pennsylvania are poorly defined, except for those of the Desmoinesian and, in western Pennsylvania, the Missourian.

DEPOSITIONAL HISTORY

Sediments of the Mississippian and Pennsylvanian Periods were deposited upon the vast Upper Devonian Catskill deltaic complex. These sediments were derived from the southeastern orogenic uplift, which had formed along the impact margin of the North American and African continental plates, and also from the edge of the North American cratonic heartland and the older Taconic impact area to the north and northeast.

The Catskill deltaic complex achieved maximum westward progradation during the late part of the Late Devonian (Chautauquan) (fig. 12A). Shortly before the end of that period, a widespread and relatively abrupt marine transgression terminated the Catskill deltaic complex, overrunning its upper surface by 80–160 km (50–100 mi) and depositing the Riceville Shale and Oswayo Formation (fig. 12B). Some thin marine tongues advanced briefly as far east as Clinton and Bedford Counties. The effects of the transgression were such that even the equivalent nonmarine Huntley Mountain, Rockwell, and Spechty Kopf Formations lost most of the typical Catskill characteristics, notably most of the distinctive red coloration. The presence of some possible glaciolacustrine sediments in the Spechty Kopf and Rockwell (Sevon, 1969, 1973) suggests a more severe climate and the presence of glaciers in the orogenic highlands to the east.

During Early Mississippian (Kinderhookian) time (fig. 12C), some westward progradation took place, but, in general, a fairly stable coastal plain was established, dominated by delta-lobe development (Demarest, 1946; Pepper and others, 1954). This episode was followed by the westward extension of the elongate anastomosing alluvial-deltaic Burgoon sand plain during early middle Mississippian (Osagean) time (fig. 12D.)

Three notable changes in the depositional environment were introduced, more or less simultaneously, in middle-Late Mississippian (Meramecian) time (fig. 12E). Mild epeirogenic uplift across northwestern Pennsylvania and adjacent New York ended deposition in that area and initiated some erosion of the Burgoon and equivalents and of older rocks. Similar upwarping probably affected extreme northeastern Pennsylvania. In southeastern Pennsylvania, strong sediment influx initiated redbed deposition of the Mauch Chunk delta. Between the northwestward-prograding Mauch Chunk delta and the upwarped area in the northwest, a shallow restricted embayment penetrated as far as Sullivan County, depositing the Loyalhanna calcareous sandstone, a lateral equivalent of the Greenbrier marine carbonate sequence of West Virginia (Adams, 1970; Wells, 1974). Influx of sand streaming off the wasting Burgoon to the north introduced a strong sand fraction to the Loyalhanna. Similarly, red clastic material from the advancing Mauch Chunk delta gave the Loyalhanna facies a strong red cast in places.

During the Late Mississippian (Chesterian) and Early Pennsylvanian (early Morrowan) time, the Mauch Chunk encroached northwestward, squeezing out the Greenbrier-Loyalhanna embayment except in extreme southwest Pennsylvania (fig. 12E). The Mauch Chunk apparently encroached across the uplifted northwest area for some unknown, but probably limited, distance before continued uplift resulted in erosion of the Mauch Chunk margin and further wearing away of the Burgoon and lower strata. The Mauch Chunk itself was overrun from the southeast by the course alluvial clastic material of the Tumbling Run and Schuylkill Members of the Pottsville Formation.

By Early-Middle Pennsylvanian (late Morrowan-Atokan), Pottsville alluvial clastic deposits from the southeast orogenic source had spread across all but the northwest quarter of Pennsylvania and adjacent New York (fig. 13A). Renewed Pottsville alluvial influx from the fringes of the North American craton spilled across New York and northwestern Pennsylvania. The northwest and southeast Pottsville clastic deposits merged, burying almost all older rocks. In a narrow band across Jefferson, Clearfield, Centre, and Clinton Counties, however, a cuestalike erosional remnant of the Burgoon Sandstone (and, locally, a similar remnant of a lower Mauch Chunk sandstone) stood high enough to escape burial (fig. 13A). Along the crest of these sandstone ridges, the unusual Mercer high-alumina flint clays formed (Edmunds and Berg, 1971, p. 57–61).

A general marine transgression during Middle Pennsylvanian (early Desmoinesian) produced a shallow marine embayment across west-central Pennsylvania surrounded by lower and upper delta-plain and alluvial-plain environments (fig. 13B) (Ferm, 1974; Ferm and Cavaroc, 1969). The associated sediments of the upper Pottsville and lower Allegheny Groups in the west, and the upper Sharp Mountain and lower Llewellyn Formations in the east are typically complex and variable.

By late Desmoinesian time, the sea had withdrawn westward into Ohio, allowing deposition of the entirely nonmarine upper Allegheny Group and lower quarter of the Glenshaw Formation in Pennsylvania (fig. 13) (Ferm, 1974).

Widespread marine invasions spread across western Pennsylvania during early Missourian time, reintroducing the shallow marine and lower delta-plain sediments associated with the upper three-quarters of the Glenshaw Formation (fig. 13D) (Donahue and Rollins, 1974; Morris, 1967). One of these brief marine transgressions, represented by the Mill Creek Limestone (Chow, 1951), went as far east as Wilkes-Barre, the most easterly marine penetration since early Late Devonian.

The sea withdrew completely and permanently by late Missourian to early Virgilian time, leaving Pennsylvania almost isolated at the extreme northeastern end of a very restricted estuary. The Casselman Formation was deposited as alluvial-deltaic sediments along the estuary margin.

By late Virgilian time, the northeastern end of the Appalachian basin is believed to have been totally severed from any marine connection, and a widespread lake or system of lakes formed, receiving the Upper Pennsylvanian Monongahela Group sediments, as well as those of the succeeding Permian(?) Dunkard Group (fig. 13F) (Berryhill and others, 1971; Donaldson, 1969, 1974).

The sedimentological origin of the Pennsylvania coal-bearing sequence has been the object of intense speculation for well over a century. Early studies attributed a high degree of lateral persistence to various thin lithosomes found in the Pennsylvanian sequence, most particularly to the coal beds (Rogers, 1858; Lesley, 1879). The concept of coal bed persistence was raised to the level of official dogma when the boundaries of the lithostratigraphic subdivisions of the Pennsylvanian were formally defined by key bed coals.

In the late 1920's, a standardized repetitive sequence of rock types, called the cyclothem, was devised for the Pennsylvanian of the midcontinent (Wanless, 1931). The cyclothem concept called for strong lateral continuity of the individual rock types and, by inference, cyclic repetition of widespread depositional environments, caused and controlled by basinwide geological phenomena. Local geological phenomena were relegated to the minor role of "disrupters" of what would otherwise have been a "normal complete" cyclothem. In the central Appalachians, coal seams and other rocks had long been presumed to be thin but enormously widespread lithosomes; the cyclothem concept suddenly promised to provide the long-desired theoretical foundation for the assumption of widespread lateral continuity of lithosomes. Only Ashley (1931) tended

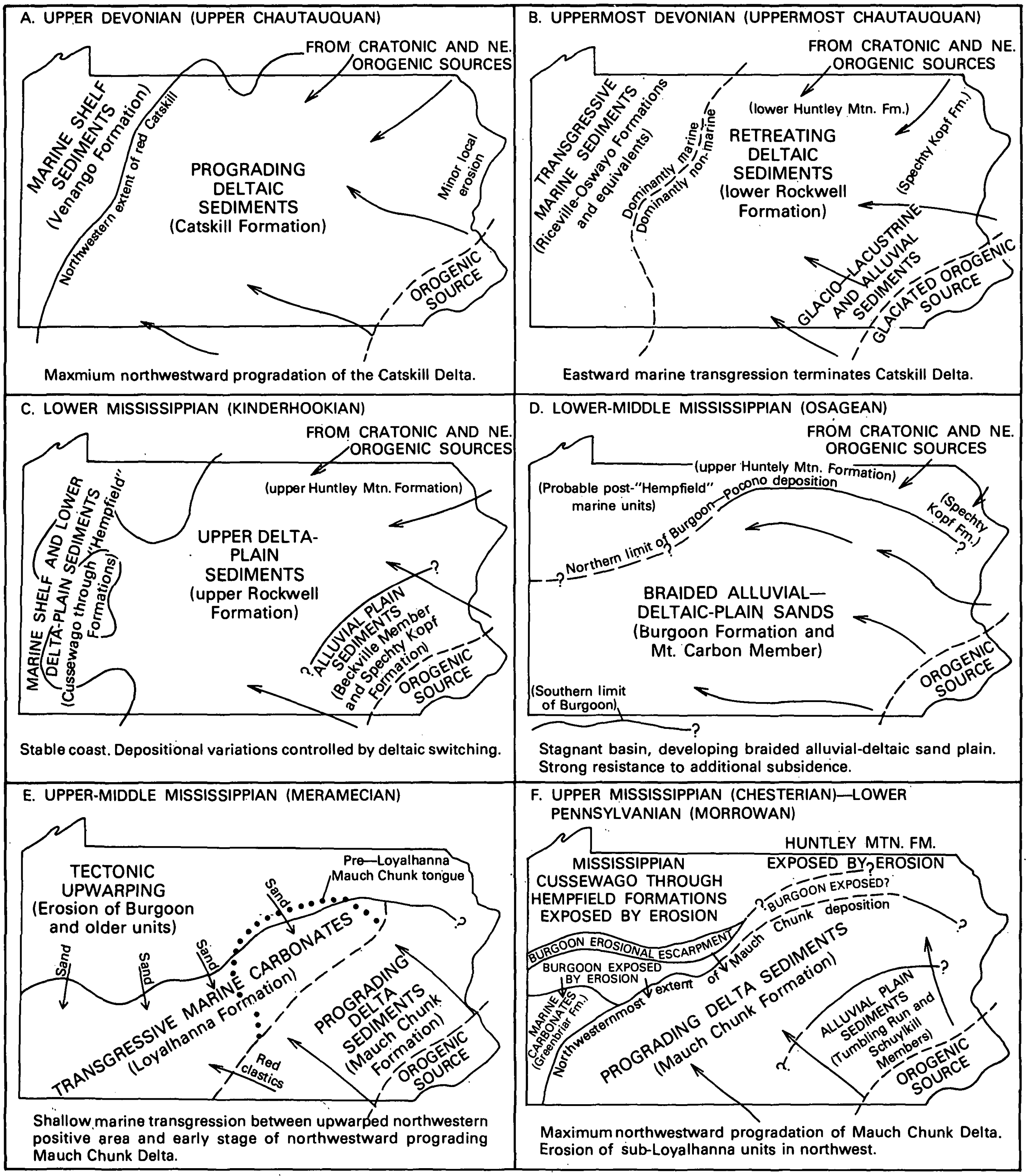

FIGURE 12.—Upper Devonian, Mississippian, and Pennsylvanian paleogeography and depositional environments.

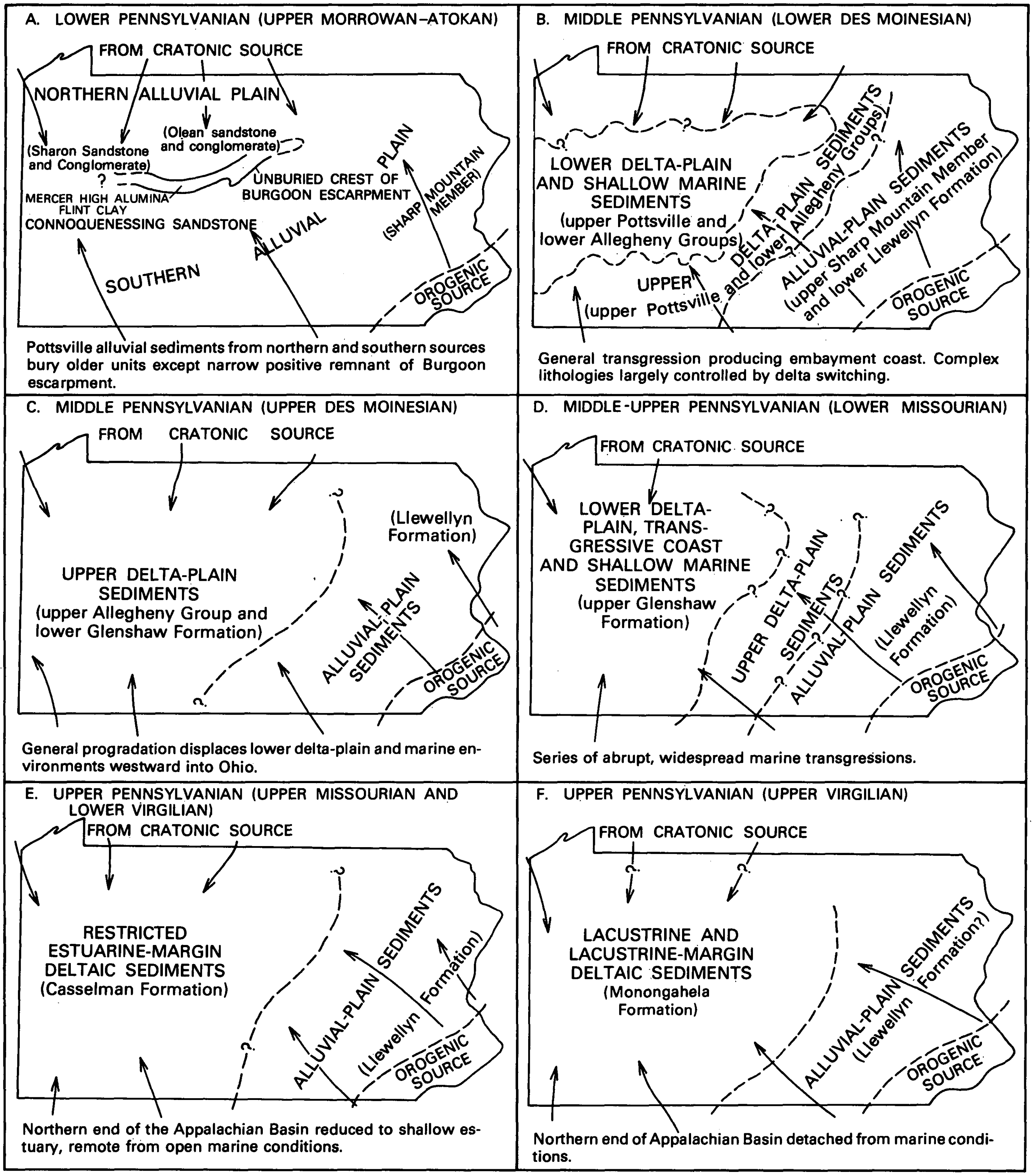

Figure 13.—Pennsylvanian paleogeography and depositional environments.

to reject the existence of a detailed Appalachian cyclothem.

Decades were spent trying to fashion the Appalachian cyclothem or cyclothems (Stout, 1931; Reger, 1931; Beerbower, 1961; Branson, 1962; Sturgeon and others, 1958). Eventually, it became apparent that no single cyclothem or reasonably small number of cyclothems could be devised for the Pennsylvanian of the central Appalachians, because of the very limited vertical or lateral lithic continuity.

In the past 30 years, a huge body of fact and theory has evolved dealing with sediments and processes of modern coastal plains. The application of these concepts (Ferm, 1974; Donaldson, 1974) to the Pennsylvanian rocks of the central Appalachians has provided the key to understanding the Pennsylvanian sequence in all its lithologic complexity and variability without resorting to oversimplification.

It seems reasonably certain that the deposition of individual Pennsylvanian lithosomes is not controlled entirely by basinwide agencies, but rather by relatively local conditions of sedimentation having relatively little areal extent and even less temporal persistence. Basinwide sedimentation controls are only overprinted on dominantly local controls. Basinwide geological phenomena did produce most of the gross character of the Pennsylvanian, or large parts of it, such as: the general presence or absence of redbeds, marine units, or freshwater limestones; the average thickness of coal beds; and the overall coarseness of the clastic fraction. Basinwide phenomena did not, however, dictate the lithology or vertical and horizontal arrangement of individual lithosomes.

ECONOMIC GEOLOGY

COAL

Coal fields.—Pennsylvania, which is at the northern end of the Appalachian coal basin, has about 39,000 km^2 (15,000 sq mi) that is underlain by one or more coal beds.

Geographically, the coal-bearing areas of Pennsylvania can be divided into the following fields (fig. 14):

1. Main Bituminous field.
2. George Creek (Wellersburg) field.
3. Broad Top field.
4. North-Central fields (five small fields).
5. Northern Anthracite field.
6. Western Middle Anthracite field.
7. Eastern Middle Anthracite field.
8. Southern Anthracite field.

More than 90 percent of current production comes from the Main Bituminous field.

Rank and heat value.—Pennsylvania coal ranges in rank from high-volatile bituminous to anthracite; rank increases from west to east (fig. 15). Fixed carbon content ranges from 55 to 97.5 percent (dry, ash-free proximate analysis)

On a dry, ash-free basis, the heat value of Pennsylvania coal increases from an average low of about 8,200 cal/g (14,700 Btu/lb) in Beaver and Lawrence Counties to an average maximum of 8,800 cal/g (15,800 Btu/lb) in northern Somerset and southern Cambria Counties, and in the Broad Top and Georges Creek fields. From this high, the heat value decreases with increasing rank to a minimum of about 8,000 cal/g (14,400 Btu/lb) in Carbon County. Mined coal on an as-received basis will generally yield 550 to 1100 cal/g (1,000 to 2,000 Btu/lb) less than the dry, ash-free value.

Sulfur content.—Although the sulfur content of Pennsylvania coal can vary widely for any one seam, even on a local scale, the following two generalizations apply: (1) the average sulfur content of coal seams increases westward, and (2) the stratigraphically lower mineable coals tend to contain more sulfur. In both generalizations, the high concentration of sulfur is related to the brackish to marine depositional environment interpreted for the overlying clastic sediments.

Most coal in the anthracite fields contains 0.5 to 1.5 percent sulfur. The Pennsylvania anthracite fields represent one of the largest reserves of low-sulfur coal in the Eastern United States.

Main Bituminous field coal is mostly high-sulfur (more than 2 percent S), perhaps 5 to 10 percent of the coal is low-sulfur (less than 1 percent S), and 25 to 30 percent is medium-sulfur (1 to 2 percent S). Much of the low-sulfur reserves are concentrated in the Pittsburgh seam.

The small reserves of the Georges Creek and Broad Top fields are medium-sulfur; those of the North-Central fields are low- to medium-sulfur.

Coking potential.—Except for minor nonbanded varieties, all Pennsylvania coal cokes to a degree expected of its rank. That is, the bituminous coal cokes well, and the anthracite and semianthracite coal cokes poorly, or not at all.

Bituminous coal usually has a free swelling index of 5 to 9 and an agglutinating value of 6.5 to 11.0. Most medium- and high-volatile bituminous coal contracts upon coking, whereas low-volatile bituminous coal expands strongly. The low-volatile coal is especially valuable for upgrade blending with more abundant high-volatile coal.

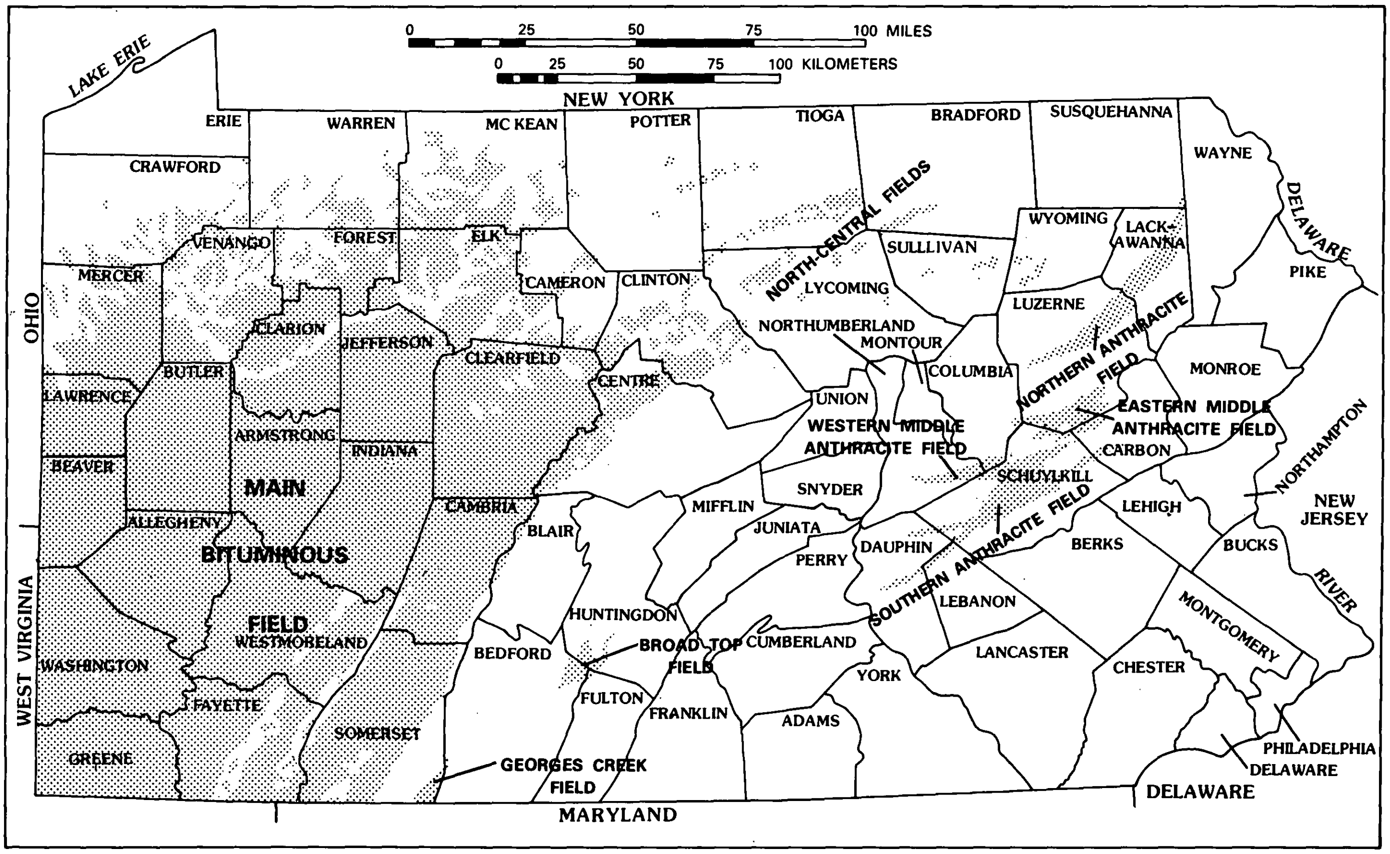

FIGURE 14.—Coal fields of Pennsylvania.

Results of ASTM coke strength tests indicate that Pennsylvania coals behave as would be expected of their rank, although individual samples may vary considerably. If properly blended, most Pennsylvania coke will have adequate strength.

On an as-received and as-carbonized basis, Pennsylvania coal usually produces the following percentage of coking products: coke—66 to 81 percent, gas—10 to 17 percent, tar—2 to 9 percent, and ammonium compounds—4 to 10 percent. The percentage of coke increases and the percentage of other products decreases with increasing rank.

High sulfur content is the persistant detrimental factor in the use of Pennsylvania coal for coking purposes.

Anthracite, semianthracite, and nonbanded bituminous coal are nonagglomerating and noncoking. A small amount of anthracite is used in some coke blends and in foundry coke.

In 1975, Pennsylvania produced 26 million tons of coal for coke manufacture, largely from Washington, Greene, Allegheny, Westmoreland, and Cambria Counties.

Mining and production.—In 1976, 820 mining companies in Pennsylvania produced 85,591,169 t (metric tons) (91,039,650 short tons) of coal from 2,038 mines. Of this total, 29 companies and affiliates produced 41,595,051 t (45,849,925 short tons) or about 50 percent. Table 1 summarizes coal production for 1976.

Resources.—The estimated recoverable coal resources of Pennsylvania as of January 1, 1970, are summarized in table 2 (Edmunds, 1972). Production since January 1, 1970, has been about 32 million t of anthracite and 650 million t of bituminous.

In-place coal resources for Pennsylvania are approximately 57 billion t of bituminous in beds more than 46 cm (18 in.) thick and 15 billion t of anthracite in beds more than 61 cm (24 in.) thick.

Coal-seam correlations.—All significant coal

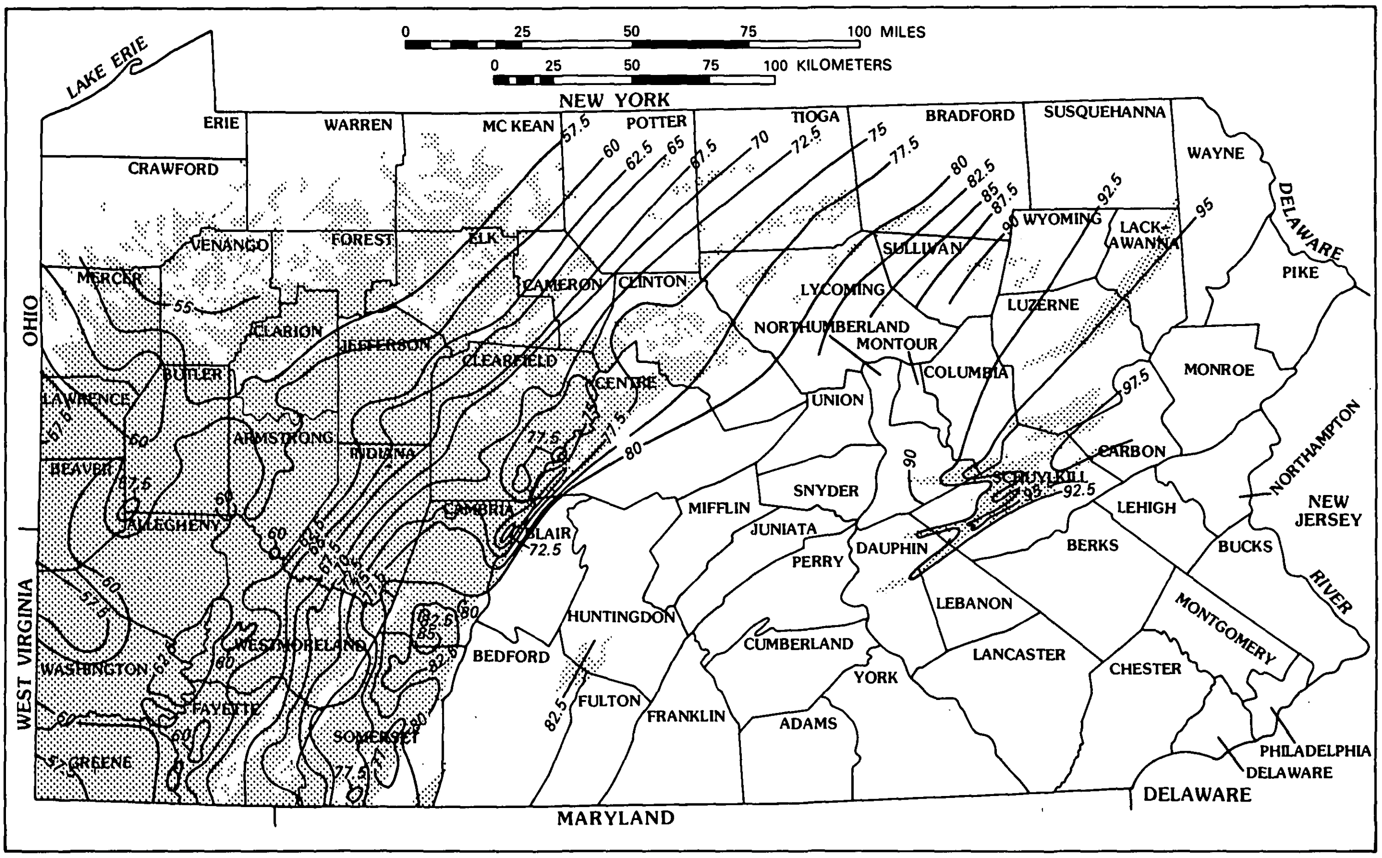

FIGURE 15.—Isocarb map of Pennsylvania.

seams of Pennsylvania are of Pennsylvanian-Permian age and thus are broadly equivalent throughout the State. The lowest (Lykens) coals of the Southern and Western Middle Anthracite fields are somewhat older (Morrowan) than any other coal in the State, and the highest Permian coals in the southwest corner of the Main Bituminous field are the youngest.

Many of the difficulties in determining the properties and extent of individual coal seams stem from the custom of considering each coal as a single, indefinitely continuous bed. Most coal names (such as Brookville, Lower Freeport, Sewickley, etc.) actually represent several areally limited individual coal lenses, or multiply-split coal complexes at about the same stratigraphic position within the coal-bearing sequence. Except for the extraordinarily widespread Pittsburgh coal, most coal seams appear to be continuous for at most several thousand square kilometers and usually very much less.

Keeping in mind the fact that individual coal names represent similar stratigraphic position more than actual bed continuity, customary seam nomenclature within each of the coal fields is as shown in figure 16.

OIL AND GAS

Thousands of wells drilled in western Pennsylvania, primarily for Upper Devonian objectives, have penetrated the Carboniferous section. Commercial quantities of both oil and gas have been discovered within the Carboniferous of western Pennsylvania (fig. 17), although this production is at present relatively small in comparison with production from Upper Devonian rocks.

Mississippian system.—The Mississippian System in the subsurface of western Pennsylvania comprises, in upward succession, the Pocono Group, the Greenbrier Group, and the Mauch Chunk Formation. The Pocono Group (used here as a subsurface term) consists of sand and shale and contains several

TABLE 1.—*Pennsylvania coal production (metric tons), 1976*

[Data from Pennsylvania Dept. Environmental Resources, 1977]

Type mine	Bituminous		Anthracite		Combined	
	Tonnage	Number of mines	Tonnage	Number of mines	Tonnage	Number of mines
Deep	40,214,887	159	468,437	109	40,683,324	268
Strip	36,507,906	1,498	2,683,602	119	39,191,508	1,617
Culm and silt bank reprocessing	784,249	16	1,648,660	73	2,432,909	89
Auger	283,428	64	None	None	283,428	64
Total	77,790,470	1,737	4,800,699	301	82,591,169	2,038

hydrocarbon-bearing horizons. These include the Murrysville or Cussewago sand (considered to be the basal Mississippian unit in the subsurface), which is the most important natural-gas-producing horizon within the Carboniferous. The Berea sand is stratigraphically above the Murrysville and is the most important oil-producing horizon within the Carboniferous. The Berea is stratigraphically equivalent to the Corry sandstone but has a different source area. The detailed stratigraphic relationships of the Murrysville, Berea, and Corry sands have been studied by Pepper and others (1954). Other productive sands within the Pocono Group include, in upward succession, the Squaw, the Shenango or Slippery Rock, and the Big Injun or Burgoon sands.

The Loyalhanna, which is commonly a sandy limestone, is a transitional unit between the underlying Big Injun sand and the overlying Greenbrier limestone. The Loyalhanna and Greenbrier are not known to be productive in western Pennsylvania. The Mauch Chunk red shale overlies the Greenbrier Group. The top of the Mississippian System is marked by a major unconformity, and in the subsurface, the Mauch Chunk, Greenbrier limestone, and Loyalhanna are successively truncated to the north by this unconformity.

Pennsylvanian System.—In the subsurface Pennsylvanian System of western Pennsylvania, the Pottsville Group includes the hydrocarbon-bearing Maxton sand, also referred to as the Third Salt or Lower Connoquenessing sand, the Second Salt or Upper Connoquenessing sand, and the First Salt or Homewood sand. The Salt sands produce brine and are also the largest gas producers within the Pennsylvanian System.

The Allegheny Group includes three productive sands: the Clarion or Lower Gas sand; the Kittanning sand, also known as the Middle Gas sand or the First Gas sand; and the Upper Freeport or Upper Gas sand. The top of the Allegheny Group is the Upper Freeport coal. The Upper Freeport coal contains large quantities of methane; in the future, this unit may become an important source of natural gas.

The Conemaugh Group includes several producing sandstone units: the Big Dunkard, also referred to as the Hurryup or the Mahoning sand; the Little Dunkard or Buffalo sand; the Saltsburg sand; and the Murphy or Morgantown sand. The Saltsburg sand is the most important oil-producing unit within the Pennsylvanian System, and the Big and Little Dunkard, which in places merge into one sand referred to as the Dunkard, are together second in importance for the production of oil in the Pennsylvanian System. The Dunkard was the first oil-bearing unit discovered in the Carboniferous; the first producing well was drilled in 1863, just 4 years after the Drake discovery. The Murphy or Morgantown sand is the highest producing sandstone within the Carboniferous.

One other unit must be mentioned within the Pennsylvanian System—the Pittsburgh coal, at the base of the Monongahela Group. Commercial quantities of pipeline-quality gas are being produced from the Pittsburgh coal. Since 1964, the U.S. Bureau of Mines has conducted a comprehensive methane-control research program. Three programs are currently underway in Washington County using methods devised by the U.S. Bureau of Mines to extract methane for commercial purposes from the Pittsburgh coal prior to mining. Gas obtained from coal demethanization could become an important resource in the future.

Nature of traps.—The traps within the sandstone units of the Carboniferous appear to be controlled by lithologic characteristics and minor local structural control. Production is dependent upon porosity, which in turn is dependent upon the original conditions of accumulation of the sediments and their later cementation. Production is in porous and permeable lenticular sandstone which varies greatly in persistence, texture, and thickness.

TABLE 2.—*Recoverable coal resources of Pennsylvania in beds more than 61, 71, and 91 cm thick, by counties and rank, as of January 1, 1970 (millions of metric tons)*

[Data from Edmunds, 1972. Figures are rounded to first two digits (first digit 9 million or less). Numbers will not total exactly because of independent rounding]

COUNTY [1]	Recoverable reserves more than 61 cm thick						Recoverable reserves more than 71 cm thick						Recoverable reserves more than 91 cm thick					
	Total	High-volatile bituminous	Medium-volatile bituminous	Low-volatile bituminous	Semi-anthracite	Anthracite	Total	High-volatile bituminous	Medium-volatile bituminous	Low-volatile bituminous	Semi-anthracite	Anthracite	Total	High-volatile bituminous	Medium-volatile bituminous	Low-volatile bituminous	Semi-anthracite	Anthracite
MAIN BITUMINOUS AND GEORGES CREEK FIELDS																		
Allegheny	770	770	----	----	----	----	620	620	----	----	----	----	240	240	----	----	----	----
Armstrong	1,100	1,100	----	----	----	----	960	960	----	----	----	----	750	750	----	----	----	----
Beaver	620	620	----	----	----	----	320	320	----	----	----	----	180	180	----	----	----	----
Blair	10	----	7	3	----	----	8	----	6	2	----	----	3	----	2	1	----	----
Butler	1,000	1,000	----	----	----	----	780	780	----	----	----	----	330	330	----	----	----	----
Cambria	1,300	----	510	790	----	----	910	----	360	550	----	----	350	----	150	200	----	----
Cameron	17	11	6	----	----	----	11	7	4	----	----	----	0	0	0	----	----	----
Centre	110	----	110	----	----	----	75	----	75	----	----	----	3	----	3	----	----	----
Clarion	570	570	----	----	----	----	410	410	----	----	----	----	73	73	----	----	----	----
Clearfield	910	230	880	----	----	----	650	160	490	----	----	----	82	20	62	----	----	----
Clinton	14	----	14	----	----	----	9	----	9	----	----	----	5	----	5	----	----	----
Elk	130	130	----	----	----	----	100	100	----	----	----	----	42	42	----	----	----	----
Fayette	2,300	1,800	500	----	----	----	1,900	1,500	400	----	----	----	1,000	750	250	----	----	----
Greene	4,100	4,100	----	----	----	----	3,600	3,600	----	----	----	----	2,500	2,500	----	----	----	----
Indiana	2,000	1,500	500	----	----	----	1,500	1,100	400	----	----	----	570	430	140	----	----	----
Jefferson	1,000	1,000	----	----	----	----	800	800	----	----	----	----	240	240	----	----	----	----
Lawrence	150	150	----	----	----	----	140	140	----	----	----	----	70	70	----	----	----	----
McKean	120	120	----	----	----	----	87	87	----	----	----	----	5	5	----	----	----	----
Mercer	100	100	----	----	----	----	74	74	----	----	----	----	19	19	----	----	----	----
Somerset	1,900	----	950	950	----	----	1,500	----	750	750	----	----	610	----	310	300	----	----
Venango	110	110	----	----	----	----	73	73	----	----	----	----	7	7	----	----	----	----
Washington	3,900	3,900	----	----	----	----	3,500	3,500	----	----	----	----	2,400	2,400	----	----	----	----
Westmoreland	2,000	1,500	500	----	----	----	1,800	1,400	400	----	----	----	1,200	960	240	----	----	----
Field totals	24,000	18,000	4,000	1,700	----	----	20,000	16,000	2,900	1,300	----	----	10,000	8,800	1,200	500	----	----
BROAD TOP FIELD																		
Bedford	64	----	----	64	----	----	60	----	----	60	----	----	52	----	----	52	----	----
Fulton	9	----	----	9	----	----	7	----	----	7	----	----	4	----	----	4	----	----
Huntingdon	22	----	----	22	----	----	16	----	----	16	----	----	5	----	----	5	----	----
Field totals	94	----	----	94	----	----	83	----	----	83	----	----	61	----	----	61	----	----
NORTH-CENTRAL FIELDS																		
Bradford	5	----	----	5	----	----	4	----	----	4	----	----	1	----	----	1	----	----
Lycoming	21	----	21	----	----	----	15	----	15	----	----	----	4	----	4	----	----	----
Sullivan	4	----	----	----	4	----	3	----	----	----	3	----	0	----	----	----	0	----
Tioga	17	----	17	----	----	----	12	----	12	----	----	----	4	----	4	----	----	----
Field totals	47	----	38	5	4	----	34	----	27	4	3	----	9	----	8	1	0	----

TABLE 2.—*Recoverable coal resources of Pennsylvania in beds more than 61, 71, and 91 cm thick, by counties and rank, as of January 1, 1970*—Continued
(millions of metric tons)

[Data from Edmunds, 1972. Figures are rounded to first two digits (first digit 9 million or less). Numbers will not total exactly because of independent rounding]

COUNTY[1]	Recoverable reserves more than 61 cm thick						Recoverable reserves more than 71 cm thick						Recoverable reserves more than 91 cm thick					
	Total	High-volatile bituminous	Medium-volatile bituminous	Low-volatile bituminous	Semi-anthracite	Anthracite	Total	High-volatile bituminous	Medium-volatile bituminous	Low-volatile bituminous	Semi-anthracite	Anthracite	Total	High-volatile bituminous	Medium-volatile bituminous	Low-volatile bituminous	Semi-anthracite	Anthracite
ANTHRACITE FIELDS																		
Carbon	140	----	----	----	----	140	[2]	----	----	----	----	[2]	[3]	----	----	----	----	[3]
Columbia	210	----	----	----	----	210	[2]	----	----	----	----	[2]	[3]	----	----	----	----	[3]
Dauphin	310	----	----	----	150	160	300	----	----	----	150	150	[3]	----	----	----	----	[3]
Lackawanna	150	----	----	----	----	150	[2]	----	----	----	----	[2]	[3]	----	----	----	----	[3]
Lebanon	430	----	----	----	----	430	410	----	----	----	----	410	[3]	----	----	----	----	[3]
Luzerne	740	----	----	----	----	740	[2]	----	----	----	----	[2]	[3]	----	----	----	----	[3]
Northumberland	850	----	----	----	280	560	[2]	----	----	----	----	[2]	[3]	----	----	----	----	[3]
Schuylkill	4,400	----	----	----	400	4,000	[2]	----	----	----	[2]	[2]	[3]	----	----	----	[3]	[3]
Susquehanna	2	----	----	----	----	2	[2]	----	----	----	[2]	[2]	[3]	----	----	----	[3]	[3]
Wayne	3	----	----	----	----	3	[2]	----	----	----	[2]	[2]	[3]	----	----	----	[3]	[3]
Field totals	7,300	----	----	----	830	6,500	[2]	----	----	----	[2]	[2]	[3]	----	----	----	[3]	[3]
TOTALS																		
Pennsylvania total	31,000	18,000	4,000	1,800	830	6,500	20,000	16,000	2,900	1,400	3[4]	[2]	10,000[4]	8,800	1,200	560	0[4]	[3]

[1] Excludes small recoverable reserves from Crawford, Erie, Forest, Potter, Warren, and Wyoming Counties.
[2] Reserves in beds more than 71 cm thick cannot be separately calculated, but in most cases should be 90 percent or more of the tonnages in beds more than 61 cm thick.
[3] Reserves in beds more than 91 cm thick cannot be separately calculated.
[4] Excludes counties of the Anthracite fields.

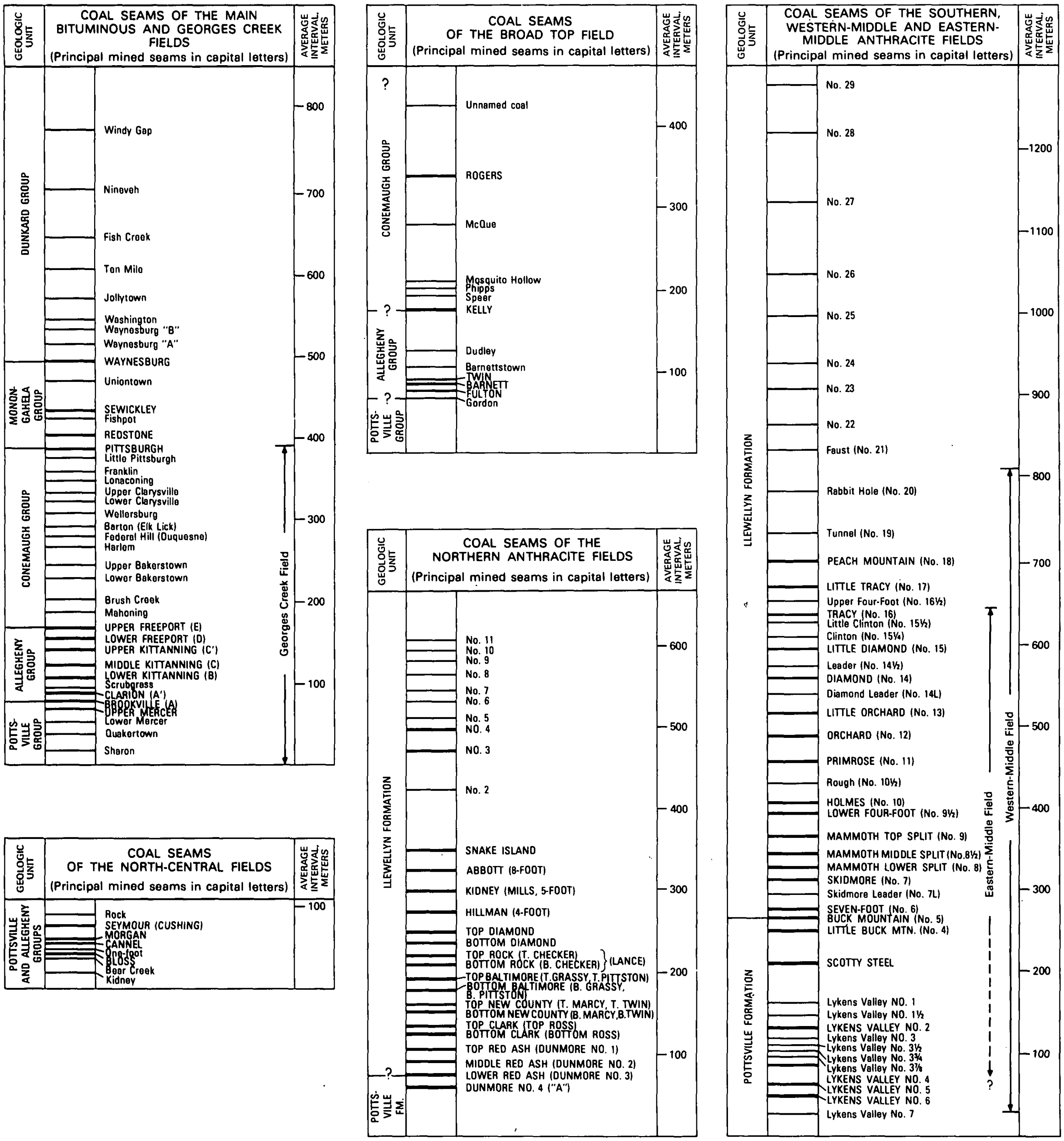

FIGURE 16.—Pennsylvania coal-seam nomenclature.

CLAY AND SHALE

The Pennsylvanian-Mississippian sequence is the source of materials suitable for producing a wide variety of ceramic products including all grades of refractories, most types of brick and tile, lightweight aggregate, and stoneware. The Allegheny Group and uppermost Pottsville Group (Mercer Formation) of western Pennsylvania are the most important sources, yielding most of the refractory-grade clay and lightweight aggregate, as well as much clay and shale suitable for most other types of brick and tile. The Conemaugh and Monongahela Groups, the Rice-

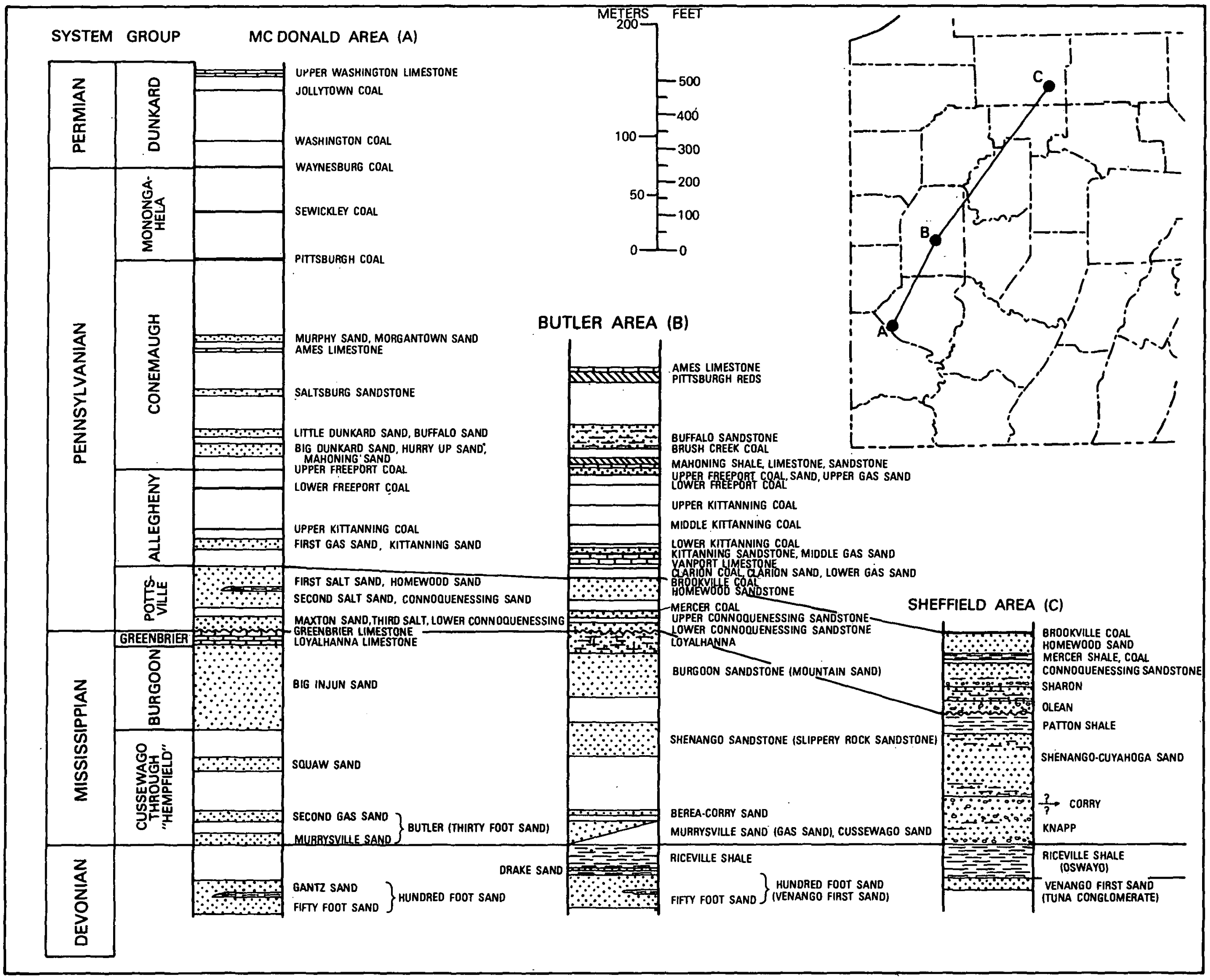

FIGURE 17.—Generalized columnar section showing stratigraphic position of oil- and gas-bearing sands in Mississippian and Pennsylvanian rocks of western Pennsylvania.

ville-Oswayo to "Hempfield" sequence, and, to a lesser degree, the Mauch Chunk Formation provide raw material for most types of nonrefractory brick and tile. Because of their high content of coarse clastic materials, the Pocono, Burgoon, Huntley Mountain, Rockwell, Spechty Kopf, Pottsville (except Mercer), and Llewellyn have only limited potential for ceramic products.

CARBONIFEROUS ROCKS OF NEW YORK STATE [1]

By LAWRENCE V. RICKARD [2]

The Carboniferous rocks of New York State are in small outliers on the hilltops in the nonglaciated part of southwestern New York, in Allegany, Cattaraugus, and Chautauqua Counties (fig. 1). The rocks consist of thin shale, sandstone, and conglomerate of marine and alluvial origin, in nearly flat-lying beds that have a gentle regional dip in a southerly direction. Rocks of Early Mississippian age are unconformably overlain by those of Early Pennsylvanian age. However, the Pennsylvanian rocks may be found directly upon the latest Devonian strata where Mississippian rocks are absent.

Among the earliest investigations of these beds, the most significant was that conducted in Cattaraugus County (Salamanca and Olean 15-minute quadrangles) by Glenn (1903) and Butts (1903). Subsequently, except for much later work by Caster

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[2] New York State Museum—Geological Survey, Albany, N.Y. 12224.

(1934) and Holland (1958), these rocks have received little attention. The stratigraphic column, given below, is a simple one, there being only three units in New York State.

Pennsylvanian Period
- Pottsvillian Series
  - Sharon Shale
  - Olean Conglomerate

Mississippian Period
- Kinderhookian Series
  - Knapp Formation

The Knapp Formation (Glenn, 1903) consists of two units of conglomerate or sandstone; shale is found above and between these units. Caster (1934) proposed formal names for some of these divisions based on exposures in northern Pennsylvania, but the names have not been used in New York. The Knapp overlies the Oswayo shale and sandstone of the latest Devonian and is unconformably overlain by the Olean conglomerate of Early Pennsylvanian age. The type section of the Knapp Formation is at Knapp Creek Station, near "Olean Rock City" in Cattaraugus County. The formation is about 18 to 32 m thick and is restricted to that county, although several outliers extend westward across the line into Chautauqua County.

The Knapp shale is described as sandy, olive-green, or rusty brown. The conglomerate, often limonitic, contains loosely cemented flat or discoidal quartz pebbles. Both units may be fossilliferous; brachiopods, pelecypods, and some plants have been found. Holland (1958) concluded that the considerable differences in the brachiopod faunas of the Knapp and the underlying Devonian strata confirmed the Mississippian age of the Knapp. The formation is not everywhere present beneath the Olean Conglomerate.

The Olean Conglomerate (Lesley, 1875) varies from a coarse cream-colored quartz sandstone containing few pebbles to a conglomerate almost entirely composed of pebbles. There is much rapid variation, both horizontally and vertically, within the Olean. However, the formation usually consists of a thickly bedded, round or ovoid quartz pebble conglomerate, 15 to 28 m thick. It is strongly cross-bedded, and the pebbles are white, milky, or rose-colored vein quartz, 10 to 90 mm in diameter.

The type section of the Olean is at Rock City, 10 km south of the city of Olean in southern Cattaraugus County, where its enlarged joints form the well-known "Olean Rock City." Elsewhere, the Olean is found in scattered hilltop exposures. Conspicuous ledges of the formation are seen because of its resistance to erosion. The formation appears to be of alluvial origin; plant remains of Pottsvillian age are the only fossils known to be indigenous to the Olean. In places, the conglomerate is at lower altitudes than the Knapp owing to the relief of the unconformity between them.

Virtually nothing is known concerning the occurrence of a thin patch of dark, sandy, ferruginous shales once exposed overlying the Olean Conglomerate near Rock City. These shales have been referred to the Sharon Shale (Rogers, 1858) of Pennsylvania, but their thickness, extent, and fossil content in New York are unknown.

There are no economic resources derived from the Carboniferous rocks of New York State.

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The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—Virginia

By KENNETH J. ENGLUND

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Prepared in cooperation with the Virginia Division of Mineral Resources

Historical review and summary of areal, stratigraphic, structural, and economic geology of Mississippian and Pennsylvanian rocks in southwestern Virginia

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CONTENTS

ILLUSTRATIONS

THE MISSISSIPPIAN AND PENNSYLVANIAN (CARBONIFEROUS) SYSTEMS IN THE UNITED STATES—VIRGINIA

By KENNETH J. ENGLUND

ABSTRACT

Carboniferous rocks in Virginia range from Early Mississippian to Middle Pennsylvanian in age and consist mostly of interbedded sandstone, siltstone, shale, limestone, claystone, and coal. These sedimentary deposits are assigned to 15 formations, which underlie areas that total approximately 7,000 km² in the Appalachian Plateaus and the Valley and Ridge physiographic provinces in the southwestern part of the State.

The sedimentation patterns and fossil content of the rock sequence have recorded fluctuations between marine and continental depositional environments in the east-central part of the Appalachian basin. In Mississippian time, marine events predominated during the deposition of a southeastward-thickening sequence of mostly limestone, shale, and siltstone, which, to the east, includes lobes of barrier-bar and terrestrial coal-bearing sediments. A repetition of marine and terrestrial environments prevailed until Early Pennsylvanian time, when a major seaward progradation of deltaic coal-bearing sediments took place. Deposition was continuous across the systemic boundary in the trough area or eastern part of the Appalachian basin, whereas on the western limb of the basin, including westernmost Virginia, Upper Mississippian and Lower Pennsylvanian rocks were eroded sufficiently to form a hiatus between the Mississippian and Pennsylvanian Systems. The deposition of terrestrial coal-bearing sediments continued throughout Early and Middle Pennsylvanian time with only an occasional marine transgression. Carboniferous rocks were folded and faulted by thrusting from the southeast during late or post-Paleozoic deformation. Consequently, strata in the Appalachian Plateaus were gently folded and, in the Cumberland overthrust sheet, thrust about 6.4 km to the northwest. At the southeastern edge of the plateaus and in the Valley and Ridge province, Carboniferous strata were highly folded and faulted.

Coal, natural gas, and limestone are the principal mineral resources of economic interest in the Carboniferous rocks of Virginia. Coal of high-volatile A to low-volatile bituminous rank is the principal developed mineral resource.

INTRODUCTION

The Mississippian and Pennsylvanian Systems in Virginia are represented by approximately 5,100 m of sedimentary rocks consisting of intercalated sandstone, siltstone, shale, claystone, limestone, and coal. The distribution of the rocks representing these systems is limited to the western part of the State, principally to the Appalachian Plateaus, and, to a lesser extent, to isolated areas of the adjoining Valley and Ridge province (fig. 1). Within the Appalachian Plateaus, strata are relatively flat and, except for sharply upturned beds near the southeastern edge, show only slight to moderate structural deformation. In contrast, correlative rocks of the Valley and Ridge province are found in several discontinuous and highly deformed fault slices that strike northeast across the west-central part of the State. Rocks of Mississippian age are the most widely distributed and include: (1) subsurface beds beneath Pennsylvanian rocks of the Appalachian Plateaus, (2) upturned beds at the southeastern edge of the plateaus, and (3) sporadic occurrences in the faulted and folded belt of the Valley and Ridge province. These rocks are largely of marine origin, but locally they grade into, and include, nearshore and terrestial deposits. Pennsylvanian rocks consist mostly of terrestial coal-bearing deposits that underlie the Appalachian Plateaus in the east-central part of the broad Appalachian coal basin and a few outliers in the faulted and folded belt. The latter areas are too small to show at the map scale.

The stratigraphic nomenclature used in this paper has not been reviewed by the Geologic Names Committee of the U.S. Geological Survey. The nomenclature used here conforms with the current usage of the Virginia Division of Mineral Resources.

EARLY INVESTIGATIONS

Early investigations of the Mississippian and Pennsylvanian rocks of Virginia were made by Lesley (1873), Stevenson (1881), Rogers (in MacFarlane, 1879), Boyd (1887), and McCreath and d'Invilliers (1888). These studies furnished pre-

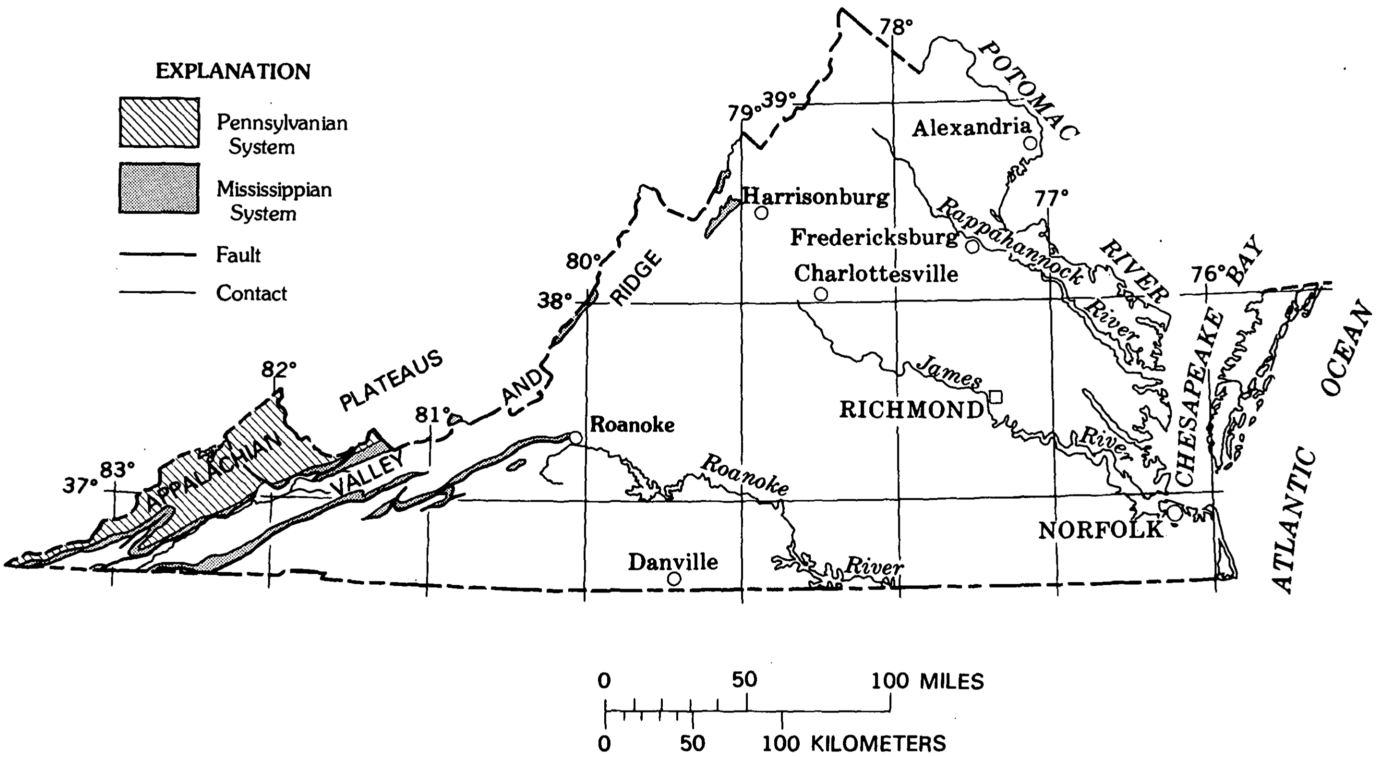

FIGURE 1.—Outcrop of the Mississippian and Pennsylvanian Systems in Virginia.

liminary assessments of the economic potential of various mineral occurrences and also provided the incentive for later comprehensive efforts to subdivide and map Carboniferous rocks (Campbell, 1893, 1894a, 1896, 1897; Ashley and Glenn, 1906; Butts, 1914; and Hinds, 1916). The nomenclature used by these workers differed from area to area, but by the early 1920's a relatively standardized set of subdivisions had been established in county and regional reports (Hinds, 1918; Harnsberger, 1919; Giles, 1921, 1925; Wentworth, 1922; Eby, 1923; and Campbell and others, 1925). Subsequent reports covered a broad range of stratigraphic studies, economic assessments, and geologic mapping that delineated occurrences of coal or natural gas in Carboniferous rocks (Butts, 1940, 1941; Averitt, 1941; Cooper, 1944; Wanless, 1946; Wilpolt and Marden, 1949; Brown and others, 1952; Huddle and others, 1956; Harris and Miller, 1958; Englund and Smith, 1960; Englund, 1964a, b; LeVan, 1962; Read and Mamay, 1964; and Miller, 1965). Recent reports emphasize both geologic mapping and regional stratigraphic studies (Englund and Delaney, 1966; Englund, 1968a, 1974; R. L. Miller, 1969; M. S. Miller, 1974; Miller and Roen, 1971).

PRESENT INVESTIGATIONS

Current studies of rocks of Mississippian and Pennsylvanian age in Virginia are concerned principally with regional stratigraphy, resource assessments, and geologic mapping. To meet the need for a standard reference section for rocks of Pennsylvanian age, the establishment of a Pennsylvanian System stratotype was initiated in 1972 by the U.S. Geological Survey in consultation with interested geologists from State surveys, industry, and universities. For this study, a composite stratotype consisting of stratigraphically overlapping outcrop sections has been assembled with the support of paleontologic investigations, geologic mapping, and core drilling (Englund and others, 1977). These sections are located along a line between Tazewell County, Va., and the Dunkard basin in west-central West Virginia.

The Virginia Division of Mineral Resources is cooperating with the U.S. Geological Survey in the collection of coal samples for analyses including ultimate and proximate, heat-content, free-swelling index, ash-fusibility, and major-, minor-, and trace-element determinations (Medlin and Coleman, 1976). This study is contributing to a nationwide program to assess the environmental and economic aspect of increased coal consumption including conversion processes, recoverable mineral by-products, and optimum utilization.

Mississippian and Pennsylvanian rocks are also being mapped in several 7½ minute quadrangles in Virginia for updating the assessment of the quantity and quality of coal resources (Miller and Meissner, 1978; Meissner and Miller, unpub. data; Englund and Warlow, unpub. data). In this study, coal beds are being mapped and sampled for information on the areal extent, thickness, chemical composition, rank, ash and sulfur contents, and lateral changes in the coal deposits. Additional research concerning thickness and lithic variations in the roof and floor rocks, depositional controls and systems, and postdepositional structural features is being conducted to determine the effect of these geologic factors on the exploration and development of coal resources.

GEOLOGIC SETTING

CONTACT RELATIONS WITH UNDERLYING ROCKS

In Virginia, Mississippian strata conformably overlie rocks of Late Devonian age. At Cumberland Gap, underlying strata consist of about 60 m of black shale assigned to the Chattanooga Shale of Late Devonian age. Northeastward, this shale increases in thickness to about 244 m at Big Stone Gap, where it includes a middle member of gray siltstone (Miller, 1965). The upper or Big Stone Gap Member of the Chattanooga Shale is a black shale or siltstone that is partly Mississippian in age (Harris and Miller, 1958). Continuing northeastward along the outcrop belt at the southeastern edge of the Appalachian Plateaus, strata of Late Devonian age increase in thickness to about 610 m in northern Tazewell County, where they consist of the Brallier Shale, a medium- to dark-gray shale with lesser amounts of interbedded siltstone and sandstone, and the Chemung Formation, a medium-light-gray very fine to fine-grained sandstone with minor amounts of greenish-gray shale. Only a few thin beds of black shale, typical of the Chattanooga Shale, are in these Upper Devonian rocks. In the northeasternmost exposures of this outcrop belt, basal Mississippian strata consist of as much as 15 m of black shale that correlates with the Big Stone Gap Member (Englund, 1968a). The discontinuous belt of Carboniferous rocks in the adjoining Valley and Ridge province also includes the Big Stone Gap Member at the base of the Mississippian System. The underlying Upper Devonian strata are assigned to the Braillier Shale and the Chemung Formation (Bartlett and Webb, 1971).

The age of Upper Devonian formations is based on conodonts (Roen, Miller, and Huddle, 1964) and brachiopods (Butts, 1940, p. 319–331; Cooper, 1944, p. 142; and Bartlett and Webb, 1971, p. 34–35).

CONTACT RELATIONS WITH OVERLYING ROCKS

The youngest Carboniferous rocks in Virginia are the Harlan Formation of Middle Pennsylvanian age. Only remnants of the formation are preserved on mountaintops in the southwesternmost part of the State where the upper contact is an erosional surface. Carboniferous rocks are not known elsewhere in Virginia where younger formation of Triassic, Cretaceous, and Tertiary age are present. In nearby areas of Kentucky and West Virginia, rocks equivalent to the Harlan Formation are conformably overlain by younger Pennsylvanian strata.

STRUCTURAL EVENTS DURING THE DEPOSITION OF CARBONIFEROUS ROCKS

The deposition of strata of Carboniferous age in the Appalachian basin took place during a period of slow subsidence as recorded by the shallow-water character of most of the sedimentary sequence. Subsidence was greatest along the eastern margin of the basin where the thickest sequence of strata accumulated. Deposition continued with only minor interruption throughout the Mississippian Period and into the early part of the Pennsylvanian Period. During deposition of the Mississippian strata, slight warping has been reported in nearby areas of West Virginia (Cooper, 1961, p. 95–99; Thomas, 1966) and along the Waverly arch in Kentucky (Englund, 1972). However, such relationships are not readily evident in Virginia.

Shortly after the deposition of the Pocahontas Formation in Early Pennsylvanian time, this southeastward-thickening wedge of Mississippian and Pennsylvanian rocks was uplifted, mostly where the western margin of deposition overlapped the eastern flank of the Cincinnati arch. Subsequent erosion truncated Lower Pennsylvanian strata including part of the New River Formation, the Pocahontas Formation, and Upper Mississippian strata, including several members in the upper part of the Bluestone Formation. Westward beyond the State, rocks of Late Mississippian age were completely eroded in places.

After the period of widespread erosion between the Mississippian and Pennsylvanian Systems, which was progressively greater toward the Cincinnati arch and along the crest of the Waverly arch, the deposition of Lower Pennsylvanian strata resumed. Again, the rate of deposition of coal-bearing strata in the Lower and Middle Pennsylvanian Series approximated the rate of subsidence, which was greatest along the eastern margin of the basin.

STRUCTURAL EVENTS FOLLOWING DEPOSITION

At the end of Carboniferous sedimentation, a southeastward-thickening wedge of sediments extended from the Cincinnati arch southeast across southwestern Virginia and into the trough of the Appalachian geosyncline. The youngest sediments of Middle Pennsylvanian age were virtually flat lying after their deposition. Perhaps an additional 300 m or more of Pennsylvanian sediments accumulated in Virginia and have since been eroded. During the Appalachian orogeny, possibly as early as Late Pennsylvanian or Early Permian time, mountain-building stresses were projected northwest with sufficient intensity to affect Carboniferous rocks throughout southwestern Virginia. Consequently, the present attitude of Carboniferous rocks reflects both the regional downwarping of the Appalachian geosyncline and structural deformation associated with postdepositional faulting.

Structurally, the areas underlain by Carboniferous rocks are divided by faulting into three distinct segments: (1) relatively flat lying rocks of the Appalachian Plateaus northeast of the Cumberland overthrust sheet, (2) gently folded and faulted rocks of the Cumberland overthrust sheet, and (3) intensely folded and faulted rocks of the Valley and Ridge province. In the area of relatively flat lying rocks of the Appalachian Plateaus, Carboniferous rocks dip mostly 1° to 2°. Locally, along gentle northeast-trending flexures, the dip increases to as much as 5°. At the southeastern edge of the area, beds are near vertical or slightly overturned.

Rocks of the Cumberland overthrust sheet have moved about 6.4 km northwestward (Englund, 1971) and are warped into two broad folds—the Middlesboro syncline and the Powell Valley anticline. In Virginia, this thrust sheet is bounded on the northeast by the Russell Fork fault and in the subsurface by the Pine Mountain overthrust fault. Strata in the trough of the Middlesboro syncline are gently warped but may dip as much as 5° on the fringes of the trough area. The syncline is outlined by resistant Lower Pennsylvanian conglomeratic sandstone, which dips from a few degrees to nearly vertical along Cumberland Mountain and from 20° to 30° along Pine Mountain on the southeast and northwest limbs, respectively. The Powell Valley anticline parallels the Middlesboro syncline and plunges northeastward beneath Carboniferous rocks, which dip from a few degrees to vertical or slightly overturned (fig. 2).

In the areas of intensely folded and faulted rocks, Carboniferous rocks are almost entirely Mississippian in age, are found in fault slices as much as 5 km wide and 170 km long, and generally dip from 0° to 50°.

STRATIGRAPHY

Carboniferous rocks in Virginia range in age from Early Mississippian to Middle Pennsylvanian and are of marine and terrestrial sedimentary origin. Of this sequence, the lower 2,500 m are assigned to eight formations of Mississippian age and the upper 2,600 m, to seven formations of Pennsylvanian age (fig. 3).

MISSISSIPPIAN SYSTEM

BIG STONE GAP MEMBER OF THE CHATTANOOGA SHALE

The Big Stone Gap Member (Stose, 1923) of Late Devonian and Early Mississippian age includes basal Carboniferous strata in most of southwestern Virginia. In the type area, Big Stone Gap, Va., it consists of black evenly bedded shale and siltstone as much as 80 m thick. Northeastward, the member thins to 3 m or less in the Bramwell area, and southwest of Big Stone Gap, it merges with the underlying part of the Chattanooga Shale, which is entirely Devonian in age at Cumberland Gap. In the type section, the member contains both Early Mississippian and Late Devonian conodont faunas. The lowest definitely Mississippian conodont fauna is found about 28 m above the base and is characterized by *Siphonodella*, which is present throughout the upper part of the member. The following species have been identified (Roen and others, 1964):

Elictognathus lacerata (Branson and Mehl)
Polygnathus communis (Branson and Mehl)
inornatus (E. R. Branson)
Pseudopolygnathus sp.
Siphonodella duplicata (Branson and Mehl)
quadruplicata (Branson and Mehl)
Spathognathodus aciedentatus (E. R. Branson)

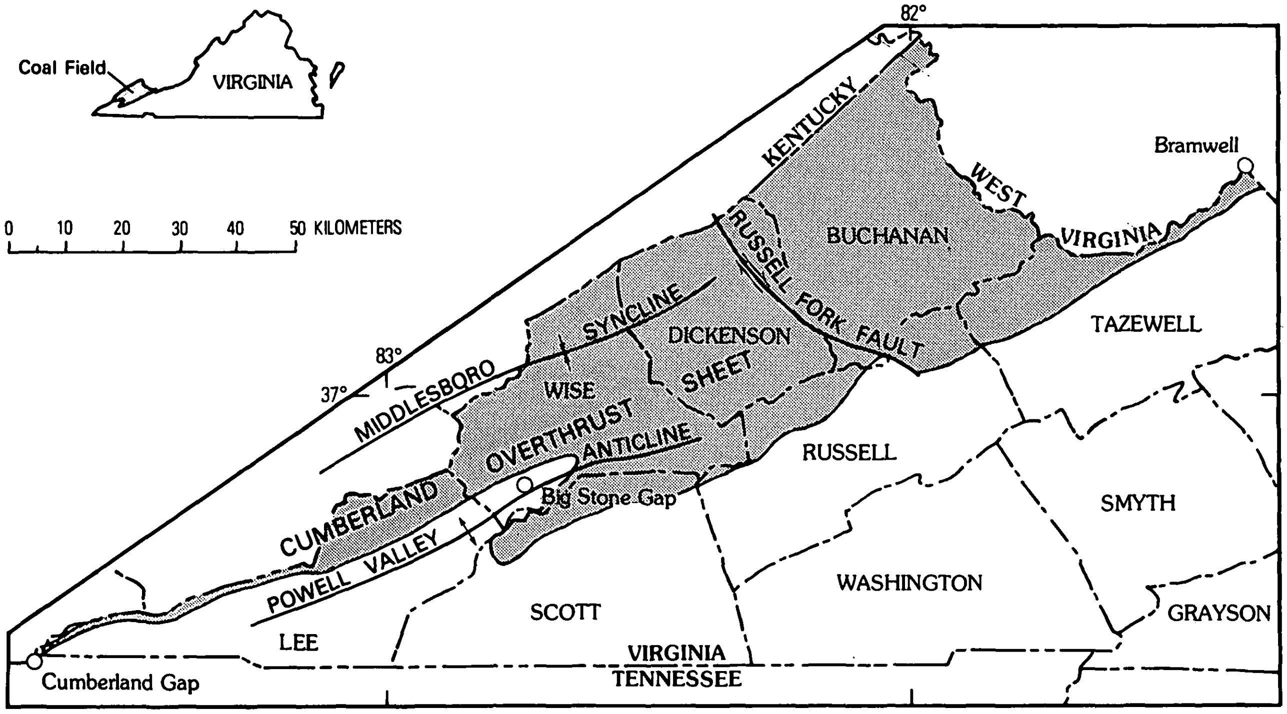

FIGURE 2.—Index map of the southwestern Virginia coal field (shaded).

PRICE FORMATION

The Price Formation (Campbell, 1894b) of Early Mississippian age is also known as the Grainger Formation in southwesternmost Virginia, where it includes the basal Mississippian strata. Elsewhere in Virginia, the formation conformably overlies the Big Stone Gap Member of the Chattanooga Shale. The Price consists largely of light-gray very fine to medium-grained sandstone and light-gray to greenish-gray shale, silty shale, and siltstone. Grayish-red beds also are present locally. Eastward in the Valley and Ridge province, the formation coarsens and includes feldspathic sandstone and well-rounded quartz pebbles and granules. Several glauconite beds have been recognized (Bartlett and Webb, 1971, p. 36), and coal beds have been locally noted in the formation (Campbell and others, 1925).

As much as 6 m of cherty dolomite, a wedge of the Fort Payne Chert, is at the top of the Price Formation at Cumberland Gap (Englund, 1964b). In the northeastern outcrops of Mississippian rocks, strata equivalent to the Price consist of coarse-grained conglomeratic sandstone assigned to the Pocono Formation, which overlies the Hampshire Formation of Devonian age. The thickness of the Price Formation increases northeastward from 90 m at Cumberland Gap to more than 500 m in the faulted and folded belt.

Marine fossils are abundant locally in the Price Formation and include the following forms (Bartlett and Webb, 1971, p. 36):

Brachiopods:
- *Camarotoechia* sp.
- *Chonetes* sp.
  - *shumardanus* De Koninck
- *Dictyoclostus burlingtonensis* (Hall)
- *Punctospirifer* sp.
- *Reticularia pseudolineata* (Hall)
- *Schellwienella*? sp.
- *Schuchertella desiderata* Hall and Clark
- *Spirifer* cf. *S. stratiformis* Meek
  - *winchelli*? Herrick
- *Teteracamera*? sp.
- *Torynifer* cf. *T. pseudolineata* (Hall)

Bryozoans:
- *Cystodictya* sp.
- *Fenestrellina regalis*? (Ulrich)
  - *tenax* (Ulrich)
- *Polypora impressa*? (Ulrich)
- *Rhombopora* sp.

Pelecypods:
- *Allorisma*? sp.
- *Aviculopecten*? sp.
- *Solemya*? sp.

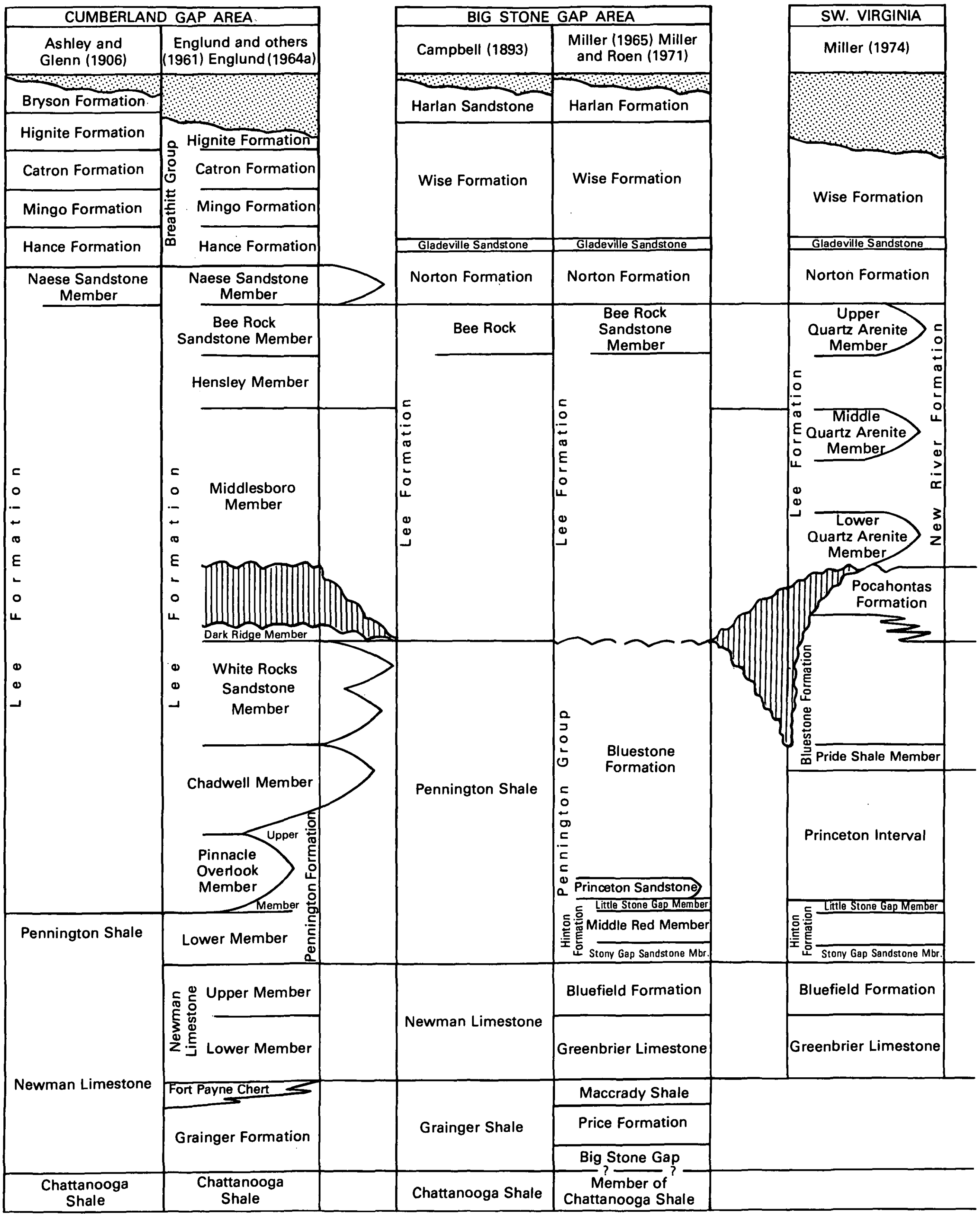

FIGURE 3.—Stratigraphic nomenclature used in southwestern Virginia; vertical lines indicate strata missing.

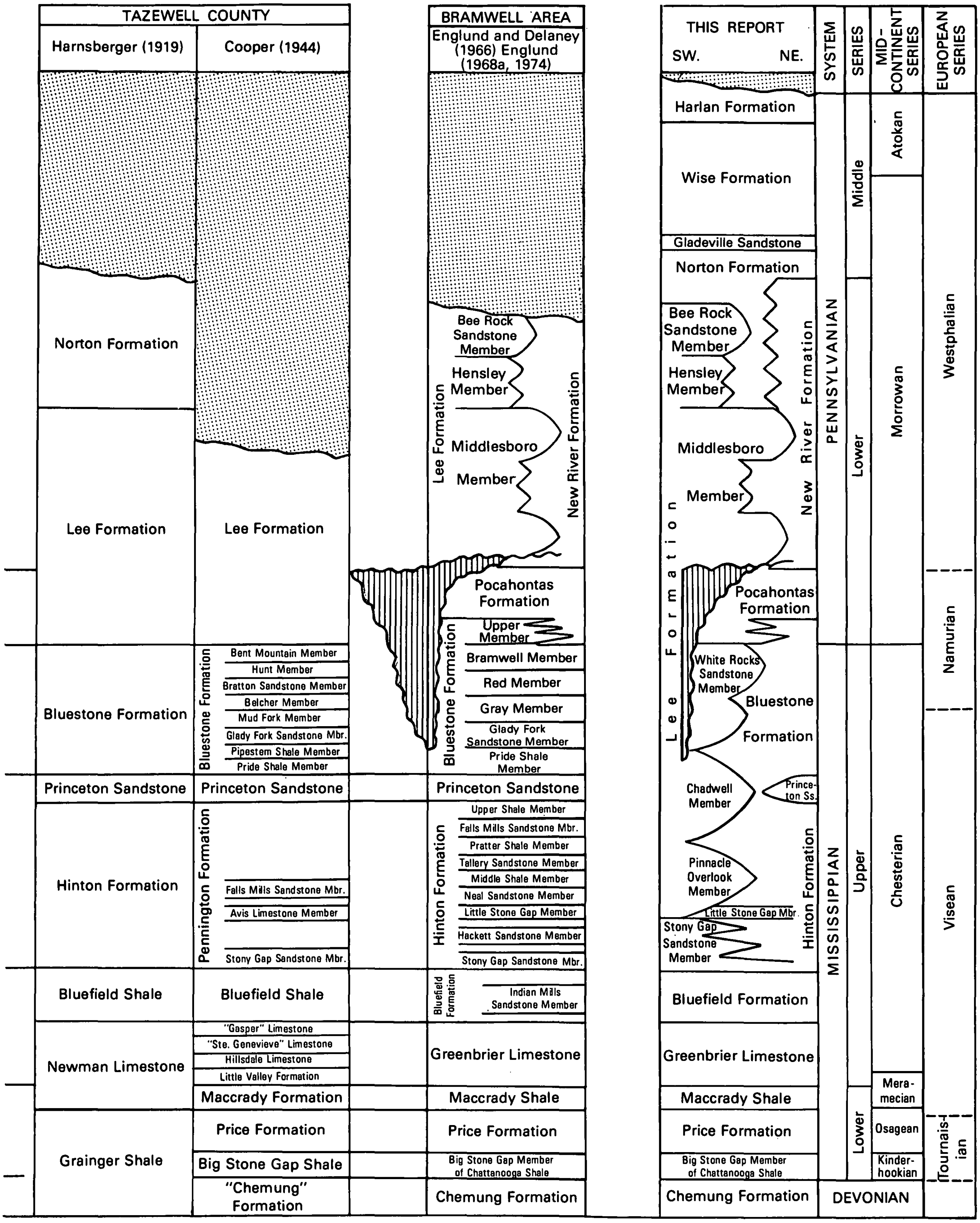

FIGURE 3.—Continued.

Gastropods:
- *Euphemites galericulatus* (Winchell)
- *Oxydiscus* sp.

Correlative beds in nearby areas of Tennessee contain the following faunas of Early Mississippian age, most likely Osagean (Englund, 1968b, p. 9):

Corals:
- *Cyathaxonia* sp. indet.
- *Amplexizaphrentis* sp. undet.
- *Trochophyllum verneuili* Milne Edwards and Haime
- "Zaphrentoid" corals
- *Cladochonus amplexus* (Rowley)

Bryozoans:
- *Fenestella* sp. indet.
- *Saffordotaxis* cf. *S. incrassatus* (Ulrich)
- *Cystodictya* sp. undet.

Brachiopods:
- *Schuchertella* sp.
- *Chonetes* aff. *C. glenparkensis* Weller
  - sp.
- Small spinoise productoid
- *Strophalosia*? sp.
- *Productina sampsoni* (Weller)?
- *Labriproductus*? sp.
- Rhynchonellid indet.
- *Punctospirifer subellipticus* (McChesney)
- *Strophopleura* sp.
- *Spirifer* aff. *S. shephardi* Weller
  - aff. *S. vernonensis* Weller
- *Spirifer* or *Branchythris* sp. indet.
- *Crurithyris* cf. *C. parva* (Weller)

Pelecypods:
- *Cypricardinia* sp.

Gastropods:
- *Platyceras* sp.

Echinoderms:
- Crinoid stems and plates
- Batocrinoid anal tube
- Echinoid plate

Trilobites:
- *Phillibole* cf. *P. conkini* Hessler
- *Proetides*? sp. indet.

Ostracodes:
- *Bairdia* sp.
- *Graphiadactyllis lineata* (Bassler)
- *Graphidactyllis*? sp.

MACCRADY SHALE

The Maccrady Shale (Stose, 1913) of Early Mississippian age is a distinctive grayish-red to bright-red shale including minor amounts of sandstone, silistone, or very finely crystalline dolomitic limestone. It attains a maximum thickness of about 45 m in the Bramwell area, thins southwestward, and is absent at Cumberland Gap. Thinning has resulted from truncation at the disconformable base of the overlying Greenbrier Limestone. Fossils, consisting of small assemblages of bryozoans and brachiopods of Osagean age, are sparse in the Maccrady Shale (Butts, 1940, p. 353; Cooper, 1944, p. 153).

GREENBRIER LIMESTONE

In southwestern Virginia, the Greenbrier Limestone (W. B. Rogers, in Macfarlane, 1879) of Late Mississippian age has been identified as part of the Newman Limestone (Campbell, 1893, p. 38) or has been divided into the Warsaw Formation and the St. Louis, Ste. Genevieve, and Gasper Limestones by Butts (1940, p. 355–381) or the Little Valley Formation and the Hillsdale, "Ste. Genevieve," and "Gasper" Limestones by Cooper (1944, p. 154–169). The Greenbrier consists mostly of thick-bedded very finely to coarsely crystalline limestone that is light olive gray and, less commonly, medium gray and brownish gray. It also includes oolitic, cherty, and yellowish-gray weathering argillaceous limestone beds and a few interbeds of greenish-gray or grayish-red shale. It extends throughout most of the area underlain by Carboniferous rocks and ranges from a minimum thickness of about 80 m at Cumberland Gap to about 335 m in the Bramwell area. A maximum thickness of about 900 m is found in the faulted and folded belt. Marine faunas of Late Mississippian age are present in nearly all beds of the Greenbrier Limestone. The following fossils were collected from basal beds assigned to the Little Valley Formation by Cooper (1944, p. 156–157):

Protozoan:
- *Endothyra* sp.

Coral:
- *Triplophyllum compressum* (Edwards and Haime)

Blastoid:
- *Pentremites conoideus* Hall

Bryozoans:
- *Fenestralia sancti-ludovici* (Prout)
- *Fenestrellina serratula* (Ulrich)
  - *tenax* (Ulrich)
- *Fistulipora* sp.
- *Stenopora* sp.
- *Worthenopora spinosa* (Ulrich)

Brachiopods:
- *Camarotoechia* cf. *C. grosvenori* (Hall)
  - *mutata* (Hall)
- *Cliothyridina* sp.
- *Echinoconchus biseriatus* (Hall)
- *Orthotetes kaskaskiensis* (McChesney)
- *Productus* cf. *P. altonensis* Norwood and Pratten
  - *indianiensis* Hall
  - *tenuicostus* Hall
- *Reticularia salemensis* Weller
- *Spirifer bifurcatus* Hall
- *Streptorhynchus ruginosum* (Hall)

Pelecypod:
- *Aviculopecten amplus* Meek and Worthen

The lower middle part of the Greenbrier, assigned to the Hillsdale Formation, has yielded the following forms (Cooper, 1944, p. 159):

Algae:
- "*Giranvella*" sp.

Corals:
- *Lithostrotionella "canadensis"* (Castlenau)
  - *prolifera* (Hall)
- *Syringopora virginica* Butts

Bryozoans:
- *Dichotrypa* sp.
- *Fenestrellina tenax* (Ulrich)
- *Hemitrypa proutana* Ulrich
- *Polypora bisertiata* Ulrich
- *Stenopora* sp.

Brachiopods:
- *Brachythyris altonensis* Weller
- *Cliothyridina sublamellosa* (Hall)
- *Dielasma* sp.
- *Orthotetes kaskaskiensis* (McChesney)
- *Productus ovatus* Hall
  - *gallatinensis* Beede
  - *tenuicostus* Hall
- *Spirifer delicatus* Rowley
  - cf. *S. pellaensis* Weller

Gastropod:
- *Bellerophon* cf. *B. sublaevis* Hall

The following fossils were collected from the upper middle part ("Ste. Genevieve" equivalent) of the Greenbrier Limestone (Cooper, 1944, p. 163–164):

Corals:
- *Menophyllum princetonensis* (Ulrich)
- *Syringopora* sp.
- *Triplophyllum spinulosum* (Edwards and Haime)

Blastoids:
- *Pentremites princetonensis* Ulrich
  - *buttsi* Ulrich
  - *pulchellus* Ulrich

Crinoid:
- *Platycrinites huntsvillae* Safford

Bryozoans:
- *Batostomella interstincta* Ulrich
- *Fistulipora peculiaris* Rominger
- *Lioclemella* sp.

Brachiopods:
- *Athyris densa* Hall
- *Cliothyridina* cf. *C. parvirostris* (Meek and Worthen)
  - *hirsuta* (Hall)
  - *sublamellosa* (Hall)
- *Dielasma* sp.
- *Echinoconchus genevievensis* Weller
- *Girtyella indianensis* (Girty)
- *Productus ovatus* Hall
  - *inflatus* McChesney
  - *parvus* Meek and Worthen
- *Spiriferina* sp.
- *Spirifer pellaensis* Weller

Fossils in the upper part, ("Gasper" equivalent) of the Greenbrier include (Cooper, 1944, p. 168):

Corals:
- *Campophyllum gasperense* Butts
- *Triplophyllum spinulosum* (Edwards and Haime)

Blastoids:
- *Pentremites "godoni"* Ulrich
  - *pyriformis* Say
  - sp.
  - *cervinus* Hall
  - *patei* Ulrich

Crinoids:
- *Agassizocrinus* sp.
  - cf. *A. conicus* Wachsmuth and Springer
- *Platycrinites* sp. (stem plates not spinose)
- *Pterotocrinus serratus* Weller
  - *spatulatus* Wetherby
- *Talarocrinus inflatus* Ulrich
  - *ovatus* Worthen

Bryozoans:
- *Archimedes proutanus* Ulrich
  - sp.
- *Cystodictya* sp.

Brachiopods:
- *Chonetes* cf. *C. chesterensis* Weller
- *Cliothyridina sublamellosa* (Hall)

Composita trinuclea (Hall)
Diaphragmus elegans (Norwood and Pratten)
Echinoconchus sp.
Eumetria verneuilana (Hall)
Orthotetes cf. *O. kaskaskiensis* (McChesney)
Spirifer leidyi Norwood and Pratten
Spiriferina cf. *S. spinosa* (Norwood and Pratten)

BLUEFIELD FORMATION

The Bluefield Formation (Campbell, 1896) of Late Mississippian age is also identified in southwestern Virginia as the upper member of the Newman Limestone. It conformably overlies the Greenbrier Limestone and consists mostly of medium- to medium-dark-gray, greenish-gray, and grayish-red partly calcareous shale. Interbedded limestone and argillaceous limestone is fine crystalline to medium crystalline and light olive gray to medium gray. Locally, the formation includes beds of siltstone or fine-grained sandstone as much as 24 m thick. Also, a few thin coal beds associated with underclay and carbonaceous shale are present in places. The Bluefield Formation increases in thickness eastward from about 90 m at Cumberland Gap to 365 m in the Bramwell area. It is found throughout the area of Carboniferous rocks in southwestern Virginia, except for a few localities where only lower Mississippian rocks are preserved.

The Bluefield is abundantly fossiliferous, particularly the limestone and calcareous shale beds in the lower part of the formation. The forms listed below indicate that the Bluefield is correlative with the Glen Dean Limestone and possibly the Golconda Limestone of the midcontinent region (Cooper, 1944, p. 171–172):

Blastoids:
Pentremites brevis Ulrich
maccalliei Schuchert
Crinoid:
Pterotocrinus spatulatus Wetherby
Bryozoans:
Archimedes communis Ulrich
sp.
Fenestrellina cf. *F. tenax* (Ulrich)
Fistulipora sp.
Polypora sp.
Septopora subquadrans Ulrich
Stenopora sp.
Brachiopods:
Camarophoria explanata (McChesney)
Cliothyridina sublamellosa (Hall)
Diaphragmus elegans (Norwood and Pratten)
Eumetria verneuilana (Hall)
Orthotetes cf. *O. kaskaskiensis* (McChesney)
Productus cf. *P. inflatus* McChesney
Reticularia setigera (Hall)
Spirifer cf. *S. increbescens* Hall
cf. *S. transversa* (McChesney)
Pelecypods:
Aviculopecten sp.
Edmonia sp.
Myalina sp.
Sphenotus sp.

HINTON FORMATION

The Hinton Formation (Campbell and Mendenhall, 1896) of Late Mississippian age is characterized by abundant grayish-red partly calcareous shale and siltstone, but it also includes several intercalated sandstone beds, minor amounts of medium-gray and greenish-gray shale, fossiliferous limestone and calcareous shale, and a few thin beds of coal or carbonaceous shale underlain by rooted underclay. It conformably overlies and locally intertongues with the Bluefield Formation. Southwestward from Big Stone Gap, correlative strata have been included in the Pennington Formation or Group.

The Stony Gap Sandstone Member at the base of the Hinton is commonly quartzose, highly resistant, ripple bedded and as much as 30 m thick. It consists of white to very light-gray, very fine to medium-grained sandstone, which locally splits into two or more beds with greenish-gray or grayish-red shale intervening. Well-rounded pebbles and cobbles also are found in the member at a few localities. In places, the member grades to micaceous ripple-bedded sandstone that contains a relatively small amount of quartz.

The thickest and most widespread of several marine beds in the Hinton Formation is the Little Stone Gap Member (Miller, 1964) or Avis Limestone of Reger (1926). It is found as much as 185 m above the Stony Gap Standstone Member in the Bramwell area but converges southwestward to within 25 m of the top of the Stony Gap Sanstone Member near Cumberland Gap. The Little Stone Gap Member consists of medium-gray limestone, argillaceous limestone, and calcareous shale that totals as much as 23 m in thickness. Marine fossils, including brachiopods, pelecypods, bryozoans, and gastropods of Chesterian age are common in the member.

The Tallery Sandstone Member is the most prominent and widely distributed of several sandstone units in the upper part of the Hinton Formation. It is white to light gray, very fine to medium grained, thick bedded to massive, and, in most places, quartzose. It commonly contains well-rounded quartz pebbles and, for this reason, has been misidentified as the stratigraphically higher Princeton Sandstone (fig. 4).

The Tallery Sandstone Member ranges from 0 to 50 m in thickness and is split locally into two or more beds separated by medium-gray or greenish-gray shale.

The total thickness of the Hinton Formation ranges from a minimum of 50 m at Cumberland Gap to as much as 395 m in the Bramwell area.

PRINCETON SANDSTONE

The lithically distinctive Princeton Sandstone (Campbell and Mendenhall, 1896) of Late Mississippian age conformably overlies the Hinton Formation. It has been described as a polymictic conglomerate or as a coarse conglomeratic subgraywacke (Cooper, 1961, p. 69) and consists mainly of light-gray, fine- to coarse-grained, thick-bedded to massive calcite-cemented sandstone. Clasts in the formation are highly diverse in composition, size, and abundance and are composed of well-rounded to angular fragments of quartz, shale, siltstone, limestone, chert, and ironstone. The Princeton Sandstone attains a maximum thickness of about 18 m in the Bramwell area. Southwestward it becomes thinner, less conglomeratic, and grades to a very fine grained ripple-bedded sandstone before wedging out at the base of the Pride Shale Member of the overlying Bluestone Formation in west-central Tazewell County, Va. Fossils in the Princeton are largely limited to reworked specimens in limestone clasts.

MISSISSIPPIAN AND PENNSYLVANIAN SYSTEMS

BLUESTONE FORMATION

The youngest Mississippian strata in Virginia are included in the Bluestone Formation (Campbell, 1896), which consists of six widely recognized members. The Bluestone attains a maximum thickness of about 250 m in Tazewell County, Va..

The Pride Shale Member (Reger, 1926), at the base of the formation, is a dark-gray evenly bedded shale that grades locally to silty shale or to interlaminated siltstone and shale. Basal beds of the member may include partly calcareous greenish-gray and grayish-red shale. Pyrite and ironstone nodules and lenses as much as 1.3 cm thick are common in the dark-gray shale. A characteristic feature of the member is a grooved or fluted vertical surface in relatively fresh or slightly weathered exposures. From a maximum thickness of about 80 m in the Bramwell area, the Pride Shale thins southwestward and is not differentiated southwest of Big Stone Gap. Marine and brackish-water fossils are found locally in the member.

The Glady Fork Sandstone Member (Reger, 1926) varies in composition from silty ripple-bedded sandstone to coarse conglomeratic subgraywacke. The sandstone is light gray, fine to coarse grained, and thin bedded to massive. Well-rounded to angular clasts in the member are composed of quartz, shale, siltstone, limestone, chert, and ironstone. The Glady Fork sandstone is found only in Tazewell County where it ranges from 0 to 18 m in thickness.

The gray member of the Bluestone Formation is a wedge of interbedded medium-gray shale, light-gray sandstone, siltstone, argillaceous limestone, and a few thin beds of coal and associated underclay. It is restricted to Tazewell County, where it attains a maximum thickness of 60 m, and, where the Gladys Fork Sandstone wedges out, the gray member merges southwestward with the Pride Shale Member. Fresh- or brackish-water ostracodes and pelecypods are found in several beds of carbonaceous shale. A flora, dominated by *Stigmaria stellata* is found in several beds of the member (Gillespie and Pfefferkorn, 1977).

The red member of the Bluestone Formation is largely grayish-red, partly calcareous shale, siltstone, and sandstone. Lesser amounts of greenish-gray to medium-gray shale, siltstone, sandstone, argillaceous limestone, rooted underclay, coal, and carbonaceous shale are also present. The member is as much as 100 m thick in the Bramwell area, thins southwestward, and wedges out in the Big Stone Gap area. Ostracodes and *Lingula* are common in carbonaceous shale beds.

The Bramwell Member (Englund, 1968a), the uppermost unit of Mississippian age in the Bluestone Formation, is predominantly medium-gray to medium-dark-gray shale that coarsens upward and locally grades from very fine to fine-grained ripple-bedded sandstone. A persistent basal bed of black carbonaceous shale contains abundant ostracodes, pelecypods, and *Lingula;* overlying beds of the

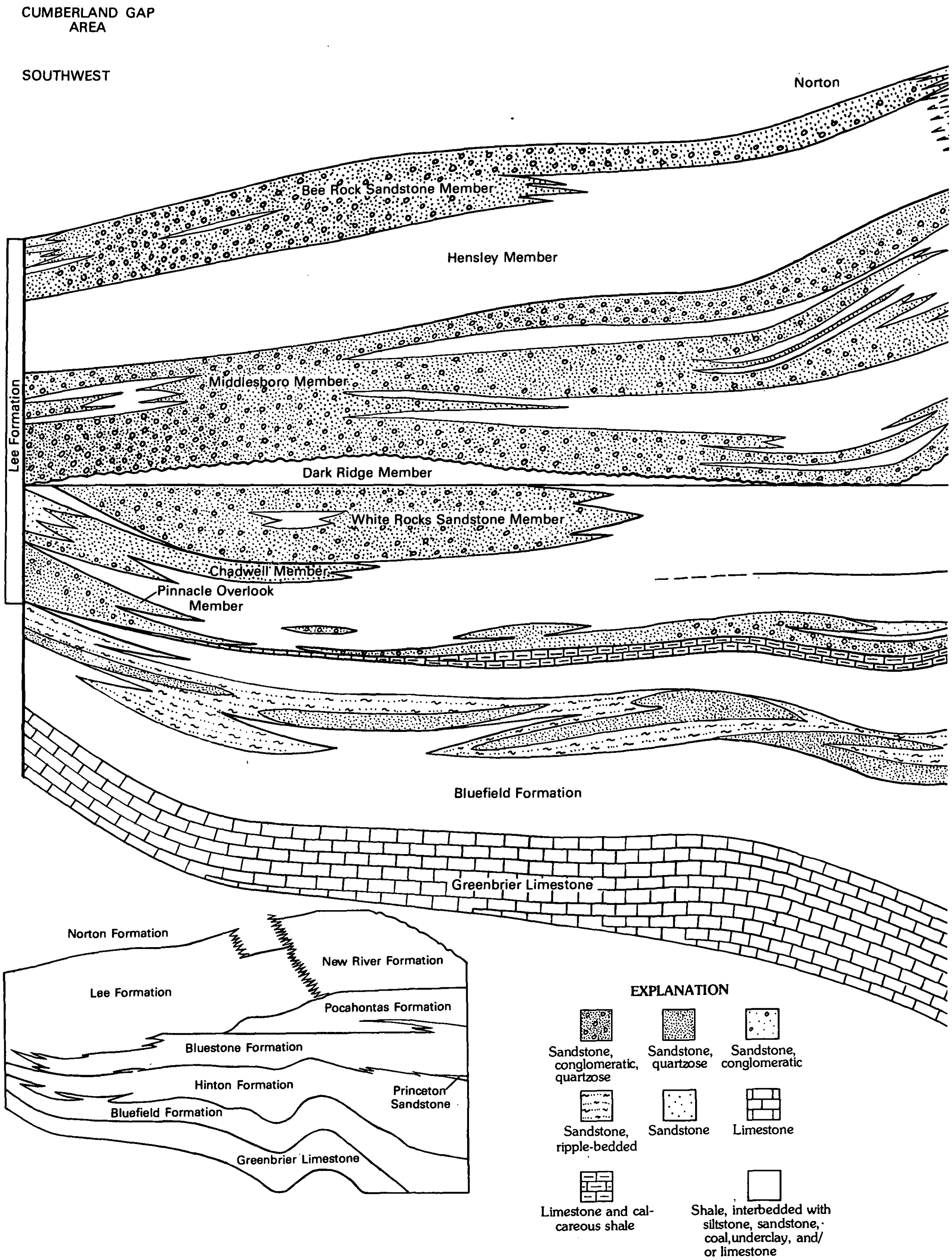

FIGURE 4.—Stratigraphic cross section showing the relation of formations to the Mississippian-Pennylvanian systemic boundary between the Cumberland Gap and Bramwell areas of the southwestern Virginia coal field. Line of section shown in figure 2.

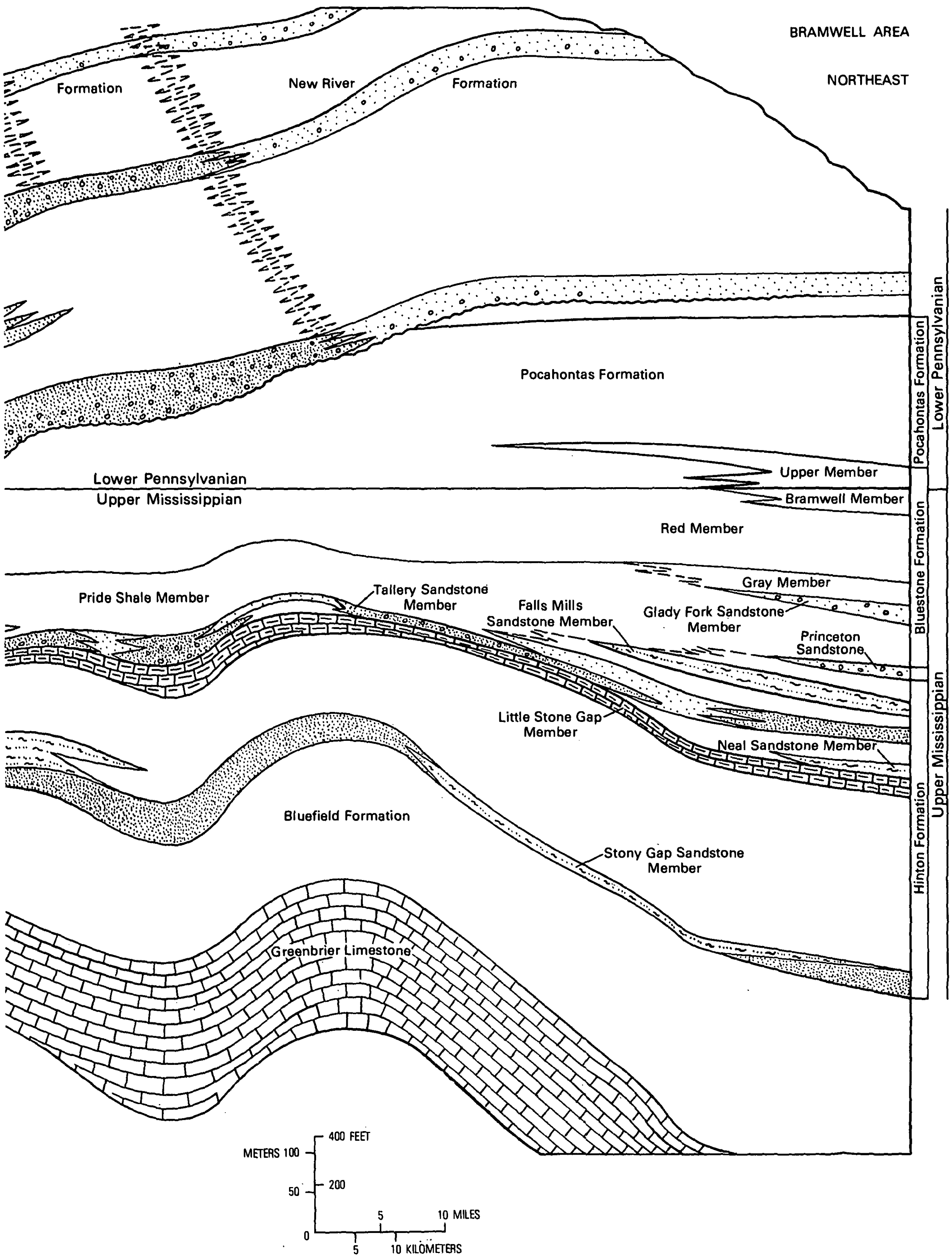

FIGURE 4.—Continued.

member contain articulate brachipods and pelecypods. Ellipsoidal argillaceous limestone concretions, 15–50 cm in diameter, are found locally. In Virginia, the member is limited to Tazewell County, where it ranges from 16 to 36 m in thickness. The following assemblages of Late Mississippian age were collected from a marine faunule in the Bramwell Member (Englund, 1974, p. 34).

USGS 22500–PC
- *Fenestella* sp.
- *Polypora?* sp.
- *Lingula* sp.
- *Orbiculoidea* sp. indet.
- *Orthotetes* cf. *O. kaskaskiensis* (McChesney)
- *Diaphragmus* cf. *D. cestriensis* (McChesney)
- *Ovatia* sp.
- *Anthracospirifer leidyi* (Norwood and Pratten)
- *Eumetria* cf. *E. vera* (Hall)
- *Polidevcia* sp.
- *Paleyoldia* sp. indet.
- *Aviculopecten* sp. (approaching Limipecten)
- *Posidonia?* sp. indet.
- *Solenomya* sp.
- *Sphenotus* sp. indet.
- *Wilkingia?* sp.
- *Edmondia* sp.
- *Composita subquadrata* (Hall)
- *Knightites (Retispira)* sp.

USGS 22754–PC
- *Lingula* sp.
- *Orbiculoidea?* sp. indet.
- *Orthotetes* aff. *O. kaskaskiensis* (McChesney)
- *Diaphragmus* cf. *D. cestriensis*
- *Ovatia* cf *O. elongata* Muir-Wood and Cooper
- *Anthracospirifer leidyi* (Norwood and Pratten)
- *Composita subquadrata* (Hall)
  sp.
- *Eumetria* cf. *E. vera* Hall
- *Beecheria* cf. *B. whitfieldi* (Girty)
- *Schizodus* sp.
- *Cypricardella?* sp.
- *Sphenotus* sp. indet.
- Bellerophontid gastropod, indet.
- Trilobite pygidium (fragment)

The upper member of the Bluestone Formation consists principally of slightly calcareous shale and siltstone that show the typical grayish-red and greenish-gray colors of the Bluestone Formation. A persistent bed of light-greenish-gray sparsely rooted claystone and scattered ironstone spherules is at the top of the member. The member intertongues and grades laterally with the lower sandstone member of the Pocahontas Formation of Early Pennslyvanian age. For this reason and because of the presence of *Neuropteris pocahontas*, a Lower Pennsylvanian fossil, the upper member is classified as Pennsylvanian in age. The member ranges from 0 to 24 m in thickness and merges westward with the red member of the Bluestone Formation.

LEE FORMATION

The Lee Formation (Campbell, 1893) of Late Mississippian and Early Pennsylvanian age has been divided in the type area, Lee County, Va., into seven mapped members, which are, in ascending order: Pinnacle Overlook, Chadwell, White Rocks Sandstone, Dark Ridge, Middlesboro, Hensley, and Bee Rock Sandstone Members (Englund, 1964a). The Late Mississippian members—Pinnacle Overlook, Chadwell, and White Rocks Sandstone Members—are quartzose sandstone and conglomeratic sandstone lobes that total as much as 135 m in thickness, and intertongue with the Bluestone or Pennington Formation. Basal Pennsylvanian beds consist of dark-gray shale, fine-grained sandstone, coal, and underclay which constitute the Dark Ridge Member, a correlative of the Pocahontas Formation. The Middlesboro Member disconformably overlies the Dark Ridge Member, Pocahontas Formation, or the Bluestone Formation. It is the most prominent and extensive member of the Lee Formation, especially in the Cumberland Gap and Big Stone Gap areas, where it consists of four locally coalescing quartzose and conglomeratic sandstone tongues that total as much as 150 m in thickness. Northeastward, the proportion of nonresistant strata in the member increases, a relationship that is accompanied by a divergence and splitting of the quartzose conglomeratic tongues (fig. 4). The lower and upper tongues of the member were designated lower and middle quartz arenite members of the Lee Formation by Miller (1974, p. 63).

The Hensley Member of the Lee Formation is a sequence of nonresistant sandstone, siltstone, shale, coal, and underclay as much as 122 m thick. Where the Bee Rock Sandstone Member tongues out, strata equivalent to the Hensley Member are included in the Norton Formation (fig. 4).

The Bee Rock Sandstone Member, the uppermost unit of the Lee Formation in Virginia, consists of two lobes of quartzose conglomeratic sandstone that are as much as 90 m thick. It grades at its northeastern fringe to nonresistant feldspathic sandstone of the Norton Formation.

The seven members of the Lee Formation aggregate 485 m in thickness. Plant fossils are found throughout the Lee Formation, and the floras are similar to those listed for the New River and Pocahontas Formations. Fresh- and brackish-water invertebrate faunas are also present.

PENNSYLVANIAN SYSTEM

POCAHONTAS FORMATION

The Pocahontas Formation (Campbell, 1896) is a northwestward-thinning wedge of coal-bearing clastic rocks that underlies an area of about 9,000 km^2 at the southeastern edge of the Appalachian coal field. It conformably overlies the Bluestone Formation, and, in contrast to the variegated and calcareous beds of that formation, the Pocahontas consists of interbedded light- to dark-gray sandstone, siltstone, shale, coal, and underclay. Of these, sandstone is most abundant and constitutes about 70 percent of the formation; siltstone, shale, and underclay total 28 percent; and coal, the remaining 2 percent. Outcrops in Virginia are limited to a narrow discontinuous belt of upturned beds at the southeastern edge of the coal field (fig. 2). From a maximum thickness of about 299 m in the outcrop area, the formation thins northwestward for about 48 km to where it wedges out in the subsurface at an average depth of about 450 m below the principal valley floors.

Fresh- or brackish-water pelecypods and *Lingula* are present in several beds; plant fossils, including stems, leaves, and roots, are found throughout the formation. The flora is characterized by an abundance of *Neuropteris pocahontas*, and other reported forms are as follows (Pfefferkorn and Gillespie, 1977):

Lyginopteris sp.
Mesocalamites sp.
Mariopteris pottsvillea White
Calamites sp.
Palmatopteris furcata (Brongniart) H. Potonie
Asterophyllites charaeformis Sternberg
Neuropteris smithsii Lesquereux

NEW RIVER FORMATION

The Pocahontas Formation is conformably overlain by the New River Formation of Early Pennsylvanian age in most outcrop areas. This conformable contact, placed at the base of the Pocahontas No. 8 coal bed, extends northwestward for several kilometers to where the upper beds of the Pocahontas Formation are truncated by the unconformity at the base of the Pineville Sandstone Member of the New River Formation or the correlative Middlesboro Member of the Lee Formation. Northwest of the area underlain by the Pocahontas Formation, upper beds of the Bluestone Formation were also eroded away, and there the disconformity at the base of the New River coincides with the widespread Mississippian-Pennsylvanian unconformity (Englund, 1969). In addition, a hiatus is substantiated by the absence of floral zone 4 of Read and Mamay (1964).

The New River Formation (Fontaine, 1874) is widely recognized in West Virginia, but in Virginia it is limited to parts of Buchanan and Tazewell Counties where the laterally equivalent Lee Formation has tongued out. The New River ranges from about 425 to 520 m in thickness and is a coal-bearing sequence of sandstone, siltstone, shale, and underclay. Lithically, it is similar to the Pocahontas Formation except for the presence of thicker and more widespread beds of quartz-pebble conglomerate or congomeratic sandstone. To the southwest and west, these coarse clastic rocks grade to quartzose conglomeratic sandstone of the Lee Formation (Englund and Delaney, 1966). Sandstone in the New River Formation is typically light gray, fine to coarse grained, thin to thick bedded, and locally massive. In addition to quartz, which ranges from 45 to 65 percent, the sandstone contains a notable amount of white-weathering feldspar, mica, and carbonaceous grains. Fossil plants are abundant in the formation, including the following forms, which were identified in conjunction with the Pennsylvaian System stratotype study in nearby areas of West Virginia (Pfefferkorn and Gillespie, 1977):

Calamites sp.
Asterophyllites charaeformis Sternberg
Lyginopteris sp.
Mariopteris pottsvillea White
Alethopteris decurrens Artis
Sphenophyllum cumeifolium (Sternberg) Zeiller

Fresh- or brackish-water faunules are found in several beds of the New River Formation. A marine assemblage collected from a calcareous shale overlying the Pocahontas No. 8 coal bed in Buchanan and Tazewell Counties (Henry and Gordon, 1977) includes:

Rugose coral, gen. and sp. indet.
Small pelecypods indet.
Pelmatozoan columnals
Paleyoldia? sp.
Lingula carbonaria McChesney
Schizodus? sp. indet.

Orbiculoidea sp. indet. (fragment)
Bellerophontacean, gen. and sp. indet.
Small marginiferid productoid?
Straparollus (*Euomphalus*?) sp. indet.
Composita sp. indet.
Pleurotomaracean gen. and sp. indet.
Nuculopsis cf. *N. girtyi* Schenck
Palaeosolen sp.
Phestia sp.
Fish scales

NORTON FORMATION

The Norton Formation (Campbell, 1893) of Early and Middle Pennsylvanian age is composed mostly of medium- to dark-gray shale and siltstone and lesser amounts of fine- to medium-grained sandstone, coal, and underclay. In contrast to the quartzose conglomeratic sandstone typical of the Lee Formation, that of the Norton tends to be finer grained, feldspathic, and micaceous, and has a relatively low quartz content of 50 to 60 percent. In most areas, the Norton Formation conformably overlies the Lee Formation; however, where the Lee is absent along the Virginia-West Virginia State line, correlative beds are assigned to the Kanawha Formation, which overlies the New River Formation. The thickness of the Norton increases northeastward from a minimum of 165 m to as much as 600 m. Fossil plants, including stems, leaves, and roots, are found throughout the formation. Several carbonaceous shale beds contain fresh- or brackish-water pelecypods and *Lingula.*

GLADEVILLE SANDSTONE

The Gladeville Sandstone (Campbell, 1893) is a widely recognized resistant unit that conformably overlies the Norton Formation. In the type area, Miller (1969) described the formation as a massive, strongly crossbedded medium-grained quartzose sandstone about 15.5 m thick. Regionally, the Gladeville grades to fine-grained feldspathic micaceous sandstone that is nonresistant and possibly absent in places.

WISE FORMATION

The Wise Formation (Campbell, 1893) of Middle Pennsylvanian age is an important coal-bearing sequence in the southwestern Virginia coal field. It conformably overlies the Gladeville Sandstone and, in addition to coal, consists of sandstone, siltstone, shale, underclay, and limestone. The sandstone is light gray, fine to medium grained, thin bedded to massive, micaceous, feldspathic, and contains about 50–60 percent quartz. Several sandstone members, including the Robbins Chapel, Keokee, Clover Fork, and Reynolds Sandstone Members are as much as 30 m thick (Miller, 1969, p. 25–30). The shale and siltstone are mostly medium to dark gray, but beds of black carbonaceous shale and calcareous shale are also present. Two widespread marine units in the formation—Kendrick Shale of Jillson (1919) and the Magoffin Beds of Morse (1931)—consist of limestone, calcareous shale, or siltstone that contains abundant brachiopods and pelecypods. Fossil plants are abundant in many shale and siltstone beds. The Wise Formation averages about 580 m in thickness.

HARLAN FORMATION

The Harlan Formation (Campbell, 1893) of Middle Pennsylvanian age conformably overlies the Wise Formation and includes the youngest Carboniferous rocks in Virginia. Sandstone is the dominant lithology; it ranges from fine to coarse grained, light to medium light gray, and feldspathic to quartzose. At the base of the formation the sandstone is massive, cliff forming, and occupies channels that truncate underlying beds. Siltstone, shale, and several coals and associated underclay are present in overlying beds. The Harlan Formation attains a maximum thickness of about 200 m in the highest mountaintops along the Virginia-Kentucky State line. Plant fossils are found throughout the formulation.

MISSISSIPPIAN-PENNSYLVANIAN BOUNDARY

The boundary between the Mississippian and Pennsylvanian Systems in Virginia has been placed, by definition and on the basis of paleontologic data, at the contact between the Bluestone and Pocahontas Formations. This long-standing practice has continued in recent studies in the southeasternmost outcrops where the Pocahontas attains its maximum thickness of about 213 m. However, a modification of this relationship, the systemic boundary ex- to the northwest of the lower sandstone member of the basal tongue of the Pocahontas Formation in the upper part of the Bluestone Formation. Because of this relationship, the systematic boundary extends from the base of that sandstone member into the upper part of the Bluestone Formation at approximately the contact between the Bramwell Member and the upper member (fig. 4). About 48 km northwest of the outcrop area, the unconformity at the base of the Pineville Sandstone Member of the

New River Formation, or the Middlesboro Member of the Lee Formation, truncates the Pocahontas Formation and the upper part of the Bluestone Formation. Thus, the depositional continuity of beds across the systemic boundary is replaced to the northwest by a widely recognized hiatus. Maximum truncation of Mississippian beds takes place near the Virginia-Kentucky State line, where the Middlesboro Member disconformably overlies the Pride Shale Member of the Bluestone Formation.

FACIES CHANGES

The facies in the Carboniferous rocks of Virginia are representative of various continental and marine depositional environments. For example, the Lower Mississippian Price Formation and its correlatives consist of greenish-gray shale and siltstone containing marine fossils in the Cumberland Gap area and westward. In the easternmost outcrops of the faulted and folded belt, this part of the stratigraphic section is a coarse clastic terrestrial coal-bearing sequence. Similarly, a largely marine facies of fine clastic rocks in the Bluestone Formation of the Bramwell area is represented to the southwest by nearshore deposits of coarse orthoquartzite that dominate the Lee Formation in the Cumberland Gap area. The latter rock type in overlying beds of the Lee also intertongues and grades laterally with coal-bearing paludal and fluvial facies of the Norton and New River Formations, which are characterized by feldspathic subgraywacke sandstones. An idealized facies relationship between marine and continental rocks is also shown by marine shale in the Bluestone Formation and clean-washed bar sandstone, alluvial distributary sandstone, and coal-bearing paludal deposits in the Pocahontas Formation, which are found in lateral sequence southeastward across the southwestern Virginia coal field (Englund, 1974).

DEPOSITIONAL ENVIRONMENTS

Patterns of sedimentation in the Carboniferous rocks of Virginia record the fluctuations of marine and continental environments in a shallow, slowly subsiding basin. Southwestern Virginia was inundated by a shallow marine sea during the initial deposition of Early Mississippian sediments in the Big Stone Gap Member of the Chattanooga Shale. A detailed study of the lithically similar Chattanooga Shale in Tennessee by Conant and Swanson (1961, p. 60–62) concluded on the basis of paleontologic and sedimentologic data that deposition was in a shallow-water marine environment. The overlying Price Formation recorded the first seaward progradation of terrestrial sediments during Mississippian time in Virginia. Beds of coal and carbonaceous shale intercalated with fluvial sandstone indicate that deposition took place in broad coastal swamps that were periodically crossed by fluvial distributaries, while marine deposition continued to the west in the correlative Grainger Shale of the Cumberland Gap area.

Extensive marine transgression is again evident in the overlying Maccrady Shale, which may represent nearshore tidal deposits that were uplifted and eroded slightly prior to the onlap of subtidal to supratidal clastic and nonclastic Greenbrier sediments. Marine organisms flourished during deposition of the Greenbrier, and the fragmental condition of the fossils indicates a nearshore or tidal environment of deposition. A seaward encroachment of nearshore mud and sand and brief periods of marine transgression are recorded in the overlying Bluefield Formation. At times, brackish- or fresh-water swamps supported vegetation growth and peat accumulation. The Stoney Gap Sandstone Member at the base of the Hinton Formation records a convergence of offshore bars, as indicated by sandstone distribution patterns, by the clean, well-washed, and well-sorted character of the sand, and by the occurrence of marine limestone beds a few meters above and below the member. A repetition of terrestrial and marine environments continued throughout the deposition of the Hinton Formation, as shown by the local occurrences of coal, lagoonal shale, bar sandstone, and limestone.

The deposition of the Princeton Sandstone suggests a high-energy prograding shoreline where well-rounded quartz and chert pebbles were transported by longshore and tidal currents together with locally derived limestone clasts. Miller (1974, p. 109) proposed a quiet-water lagoonal environment, directly behind beach-barrier bars for the origin of the overlying Pride Shale Member, which contains both brackish-water and marine faunas. The Glady Fork Sandstone Member represents the intertidal redistribution of sand and gravel by current and wave action which preceded the seaward progradation of terrestrial sediments of the gray member of the Bluestone. The red member of the Bluestone contains thin nodular limestone of a supratidal environment as well as tidal-creek channels. The drowning of the coastal plain on which the red member was deposited took place during the deposition of marine sediments of the Bramwell Member of the Bluestone.

Deposition of the Pocahontas Formation began with a coarse clastic wedge building seaward over marine sediments and intertonguing with the prodeltaic mud of the upper member of the Bluestone Formation. Thickness and lithic variations in this clastic wedge demonstrate that sand deposition was concentrated in several merging delta lobes and was interspersed with quartz-pebble gravel along some of the main distributaries. The orientation of these delta lobes indicates a general northwest progradation of sediments originating from the southeast. During deposition of the upper part of the basal sand wedge, a decrease in the influx of sand was accompanied by southeastward encroachment by mud over areas of relatively thin sand, mostly in the interlobe areas. The main distributaries continued to disperse sand at a reduced rate but in sufficient quantities to permit intertonguing on a small scale with mud during the final phase of sand deposition. Deposition of the silt and mud was followed by accumulation of peat, as recorded by coal as much as 1.2 m thick over the sand lobes. The concentration of peat on abandoned lobes may have been due to the greater compactibility of mud in the interlobe areas, resulting in lagoons with water too deep for optimum growth of vegetation.

Marine regression to the northwest resumed during deposition of the middle and upper parts of the Pocahontas Formation, which consist of several delta lobes stacked above those of the lower unit. The superposition of lobes over lower ones indicates that the sediments were transported generally along the same drainage lines that existed previously. During the deposition of these beds, the shoreline stabilized sufficiently for the formation of a barrier bar of clean well-washed sand. The location of the thickest part of the bar just beyond a large centrally located lobe suggests that distributaries of this lobe were the principal source of sand. At the distal edges of the lobe, the sand was subject to reworking and winnowing by waves and longshore currents, possibly from the northeast, as indicated by a gradual southwestward thinning of the bar away from distributaries of the principal lobe. Continued regression during the deposition of the Pocahontas was accompanied by a northwestward growth of alluvial distributaries over and beyond the barrier bar. Swamp deposits are more extensive upward in the sequence and consist of silt, mud, and peat that accumulated over abandoned sublobes and, to a lesser extent, in interlobe areas. The widespread occurrence of peat may have been related to shoreline stability as well as to a minimum influx of sediments. Incursion of clastic materials decreased abruptly, and widespread swamp conditions prevailed during deposition of the Pocahontas No. 3 coal bed.

After the deposition of the Pocahontas Formation, much of the area was inundated by a transgressing sea, and marine muds were deposited locally above the Pocahontas No. 8 coal bed. Shortly thereafter, the northwestern edge of the formation was uplifted and extensively eroded. Truncation of the Pocahontas Formation and beds in the upper part of the underlying Bluestone Formation was followed by the deposition of the overlying New River and Lee Formations in environments dominated by coastal and near-coastal deltaic processes. Sedimentation was similar in many respects to that of the Pocahontas Formation, except for the formation of more widespread and thicker barrier bars of clean well-washed sand.

The Norton Formation, which intertongues with the Lee Formation in Virginia, represents back-barrier, lagoonal, and lower delta-plain environments where coal beds are relatively thin and discontinuous. Landward from the deposits, the coal beds are thicker and more widespread, and intervening sandstones occupy channels characteristic of the upper delta plain. A similar relationship is recorded upward in the Norton and overlying formations, except for the Wise and Harlan Formations which also contain fluvial sandstones that occupy deeply incised channels of an alluvial plain. Therefore, the environmental sequence extends laterally as well as upward from the Lee Formation, from back-barrier, through lower and upper delta-plain, to an alluvial-plain environment.

IGNEOUS ROCKS

Igneous activity during the deposition of Carboniferous rocks in Virginia is suggested by the occurrence of sanidine in a bentonite bed associated with a coal bed of uncertain correlation in the Wise Formation (Nelson, 1959). Sanidine also occurs in a flint clay bed in the Fire Clay coal of Kentucky (Seiders, 1965), a correlative of the Wallins Creen coal bed of the Wise Formation. These occurrences, which may represent the same bed, have been attributed to a volcanic origin.

ECONOMIC RESOURCES

COAL

Bituminous coal is the principal developed mineral resource in rocks of Carboniferous age in Virginia. Commercial mining, which began in the late 1880's in the southwestern Virginia coal field has depleted extensive areas of the most accessible high-quality coal. Most production has come from underground mines, including both large mines that have facilities for rail shipment and many small mines that use truck haulage. Large-scale surface mining began in the 1940's and now accounts for 30 percent of total production, mostly from narrow contour strips on mountain slopes which locally are accompanied by auger mining. A record amount of 36 million metric tons of coal was mined from underground and surface operations in 1976 (Virginia Dept. of Labor and Industry, 1977).

Small-scale mining of semianthracite, which began in the early 1900's in the Valley coal fields of the faulted and folded belt, attained a maximum annual production of about 247,000 metric tons in 1926 (Brown and others, 1952, p. 39). Commercial mining of this coal was inactive in 1976.

Coal in the southwestern Virginia coal field consists of common banded varieties that range in rank from high-volatile A to low-volatile bituminous. Mined coal beds commonly have a high free-swelling index (Nos. 5–9), a low to medium sulfur content (0.5 to 2.0 percent), a high heat value (13,500 to 14,900 Btu), and a low ash content (2 to 9 percent). Because of its excellent coking properties, the coal is in demand by both the domestic and foreign markets. A comparison of the trace-element content of Virginia coal beds with those of other areas shows essentially the same or much lower concentration (Medlin and Coleman, 1976). Available analyses of semianthracite from the Valley coal field indicate that the coal is mostly low in sulfur content (0.3 to 1.2 percent), moderately high in ash (12.8 to 28.4), and moderately high in heat value (10,530 to 12,890 Btu) (U.S. Bureau of Mines, 1944).

Coal is found in nine formations of Carboniferous age in Virginia and in at least 120 beds, of which 55 are of economic importance. The Pocahontas, New River, Norton, and Wise Formations contain most of the coal resources and mining development. The distribution of individual coal beds ranges from those a few square kilometers in area to widespread beds that extend throughout much of the southwestern Virginia coal field. Coal bed thicknesses range from less than 1 cm to as much as 5 m, but more commonly from 1 to 1.5 m in mining areas.

Coal beds of Carboniferous age contain a total remaining identified resource of 8,662 million metric tons (Averitt, 1975, p. 15). Of this total, about 47 percent is in thin beds (35–70 cm thick), about 35 percent in intermediate beds (70–105 cm thick), and about 18 percent in thick beds (more than 105 cm thick) (Brown and others, 1952). Recent investigations have indicated the presence of an additional 4,535 million metric tons of undiscovered resources.

NATURAL GAS AND PETROLEUM

Natural gas has been produced commercially from Carboniferous rocks in Virginia since 1938. Initial production was from sandy zones in the Little Valley Limestone, equivalent to part of the Greenbrier Limestone, of the Early Grove gas field in the Ridge and Valley area of Scott County (Averitt, 1941). The first commercial gas well in the Appalachian Plateau of Virginia was completed in 1948 in sandstone of Late Mississippian age (LeVan, 1962). Gas production is currently from the Price Formation, Greenbrier Limestone, and the Hinton Formation. Nearly 7,000,000 Mcf of gas was produced from 180 wells in 1976 from Mississippian and Devonian rocks (Lytle and others, 1977). Rocks of Carboniferous age lack petroleum production, but shows of oil have been reported at several horizons in these strata.

LIMESTONE

The Greenbrier Limestone has been the principal source of crushed stone in rocks of Carboniferous age. It has been quarried at several localities for roadstone and concrete aggregate.

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CONTENTS

ILLUSTRATIONS

THE MISSISSIPPIAN AND PENNSYLVANIAN (CARBONIFEROUS) SYSTEMS IN THE UNITED STATES—WEST VIRGINIA AND MARYLAND

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ABSTRACT

This review of the upper Paleozoic rocks (Mississippian, Pennsylvanian, and Permian Systems) of West Virginia and Maryland embodies the work of outstanding 19th-century and early 20th-century geologists.

Upper Paleozoic rocks are predominantly composed of fine- to medium-grained clastic materials, which were deposited as a complex delta; exceptions are the organic and chemical deposits interspersed throughout the section. Delineation of facies changes, thickening characteristics and trends of thick units, and distribution of traceable beds such as coal and limestone, suggest structural control of deltaic sedimentation during late Paleozoic time. An irregular surface on Mississippian strata marks a break in sedimentation (unconformity) between Mississippian and Pennsylvanian time, except in areas of continuous sedimentation on or near exposures in southern West Virginia.

Mississippian rocks contain frequent marine horizons. Dally's work on Mississippian invertebrate faunas indicates that Pocono deposition was time-transgressive, ranging from early Kinderhookian through late Osagian in the south, and late Osagean through Meramecian in the north. The Maccrady Formation is Meramecian, although the basal units may be late Osagean. The basal Greenbrier Group is middle Meramecian in the south, correlating with the type area, whereas upper parts of the formations range into the Chesterian. However, the northern Greenbrier is early Chesterian. Mauch Chunk rocks are middle to late Chesterian.

Mississippian vertebrate evidence is sparse. The Pocono and Maccrady have yielded no identifiable vertebrates. Greenbrier rocks contain rare Meramecian vertebrates in the south and somewhat more common Middle and Late Mississippian faunas to the north. Mauch Chunk faunas correlate with the type Chesterian and are similar to Upper Visean rocks in Britain. Appalachian and European Carboniferous floras are very similar, although detailed correlation is hard because of lack of studies.

Invertebrate faunas in Pennsylvanian rocks are relatively uncommon. In the older mining district (southern West Virginia), the Pocahontas and New River Formations contain no useful marine beds. The Kanawha Formation contains several marine faunas of Morrowan, Atokan, and basal Desmoinesian age. Vertebrate evidence is similarly lacking in the older mining district. One basal Kanawha Formation locality yields vertebrates giving a tentative Morrowan age. Allegheny rocks of the younger mining district (northern West Virginia) possess no useful marine beds, although correlative strata in adjacent States are Desmoinesian. Lower Conemaugh marine zones are Missourian through lower Virgilian in age. Upper Conemaugh, Monongahela, and Dunkard beds are barren of marine fossils.

Conemaugh and early Monongahela vertebrates in the younger mining district show Virgilian affinities. Sediments above the Benwood limestone contain vertebrates corresponding to Wolfcampian faunas. The upper part of the Greene Formation above the Burton sandstone has a possible Leonardian correlation. Pennsylvanian paleobotany needs more study, but a basic zonation is being worked out and correlated with the European sequence.

INTRODUCTION

Upper Paleozoic rocks underlie 81 percent of western and southern West Virginia and much of Garrett County, smaller areas of Allegany County, and a few hilltops of Washington County in Maryland. This paper reviews the early geologic work, physiography, structure, and mineral resources, and focuses upon the lithostratigraphy and biostratigraphy.

Figure 1 shows the historical development, to the present, of West Virginia/Maryland late Paleozoic nomenclature. It also shows the approximate relationships of rock divisions to (1) U.S. midcontinent series time-rock units, and (2) the European stages (Moore and others, 1944, chart 6; Weller and others, 1948, chart 5; Dunbar and others, 1960, chart 7; McKee and Crosby, 1975, p. 2).

The Mississippian and Pennsylvanian sections in the United States are approximate equivalents of,

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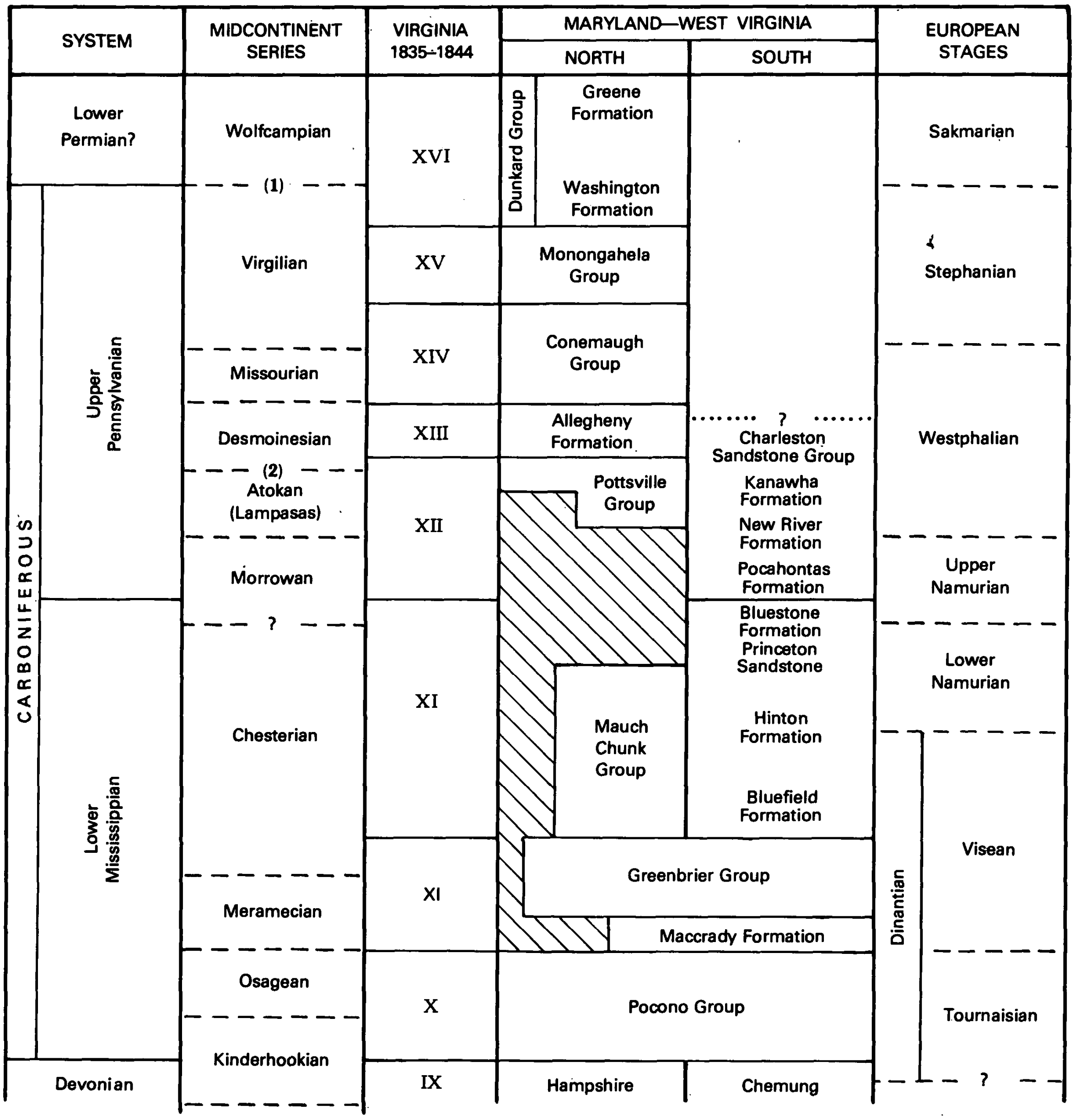

(1) Position of Washington coal. (2) Position of Coalburg or Stockton coals.

FIGURE 1.—Late Paleozoic classification.

respectively, the lower and upper Carboniferous of Europe. The term "Permo-Carboniferous" (Wilmarth, 1938, p. 1640) was commonly used in early geologic reports in the United States, following the practice of many European workers. The U.S. Geological Survey included the Permian Series as the upper epoch of the Carboniferous until 1941 (Dunbar and others, 1960, p. 1767). The Dunkard Group, essentially of Permian age, is included in this discussion, because sedimentation continued without interruption from the Monongahela Group of Pennsylvanian time into the Dunkard Group. A long controversy continues over the assignment of the Dunkard Group to the Permian System (Fontaine and White, 1880, p. 105–120; Dunbar and others, 1960, p. 1789, 1790; Barlow, 1975, p. vii–xviii).

The stratigraphic nomenclature used in this paper has not been reviewed by the Geologic Names Committee of the U.S. Geological Survey. The nomenclature used here conforms with the current usage of the West Virginia Geological and Economic Survey, with the exceptions of the term "Charleston Sandstone Group" (fig. 1) and Lower No. 5 Block, Upper No. 5 Block, and No. 6 Block coals (R. S. Reppert, oral commun., 1977) (fig. 10).

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Biostratigraphic material was prepared as follows: Mississippian, Pennsylvanian, and Permian plants, by William H. Gillespie, West Virginia University, Morgantown, W. Va., and Herman W. Pfefferkorn, University of Pennsylvania, Philadelphia, Pa.; Mississippian, Pennsylvanian, and Permian vertebrates, by Richard Lund, Adelphi University, Garden City, Long Island, N.Y.; Pennsylvanian invertebrates, by C. Warren Norton, and Mississippian invertebrates, by Richard A. Smosna, both of the West Virginia Geological and Economic Survey, Morgantown.

The remaining sections of the paper were prepared by members of the staff of the West Virginia Geological and Economic Survey: Introduction, early geologic work, physiography, structure, coal, and lithostratigraphy of Pennsylvanian and Permian Systems, by Thomas Arkle, Jr.; ground water, by Dennis R. Beissel; construction and industrial minerals and iron ore, by Edward B. Nuhfer and Richard E. Larese; oil and natural gas, by Douglas G. Patchen; and lithostratigraphy of Mississippian System, by Richard A. Smosna.

EARLY GEOLOGIC WORK

A colonial military road crossed Maryland and Pennsylvania to Fort Duquesne (Pittsburgh) in the mid-18th century. This road was extended to Wheeling in what was then western Virginia and became the National Road in 1818, parts of which are now U.S. Route 40. Improvements to this road and the completion in 1852 of the Baltimore and Ohio Railroad across Maryland and northwestern Virginia (between Baltimore and Wheeling) opened the area for geologic study and subsequent mineral developments during the first half of the 19th century.

The major rock divisions of late Paleozoic age in western Viriginia (much of which became West Virginia on June 20, 1863) and Maryland (fig. 1) were first studied and described between 1835 and 1844 by W. B. Rogers (1884), State Geologist of Virginia, and by his brother H. D. Rogers (1838, 1840, 1844, 1858), State Geologist of Pennsylvania.

The Rogers brothers (Pennsylvania's First Survey) and the staff of the Second Pennsylvania Geological Survey in 1875, under J. P. Lesley (1876), contributed greatly to geologic knowledge of Maryland, the Virginias, Pennsylvania, and Ohio.

The first Maryland Geological Survey was organized in 1833 under J. T. Ducatel, State Geologist, and J. B. Alexander, State Topographic Engineer; the third and present Maryland Survey was organized on March 11, 1896, under William B. Clark (1897, 1905). The West Virginia Geological Survey was organized on February 20, 1897, under Israel C. White (1891, 1903, 1908), formerly of the Pennsylvania and U.S. Geological Surveys.

A growing coal industry focused on commercial coals during the first quarter of the 20th century. Correlation problems, particularly in Middle Pennsylvanian strata, were posed by bed configuration and lithofacies changes between the strata deposited on the northwestern West Virginia/Maryland craton and the southern West Virginia basin.

The paleobotanical work of White (1900a, b; 1913), showed that northern West Virginia's Allegheny Formation coal was younger than that of southern West Virginia's Kanawha Formation. Campbell (1903) resolved the mapper's dilemma by showing a facies change involving the stratigraphic equivalents of: (1) the upper Pottsville (Homewood sandstone), Allegheny, and lower Conemaugh strata of northern West Virginia; and, (2) the Charleston sandstone (Campbell, 1901, p. 5) along the Elk River near Charleston (fig. 1).

Geologic maps and reports on the upper Paleozoic rocks of West Virginia were completed between 1906 and 1939 by G. P. Grimsley, Ray V. Hennen, C. E. Krebs, D. B. Reger, J. L. Tilton, P. H. Price, and L. M. Morris, assisted by W. A. Price, Rietz C.

Tucker, W. F. Prouty, D. D. Teets, Jr., Robert M. Gawthrop, and E. T. Heck of the West Virginia Geological Survey, and David G. White and George H. Girty of the U.S. Geological Survey.

Maps and reports on upper Paleozoic geology in Maryland's Allegany, Garrett, and Washington Counties were completed between 1900 and 1951 by Cleveland Abbe, Jr., G. C. Martin, C. C. O'Hara, W. B. Clark, R. B. Clark, R. B. Rowe, Heinrich Ries, and Ernest Cloos, of the Maryland Geological Survey, which by the 1950's had become the Maryland Department of Geology, Mines, and Water Resources. The stratigraphy of Maryland's coal measures was revised in the second coal report (Swartz and Baker, 1922). During World War II, exploration for coal and refractory clay by the U.S. Bureau of Mines and the U.S. Geological Survey culminated in the remapping of the Pennsylvanian of Maryland. This remapping was done in the early 1950's by Karl Waage of the U.S. Geological Survey and T. M. Amsden of the then Maryland Department of Geology, Mines, and Water Resources. (fig. 2).

PHYSIOGRAPHY

The upper Paleozoic strata of West Virginia and Maryland form part of the Appalachian Plateaus province (fig. 3) and limited synclinal-mountain areas of the Valley and Ridge province farther east. The Appalachian Plateaus province extends from west of the Ohio River eastward across the Allegheny Mountain section of the plateau, to the Allegheny Front. The Allegheny Front is underlain by resistant Pottsville sandstone. The steep slope to the east, leading down to the Valley and Ridge province,

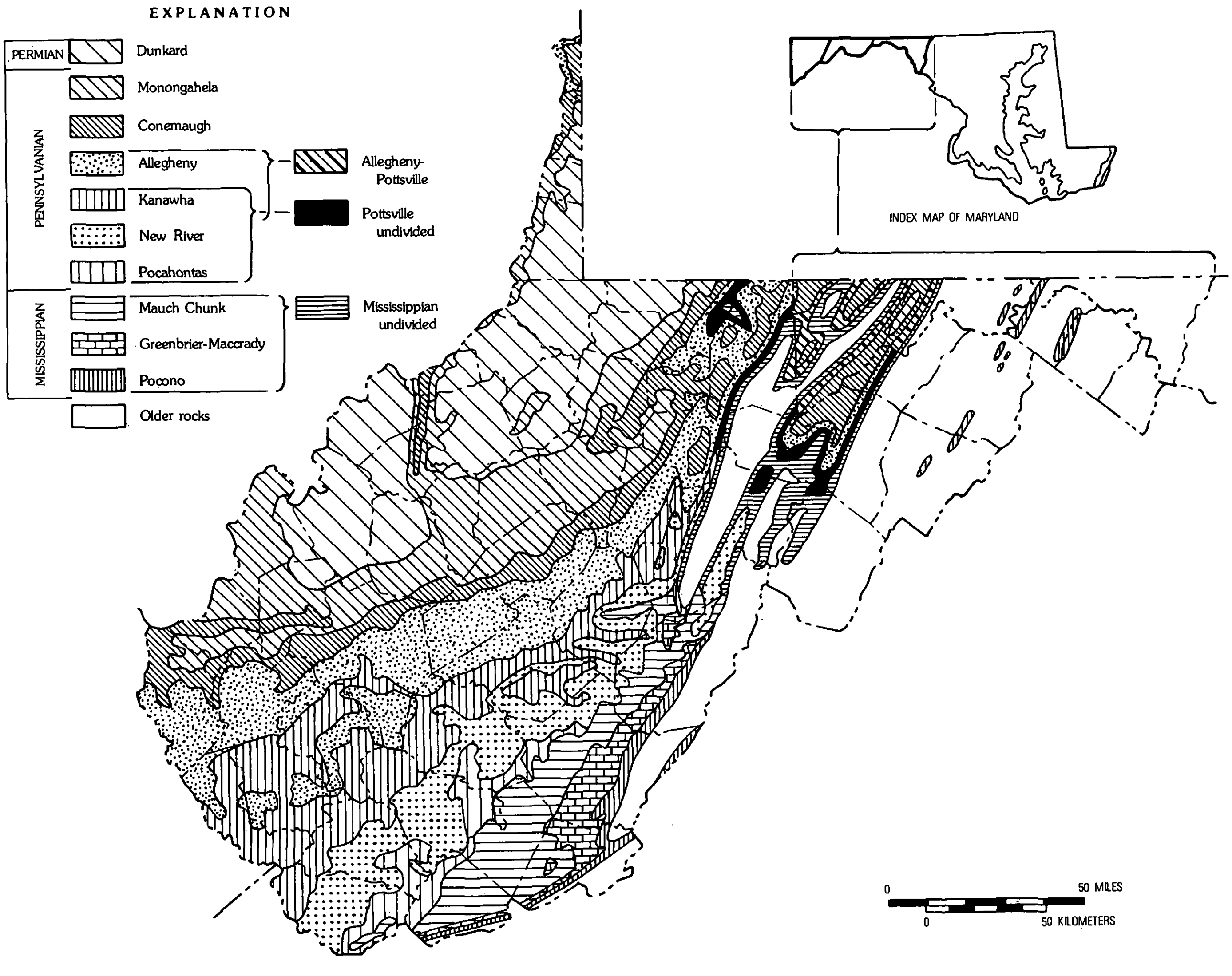

FIGURE 2.—Geologic map of the late Paleozoic of West Virginia and Maryland.

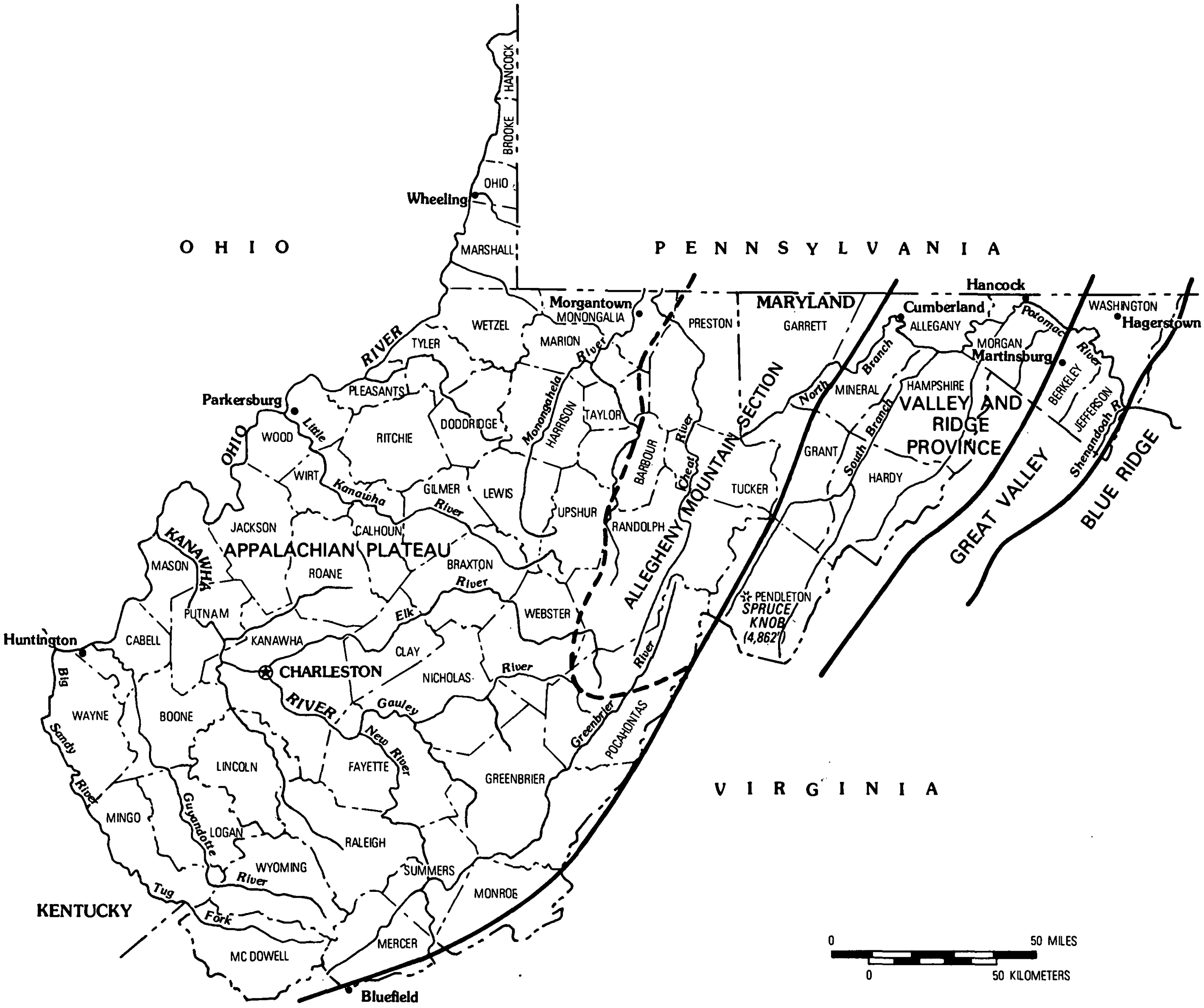

FIGURE 3.—Physiographic map of West Virginia and adjacent Maryland.

is on less resistant Mississippian and older strata. The Appalachian Plateaus province is deeply dissected, hilly to mountainous country, and the outliers are linear mountainous ridges of sandstone and shale containing a few irregular coal beds (figs. 2–4).

The water of the plateau and southeastern Lower Mississippian outliers drains westward to the Ohio River. As shown in figure 3, the north-flowing Monongahela drainage, the south-flowing Greenbrier River, and the west-flowing Elk and Little Kanawha Rivers all begin in the high country of Randolph and Upshur Counties near Spruce Knob, Pendleton County, the highest point in West Virginia (1,482 m or 4,862 ft) and the environs of the Catskill-Pocono stratigraphic anomaly (Flowers, 1956, p. 8, 10–14; fig. 4). Waters of eastern Tucker, Grant, and Mineral Counties, West Virginia, the eastern slope of the Allegheny Front, most of western Maryland, and the northern lower Mississippian outliers flow into the Potomac River, thence east to the Chesapeake Bay and the Atlantic Ocean.

Only two rivers entirely cross West Virginia: the Ohio crosses the State from north to south, and the New/Kanawha Rivers, as a system, cross east to west. The Ohio River's glaciofluvial sand-and-gravel deposits are dominated by rock debris from hard sandstone and quartzite that emanated from ablat-

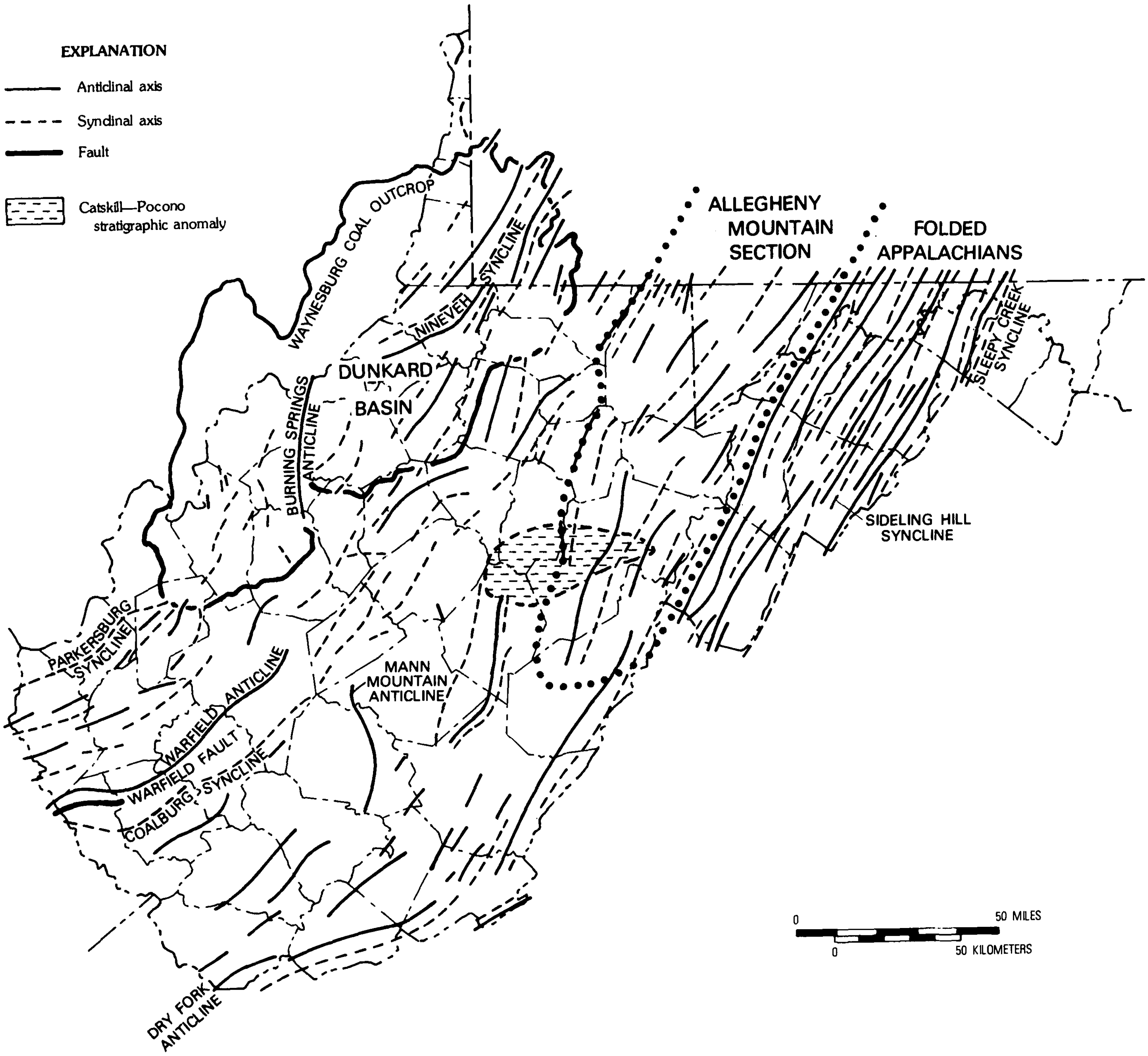

FIGURE 4.—Structural map of the late Paleozoic of West Virginia and Maryland.

ing Pleistocene glaciers north of West Virginia. The New/Kanawha River system begins near Blowing Rock in North Carolina's Blue Ridge Mountains and flows across the Valley and Ridge province, and the Appalachian Plateaus province to Point Pleasant on the Ohio River. Some granitic and metamorphic rocks are present in the bedload deposits of the New/Kanawha Rivers. The bedload sand-and-gravel deposits of all other streams of West Virginia are largely of sandstone, the rock most resistant to physical and chemical disintegration, and other sedimentary rock types indigenous to the Valley and Ridge and Appalachian Plateaus provinces.

STRUCTURE

The upper Paleozoic strata of West Virginia and Maryland are exposed on the eastern side of a synclinal belt extending north-northeast from the subsurface in Alabama to near the Great Lakes in Ohio and New York, a distance of 1,448 km (900 mi) (fig. 4). These strata are infolded between the Appalachian tectonic belt on the east and the more stable Indiana-Ohio upland and the Lexington (Kentucky) and Jessamine (Tennessee) domes on the west.

Early work depicted the surface structures of upper Paleozoic strata as reflections of episodic basement deformation. The deformation intensity declined progressively from the crystalline Appalachians (Piedmont and Blue Ridge provinces) on the east to the basement of the sedimentary Appalachians (Valley and Ridge and Appalachian Plateaus provinces) on the west. Since World War II, however, deep drilling for natural gas on anticlinal structures of the sedimentary Appalachians has found many thrust faults. A restudy of the structures, based on drilling, geophysical logging, and surface geological investigations, suggests this alternative view of Appalachian tectonics: A décollement zone (perhaps in Silurian evaporites) and associated thrust faults extending upward into Middle Devonian strata, plus folding, are suggested as the mechanisms for the formation of surface structures in the Valley and Ridge and subsurface structures in the Appalachian Plateaus. Structural manifestations in Cambrian and Precambrian strata are believed coincidental to this later tectonic activity in the Valley and Ridge province and subsurface of the Appalachian Plateaus province (Rodgers, 1972).

Delineation of facies changes, thickening characteristics and trends of thick units, and distribution of traceable beds such as coal and limestone, suggest later structural control of deltaic sedimentation during late Paleozoic time (Arkle, 1974). Compressional forces formed the surface structure of the Appalachians from at least Mississippian time through the rest of Paleozoic deposition, after the earlier period of extensional tectonics. The entire rock section was further deformed at the end of Paleozoic deposition (Rodgers, 1972, p. 4).

Two surface-structural trends, running east-northeast and north-northeast, are evident in West Virginia (note arrows in fig. 8, and relate these to fig. 4). These trends conform to the structural salients of the Appalachian Mountains. Southern West Virginia's upper Paleozoic strata are shown in a northeast-trending, northwest-dipping broad monoclinal structure (fig. 4). Strata inclination is moderate, reaching 48 m/km (250 ft/mi) on the Warfield anticline, the dominant structure. This dip increases to 57 m/km (300 ft/mile) on the Dry Fork anticline, bringing Upper Mississipian strata to the surface and exposing basal Pennsylvanian beds just to the southeast. Farther southeast, in southeastern Mercer and Monroe Counties (see fig. 3 for county location), deformation intensity of the thick, less resistant Mississippian strata increases progressively between the higher Pennsylvanian escarpment and the Valley and Ridge province, where middle and lower Mississippian (and older) strata are vertical or slightly overturned (figs. 2–4).

En echelon structures, trending north-northeast in the Allegheny Mountain section (figs. 3 and 4) bring resistant Pottsville sandstone to the surface, forming mountainous areas. More hospitable country is formed on the less resistant Mississippian and Devonian strata in breached anticlines and on the younger Pennsylvanian coal-bearing strata in adjacent synclines. Anticlines are slightly asymmetric to the west, and maximum dips are 20°. The anticlines plunge south-southwest over the Catskill-Pocono stratigraphic anomaly and lose identity in southern West Virginia monoclinal structure.

The Nineveh syncline is the axis of the Dunkard basin, a north-northeast-trending synclinorium extending from Huntington, W. Va., to Pittsburgh, Pa. The basin configuration is best delineated by Pittsburgh coal exposures (fig. 4). Normal to the Nineveh syncline, the Pittsburgh coal is 518 m (1,700 ft) above sea level on Scotch Hill, Preston County, and 320 m (1,050 ft) at the head of the Monongahela River in Marion County, both in west Virginia; it is 378 m (1,240 ft) at its western exposure in Belmont County, Ohio. The Pittsburgh coal is slightly above sea level along the Nineveh axis in West Virginia. West of the Allegheny Mountain section, strata in the synclinorium dip 38 m/km (200 ft/mi), decreasing to less than 4 m/km (20 ft/mi) on the Ohio River.

The anomalous Burning Springs anticline lies athwart the Dunkard basin axis. This anticline is complex, steeply dipping, north-trending and plunging, and is surrounded by nearly flat-lying strata. Surface dips range from as much as 55° on a narrow flat crest on the east flank, to 70° on the west flank. Here, as on many other anticlines in the Appalachian Plateaus province, deep drilling has disclosed thrust faults extending into the Devonian. Projection of the relatively simple Appalachian Plateaus surface structures into the subsurface is not valid because they may not be maintained at depth (Woodward and others, 1959, p. 164).

MINERAL RESOURCES

Mineral resources from upper Paleozoic rocks (fig. 5) are economically important to West Virginia and Maryland. Coal accounted for 94 percent of West Virginia's mineral resources, which were

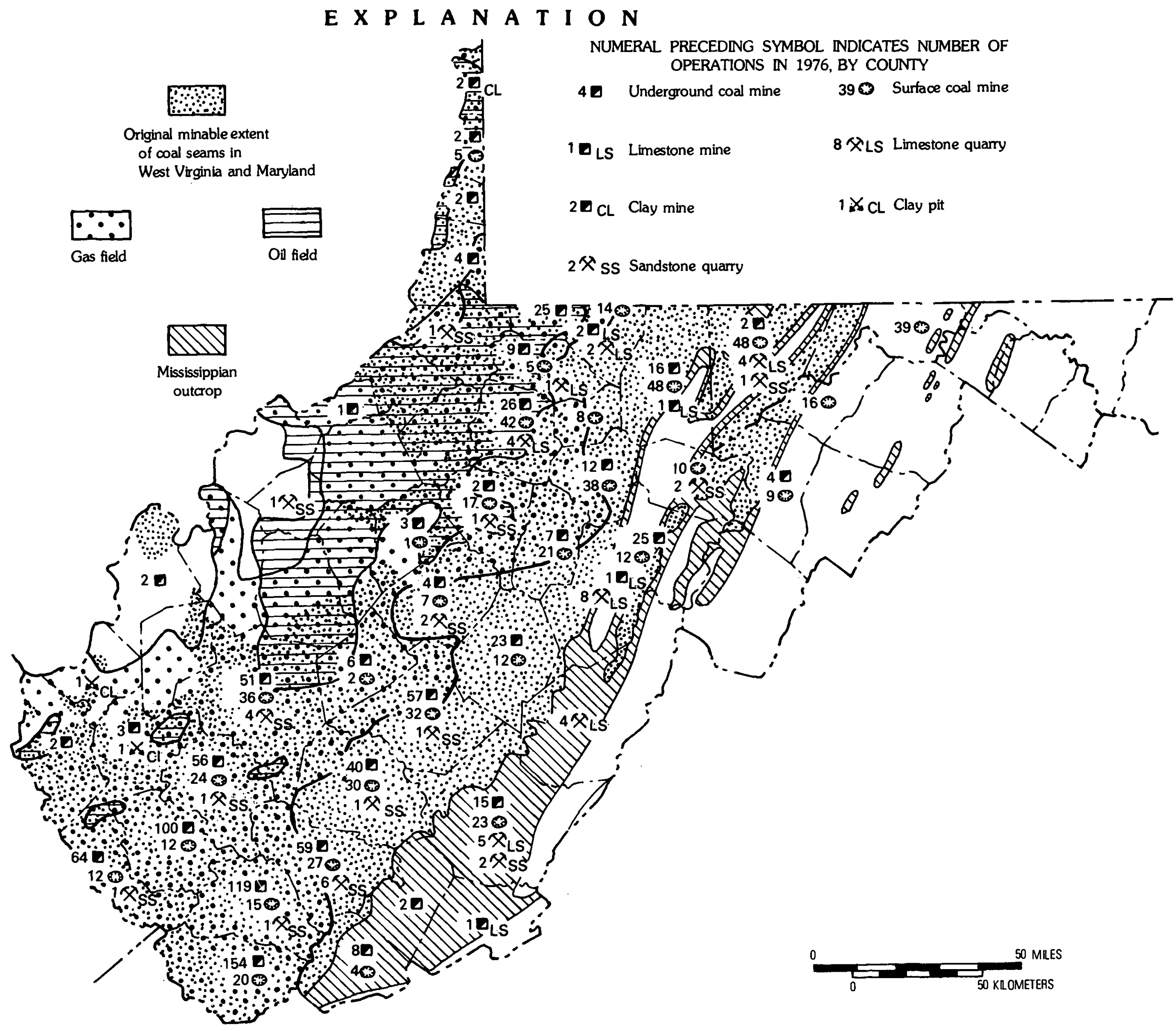

FIGURE 5.—Late Paleozoic mineral resources of West Virginia and Maryland.

valued at $3.5 billion (at the source) in 1976; it accounted for 28 percent of Maryland's mineral resources, valued at $172.9 million in 1974. Upper Paleozoic strata also provide the following materials in West Virginia and Maryland: all the refractory clay; all the concrete sand from crushed sandstone; most of the oil, clay, shale, and crushed sandstone; appreciable natural gas; appreciable limestone for aggregate and cement manufacture; and some industrial limestone.

COAL

During the mid-1700's, explorers and surveyors noted the existence of coal in West Virginia and Maryland. In 1811, coal fired the first steamboat on the Ohio River. In 1840, W. B. Rogers (1884) reported coal production of 271,157 t (metric tons) (298,894 short tons) in West Virginia; about 70 percent of this coal was used by the salt industry on the Kanawha River above Charleston.

In Maryland, two coal mines operated as early as 1782 and 1804. Coal was carried east to Cumberland, Md., over the National Road as early as 1820. Access to the northern coal fields was provided by the Chesapeake and Ohio Canal (completed in 1850) and the Baltimore and Ohio Railroad (completed in 1843), both connecting the eastern seaboard to Cumberland.

West Virginia coal production increased slowly until the completion of the rail network in the late 1800s. Original coal resources, measured to 30.5 cm (12 in.) thick in the western 69 percent of the State, were estimated at 105.9 billion t (116.7 short tons). Production expanded rapidly to 132.5 million t (146.1 million short tons) in 1927. Only during World War II and the postwar years to 1947 did production exceed 136.1 million t (150 million short tons). Production remained high through the recent 1965–67 peak, and fell irregularly to a 92.3-million-t (101.7 million short tons) low in 1974. Coal production in 1976 was 98.1 million t (108.1 million short tons) from 903 underground and 504 surface or "outside" mines (West Virginia Dept. Mines, 1976, p. 15); surface mining accounts for 19 percent annually.

More than 70 percent of West Virginia's annual coal production comes from low- to high-volatile, generally low-sulfur (<1 percent) seams at multilevels in southern West Virginia. The remainder is produced from high-volatile, high-sulfur (>1 percent) coal of northern West Virginia, principally the thick, uniform Pittsburgh coal. Correlative coals grade into low- to medium-volatile (and locally low-sulfur) coal in the Allegheny Mountain section (fig. 4) of West Virginia and Maryland. Much of Maryland's early production was from the Pittsburgh coal in Allegany County, but when this coal was depleted early in the 20th century, mining shifted to the less uniform and thinner Allegheny and Conemaugh coals.

About a third of the coal production of West Virginia is used to generate electricity annually, more than half is used domestically or exported for metallurgical purposes, and the remainder supplies industrial and retail markets. Mining employment reached 121,280 in 1923. After machines were introduced, employment declined to 41,593 in 1968, and stood at 59,802 in 1976 (West Virginia Dept. Mines, 1976, p. 13–14).

West Virginia coal reserves are estimated at 33.1 billion t (36.5 billion short tons) from seams >71.1 cm (28 in.) thick. Appreciable reserves <71.1 cm (28 in.) thick are available. About 1.9 billion t (2.1 billion short tons) of reserves is recoverable by surface mining. Some 33.4 percent of reserves is low-sulfur (<1 percent) coal (U.S. Bur. Mines, 1971, p. 118; 1974, p. 275).

Maryland's coal production increased from 1,548 t (1,706 short tons) in 1842 to a 5.0-million-t (5.5 million short tons) peak in 1907. Subsequently, production averaged about 4.1 million t (4.5 million short tons) per year until 1918, and thereafter declined irregularly to a 453,600-t (500,000 short tons) low in 1954. In recent years, coal production for steam generation has increased slowly to a 2.4-million-t (2.7 million short tons) high in 1976. Surface-mining methods, introduced during World War II, now account for 94 percent of Maryland's coal production.

Total recoverable reserves in Maryland are estimated at 775.6 million t (854.9 million short tons) for seams more than 68.6 cm (27 in.) thick. About 90.7 million t (100 million short tons) is recoverable by surface-mining methods; the remainder is recoverable only by underground mining. Additional coal reserves exist in seams thinner than 68.6 cm (27 in.) (Weaver and others, 1976, p. 1–3).

OIL AND NATURAL GAS

West Virginia's oil and gas industry began with oil production from the Rathbone Well (Wirt County) in 1859. The State ranked second or third in crude oil production from then until 1900, the peak year. Production and the State's rank have both decreased steadily during this century. Annual oil production is now only 12 percent of 1900's, and annual gas production is now about 52 percent of that produced during the peak gas year, 1916.

During the early years of the industry (the last half of the 19th century), shallow Pennsylvanian sandstone (Pottsville, Allegheny, Conemaugh, and Monongahela strata) along the Burning Springs anticline and Ohio River was drilled for oil and associated natural gas. Deeper drilling penetrated important oil and natural-gas reservoirs in Mississippian sandstone and in thin basal Greenbrier sandy dolomite in western West Virginia. More recently, natural-gas reservoirs have been developed in Mississippian sandstones in southern West Virginia (fig. 5). Driller's names have been given to 11 Mississippian and 10 Pennsylvanian producing sands between the Berea sand (base of Pocono Group) and the Minshall sand (Monongahela Group).

West Virginia has 357 fields in 53 counties; Maryland has 1 field. In West Virginia, oil and natural gas are produced from upper Paleozoic reservoirs in 43 of the 53 counties; in Maryland, no county produces oil or gas from upper Paleozoic rocks.

At the end of 1976, West Virginia's original oil in place was estimated at 351,966 thousand t (2,625,-316 thousand barrels), 10.7 percent in Pennsylvanian reservoirs and 58.5 percent in Mississippian. An estimated 73,089 thousand t (545,173 thousand bbls) was assumed to be recoverable, 6.6 percent in

Pennsylvanian and 55.3 percent in Mississippian reservoirs.

Currently, Pocono and Greenbrier reservoirs are the most common Mississippian targets in the State for development and in several southern counties for exploration. The Mauch Chunk sands are also productive in this southern area. In Pennsylvanian strata, only basal sands are being developed at present.

CONSTRUCTION AND INDUSTRIAL MINERALS

Limestone.—Commercial limestone production (fig. 5) indicates the economic importance of the Mississippian Greenbrier Group. The Greenbrier, a group of marine limestones, has exceptional thickness, persistent continuity, generally acceptable purity, and extensive areas of surface exposure. Most Greenbrier limestone is used for road aggregate, cement, and agricultural lime. High-purity limestone from the southern counties is also used as rock dust in coal mines.

Lateral and vertical variations in purity are documented in the Greenbrier Group. Textural and mineralogical variations along the northeast-trending outcrop belt from Tucker County to Monroe County W. Va., have been described by Leonard (1968). The entire limestone sequence of the Greenbrier is usable, but the highest purity limestone is found in the Union Formation. The "white oolite member" of the upper Union (Leonard, 1968, p. 101) persists through Monroe County and much of Greenbrier County, where it is extensively quarried. As the oolitic beds diminish in size and continuity to the northeast, limestone purity generally decreases. Westward, beneath the plateau, insoluble residues generally increase as the Greenbrier grades toward the sandier facies found in the subsurface of western West Virginia. Four quarries operate in the basal sandy Greenbrier (Loyalhanna) in Garrett County, Md.

Present mining operations are restricted to outcrop areas and include both open-pit and underground mines (Larese and others, 1977). The underground mines enter surface exposures and follow only the gentle dips of the strata. Deep shaft mining in western West Virginia has been discussed (Kusler and Corre, 1968) but has not yet been undertaken.

Some thin Pennsylvanian limestone beds of minor economic importance are utilized locally. These beds were described by McCue, Lucke, and Woodward (1939); they were further discussed and were classified according to their usability, by the West Virginia University Coal Research Bureau (1965). Most of this limestone is nonmarine; a lacustrine origin has been attributed to some beds. All beds have persistently high dolomite and (or) insoluble-residue content and are not potential sources of high-calcium limestone. Of these beds, the Benwood and Redstone limestones of the Monongahela Group are the most important commercial sources. Benwood exposures occur in Ohio, Brooke, Tyler, Doddridge, and Harrison Counties; minable thicknesses of the Redstone occur in Monongalia, Harrison, Marion, and Upshur Counties. Present extraction yields local road aggregate and minor amounts of agricultural lime.

Sandstone.—Upper Paleozoic sandstone is currently extracted in 23 quarries in 13 counties (fig. 5) and is used as road-base aggregate, concrete sand, and, to a lesser extent, dimension stone.

High-silica (98 percent) sandstone is mostly restricted to the Pottsville Group (Lower Pennsylvanian), Mauch Chunk Group (Upper Mississippian), and Pocono Group (Lower Mississippian) (Arkle and Hunter, 1957). In northern West Virginia, the Connoquenessing and Homewood Sandstones (Pottsville Group) have been quarried for glass sand. In the southern part of the State, high-silica material at the horizons of the Nuttall, Raleigh, and Pineville sandstones (New River Formation, Pottsville Group) underlies small areas, which are suitably located for mining (Arkle and Hunter, 1957).

Sandstones of the Mauch Chunk and Pocono Groups are impure, commonly containing appreciable argillaceous material; consequently, many do not qualify for high-silica applications. However, two sandstones within the Mauch Chunk Group, the Stony Gap and Droop, are relatively pure and may have potential as special-purpose sands. An additional pure quartz-cemented conglomeratic member of the Pocono Group has been quarried for construction aggregate in Preston County and adjacent areas of Maryland.

The youngest Paleozoic sandstones in West Virginia—the Conemaugh-Monongahela Group in the Pennsylvanian and the Dunkard Group in the Permian—are generally too impure to be high-silica sandstone sources. These units are locally quarried for road-base aggregate and historically have been used for dimension sandstone and abrasive stone (grindstone, pulpstone) (Eggleston, 1975).

Clay and shale.—West Virginia's clay and shale industry is relatively small. Four mines produce clay and shale for manufacturing common brick, fire brick, block, and clay stemming.

Only clay and shale of the Pennsylvanian Allegheny Formation and Conemaugh Group are currently being used. Two Allegheny clays, the Lower Kittanning and Clarion, have excellent fire-clay qualities and are presently being extracted by underground methods in Hancock County (fig. 5). These clays directly underlie the Lower Kittanning coal, and range from 2.1 to 6.7 m (7 to 22 ft) in thickness in the northern panhandle. Reserves have been estimated at 1 billion tons under less than 500 feet overburden (Cross and Schemel, 1956). Allegheny plastic and flint clays are mined for production of refractory fire brick and ground-and-calcined clay in adjacent parts of Maryland. Conemaugh shale is extracted from two quarries in Cabell and Lincoln Counties for manufacture of common brick, tile, and clay stemming.

Recent work by Lessing and Thomson (1973) has shown that many late Paleozoic clays and shales have potential for the manufacture of face brick, structural tile, lightweight aggregate, and sewer pipe.

Salt.—Natural brines from upper Paleozoic strata have been used extensively in West Virginia, although the State's brine fields are presently inactive. Major sources were the "Salt Sands" in the Pennsylvanian Pottsville Group and the "Big Injun Sand" of the Mississippian Pocono Group. A compilation of geological information, production sites, chemical analyses, and economic utilization of these brines has been provided by Price and others (1937).

IRON ORE

Although there is no present iron mining in West Virginia, an active history of production from Pennsylvanian rocks was noted by Eggleston (1975, p. 25) and Grimsley (1909, p. 106–107). The latter reference also gives the location, analyses, and nature of the ore in various counties. Iron deposits from Pennsylvanian strata consist of impure sideritic-limonitic nodular beds which are discontinuous and sporadically distributed through the coal measures in a broad belt from Preston and Monongalia Counties through Kanawha and Wayne Counties. These occurrences will probably not be economically important in the foreseeable future. The sites, together with the abandoned remnants of iron furnaces and the implements made there, are mainly of historical interest.

GROUND WATER

Three factors affect water quality from upper Paleozoic strata: (1) Mine drainage from Pennsylvanian strata pollutes water, principally in the northern part of the State, (2) in the oil and gas fields (fig. 5), fresh water is degraded by upward migration of brine, and (3) variable ground-water quality conditions, both within and between aquifers, are caused by local geologic, hydrologic, and cultural phenomena.

MISSISSIPPIAN SYSTEM

Ground-water availability is highly variable in the Mississippian outcrop belt in West Virginia. Clark and others (1976) found well yields in southeastern West Virginia to be governed primarily by well depth, topography, geologic structure, and stratigraphy. Yields were generally higher in deep wells, valley wells, and wells near axes. Valley wells in the Mauch Chunk Group had a higher median specific capacity than wells in any other Mississippian unit.

Ground-water occurrence in the karst region, underlain by Greenbrier limestone in southeastern West Virginia, is controlled by interconnection of solution cavities and channels along fracture systems in carbonate strata. Wells in the Maccrady Formation and Pocono Group yield moderate water, but hillside and hilltop wells in the Maccrady may not yield enough for domestic use (Clark and others, 1976).

In northeastern West Virginia, wells penetrating the Greenbrier and Pocono Groups have yields adequate for domestic use. Few wells tap Mississippian-age rocks outside the outcrop belt in eastern West Virginia and western Maryland; consequently, yield data are scarce. In the subsurface of western West Virginia, Mississippian-age rocks are usually below the freshwater/saltwater interface.

PENNSYLVANIAN AND PERMIAN SYSTEMS

Southern West Virginia.—Ground-water data for Pennsylvanian strata in southern West Virginia are scarce. A water-resources study of this area's Guyandotte River basin is in progress.

Pottsville Group sandstones are the most extensive aquifers in southern West Virginia. Doll and others (1960) found that Pottsville sandstone in Kanawha County yields more water than does shale of the same group. Well yields ranged from 1 to 522 gpm, averaging 118 gpm. The freshwater/saltwater interface is 90–150 m (300–500 ft) deep. Wilmoth (1967) reported 88,000 gpd/ft transmissivity from an aquifer test in the Pottsville Group in Raleigh County. To the southeast in the New River basin, Clark and others (1976) found Pottsville wells to have a median specific capacity of 0.23 gpm/ft. They suggested that valley wells in the Pottsville would yield sufficient water for small municipal and industrial supplies.

Sandstones overyling the Pottsville are also major aquifers in southern West Virginia. Wells in these sandstones produce primarily from fractures. In Kanawha County, the average well yield was 125 gpm, the deepest freshwater well being at 93 m (306 ft) (Doll and others, 1960). A 13,000-gpd/ft transmissivity was reported by Wilmoth (1967) from an aquifer test in the same sandstones.

Northern West Virginia and western Maryland.—In northern West Virginia, Pottsville strata have the highest potential for ground-water development. In the Monongahela River basin, Pottsville wells yield an average 44 gpm (Ward and Wilmoth, 1968). Yields reach a maximum of 250 gpm, valley wells being the highest producers. Transmissivity values from aquifer tests reached a maximum of 10,000 gpd/ft. The Pottsville contains saltwater west of a line from Morgantown in Monongalia County to Buckhannon in Upshur County.

A ground-water study of eastern Monongalia County by Quagliotti (1974) revealed an average Pottsville sandstone well yield of 57 gpm. Major aquifers were found throughout the Pottsville Group, but the lower Pottsville had the highest potential.

Allegheny Formation sandstones provide adequate water for small to moderate industrial and public drinking supplies (Ward and Wilmoth, 1968). As in other Pennsylvanian strata, well yields in the Allegheny generally decrease from east to west in northern West Virginia. Average yields ranged from 31 gpm in eastern Monongalia County (Quagliotti, 1974) to 26 gpm over the entire Monongahela River basin (Ward and Wilmoth, 1968). In the Little Kanawha River basin, Allegheny well yields were less, but no average was reported (Bain and Friel, 1972). All the highest yielding Allegheny wells were in valleys underlain by thick sandstone beds. A 27,000-gpd/ft transmissivity was determined from an aquifer test in Allegheny strata in Taylor County (Ward and Wilmoth, 1968).

Several Conemaugh Group sandstone units are considered to be aquifers in northern West Virginia and western Maryland. Well yields average about 10 gpm, but transmissivities are generally less than 1,000 gpd/ft. Basal Conemaugh sands contain saltwater in the western part of the Monongahela River basin (Wilmoth, 1966), and because of mining and drilling activity, poor quality water is found as far east as eastern Harrison County (Nace and Bieber, 1958).

Wells producing from Monongahela strata generally have low yields. Mining activity throughout northern West Virginia and western Maryland has drained much of the Monongahela Group, particularly in outcrop areas.

Basal Dunkard sandstones are the most important Permo-Pennsylvanian-age aquifers in Harrison County (Nace and Bieber, 1958) and the Little Kanawha River basin (Bain and Friel, 1972). Wells in the Dunkard Group average 13 gpm in the Monongahela River basin and 6 gpm in Mason and Putnam Counties (Wilmoth, 1966). The Dunkard is contaminated locally with saltwater from old oil wells. It also feeds many springs with freshwater. In Wetzel County, Dunkard wells close to mapped fracture traces had significantly higher yields than did other wells (Sole and others, 1976).

MISSISSIPPIAN SYSTEM

LITHOSTRATIGRAPHY

Lithologically, the Mississippian System may be divided into three parts (fig. 6): (1) Lower sandstone (Pocono Formation) and overlying red shale (Maccrady Formation), (2) middle limestone (Greenbrier Group), and (3) upper red shale (Mauch Chunk Group). Mississippian strata crop out in or underlie all West Virginia counties (except Jefferson), but important exposures—including many type sections—occur only along the eastern part of the State (fig. 6).

Cooper (1948, p. 258), pleading for future investigations, claimed that in the central Appalachians, geologists will find "some of the thickest and most varied sections of the Mississippian. * * *" Moreover, in Virginia and West Virginia, "the system therein probably contains the fullest Mississippian section on the North American continent." Indeed, the Mauch Chunk and Maccrady red beds are extraordinarily thick and extensive, whereas the Greenbrier limestones reflect the final major marine flooding of the region. Yet so little published work on the Mississippian of the State is available!

For this reason, most stratigraphic data in this paper are from West Virginia Geological Survey County Geologic Reports published between 1907 and 1939 and from more recent unpublished graduate theses. Also, Dennison and Wheeler (1975)

SYSTEM	SERIES	SOUTHEAST GROUP	SOUTHEAST FORMATION	NORTH FORMATION
MISSISSIPPIAN	Chesterian	Mauch Chunk	Bluestone Formation[1]	Mauch Chunk Formation
			Princeton Sandstone	
			Hinton Formation	
				?
			Bluefield Formation	Greenbrier Limestone
		Greenbrier	Alderson Limestone	
			Greenville Shale	
			Union Limestone	
			Pickaway Limestone	
			Taggard Formation	
	Meramecian		Denmar Formation	Pocono Formation
			Hillsdale Limestone	
	Osagean	Maccrady Formation[2]		
	Kinderhookian	Pocono Formation		Hampshire Formation[3]

[1]In extreme southern West Virginia, uppermost beds of Bluestone Formation are Pennsylvanian

[2]Lower Maccrady Formation may be Osagean

[3]Most of Hampshire Formation is Devonian

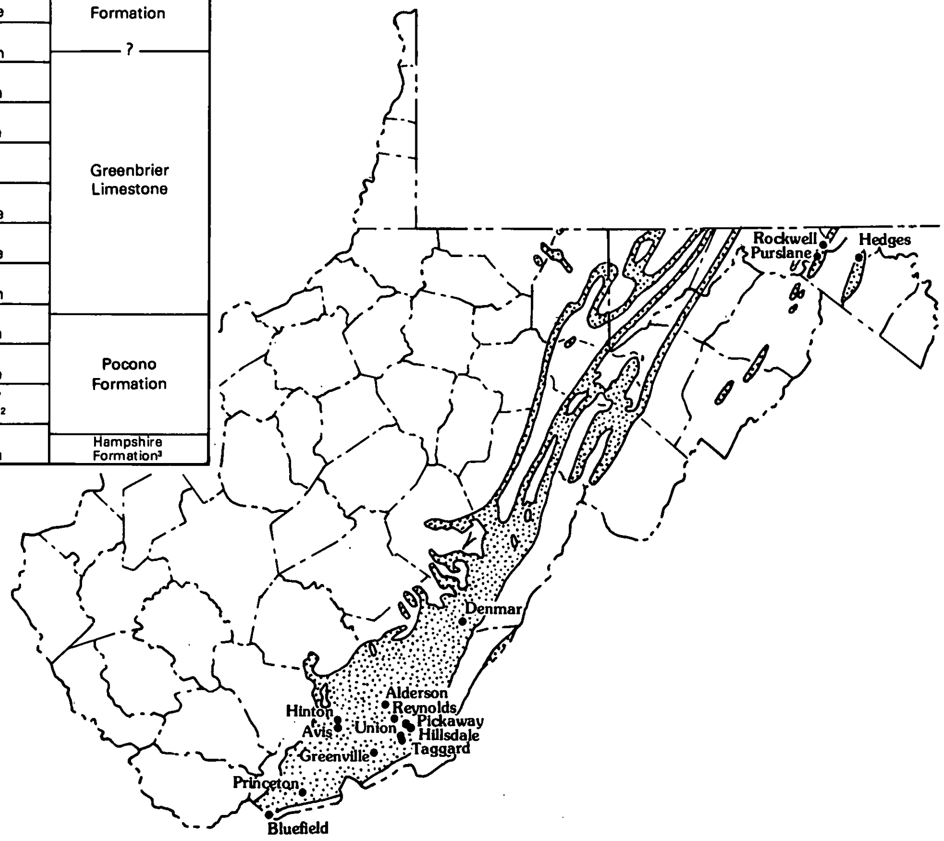

FIGURE 6.—Outcrop of the Mississippian (stippled) and type sections in West Virginia and Maryland.

have provided a general review of fluvial Mississippian strata of the southeastern United States.

SYSTEMIC BOUNDARIES

With only limited paleontological evidence, the Mississippian System base is traditionally put at the base of the Pocono Formation. The Berea Sandstone Member is the basal subdivision of the Pocono in the subsurface and consequently is considered to be the basal Mississippian stratigraphic unit, established solely as a convenient lithologic marker.

Throughout most of West Virginia, lowest Pocono rocks intertongue with Upper Devonian Hampshire (Catskill) Formation red beds. The interpretation follows that the time boundary is not coincident with a lithologic boundary, and Dally (1956) thought the upper Hampshire to be partly of Mississippian age. In the southernmost counties, however, the Pocono grades downward into the Upper Devonian Chemung Group, the boundary being vaguely placed where thick beds of crossbedded, conglomeratic Pocono sandstone rest on flaggy beds of Chemung sandstone.

The Mississippian upper boundary clearly coincides with a marked erosional unconformity. From southeast to northwest across the State, the Pennsylvanian Pottsville Group rests on successively older units of the Mississippian Mauch Chunk Group. In fact, pre-Pottsville erosion removed the entire Mauch Chunk and part to all of the Greenbrier in north-central and western West Virginia (Youse, 1964). In Hancock County (northern panhandle), the Pottsville sits directly on the Pocono Formation. Only in very southern West Virginia is the Mississippian-Pennsylvanian contact conformable. Along the West Virginia/Virginia State line, lowest Pottsville sandstones from the southeast intertongue with variegated Mauch Chunk shale and siltstone to the northwest (England and others, 1976). The uppermost Mauch Chunk beds there are of Pennsylvanian age.

TECTONIC INFLUENCE ON SEDIMENTATION

Tectonism concurrent with sedimentation is illustrated by (1) the pronounced subsidence of the southern basin and (2) the enormous volume of detritus in the Appalachian basin. In the southern basin, as much as 1,700 m (5,576 ft) of continental and shallow-marine sediments was deposited (fig. 7); simultaneously, less than 300 m (984 ft) was laid down on a relatively stable shelf in the northwestern two-thirds of the State. In between, the Mississippian System thickens notably over a short distance (hinge line). In the Appalachian basin, combined uplift and erosion of an eastern landmass supplied the enormous volume of detritus, including the molasse facies of the Pocono (Dally, 1956) and Mauch Chunk (Hoque, 1968). In southern West Virginia and Virginia, polymictic conglomerates of the Princeton Sandstone (Mauch Chunk Group) have been identified as reworked Silurian, Devonian, and Mississippian sediments (Thomas, 1966).

POCONO FORMATION

The Pocono Formation has been mapped throughout the eastern outcrop belt, but subdivisions are generally thin and cannot be traced from one region to the next. Only in the extreme eastern panhandle are mappable units within the Pocono distinguished; hence, where the Rockwell, Purslane, and Hedges Formations (in ascending order) can be distinguished, the Pocono is raised to the rank of "group."

The thickest Pocono Group section is in Berkeley County, where it totals 335 m (1,099 ft); it thins to

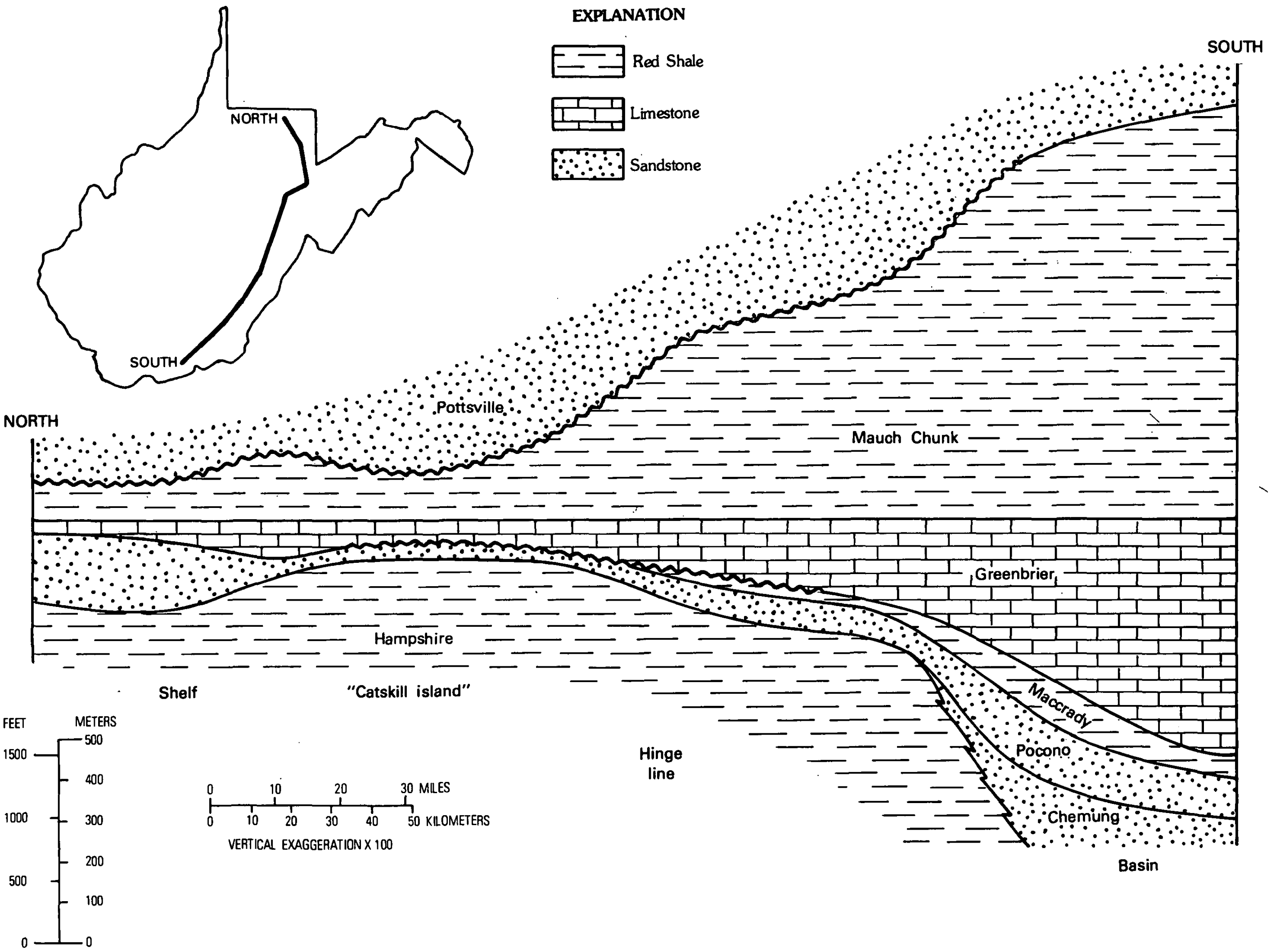

FIGURE 7.—Cross section of Mississippian strata along outcrop belt.

150 m (492 ft) to the southwest in Hampshire and Hardy Counties. The Rockwell Formation includes interbedded arkosic, conglomeratic, and argillaceous sandstone; sandy and silty shale; fine conglomerate; coal; and occasional plant fossils. The Purslane Sandstone is predominantly fine-grained sandstone alternating with conglomerate and some sandy shale; at the top are beds of black shale and coal. The Hedges Formation consists of sandy shale, thin beds of laminated argillaceous sandstone, black shale, and semianthracite coal. Plant fossils have been reported from the black shale in Hampshire County; this unit thins to the southwest and is absent in Hardy County. The upper contact of the Pocono Group is not seen because rocks younger than Pocono are not present in this area.

In southern West Virginia, the Pocono Formation resembles the Pocono Group of the Hampshire-Berkeley County area, except that it is noticeably thinner (fig. 7). The undifferentiated Pocono ranges from 60 to 180 m (197 to 582 ft) in thickness, consisting primarily of brown, coarse-grained and conglomeratic crossbedded sandstone. Sandy shale, some red, and lenses of impure coal and conglomerate are also present. In the southern counties, the Sunbury Shale Member (traced via the subsurface to its type section in Ohio) is a black sandy shale containing minor sandstone; its thickness ranges from 5 to 50 m (16 to 164 ft). Several authors have recognized the basal Berea Sandstone Member (a gas reservoir in the west) in the outcrop. In this area, the upper limit of the Pocono is placed above the coal-bearing strata and below Maccrady Formation red shale or limestone.

The Pocono Formation thins drastically in central West Virginia and actually is missing over a large territory called the "Catskill island" (Figs. 2 and 7). The island was a deltaic lobe, standing above sea level (Dally, 1956). Consequently, an unconformity is present here between the Hampshire (Catskill) Formation and the overlying Greenbrier Limestone.

North of this area, the Pocono Formation progressively thickens, reaching a maximum of 200 m (656 ft) in Monongalia County (the thickening is mostly in the lower part). The unit is predominantly conglomeratic sandstone containing interbedded sandy or calcareous shale, siltstone, rare limestone, and occasional coal streaks (Tucker County only). Coquinas of marine fossils, particularly brachiopods, are scarce in the sandstone beds. The upper contact with limestone of the Greenbrier Formation is sharp.

MACCRADY FORMATION

The Maccrady Formation is restricted to outcrops in the southeastern counties and to the subsurface in the south. Its maximum thickness in the State, 125 m (410 ft), is in Monroe County, but it thickens to the southeast into Virginia (where the type section is situated). The unit thins to the north and northwest and is absent north of Randolph County (fig. 7). On the whole, Maccrady thickness is quite variable, particularly in the subsurface, and indicates an upper erosion surface in those areas where it thins and pinches out (Youse, 1964; Flowers, 1956). The formation consists of red and purple arenaceous shale and siltstone and varying amounts of green and yellow shale, yellow limestone in the upper part, and calcareous sandstone. Minor anhydrite has been reported from these red beds in Wayne, McDowell, and Raleigh Counties.

The Maccrady Formation has received scant geologic attention. Plant fossils are rare, as are marine fossils in the limestone beds. Dennison and Wheeler (1975) considered most of the Maccrady north of Mercer and Monroe Counties to be of marine origin.

GREENBRIER GROUP

Southeastern West Virginia's Greenbrier Group is lithologically complex and very thick. It is dominated by limestone; interbedded shales provide a basis for subdivision. Marine fossils are abundant, and a few strata contain plant fossils. The lowest formation, the Hillsdale, is a cherty, argillaceous limestone which loses its shaly nature and thins to the north, pinching out in Pocahontas County. The overlying Denmar Formation consists of both cherty and oolitic limestone, becoming shaly near the top (Wells, 1950). This shale may be red, calcareous or sandy, and contains plant and marine fossils. The next higher Taggard Formation is distinguished by red and green occasionally sandy shale, interbedded with oolitic limestone. The formation never exceeds 15 m (49 ft) in thickness and is succeeded by the Pickaway Limestone, which has a diverse character —sandy and micritic in some parts and oolitic elsewhere, containing fossiliferous beds and an occasional red streak, and marked by stylolites and characteristic jointing. Like all Greenbrier subdivisions, the Pickaway thins to the north.

Above is the notably oolitic Union Limestone. It is very fossiliferous, and in the middle it is somewhat shaly (red). Both massive and lenticular beds have been reported. The clastic Greenville Shale may or may not be present on top of the Union; it is dark or black, calcareous, and lenticular. The highest

Greenbrier formation is the sandy and oolitic Alderson Limestone.

In Randolph County, the Greenbrier Group changes drastically; it thins to the north, the lower formations pinching out; simultaneously, the facies change. To the south the limestone generally includes more micrite and oolite, whereas the northern Greenbrier contains more clastic (though nonoolitic) limestone (Leonard, 1968).

North of central Randolph County, the Greenbrier has not been divided; hence, its rank is reduced to "Greenbrier Limestone." A threefold division is useful, however: (1) the basal Loyalhanna Member is a crossbedded arenaceous limestone or calcareous sandstone, (2) the middle red and green shale and siltstone, tentatively equated with the Taggard and Pickaway Formations of the south (Leonard, 1968), intertongue with basal Mauch Chunk red beds in Pennsylvania, and (3) the upper, abundantly fossiliferous limestone correlates with the Greenbrier Member of the Mauch Chunk Formation in Pennsylvania. Lithologic correlation with the southern Union and Alderson Formations is questionable.

The basal member in the north-central West Virginia subsurface is a sandy limestone or a calcareous sandstone, typically less than 12 m (39 ft) thick; it has been dolomitized throughout most of this region (Martens and Hoskins, 1948). To the southwest, the basal member is generally oolitic. Oolite distribution was determined by topographic features on the pre-Greenbrier erosional surface (Youse, 1964). Anhydrite traces are commonly found in the lowermost Greenbrier of the southwestern counties.

The Greenbrier Group (Formation) extends across the State, except for small areas along the Ohio River and in most of the eastern panhandle. In northern West Virginia, its thickness ranges from 15 to 30 m (49 to 98 ft), and in the west, from 15 to 45 m (49 to 148 ft); it thickens systematically to a maximum in Mercer County, 550 m (1,804 ft). The upper contact is everywhere gradational with the Mauch Chunk Group in outcrop, there being red shale in the upper part of the Greenbrier Limestone and marine limestone in the lowest Mauch Chunk shale.

MAUCH CHUNK GROUP

Like other major Mississippian stratigraphic units, the Mauch Chunk Group (of prevailing red and variegated shale) has different characteristics in different geographical areas. In the southern basin it is a thicker, more variable group divisible into several formations; in the north and northwest across the hinge line, it is thinner and more uniform (fig. 7).

In Mercer, Monroe, and Summers Counties, the Mauch Chunk Group is almost 1,000 m (3,280 ft) thick, and four formations are recognized. These units are traced as far north as Randolph County, although the total thickness is halved. The lowest third of the oldest (Bluefield) formation is gradational with the underlying Greenbrier, containing interbedded gray and green marine shale and limestone and minor amounts of terrestrial shale and sandstone. An important member, relatively thin but areally extensive, is the Reynolds Limestone. The upper part of the Bluefield contains terrestrial shale and sandstone, mostly red, and some coal and marine and freshwater limestone.

The overlying Hinton Formation is composed of interbedded red, arenaceous, partly calcareous shale and siltstone; ferruginous and calcareous sandstone; many fossiliferous limestone beds; and coal and associated underclay. One significant member is the Avis Limestone, which, like the Reynolds, resembles the Greenbrier in lithology and faunal assemblage. The overlying coarse-grained, pebbly, crossbedded Princeton Sandstone reportedly contains shale and plant fossils. The thickness of this littoral deposit, 6 to 24 m (20 to 79 ft), varies erratically across the southern outcrops.

The youngest formation, the Bluestone (named for the river in Mercer County), is similar to the lowest two Mauch Chunk formations, consisting of red and green calcareous shale and siltstone, variegated sandstone, shaly and lenticular limestone, and coal and underclay. Like the Bluefield and Hinton, the Bluestone yields both plant and marine fossils and represents coastal-plain sedimentation.

North of central Randolph County, undifferentiated red and green shale interbedded with green flaggy sandstone is termed the Mauch Chunk Formation. Thin marine limestone is present near the base. Coal in the northern counties is absent, even though the formation is largely of continental origin. Only sparse plant fossils have been noted. A local conglomerate in Tucker County has been labeled the Princeton Member.

In West Virginia's subsurface, the Mauch Chunk Formation thins westward from 90 m (295 ft) in the central part of the State to nothing in Ritchie and Wood Counties. Overall, such drastic thinning is due to (1) the erosional unconformity at the top of the Mississippian System and (2) the increased distance from the southeastern source of Mississippian clastic materials (Dennison and Wheeler, 1975).

BIOSTRATIGRAPHY AND PALEONTOLOGY

Very little study has been made of Mississippian biostratigraphy (fig. 1) and paleontology in the State since 1950. Most recent papers merely restate age relationships published in older reports.

INVERTEBRATE

On the basis of marine invertebrates, Dally (1956) concluded that the Pocono Formation of the south ranges from the lower Kinderhookian Series through upper Osagean. Simultaneously, the last Devonian Hampshire (Catskill) red beds were being deposited to the north. The marine invertebrate fauna to the north is late Osagean through Meramecian (Dally, 1956), noticeably younger than the southern Pocono fauna.

The Maccrady Formation has traditionally been considered late Osagean to early Meramecian, but Dally (1956) thought the entire Maccrady to be early Meramecian.

Preliminary conodont biostratigraphy (Chaplin, 1971) shows that the Hillsdale Limestone, lowest formation of the southern Greenbrier Group, correlates with the middle Meramecian of the type area. According to Wells (1950), the Hillsdale and Denmar Formations are middle and late Meramecian, respectively, whereas the Taggard Formation straddles the Meramecian-Chesterian boundary. The Pickaway and Union Limestones contain an early Chesterian fauna (Hickman, 1951). The Greenbrier Formation appears to be younger to the north, that is, entirely Chesterian. A late Chesterian pelecypod and endothyroid foraminiferal fauna was identified from the upper Greenbrier Limestone in Monongalia County (Wray, 1952). On the other hand, Uttley (1974) put the lower Loyalhanna Member of northern West Virginia and Pennsylvania in the Meramecian because of the contained conodont elements. He believed that the rest of the Greenbrier Limestone was Chesterian.

The Mauch Chunk, then, is middle to late Chesterian. Middle Chesterian conodonts were recovered from the Bluefield Formation by Rexroad and Clarke (1960). In southern West Virginia, Englund and others (1976) reported a (late?) Chesterian marine invertebrate fauna from a calcareous siltstone near the top of the Bluestone Formation; the overlying member of shale and siltstone (also of the Bluestone) intertongues with the Pennsylvanian Pottsville Group. In Mercer County, where the Mississippian-Pennsylvanian contact is gradational, the uppermost Mauch Chunk beds (perhaps 15 m, 49 ft) are of Pennsylvanian age.

VERTEBRATE

Carboniferous vertebrate biostratigraphy is an uncertain art at best, made difficult by scarce material, consisting principally of isolated chondrichthyan teeth and scales. Ample evidence exists that most Carboniferous chondrichthyans, particularly among the bradyodonts, had heterodont dentitions, but articulated dentitions with associations of tooth "species" are very rare.

Extensive early work, but no recent revision, has been done on the lower Carboniferous of the central United States (Newberry and Worthen, 1866; St. John and Worthen, 1875, 1883) and Europe (Davis, 1883; Woodward, 1889).

Early Carboniferous vertebrates from West Virginia are particularly scarce. The area's geologic setting is at the interface between the midcontinental seas and the fluviatile environment of the rising Appalachian mountains, as well as at the junction between the northeastern and southeastern United States Carboniferous coal basins.

At a time when the vertebrate record could provide vital evidence in the study of plate tectonics, it is embarrassing that we know nothing whatsoever about a region of undeformed sediments across the center of the possible dispersal route among European, North American, and Gondwanaland faunas.

The following discussion is based of necessity upon limited collections in the Carnegie Museum, Pittsburgh, Pa.

Marine.—The basal Mississippian Pocono Group and Maccrady Formation have yielded only occasional unidentified bone and scale fragments. However, the Greenbrier Group contains useful fossils. Two chondrichthyan teeth, a petalodont and an orodont, have been found in Benedict's Cave, Greenbrier County. Neither can be presently identified to genus. Isolated fish teeth and spines become rarer southward. The spine, *Physonemus falcatus* (St. John and Worthen, 1883), from about 27 m (90 ft) below the top of the Greenbrier in the Acme quarries at Alderson, and the tooth, *Poecilodus st. ludovicii* (St. John and Worthen, 1883), from the top of the Greenbrier at the Savannah Lane quarries, Lewisburg, are both named from the type St. Louis limestone. *Physonemus falcatus* is abundant in the upper Chesterian Bear limestone of Montana, and *Poecilodus* ranges into the Pennsylvanian (St. John and Worthen, 1883).

The Greenbrier at the Lake Lynn quarry, Fayette County, Pa., yields acanthodian and petalodontiform denticles and a variety of teeth. These are the elasmobranchs *Cladodus* sp. and *Hybocladodus* sp. (mid-Carboniferous), the bradyodonts *Venustodus argutus* (Chesterian), *V. leidyi* (also from the type St. Louis limestone), *V. variabilis* (also Burlington limestone of Iowa), *Psephodus crenulatus* (found in the Keokuk limestone), *P. Concolutus* (Burlington limestone), and *Helodus*-like anterior cochliodont teeth. The orodont *Desmiodus tumidus* is known from the Loyalhanna limestone (at Breakneck, Fayette County, Pa.) and the St. Louis limestone, and the acanthodian *Gyracanthus* is present in the Greenbrier of Uniontown, Pa., plus the rest of the world.

At present, we have little basis for faunal differentiation between Meramecian and Chesterian vertebrates, either in the upper Greenbrier or elsewhere. Possibly, if additional prospecting is carried out, the lower Greenbrier of southern West Virginia might yield a conspicuously different fauna.

Nonmarine.—The earliest nonmarine West Virginia Mississippian vertebrates are in the Bickett shale, Bluefield Formation, Mauch Chunk Group of Greer, Monongalia County. The anthracosaurian amphibian *Proterogyrinus scheelei* (Romer, 1970) (=*Mauchchunkia bassa,* Hotton, 1970; see Panchen, 1975) and the temnospondylous amphibian *Greererpeton burkemorani* (Romer, 1969) occur with the lungfish *Tranodis castrensis* (Thomson, 1965).

The fauna is similar to that of the British Upper Visean Oil Shale Group (Panchen, 1973, 1975); *Tranodis* also occurs in the type Chesterian. Bone fragments are not uncommon from the Bluefield Formation elsewhere in northern West Virginia. Fragmentary fish and amphibians have been found in the Hinton formation, Mauch Chunk Group (Romer, 1941; Panchen, 1967).

PALEOBOTANY

HISTORY OF STUDY

William B. Rogers was the first professional geologist to study the upper Paleozoic rocks of the area (1835–41). Although his classification was based solely on physical stratigraphy, tempered with economics (Rogers, 1884), he did mention several fossiliferous horizons. The first article on the area's fossil plants was published by two medical doctors (Hildreth and Morton, 1835) at about the same time as Rogers' first report (Gillespie and Latimer, 1961). In the early-to-middle 1850's, Lesquereux collected in the Ohio and Kanawha Valleys; he also studied and described Hildreth's and other collections (Lesquereux, 1858), which he later included in his several-volume summary (Lesquereux, 1880–84). This work also included the first attempt in North America to use plant fossils biostratigraphically. Fontaine and White (1880), in their volume on West Virginia and Pennsylvania Dunkard floras, suggested that Permian rocks might be present, thus initiating a controversy that still is not settled (Barlow, 1975).

Many of David White's pioneering studies (middle 1880's and later) were based on fieldwork in West Virginia. He (White, 1913, 1936) and Darrah (1934) suggested that at least part of the European and Appalachian upper Paleozoic geologic columns were roughly correlative in detail. Jongmans and others (1937, both papers), after collecting in West Virginia in the early 1930's, and Bertrand (1939), after collecting in Pennsylvania at about the same time, agreed with White. As the result of an extensive collecting trip in 1956, Bode (1958) concluded that the similarities between European and American floras were much greater than the differences.

Read and Mamay (1964) established a comprehensive zonation of North American Carboniferous and Permian floras, and Darrah (1969) reviewed the American literature and summarized his extensive personal observations. Remy and Remy (1977) reviewed the literature on North American late Paleozoic floras and compared the results with their version of the European late Paleozoic. The latest studies have been made in conjunction with the U.S. Geological Survey's Pennsylvanian System Stratotype program (Gillespie and Pfefferkorn, 1976, 1977; Pfefferkorn and Gillespie, 1977a, b, c). We have known for years that the great majority of genera and many species of Carboniferous and Permian plant compressions are common to Europe and North America. However, the lack of a readily available, comprehensive, up-to-date reference has resulted in misunderstandings and a lack of attention to floral characterization of chronostratigraphic divisions.

Also, the rarity of Appalachian upper Paleozoic marine horizons has led to correlation problems with the type Permian. Wagner's (1974) work in Spain on the upper Carboniferous indicates a marine invertebrate/plant compression/palynological West European-Russian correlation. It may be possible to extend the results to the American midcontinent using marine faunas, and then to the Appalachians using compression and palynological floras found in terrestrial sediments. This correlation should resolve whether the Autuniun is late Carboniferous or Permian (Havlena, 1975) and, therefore, whether Permian sediments exist in the Appalachians.

The Amerosinian Megaprovince's remarkable similarities probably begin with the Late Devonian *Archaeopteris* and *Rhacophyton* floras. These similarities continue through the late Paleozoic, culminating with the latest Dunkard floras—Late Pennsylvanian or Early Permian.

MISSISSIPPIAN FLORA

In West Virginia, the Early Mississippian or Pocono flora is characterized by *Lepidodendropsis* (Read, 1955). In basal units, *Adiantites* and *Rhodea* are the most commonly associated plants. *Adiantites* is replaced by *Triphyllopteris* in the upper Pocono. Plant fossils are scarce in the Maccrady and marine Greenbrier, although shaly lenses in the upper Greenbrier and Mauch Chunk (Upper Mississippian) usually contain *Fryopsis, Cardiopteridium*, fragmented stems, and megaspore clusters. The upper Mauch Chunk is characterized by a consistently occurring flora dominated by *Stigmaria stellata, Sphenopteris elegans*, and *Sphenophyllum tenerrimum*. This flora, also present in several other Eastern and Midwestern States, is characteristic of the Namurian A.

Thus, the major difference between the European lower and upper Carboniferous and the North American Mississippian and Pennsylvanian is the Namurian A, located at the base of the European upper Carboniferous and at the top of the North American Mississippian (White, 1936; Gillespie and Pfefferkorn, 1977).

PENNSYLVANIAN AND PERMIAN SYSTEMS

LITHOSTRATIGRAPHY

A general map (fig. 8), four cross sections, and two classifications with an incomplete plethora of stratigraphically arranged names, support this discussion of a thick diverse rock section. The cross sections (figs. 9, 11) show representative highly repetitious assemblages of strata typical of the Pennsylvanian and Permian. Selected coals (from a list of 117), a few limestones, argillaceous beds, and sandstones are included in the classifications (figs. 10, 12). Sandstones are found close above most coals, and, except for the Pocahontas-New River sandstone, each sandstone assumes the name of the underlying coal (unless an earlier name has preference, or a special depositional situation exists).

The area of Pennsylvanian-Permian strata is arbitrarily divided into the "older mining district" and the "younger mining district" (fig. 8). The older mining district conforms to an east-northeast-trending geologically older coal basin in southern West Virginia (which swings southwest to include strata in eastern Kentucky, western Virginia, central Tennessee, and northwestern Alabama). The younger mining district generally conforms to a north-northeast-trending geologically younger coal basin in northern West Virginia, western Maryland, southwestern Pennsylvania, eastern Ohio, and northeastern Kentucky (Arkle, 1974, p. 9).

On the east in the Allegheny Mountain Section (fig. 2), the Pottsville Group consists of much quartzose sandstone, some subgraywacke, argillaceous beds, and irregular thin coal beds; subdivision is difficult. As the unit thickens to the south-southeast, the quartzose sandstones are confined to upper beds or thin toward southeasternmost exposures; they disappear to the southwest in the State's central Upshur and Webster Counties. The westerly disappearance of the quartzose sandstones trends north in the subsurface into Pennsylvania. On exposures in southeastern West Virginia, Allegheny and Conemaugh strata thin perceptibly, change facies, and lose coals.

The Pottsville Group is composed of subgraywacke and argillaceous beds above an irregular Mississippian surface north of the 61-m (200-ft) isopach in the subsurface of Mason, Wood, and Pleasants Counties of north-central West Virginia (fig. 8). From here, the Pottsville section thickens rapidly to the south-southeast in southwestern West Virginia, and the Allegheny Formation loses identity below Conemaugh red beds. The lithologic characteristics of the subsurface section, based on limited data, are a thin replica of the thickening exposed section to the south.

OLDER MINING DISTRICT

Sediments from a southerly source were deposited in a rapidly but intermittently subsiding basin in southern West Virginia. Little paleogeographic change took place during Mississippian and early Pennsylvanian time. Source materials became coarser and more abundant, and the paleoclimate fostered extensive flora growth and plant-debris preservation in a chemically reducing environment during deposition.

The district includes the Pocahontas, New River, and Kanawha Formations and the Charleston Sandstone Group; these units have a maximum cumula-

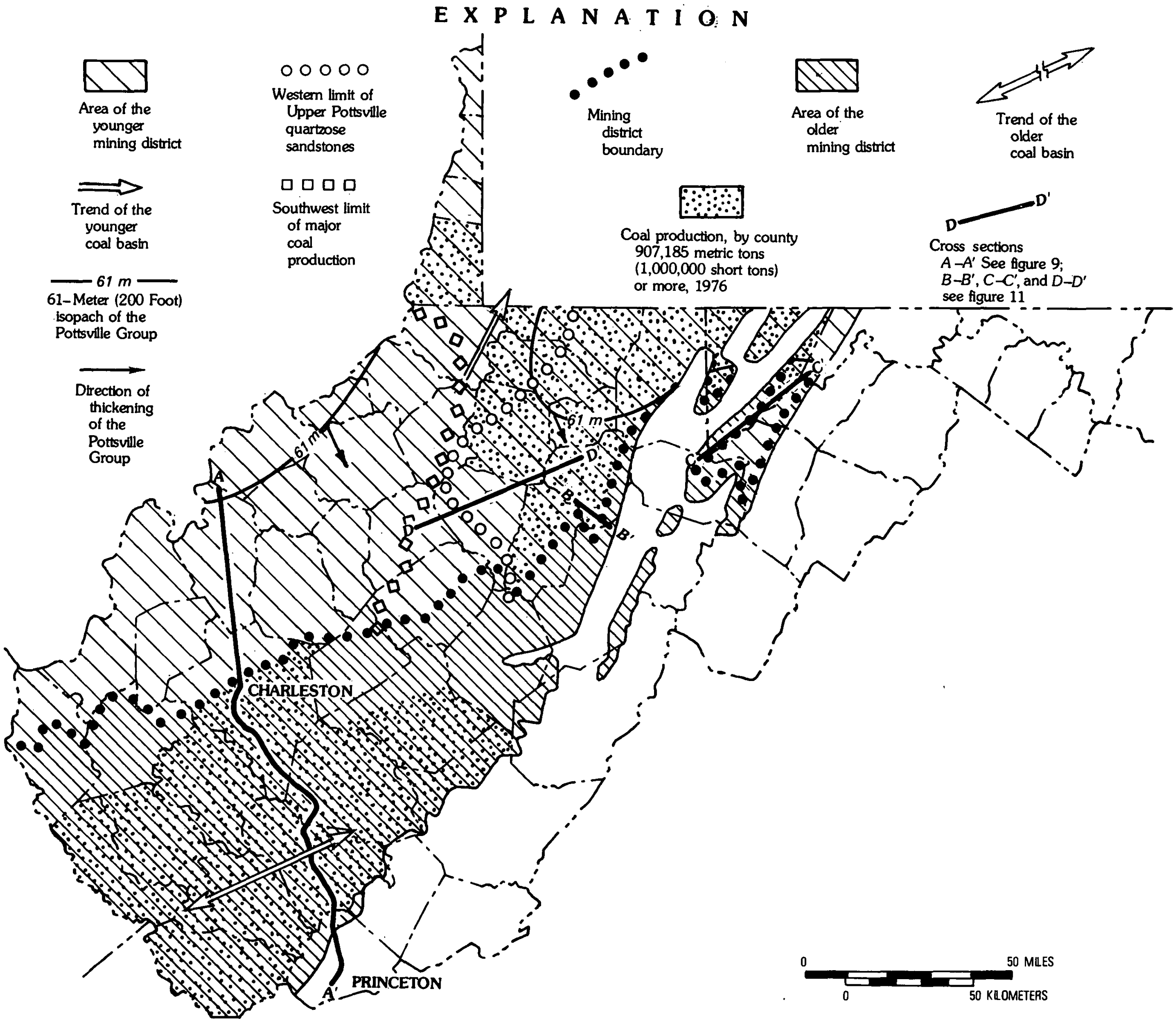

FIGURE 8.—Basin trends and coal-mining features of Pennsylvanian-Permian strata in West Virginia and Maryland.

tive thickness of about 1,326 m (4,350 ft). (The older term "Charleston Sandstone Group" (Campbell, 1901, p. 5) informally describes the lithostratigraphy without regard to time-rock relationships, which are currently being studied by the USGS in connection with the stratotype section project for the Ninth International Carboniferous Congress.) The younger mining district of northern and western West Virginia includes the Pottsville, Allegheny, Conemaugh, Monongahela, and Dunkard Groups; these units have a maximum cumulative thickness of about 914 m (3,000 ft) (fig. 1). Strata of the upper Pottsville, Allegheny, and possibly the lower Conemaugh to the north have a facies relationship with the essentially subgraywacke Charleston Sandstone Group sequence to the south.

The boundary between mining districts is the surface expression of an atypical north-northwest-thinning section of the older mining district, subjacent to the east-southeast-thinning of an atypical section of the younger mining district. In the north, the division is the base of the upper Pottsville quartzose sandstones; farther southwest, it is the Conemaugh red-beds base and the top of the Charleston Sandstone Group.

The Pottsville Group of the younger mining district was deposited on an irregular Mississippian surface and shows a fairly uniform (although variable) thickness north of the 61-m (200-ft) isopach line in northern West Virginia, in western Maryland, and throughout much of the northern remainder of the Appalachian coal field.

Younger strata of the Pocahontas and New River Formations were deposited on an irregular older Mississippian surface to the north-northwest (in the direction of thinning). In the subsurface, the New River quartzose sandstone facies was deposited on an irregular Lower Mississippian surface on the Burning Spring anticline of Pleasants, Wood, and Wirt Counties (Flowers, 1956, p. 15). A transition zone between Mississippian and Pennsylvanian time marks a continuous-deposition area on exposures in Mercer and Summers Counties and in the subsurface farther north in McDowell, Wyoming, and Raleigh Counties (Arkle and Latimer, 1961, p. 121; Englund and others, 1977, p. 38, 39).

The coal-bearing facies of the Pocahontas, New River, and Kanawha Formations and the Charleston Sandstone Group is exposed ever farther north-northwest on a broad north-northwest-dipping monocline in ascending the section. Major coals have formed in narrow linear patterns paralleling the east-northeast basinal trend. They are eroded on southeasternmost exposures where many coals are thickest. Coals of the New River Formation and Charleston Sandstone Group thin southeast of their maximum development and possibly disappear in that direction. All coals thin and disappear in ascending order, farther to the northwest.

The Kanawha and Charleston Sandstone section shows that a back-barrier delta environment during Pocahontas and New River time gave way to lower and upper delta-plain environments. Deposition of the Charleston Sandstone Group culminated with deposition of deltaic subgraywacke between the No. 6 Block coal and the base of the Conemaugh redbeds (figs. 9 and 10).

POCAHONTAS FORMATION

The Pocahontas Formation (fig. 10) includes strata from the top of the Mauch Chunk red beds and the base of the lowest Pennsylvanian sandstone to the top of the Flattop Mountain sandstones. A thickness of 216 m (710 ft) can be seen between Pocahontas, Va., and Great Flattop Mountain (at the common corner of McDowell and Mercer Counties, W. Va., and Tazewell County, Va.) (White,

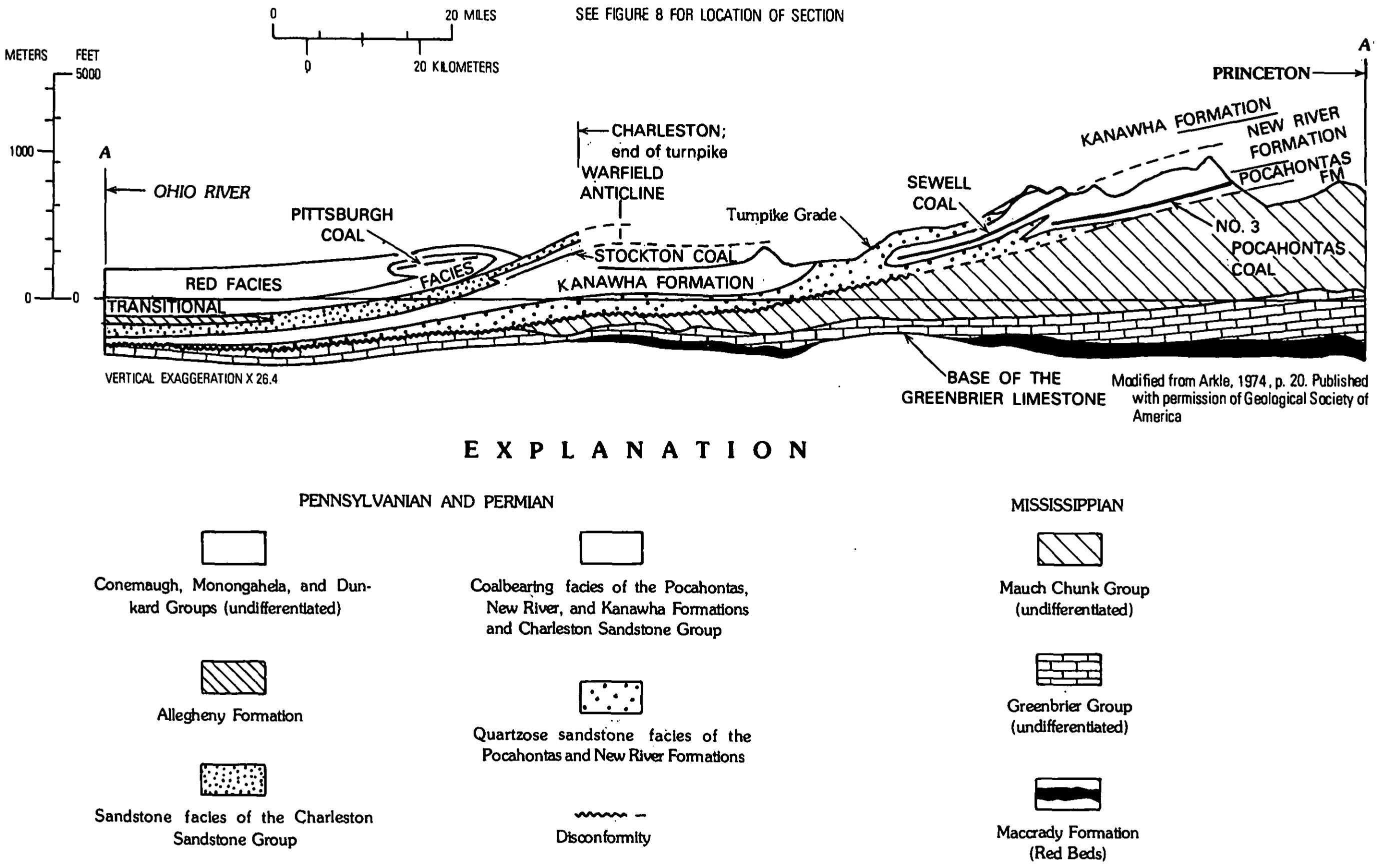

FIGURE 9.—Geologic cross section from the Ohio River to Princeton, W. Va.

Conemaugh Group	
Charleston Sandstone Group 107 m (350 ft maximum)	No. 6 Block coal Upper No. 5 Block coal (North Coalburg) Lower No. 5 Block coal (No. 5 Block) Homewood Sandstone Kanawha Black flint[1] Stockton coal
Kanawha Formation 640 m (2100 ft maximum)	Coalburg coal Winifrede coal Chilton "A" coal Winifrede limestone[1] Chilton coal Hernshaw coal Dingess coal Dingess limestone[1] Seth limestone[1] Cedar Grove coal Alma coal Campbells Creek limestone[1] Peerless coal Campbells Creek coal Powellton coal Stockton limestone[2] Unnamed shale[2] Eagle coal Eagle limestone[1] Lower War Eagle coal Gilbert shale[1] Gilbert coal Douglas coal Douglas sandstone Douglas shale[2]
New River Formation 0 to 314 m (1030 ft)	Nuttall sandstone Skelt shale[2] Hartridge shale[2] Sewell coal ("Pocahontas No. 12") Beckley coal ("Pocahontas No. 11") Quinnimont shale Fire Creek coal ("Pocahontas No. 10") Pocahontas No. 9 coal Pineville sandstone Pocahontas No. 8 coal
Pocahontas Formation 0 to 216 m (710 ft)	Flattop Mountain sandstone Pocahontas No. 6 coal Pocahontas No. 4 coal Unnamed shale[2] Pocahontas No. 3 coal North Fork shale[2] Squire Jim coal
MISSISSIPPIAN SYSTEM	

[1]Marine
[2]Fresh or brackish

FIGURE 10.—Pennsylvanian System selective classification—older mining district (southern West Virginia).

1908, p. 13). The formation thins rapidly to the north-northwest and disappears to the northeast in Greenbrier County, W. Va. (fig. 2).

The Pocahontas is composed of subgraywacke (repetitious, massive, slightly argillaceous, medium grained, and locally conglomeratic) and gray to medium-gray shale intercalated with thin impure underclay and coal. Thin sideritic nodules and lenses are present. Penecontemporaneous slumping and sedimentary features (such as crosslaminations) are common.

Thirteen coals have been named; the Squire Jim is the thickest of four basal coals. Successive coals are the Pocahontas Nos. 1 to 7; 3, 4, and 6 are commercially important. These coals are generally less than 1.8 m (6 ft) thick, although in one area, the Pocahontas No. 3 coal is 3.4–4.5 m (11–15 ft) thick.

Other Pocahontas coals are thinner and more irregular. Most have been surface mined, at least locally. The soft bright metallurgical coals, often multibedded, are low volatile (13.0± percent), low sulfur (0.5+ percent), and have high caloric value (15,000± Btu).

NEW RIVER FORMATION

The New River Formation (fig. 10) includes strata from the top of the Flattop Mountain subgraywacke to the top of the quartzose Nuttall sandstone. A thickness of 314 m (1,030 ft) can be seen along the New River Gorge of Fayette and Summers Counties and on exposures in southern West Virginia (Hennen, 1919, p. 294). In the subsurface to the north-northwest, the Pocahontas(?) and New River Formations are represented by only 106.7 m (350 ft) of quartzose sandstone, which thins rapidly where it is exposed to the northeast and which loses identity farther northwest in Tucker County (fig. 8 and 11, cross section *C–C*).

The formation is composed of subgraywacke (repetitious, massive, slightly argillaceous, medium grained, locally conglomeratic), quartzose sandstone, and gray to medium-gray shale, intercalated with thin impure underclay and coal. Siderite nodules and lenses are present. The 1:1 sandstone/shale ratio increases (in sandstone) perceptibly north-northwest. Medium-scale crosslaminations are common in quartzose sandstones, which are fewer and thinner south-southeast from the type locality.

Sixteen coals are named; successive coals in the basal strata are numbered Pocahontas Nos. 8 and 9 above the Pocahontas Formation, and miners designate the younger commercial Fire Creek, Beckley, and Sewell coals as Pocahontas Nos. 10, 11, and 12, respectively.

The coals' physical and chemical characteristics are similar to those of Pocahontas Formation coals, although they are gradationally higher in volatile matter. Commercial coals are generally <1.8 m (6 ft) thick, although the Fire Creek and Beckley coals are 2.7 m (9 ft) thick locally. Other thinner, less uniform coals have been mined, both underground (in the past) and surface (more recently and extensively). The coals are soft, bright, medium volatile (>18.0+ percent), and low sulfur (0.5+ percent), with 14,500+ Btu caloric values. Correlative coals are fewer and less uniform in the thinning section northeast of Fayette County, where they become high-volatile and low-sulfur metallurgical coals.

New River and Pocahontas smokeless coals were used in the past on ships because of high caloric values and freedom from spontaneous combustion. They were also used early (1863) for manufacturing weak coke in "beehive" ovens. To enhance coke strength, low-medium volatile coals have been blended for many years with more reactive, high-volatile coking coal in byproduct ovens.

KANAWHA FORMATION AND CHARLESTON SANDSTONE GROUP

The Kanawha Formation (fig. 10) includes strata from the top of the Nuttall quartzose sandstone to the base of the Stockton coal or, in its absence, the overlying Kanawha Black Flint. The Charleston Sandstone Group extends upward to the base of the Conemaugh Group red beds.

The Kanawha Formation, 305 m (1,000 ft) thick east of the city of Charleston, thickens to more than 640 m (2,100 ft) on southeastern exposures. The section and coals thin on exposures toward the northeast and lose identity in the subsurface (figs. 8 and 11, cross section *C–C′*).

The Charleston Sandstone Group is 107.7 m (350 ft) thick at Charleston, where basal subgraywacke changes to the coal-bearing facies (figs. 9 and 10) farther southeast. The unit is traceable to Kentucky and loses identity north-northeast in Lewis and Webster Counties (fig. 8).

The Kanawha Formation and Charleston Sandstone Group are complex stratigraphic units, composed of subgraywacke (repetitive, irregular, thin to massive beds, locally conglomeratic) and light to medium-gray shale/mudstone (1:1) intercalated with thin carbonate strata and 42 multibedded coal seams. Above the Winifrede coal, subgraywackes of fine to medium-grained sand in a sideritic/argillaceous-mineral matrix become medium-grained sand in an argillaceous-mineral matrix. The upper Kanawha and Charleston sections are principally subgraywacke, and the coals are thinner or absent as the section passes below drainage on the northwest and on exposures to the southeast in Wyoming and Mingo Counties. Three lacustrine-brackish and six marine limestones, also shale and impure sideritic concentrations, are present below the Winifrede coal. The only exception is the marine Kanawha Black Flint, shale, and siltstone above the Stockton coal. These units occur as thin beds, lenses, and concretionary bodies as much as 0.9 m (3 ft) thick. Underclays are thin or absent in Kanawha/Charleston strata.

Ascending the section, the lower group of 24 coals (to above the Cedar Grove) and the upper group of 18 coals (including the remainder of the Kanawha and Charleston coals) are physically transitional. The lower group is 364 m (1,195 ft) thick (maximum), and the upper group is 326 m (1,070 ft) thick (maximum).

Of the lower coal group, the 11 coals immediately above the Nuttall sandstone are generally minable only in the thickest section in Mingo, McDowell, and Wyoming Counties. Of these, the Douglas and Lower War Eagle are soft bright medium volatile (26.0+ percent) and low sulfur (0.6+ percent), attaining minable thicknesses of >0.6 m (2 ft). Locally, the sulfur content of the Gilbert and associated coals is >1.0 percent. The remaining 13 coals are bright gas-and-coking coals, high volatile (29.0–35.0 percent), sulfur <1.0 percent (but locally as much as 2.0 percent), and 14,500+ Btu. The more important are the Eagle (No. 1 Gas), Powellton, Campbell Creek (No. 2 Gas), Peerless, Alma, and Cedar Grove.

The upper group contains 18 coals. The Hernshaw and Chilton are physically transitional between the soft, bright, high-volatile gas coals (below) and the dull (splint) coal interbedded with thin beds of cannel and ordinary blocky-weathering bituminous coal (above). The transitional coals are chemically similar to those below and above, except that sulfur content is <1.0 to >3.0 percent.

The upper group's principal coals are the locally thick Winifrede, Coalburg, Stockton, and No. 5 Block, all characterized as high-volatile, low-sulfur coals, split into many benches by thin-to-thick shale, clay, and bone partings. These steam coals, 0.9–3.6 m (3–13 ft) thick, resist pulverization from transportation and handling and lose little fuel value in storage. They have been marketed as "Kanawha Splints." In manufacturing coke, the No. 5 Block coal is blended with low-volatile coals.

YOUNGER MINING DISTRICT

Sediments from a southerly source were deposited in a gently subsiding, north-northeast-trending basin in northern West Virginia and western Maryland during Pennsylvanian and Permian times (fig. 8). Lacustrine-swamp-deposit thickness and development suggest that repetitive-strata-assemblage axes (fig. 11), in ascending order, shifted east-southeast from the Dunkard basin axis after Allegheny time to the Allegheny Mountain section (fig. 4) during Conemaugh time. The axes then migrated west during the rest of the Paleozoic deposition. The late Dunkard deposition axis coincided again with the Dunkard basin axis at the end of late Paleozoic time.

Allegheny, Conemaugh, Monogahela, and Dunkard (Washington and Greene formations) strata thin from axes west-northwest into Ohio and east-southeast in northern West Virginia and Maryland. On southeast exposures, Allegheny coals thin and disappear in a facies of gray shale and fine- to medium-grained subgraywacke (figs. 8 and 11, cross section *B–B′*). To the southwest, lacustrine and marine limestone and coal of the Conemaugh and younger strata are transitional with red shale, red mudstone, and increasing percentages of subgraywacke. The transitional facies usually contains thin, areally limited coal, irregular lacustrine and marine limestone, and shale, intercalated with or associated with red shale, mudstone, and subgraywacke (figs. 8, 9, and 11, and cross section *A–A′* and *D–D′*). Subgraywackes coalesce locally in the transitional and red facies to form cliffs more than 30 m (100 ft) thick (Arkle, 1959, p. 122).

A back-barrier environment dominated regionally in Pottsville time, giving way to lower and upper delta-plain environments as late as early Conemaugh time. Although occasional lacustrine-marine and swamp incursions extended south-southwest, terrestrial sediments encroached inexorably north-northeast on a broad coastal plain, as can be seen in ascending the Conemaugh, Monongahela, and Dunkard section.

POTTSVILLE GROUP

Lesley (1876, p. 222, 224) used the name "Pottsville" for 18 m (59 ft) of white sandstone overlying probable Mauch Chunk Umbral red shale and underlying XIII, the Lower Coal Group (Allegheny Formation) in the Boyd's Hill well group near Pittsburgh (fig. 1). He (1876, p. 232) coined the term Pottsville from a town of the same name in the Southern Anthracite coal field of eastern Pennsylvania.

The Pottsville Group (fig. 12) extends from the irregular Mississippian surface to the Brookville coal and Mt. Savage clay directly overlying the Homewood Sandstone. The top of the quartzose Homewood sandstone is normally used as the top of the Pottsville Group in the area of limited exposures in West Virginia (fig. 8), because the Brookville coal and Mt. Savage clay are not identified in northern West Virginia.

Three coals—thin, irregular, and not useful stratigraphically—in the upper 61 m (200 ft) of the

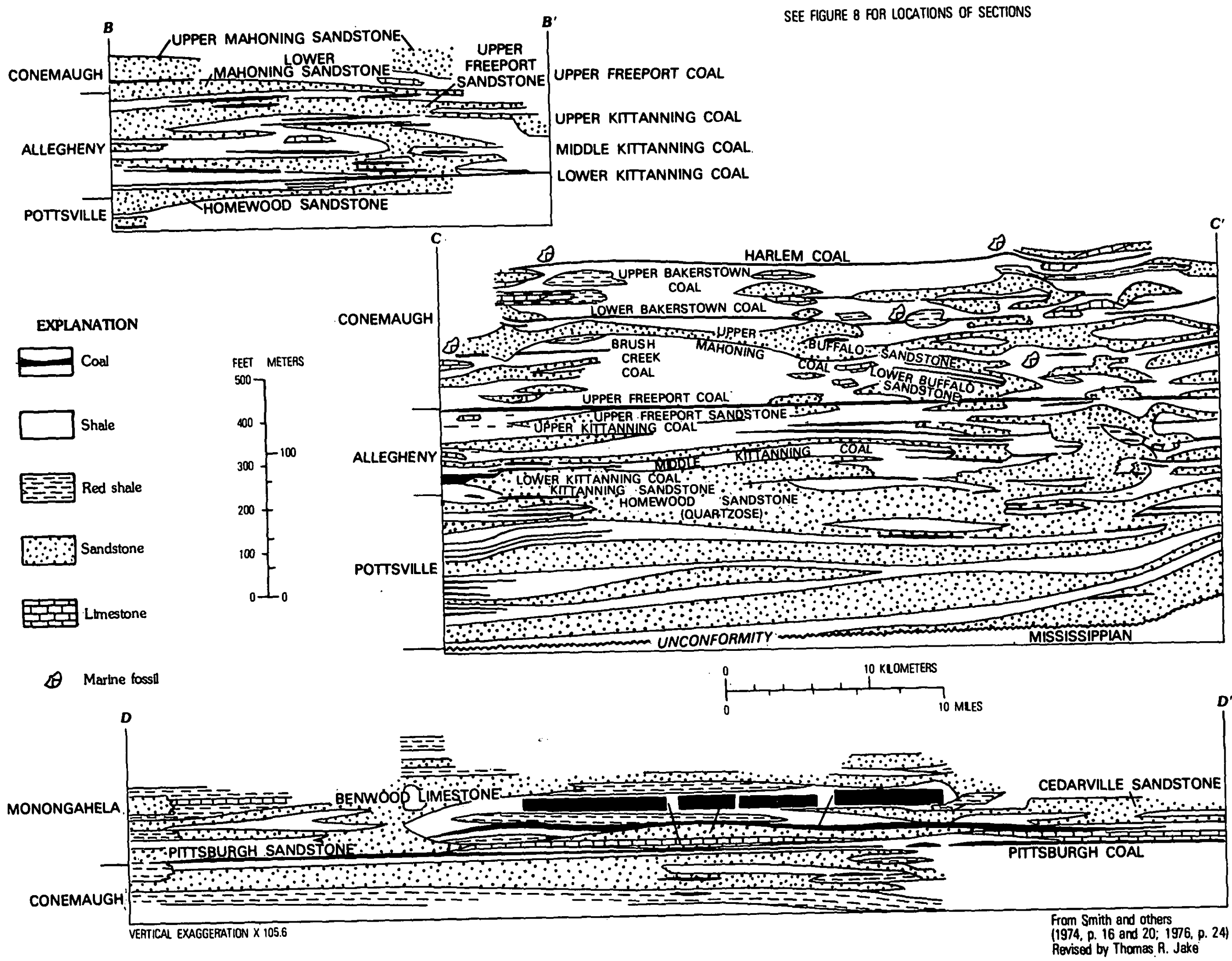

FIGURE 11.—Cross sections showing rock assemblages of the younger mining district.

northern West Virginia Pottsville are described in the southwestern Pennsylvania Pottsville (figs. 8 and 11, cross section *C–C'*).

ALLEGHENY FORMATION

H. D. Rogers (1840) described the Allegheny series in the Allegheny River valley above Pittsburgh, Pa. Stevens (1873, p. 15) redefined the Allegheny to include only those strata between the top of the Homewood sandstone and the base of the Mahoning sandstone (or the top of the Upper Freeport coal). Typical Allegheny strata are exposed above drainage in the Allegheny Mountain section of West Virginia and Maryland, along the Ohio River in Hancock County, on the northern end of the Burning Springs anticline of Pleasants and Wood counties, and on the Tug Fork River, just below Fort Gay, all in West Virginia. The formation is 46 m (125 ft) thick on southeastern exposures in Tucker County, W. Va., more than 61 m (200 ft) thick in Maryland, and about 76 m (250 ft) thick in Hancock County, W. Va.

The Allegheny Formation (fig. 12) is a complex sequence of lenticular, thin- to massive-bedded subgraywacke and light-gray to gray shale and mudstone, intercalated with irregularly thick, low-duty refractory underclay and coal (figs. 8 and 11, cross sections *B–B'* and *C–C'*). Thick deposits of Lower Kittanning and Clarion refractory clay have been mined extensively in Hancock County, W. Va. (two mines at present), and Allegany County, Md. Subgraywacke is locally quartzose in the Allegheny Mountain section of West Virginia and Maryland. Locally, thin lacustrine limestone underlies the Upper Kittanning and younger coal in Preston and Hancock Counties, W. Va., and in Maryland. In

END OF THE LATE PALEOZOIC	
Dunkard Group 335 m + (1100 ft)	Proctor sandstone Windy Gap limestone Nineveh coal Nineveh limestone Jollytown sandstone Jollytown coal Hundred sandstone Upper Washington limestone Lower Marietta sandstone Washington coal Waynesburg sandstone Cassville shale—Elm Grove limestone
Monongahela Group 70–122 m + (230–400 ft)	Waynesburg coal Gilboy sandstone Uniontown coal Benwood limestone Sewickley coal Redstone coal Redstone limestone Upper Pittsburgh sandstone Pittsburgh coal
Conemaugh Group 137–259 m (450–850 ft)	Lower Pittsburgh sandstone Elk Lick coal Ames limestone[1] Harlem coal Saltsburg sandstone Woods Run limestone[1] Bakerstown coal Pine Creek limestone[1] Buffalo sandstone Brush Creek limestone[1] Brush Creek coal Mahoning sandstone { Mahoning coal, Thornton fire clay } Uffington shale
Allegheny Formation 30–91 m (100–300 ft)	Upper Freeport coal Bolivar fire clay Upper Freeport sandstone Lower Freeport coal Upper Kittanning coal Washingtonville limestone[1] Middle Kittanning coal Hamden (Columbiana) limestone[1] Lower Kittanning coal Lower Kittanning clay Vanport (Ferriferous) limestone[1] Clarion fire clay
Pottsville Group 15(?)–61 m (50–200 ft)	Homewood sandstone Mercer coal Connoquenessing sandstone Sharon sandstone(?)
MISSISSIPPIAN SYSTEM	

[1]Marine

FIGURE 12.—Pennsylvanian and Permian Systems selective classification—younger mining district (northern West Virginia and Maryland).

lower Allegheny strata, a thin local marine zone in sandstone is exposed on the Burning Springs anticline, and three marine shale horizons are exposed on the Ohio River in Hancock County.

The Lower Kittanning and Upper Freeport coals are mined, both underground and surface (more extensively) in the Allegheny Mountain section. The mining section is often thick (>2.4 m, 8 ft). The coals are separated into benches by irregular, thin to thick partings. West of the Allegheny Mountain section, they are blocky weathering, bright, high volatile (>29.0 percent), high sulfur (>2.0 percent), and have caloric values of 14,000+ Btu. The coals change to medium volatile (20.0–29.0 percent) in Tucker County, W. Va., and become low volatile (<20.0 percent) locally on exposures in Maryland. Locally, the coals are low to medium sulfur (<1.5 percent).

CONEMAUGH GROUP

Platt (1875, p. 8) named the strata (fig. 12) between the Upper Freeport coal and the base of the Pittsburgh coal for the Conemaugh River, a Monongahela tributary. The group thickens from 137 m (450 ft) on the Ohio River to 250 m (850 ft) at the Maryland-West Virginia boundary in Tucker County, W. Va. It thins to 150 m (500 ft) in the Barbour-Randolph-Upshur County area, and apparently to 53 m (350 ft) on exposures in Clay, Kanawha, Lincoln, and Wayne Counties, all in West Virginia.

The Conemaugh Group is composed of red or light-gray to gray shale and mudstone, and thin- to massive-bedded fine- to medium-grained subgraywacke, intercalated with thin beds of marine and lacustrine limestone and thin irregular coals (Allegheny Mountain section excepted). The entire section is transitional, having principally red shale and mudstone; the percentage of subgraywackes perceptably increases to the southwest.

Widespread thin marine limestone and associated thicker shale were deposited during Brush Creek, Pine Creek, Woods Run, and Ames times in the lower part of the Conemaugh in western and northern West Virginia. No marine strata are evident on exposures in Braxton, Clay, Kanawha, or Lincoln Counties (fig. 2).

The Mahoning and Bakerstown coals, <1.8 m (6 ft) thick, have been underground mined. The Mahoning, Brush Creek, Bakerstown, Harlem, Elk Lick, Little Clarksburg, and Little Pittsburgh coals have been surface mined. Conemaugh coals are blocky weathering, bright and dull banded, high volatile (>35.0 percent), high sulfur (>2.0 percent), and have caloric values of 14,000+ Btu. Volatility decreases to 15.0 percent in the Allegheny Mountain section, where the coals are low to medium sulfur. The Bakerstown coal has <1.0 percent sulfur on the Potomac River in Tucker and Grant Counties.

MONONGAHELA GROUP

This group best shows the lateral transition from terrestrial red beds to lacustrine swamp deposits because of its geographic distribution and the uniformity and thickness of its limestone and coal (figs. 8 and 11, cross section *D–D′*).

H. D. Rogers (1840, p. 150) named the strata for the Monongahela River where they cropped out near Pittsburgh, Pa. Stevenson (1873, p. 15) redefined the group to include those strata between the base of Pittsburgh coal and Waynesburg sandstone (fig. 12). Fontaine and White (1880, p. 105–120), describing fossils with Permian affinities in the Cassville shale below the Waynesburg sandstone, placed the Pennsylvanian-Permian boundary atop the Waynesburg coal.

The group is 76 m (250 ft) thick on the Ohio River, 122 m (400 ft) thick on the Monongahela River, and 107 m (350 ft) thick at one locality in the Allegheny Mountain section of Maryland.

The section is composed of gray shale and mudstone, thin- to massive-bedded subgraywacke, lacustrine limestone, and coal. Gray shale and mudstone are transitional with red shale and mudstone, and subgraywacke increases perceptibly as limestone and coal disappear to the southwest (figs. 8 and 11, cross section *D–D′*). The Redstone, Benwood, and Waynesburg thin-bedded lacustrine limestone and associated thin mudstone are thick carbonate accumulations. The Pittsburgh, Redstone, Sewickley, and Waynesburg coals are widespread in the northern part of the Dunkard basin.

The Pittsburgh coal, accounting for about 24 percent of the State's annual production, is thick and uniform in the Dunkard basin. Only basal beds of the Monongahela Group as high as the Sewickley coal are locally present in upland areas of the Allegheny Mountain section synclines. The mining of a large area of thick Pittsburgh coal in Allegany County, Md., accounted for the early peak (1907) in that State's coal production. The mining section is 1.5 m (5 ft) thick on the Ohio River, 2.7 m (9 ft) thick on the Monongahela River, and 3.6+ m (12 ft) thick in the Allegheny Mountain section.

Monongahela Group coals are blocky weathering, bright and dull banded. The Pittsburgh and Redstone are high volatile and high sulfur (>2.0 percent) and have caloric values of 14,000± Btu. The Redstone is minable only in Barbour, Lewis, and Upshur Counties, in a small area north of Morgantown, and in Mason County. In the Allegheny Mountain section, and in areas contiguous with the section, both coals are locally 1.5 percent sulfur and of metallurgical grade (fig. 3).

The Sewickley coal is similar to the older Pittsburgh and Redstone but generally has a higher sulfur content (>3.0 percent). The three coals notably lack the thick partings prevalent in the Allegheny and upper Kanawha coals. Pittsburgh and Sewickley volatility decreases to 20.0± percent in the Allegheny Mountain section. The thick Waynesburg coal is broken into 0.6–0.9 m (2–3 ft) benches by thin to thick partings. It tends toward high ash (>8.0 percent) and high sulfur (>2.0 percent) content. It is thickest on the Monongahela River, where it is surface mined, and locally in West Virginia's northern panhandle on the Ohio River.

DUNKARD GROUP

The Dunkard Group was described on Dunkard Creek, a Monongahela River tributary in southwestern Pennsylvania (White, 1891, p. 22). It extends from the top of the Waynesburg coal (fig. 12) to above the Windy Gap coal and limestone (which are the youngest swamp lacustrine deposits of the late Paleozoic). The Dunkard Group is more than 335 m (1,100 ft) thick along the Dunkard basin axis in Pennsylvania's southwestern corner and contiguous areas of West Virginia. In recent years, some have placed the base of the Permian at the Washington coal, 30–46 m (100–150 ft) above the Dunkard base. Sedimentation from at least early Conemaugh time continued without interruption to the end of Dunkard deposition.

The Dunkard section, rarely divisible into Washington and Greene Formations in West Virginia, is composed principally of red shale, mudstone, and thin- to massive-bedded graywacke. The Waynesburg "A" (between the Waynesburg sandstone and Washington coal) and Washington coals are high volatile, high ash, and high sulfur. They are associated with gray shale, mudstone, and lacustrine limestone in the basal 30.5–43.7 m (100–150 ft) of the Dunkard Group. They are usually present in northern West Virginia, but are thickest along the Ohio River in one or more benches 0.6–0.9 m (2–3 ft) thick, separated by variable partings. Thin lacustrine limestone, thin coal (<0.3 m or 1 ft), and associated gray beds extend above to the Nineveh limestone only in northern West Virginia. Beginning with the Nineveh, the high Greene limestone and associated coal streaks are exposed in the hilltops along the Ohio River, between the area of greatest thickness in Pennsylvania and Jackson County, W. Va.

BIOSTRATIGRAPHY AND PALEONTOLOGY

INVERTEBRATE

Marine invertebrate faunas in West Virginia's Pennsylvanian rocks are uncommon and, when present, are often composed of long-ranging taxa inappropriate for biostratigraphic work. In addition, the bulk of published papers on the State's Pennsylvanian paleontology is still exploratory and largely taxonomic; detailed biostratigraphy is not available.

The geologically younger mining district in northern and western West Virginia consists of largely Middle and Upper Pennsylvanian rocks similar to those of surrounding States (figs. 2 and 8). It has attracted most researchers because it contains several regional marine intervals and coal of great economic and stratigraphic value. By contrast, the geologically older mining district to the south contains a Lower and Middle Pennsylvanian stratigraphic section dissimilar to that of the north and is complex lithologically. Although the need is greater in the older district, very few researchers have studied faunal elements there.

Older mining district.—The North Fork shale of the Pocahontas Formation contains a local brackish-marine fauna (fig. 10) that has been little studied, and only long-ranging nondiagnostic taxa have been found (Hennen and Gawthrop, 1915). Local brackish-water fossils from the Pocahontas No. 6 coal roof shale (Price, 1916) complete the limited suite of invertebrate fossils from localities in the Pocahontas Formation.

The New River Formation includes local brackish-water faunas in the roof shales of the Sewell and Sewell "B" coals. Durden (1969) placed the Quinnimont shale in the Namurian C (lower Morrowan) on the basis of blattoid insect wings.

The Kanawha Formation contains several marine horizons that have locally abundant, well-preserved faunas. As is true of the lower formations, few studies of Kanawha faunas exist, and most are necessarily preliminary. Lower marine units—Gilbert shale, Eagle limestone, Campbell Creek limestone and Seth limestone—have had almost no attention (Price, 1915, 1916). Cephalopods and crinoids (Furnish and Knapp, 1966; Strimple and Knapp, 1966) place the Dingess and Winifrede limestones in the upper Morrowan (Westphalian B) *Gastrioceras* (cephalopod) zone and the *Stereobrachicrinus* (crinoid) zone. Moore and others (1944) assigned the Winifrede limestone to the lower Atokan *Mesolobus striatus* (brachiopod) zone. Merrill (1973) concluded that the Kanawha Black Flint belonged in the basal Desmoinesian *Cavusgnathus* biofacies of the *Neognathodus* n. sp. B (conondont) zone (upper Westphalian B).

Younger mining district.—Few biostratigraphically useful Pottsville rocks are found in the younger mining district. Durden (1969) studied blattoid wings in shales of the Connoquenessing sandstone, dating them as lower Westphalian B (Morrowan). Brackish-water faunas, found in several places in Pottsville rocks in the Georges Creek-Potomac basin (western Maryland and adjacent West Virginia), have not been studied.

Allegheny rocks in the younger mining district lack continuous marine marker horizons. The Vanport and Hamden limestones are reported locally in northern West Virginia but not in Maryland. Both are considered middle Desmoinesian in surrounding States, on the basis of diagnostic fossils—cephalopods (*Wellerites* zone—Unkelsbay, 1954), fusulinids (*Fusulina* zone—Smyth, 1974), and conodonts (*Neognathodus roundyi* zone—Lane and others, 1971). Insect faunas from the Georges Creek-Potomac basin (Durden, 1969) show the Parker coal (Lower Freeport) to be lower Westphalian D.

Lower Conemaugh rocks contain several important marine zones. The Brush Creek and Ames limestones are useful marker horizons, and the Pine Creek and Woods Run limestones are locally present. They have not been studied in West Virginia, but surrounding States yield excellent faunas. The Brush Creek limestone is basal Missourian, evidenced by cephalopods (*Eothalassoceras* zone—Unklesbay, 1954), fusulinids (*Triticites irregularis* subzone—Smyth, 1974), and conodonts (*Spathognathodus cancellosus/S. elegantulus* zone—Lane and others, 1971). The Woods Run limestone is middle Missourian, evidenced by fusulinid (*Triticites irregularis* subzone—Smyth, 1974) and conodont (*Spathognathodus excelsus/S. gracilus* zone—Lane and others, 1971) data. The Ames limestone is lowermost Virgilian, from its fusulinid (*Triticites cullomanensis* subzone—Wilde, 1975) and conodont (*Spathognathodus elegantulus/S. elongatus* zone—Lane and others, 1971) fossils. Blattoids (Durden, 1969) reinforce this interpretation, together with Stephanian A faunas from the Mason coal (below the Brush Creek coal) and Bakerstown coal, and Stephanian C insects from the freshwater Duquesne limestone (between the Ames limestone and Elk Lick coal).

Neither upper Conemaugh, Monongahela, nor Dunkard beds contain marine fossils. This has created ambiguity in Permo-Carboniferous boundary placement. Correlation attempts have been made using nonmarine invertebrates. Eager (1972) studied upper Monongahela Group freshwater bivalves and concluded that they were more allied to Rotliegendes Permian faunas than to the European upper Carboniferous. Durden (1975) and Tasch (1975) contributed findings on Dunkard blattoids and estheriids, respectively, both concluding that the faunas are distinctively Permian. Indeed, upper Dunkard insects are correlative with the Leonardian of Texas and New Mexico.

VERTEBRATE

Nonmarine Pennsylvanian vertebrates. — West Virginia's Pennsylvanian vertebrates are rare and little studied. The younger mining district vertebrate record has been explored to a limited extent (Lund, 1975, 1976; Olson, 1975), but the older mining district is paleontological terra incognita.

The earliest known Pennsylvanian vertebrates from West Virginia occur near Ansted (southeast of Charleston), at about the level of the Lower Douglas coal (basal Kanawha Formation, Pottsville Group, fig. 10). This is the only known vertebrate horizon from the southeastern coal basin. Investigators to date have uncovered xenacanth shark teeth (*Xenacanthus* sp. cf. *X. triodus*) and *Helodus simplex* spines and a dental battery (Bradyodonti: Helodontiformes) among the chondrichthyans, and *Megalichthyes* scales (Rhipidistia) and a trissolepid near *Sphaerolepis* among the bony fishes.

The *Helodus* material is the first associated dentition of this species from the Western Hemisphere. It was originally reported from Britain's Knowles Ironstone (Moy-Thomas, 1936). Isolated teeth have been reported through the Dunkard in freshwater deposits (Lund, 1975) but are hard to distinguish from the helodontiform anterior teeth of various cochliodonts (Lund, 1976).

The sphaerolepid is a morphological predecessor of fish from the Virgilian Birmingham shale of Pittsburgh (Lund, 1975). These forms are related to but are distinct from *Sphaerolepis*, from the Upper Pennsylvanian of Kounova, Bohemia, Czechoslovakia (Gardiner, 1967).

The Kounova and Pittsburgh specimens have cycloidal scales that have very fine enameloid pectinations and points, whereas the headless Ansted specimen has the distinctive scales only on the lower flank. Nonmarine vertebrate faunas from northern West Virginia, southwestern Pennsylvania, and eastern Ohio are relatively well known and indicate a Virgilian age for rocks from the Conemaugh Group above the Mason shale to the lower half of the Monongahela Group (Lund, 1975), correlating with European Stephanian faunas.

Marine Pennsylvanian vertebrates.—The limited lower and middle Conemaugh marine fauna contains very few identifiable vertebrates. Identifiable remains from the Ames limestone (fig. 12) include acanthodians: *Cladodus* sp. (Chondrichythyes: Elasmobranchii); *Petalodus ohioensis; Janassa striglina, "Peltodus" transversus, Peripristis semicircularis* (Bradyodonti:Petalodontiformes); the orodont *Chomatodus* sp.; the cochliodont *Deltodus angularis;* and *Physonemus* cf. *P. ancinaciformes* (incertae sedis). Vaughn (1967) described a vertebrate (in certae classis) found in the Ames limestone as well.

The few useful teeth and spines (Romer, 1952; Baird, 1957) roughly indicate a Late Pennsylvanian age, which, surprisingly, agrees with the age of the nonmarine vertebrates. A faunal continuity with the lower Permian is indicated.

Nonmarine Permian vertebrates.—The Benwood limestone (fig. 12) seems to herald a marked, though primarily evolutionary change in the vertebrate fauna. The larger fossil vertebrates from the top of the Benwood limestone through the uppermost Greene Formation beds correspond in detail to Autuniun European faunas as well as to those from the western United States Wolfcamp. The uppermost Greene Formation has possible Leonardian faunal affinities (Lund, 1976; Olson, 1975).

The vertebrates show evolutionary continuity from the Conemaugh through the Dunkard, changing with depositional environment changes as the Pennsylvanian epicontinental sea retreated. There are no faunal discontinuities. The vertebrate record indicates a Wolfcampian age for the Uniontown, Waynesburg, Washington, and Greene formations, and a possible Leonardian age for beds roughly about the Nineveh limestone and above. The Virgilian-Wolfcampian boundary has been classically accepted as the end of the Pennsylvanian (see Introduction and Dunkard Group discussion).

PALEOBOTANY

In West Virginia, the lithostratigraphically prescribed Mississippian/Pennsylvanian boundary is the base of the Bluestone Formation Upper Member, which intertongues with the basal unit of the overlying Pocahontas Formation. The Namurian A flora disappears, and the zone of *Neuropteris pocahontas* begins in the Upper Member. Consequently, the lowermost plant biostratigraphic zone in the Pennsylvanian is defined by *N. pocahontas,* a close relative of *N. schlehani,* the characteristic plant in the lowermost upper Carboniferous of Europe. Some taxonomists believe that these plants may be varieties of the same species (Williams, 1937; Bode, 1958).

Many plant biostratigraphic zones, based on first occurrences and concurrent ranges, are now being established for the remaining upper Paleozoic sediments. They do not coincide exactly with established lithostratigraphic boundaries. More than 200 floras have been collected in West Virginia during the last four field seasons by the U.S. Geological Survey's Pennsylvanian Stratotype Study. These, along with past collections and illustrated reports, indicate that the upper Paleozoic rock sequence in West Virginia is correlative with similarly aged rocks across the United States, and with established Namurian, Westphalian, Stephanian, and Autuniun sequences.

Neuropteris pocahontas generally characterizes basal Pocahontas Formation units. *Lyginopteris* (ranges of *L. stangeri, L. hoeninghausi,* and others, are not firmly established) begins just below the Pocahontas No. 1 coal. *Mariopteris eremopteroides* appears just above the Pocahontas No. 2 coal. *Sphenopteris, Calamites, Alethopteris, Lepidodendron, Sphenophyllum,* and *Asterophyllites* species form other zones in the Pocahontas, although ranges are not completely known. *Neuropteris smithsii,* a large-pinnuled *N. pocahontas* variant, and *Mariopteris pottsvillea, M. eremopteroides* variant, appear near the Pocahontas No. 7 coal.

Important New River Formation additions are *Alethopteris decurrens* near the Beckley coal and *Sphenophyllum cuneifolium, Neuropteris heterophylla, N. obliqua,* and *Asterophyllites equisetiformis* slightly above the Sewell coal. *N. pocahontas* and *N. smithsii* disappear near the Sewell B coal.

The Kanawha Formation base is marked by the appearance of *Neuropteris gigantea* and the end of the lyginopterids and *Alethopteris decurrens.* Other important Kanawha plants are *Alethopteris lonchitica, Annularia radiata, Sphenophyllum majus, S. cuneifolium,* and *S. emarginatum. Neuropteris scheuchzeri* and *N. ovata* appear near the top.

In the lower Allegheny Group (fig. 12), several species disappear: *Alethopteris lonchitica, Neuropteris obliqua, N. heterophylla, N. gigantea, N. rarinervis, Linopteris* spp., *Sphenophyllum cuneifolium,* and *S. majus. S. oblongifolium* appears, pecopterids become more numerous, and *Asolanus camptotaenia* becomes common. The Charleston Group flora is similar. Allegheny floras continue through the Conemaugh Group with more *Sphenophyllum oblongifolium* and increased pecopterid species.

Near the base of the Monongahela Group, the following join with *Neuropteris ovata* and *N. scheuchzeri* as major species: *Alethopteris zeilleri, Danaeides emersonii, Lescuropteris moorei, Nemejeopteris feminaeformis, Pecopteris unita, P. arborescens, Sphenophyllum longifolium, Callipteridium pteridum,* and *C. gigas.* All continue well into the Dunkard Group. Some occur only rarely.

At about the upper Washington limestone horizon, undoubted *Callipteris conferta* is found (Gillespie and others, 1975). Fontaine and White (1880) listed this species from the Washington coal roof shales in Monongalia County, and Darrah (1975) concurred. Bode (1958) believed it to be a different species, probably *C. lyratifolia.* Others, such as *Plagiozamites* cf. *P. planchardi, Walchia,* and *Taeniopteris* sp., have been reported from the upper Conemaugh through the Dunkard (Darrah, 1975), but they are facies-dependent and exceedingly rare.

When these data are compared with those of the European section, several important correlations can be made: (1) the Namurian A is well defined by *Stigmaria stellata, Sphenopteris elegans,* and *Sphenophyllum tenerrimum,* (2) the Westphalian B base is marked by disappearance of the lyginopterids, (3) the Westphalian C is marked by abundance of neuropterids and *Alethopteris lonchitica,* (4) the Westphalian D is marked by the first appearance of *Neuropteris ovata,* and (5) the Stephanian is marked by the beginning of *Sphenophyllum oblongifolium, Alethopteris zeilleri, Nemejeopteris feminaeformis,* and *Callipteridium gigas.* The Autuniun begins with the first occurrence of *Callipteris conferta.*

Several of the historically used biostratigraphic boundaries of Europe can be recognized generally in West Virginia and across North America. The many first-occurrence and concurrent biostratigraphic zones being established in West Virginia will greatly refine the present knowledge for this continent.

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The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—Ohio

By HORACE R. COLLINS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1110-E

Prepared in cooperation with the Ohio Department of Natural Resources, Division of Geological Survey

Historical review and summary of areal, stratigraphic, structural, and economic geology of Mississippian and Pennsylvanian and Lower Permian rocks in Ohio

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CONTENTS

ILLUSTRATIONS

TABLES

THE MISSISSIPPIAN AND PENNSYLANIAN (CARBONIFEROUS) SYSTEMS IN THE UNITED STATES—OHIO

By HORACE R. COLLINS [1]

ABSTRACT

Carboniferous rocks in Ohio are present at the surface over most of the eastern half of the State and have been intensively studied for more than 150 years. All Ohio's coal and sandstone and most of its clay and shale resources are derived from units of this age. Much of the work on the Ohio Carboniferous is oriented toward the economic possibilities of these rocks. The stratigraphic classification of the Pennsylvanian (upper Carboniferous) was established originally to emphasize the economic importance of the subdivisions.

The Mississippian (lower Carboniferous) is predominantly clastic deposits; the Pennsylvanian is a complex repetitive sequence of sandstone, mudstone, shale, limestone, coal, and clay. The contact between the Mississippian and Pennsylvanian is everywhere marked by a major disconformity.

Biostratigraphically, the marine carbonate units of both the Mississippian and the Pennsylvanian have been zoned and correlated with the U.S. midcontinent region on the basis of invertebrate microfossils; Pennsylvanian rocks also have been zoned and correlated with the northern Appalachian region on the basis of plant macrofossils. Invertebrate macrofossils are important in both regional correlation and age assignment.

The Carboniferous of Ohio is not structurally complex, although important exceptions are found in the southeastern part of the State. The contacts with both the underlying Devonian and the overlying Permian Systems are gradual and are not marked by recognizable disconformities. The break between Permian- and Pennsylvanian-age rocks, however, is a controversial matter and is made on the basis of paleontology and not lithology.

INTRODUCTION

To most present-day workers, the Carboniferous of Ohio normally includes only the Mississippian and Pennsylvanian Systems; however, most authors of the middle and late 1800's included rocks now classified as Permian (or Permian-Pennsylvanian transition) in the Carboniferous. Prosser (1905, p. 2) assigned the Upper Barren Coal-measures to the Dunkard Formation and placed the formation in the Permian (?) System; he did not, however, include the Permian in the Carboniferous. The general classification of Devonian, Carboniferous, and Permian in Ohio has changed little since Prosser's 1905 revision. A significant name change, however, was made in the early 1900's when most American geologists generally accepted the terms Mississippian and Pennsylvanian for the now little-used Carboniferous. A brief discussion of the Permian age question and of the rocks traditionally assigned to this system will be given later. In following the usual practice of Ohio geologists and the current practice of the U.S. Geological Survey, I did not include Permian rocks in the Carboniferous System.

Outcrops of Carboniferous-age rocks in Ohio are confined approximately to the eastern half of the State (fig. 1). Mississippian units crop out along a band extending more than 480 km (300 mi) from Ashtabula and Trumbull Counties (see fig. 2 for county locations) on the northeast, westward to Erie and Huron Counties in the north-central part of the State, and then southward to Adams and Scioto Counties on the Ohio River. The outcrop belt ranges from 8 km (5 mi) to slightly more than 80 km (50 mi) in width. Lamborn and others (1938, p. 43) estimated that Mississippian outcrops are present over an approximate area of 8,586 mi^2 (22,238 km^2). Except in the southernmost part of the State, outcrops are largely mantled by glacial drift. Mississippian rocks dip under cover to the south-southeast, where they are overlain by Pennsylvanian-age units. A small area of Mississippian-age rocks is present in Fulton, Defiance, and Williams Counties in extreme northwestern Ohio. This area is covered by thick glacial drift, and no outcrops are known.

South of Ross County, beyond the glacial boundary, Mississippian exposures are common. Many excellent exposures are also found in the narrow belt east of the drift limit from Ross County north to Holmes County. In the areas covered by glacial drift, exposures are less common; however, along principal streams near the edge of the drift boundary, good outcrops can commonly be found. Away from the glacial boundary, where drift is thicker,

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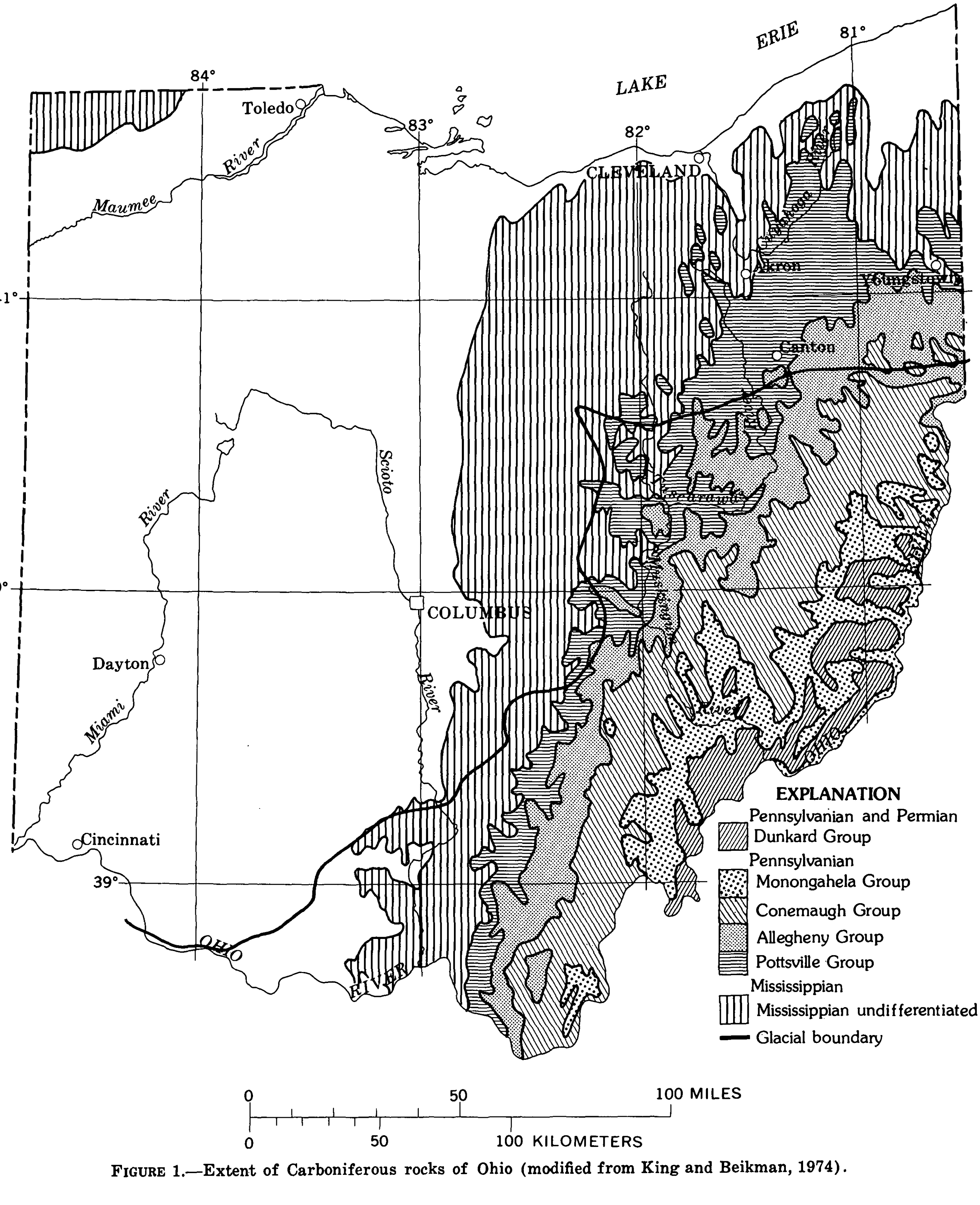

FIGURE 1.—Extent of Carboniferous rocks of Ohio (modified from King and Beikman, 1974).

FIGURE 2.—Location of counties in Ohio.

bedrock crops can generally be found only along major streams.

Highway cuts and quarries provide additional exposures in areas where glacial drift obscures outcrops. Hyde (1953) and Pepper and others (1954) discussed various aspects of middle and Lower Mississipian stratigraphy on a more or less statewide basis; their reports are invaluable guides to specific outcrops. Szmuc (1970) described the Mississippian of northeastern Ohio and gave many section localities.

Pennsylvanian-age rocks lie to the east and south of the Mississippian outcrop belt and cover approximately the easternmost third of the State. Most of the Pennsylvanian rocks lie beyond the limit of glacial drift; exposures are numerous. Glacial drift mantles parts of the section in the northeasternmost counties; however, the drift is relatively thin, and good exposures can generally be found. Highway cuts in many places provide the best sections in the glaciated parts of the system. Active open-pit mines generally provide excellent exposure; however, after mining has been completed, rapid modern reclamation methods essentially eliminate strip mines as stratigraphic study areas. Denton and others (1961) gave many section descriptions and localities representative of the Pennsylvanian in Ohio; their report is useful as a general guide to the system in the State.

Permian-age rocks cap the Pennsylvanian System in the eastern and southeastern counties of Athens, Belmont, Meigs, Monroe, Morgan, Noble, and Washington. Outcrops of Permian and Permian-Pennsylvanian transition-age rocks are abundant throughout their area of occurrence. The abundance of incompetent red mudstone in this part of the section, as well as in the underlying Monongahela and Conemaugh Groups, leads to a high incidence of slumping, which masks many outcrops. Highway cuts, however, particularly along the interstate system, provide excellent exposures.

The stratigraphic nomenclature used in this paper has not been reviewed by the Geologic Names Committee of the U.S. Geological Survey. The nomenclature used here conforms with the current usage of the Ohio Department of Natural Resources, Division of Geological Survey.

HISTORY OF CLASSIFICATION

MISSISSIPPIAN

The present classification (fig. 3) of the Mississippian System (lower Carboniferous) in Ohio, unlike that of the Pennsylvanian System (upper Carboniferous), was largely developed by geologists working principally for the State geological survey. In the first annual report of the newly organized geological survey, Briggs (1838, p. 79–80) introduced the term Waverly sandstone series for all the rocks lying above what is now recognized as the Ohio Shale (Devonian) and below a conglomerate presently known to correlate with the basal Pennsylvanian-age Sharon conglomerate. Andrews (1871, p. 83) named the Upper Mississippian Maxville Limestone, which he described as being discontinuous and lying on the Logan Sandstone group; this was the first such usage of Logan in the geological literature of Ohio. Andrews also referred to the Logan Sandstone group as the Upper Waverly group. Newberry (1870, p. 21) listed the principal elements of the Waverly group in northern Ohio as being, in ascending order, Cleveland Shale, Bedford Shale, Berea Grit, and Cuyahoga Shale." The Cleveland Shale was subsequently assigned to the underlying Devonian-age Ohio Shale.

It remained for Hicks (1878, p. 216) to describe the Sunbury Formation and formally introduce that name. Hicks (p. 216–217) introduced also the term Black Hand for a thick sandstone and conglomerate in the Black Hand gorge on the Licking River. The Black Hand sandstone was subsequently made a member of the Cuyahoga Formation.

Although some minor differences existed in the terminology and in the precise positions of boundaries, the basic classification of the Mississippian section in Ohio was well established by the late 1800's. Prosser (1905, p. 4) listed the accepted units, in ascending order, as Bedford Shale; Berea Grit, Sunbury Shale; Cuyahoga, Black Hand, and Logan Formations; and Maxville Limestone". With the exception of the Black Hand Formation, Prosser's classification is still valid.

On the basis of several facies that could be recognized within the unit, Hyde (1915) proposed a subdivision of the Cuyahoga Formation. Hyde divided the outcrop region into several areas that had few lateral changes and, in general, had vertically uniform lithologies (fig. 4). Each facies, consisting of one to several members (table 1), was given a name taken from an area that typified a

TABLE 1.—*Subdivision of the Cuyahoga Formation proposed by Holden (1942)*[1]

1. Henley shale facies: Henley shale member.	2. Hocking Valley conglomerate facies: Black Hand conglomerate member. Fairfield sandstone member. Lithopolis siltstone member.
3. Granville shale facies: Black Hand siltstone member. Raccoon shale member.	4. Toboso conglomerate facies: Black Hand conglomerate member. Pleasant Valley shale and sandstone member.
5. Killbuck shale facies: Black Hand shale member. Armstrong sandstone member. Burbank shale and sandstone member.	6. River Styx sandstone facies: Black Hand sandstone member. Armstrong sandstone member. Rittman conglomerate submember.
7. Tinkers Creek shale facies: Meadville shale member. Sharpsville sandstone member. Orangeville shale member. Aurora sandstone submember.	

[1] Modified by Holden from Hyde (1915).

SYSTEM	GROUP	FORMATION OR BED	MEMBER
PERMIAN	Dunkard	Washington (No. 12) coal	
PERMIAN—PENNSYLVANIAN	Dunkard		
PENNSYLVANIAN	Monongahela	Waynesburg (No. 11) coal Pittsburgh (No. 8) coal	
PENNSYLVANIAN	Conemaugh	Ames Limestone	
PENNSYLVANIAN	Allegheny	Upper Freeport (No. 7) coal Brookville (No. 4) coal	
PENNSYLVANIAN	Pottsville	Sharon Conglomerate	
MISSISSIPPIAN	Waverly	Maxville Limestone	
MISSISSIPPIAN	Waverly	Logan Formation	Vinton Sandstone Allensville Conglomerate Byer Sandstone
MISSISSIPPIAN	Waverly	Cuyahoga Formation	Berne Conglomerate Black Hand Sandstone Portsmouth Shale Buena Vista Sandstone Henley Shale
MISSISSIPPIAN	Waverly	Sunbury Shale	
MISSISSIPPIAN	Waverly	Berea Sandstone	
MISSISSIPPIAN	Waverly	Bedford Shale	Sagamore Shale Euclid Shale
DEVONIAN		Ohio Shale	Cleveland Shale Chagrin Shale Huron Shale

FIGURE 3.—Generalized stratigraphic column of the Carboniferous section of Ohio (including immediately overlying and underlying units).

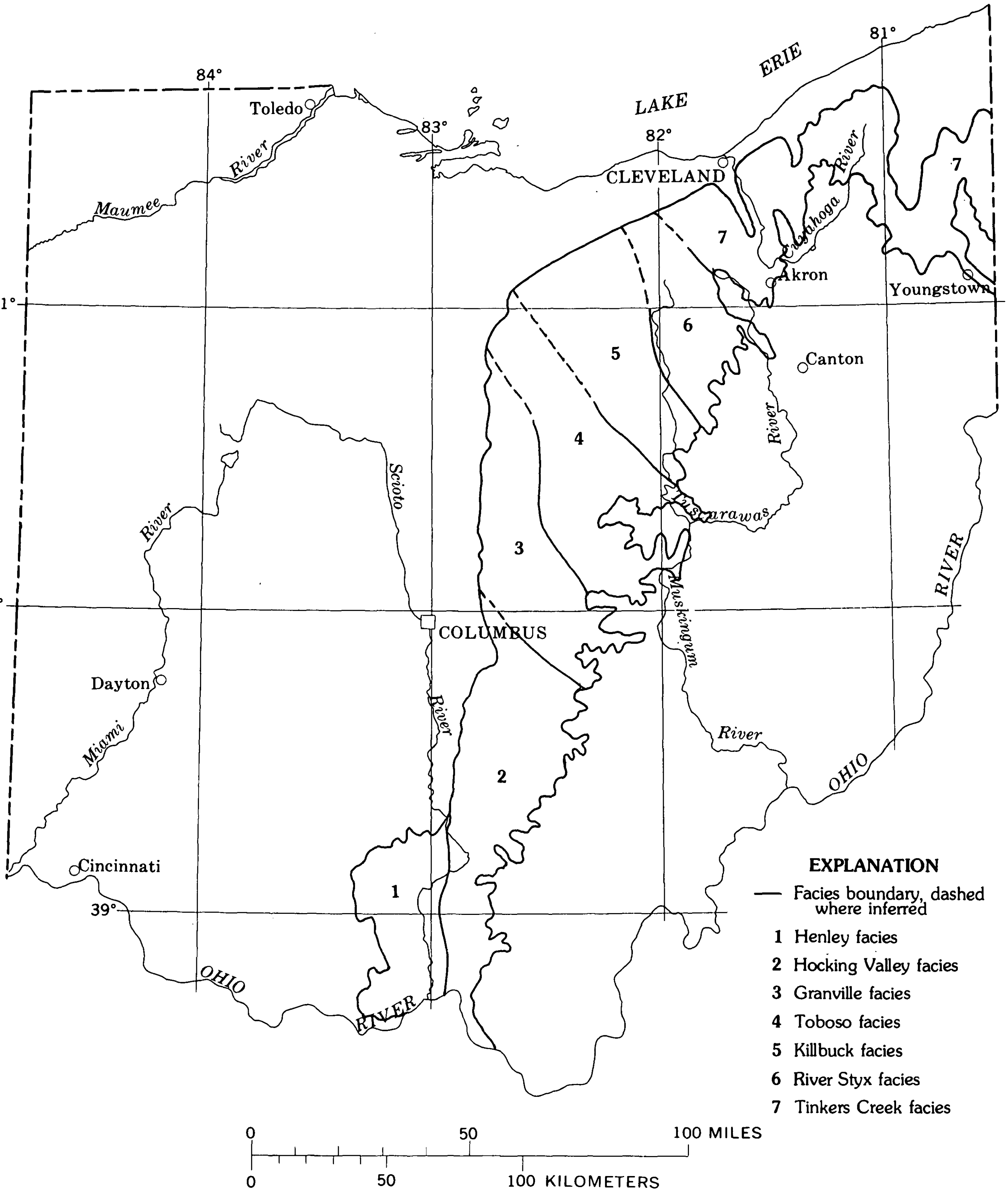

FIGURE 4.—Extent of proposed facies of the Cuyahoga Formation; Hocking Valley, Granville, and Toboso facies from Hyde, 1915, figure 1; Henley, Killbuck, River Styx, and Tinkers Creek facies from Holden, 1942, figure 2 (modified from Wolfe and others, 1962).

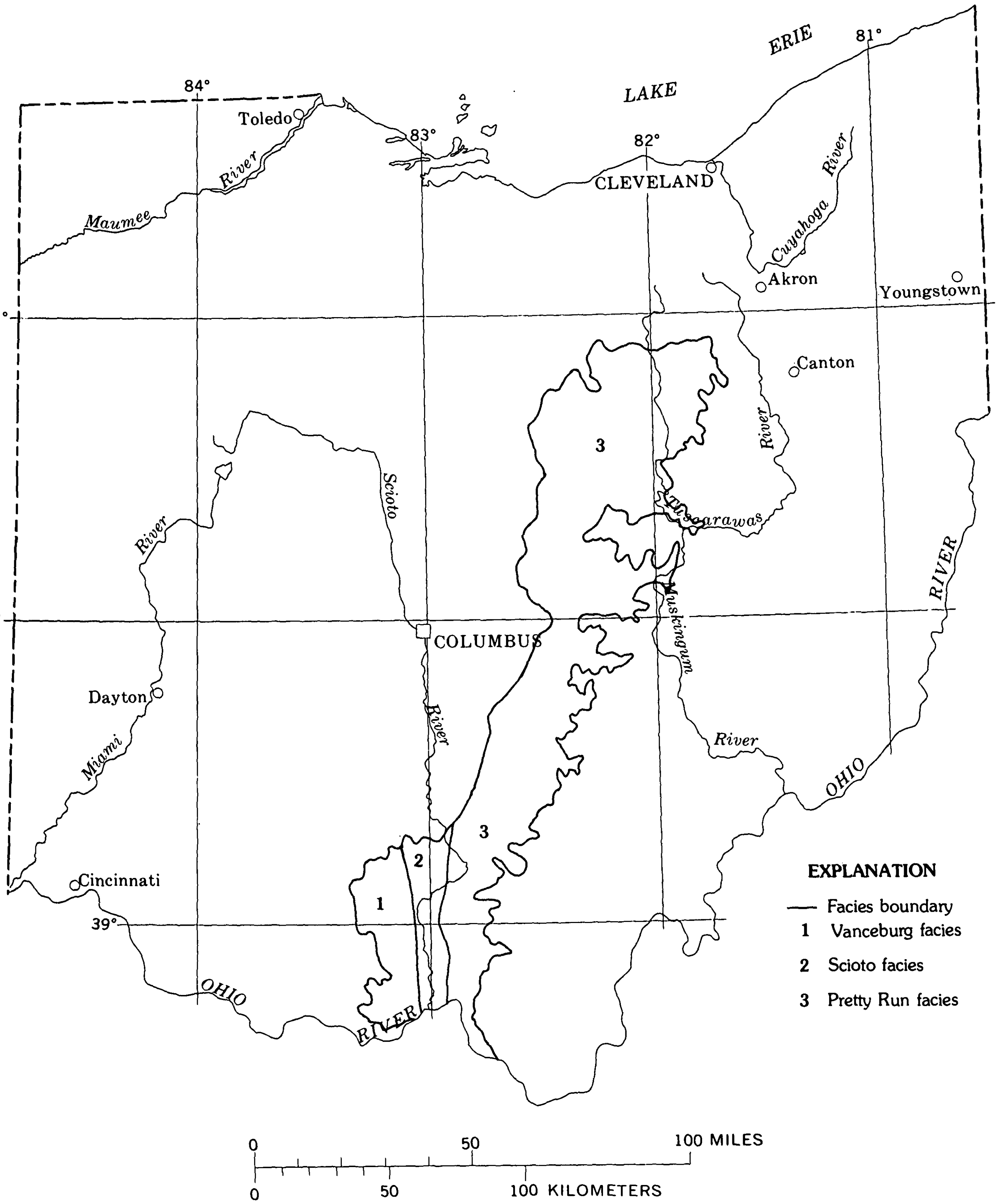

FIGURE 5.—Extent of proposed facies of the Logan Formation, from Holden, 1942, figure 3 (modified from Wolfe and others, 1962).

TABLE 2.—*Subdivision of the Logan Formation proposed by Holden (1942)*

1. Vanceburg siltstone facies:
   - Vinton sandstone member.
   - Churn Creek siltstone and shale member.
   - Vanceburg siltstone member.
   - Rarden shale member.
   - Buena Vista sandstone member.
2. Scioto Valley shale facies:
   - Vinton sandstone member.
   - Portsmouth shale member.
   - Buena Vista sandstone member.
3. Pretty Run sandstone facies:
   - Rushville shale member.
   - Vinton sandstone member.
   - Allensville conglomerate member.
   - Byer sandstone member.
   - Berne conglomerate member.

particular facies. Holden (1942), following Hyde's original proposal, enlarged and in part modified the subdivision of the Cuyahoga and extended the concept into the overlying Logan Formation (fig. 5; table 2).

However, Hyde's and Holden's proposed subdivisions of the Cuyahoga and Logan Formations to date have not been widely used.

PENNSYLVANIAN

The Pennsylvanian sequence in Ohio has four major subdivisions. These subdivisions were established on practical rather than lithologic or paleontologic criteria and basically follow the original classification established by Rogers (1858) for Pennsylvania. The basis for the subdivisions, as Rogers' original names suggest, is the relative abundance of minable coal. Rogers' units, in ascending order, were Seral Conglomerate, Lower Productive (Older) Coal Measures, Lower Barren (Older) Coal Measures, Upper Productive (Newer) Coal Measures. Various geologists, working primarily in Pennsylvania, made a number of modifications in the original proposal, and Prosser (1905) adopted for Ohio the names and overall classification accepted at that time. In ascending order, the units are Pottsville, Allegheny, Conemaugh, and Monongahela. These units, which in Ohio have been called formations, series, measures, and groups, are presently considered to be groups.

The group boundaries as presently used in Ohio are: Pottsville—Sharon conglomerate to the base of the Brookville (No. 4) coal; Allegheny—base of the Brookville coal to top of the Upper Freeport (No. 7) coal; Conemaugh—top of the Upper Freeport coal to the base of the Pittsburgh (No. 8) coal; Monongahela—base of the Pittsburgh coal to the top of the Waynesburg (No. 11) coal. The Waynesburg coal marks the base and the Washington (No. 12) coal the top of a Permian-Pennsylvanian transition zone, which includes the lower part of the Dunkard Group. Strata above the Washington coal include the upper part of the Dunkard, which is presently considered to be Permian in age.

Within the four groups, individual economically important and persistent units have been named. However, many of these units, considered to be beds according to the American Code of Stratigraphic Nomenclature are, although named, not persistent or economically important.

More than 100 individual beds have been named in the Pennsylvanian section of Ohio. (See tables 4–8.) The large number of named units is related, in part, to the early geologic concept that sedimentary rock units were tabular in nature and could correlated over a wide geographic area. This concept was aided in Ohio by the fact that a few Pennsylvanian-age beds do have a reasonably wide areal extent and also by the fact that, because of the repetitive nature of the sequence, many beds have a general although not precise relationship to similar beds at different localities. The proliferation of named units was also, in part, a response to the need of a growing industrial society to have identifying terms to use in the exploration and development of the region's mineral resources.

A second system of classification, proposed by Stout (1931), was based on lithologic and paleontologic consideration. Stout noted that a threefold division of the Pennsylvanian could be made on the basis of whether the calcareous beds were deposited under marine or freshwater conditions. Stout's classification consisted of (1) a lower unit encompassing all the rocks from the base of the Sharon conglomerate to the base of the Hamden limestone, containing marine shale and limestone, (2) a middle transitional unit from the base of the Hamden to the top of the Skelley limestone, containing both marine and freshwater limestone, and (3) an upper unit from the top of the Skelley limestone to the top of the Waynesburg coal, containing only freshwater limestone. A minor change in Stout's boundary between the lower and middle units would be needed to accommodate the fact that the type Hamden limestone was subsequently shown to be nonmarine (Sturgeon and others, 1958). For unknown reasons, possibly entrenchment of the earlier system, lack of correlation with the more clastic section of neighboring Pennsylvania and West Virginia, or some dissatisfaction by the proposer, this classification was never adopted.

TABLE 3.—*Basic types of cyclothems in the Pennsylvanian System of Ohio*[1]

Lower unit	Middle unit (transitional)	Upper unit
1. Clay, nonmarine. Shale and sandstone, largely marine. Iron ore, marine. Limestone, marine. Coal, nonmarine.	Cycle same as 2 in lower unit.	Cycle same as 5 in middle unit.
2. Clay, nonmarine[2]. Shale and sandstone, largely marine. Limestone, marine. Coal, nonmarine.	4. Clay nonmarine[3]. Limestone, nonmarine. Shale and sandstone, partly marine. Limestone, marine. Coal, nonmarine.	6. Clay nonmarine[3]. Limestone and calcareous shale, nonmarine. Coal, nonmarine.
3. Clay, nonmarine. Shale and sandstone, probably brackish water or marine. Shale, fossiliferous, brackish water. Coal, nonmarine.	5. Clay, nonmarine. Limestone, nonmarine. Shale and sandstone, nonmarine. Coal, nonmarine.	7. Clay, nonmarine. Shale and sandstone, nonmarine. Coal, nonmarine.

[1]From Stout, 1931.
[2] Commonest cycle in lower unit.
[3] Distinctive cycles of the unit in which they occur.

The cyclical nature of Pennsylvanian strata was noted by some early workers, but the concept of the cyclothem was proposed and elaborated on by Weller (1930, 1931) and Wanless and Weller (1932). Stout (1931) also recognized cycles in Ohio and described seven basic types (table 3) and their distribution within his proposed threefold classification of the Pennsylvanian section. The concept of the cyclothem has been used extensively by most Pennsylvanian workers in Ohio and has proved to be an extremely valuable field tool. A few workers have used cyclothems in a formal stratigraphic sense in reporting field investigations.

More recently, a number of workers have called attention to the deltaic nature of Pennsylvanian rocks. The similarities between the sedimentary framework of Pennsylvanian rocks in the northern Appalachian basin and the sediments of modern deltas are so great that Ferm and Cavaroc (1969) used the same terminology for specific recent environments and for ancient environments. No comprehensive classification, however, has been offered for the complex sequence of Pennsylvanian rocks on the basis of deltaic models.

PERMIAN

As stated earlier, rocks now considered to be Permian-Pennsylvanian transition in age were, prior to 1900, included in the Carboniferous. The U.S. Geological Survey included the Permian in the Carboniferous as late as 1957. Rogers' (1858) Upper Barren Measures was subsequently named the Dunkard Series (originally Dunkard Creek Series) by White (1891). White placed the lower boundary of the Dunkard at the top of the Waynesburg coal and included all the overlying strata in the Appalachian region in the Dunkard. Fontaine and White (1880) had previously correlated the rocks in this interval as Permian in age. The break between the Pennsylvanian and Permian is not lithologic, but rather is based primarily on the presence of *Callipteris conferta*, considered by many to be an index fossil of the Permian. Cross (1958) failed to find undisputed *Callipteris conferta* below the Washington coal. In November 1959, members of the U.S. Geological Survey and the Pennsylvania, Ohio, and West Virginia Geological Surveys agreed to consider the Washington Formation (lower Dunkard) as Pennsylvanian and Permian in age and the Greene Formation (upper Dunkard) as Permian in age. Berryhill and Swanson (1962, p. C43) placed the base of the Permian at the base of the Washington coal. Rocks between the base of the Waynesburg coal and the base of the Washington coal were designated the Waynesburg Formation of Pennsylvanian and Permian age. The Waynesburg Formation has not been formally used in Ohio; however, the base of the Permian has been accepted as being at the position of the Washington coal (Collins and Smith, 1977).

The lack of a lithologic break in the sequence from basal Conemaugh through the highest rocks in the section, a thickness of more than 360 m (1,200 ft), coupled with only a gradual waning of Pennsylvanian floral types and only generally an increase in Permian flora, have led some workers (Gillespie and Clendening, 1969; Gillespie and others, 1975; Clendening, 1975) to argue for a Pennsylvanian age for all rocks now classified as Permian. The age of the Dunkard is still an enigma.

GEOLOGIC SETTING

Basal Mississippian rocks in Ohio are, at the surface, everywhere underlain by the Devonian-age Ohio Shale. The Ohio Shale in central and southern Ohio consists of black to brownish-black fissile shale. In the northern part of the State, the Ohio Shale can be subdivided, in ascending order, into the

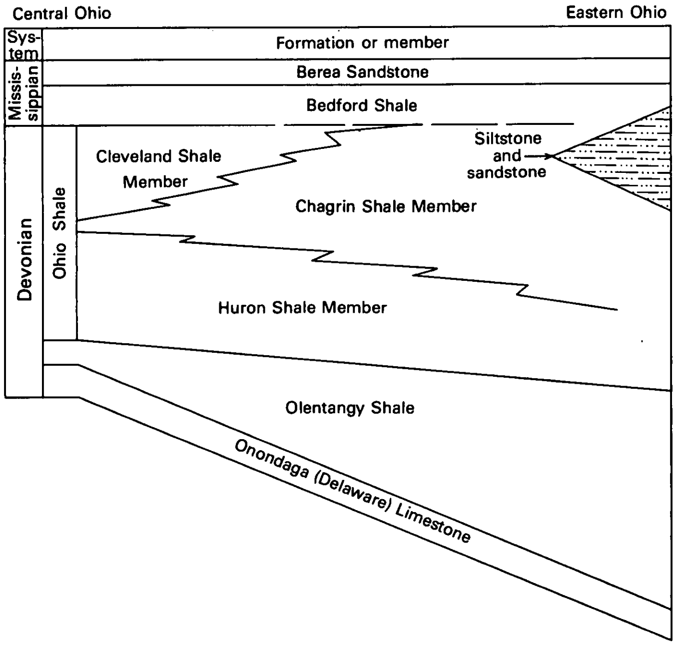

FIGURE 6.—Schematic cross section showing thickness changes of Devonian shales in eastern Ohio; lens of siltstone and sandstone shown represents the occurrence of these clastic rocks in several stratigraphic positions within the Chagrin Shale Member of the Ohio Shale as far west as Guernsey County (modified from Janssens and de Witt, 1976).

Huron, Chagrin, and Cleveland Shale Members. The Cleveland Member is a predominantly black bituminous shale containing intercalated beds of gray shale and siltstone of the interfingering Chagrin Member. The Chagrin Member is composed of gray shale and siltstone and interfingers to the west with the Cleveland Member (fig. 6). In northern Ohio along Lake Erie to the Ohio-Pennsylvania border, the Mississippian Bedford Shale is underlain by the Cleveland Member on the west and the Chagrin Member on the east.

The nature of the contact between the Devonian and Mississippian has not been studied in great detail; however, little evidence for a major unconformity at this contact is seen. Where adjacent rock types are relatively dissimilar (that is, red Bedford over black Ohio Shale) the contact is distinct and easily identified. However, where the Bedford consists of gray shale overlying gray shale and siltstone of the Chagrin shale, the contact is indistinct and cannot be readily identified; in such areas some workers have included the Bedford in the Devonian.

The contact between the Mississippian and the Pennsylvanian is clearly disconformable. The contact between the upper Mississippian Maxville Limestone and the middle Mississippian Logan Formation is also disconformable, as first noted by Morse (1910). Hyde (1953, p. 58) suggested that the "absolute range of relief on the pre-Pennsylvania [sic] erosion surface may amount to 350 or even 400 feet [107 to 122 m]." Local relief, however, is more probably about 15 to 23 m (50 to 75 ft). Basal Pennsylvanian rocks may rest directly on the Maxville Limestone, the Logan Formation, or even the Cuyahoga Formation, depending on the degree of post-Mississippian erosion in the area. Pennsylvanian beds in the Pottsville Group as high as the Massillon sandstone are reported as being in direct contact with the Cuyahoga Formation.

The contact between the Pennsylvanian and overlying Permian definitely lacks a clear-cut break of any type. Rocks presently assigned to the Permian and Permian-Pennsylvanian transition are indistinguishable from beds in the underlying Monongahela and Conemaugh Groups, which are considered unquestionably Pennsylvanian in age.

STRUCTURE

The Carboniferous rocks of Ohio are not structurally complex except in the region of the Burning Springs anticline, the Cambridge arch, and the Parkersburg-Lorain syncline, which will be discussed later. Mississippian and Pennsylvanian rocks were deposited on the west and northwest flank of the Pittsburgh-Huntington basin. For the most part, units dip gently (0°20′) southeast into the basin, but along the northern margin of the basin the dip component is southerly; in the southernmost part of the State, the dip is somewhat easterly. This regional trend is broken locally by minor structures generally considered to be largely penecontemporaneous features. Faults are relatively rare and generally have displacements of less than 1 m.

The principal structural features affecting Carboniferous rocks in Ohio are the post-Permian-age Burning Springs anticline, the Cambridge arch, and the Parkersburg-Lorain syncline (fig. 7). The northernmost part of the Burning Springs anticline crosses the Ohio River from West Virginia near Newport in Washington County and extends to about the Washington-Monroe County line, where it disappears on the surface. The trend of the Burning Springs anticline is north-south and follows the westward pinchout of the Silurian-age Salina F_4 salt. The structure may be the result of imbricate thrust faulting caused by termination of the décollement glide zone of a westward-northwestward-moving thrust sheet (Gwinn, 1964; Rodgers, 1963; Woodward, 1959).

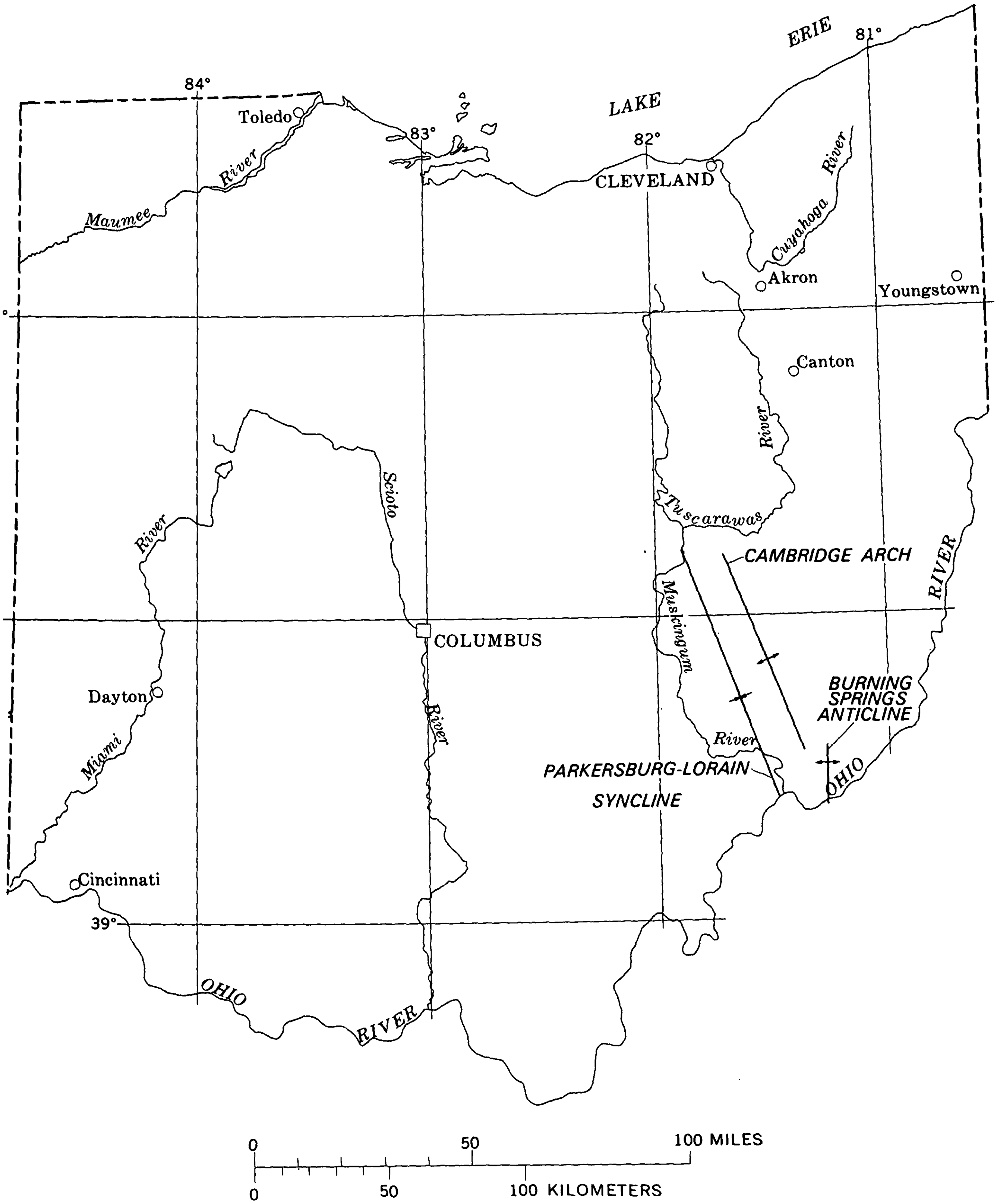

FIGURE 7.—General trend of the principal structural features of southeastern Ohio.

The Cambridge arch is a prominent structural feature that affects Carboniferous rocks in southeastern Ohio. This feature trends northwest-southeast from northern Washington County through Cambridge in central Guernsey County and into Muskingum County. Mapping by Collins and Smith (1977) in Washington County indicates that this feature is not, as some workers have suggested, a continuation of the Burning Springs anticline. Clifford and Collins (1974) reported that the Cambridge arch follows the pinchout of the Silurian-age Salina E salt; east of the pinchout, elevations of the Pittsburgh coal are about 91 m (300 ft) higher than those to the west. Only a gentle southeastward dip is found below the salt. These authors interpreted the structure to be the result of movement of a southeastward-thickening block of supra-Salina rocks northwestward along a salt glide plane. A postulated nearly vertical tear fault (or series of faults) marks the western limit of this movement.

The Parkersburg-Lorain syncline is a broad troughlike structure that trends northwest from Washington County to Lorain County. Stout and others (1935, p. 898) considered it to be "the most outstanding structural feature of the eastern half of the state * * * which can be traced on surface beds from Parkersburg [Wood County, West Virginia] on the Ohio River, northwest to Lorain County [Ohio] at Lake Erie." Little work beyond that of Stout and others has been done on this structural feature, and its precise nature remains largely unknown.

LITHOSTRATIGRAPHY

MISSISSIPPIAN

The Mississippian System in Ohio consists of six formations, which are, in ascending order, Bedford Shale, Berea Sandstone, Sunbury Shale, Cuyahoga Formation, Logan Formation, and Maxville Limestone. Thicknesses of the clastic units differ considerably, but average on the outcrop 29, 11, 6, 103, and 51 m (95, 35, 20, 339, and 166 ft), respectively. The Maxville Limestone, because of intensive post-Mississippian erosion, differs extremely in thickness, generally not exceeding 15 meters (50 ft) on the outcrop. The stratigraphy of most of these formations has been widely studied; however, the Cuyahoga and Logan have undoubtedly received the most attention because of efforts to subdivide these units.

With the exception of the Maxville Limestone, the Mississippian rocks of Ohio form a northwestward-thickening clastic sequence of shale, sandstone, and conglomerate. Erosion has everywhere reduced the original thickness of the Mississippian; however, as much as 305 m (1,000 ft) of clastic strata is reported by Hyde (1927, p. 43) in Vinton County. The Maxville Limestone is thickest in the southern part of the State and is absent in the northern part, but the original thickness trend of the unit is not apparent because of severe erosion, which has completely removed the unit in many areas.

BEDFORD SHALE

The Bedford Shale, as stated above, rests directly on Devonian-age shale and in many places is essentially indistinguishable from the underlying beds. The formation takes its name from the town of Bedford in Cuyahoga County. The Bedford in southern Ohio consists largely of bluish-gray sandy shale containing, particularly in the upper part, sandstone and siltstone. In the central and north-central parts of the State, the unit becomes red to reddish brown, although bluish-gray shale is also present; the unit is also much more argillaceous than it is to the south. Both the red and gray shales are used by the ceramic industry in Franklin and Delaware Counties. North from Franklin County to Lorain County, the amount of red shale increases, and red shale predominates in the north. From Cuyahoga County to the Ohio-Pennsylvania line, red shale is largely replaced by gray to blue-gray shale and interbedded siltstone. Two such massive siltstone members in Cuyahoga County have been named the Sagamore and Euclid siltstones (fig. 3). The Euclid member was formerly quarried for flagstone. In extreme eastern Ashtabula and Trumbull Counties the Bedford rests on the Cussewago Sandstone, which is the basal Mississippian unit in this area.

BEREA SANDSTONE

The Berea Sandstone takes its name from the town in Cuyahoga County. This unit as well as the underlying Bedford has been described and discussed in detail by Pepper and others (1954), who made a classic report and an in-depth analysis of these units. In southern Ohio, the Berea is represented by light-gray to buff siltstone, which in many areas cannot be distinguished from the underlying Bedford. From about central Ohio (Franklin County) north to the type area and east to the Pennsylvania-Ohio border, the unit consists of fine- to medium-grained sandstone. In the north-central part of that area, the basal part of the Berea is represented by a massive channel sand that reaches a thickness of more than 72 m (235 ft) at the Buckeye quarry at South Amherst, Lorain County (Pepper and others, 1954, p. 28). In many areas, massive channel sand is overlain by ripple-marked thin-bedded sandstone.

SUNBURY SHALE

The Sunbury Shale, which was named for the village in Delaware County, consists of thinly bedded fissile carbonaceous black shale. The unit is thin, averaging only about 6 m (20 ft), but is remarkebly persistent and can be traced from the Ohio-Kentucky line north to Cuyahoga County. East from Cuyahoga County to the Ohio-Pennsylvania line, however, the Sunbury cannot be separated from the overlying Orangeville shale of the Cuyahoga Formation.

CUYAHOGA FORMATION

The Cuyahoga Formation is a thick rather complex sequence of shale, sandstone, and conglomerate. The unit takes its name from Cuyahoga County, where it was first described. The thickness of the unit differs; a maximum of about 190 m (625 ft) was reported in the Hocking Valley region by Hyde (1915, p. 670). The Henley shale, Buena Vista sandstone, and Portsmouth shale (ascending order) are significant members in southern Ohio. The higher Black Hand sandstone and Berne conglomerate members are widespread in the central part of the State. In northern Ohio, the unit is predominantly bluish-gray shale.

LOGAN FORMATION

The Logan Formation, which was named for the town in Hocking County, marks the top of the clastic part of the Mississippian sequence in Ohio. The Logan consists of sandstone, conglomerate, sandy shale, and shaly sand. The Byer sandstone, Allensville conglomerate, and Vinton sandstone (ascending order) are widely recognized members in the southern and south-central parts of the State. The Logan extends northward only to about Wayne County and is not present in northern or northeastern Ohio.

MAXVILLE LIMESTONE

The Maxville Limestone, named for the village in Perry County, is the only carbonate unit in the Mississippian section of Ohio. The unit is very discontinuous on the outcrop and only slightly more persistent in the subsurface. Morse (1910) recognized that the Maxville rested disconformably on the underlying Logan Formation; other workers have subsequently confirmed this fact. Uttley (1974) reviewed the existing data on the pre-Maxville disconformity and concluded that its relief was relatively low. The discontinuous nature of the Maxville is a reflection of dissection that took place between the close of Mississippian deposition and the beginning of Pennsylvanian deposition. Limestone is confined mainly to the area south of a line from Muskingum County to Belmont County. Maxville pebbles, however, are incorporated in basal Pennsylvanian rocks on the outcrop as far north as Wayne County, and Uttley (1974) reported a small area of limestone in Jefferson County. The thickness of the unit differs considerably, generally being less than 15 m (50 ft) on the outcrop and perhaps reaching as much as 59 m (195 ft) in the subsurface. These data clearly show that the Maxville once covered a much larger area and that the present distribution is the result of severe widespread post-Mississippian erosion.

The possibility has long been recognized that rocks correlated with Maxville represented more than one correlative stratigraphic and age unit. Uttley (1974), on the basis of a synthesis of available paleontological and stratigraphic data, suggested that the Maxville could be divided into units of formational rank and that it spans both Meramecian and Chesterian time. (See fig. 8.)

PENNSYLVANIAN

The Pennsylvanian rocks of Ohio are a repetitive sequence of lenticular sandstones, mudstones, freshwater and marine limestones, clays, and coals, averaging about 335 m (1,100 ft) in thickness. Rapid facies changes are the norm, and most beds do not have good lateral continuity. Because of the general lack of distinctive lithologic or faunal differences within any individual group, correlation must be made on the basis of gross lithologic characteristics and stratigraphic sequence.

Unlike the underlying Mississippian rocks, the Pennsylvanian rocks of Ohio thicken slightly to the southeast. Greatest thickness is along the Ohio River in Monroe and Washington Counties, where an increase in thickness of about 67 m (200 ft) more than the outcrop average is found. Basal Pennsylvanian units reach as high as the Massillon sandstone and rest directly on the Maxville Limestone, Logan Formation, or Cuyahoga Formation, depending on the depth of the pre-Pennsylvanian erosion.

Sandstone ranges from massive to shaly bedded and from very fine grained to coarse grained and conglomeratic. The mineralogic composition of several sandstone units in the Monongahela and Dunkard Groups ranges from 62 to 90 percent quartz, 2 to 21 percent clay and silt, 0.1 to 1 percent heavy minerals, 2 to 10 percent feldspar, 1 to 8 percent mica, and 1 to 9 percent rock fragments (Collins and Smith, 1977). The lowest sandstone of the Pottsville Group tends to be much cleaner and contains 98 to 99 percent quartz.

Mudstone units are prominent in the Conemaugh, Monongahela, and Dunkard Groups. Mudstone units are virtually nonbedded, break with an irregular fracture, are generally calcareous and have limy nodules, are semiplastic to nonplastic, and consist predominantly of clay- and silt-size particles. Mudstones are predominantly red or some shade of red, and green to greenish-gray mottling is common. Such units have been variously called clay-shale, shale, marl, and red beds.

Nonmarine limestones range from light to dark gray and are generally cryptocrystalline to very finely crystalline and homogeneous. They normally have a relatively high clay content and break down readily on weathering. Conglomeratic or brecciated nonmarine limestones, in which both matrix and pebbles are composed of similar material, are relatively common.

Marine limestones vary from black to medium greenish gray to light gray and are generally medium crystalline to coarsely crystalline. The beds range from relatively pure limestone (>90 percent $CaCO_3$) to calcareous shale. In some areas, the limestones of the Allegheny and Pottsville Groups grade into marine flints.

Clays are present under most coals and are generally illitic, noncalcareous, plastic to semiplastic, light to dark gray, nonbedded, and in many places bear root traces. In the Allegheny and Pottsville Groups, much of the clay is a kaolinitic nonplastic "flint" type.

Ohio's coal is of high-volatile bituminous rank, and, on an "as received" basis, ranges from about 5 to 20 percent ash, from 1 to 6 percent sulfur, and from 10,000 to 13,000 Btu (British thermal units). Coals overlain by marine shale and limestone tend to contain more sulfur than those overlain by nonmarine strata.

POTTSVILLE GROUP

The Pottsville is the basal group of the Pennsylvanian System in Ohio. The group averages 78 m (256 ft) in thickness on the outcrop and consists of thick conglomerates, sandstones, and shales, and of thin coals, marine limestones, and shales. Stout and others (1943, p. 140) estimated that sandstones constitute about 42 percent of the total thickness of the group. Very thin iron carbonate or clay ironstone beds are associated with many of the marine zones; although no longer of commercial interest, these "ores" were the basis for the historically important Hanging Rock iron district of southern Ohio and northern Kentucky. Nonmarine limestone is not known to be present in this group.

The named beds in the Pottsville of Ohio number 26 (table 4). The Sharon conglomerate, which is the lowest significant unit in the group, is very erratic in distribution, having been deposited in valleys cut in the underlying Mississippian. The Sharon is typically composed of clean medium to coarse quartz sand or pebbles. This unit's principal area of occurrence is Summit, Portage, Geauga, and adjacent counties in northern Ohio. The unit also is present in Jackson, Pike, and Scioto Counties to the south. The Sharon and the higher Massillon sandstone are both noted for high-purity silica; both units are economically important. The Sharon (No. 1) and Quakertown (No. 2) coals, which are associated with these units, also tend to be the Ohio coals lowest in sulfur.

Like the Sharon conglomerate, all beds from the base of the Pottsville to the Massillon sandstone were deposited on a rather deeply dissected Mississippian surface and, for that reason, are erratic in occurrence. Above the Massillon sandstone the sec-

TABLE 4.—*Generalized stratigraphic column for the Pottsville Group of Ohio*

Bed	Material
Homewood	Shale or sandstone.
Tionesta No. 3b	Coal, local.
Upper Mercer, Big Red Block	Ore, irregular
Upper Mercer	Limestone or flint.
Bedford	Coal, patchy.
Sand Block	Ore, siliceous, local.
Upper Mercer No. 3a	Coal, local.
Lower Mercer, Little Red Block	Ore, kidney.
Lower Mercer	Limestone, persistent, marine.
Middle Mercer	Coal, persistent, thin.
Flint Ridge	Coal, thin, local.
Boggs	Ore and limestone, marine.
Lower Mercer No. 3	Coal, persistent, thin.
Lowellville (Poverty Run)	Coal, thin, nonpersistent.
Vandusen	Limestone, or ore, marine.
Bear Run	Coal, local.
Massillon (Connoquenessing)	Shale or sandstone.
Quakertown No. 2	Coal, patchy.
Huckleberry	Coal, thin, local.
Guinea Fowl	Ore, local.
Anthony	Coal, thin.
Sciotoville	Clay, flint and plastic.
Sharon	Ore, local, marine.
Sharon No. 1	Coal, patchy.
Sharon	Conglomerate, patchy.
Harrison	Ore, local, impure.

tion becomes more regular, but, because of rapidly changing facies, individual beds are generally difficult to trace for great lateral distances.

ALLEGHENY GROUP

The Allegheny Group has 32 named beds (table 5) averaging about 65 m (212 ft) in thickness, and is similar in most respects to the underlying Pottsville Group. A major lithologic difference is the appearance of thin nonmarine limestone in the Allegheny Group. The Hamden limestone is the lowest freshwater limestone in the Pennsylvanian of Ohio and appears slightly above the Lower Kittanning (No. 5) coal. This group is of major economic importance in the State because of its large coal and clay resources and lesser, but important, limestone resources.

CONEMAUGH GROUP

The Conemaugh, containing 40 named beds (table 6), is the thickest of the four groups composing the Pennsylvanian section. The group averages 122 m (400 ft) on the outcrop. The Conemaugh is virtually devoid of major economically important coals. Thick sandstones, mudstones, and shales are abundant. Thin coals, freshwater and marine limestones, marine shales, and clays are also present. Above the Skelley limestone, the section becomes more continental, and marine units disappear from the section; *Lingula* specimens, however, are present in a very few localities at the position of the much higher Permian-age Washington coal. In general, the freshwater limestones become much thicker in the upper half of the group.

The first appearance of red coloration in this group indicates an important change in Pennsylvanian-age rocks. Red rocks are not present in the underlying Pottsville or Allegheny Groups. Red mudstones and thinner red shales become quite abundant from about the Anderson coal upward. The first occurrence of red strata, however, is normally at, or slightly above, the Upper Freeport coal. Thus, the appearance of red beds is quite useful as a general stratigraphic marker, particularly in the subsurface.

MONONGAHELA GROUP

The Monongahela Group, containing 25 named beds (table 7), averages 75 m (247 ft) in thickness

TABLE 5.—*Generalized stratigraphic column for the Allegheny Group of Ohio.*

Bed	*Material*
Upper Freeport No. 7	Coal, patchy.
Upper Freeport	Limestone and marly shale.
Bolivar	Coal, local, thin.
Bolivar	Clay, flint and plastic.
Upper Freeport	Shale or sandstone.
Dorr Run	Shale, marine, local.
Lower Freeport (Rogers)	Coal, patchy.
Lower Freeport	Limestone, local.
Lower Freeport	Shale or sandstone.
Upper Kittanning	Coal, seldom present.
Washingtonville (Yellow Kidney ore)	Shale, marine.
Middle Kittanning No. 6	Coal, persistent.
Leetonia	Limestone, local.
Red Kidney ore	Shale, siliceous.
Strasburg	Coal, local.
Oak Hill	Clay, flint and plastic.
Hamden	Limestone, nonpersistent.
Columbiana	Limestone, marine, local.
Lower Kittanning No. 5	Coal.
Lawrence	Coal, shaly, local.
Kittanning	Shale and sandstone.
Ferriferous	Ore, irregular.
Vanport	Limestone, marine.
Scrubgrass	Coal, seldom present.
Clarion No. 4a	Coal, patchy.
Canary	Ore, very local.
Clarion	Sandstone, irregular.
Winters	Coal, very local.
Zaleski	Flint, impure, marine.
Ogan	Coal, local.
Putnam Hill	Limestone, marine.
Brookville No. 4	Coal, persistent.

TABLE 6.—*Generalized stratigraphic column for the Conemaugh Group of Ohio*

Bed	*Material*
Upper Pittsburgh	Limestone, irregular.
Upper Little Pittsburgh	Coal, very local.
Bellaire	Sandstone, local.
Lower Little Pittsburgh	Coal, seldom present.
Summerfield (Lower Pittsburgh)	Limestone.
Connellsville	Sandstone, local.
Clarksburg	Coal, local.
Clarksburg	Limestone and marly shale.
Morgantown	Sandstone, local.
Elk Lick	Coal, usually wanting.
Elk Lick	Limestone and marly shale.
Birmingham	Shale, siliceous.
Skelley	Limestone, local, marine.
Duquesne	Coal, seldom evident.
Gaysport	Limestone, siliceous, marine.
Ames	Limestone, marine.
Ames	Coal, very local.
Harlem	Coal, persistent.
Rock Riffle	Limestone, very local.
Round Knob-Pittsburgh	Clay, calcareous.
Saltzburg	Sandstone, local.
Barton	Coal, local.
Ewing	Limestone, ferruginous.
Cow Run	Sandstone, local.
Portersville	Limestone, marine.
Anderson	Coal, persistent.
Bloomfield	Limestone, local.
Cambridge	Limestone, marine.
Wilgus	Coal, nonpersistent.
Buffalo	Shale or sandstone.
Upper Brush Creek	Limestone, marine.
Upper Brush Creek	Coal, local.
Lower Brush Creek	Limestone and shale, marine.
Lower Brush Creek	Coal, local.
Mason	Coal, local.
Upper Mahoning	Shale or sandstone.
Mahoning (Groff)	Coal.
Thornton	Clay, irregular.
Mahoning	Limestone, local.
Lower Mahoning	Shale or sandstone.

and, except for the presence of several commercially important coal beds, is very much like the upper half of the Conemaugh. Arkle (1959) described three facies in the Monongahela Group in the Appalachian basin. These facies in the Ohio part of the basin are: (1) a gray facies consisting of many alternating thin gray shale and limestone beds and thick coals in the northern and central part of the outcrop area, (2) a red facies consisting of thin variegated red and yellow mudstone and massive sandstone in the southeastern part of the State; coal is lacking or much thinner than that in the northern area, and (3) a transitional facies consisting of thin impure coals, limestones, and variegated red and yellow mudstones in central eastern Ohio tying together the northern and southern areas. As stated above, no marine units are known in the group.

DUNKARD GROUP

As presently interpreted, rocks assignable to the Dunkard Group span the Permian-Pennsylvanian boundary; for this reason these rocks are discussed both here and under the Permian. (See table 8 for stratigraphic column.) The Dunkard Group in Ohio averages 191 m (626 ft) in thickness on the outcrop and, as stated above, has traditionally been assigned to the Permian System. Presently, however, the rocks from the top of the Monongahela Group (Waynesburg coal) to the base of the Washington coal (lower Dunkard) are classified as Permian-Pennsylvanian in age. The rocks in this interval average 33 m (109 ft) and are indistinguishable from the underlying Monongahela Group. The age assignment for this part of the Dunkard is based not on lithology but rather on the waning of a typically Pennsylvanian flora and an increase of a Permian flora.

TABLE 7.—*Generalized stratigraphic column for the Monongahela Group of Ohio*

Bed	*Material*
Waynesburg No. 11	Coal, fair purity.
Gilboy	Shale and sandstone.
Little Waynesburg	Coal, persistent.
Waynesburg	Limestone and marly shale.
Uniontown	Shale or sandstone.
Uniontown No. 10	Coal.
Lower Uniontown	Coal, very local.
Uniontown	Shale, siliceous, and limestone.
Arnoldsburg	Sandstone.
Arnoldsburg	Coal, wanting.
Arnoldsburg	Limestone and calcareous shale.
Fulton	Shale, green, or shaly sandstone.
Benwood	Coal, very local.
Benwood	Limestone and calcareous shale.
Upper Sewickley	Sandstone, local.
Meigs Creek No. 9 (Sewickley)	Coal.
Lower Sewickley	Sandstone.
Fishpot	Coal, persistent, thin.
Fishpot	Limestone and marly shale.
Pomeroy (Fishpot)	Sandstone.
Pomeroy (Redstone)	Coal, nonpersistent.
Lower Meigs Creek (Lower Sewickley)	Coal, local.
Redstone	Limestone and marly shale.
Upper Pittsburgh	Sandstone, local.
Pittsburgh No. 8	Coal, persistent.

PERMIAN

Following U.S. Geological Survey usage, the Dunkard Group in Ohio traditionally has been divided into the Washington and Greene Formations The Washington averages 67 m (221 ft) in thickness and the Greene, 123 m (405 ft). No lithologic basis exists in Ohio for dividing the Dunkard into two formations and, unlike the underlying Pennsylvanian groups, neither is there a practical basis (table 8). The fact that undisputed *Callipteris conferta* specimens have not been found lower than the Washington coal (lower half of the Washington Formation) and the generally Permian character of the flora above the Washington coal form the basis for the current classification of these rocks. (See discussions of the Permian and Dunkard elsewhere in this paper.)

The following statement from Stauffer and Schroyer (1920, p. 15) provides an apt description of the Dunkard in Ohio:

The Dunkard is a most variable series of rocks. There are sandstones, shales, beds of limestone, and coal; in fact it

TABLE 8.—*Generalized stratigraphic column for the Dunkard Group of Ohio*

Bed	*Material*
Gilmore	Sandstone.
Do.	Limestone, local.
Nineveh	Sandstone, local.
Do.	Coal, local, shaly.
Do.	Limestone, irregular.
Hostetter	Coal, thin, shaly, local.
Fish Creek	Coal, very local.
Do.	Sandstone, local.
Dunkard	Coal, local, impure.
Jollytown	Sandstone, local.
Jollytown 'A"	Coal, local, impure
Upper Washington	Shale, variable.
Hundred	Sandstone, local.
Upper Marietta	Sandstone.
Washington "A"	Coal, shaly, local.
Creston-Reds (Little Washington)	Limestone.
Lower Washington	Limestone.
Lower Marietta	Sandstone, local.
Washington	Coal, shaly.
Little Washington	Coal, shaly.
Mannington	Sandstone, local.
Waynesburg "A"	Coal, nonpersistent.
Waynesburg	Sandstone, rather steady.
Elm Grove	Limestone.
Cassville	Shale, gray.

includes nearly all the different varieties of sediments from coarse sandstone and conglomerate to the finest grained shale. These change rather rapidly from one to the other, so that it is often impossible to trace a horizon for any great distance. And then too, there is considerable similarity between a number of beds at different stratigraphic elevations. This is especially true of the shales which are often featureless and devoid of any marks whereby they may be recognized. Shale is the most abundant rock in the series. The higher shales are often red in the northern part of the area, while to the south red is the prevailing color of the shale throughout the whole series. Selenite crystals are occasionally to be found in these red shales. This is especially true in the vicinity of Marietta. Most of the limestones occur in the northern part of the area where the sandstones are but poorly developed. As the limestones are traced southward they pass into calcareous shales which are often full of nuggets of lime. Finally these disappear as do also nearly all traces of coal beds, and the series becomes one of chiefly shale and sandstone. These latter increase materially in importance in the southern part of the Dunkard field.

The shales referred to by Stauffer and Schroyer are, in fact, the mudstones (commonly called red beds) described in the lithostratigraphy section.

BIOSTRATIGRAPHY

The subdivisions used in the Carboniferous of Ohio are mainly rock-stratigraphic units and were established with little regard for time stratigraphy; this is especially true for the Pennsylvanian, where the classification is based largely on the relative abundance of minable coals. Age correlations have been made of the Carboniferous of the northern Appalachians, of the American midcontinent region, and of the European section (fig. 8).

The lower Mississippian in Ohio is age-correlated primarily on the basis of invertebrate macrofossils. Floral zones have been established for the Mississippian in the Eastern United States, but plants are far too rare in the Ohio section to be of value. The uppermost Mississippian (Maxville Limestone) has been correlated primarily on the basis of conodonts. The Pennsylvanian of Ohio has been correlated mainly on the basis of floral zones and fusulinids.

MISSISSIPPIAN

Although locally fossiliferous, the clastic units of the Mississippian in Ohio are not known for their abundant biota. Marine to brackish-water invertebrate faunas represent the most abundant group of fossils; vertebrate forms and plants are rare.

BEDFORD SHALE

In northern and central Ohio the Bedford Shale is fossiliferous in the basal few feet. This zone, at the contact with the underlying Cleveland shale (Devonian), yields abundant specimens of *Lingula* and *Orbiculoidea.* Mollusks, particularly bivalves, dominate the fauna of the soft gray shale and ironstone concretions of the basal few feet. The large spiriferid *Syringothyris bedfordensis* also is abundant in this zone.

Very little work has been done on the Bedford fauna since the reports of Herrick (1888a, b), Girty (1912), Cushing and others (1931), and Hyde (1953).

BEREA SANDSTONE

Very few fossils have been obtained from the Berea in Ohio. Rare fish remains have been reported: chondrichthyan dermal spines referred to *Ctenacanthus* (Newberry, 1889) and most notably well-preserved remains of the paleoniscoid *"Palaeoniscum" (Gonatodus) brainerdi.* Newberry reported numerous specimens from a now long-abandoned quarry at Chagrin Falls (eastern Cuyahoga County) (1873) and from Independence (south-central Cuyahoga County) (1889).

Plant remains, mostly carbonized fragments of *Annularia,* and poorly preserved brachiopods, including *Lingula melie* and *Trigonoglossa,* have been reported (Szmuc, 1970).

SUNBURY SHALE

The Sunbury Shale has yielded fish remains and a restricted invertebrate assemblage that includes the brachiopods *Lingula melie* and *Orbiculoidea herzeri,* sponge spicules, scolecodonts, conodonts, and foraminifers (Szmuc, 1957). Localities in northern Ohio have yielded well-preserved, although disarticulated, remains of the shark *Stethacanthus.*

CUYAHOGA FORMATION

Certain members of the Cuyahoga Formation are abundantly fossiliferous locally throughout the State. In northern Ohio, Szmuc (1957) reported the following generic diversity for the Cuyahoga macrofauna: brachiopods, 37; bivalves, 20; gastropods, 9; cephalopods, 4; sponges, 4; anthozoans, 2; bryozoans, 5; arthropods, 3. The most notably abundant and diverse macrofauna is that of the Meadville member in the Cuyahoga Valley, particularly in Medina County. Szmuc (1970) indicated that the Meadville member is the most fossiliferous unit in northeastern Ohio, and more than 125 species of invertebrates have been reported; most common are bryozoans and the brachiopods *Unispirifer* and *Ericiatia. Szmuc* (1970) summarized the paleontology of the remaining members of the Cuyahoga Formation in northern Ohio.

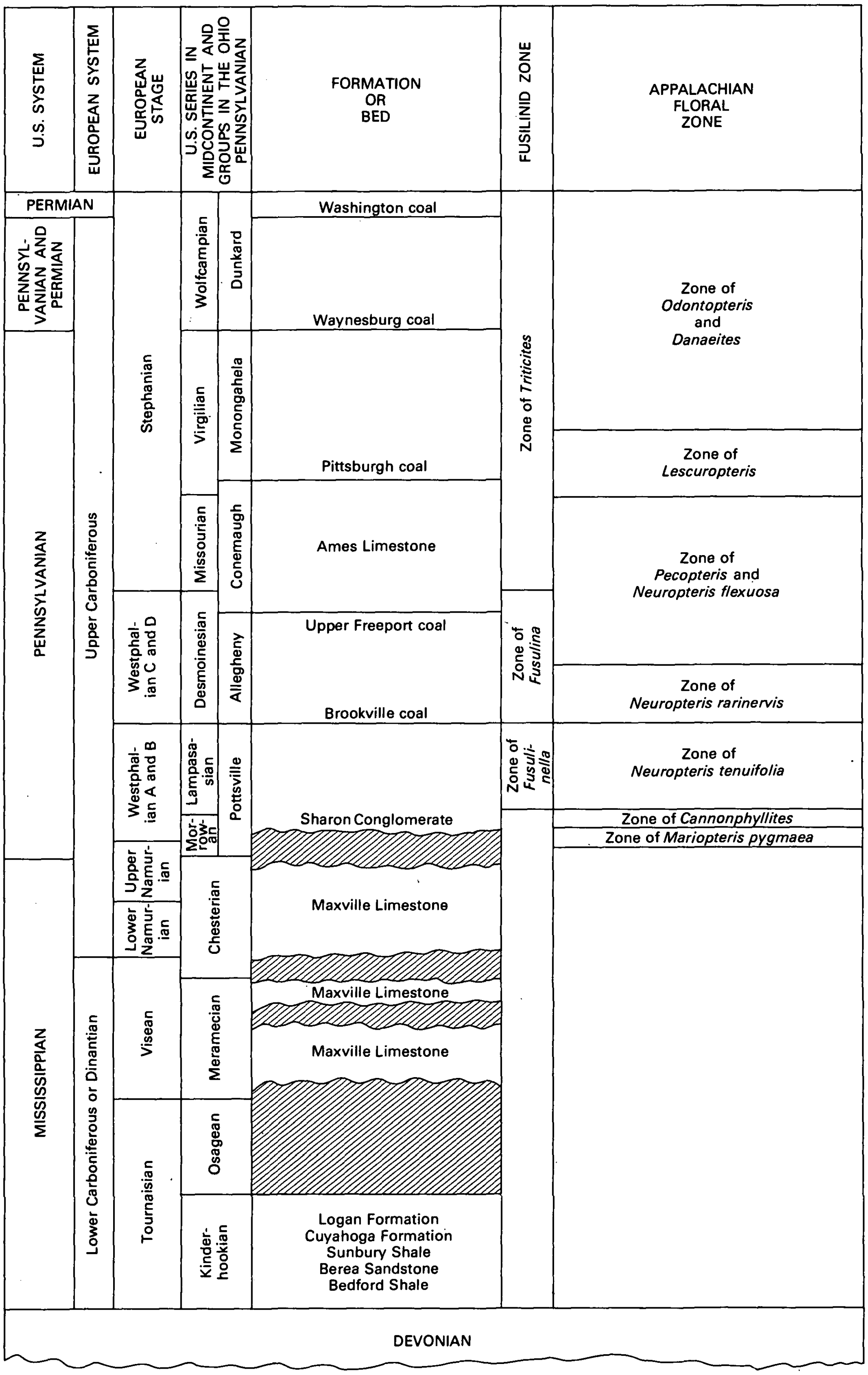

FIGURE 8.—Correlation chart showing the relationship of the Carboniferous section of Ohio to the European and U.S. midcontinent classification (modified from Moore and others, 1944; Weller and others, 1948; Dunbar and others, 1960).

The Cuyahoga fauna of central and southern Ohio has been reported upon most extensively by Hyde (1953), who listed numerous collecting localities. Manger (1971a) reported upon ammonoid cephalopods from the Cuyahoga of southern Ohio.

The most notable of the many collecting localities reported for the Cuyahoga Formation by Hyde (1953), is the Sciotoville Bar locality, a ledge along the northeast bank of the Ohio River in Scioto County, Ohio. This classic locality, from which Hyde obtained a large part of the fauna illustrated in the 1953 report, has been submerged since 1920 because of construction of a lock and dam. Manger (1971b) assigned the Sciotoville Bar locality to the upper part of the Portsmouth member.

LOGAN FORMATION

The fauna of the Logan Formation was described by Hyde (1953) and most comprehensively by Fagadau (1952). The clastic lithotope of the Logan Formation results in differing and, in some places, imperfect preservation of the macrofauna; however, Fagadau listed the following generic diversity of the Logan: bivalves, 22; brachiopods, 20; gastropods, 5; coelenterates, 5; ostracods, 2; trilobites, echinoderms, annelids, bryozoans, and scaphopods, 1 genus each.

Fagadau divided the Logan Formation into two faunal zones. The lower zone, which includes all strata below the Vinton member, is dominated by brachiopods, particularly *Rhipidomella missouriensis* var. *sulchella*, *Chonetes* cf. *C. pulchellus*, and *Spiriferina depressa*; however, the bivalve *Allorisma winchelli* and the gastropods *Tropidodiscus cyrtolites*, *"Worthenia" strigillata*, and *Platyceras haliotoides* are locally abundant. This lower zone of the Logan has faunal affinities with the underlying Cuyahoga Formation, as indicated by the mutual occurrence of 26 of the 62 species known from the Logan.

The upper zone of the Logan Formation, which includes the Vinton member, is dominated by brachiopods, of which *Dictyoclostus agmenes*, *Rhipidomella mesiolis*, and *Rhynchopora cooperensis* are the most important. *Composita* and *Pugnoides* make their first appearance in the middle part of this zone. Of the 25 species reported from the upper zone, 8 are present in the lower zone and 6 are known from the Cuyahoga Formation.

The Logan Formation is locally fossiliferous throughout its area of outcrop; however, the best collecting areas are in Licking, Fairfield, Ross and Scioto Counties. Fagadau (1952, p. 99) listed numerous localities, as did Hyde (1953).

MAXVILLE LIMESTONE

The macrofauna of the Maxville Limestone was studied by Morse (1910, 1911). Scatterday (1963) studied the conodont fauna, which serves as the principal basis for correlation of this unit. Of the 36 Maxville species listed by Morse (1910), 21 are mollusks; brachiopods, however are numerically dominant. Macrofossils are present throughout the Maxville, but they are most abundant, most easily obtained, and best preserved in the light-gray calcareous shale units. The massive sublithographic beds are seemingly less fossiliferous.

Numerous Maxville localities are listed by Morse (1910, 1911), Scatterday (1963), and Uttley (1974). A locality of particular note is the quarry Somerset Lime and Stone, Inc., west of Somerset in Hopewell Township, Perry County, Ohio.

PENNSYLVANIAN

The Pennsylvanian biota of Ohio has received considerable attention for more than a century, encouraged, in part, by the presence of economically valuable mineral deposits in these strata.

MARINE FAUNAS

Marine invertebrate faunas of the Pennsylvanian have been studied extensively, beginning in Ohio with the reports of the Ohio Geological Survey under the direction of J. S. Newberry (1869–1882). Smyth (1957) published on fusulinids, and Mark (1912) and Morningstar (1922) reported on the faunas of the Conemaugh and Pottsville Groups, respectively. More recently, Sturgeon and Hoare (1968) wrote the first monagraph on Pennsylvanian invertebrate groups in Ohio, a volume on brachiopods.

Sturgeon and Hoare (1968, p. 12), in reference to the brachiopod fauna, indicated that the Ohio fauna is slightly less diverse than that of the Western Interior basin; there are 42 genera and 93 species and varieties from the Ohio Pennsylvanian versus 46 genera and 130 species for the Western Interior basin. This reduced diversity for the Appalachian basin is probably evident in other faunal groups also. Multiple factors, including less favorable environments and physical barriers to migration into the Appalachian basin, are responsible for this reduction in diversity. In addition, an influential factor must be the absence of marine units in the upper Conemaugh and Monongahela Groups, which represent almost all the Virgilian sequence of the Western Interior basin (Sturgeon and Hoare, 1968, p. 13). Paleoecology of the Pennsylvanian marine faunas and environments have only recently received serious investigation. Principal investigators have been Donahue and Rollins (1974) and their students and Ferm (1970) and his students.

In Ohio, 28 marine horizons of Pennsylvanian age have been reported; only about 9 of these, however, can be considered important from the standpoint of yielding abundant and diverse faunas and of being widespread. The important units have produced faunas that include corals, bryozoans, fusulinids, arthropods, sponges, mollusks, and brachiopods. Generally, brachiopods are numerically dominant; however, the molluscan assemblage is more diverse. These units and faunas are most conveniently discussed by stratigraphic groups.

Pottsville Group.—Although 11 marine horizons have produced fossils in the Pottsville, the Lower and Upper Mercer limestones are most significant. Distinctive brachiopods in the Pottsville include *Cleiothyridina orbicularis* var. *crassalamellosa, Schizophoria resupinoides?, Rugosochonetes delicatus, Plicochonetes dotus, Desmoinesia muricatina* var. *missouriensis, Antiquatonia costellata, Juresania nebrascensis* var. *inflatia*, and *Krotovia paucispina* (Sturgeon and Hoare, 1968). Distinctive Pottsville fusulinids are *Fusulinella iowensis* and *F. stouti* (Smyth, 1957).

Allegheny Group.—Important marine units in the Allegheny Group are, in ascending order, Putnam Hill limestone, Vanport limestone, Columbiana shale, and Washingtonville shale. Diagnostic Allegheny brachiopods include *Composita girtyi, Wellerella tetrahedra, Mesolobus mesolobus, M. lioderma, Eolissochonetes fragilis, Chonetinella crassiradiata*, and *Reticulatia rugatia* (Sturgeon and Hoare, 1968). Distinctive fusulinids include *Wedekindellina euthysepta, Fusulina carmani, F. serotina*, and *F. leei* (Smyth, 1957).

Conemaugh Group.—The Brush Creek limestone, Cambridge limestone, and Ames limestone are the most important fossiliferous units in the Conemaugh. Distinctive brachiopods include *Derbyia parvicostata, Wellerella osagensis, Enteletes hemiplicatus, Orthotetes conemaughensis, Punctospirifer kentuckyensis* var. *amesi, Composita ohioense, C. magna, Neochonetes semiacanthus, N. granulifer, Chonetinella alata, C. flemingi, Hystriculina wabashensis, Pulchratia* cf. *P. ovalis, P. symmetrica* var. *regularis, Echinaria semipunctata, E. moorei, Antiquatonia portlockiana* var. *crassicostata, Reticulatia huecoensis, Juresania nebrascensis* var. *pulchra, Linoproductus* cf. *L. platyumbonus, L.* cf. *L. magnispinus*, and *L. oklahomae* (Sturgeon and Hoare, 1968). Distinctive Conemaugh fusulinids are *Triticites ohioensis, T. skinneri*, and *T. cullomensis* (Smyth, 1957).

Collecting localities.—Sturgeon and Hoare (1968) listed 346 localities from which they obtained 30,000 brachiopod specimens. Most of these localities have yielded a diverse assemblage of other invertebrate groups, and perhaps one-fourth have produced teeth or dermal spines of chondrichthyan fish. This locality register is the most comprehensive and up-to-date record available for marine Pennsylvanian fossils in Ohio.

NONMARINE FAUNAS (INCLUDING PERMIAN)

Nonmarine units yield faunas of bivalves, ostracodes, estherids, and vertebrates, including paleoniscoid and chondrichthyan fishes and, rarely, amphibians and reptiles. The nonmarine limestones yield diminutive molluscan faunas, but these units have never been collected systematically as have the marine horizons; therefore, their faunas are less well known. Eagar (1975) collected nonmarine bivalves from units in Ohio, discussed these faunas, and made comparison with other nonmarine faunas in North America and Europe.

Localities for nonmarine fossils are localized and less well known generally than are localities for marine units. Deserving of special mention, however, is the famous Linton vertebrate locality, at the mouth of Yellow Creek just south of Wellsville, section 7, Saline Township, Jefferson County, Ohio. A layer of cannel coal, several inches in thickness, at the base of the Upper Freeport coal (uppermost Allegheny Group), has produced remains of amphibians, paleoniscoid and chondrichthyan fishes, and phyllocarid crustaceans. This fauna has received considerable study by many authors, including Newberry (1873, 1875), Cope (1875), Romer (1930, 1963), Moodie (1909, 1915, 1916), Steen (1931), Baird (1964), and Westoll (1944). The mine dump of the long-abandoned Black Diamond mine still yields fossils to diligent collectors.

The Dunkard Group in Ohio has yielded fragmentary remains of amphibians, reptiles, freshwater chondrichthyans, paleoniscoids, and dipnoans. These remains must be considered rare, although the total of these specimens indicates a diverse "lake and pond" vertebrate fauna. Olson (1975) and Berman and Berman (1975) considered the fauna correlative to the classic Lower Permian Wichita and Clear Fork Groups of Texas. These authors and Lund (1975) recently summarized the Dunkard vertebrate fauna.

Vertebrate remains appear to be more abundant in the Washington Formation. Two localities are worthy of note. Moran (1952) reported the Cameron locality in section 18, Adams Township, Monroe County, Ohio, and Romer (1952) evaluated its fauna, which includes pleuracanth teeth, dipnoan remains, and the tetrapods *Eryops, Diploceraspis, Melanothyris,* and *Edaphosaurus,* among others. The Cameron locality yields fossils from a limestone and shale sequence about 2 to 3 m (7 to 10 ft) below the Waynesburg "A" coal. Olson (1970) summarized information on this locality.

The most productive vertebrate locality in the Dunkard Group of Ohio has been a localized channel conglomerate exposed near Belpre, Washington County. This deposit lies above the Upper Marietta sandstone near the top of the Washington Formation and has yielded a diverse, although fragmentary, vertebrate assemblage. Olson (1970, 1975) summarized the fauna of the Belpre locality; this fauna includes chondrichthyans, dipnonas, paleoniscoids, and the tetrapods *Eryops, Diploceraspis, Megamolgophus, Diadectes, Edaphosaurus,* and *Dimetrodon.*

An important nonmarine invertebrate occurrence in Belmont County is the presence of *Lingula permiana* in a shale parting of the Washington coal. This is the only known appearance in Ohio of a brackish-water form above the mid-Conemaugh Skelley limestone.

PLANTS (INCLUDING PERMIAN)

Plant impressions and compressions are abundant throughout the section, particularly in the shales overlying coals. The flora of the Pennsylvanian in the Appalachian basin was divided into several zones by Read (1947). The flora of Read's *Mariopteris pygmaea* zone (fig. 8) is found in the roof shale of the Sharon coal (Pottsville Group) in northeastern Ohio. Casts and molds of *Lepidodendron, Stigmaria,* and *Calamites* are common in sandstone, particularly that directly overlying coal. Petrifactions are less common, although some notable examples have been found. The Middle Branch of the Shade River in Lodi Township, Athens County, has long been famous for well-preserved (petrified) *Psaronius.* Hildreth (1838, p. 43) first described this general locality, and Andrews (1873, p. 287–288) placed the stratigraphic position in the lower part of the Monongahela (above the Pomeroy coal of Andrews); Andrews also used the term *Psaronius* in his text. Blickle (1940) and Morgan (1959) described *Psaronius* of the Shade River area in detail from the extensive collection of Blickle. Coal balls containing poorly preserved material have been known from Ohio for several years (Denton and others, 1961, p. 154); however, only recently did Rothwell (1976) and Good and Taylor (1974) describe well-preserved coal-ball floras from the middle Conemaugh and Monongahela Groups, respectively.

The first flora reported from Ohio and one of the earliest, if not the earliest, paleobotanical account in the United States was published in 1821 by Ebenezer Granger on plant impressions found in the uppermost part of the Pottsville Group at Zanesville, Muskingum County, Ohio. The material, which included *Neuropteris grangeri* Brongniart, was collected by Granger probably just below the Brookville coal at the Putnam Hill section on the west bank of the Muskingum River.

Another locality with a rich and interesting flora was described by Andrews (1875) from the lower part (7–9 m or 25–30 ft above the Maxville Limestone) of the Pottsville Group; the specimens were collected about 2 miles east of Rushville, Perry County, Ohio. Specimens identified and illustrated by Andrews included several species of *Megalopteris* and *Orthogoniopteris.* These localities, and many others, are listed and discussed by Stout (1945). Many other papers on Carboniferous floras are listed by Romans and McCann (1974).

ECONOMIC PRODUCTS

Carboniferous rocks in Ohio have been and continue to be a major source of valuable mineral resources. The Pennsylvanian is most noted for coal, but clay, sandstone, shale, and oil and gas (mostly in the past) have also made important contributions to the State's mineral wealth. Sandstone, oil and gas (mostly in the past), and shale have been the major resources produced from Mississippian rocks.

COAL

Coal is clearly the leading economic product of the Pennsylvanian System in Ohio and, in fact, is the most valuable mineral resource produced in the State. Coal beds assignable to the Monongahela Group (Upper Productive of early classifications) are the State's current major producing seams. Coals of the Allegheny Group (Lower Productive of early classifications) presently are second in total production. Coals of the Pottsville Group were formerly produced in Ohio, whereas mining of coal of the Conemaugh (Lower Barren of early classifications) has been of very minor importance. The Mississippian System in Ohio is not coal bearing.

From 1800, the first year of recorded production, to 1974, more than 2.7 billion tons of coal were mined in Ohio. The highest tonnage recorded for a single year was 55.1 million tons in 1970. The second highest year was 1918, when more than 47.9 million tons were mined. The character of the State's coal mining industry changed dramatically from 1918, when less than 2 million tons of coal was produced by open-pit methods, to 1970, when about 37 million tons of the record total was from open pits. Strip mining began in Ohio in 1914, but did not become important until World War II. From 1960 to 1970, strip mining increased and in 1970 accounted for more than 70 percent of the State's total production. In recent years, however, the percentage of the State's coal production from underground mining has been increasing slowly (Collins, 1976).

At the present time, the most productive seams are, in descending order of importance, Pittsburgh (No. 8), Meigs Creek (No. 9), Middle Kittanning (No. 6), Lower Freeport (No. 7A), and Waynesburg (No. 11). The Upper Freeport (No. 7), Lower Kittanning (No. 5), Quakertown (No. 2), and Sharon (No. 1) coals were formerly more extensively mined, but depletion of reserves, changes in mining methods, and economics have greatly reduced the importance of these seams.

Ohio's coals all fall into the high-volatile, bituminous rank and range from 5 to 20 percent ash, from 1 to 6 percent sulfur, and from 10,000 to 13,000 Btu. Low-sulfur coals, principally the Sharon and Quakertown, were formerly mined in Ohio, but most of the known reserves of these coals have been depleted. Most of the State's remaining resources fall into the medium (1.1 to 3.0 percent) to high (more than 3 percent) sulfur range.

On the basis of the latest resource tabulation of 46,488,251,000 tons (Brant and DeLong, 1960), less 5,395,442,000 tons mined and lost to mining and less 50 percent postulated to unavailability, 20, 546,404,500 tons are left as Ohio's resource base. The resource base, however, includes coal not minable under current economic and technological conditions and, therefore, does not define the amount of coal that is presently available for production.

CLAY AND SHALE

Clay was formerly produced in considerably greater quantities than it is at present. Competition from concrete and plastics and from foreign pottery has made major inroads on Ohio's pottery and structural clay products industry. However, Ohio has traditionally led the Nation in the production of fireclays (coal underclays) and the production of structural clay products (such as sewer pipe, drain tile, and brick). Ohio is also a major producer of refractories.

Buff-burning clays particularly suitable for face brick are confined entirely to the Pennsylvanian System and primarily to the Pottsville and Allegheny Groups. The Allegheny Group is the principal clay-producing sequence of the State, primarily because of the Lower Kittanning clay. The Lower Kittanning, which immediately underlies the Lower Kittanning coal, is both the State's most widespread and most productive clay unit. This unit has been worked extensively for clay used in the manufacture of such products as refractories, sewer tile, building brick, wall and floor tile, and pottery; Lower Kittanning clay also has been used in cement for lightweight aggregate and as foundry bonding clay.

The Clarion, Oak Hill, Middle Kittanning, Lower Freeport, and Upper Freeport are other important clay units of the Allegheny Group. At the present time only the Clarion is being widely produced.

The clay resources of the Pottsville Group are the second most important in the State in production. The Tionesta and Brookville clays are worked rather extensively for use in the manufacture of face brick, sewer tile, wall tile, and refractories and are next in importance to the Lower Kittanning.

The clays of the Conemaugh and Monongahela Groups tend to be thin and discontinuous and are for the most part unsuited for ceramic use; these clays have been of little importance to the State's ceramic industry.

The Mississippian-age Bedford Shale and Logan Formation are worked in several localities in the State for clay used in the manufacture of face brick and tile. Pennsylvanian-age shale is sometimes blended with the clay to lower the firing range of the product.

SANDSTONE

Ohio is the largest producer of sandstone in the United States. Sandstone was one of the first mineral resources of the Carboniferous to be exploited by the early European settlers in Ohio (Stout, 1944). Sandstones useful for building stone, flagging, curb stone, decorative stone, refractories, grindstonė, and pulpstone are abundant throughout the Carboniferous. In a few localities, upper Mississippian and lower Pennsylvanian sandstones are suitable sources of glass sands and silica pebble.

The use of sandstone as building stone has decreased substantially since the early 1900's owing to the use of cement block and brick. Grindstones have similarly lost favor to artificial abrasives. Even though many classical uses of sandstone have diminished over the years, other uses have been found, and production still remains relatively high. Present uses include dimension stone, aggregate, glass sand, metallurgical pebble, refractory linings, foundry sand, and riprap.

The principal sandstone units that have been developed in the Mississippian include units in the Bedford and Berea and units of the Cuyahoga, notably the Buena Vista and the Black Hand. Presently the Berea Sandstone in Lorain, Erie, and Huron Counties to the north and the Buena Vista member of the Cuyahoga Formation in Scioto County to the south are the principal producing units.

The Pennsylvanian System in Ohio contains many beds of sandstone about 6 to 12 m (20 to 40 ft) in thickness and several that locally thicken to as much as 31+ m (100+ ft). Many of these units have been exploited locally on a small scale. Two units, the Sharon conglomerate and Massillon sandstone, have been rather widely developed commercially and are the principal producing units at the present time.

OIL AND GAS

Carboniferous rocks have played a significant role in the development of the oil and gas industry in Ohio. Oil was known to exist in Ohio from the earliest days of statehood. A brine well drilled in 1814 in Noble County yielded large quantities of oil and gas (Hildreth, 1833, p. 64). Commercial development, however, did not start until 1859–60, when a gas well was developed in the Berea Sandstone at East Liverpool, Columbiana County. The success of the Drake well in western Pennsylvania in 1859 sparked drilling activity in several areas of eastern Ohio. Carboniferous rocks were the object of interest in these early exploration programs.

Oil was discovered in 1860 at Macksburg, Washington County, in stratigraphic units assignable to the Pennsylvanian-age Conemaugh Group and in Mecca Township, Trumbull County, in the Mississippian-age Berea Sandstone. By the late 1800's, oil and gas had been discovered also in the Mississippian-age Cuyahoga and Logan Formations and in the Pennsylvanian-age Pottsville and Allegheny Groups.

With the exception of the Berea Sandstone, extensive development of Carboniferous rocks in Ohio for oil and gas seems to be unlikely. The Berea, because of its much greater persistence and, in some areas, more uniform thickness, still offers opportunity for development.

LIMESTONE

The Maxville Limestone, as stated earlier, is the only carbonate unit in the Mississippian System of Ohio, and is the single most important limestone in the Carboniferous. The Maxville has been used for the manufacture of agricultural lime, quicklime, cement, road metal, railroad ballast, blast-furnace flux, and dimension stone. Presently, the unit is worked underground in Muskingum County for the manufacture of cement. Stone for riprap, road metal, concrete aggregate, and agricultural lime is quarried in the same area, as well as in Perry County. The Maxville formerly was deep-mined in Upper Township, Lawrence County, for cement stone.

Several Pennsylvanian-age marine limestones are commercially quarried: the Putnam Hill and Vanport limestones in the Allegheny Group and the Brush Creek and Cambridge limestones in the Conemaugh Group. The Vanport is the most extensively worked of these units. The bed is presently quarried for cement stone in Lawrence and Mahoning Counties and for riprap, road metal, and cement aggregate in Jackson, Lawrence, Mahoning, and Tuscarawas Counties. The unit is quarried for fluxstone in Mahoning County.

The Putnam Hill is worked for cement stone as well as for crushed stone in Stark County. The Brush Creek limestone is quarried for crushed stone in Athens County, and the Cambridge limestone is quarried for the same purpose in Guernsey County.

Freshwater limestones of the Conemaugh and Monongahela Groups are worked in a very small way for agricultural lime and for road metal. The Ewing limestone (Conemaugh Group) in Noble County, the Fishpot limestone (Monongahela Group) in Belmont and Harrison Counties, and the Benwood limestone (Monongahela Group) in Morgan and Washington Counties are the units presently being worked.

Other Pennsylvanian units have been worked on a minor scale. The thinness of the marine beds and the poor quality of the freshwater units are limiting factors in the use and development of these resources.

GROUND WATER

Ground water is not produced in prolific amounts from the Carboniferous rocks of Ohio, and major supplies must be obtained from surface waters. Units in the Pennsylvanian System throughout the State, with some notable exceptions, produce water at a general rate of 0.3 liters per second (5 gallons per minute) or less. Major exceptions are the Sharon and Massillon sandstones (Pottsville Group), which normally produce 2 to 6 liters per second (25 to 100 gallons per minute). Rare local exceptions do occur, and production of several hundred gallons per minute has been reported from Pennsylvanian units. Low ground-water yield is related to the fact that the Pennsylvanian section is to a large extent composed of impermeable shale and mudstone and sandstone which tend to have relatively low permeabilities.

Mississippian sandstone is generally somewhat cleaner, better sorted, and more permeable. Mississippian sands also tend to be somewhat more regular in distribution. Most of the region where water may be obtained from these sands will yield 0.3 to 2 liters per second (5 to 25 gallons per minute). As in the overlying Pennsylvanian, a unit rarely delivers several hundred gallons per minute.

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The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—Kentucky

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CONTENTS

ILLUSTRATIONS

THE MISSISSIPPIAN AND PENNSYLVANIAN (CARBONIFEROUS) SYSTEMS IN THE UNITED STATES—KENTUCKY

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ABSTRACT

Kentucky is unique among the States of the Eastern United States in that it contains parts of two major sedimentary basins that have nearly complete successions of Carboniferous rocks. These basins, the Appalachian and Eastern Interior, each contain more than 2,100 m of Mississippian and Pennsylvanian strata.

Carboniferous strata directly underlie four of Kentucky's six principal physiographic regions: the Knobs, Mississippian Plateau, Western Coal Field, and Cumberland Plateau. Weathering and erosion of Carboniferous rocks in these regions have produced a variety of scenic features such as caverns, gorges, natural bridges, and waterfalls.

Mississippian rocks conformably overlie Late Devonian strata and are principally of marine origin. Environments of deposition ranged from relatively deepwater basin to lower delta plain. The Mississippian succession in the State consists of four major lithogenetic groups: (1) distal terrigenous detrital deposits of westward and southward prograding deltaic systems (Kinderhook, Osage); (2) marine carbonate deposits, partly basinal, but dominantly shelf limestone and dolomite (Osage, Meramec); (3) rhythmically alternating marine carbonate and terrigenous detrital deposits, shelf limestone alternating with sandstone and shale from a southward and southwestward prograding delta (Chester); and (4) terrigenous detrital deposits of westward- and southward-prograding deltaic systems (Chester). Major source areas for terrigenous sediments were to the northeast and east of Kentucky. Penecontemporaneous tectonic activity is suggested by distinct variations in the thickness and distribution of units along the trends of major structural features in parts of the State. Some biostratigraphic zones virtually correspond with lithostratigraphic units and serve as practical aids in field identification.

The Mississippian-Pennsylvanian systemic boundary generally is marked by an erosional unconformity, which locally may represent a removal of more than 275 m of Mississippian strata in western Kentucky and more than 60 m in eastern Kentucky. In southeastern Kentucky, deposition was continuous from Late Mississippian into Early Pennsylvanian time. A recently proposed thesis that the Mississippian-Pennsylvanian unconformity in northeastern Kentucky is a depositional or facies boundary is untenable in view of field relationships between lithologic units in the area. The sub-Pennsylvanian surface across east-central and northeastern Kentucky also shows a truncation of progressively older Mississippian strata toward the north.

The Pennsylvanian strata of eastern Kentucky form a clastic wedge that thickens southeastward toward the axis of the Appalachian basin. The rocks are largely deltaic in origin, dominantly thick orthoquartzite in the lower part and siltstone, shale, and relatively thin discontinuous subgraywacke in the upper part. Channel-fill deposits of pebbly orthoquartzite of the Lee Formation (Morrow) form a series of broad lobes generally oriented northeast-southwest, parallel with the axis of the Appalachian basin and with a dominant southwest transport direction. The Breathitt Formation (Morrow, Atoka, Des Moines) consists of siltstone, clay shale, subgraywacke, coal, ironstone, and limestone. It was deposited largely in lower and upper delta-plain environments: tidal flats, interdistributary bays, swamps, and shallow anastomosing stream channels. As many as 30 major coal beds or coal zones are present in the formation. Stratigraphic subdivision of the Breathitt is based on recognition of key beds, particularly marine units, and sequences of key beds. The Conemaugh and Monongahela Formations (Missouri, Virgil) are present in northeastern Kentucky. In contrast with the dark-colored shale of the Breathitt, the Conemaugh and Monongahela are characterized by the presence of red, green, and variegated shale. The formations apparently represent deltaic deposits that were repeatedly inundated by eastward-transgressing seas.

The Pennsylvanian strata of western Kentucky in the southern part of the Eastern Interior basin also are largely deltaic in origin. Their lithology is similar to that of the Lee and Breathitt Formations of eastern Kentucky except that marine limestones, representing as many as 35 transgressions, form a larger part of the succession. About 24 principal coal beds or coal zones have been identified in western Kentucky. Limestones are important key beds for stratigraphic subdivision, but the most useful marker bed is the No. 11 coal bed which has a distinctive clay shale parting. Subsidence was relatively uniform across the basin during Early and Middle Pennsylvanian time; the alternation of shallow marine and deltaic deposits probably is related to the shifting of southward and southwestward prograding delta lobes.

Carboniferous rocks are the major source of mineral resources in Kentucky. The State currently is the leading producer of bituminous coal in the United States and has an estimated original reserve of about 65.6×10^9 metric tons of

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high-voltatile A and B bituminous coal in the Pennsylvanian deposits of eastern and western Kentucky. A large percentage of the oil, natural gas, and industrial and metalic minerals produced in the State has come from Carboniferous rocks.

INTRODUCTION

Carboniferous strata underlie and crop out in about two-thirds of the surface area of Kentucky (fig. 1). The State is unique in the Eastern United States because it contains parts of two major sedimentary basins that have nearly complete successions of Carboniferous rocks. These basins, the Appalachian and the Eastern Interior, though different in their tectonic and depositional histories, each contain more than 2,100 m of Carboniferous strata in Kentucky representing both the Mississippian and Pennsylvanian Systems. The basins are linked by a belt of lower Carboniferous rocks (Mississippian Osage and Meramec ages) extending across the Cincinnati arch in south-central Kentucky. Mississippian rocks (mainly limestone, sandstone, shale, and siltstone) are dominantly marine in origin, and Pennsylvanian rocks (mainly sandstone, siltstone, shale, and coal) are dominantly of deltaic and fluvial origin.

Carboniferous rocks are the major source of mineral resources in Kentucky. The State currently is the leading producer of bituminous coal in the United States, producing from Pennsylvanian deposits in both the Appalachian and Eastern Interior basins—the eastern and western Kentucky coal fields, respectively. Carboniferous units are also a principal source of petroleum, natural gas, limestone, sandstone, shale, clay, fluorspar, sphalerite, galena, barite, and, formerly, iron ore.

The stratigraphic nomenclature used in this paper has not been reviewed by the Geologic Names Committee of the U.S. Geological Survey. The nomenclature used here conforms with current usage of the Kentucky Geological Survey.

PHYSIOGRAPHY

Carboniferous strata directly underlie four of Kentucky's six principal physiographic regions: the Knobs, Mississippian Plateau, Western Coal Field, and Cumberland Plateau (fig. 2). The other regions in the State are the Blue Grass, underlain by Ordovician, Silurian, and Devonian rocks, and the Mississippi Embayment where Cretaceous and Tertiary sedimentary deposits rest on Paleozoic rocks.

The Knobs region is a narrow, arcuate belt of conical hills, or knobs, around the outer border of the Blue Grass region. The Knobs are erosional remnants, consisting of Mississippian (Osage) shale and siltstone, which occur along the front of the Pottsville escarpment across east-central Kentucky and along the front of Muldraughs Hill across west-central and south-central Kentucky. Muldraughs Hill is a limestone-capped escarpment bordering the

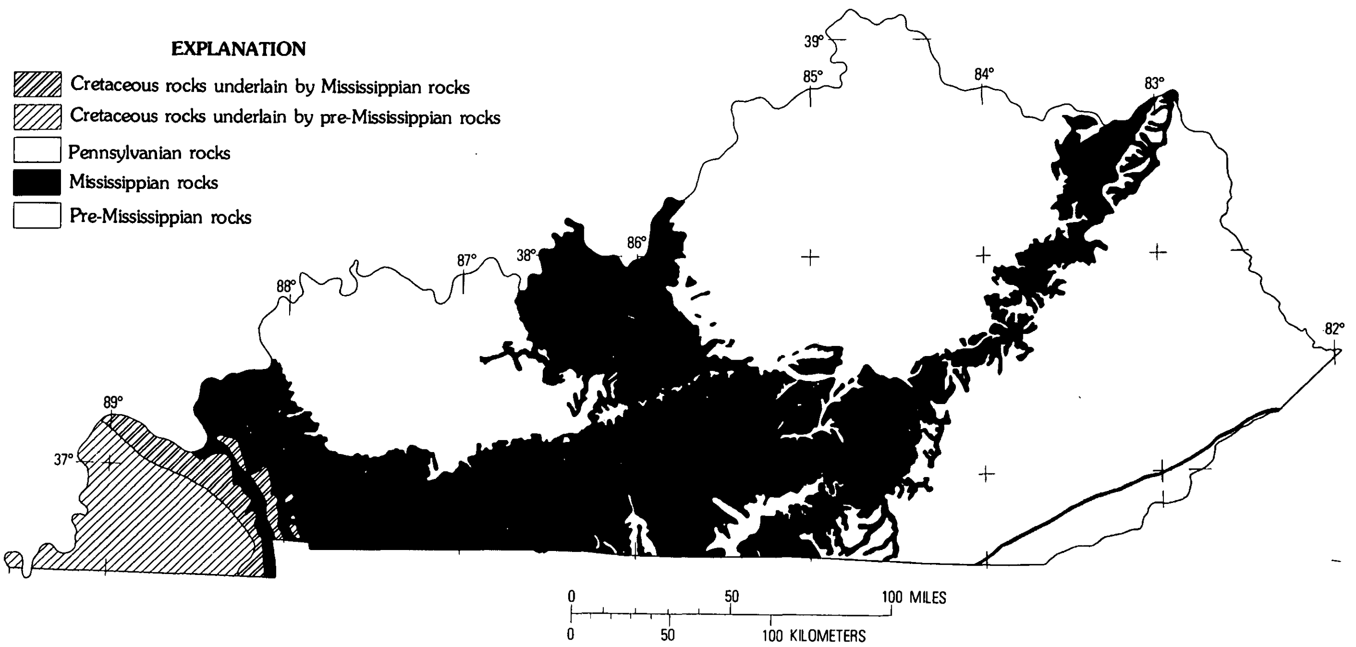

FIGURE 1.—Geologic map of Kentucky showing distribution of Carboniferous rocks.

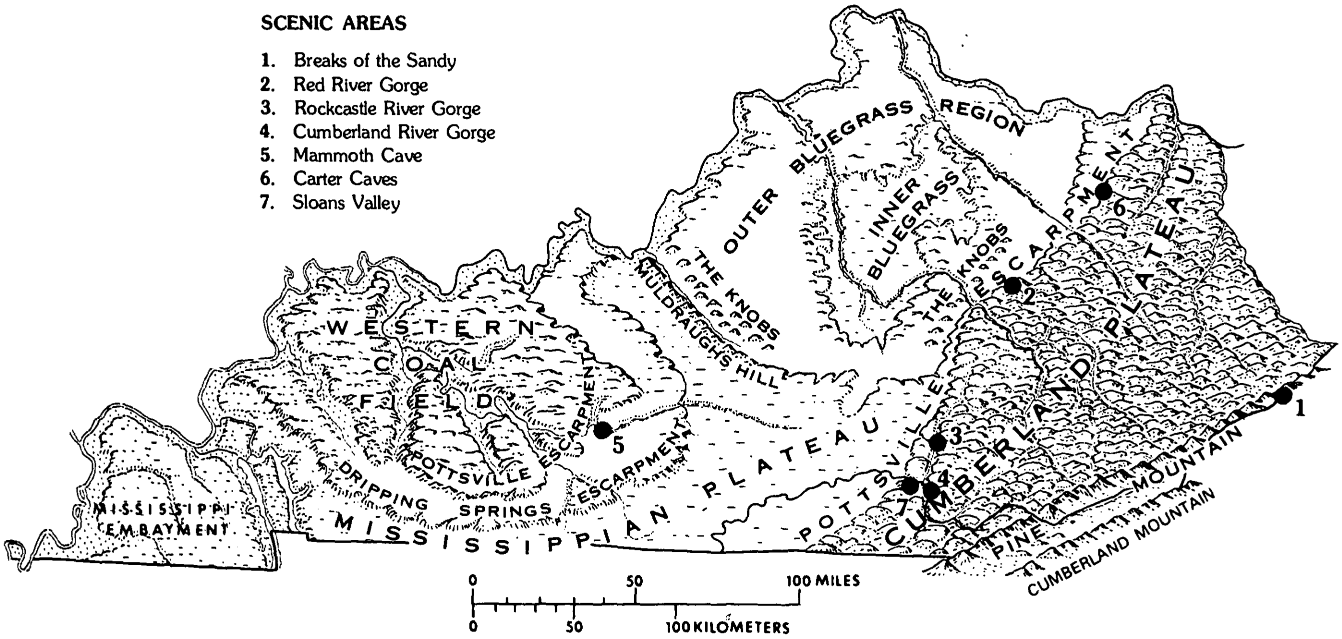

FIGURE 2.—Physiographic diagram of Kentucky (From Lobeck, 1929), showing the location of scenic areas.

Mississippian Plateau region; the Pottsville escarpment, capped by Lower Pennsylvanian sandstone, borders the Cumberland Plateau.

The Mississippian Plateau forms a broad, arcuate belt around the Western Coal Field and extends eastward to the Pottsville escarpment. It consists of two principal parts divided by the Dripping Springs escarpment, an east- and south-facing ridge generally capped by the Big Clifty Sandstone Member of the Golconda Formation (Chester). The outer part is a broad plain with extensive karst development underlain mostly by the St. Louis and Ste. Genevieve Limestones (Meramec). The inner part of the plateau is a dissected upland of moderate relief underlain by limestone, sandstone, and shale of Chester age.

The Western Coal Field is a gently rolling to hilly upland dissected by streams occupying broad, very flat, poorly drained and often swampy valleys. Two major rivers drain the area; one has its headwaters in the coal field. The area is underlain by Pennsylvanian (Morrow-Virgil) shale, sandstone, limestone, and coal. Deep weathering has made natural exposures sparse except along the margins of the basin where streams have cut into the older and generally more resistant Lower Pennsylvanian rocks. Sandstone of the Caseyville Formation (Morrow) forms prominent ridges and cliffs along parts of the border of the coal field, and these constitute the Pottsville escarpment of that area.

The Cumberland Plateau, which is underlain by Pennsylvanian (Morrow-Virgil) shale, sandstone, and coal, is an intricately dissected upland of concordant sharp ridges and V-shaped valleys. It is bordered on the west by the Pottsville escarpment. Lower Pennsylvanian (Morrow) sandstone, overlain by less resistant shale, locally forms broad uplands of little relief along the south-central and southwest border of the plateau. Pine and Cumberland Mountains, two northeast-trending ridges also capped by Lower Pennsylvanian (Morrow) sandstone, border the plateau on the southeast. Four rivers drain the area, three of which have their headwaters generally in or near Pine and Cumberland Mountains where local relief is as much as 700 m.

SCENIC FEATURES

Weathering and erosion of Carboniferous rocks in Kentucky have produced a variety of scenic features of interest to both laymen and geologists (McFarlan, 1958). Many of these features are available to the general public and have been incorporated into State and National parks (fig. 2). Some of the most spectacular scenery in the State is found in the Breaks of the Sandy, a gorge cut through the north end of Pine Mountain by the Russell Fork of the Big Sandy River (McGrain, 1975), and in the gorges of the Red, Rockcastle, and Cumberland Rivers and South Fork of the Cumberland River along the western border of the Cumberland Plateau. Many natural bridges have formed in narrow, sandstone-capped divides, particularly in the Red River area (McFarlan, 1954), and many waterfalls, including the 20-m Cumberland Falls (McGrain, 1955), have formed on resistant Pennsylvanian sandstone.

The Mississippian Plateau of western Kentucky is a classic karst region, containing a broad sinkhole plain and extensive systems of underground drainage and caverns, including the Mammoth Cave-Flint Ridge cave system, formed in the St. Louis and Ste. Genevieve Limestones, and Girkin Formation (Mississippian) (Liversay, 1953). In eastern Kentucky, caves that have formed locally in the Mississippian limestone northwest of the Pottsville escarpment include the Carter and Cascade Caves in the northern part of the area (McGrain, 1954) and those in the Sloans Valley system near the south border of the State (Malott and McGrain, 1977).

The conical hills of the Knobs, remnants of the uplands behind the retreating Muldraughs Hill and Pottsville escarpment, form a striking example of an erosional landscape (McGrain, 1967).

Many exposures of Carboniferous rocks can be found in roadcuts along major Federal and State highways, in strip mines of the eastern and western coal fields, and in limestone quarries. (See, for example, Dever and McGrain, 1969; Smith and others, 1969, 1971; Stokley and McFarlan, 1952). Extensive exposures of complex Pennsylvanian deltaic sequences of shale, sandstone, and coal are found in roadcuts as much as 100 m high in eastern Kentucky, particularly along U.S. Highway 23 in the vicinity of Pikeville.

GENERAL HISTORY OF THE CARBONIFEROUS

The Carboniferous periods in Kentucky have generally been treated as three separate topics: the Mississippian and the Pennsylvanian of eastern Kentucky and the Pennsylvanian of western Kentucky.

Miller (1919, p. 94–141), in the first comprehensive synthesis of the geology of Kentucky, cited early work on Mississippian rocks by D. D. Owen, A. F. Foerste, E. O. Ulrich, Charles Butts, Stuart Weller, and others. These pioneer efforts were followed by systematic studies of Mississippian rocks in Kentucky and adjacent States by Butts (1917, 1922), Ulrich (1917), Stockdale (1939), and by several State surveys in a cooperative plan for geologic mapping along the borders of the Eastern Interior basin (Weller and Sutton, 1940). McFarlan (1943, p. 57–95), incorporated results of these later studies in an expanded revision of Miller's earlier synthesis. Definitions and correlations of Upper Mississippian rock units in western Kentucky were refined by Stouder (1941) and McFarlan and others (1955), and in eastern Kentucky by McFarlan and Walker (1956).

The first usable subdivision of the Pennsylvanian strata of eastern Kentucky was made by Campbell. He named the Lee Formation in the Cumberland Mountains (1893) and later described the formation in exposures near the Pottsville escarpment (1898), giving the name Breathitt Formation to the overlying Pennsylvanian rocks. In northeastern Kentucky, Phalen (1912) divided the Pennsylvanian rocks into the Pottsville, Allegheny, Conemaugh, and Monongahela Formations. Ashley and Glenn (1906) subdivided the thick sequence of Breathitt rocks of the Cumberland overthrust block and named the Hance, Mingo, Catron, Hignite, and Bryson Formations, selecting certain coal beds as formational boundaries.

Extensive stratigraphic analyses and syntheses of the Pennsylvanian rocks of eastern Kentucky have been made by Wanless (1939, 1946, and 1975a) as a part of his studies of the Appalachian basin. Huddle and others (1963), aided by many earlier reports of the Kentucky Geological Survey and the U.S. Geological Survey, made detailed stratigraphic analyses of each coal district in eastern Kentucky and computed its coal reserves.

The earliest geological work in the western Kentucky coal field was carried out by Owen from early 1854 to 1859. He named the Caseyville Formation and the principal limestone beds of the overlying "Coal Measures," and established the system of numbering coal beds that has been only slightly modified by subsequent work. Significant stratigraphic contributions were made by Glenn (1912a and b, and 1922), who named the Tradewater, Lisman, and Dixon Formations, and extended the Carbondale Formation from Illinois into Kentucky. Kehn (1973) combined the Lisman and Henshaw Formations to form the Sturgis Formation. Other important contributions include reports by Hutchinson (1912) and Lee (1916), who were first to map and describe in detail the stratigraphy of the Pennsylvanian of western Kentucky, and Smith and Smith (1967), who were first to describe in detail the upper part of the Pennsylvanian section. Wanless (1975b) summarized the stratigraphy of the Western Coal Field as a part of his investigation of the Pennsylvanian of the Eastern Interior basin (Illinois basin).

In 1960, the U.S. Geological Survey and the Kentucky Geological Survey began a cooperative geological mapping program, and by 1977, all Kentucky had been mapped geologically at a scale of 1:24,000; these maps are published in the GQ (Geologic Quadrangle) Map Series of the U.S. Geological Survey. During this period, many refinements were made in Carboniferous lithostratigraphy (Englund and Windolph, 1971; Kepferle, 1971; Kepferle and Lewis, 1974; Lewis, 1971; Outerbridge, 1976; Sable and others, 1966; Weir and others, 1966); resource investigations by the Kentucky Geological Survey involving oil and gas, coal, limestone, and clay were accelerated, along with associated stratigraphic studies, and have resulted in many publications by the State Survey. Investigators using the geologic maps have published other research reports on details of the stratigraphy and sedimentation of the Mississippian (Kepferle, 1977; Weir, 1970; Indiana University, 1969, 1972; Vincent, 1975) and of the Pennsylvanian (Englund, 1964; Kehn, 1973; Kosanke, 1973). The most recent summary of Carboniferous rocks of the Eastern Interior basin (Pryor and Sable, 1974) covers parts of Kentucky and cites principal modern references. Stratigraphic information collected during the cooperative mapping program was used in compiling the present report.

MISSISSIPPIAN SYSTEM

Mississippian rocks in Kentucky are principally marine; environments of deposition ranged from relatively deepwater basin through shallow subtidal and supratidal to lower delta plain. Dominant lithologies, relative thicknesses, and relationships of Mississippian units are shown in figure 3. Nomenclature and unit correlations currently used in Kentucky are basically lithostratigraphic (figs. 4 and 5). Some biostratigraphic zones virtually correspond with lithostratigraphic units and serve as practical aids in field identification and mapping (fig. 6).

GEOLOGIC SETTING

Basal Mississippian rocks throughout Kentucky conformably overlie rocks of Late Devonian age, which are principally dark carbonaceous shale (Chattanooga, New Albany, and Ohio Shales) (fig. 4). The top of the Chattanooga and New Albany is the top of the Devonian succession in western, southern, and west-central Kentucky. Carbonaceous shale of Mississippian age, correlative with the Sunbury Shale, is present in uppermost New Albany beds of east-central Kentucky and the upper Chattanooga of southeastern Kentucky. In the parts of northeastern and southeastern Kentucky where the Bedford Shale and Berea Sandstone are present between the Ohio (or Chattanooga) and Sunbury Shales, the systemic boundary is within the Bedford Shale.

Mississippian strata in much of Kentucky are overlain by Pennsylvanian (Morrow) rocks. The systemic boundary generally is a disconformity, but strata that show continuous deposition extending from Late Mississippian into Early Pennsylvanian time are locally preserved in southeastern Kentucky. In extreme western Kentucky, Cretaceous sediments of the Mississippi Embayment unconformably overlie Mississippian units (fig. 1).

The Appalachian and Eastern Interior basins presently are separated by the north-trending Cincinnati arch. (See fig. 15.) The exact nature of the arch during Carboniferous time is uncertain. It was a positive feature during Late Devonian time, but depositional patterns in the Borden Formation (Osage) show no evidence of a north-trending arch across central Kentucky in Early Mississippian time. The Appalachian and Eastern Interior basins apparently were connected across southern Kentucky throughout Mississippian time, but the arch may have been a shoal or emergent lowland in northern Kentucky during the Late Mississippian. Tectonic activity during the Carboniferous is suggested by distinct thickness variations in Upper Mississippian units along the trends of the Kentucky River fault system and Waverly arch in northeastern Kentucky (Dever and others, 1977) and, conjecturally, along the trend of the Rough Creek fault system in western Kentucky (Craig and Connor, 1978) (see fig. 15).

STRATIGRAPHY

The Mississippian succession in Kentucky consists of four major lithogenetic groupings:

1. Distal terrigenous detrital deposits (shale, siltstone, and sandstone) of westward and southward prograding deltaic systems (Kinderhook, Osage): Bedford Shale, Berea Sandstone, Sunbury Shale, and Borden Formation below the Floyds Knob Bed.
2. Marine carbonate deposits, partly basinal but dominantly shallow-water shelf limestone and dolomite (Osage, Meramec): Fort Payne Formation, Muldraugh and Renfro Members of Borden Formation; Warsaw, Harrodsburg, Salem, St. Louis, and Ste. Genevieve Limestones.
3. Rhythmically alternating marine carbonate and terrigenous detrital deposits, shallow-water shelf limestone alternating with sandstone and shale from a southward and southwestward

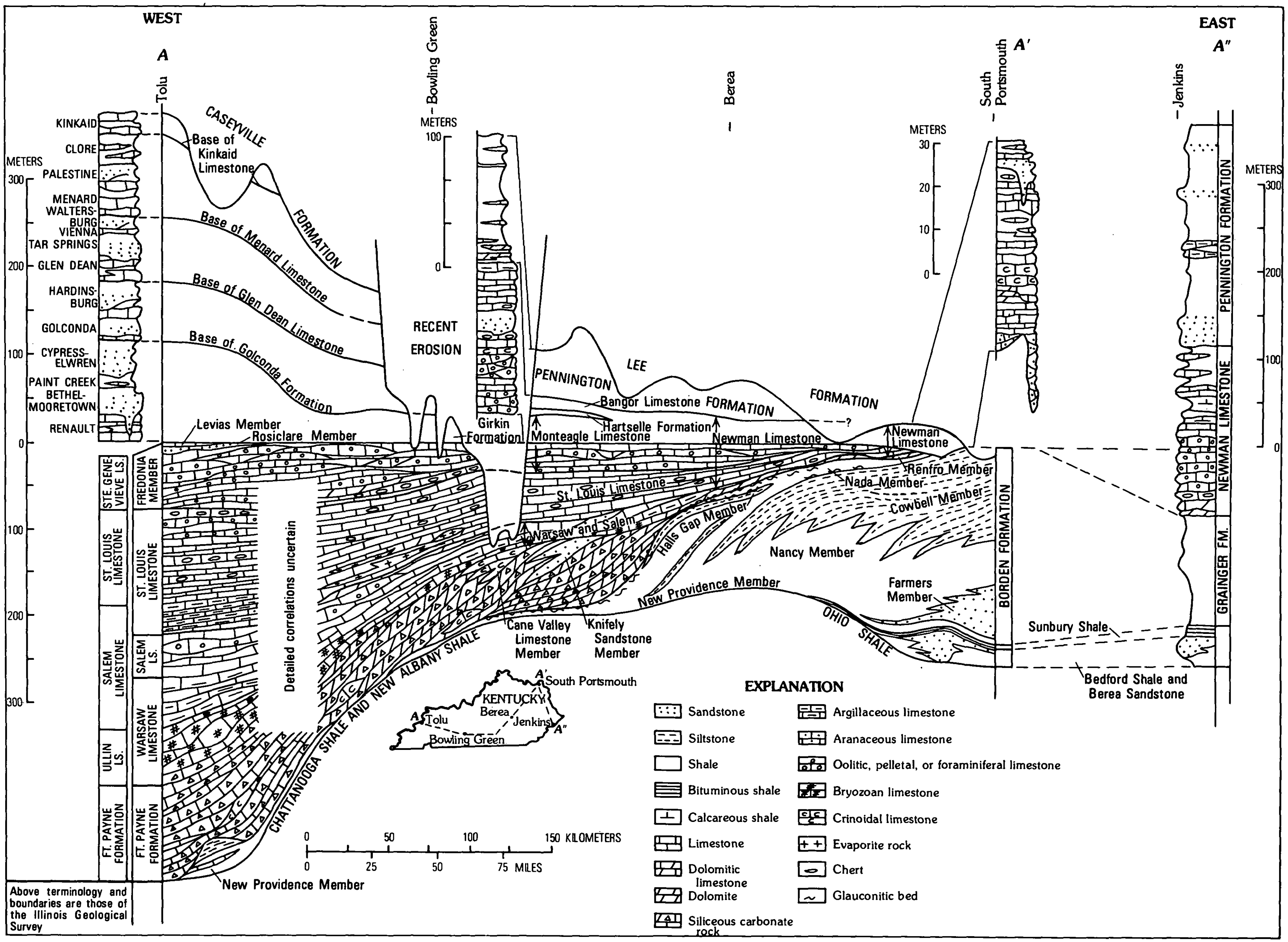

FIGURE 3.—Cross section showing Mississippian rock units and relationships in Kentucky. (All scales approximate.)

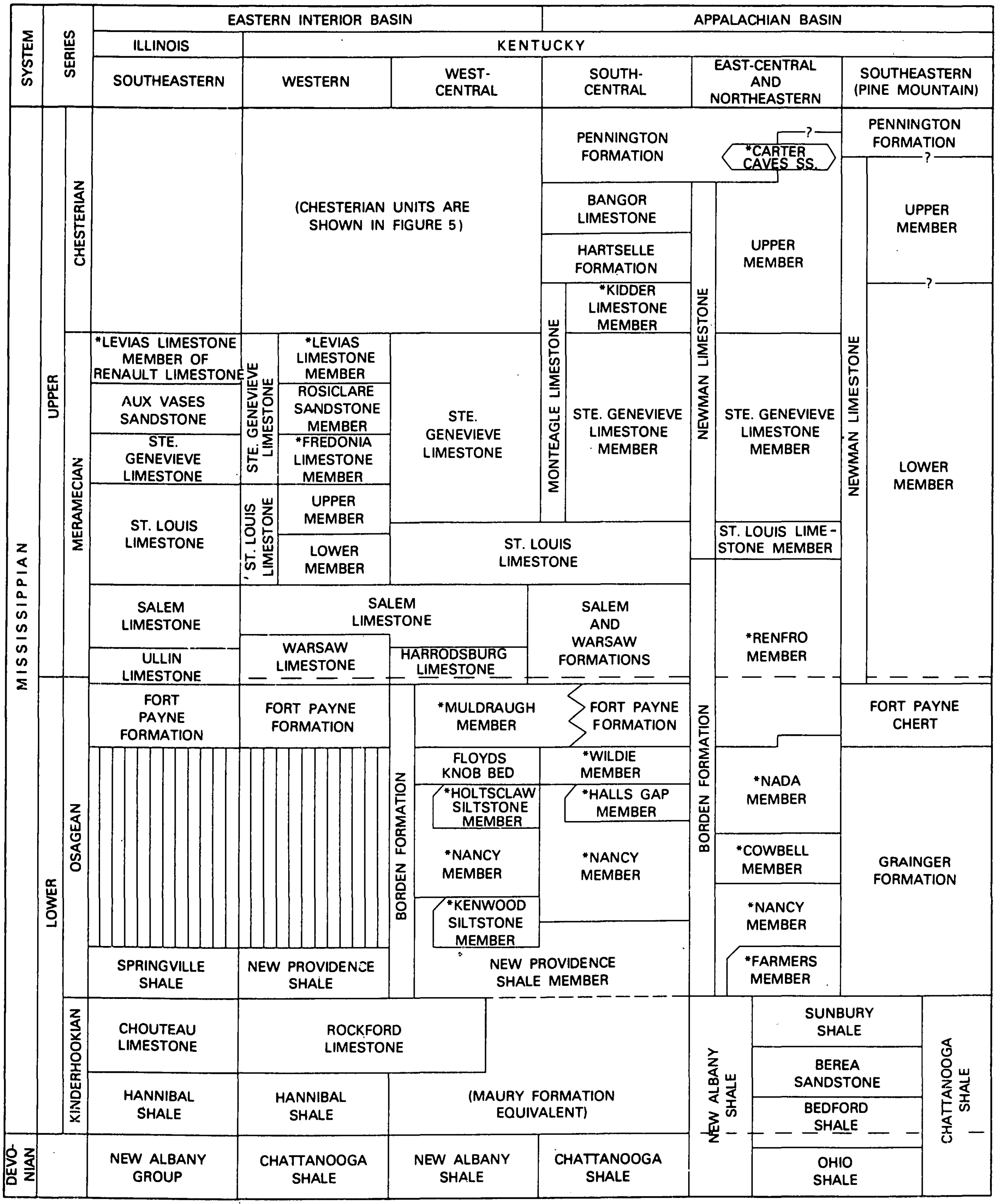

FIGURE 4.—Stratigraphic nomenclature of the Mississippian System in Kentucky and southeastern Illinois. Asterisk (*) indicates type section in Kentucky.

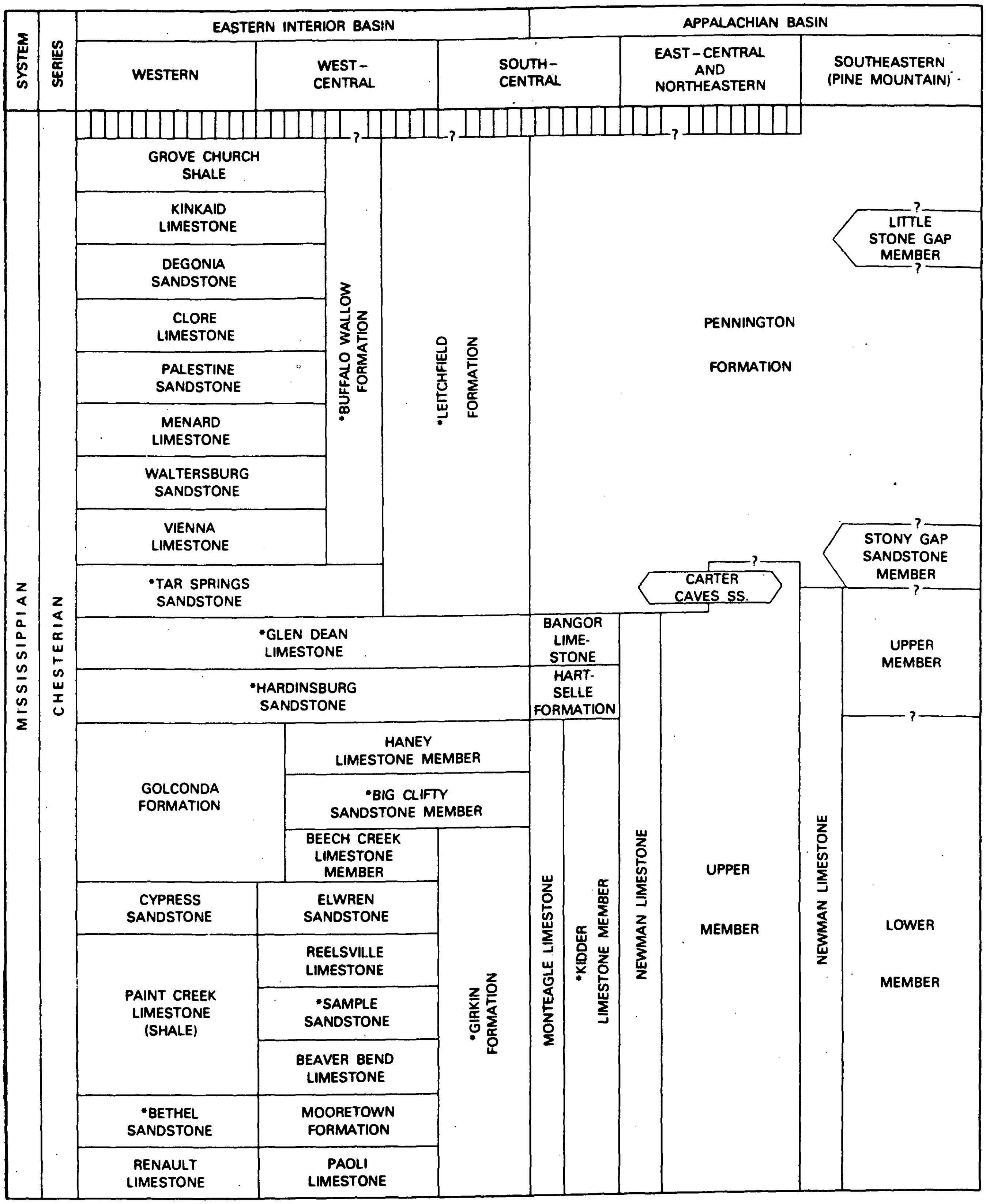

FIGURE 5.—Stratigraphic nomenclature of the Chester Series and equivalent strata in Kentucky. Asterisk (*) indicates type section in Kentucky.

prograding delta (Chester): Paoli-Renault Limestone through Grove Church Shale of western Kentucky; Paoli Limestone through Glen Dean Limestone correlatives in the Newman Limestone, Monteagle Limestone, Hartselle Formation and Bangor Limestone of south-central and eastern Kentucky.

4. Terrigenous detrital deposits (dominantly shale, varied amounts of sandstone, some marine limestone and dolomite) of westward and southward prograding deltaic systems (Chester): Pennington Formation of eastern Kentucky; Buffalo Wallow and Leitchfield Formations of western Kentucky.

Major source areas for Mississippian terrigenous sediments were (1) to the northeast, within or beyond the Acadian tectonic belts of the Northeastern United States and eastern Canada, and, possibly, northern Canada; and (2) to the east, within or beyond the Piedmont province of the Eastern United States. A third possible source for Upper Mississippian sediments has been reported to the south in the area between the Ouachita Mountains of Arkansas and the Black Warrior basin of Alabama and Mississippi (Thomas, 1974).

During Kinderhook time, distal deltaic deposits (Bedford Shale, Berea Sandstone) prograded southward and westward into eastern Kentucky, spreading across Late Devonian carbonaceous sediments (Ohio and Chattanooga Shales) (Pepper and others, 1954). When progradation ceased, the deltaic deposits were onlapped eastward and northeastward by carbonaceous sediments of Mississippian age (Sunbury Shale). Thin distal deposits of shale and limestone (Hannibal Shale, Rockford Limestone) probably from northern sources are preserved in western Kentucky, but across much of the State, the Kinderhook is locally represented only by a very thin stratum of clay shale and phosphatic nodules, suggesting starved-basin conditions.

Osage time was marked by a major renewal in westward and southwestward deltaic progradation into Kentucky. The lower and middle Borden Formation is a sequence that coarsens progressive from deepwater, prodelta clay shale (New Providence Shale Member) upward through silty shale (Nancy Member) into siltstone (Holtsclaw Siltstone, Halls Gap, and Cowbell Members) containing local delta-front turbidite deposits (Kenwood Siltstone, Farmers, and Wildie Members) (Kepferle, 1977; Moore and Clarke, 1970; Peterson and Kepferle, 1970; Weir, 1970). The western limit of foreset siltstone forms a remarkably straight, northwestward-trending Borden delta front, extending across west-central and south-central Kentucky. Water depths seaward of the front may have been as great as 85 m (Indiana University, 1972). A depositional hiatus following active progradation is indicated by the presence of a thin glauconitic unit (Floyds Knob Bed, Floyds Knob correlative in Wilde and Nada Members) extending across the outer delta platform and slope and into the basin.

Extensive carbonate deposition began during Osage time, partly contemporaneous with but mostly following the deltaic progradation, and continued through Meramec into Chester time. The initial deposits were argillaceous and siliceous, dolomitic siltstone, silty dolomite, and micrograined and crinoidal limestone (Fort Payne Formation, Muldraugh and lower Renfro Members of the Borden Formation), which were deposited seaward (west) of the delta front and across the prodelta slope and outer delta platform in basinal to supratidal environments. Locally, distinct elongate bodies of limestone and sandstone (Cane Valley Limestone and Knifley Sandstone Members of the Fort Payne Formation) were formed as submarine barrier-shoals and banks parallel to and seaward of the delta front (Indiana University, 1972). Succeeding bryozoan-crinoidal limestone (Harrodsburg and Warsaw Limestones) and bioclastic, pelletal, and foraminiferal limestones (Salem Limestone) form widespread units in western and south-central Kentucky, but pinch out northeastward across east-central Kentucky. These units contain varied amounts of dolomitic limestone, shale, and sandstone. The Warsaw in western Kentucky has a variable thickness reflecting deposition on the irregular basinal deposits of the Fort Payne. The first major cycle of carbonate deposition during this period is capped by a sequence of tidal-flat and supratidal dolomite and limestone containing evaporite deposits (lower St. Louis Limestone, upper Renfro Member of the Borden Formation).

During renewed transgression in late Meramec time, the initial deposits were subtidal, fossiliferous, micrograined, and bioclastic limestone (upper St. Louis Limestone), succeeded by shallow subtidal oolitic and bioclastic limestone (Ste. Genevieve Limestone). In western Kentucky, subsidence virtually in equilibrium with basin filling probably began in St. Louis time or somewhat earlier and continued through the remainder of the Mississippian Period. Carbonate deposition was interrupted at the end of Meramec time by a period of widespread exposure. A prominent zone of altered limestone

(Bryantsville Breccia Bed) formed during subaerial exposure and vadose diagenesis at the top of the Ste. Geneieve throughout much of its outcrop belt across the State. Episodes of renewed activity along the early Paleozoic Waverly arch and Kentucky River fault system interrupted St. Louis and Ste. Genevieve deposition in northeastern Kentucky and were followed by a period of extensive erosion on the upthrown (northern) side of the fault system.

During Chester time, about 370 m of rhythmically alternating carbonate and terrigenous detrital units accumulated in western Kentucky in very shallow water. Carbonate sediments were deposited on a broad shallow marine shelf; terrigenous sand and clay were brought in by prograding deltaic lobes of the Michigan River, which intermittently encroached southward into the shallow shelf environment (Potter, 1963; Swann, 1963, 1964). Elongate sandstone bodies were probably mainly of distributary origin, containing one or more tidal-channel deposits (Mooretown-Bethel); widespread shale was delta platform clay and prodelta clay. Thin coal was formed locally. Lateral shifting of the Michigan River system across central Illinois and Indiana was a controlling factor that determined gross variations in detrital sediment distribution in Kentucky; periodic climatic or tectonic oscillations in source areas controlled the volume of detrital input into the Eastern Interior basin. The Cincinnati and Ozark arch areas were relatively positive features, possibly shoals or emergent lowlands, which partly controlled the axis of detrital deposition (Swann, 1963, p. 15). Major shoreline fluctuations, combined with diminished detrital supply, contributed to widespread carbonate deposition between times of maximum detrital deposition. The proportion of shale and sandstone to limestone generally increases northward across western Kentucky and upward within the Chester succession.

In southern and eastern Kentucky, lower and middle Chester units and their correlatives are dominantly limestone; detrital units that are relatively thick and extensive in western Kentucky commonly are represented only by thin deposits of shale. Sandstone (Hartselle Formation) possibly derived from a southern source area, extends into south-central Kentucky from Tennessee and may have been deposited as a barrier island or an offshore bar (Thomas, 1974). Limestone of lower Chester age contains several zones of alteration that were formed in part during prolonged exposure and diagenesis of tidal-flat and supratidal deposits capping a series of fining-upward sequences. In northeastern Kentucky, the distribution of lower Chester correlatives reflects deposition on the post-Ste. Genevieve erosional surface and the persistence of the Waverly arch (see structure map, fig. 15) as a positive feature. In southeastern Kentucky, the Meramec and lower through middle(?) Chester correlatives exposed along Pine Mountain consist of very thick deposits of shelf limestone and thin shale. These deposits indicate that shallow marine carbonate deposition kept pace with the relatively rapid subsidence of this part of the Appalachian basin.

During latest Chester time, terrigenous detrital deposits (Pennington Formation; upper Newman Limestone (Englund and Windolph, 1971)) of westward-prograding deltaic systems spread across eastern Kentucky. The change from carbonate deposition to deltaic detrital deposition was gradual; the upper part of the carbonate succession contains increased amounts of interbedded shale and argillaceous limestone. The Pennington is dominantly shale containing varied amounts of sandstone, some limestone and dolomite, and minor coal, representing offshore-bar, lagoonal, tidal-flat, estuarine, distributary, and coastal-marsh deposits. Southeastward, sandstone becomes a major constituent of the Pennington. A linear sandstone body (Carter Caves Sandstone) in northeastern Kentucky is described variously as an offshore bar (Englund and Windolph, 1971), a beach-barrier island system (Horne and others, 1974), or a tidal-channel deposit paralleling the Waverly arch (Ettensohn, 1977, p. 18–29).

In west-central Kentucky, the upper part of the Chester succession (Buffalo Wallow and Leitchfield Formations) in the eastern part of the Eastern Interior basin is lithologically similar to the Pennington of eastern Kentucky. The geographic proximity and lithologic similarity of these approximately correlative units suggest that the Buffalo Wallow and Leitchfield may contain detrital rocks derived from both the southward-prograding Michigan River and westward-prograding Pennington deltaic systems.

BIOSTRATIGRAPHY

Taxonomy and zonation of megafossils in Mississippian rocks stem from extensive early studies in Kentucky and adjacent States by Stuart Weller (1920, 1926), J. M. Weller (1931), Butts (1915, 1917, 1922), and Ulrich (1917), and others. These studies were reviewed and updated by Weller and Sutton 1940). Crinoids, brachiopods, blastoids, bryozoans, solitary and colonial corals, and echinoids are dominant forms in the Mississippian assemblage; pelecypods, gastropods, and trilobites are locally abundant. Crinoid studies by Horowitz (1965), and biofacies studies of a Chester rock unit (Vincent, 1975) are two examples of the many selective studies done in recent years.

A significant change in the crinoid fauna marks the Chester-Meramec series boundary in western, west-central, and south-central Kentucky—the change from *Platycrinites penicillus* Meek and Worthen, a Meramec form, to *Talarocrinus* spp., a Chester form. The fauna change corresponds to the time of formation of a widespread zone of altered limestone (Bryantsville Breccia Bed) interpreted to have developed during subaerial exposure and diagenesis. Other Mississippian boundaries and the Devonian-Mississippian systemic boundary appear to occur within intervals of continuously deposited strata, and faunal criteria for specific boundary demarcation are not conclusive. However, many specific and generic forms have proved valuable aids in practical recognition and mapping of stratigraphic units. Figure 6 shows general stratigraphic occurrences of selected fossil faunal elements that have been successfully used in mapping Mississippian rock units in Kentucky. The list is incomplete and does not show faunal ranges.

Microfossils in Mississippian rocks of Kentucky include endothyrid and paleotextulariid Foraminifera, conodonts, and ostracodes. Although no systematic studies have been done for the entire system in Kentucky, foraminiferal studies include those by Browne and Pohl (1973), Browne and others (1977), Conkin (1954, 1956, 1961), Pohl and others (1968), and Pohl (1970). Conodont studies, following zonation used in the Mississippi Valley (Collinson and others, 1962, 1971), include those by Rexroad (1958, 1969), Nicoll and Rexroad (1975), Rexroad and Liebe (1962), and Howoritz and Rexroad (1972).

The zonation of plant megafossils in western Kentucky and adjacent States of the Eastern Interior basin has established criteria for distinguishing Mississippian sandstone from lithologically similar Pennsylvanian strata (Jennings, 1977). A rare lycopod occurrence in the basal St. Louis Limestone of west-central Kentucky was reported by Browne and Bryant (1970).

MISSISSIPPIAN-PENNSYLVANIAN BOUNDARY

The Mississippian-Pennsylvanian boundary along the margins of the Western Coal Field and northwest margin of the Cumberland Plateau has long been interpreted to represent a regional unconformity (Miller, 1919, p. 252). Extensive subsurface work by Bristol and Howard (1971) in western Kentucky helped to identify a general northward and northeastward truncation of progressively older Mississippian strata and several broad southwest-trending sub-Pennsylvanian valleys (fig. 7). These valleys or channels are incised as much as 75 m into the gently rolling plain of the truncated Mississippian surface and may locally represent removal of more than 275 m of Mississippian strata. Detailed studies of parts of these channels have been made by Davis and others (1974) and Shawe and Gildersleeve (1969). Extending eastward from the easternmost channel shown in figure 7 is a tongue of conglomeratic sandstone that has been interpreted by Burroughs (1923) as the remnants of a "Pottsville-filled channel" resting on rocks as old as the St. Louis Limestone (Mississippian).

In the narrow outcrop belt along the western edge of the Cumberland Plateau of eastern Kentucky, the unconformity is marked by channels as much as 60 m deep and locally by paleokarst topography developed on Mississippian limestone. The sub-Pennsylvanian surface (fig. 8) also shows a north or north-northwestward truncation of Mississippian strata, probably reflecting the influence of the Cincinnati and Waverly arches at that time (Englund, 1972).[1]

The existence of the Mississippian-Pennsylvanian unconformity in northeastern Kentucky was challenged by Horne and Ferm (1970), Horne and others (1971), Ferm and others (1972), Ferm (1974), and Horne and others (1974), who attempted to show the relationship of the largely terrestrial Pennsylvanian deposits (Lee and Breathitt Formations) above the unconformity to the underlying marine Mississippian strata by means of a depositional model. If correct, their thesis is highly significant in considering the age and stratigraphic relations of many Carboniferous units in the Appalachian and midcontinent area. Their depositional model, called the "Lee-Newman barrier shoreline model" (Horne and others, 1971), identifies orthoquartzite (commonly Lee Formation) as beach-barrier deposits that grade landward into lagoonal and lower delta-plain shale, subgraywacke, and coal (Breathitt Formation) and seaward into red and green marine shale (Pennington Formation and Nada Member of Borden Formation) that surrounds offshore carbonate islands (Newman Limestone).

[1]Strata in northeastern Kentucky identified as Pennington by various workers have been assigned to the Newman Limestone by Englund and Windolph (1971). The relations of these rocks, generally less than 10 m thick, to strata of the Pennington Formation in south-central Kentucky, as much as 50 m thick, or those in the type area of Cumberland Mountain, as much as 350 m thick, are uncertain.

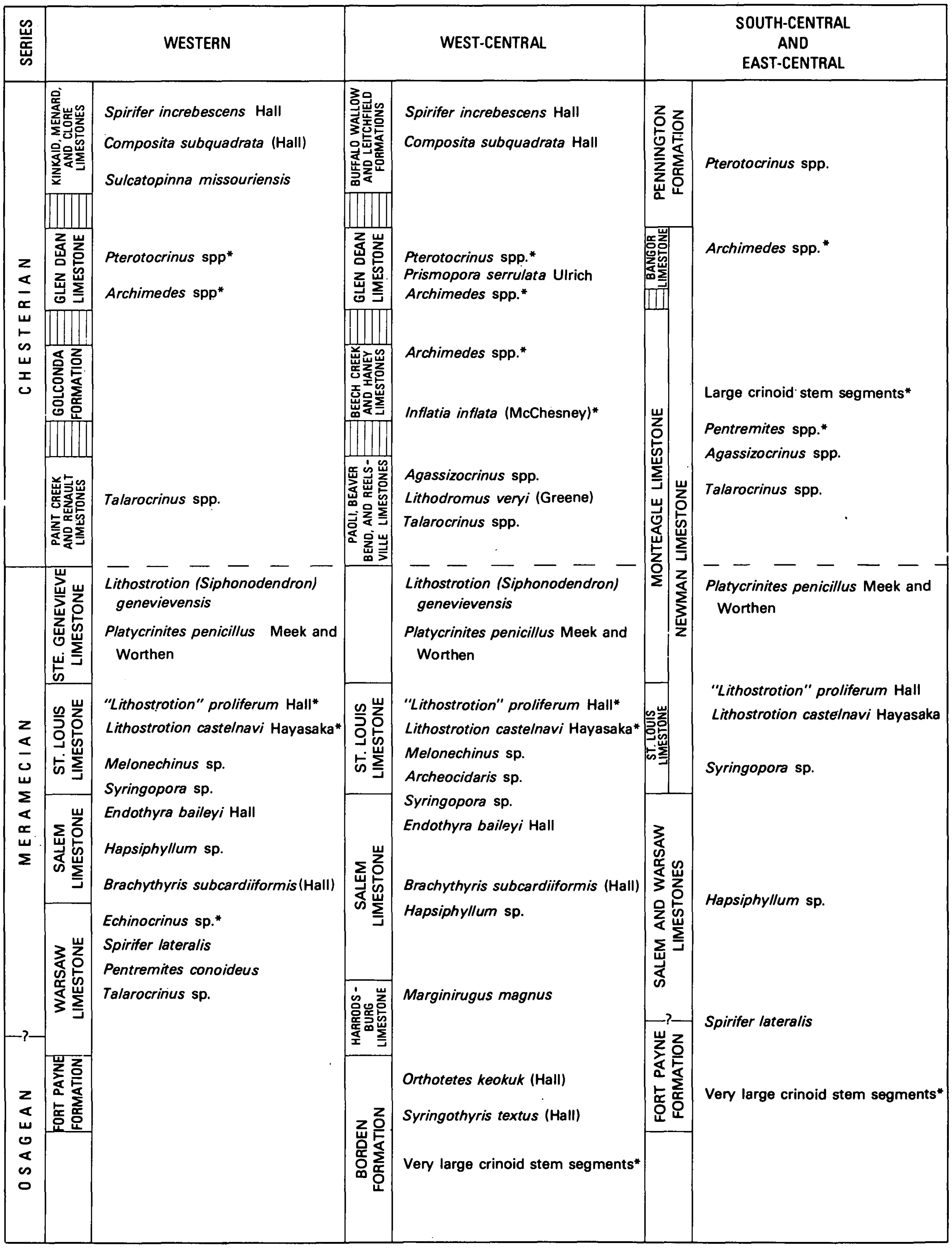

FIGURE 6.—Stratigraphic occurrence of selected Mississippian fossil fauna, on the basis of general abundance and ease of recognition, that are helpful in recognition of map units in Kentucky. Asterisk denotes very abundant; shaded areas denote intervals of largely terrigenous detrital strata.

They interpreted the intra- and post-Mississippian erosional unconformities, described by previous workers, to be depositional or facies-controlled boundaries.

Central to the development of the Lee-Newman model is a cross section of Carboniferous rocks ex-

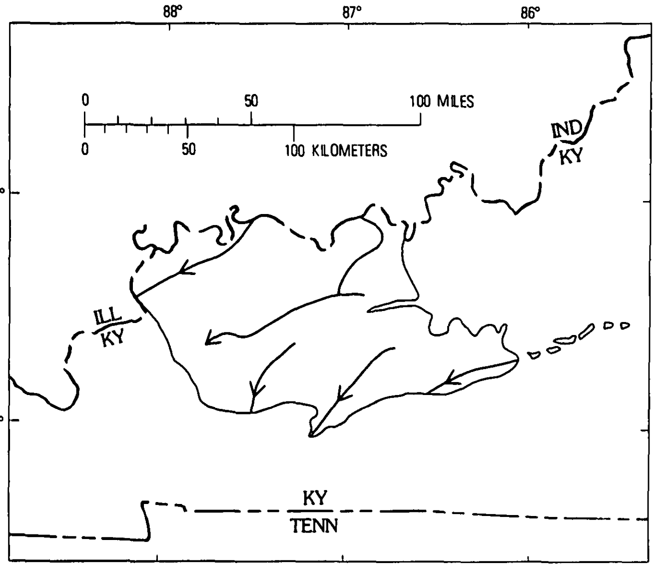

FIGURE 7.—Sub-Pennsylvanian valley systems in the western Kentucky coal field.

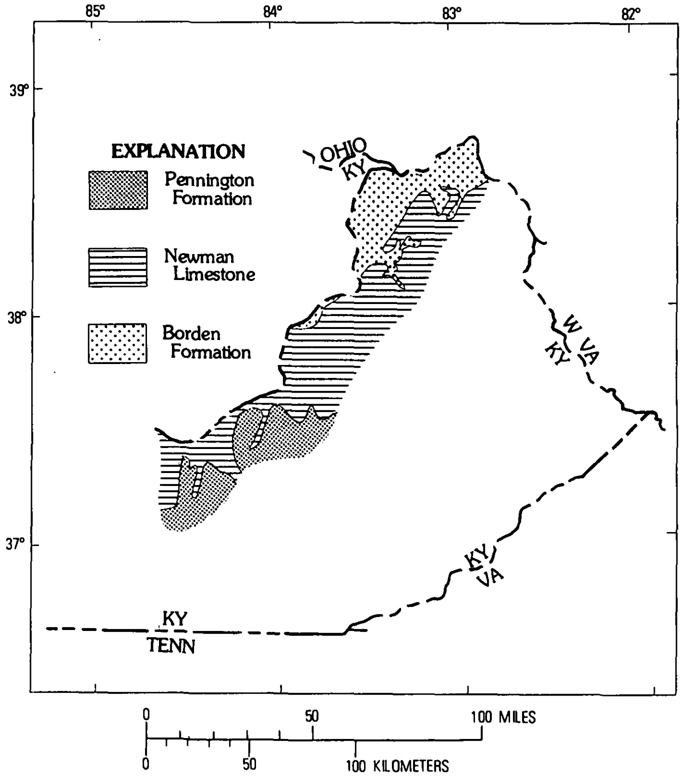

FIGURE 8.—Generalized geologic map of the pre-Pennsylvanian surface in the northwest part of the Cumberland Plateau, eastern Kentucky.

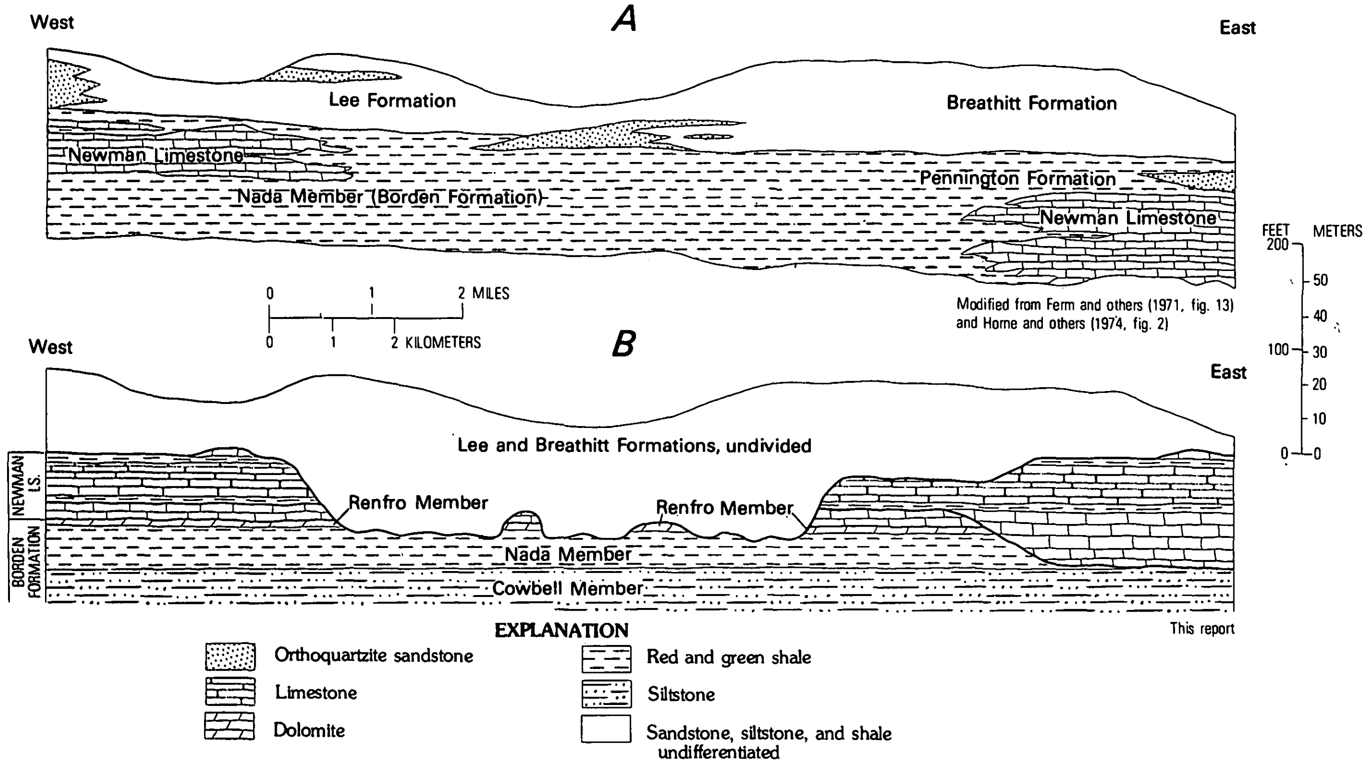

FIGURE 9.—Generalized cross sections showing two interpretations of Carboniferous rocks exposed along Interstate Highway 64, eastern Rowan and western Carter Counties, northeastern Kentucky.

posed along Interstate Highway 64 in northeastern Kentucky. Relations between rock units along part of the highway as interpreted by Ferm and others (1971, fig. 13) and Horne and others (1974, fig. 2) are shown in fig. 9A. The intertonguing of a thick sequence of marine shale (Pennington and Nada) with two isolated bodies of carbonate rocks (Newman) and lenses of orthoquartzite (Lee) is intended to show a west-migrating shoreline environment.

The proposed depositional model is untenable in view of field relationships between lithologic units in the area. Study of exposures along the interstate highway by the present writers has established the presence of erosional remnants and lithologic sequences that indicate the former continuity of carbonate units across the area (fig. 9B). No intertonguing of limestone and shale along the margins of the carbonate bodies was seen. Red and green shales in the road section were found to belong to the Nada Member of the Borden Formation and two thin shale units in the Newman Limestone; the measured thicknesses of these shales are less than half that indicated in figure 9A. In the authors' opinion, the distribution of rock units shown in figure 9B reflects erosional and depositional thinning related to two regional unconformities that have been described by Dever and others (1977), Patterson and Hosterman (1962), and Sheppard (1964). The lower unconformity followed deposition of the basal limestone unit of the Newman and locally cuts into the Cowbell Member of the Borden Formation. The upper unconformity is Mississippian-Pennsylvanian; it is overlain by deltaic carbonaceous shale and siltstone containing minor sandstone bodies that are dominantly fluviatile in origin. The unconformity has a local relief of about 25 m; total thickness of missing Mississippian strata may be more than 50 m.

In southeastern Kentucky, the Mississippi-Pennsylvanian systemic boundary occurs in the upper part of the Pennington Formation in an intertonguing and intergrading sequence of siltstone, sandstone, and shale: strata above are largely continental, and those below are largely marine. Englund (1974, p. 38) identified a major Pennsylvanian unconformity at the base of the New River Formation in Virginia and West Virginia and at the base of the Middlesboro Member of the Lee Formation in southeastern Kentucky. (See fig. 12.) He showed that this unconformity cuts progressively older strata northwestward and suggested that it coincides with the widespread Mississippian-Pennsylvanian unconformity of the midcontinent region.

PENNSYLVANIAN STRATA OF EASTERN KENTUCKY

The Pennsylvanian rocks of eastern Kentucky form a clastic wedge that thickens southeastward toward the axis of the Appalachian basin. The rocks crop out in an area of about 27,000 km^2 and occupy a central part of the Appalachian coal field that extends from New York to Alabama.

The depositional character of the Pennsylvanian strata is deltaic. The lower part generally is dominated by thick orthoquartzite and the upper part by siltstone, shale, and generally thin discontinuous subgraywacke. Although only a few widespread marine transgressions took place during Pennsylvanian time, many coal beds are overlain by shale that locally contains sparse brackish-water or marine fauna.

GEOLOGIC SETTING

By Late Mississippian time, eastern Kentucky was the site of shallow-water clastic deposition, which, except where interrupted by the formation of swamps, continued throughout Pennsylvanian time. In southeastern Kentucky, or the central part of the basin, continuous deposition took place across the systemic boundary, while to the northwest, basal Pennsylvanian sediments were disconformably deposited on the eroded Mississippian surface.

Pennsylvanian deposition was strongly influenced by the rapidly subsiding Appalachian trough, whose axis was southeast of and generally parallel to the strike of Pine and Cumberland Mountains. The cross section in figure 10 shows the great thickening of sedimentary rocks toward the axis of the trough. Figure 11 illustrates the influence of the subsiding trough on deposition of part of the Breathitt Formation. Campbell (1898) thought that much of the northwestward thinning of Early Pennsylvanian strata was due to onlap and that as much as one-quarter of the basal Lee section is not present in outcrops of the Pottsville escarpment along the western border of the basin.

Most Upper Pennsylvanian rocks have been eroded from eastern Kentucky, except for those preserved in a broad syncline in northeastern Kentucky. (See fig. 15.) Although the section locally may be thick enough to include Permian strata, such have not been identified.

STRATIGRAPHY

The Pennsylvanian strata of eastern Kentucky comprise locally part of the Pennington Formation

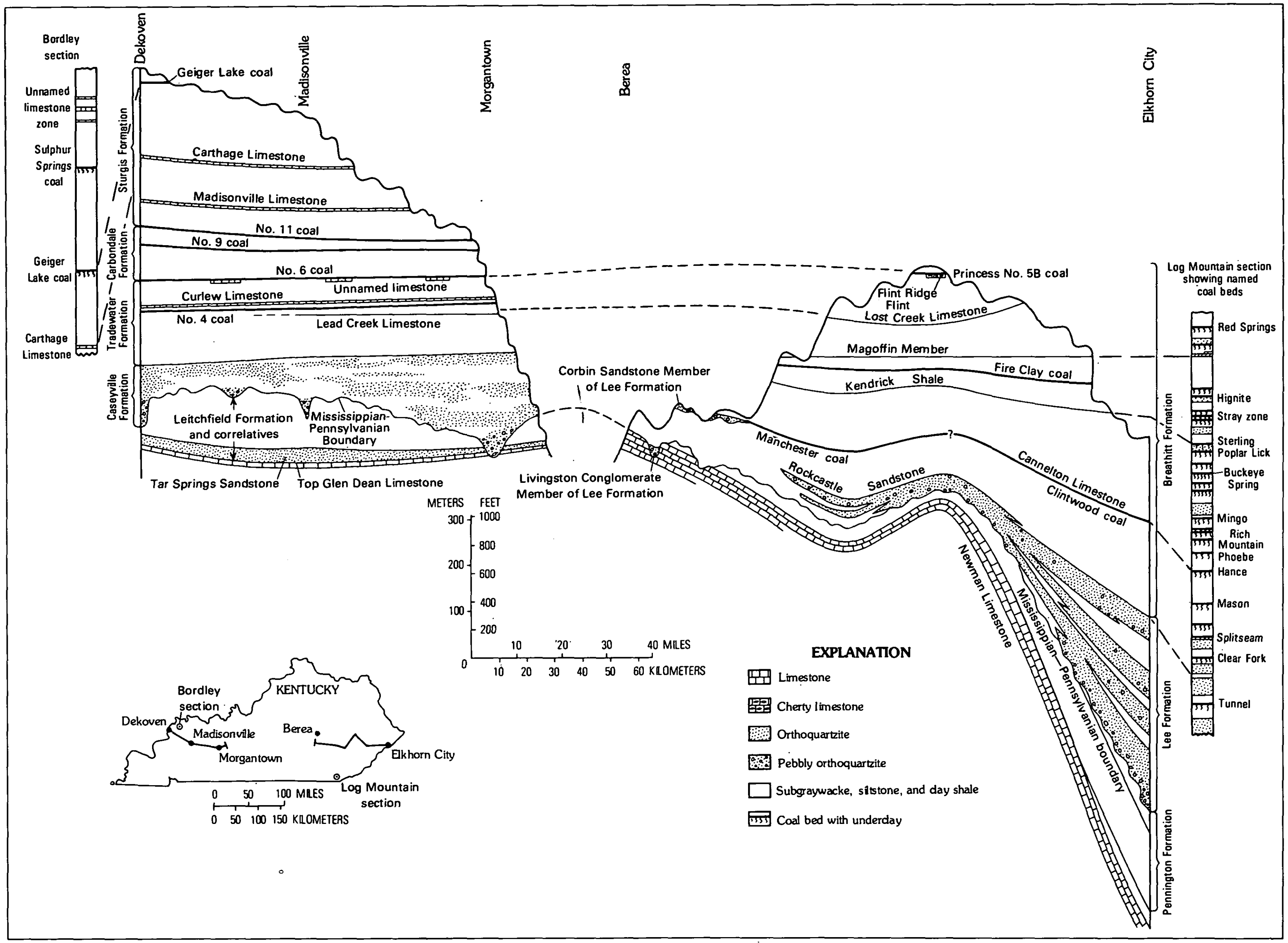

Figure 10.—Generalized cross sections of the Pennsylvanian of eastern and western Kentucky. Missing section above land surface across Cincinnati arch represents a gap of about 200 km. Anticlinal structure in eastern Kentucky cross section is only apparent and is due to placement of section line. Sandstone of the Log Mountain section is subgraywacke except that of the Lee Formation.

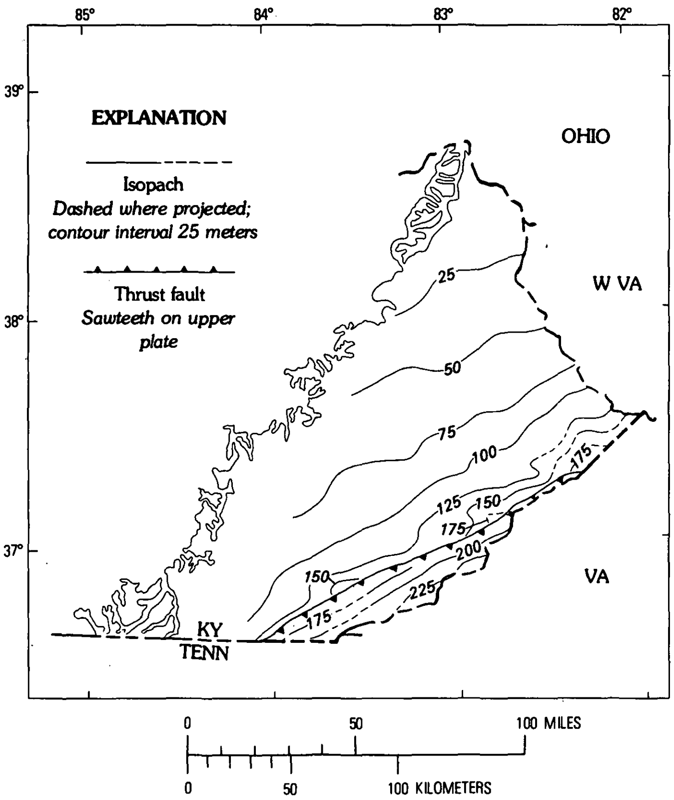

FIGURE 11.—Isopach map showing interval between the base of the Kendrick Shale of Jillson (1919) and the base of the Magoffin Member of the Breathitt Formation in eastern Kentucky.

and all the overlying Lee, Breathitt, Conemaugh, and Monongahela Formations.

PENNINGTON FORMATION

The upper part of the Pennington Formation in southeastern Kentucky contains Pennsylvanian flora (Maughan, 1976). The Mississippian-Pennsylvanian systemic boundary there occurs in a gradational sequence between the highest marine unit (Little Stone Gap Member of the Pennington Formation of Mississippian age) and the base of the Middlesboro Member of the Lee Formation. This sequence includes reddish-, greenish- and dark-gray clay shale, gray and brownish-gray siltstone, coarse- to fine-grained pebbly orthoquartzite, and fine-grained silty sandstone. Thin coal beds and underclay that occur near the top of the Pennington are truncated locally by the Middlesboro Member of the Lee Formation in southeastern Kentucky.

LEE FORMATION

The Lee Formation is characterized by massive pebbly orthoquartzite that locally contains lenses of conglomerate; in places, sandstone makes up more than 80 percent of the formation. In extreme southeastern Kentucky, the unit is locally more than 500 m thick and has been divided into eight members, six of which, the Pinnacle Overlook, Chadwell, White Rocks, Middlesboro, Bee Rock Sandstone, and Naese Sandstone Members, are dominantly sandstone (Englund, 1964). The other two, the Dark Ridge and Hensly Members, consist generally of carbonaceous siltstone and shale, thin bedded subgraywacke, and coal. Figure 12 shows the relations of these units in various parts of the Cumberland overthrust block.

Along the Pottsville escarpment, only the extensively mapped and named pebbly orthoquartzite units are assigned to the Lee Formation: the Livingston Conglomerate, Rockcastle Sandstone, Corbin Sandstone, and Grayson Sandstone Members. Other quartzose sandstones occur between these named members, but they are generally thin and discontinuous, and all pinch out into or locally intergrade with siltstone or subgraywacke of the Breathitt Formation.

The Lee Formation is composed of a series of broad orthoquartzite lobes generally oriented northeast, generally parallel with the axis of the Appalachian basin and showing a dominant southwest transport direction (Potter and Siever, 1956 a and b; Englund and Delaney, 1966; Englund, 1974). The orthoquartzite lobes of the Cumberland overthrust block intertongue with or grade into nonresistant subgraywacke to the southeast in southwestern Virginia, and siltstone and subgraywacke to the northwest (Englund, 1968, pl. 5). The thickest part of each successive sandstone member is farther northwest, and in places it cuts into the older sandstone member. Thus, the top of the Lee Formation is placed at stratigraphically higher levels toward the northwest as shown in figure 13.

Ferm (1974, p. 94) and Donaldson (1974, p. 48) suggested that the Lee Formation of eastern Kentucky is a beach-barrier and back-barrier complex of northwestward-migrating shoreline environments. They suggested that the dominant southwest current direction of these strata was caused by longshore currents and southwestward migration of tidal channels. However, the marine rocks that should be associated with a beach or barrier system, are rare in the Lee Formation or intercalated Breathitt strata. On the contrary, the Rockcastle and Corbin Sandstone Members pinch out into deltaic siltstone and sandstone. Pennsylvanian strata underlying the Rockcastle and Corbin consist dominantly of car-

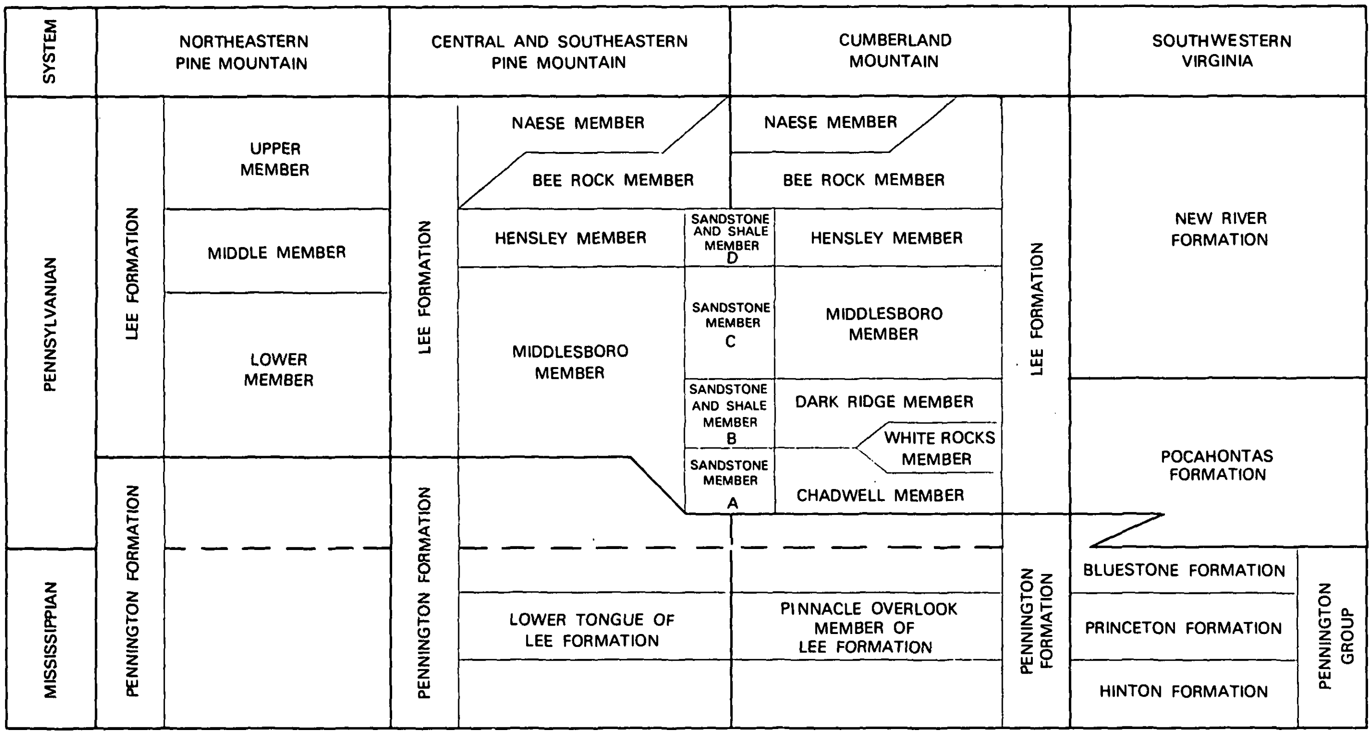

FIGURE 12.—Correlation chart of the Lee Formation in southeastern Kentucky and southwestern Virginia.

bonaceous shale and siltstone that contain plant material and coal beds, and seat rocks that contain abundant root impressions. Some of these basal strata consist of coarsening upward sequences that range from 1 m to as much as 10 m in thickness. Evidence of bioturbation is common, but few brackish-water or marine fauna are present. The sequences do not persist laterally more than a few kilometers and probably were deposited in small shallow interdistributary bays associated with lower delta-plain deposits. The lithology and interrelations of the lower part of the exposed Pennsylvanian section suggest that the sandstone members of the Lee Formation were large sand-filled distributary channels of a dominantly southwest-prograding delta.

BREATHITT FORMATION

The Breathitt Formation crops out over most of the eastern coal field.[2] The Breathitt has been locally ranked as a group and has been divided into formations on the basis of key beds, but as these formations are all lithologically alike, they are not differentiated in the following discussion. Regionally, the Breathitt and generally underlying Lee Formation intertongue. In most areas, the base of the Breathitt is placed at the top of the uppermost cliff-forming orthoquartzite, but along the Pottsville escarpment all Pennsylvanian strata except for the named members of the Lee Formation having regional extent are assigned to the Breathitt Formation (Weir and Mumma, 1973).

The Breathitt Formation is as much as 950 m thick in southeastern Kentucky but is preserved in its entirety only in northeastern Kentucky, where it is about 250 m thick. The formation is characterized not only by large differences in thickness but also by rapid lateral changes in lithology. These characteristics have made basin-wide correlations difficult, particularly in the lower part of the section. The formation contains most of the minable coal in eastern Kentucky. Coal occurs in as many as 30 major coal beds or coal zones to which more than 150 names have been applied; some of the most widely used names are included in figure 13.

The formation consists of siltstone and clay shale, subgraywacke, coal, ironstone, and limestone. Siltstone and clay shale intergrade, are commonly car-

[2] The name "Pottsville" has been generally applied to these rocks and the underlying Lee Formation. Phalen (1912) had defined the Pottsville and Allegheny Formations in Kentucky as they were generally used in Ohio and Pennsylvania; McFarlan (1943) raised both these units to series rank. The Breathitt Formation is equivalent to the upper part of the Pottsville Formation and all the overlying Allegheny Formation; the top of the Pottsville has not been identified in Kentucky but is thought to occur at about the position of the Princess No. 5 coal bed in northeastern Kentucky.

Series	Formation	North (Princess and Licking River Coal Reserve Districts)	East (Big Sandy Coal Reserve District)	Southwest (Hazard and Southwestern Coal Reserve Districts)	Southeast (Upper Cumberland River Coal Reserve District)
Upper Pennsylvanian; Missourian and Virgilian	Conemaugh and Monongahela				
		AMES LIMESTONE MEMBER			
		BRUSH CREEK LIMESTONE MEMBER			
		PRINCESS NO. 10 OR BRUSH CREEK COAL			
		PRINCESS NO. 9 COAL ZONE			
		UPPER FREEPORT COAL			
Des Moinesian		PRINCESS NO. 8 COAL			
		PRINCESS NO. 7 COAL			
		PRINCESS NO. 6 COAL			
		HITCHINS CLAY BED			
		VANPORT LIMESTONE AS USED BY PHALEN (1912)			
		PRINCESS NO. 5B COAL			
		KILGORE FLINT; FLINT RIDGE FLINT OF MORSE (1931)		FLINT RIDGE FLINT OF MORSE (1931)	
?; Atokan		PRINCESS NO. 5 OR SKYLINE COAL ZONE	RICHARDSON COAL ZONE	KNOB COAL ZONE	
		TIPTOP COAL	BROAS COAL ZONE	BROAS COAL ZONE	
		PRINCESS NO. 4 COAL		LOST CREEK LIMESTONE OF MORSE (1931)	
		MAIN BLOCK ORE	HINDMAN COAL	HINDMAN OR HAZARD NO. 9 COAL	
		PRINCESS NO. 3, MUDSEAM, OR NICKELL COAL	PEACH ORCHARD COAL ZONE	HAZARD NO. 8 OR FRANCIS COAL ZONE	
			BUFFALO CREEK COAL	HAZARD NO. 7 COAL ZONE; BIG WHEEL COAL	HIGH SPLINT COAL
		HAZARD OR INDEX COAL; PRATER COAL ZONE	HAZARD COAL ZONE; WINIFREDE COAL	HAZARD COAL ZONE; LEATHERWOOD OR BRADEN MTN. COAL	RED SPRINGS COAL
Lower and Middle Pennsylvanian		HADDIX COAL ZONE; TRACE FORK COAL	HADDIX COAL ZONE	HADDIX COAL ZONE; RED ASH COAL	LOW SPLINT OR MORRIS COAL; REYNOLDS SANDSTONE MBR.
?; Morrowan	Breathitt	MAGOFFIN MEMBER	MAGOFFIN MEMBER	MAGOFFIN MEMBER	MAGOFFIN MEMBER
		TAYLOR COAL	TAYLOR COAL	COPLAND OR SHARP COAL	LIMESTONE COAL
		HAMLIN COAL ZONE	HAMLIN COAL ZONE	HAMLIN COAL ZONE; BEACH GROVE COAL	PARDEE COAL; JESSE SANDSTONE MBR.
				HATFIELD COAL	HIGNITE OR SMITH COAL
		FIRE CLAY-WHITESBURG COAL ZONE: FIRE CLAY RIDER COAL	FIRE CLAY RIDER COAL	BIG MARY COAL	STRAY COAL ZONE
		FIRE CLAY COAL	FIRE CLAY OR HAZARD NO. 4 COAL	HAZARD NO. 4, WINDROCK, OR DEAN COAL	WALLINS CREEK COAL
		LITTLE FIRE CLAY COAL	LITTLE FIRE CLAY COAL	UPPER PIONEER COAL	
		WHITESBURG COAL	WHITESBURG COAL ZONE	WHITESBURG COAL ZONE	PUCKETT SANDSTONE MBR.
		KENDRICK SHALE OF JILLSON (1919)	KENDRICK SHALE OF JILLSON (1919)	KENDRICK SHALE OF JILLSON (1919)	KENDRICK SHALE OF JILLSON (1919)
		GUN CREEK OR CANNEL CITY COAL	WILLAMSON COAL	LOWER PIONEER COAL; AMBURGY COAL ZONE	STERLING COAL; CREECH COAL ZONE
			AMBURGY COAL ZONE	JORDAN COAL	POPLAR LICK COAL
			ELKINS FORK SHALE OF MORSE (1931)	ELKINS FORK SHALE OF MORSE (1931)	ELKINS FORK SHALE OF MORSE (1931)
		TOM COOPER, VAN LEAR, OR LITTLE CANEY COAL	UPPER ELKHORN NO. 3, THACKER, OR CEDAR GROVE COAL ZONE; NOSBEN COAL	UPPER ELKHORN NO. 3 COAL ZONE; ELK GAP COAL	TAGGART COAL ZONE; BUCKEYE SPRING OR DARBY COAL
			SIDNEY COAL	LICK FORK COAL	TAGGART MARKER OR KELLIOKA COAL
		GRASSY COAL	UPPER ELKHORN NO. 2 COAL; ALMA COAL ZONE	JELLICO COAL ZONE	MINGO OR HARLAN COAL ZONE; COLLIER COAL
			UPPER ELKHORN NO. 1 COAL		
			CAMPBELL CREEK LIMESTONE OF WHITE (1885)		
		BRUIN OR WOLF CREEK COAL	LOWER ELKHORN OR POND CREEK COAL	VIRES COAL; BLUE GEM COAL ZONE	
		GRAYSON SANDSTONE BED	POWELLTON COAL ZONE	LITTLE BLUE GEM OR BLACK WAX COAL	RICH MTN., PATH FORK, OR IMBODEN COAL
					PHOEBE COAL
		FROZEN SANDSTONE MEMBER		DIXIE COAL	
			CANNELTON LIMESTONE OF WHITE (1885)		
		ZACHARIAH OR WHEELERSBURG COAL	CLINTWOOD OR MATEWAN COAL; BINGHAM COAL ZONE	LILLY, COLONY, MANCHESTER, RIVER GEM, OR SWAMP ANGEL COAL	KENT OR BENNETTS FORK COAL; HANCE COAL ZONE
	Lee and Breathitt	VAN CLEVE COAL	CEDAR COAL; GLAMORGAN COAL ZONE	CORBIN SANDSTONE MEMBER	
		CORBIN SANDSTONE MEMBER	EAGLE LIMESTONE OF WHITE (1891)		
		MINE FORK COAL	LITTLE CEDAR OR HAGY COAL	GRAY HAWK COAL	MURRAY, CHANOA, OR MASON COAL
			SPLASH DAM COAL	BEATTYVILLE OR TATTLERS COAL	SPLITSEAM COAL
Upper Mississippian and Lower Pennsylvanian		WARM FORK COAL	ELSWICK COAL	BARREN FORK COAL	REX OR CLEAR FORK COAL
			LOWER BANNER COAL	ROCKCASTLE SANDSTONE MEMBER	YELLOW CREEK SANDSTONE MEMBER
			LEE UNDIVIDED		NAESE AND BEE ROCK SANDSTONE MEMBERS; NAESE COAL
				BEAVER CREEK COAL	TUNNEL OR RAVEN COAL
Chesterian and Morrowan		ANTHONY COAL		STERNS NO. 1½ COAL	
		OLIVE HILL CLAY BED OF CRIDER (1913)		HUDSON, LEE NO. 1, OR STERNS NO. 1 COAL	
	Pennington and Lee			LIVINGSTON CONGLOMERATE	MIDDLESBORO SANDSTONE MEMBER
					CUMBERLAND GAP COAL
					WHITE ROCKS SANDSTONE MEMBER
					CHADWELL MEMBER
					PINNACLE OVERLOOK MEMBER

FIGURE 13.—Correlation chart of the Pennsylvanian of eastern Kentucky showing coal beds and other key beds. Members of the Lee Formation are shaded. Coal reserve districts from Huddle and others (1963).

bonaceous and contain plant fragments; some thin zones contain brachiopods, pelecypods, cephalopods, gastropods, and crinoids. The subgraywacke is commonly fine grained, and grades into siltstone; it is characteristically micaceous and quartz rich (55 to 70 percent). Ironstone occurs principally as sideritic concretions in thin discontinuous lenses or nodules in siltstone or shale; iron ores in the form of silty to sandy siderite or limonite occur as pods generally less than 50 cm thick at the base of the formation and in the upper part of the section in northeastern Kentucky. Calcareous rocks occur as rare concretionary zones in sandstone and as small to large argillaceous concretions in siltstone and shale; the latter are commonly associated with marine horizons but may not contain fossils.

The Breathitt Formation is not readily divisible into lithologic units. Subdivision of the formation is based on the recognition of key beds, generally coal beds and marine zones and, because single beds do not persist across the entire basin, on sequences of key beds. The Fire Clay coal bed with its distinctive hard flint-clay parting was the first to be recognized as an important key bed, and has been used extensively as a structure horizon. The flint-clay parting, as much as 40 cm thick, is reported to contain sanidine and may be the alteration product of a volcanic ash fall (Seiders, 1965). Other coal beds are locally useful as key beds, particularly commercial coal beds that have wide extent and are exposed by mining operations.

The best stratigraphic tools for the correlation and subdivision of the Breathitt Formation are marine zones several of which are of wide extent. The most important are the Magoffin Member, the Kendrick Shale of Jillson (1919), and the Lost Creek Limestone of Morse (1931). These units resemble one another in their lithologic character and are comparable to the marine parts of Weller's cyclothem (in Wanless and Weller, 1932, p. 1003). They are an upward-coarsening, bay-fill sequence of argillaceous and sandy sediments from 1 to as much as 35 m in thickness that were deposited after rapid marine transgressions over very extensive flat shelves. The lower part of the marine deposits is a dark-gray fossiliferous clay shale that locally contains thin beds or concretions of fossiliferous limestone. These beds grade upward into gray siltstone containing thin discontinuous lenses of siderite. The marine zones commonly overlie a coal bed; the top is marked by an unconformity, generally at the base of a channel-fill sandstone or at the base of a coal bed.

None of the named marine zones extend across the entire coal field, and few have been identified in more than a small part of it. The Magoffin Member has the widest distribution, but it too becomes thin, discontinuous, and ferruginous along what is interpreted to have been the margins of its bay in northeastern Kentucky.

Marine invertebrate fossils are present in many parts of the Breathitt Formation, but they are unusual in any given section. Most occurrences other than in the named marine zones are thin, indistinct and sparsely fossiliferous marine bands in siltstone and shale sequences that have little continuity (Eagar, 1973). These marine bands do not coincide with changes of lithology and are probably related to changes in salinity in small shallow bays or tidal channels. Because many marine zones in eastern Kentucky are not associated with large open bay deposits such as the Magoffin, they must have formed at least 50 km, and perhaps more than 75 km, from such environments.

In the eastern and southeastern parts of the basin, the marine zones in the lower part of the Breathitt below the Magoffin are more numerous, thicker, more continuous, more fossiliferous and contain a larger variety of fossil fauna. This distribution suggests that open marine waters reached eastern Kentucky from the south and southwest along the axis of the subsiding Appalachian geosyncline rather than from the north and northwest as has been suggested by Donaldson (1974) and by Horne and others (1974). Similar conclusions were reached by Nelson (1925) with regard to rocks of the same age in southern Tennessee. Only in strata above the Magoffin did marine transgressions enter the basin from the west and north. The Vanport Limestone as used by Phalen (1912) and younger Pennsylvanian marine zones occur only in northeastern Kentucky and are related to southward- and southeastward-transgressing seas.

Thick (10 to 40 m) sandstone deposits of the Breathitt are generally less massive and resistant than the orthoquartzite of the Lee Formation. They appear to be stacked deposits of shallow anastomosing streams. Channel cuts deeper than 5 m are rarely observed. Grain size varies from sandstone set to set, commonly from bed to bed; only the uppermost channel deposit has in its upper part the fining-upward sequence characteristic of the classic fluviatile deposit. Thick sandstone deposits commonly show rapid lateral lithologic changes and rarely form mappable units, and even the named sandstone members are difficult to recognize short distances from their type areas.

The distribution of sandstone and shale in the Breathitt Formation has not been studied systematically. Analyses of small areas support general impressions that the lower part of the Breathitt is dominantly siltstone and shale, and the upper part mostly sandstone (Huddle and Englund, 1966). In an eight-county area across the central part of the coal field, the line of greater than 50 percent sandstone follows and generally encloses the outcrop of the upper part of the Breathitt as it is preserved along the axis of the broad eastern Kentucky syncline (Newell and Rice, 1977). (See fig. 15.) The sandstone content also apparently increases in the lower part of the formation in the easternmost part of the State. Subangular quartz grit and well-rounded quartz pebbles in coarse-grained sandstone occur locally in two areas along the margins of the State: in the Jesse and Reynolds Sandstone Members in the middle Breathitt in the northeastern part of the Cumberland overthrust block, and in the upper Breathitt in northeastern Kentucky. Current directions in the Breathitt have not been studied, but sediments probably were derived from Appalachian highlands to the east and southeast.

CONEMAUGH AND MONONGAHELA FORMATIONS

The Conemaugh and Monongahela Formations are not separately differentiated in Kentucky because of their lithologic similarity. In other areas of the Appalachian basin, the Conemaugh is defined as extending upwards from the top of the Upper Freeport coal to the base of the Pittsburgh coal. In Kentucky, both these coal horizons occur in poorly exposed shale sequences and are only tentatively identified as thin discontinuous coal or underclay zones. As a result, the base of the Conemaugh is commonly projected from other stratigraphic horizons or is placed at the base of persistent and conspicuous red and variegated shale.

The Conemaugh and Monongahela Formations crop out in an area of about 1,000 km^2 in northeastern Kentucky and have a combined thickness of more than 175 m; the thickness of the Conemaugh is estimated to be about 110 m. They are mainly siltstone and shale and contain various amounts of subgraywacke, limestone, and coal. The siltstone and shale are various shades of red, green, and gray; they are commonly calcareous and many contain thin beds and concretions of marine limestone. Black shale in the upper part of the Conemaugh locally contains conchostracans—brackish- or fresh-water bivalved crustaceans (Connor and Flores, 1978). Subgraywacke occurs locally in channel deposits as much as 30 m thick that are commonly conglomeratic at their base. Marine limestone contain brachiopods, crinoids, gastropods, and fusulinids. Only a few coal beds occur in the lower part of the Conemaugh, and these are thin and discontinuous.

Regional studies suggest that rocks of Conemaugh and Monongahela age were deposited by northwest-flowing streams (Wanless, 1975a, p. 49–53; Arkle, 1974, p. 28). Shallow fresh-water lakes formed locally on the delta plain particularly during Monongahela deposition, and deltaic deposits were repeatedly inundated by eastward-transgressing seas, particularly during Conemaugh time.

Red and green shale, characteristic of the Conemaugh, first occurs in the upper 50 m of the Breathitt Formation, where greenish-gray shale is interbedded with the usual dark-gray shale of the Breathitt, in what is perceived as a "greening" of the shales; reddish-gray shale first appears in the upper 25 m. These changes of color are thought to be related to a reduction in the amount of organic matter in the sediments and may represent a gradual shift toward less extensive swamps in contiguous areas and perhaps toward arid conditions in the source area.

PENNSYLVANIAN STRATA OF WESTERN KENTUCKY

The Pennsylvanian strata of the western Kentucky coal field occupy about 12,000 km^2 of the southeastern part of the Eastern Interior basin, and are about 1,200 m thick. Like the Pennsylvanian rocks in eastern Kentucky, they are largely deltaic in origin and contain many coal beds. However, marine limestone makes up a larger part of the section in western Kentucky than in eastern Kentucky.

GEOLOGIC SETTING

The Pennsylvanian rocks of western Kentucky unconformably overlie strata of Mississippian age. The southwestward paleoslope established in Mississippian time and shown by the sub-Pennsylvanian channel systems (fig. 7) probably was maintained throughout most of Pennsylvanian time (Potter, 1963). The oldest Pennsylvanian strata deposited in these channels are pebbly orthoquartzites, assigned to upper Morrow age by Wanless (1975b, p. 74).

Pennsylvanian strata in the Eastern Interior basin thicken toward a depocenter in southeastern Illinois (McKee and Crosby, 1975, pl. 11). In western Kentucky, the interval between the No. 9 coal bed of Pennsylvanian age and the Vienna Limestone of Mississippian age ranges only from about 370 to 460 m and suggests that subsidence was nearly uniform over the area during Early and Middle Pennsylvanian time. Some eastward thinning of strata in western Kentucky (fig. 10) might suggest the influence of the Cincinnati arch during Pennsylvanian time.

The effect of the Cincinnati arch on Pennsylvanian deposition has long been a matter of speculation (Ashley, 1907; Miller, 1910). Detailed correlations between the Appalachian and Eastern Interior basins have been hampered by the lack of key beds common to both basins and by the great variability of thickness (particularly in eastern Kentucky) and lithology of the Pennsylvanian sediments. Correlations, such as those shown in figure 10, have been based upon sparse paleontological evidence. Regional studies by Potter and Siever (1956a, b) and Siever and Potter (1956) of the petrology, crossbedding directions, and sources of the basal Pennsylvanian sediments in the Eastern Interior basin indicate that the Cincinnati arch was not a major barrier to southwest transport of sediment derived mainly from source areas in the middle and northern Appalachians and the southeastern Canadian Shield.

Fusulinids of Early Permian age from drill core samples in the Bordley quadrangle (R. C. Douglass, written commun., 1977) occur in the uppermost part of the section in a conformable sequence of shale and limestone (fig. 10).

Cretaceous rocks are present to within 24 km of the western margin of the coal field and may have overlapped Pennsylvanian strata; however, they have not been recognized in the coal field. Pleistocene lake beds and outwash cover much of the low-lying areas along stream valleys adjacent to the Ohio River; in the same area, thick deposits of loess blanket hills (Ray, 1965; Shaw, 1915, Frye and others, 1972). These preglacial Pleistocene deposits and locally as much as 60 m thick in the valleys of the Ohio and Tradewater Rivers.

STRATIGRAPHY

The Pennsylvanian strata of western Kentucky are divided into four formations, in ascending order, the Caseyville, Tradewater, Carbondale, and Sturgis Formations (fig. 14). Formations above the Caseyville are not lithostratigraphic units, and their boundaries are commonly placed at regionally persistent coal beds. The Caseyville Formation, like the Lee Formation of eastern Kentucky, is character-

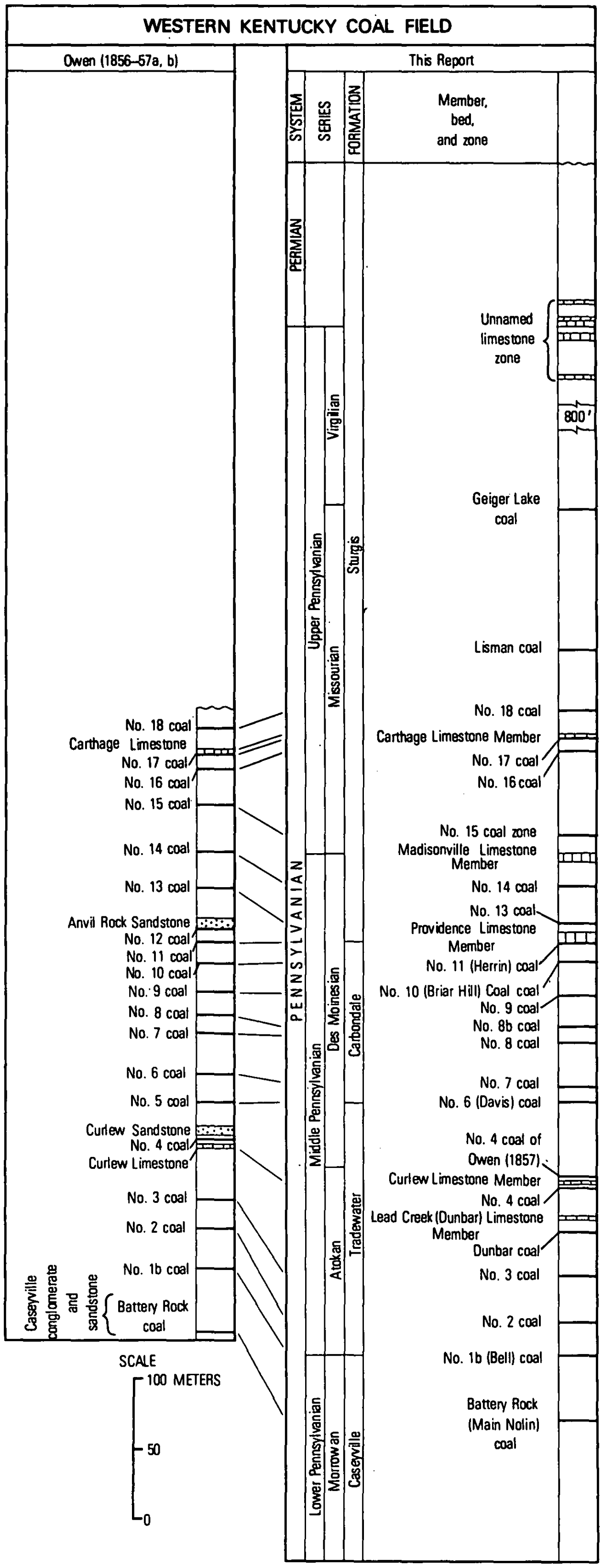

FIGURE 14.—Diagram comparing nomenclature of Owen (1856, 1857a, b) with that of this report.

ized by pebbly orthoquartzite; some of the basal sandstone is more than 75 m thick. However, the Caseyville, locally more than 200 m thick, is in places dominantly shale and siltstone. The top of the formation is arbitrarily placed at the base of the No. 1b (Bell) coal bed where present, or is placed at the top of a persistent sandstone; in many places the Caseyville cannot be differentiated from the overlying Tradewater Formation. Subgraywacke is dominant above the Caseyville, although Siever (1957) reported a transitional zone between orthoquartzite and subgraywacke in the lower part of the Tradewater Formation. Because of poor exposure, much of the stratigraphy of the Pennsylvanian of western Kentucky is known primarily from subsurface data.

The Pennsylvanian rocks consist of carbonaceous siltstone and clay shale, generally medium- to fine-grained sandstone, marine limestone containing brachiopods, pelecypods, cephalopods, gastropods, crinoids, bryozoans, corals, and fusulinids in beds from less than 2 to more than 9 m thick; and argillaceous and concretionary nonfossiliferous limestone. Sandstone and siltstone constitute about 55 to 80 percent of the Pennsylvanian section, and silty shale and clay shale, generally associated with coal and limestone beds, make up about 20 to 45 percent.

Limestone beds, although they make up only about 5 percent of the section, are an important tool for coal exploration and stratigraphic analysis. More than 35 marine transgressions have been recorded in the Pennsylvanian section of the Eastern Interior basin (Wanless, 1975b, p. 72). In western Kentucky, four limestone horizons are recognized as being regionally persistent: the Curlew Limestone Member of the Tradewater Formation, and the Providence, Madisonville, and Carthage Limestone Members of the Sturgis Formation. The Lead Creek or Dunbar Limestone Member of the Tradewater Formation is found only in the eastern part of the coal field.

About 24 principal coal beds or coal zones have been identified in western Kentucky. Most of these are shown in figure 14. The most persistent and thickest coal beds occur in the upper Tradewater Formation, the Carbondale Formation, and the lower Sturgis Formation. These include the Dunbar and Nos. 4, 6, 7, 9, 11, 12, 13, and 14 coal beds.

The No. 11 coal bed contains a distinctive clay shale parting that can be traced throughout the Eastern Interior basin, making the coal bed the most useful marker in the western Kentucky coal field. This parting, 5 to 10 cm thick, generally is light bluish gray, and is referred to as the "blue band." It has a pelletal or grainy structure similar to some flint clays but is composed of illite, chlorite, and kaolinite (Woltman, 1956).

The Pennsylvanian rocks of western Kentucky and the Eastern Interior basin were deposited in alternately deltaic and shallow marine environments resulting in repeated sequences of strata that have been attributed to diastrophic changes (Weller, 1956) or to eustatic sea level and climatic changes (Wanless and Shepard, 1936). These deposits probably resulted from a normal depositional pattern in a slowly subsiding basin that had a continuous source of terrigenous sediments (Wanless and others, 1970). Interpretations of Pennsylvanian deposition in the Eastern Interior basin indicate that it was dominated by many prograding and shifting delta lobes of the Michigan River system (Pryor and Sable, 1974).

BIOSTRATIGRAPHY OF THE PENNSYLVANIAN OF KENTUCKY

Pennsylvanian System boundaries are all poorly defined in Kentucky, and their position as shown in the column (figs. 13 and 14) should be considered approximate. Most Pennsylvanian flora and fauna in Kentucky consist of relatively long-ranging forms of little value for detailed stratigraphic work. Most have not been systematically studied. The earliest investigations of fossil flora in Kentucky by Lesquereux (1857, 1861) were in part summarized by Nóe (1923). Read and Mamay (1964) divided the Upper Paleozoic into 15 floral zones and assigned 9 of these, zones 4 through 12, to the Pennsylvanian. All the Pennsylvanian zones occur in eastern Kentucky. They have also assigned the strata in western Kentucky to floral zones 6 through 12; however, they reported that plant fossils transitional to zones 4 and 5 occur in basal Pennsylvanian strata in Indiana. None of the zonal boundaries of Read and Mamay correspond to lithostratigraphic horizons in Kentucky.

Kosanke (1965a, b, 1966, 1967, 1968, 1969, 1971, 1972) studied the spore assemblages of eastern Kentucky Pennsylvanian coals, but he indicated that the range zones of only a few taxa are useful for even the most general regional and interregional correlations. In detailed studies of coals in part of northeastern Kentucky, Kosanke (1973) suggested that the Princess 5B coal bed occurs at about the same stratigraphic position as the Davis or No. 6 coal bed of western Kentucky. (See fig. 10). He also correlated the Princess No. 7 coal bed with the Briar Hill or No. 10 coal bed of western Kentucky. These analyses refer only to the youngest coals in the Pennsylvanian section of eastern Kentucky; regional and interregional coal correlations for most of the Breathitt and Lee Formations still depend mainly upon interpretations of physical stratigraphy.

Coal-ball material has been described by Schopf (1961) from the Hamlin coal zone in eastern Kentucky and has been reported from the No. 11 coal of western Kentucky from a locality about 3.5 km northwest of Providence. (See fig. 15.) The latter contains a lycopsid-dominated assemblage that includes stems of the following genera: *Lepidocarpon, Cordaite, Sphenophyllum, Sigillaria,* and *Medullosa* (J. M. Schopf, 1963, written commun.).

Pennsylvanian fauna of Kentucky have not been studied in detail. Morse (1931) cataloged and listed most of the major Pennsylvanian marine horizons in eastern Kentucky. Furnish and Knapp (1966) and Strimple and Knapp (1966) studied ammonoids and crinoids of upper Morrowan age from the Kendrick Shale of Jillson (1919) in detail, but only limited studies of megafauna (Cox, 1857) and microfauna (Thompson and Shaver, 1964) of western Kentucky have been published.

Wanless (1975a and b) made extensive use of fusulinid zones for regional and interregional correlations of the Pennsylvanian of the Appalachian and Eastern Interior basins. These fossils locally are abundant in many of the marine limestones of western Kentucky but have not been carefully studied. A fusulinid that has "intermediate" attributes between *Profusulinella* and *Fusulinella* has been identified in the Lost Creek Limestone of Morse (1931) in southeastern Kentucky (Ping, 1978); no specific equivalent has been found in western Kentucky, but taxonomically it falls between the forms in the Lead Creek Limestone and the Curlew Limestone Members of the Tradewater Formation (R. C. Douglass, 1978, written commun.). Wanless (1975b, p. 81) indirectly correlated the Curlew Limestone of the Tradewater Formation of western Kentucky with the Magoffin Member of the Breathitt Formation of eastern Kentucky on the basis of occurrences of *Fusulinella iowensis* in the Curlew and in Mercer Limestone Members of the Pottsville Formation in Ohio. However, the Magoffin apparently occurs well below the *Fusulinella* zone and therefore below the Curlew Limestone. Limestone equivalent to the Mercer of Ohio has not yet been identified in Kentucky, but fusulinids do occur in the Vanport Limestone as used by Phalen (1912) and in the Brush Creek Limestone and Ames Limestone Members of the Conemaugh Formation in northeastern Kentucky. The Brush Creek contains *Triticites ohioensis*; a related species, *Kansanella* sp. aff. *K. Tennis*, is reported from the Carthage Limestone Member of the Sturgis Formation of western Kentucky (R. C. Douglass, 1978, written commun.).

POST-CARBONIFEROUS TECTONIC EVENTS

After deposition of the Pennsylvanian rocks, the southeastern part of the Appalachian basin was warped upward to form the broad eastern Kentucky syncline (fig. 15); this event was probably associated with a northwestward movement of about 12 km of the Cumberland overthrust block.

Two major fault systems, the Irvine-Paint Creek and the Kentucky River fault systems, cross the northern part of the Cumberland Plateau and extend into central Kentucky. They show a maximum vertical displacement of Pennsylvanian rocks of about 75 m; the down-dropped block is to the south.

The Moorman syncline in western Kentucky appears to have been a subsidiary depocenter of the Eastern Interior basin in Pennsylvanian time. In late Paleozoic or early Mesozoic time, movement in the Rough Creek and Pennyrile fault systems resulted in further downwarping of the syncline and in making it a distinct structural basin.

The Rough Creek fault system is about 5 to 8 km wide and extends westward from central Kentucky through the central part of the western Kentucky coal field. It consists of many normal and thrust(?) faults which form a series of grabens and horsts. Vertical displacement along the system is as great as 900 m.

The Kentucky River, Irvine-Paint Creek, and Rough Creek fault systems are part of the 38th parallel lineament, a west-trending alinement of structural features extending from northeastern Virginia to south-central Missouri. Post-Pennsylvanian movement appears to have been mainly vertical, although en echelon faulting of short (8 km), northeast-oriented, normal faults occurs north and south of the Rough Creek system and may represent strike-slip movement. Regional Bouguer gravity anomaly patterns in eastern and central Kentucky suggest a right-lateral offset of about 80 km in the Precambrian basement (Heyl, 1972). Peridotite intrusions and fluorite mineralization in western Kentucky and kimberlite dikes in northeastern Kentucky may be related to this deep-seated zone of weakness. Radiogenic age dating of biotite from peridotite and

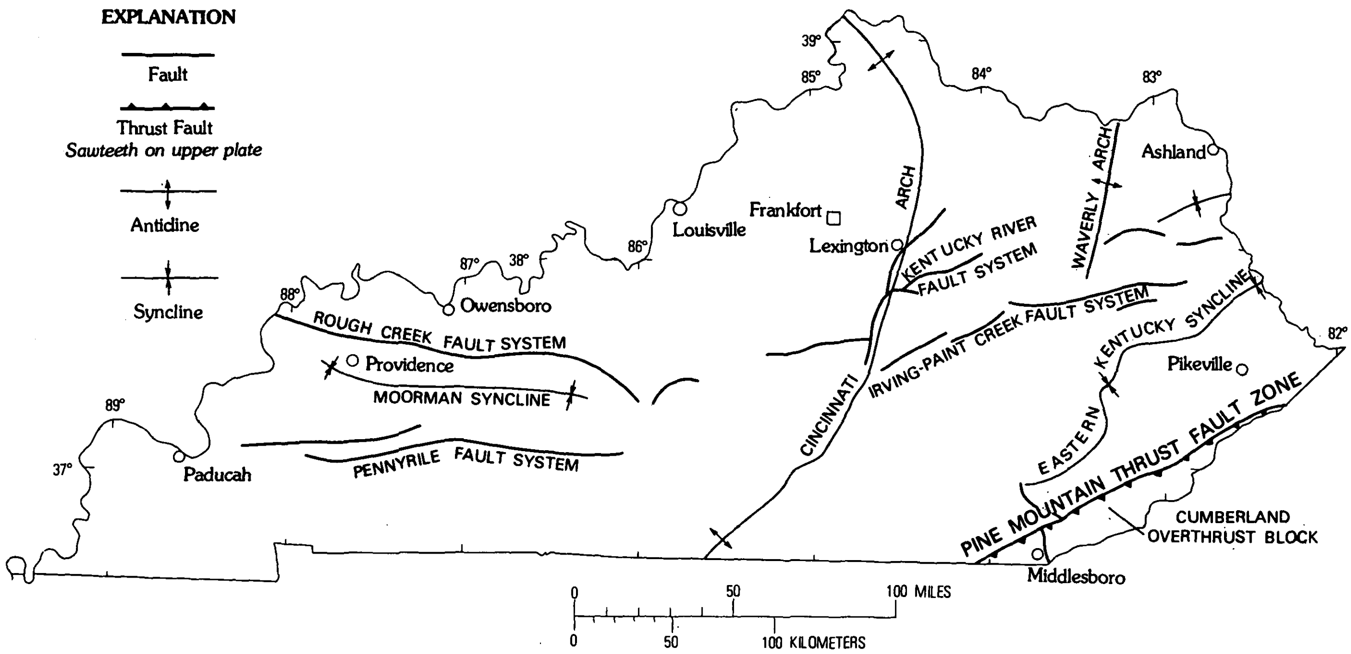

FIGURE 15.—Generalized structure map of Kentucky.

kimberlite intrusions indicates emplacement in Early Permian time (Zartman and others, 1967).

The City of Middlesboro is in a crater-like structure about 5.5 km in diameter in which the Pennsylvanian rocks are intensely deformed and locally brecciated. Englund and Roen (1962) noted shatter cones in sandstones in the center of the basin and interpreted the feature to be a meteorite-impact crater.

ECONOMIC GEOLOGY

Coal is the principal mineral resource of the Carboniferous in Kentucky. Beds of Pennsylvanian age have yielded more than 4.06×10^9 metric tons since commercial production began in about 1790 (Currens and Smith, 1977). Figure 16 shows the distribution of production between the eastern and western coal fields and the important contribution of surface mining in the last three decades. Much of eastern Kentucky production has come from coal beds in the Elkhorn coal zone; most western Kentucky production has come from the Nos. 9 and 11 coal beds.

The coal is high-volatile A and B bituminous; the eastern Kentucky coal is of higher rank and generally lower in ash and sulfur content than the western Kentucky coal. Most coal is produced for utility or steam coal, but many coals of eastern Kentucky are used in the production of high-quality metallurgical coke. Estimates of original reserves in beds thicker than 35 cm for eastern Kentucky are 30.33×10^9 metric tons and for western Kentucky, 35.27×10^9 metric tons (Huddle and others, 1963).

Carboniferous strata are also a major source of oil, natural gas, and industrial and metallic minerals in Kentucky (figs. 17 and 18). An estimated 60 to 80 percent of the State's oil production and an estimated 50 to 70 percent of its natural gas production have come from Carboniferous rocks. Kentucky's cumulative production of oil from 1883, the first year in which production records were kept (Crawford, 1958), through 1976 is 86.4×10^6 metric tons. Cumulative natural-gas production is estimated to be 92.6×10^9 m^3. Mississippian units in western Kentucky have been the principal source of Carboniferous oil, and Mississippian rocks in eastern Kentucky have been the principal source of Carboniferous natural gas. Of the 1×10^6 metric tons of oil produced in Kentucky in 1976, about 70 percent came from Mississippian sandstone and limestone and about 5 percent came from Pennsylvanian sandstone. Of the 1.8×10^9 m^3 of natural gas produced during 1976, about 55 percent was from Mississippian sandstone and limestone and about 5 percent from Pennsylvanian sandstone.

Mississippian limestone is the principal source of crushed stone for construction and agricultural use in western, south-central, and eastern Kentucky; most of the quarries and underground mines producing stone from Mississippian rocks operate

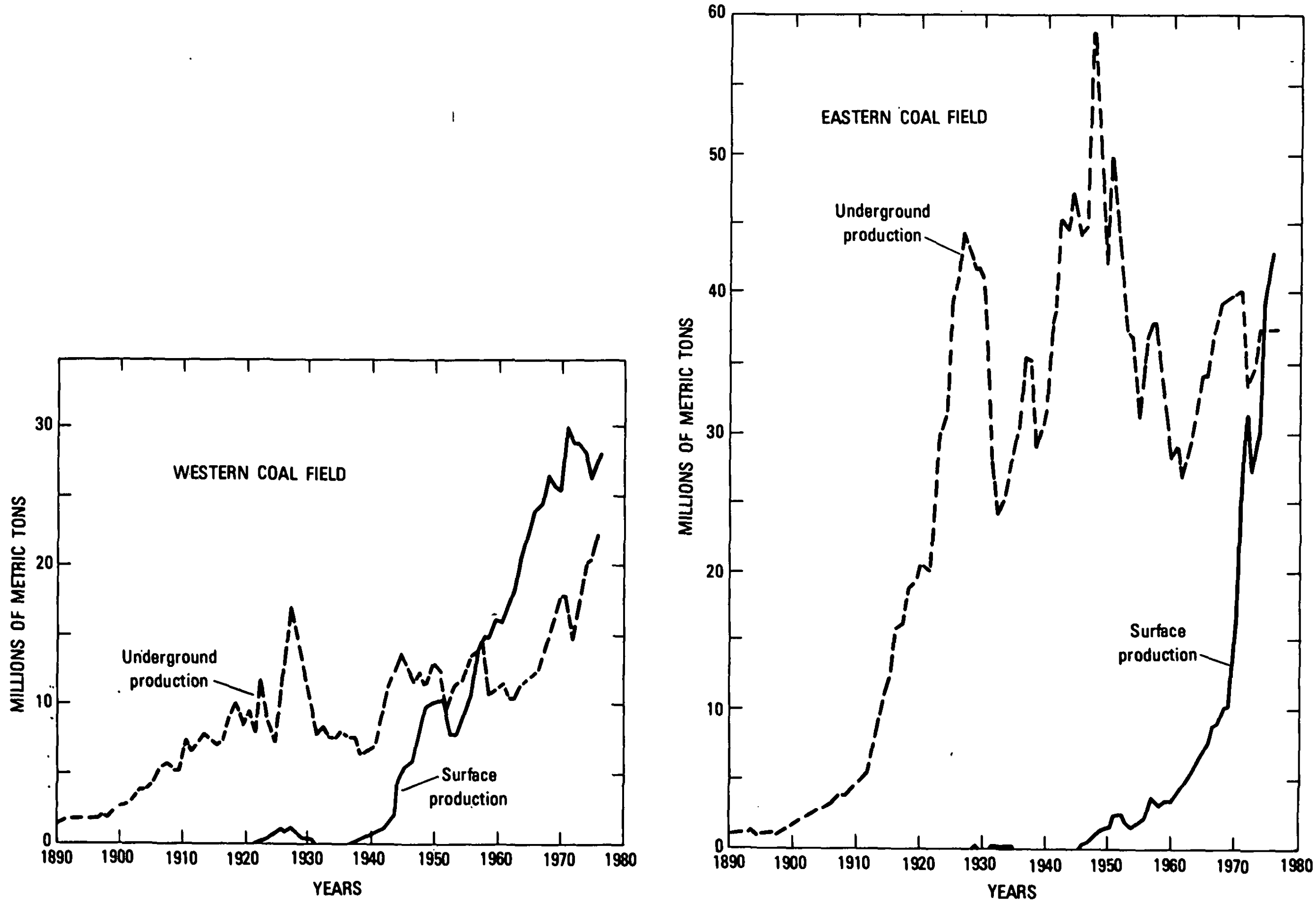

FIGURE 16.—Coal production of the eastern and western coal fields of Kentucky from 1890 to 1975 showing surface and underground mining. Auger production included in surface production. Surface production not significant and not separately reported prior to 1920. Modified from Currens and Smith (1977).

partly or entirely in the Ste. Genevieve Limestone. Small quantities of limestone have also been obtained from thin beds of Pennsylvanian age. High-calcium limestones, mainly oolitic limestones of the Ste. Genevieve Limestone, Girkin Formation, and Newman Limestone (Mississippian), are used for cement, fluxstone, rock dust for underground coal mines, and formerly for lime. Oolitic limestones of the Girkin and, to a lesser extent, the Ste. Genevieve have been quarried for building stone in south-central Kentucky. Pennsylvanian sandstone is crushed for construction aggregate. Road-surfacing material has been produced from rock asphalt deposits in sandstone of the Caseyville Formation (Pennsylvanian) and Big Clifty Sandstone Member of the Golconda Formation (Mississippian) in west-central Kentucky. Deposits of high-silica sandstone of both Mississippian and Pennsylvanian ages have been sources of glass, molding, and foundry sands, sandstone of the Caseyville is being used in the manufacture of ferrosilicon. Dimenson stone has been produced from Mississippian siltstone and sandstone and Pennsylvanian sandstone.

Mississippian shale and Pennsylvanian shale and underclay are used for the production of structural clay products, mainly brick and tile, and, at one site, for lightweight aggregate. In northeastern Kentucky, a major fire-brick industry was based on deposits of refractory clay in the Breathitt Formation (Pennsylvanian), the main source being the Olive Hill Clay Bed of Crider (1913) in the basal part of the Breathitt.

Fluorspar has been mined from deposits in Mississippian rocks of the western Kentucky fluorspar district, about 25 km northeast of Paducah. Sphalerite (locally the principal mine product), galena, barite, cadmium, germanium, and silver have been recovered as byproducts of fluorspar mining. The ore bodies occur as vein deposits along faults and, to a lesser extent, as bedding-replacement deposits (Trace, 1974).

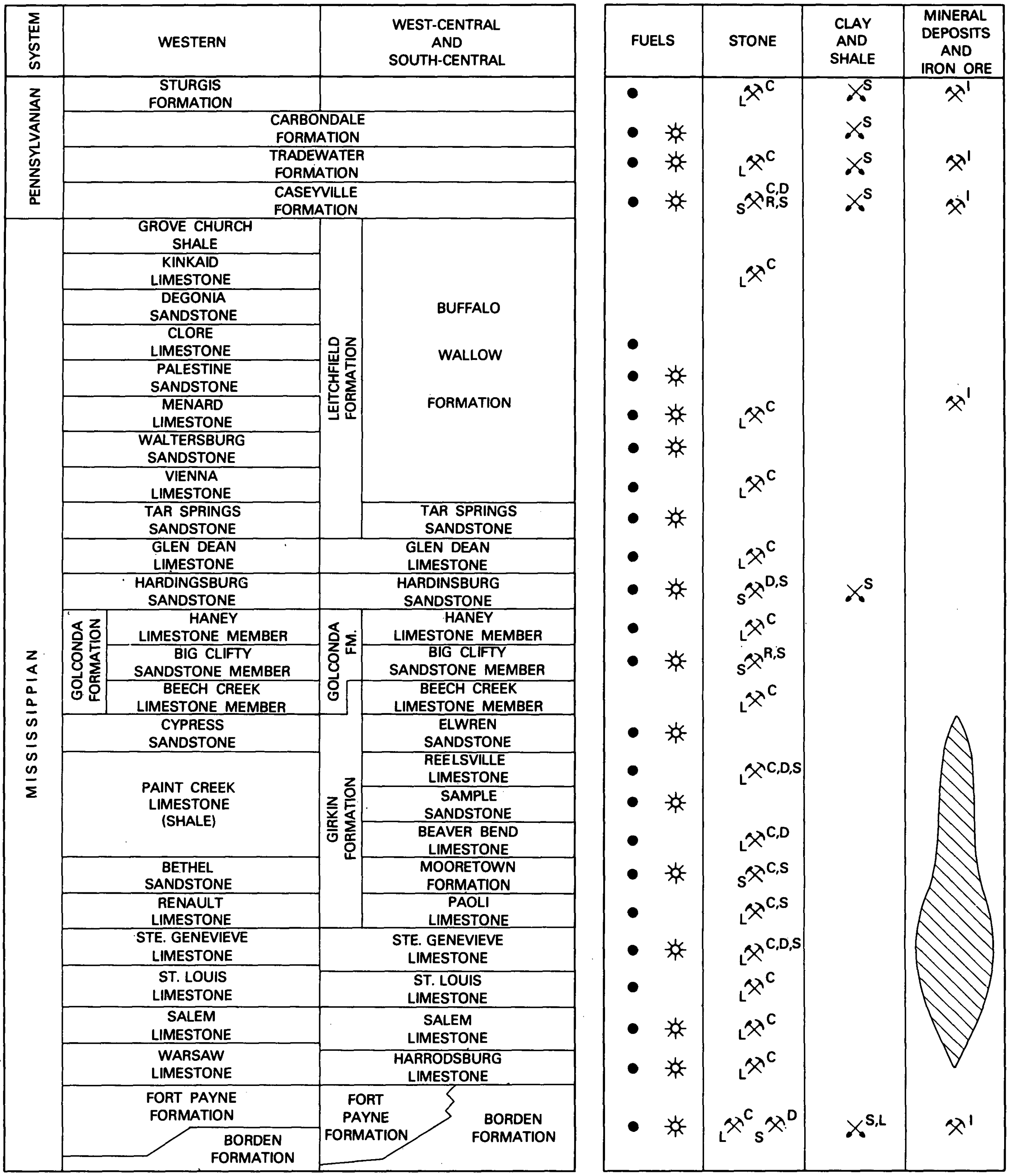

FIGURE 17.—Sources of oil, natural gas, and industrial and metallic minerals in Carboniferous rocks of western Kentucky. Stratigraphic range of principal mineral deposits from Amos (1974) and Trace (1974). For explanation see figure 18.

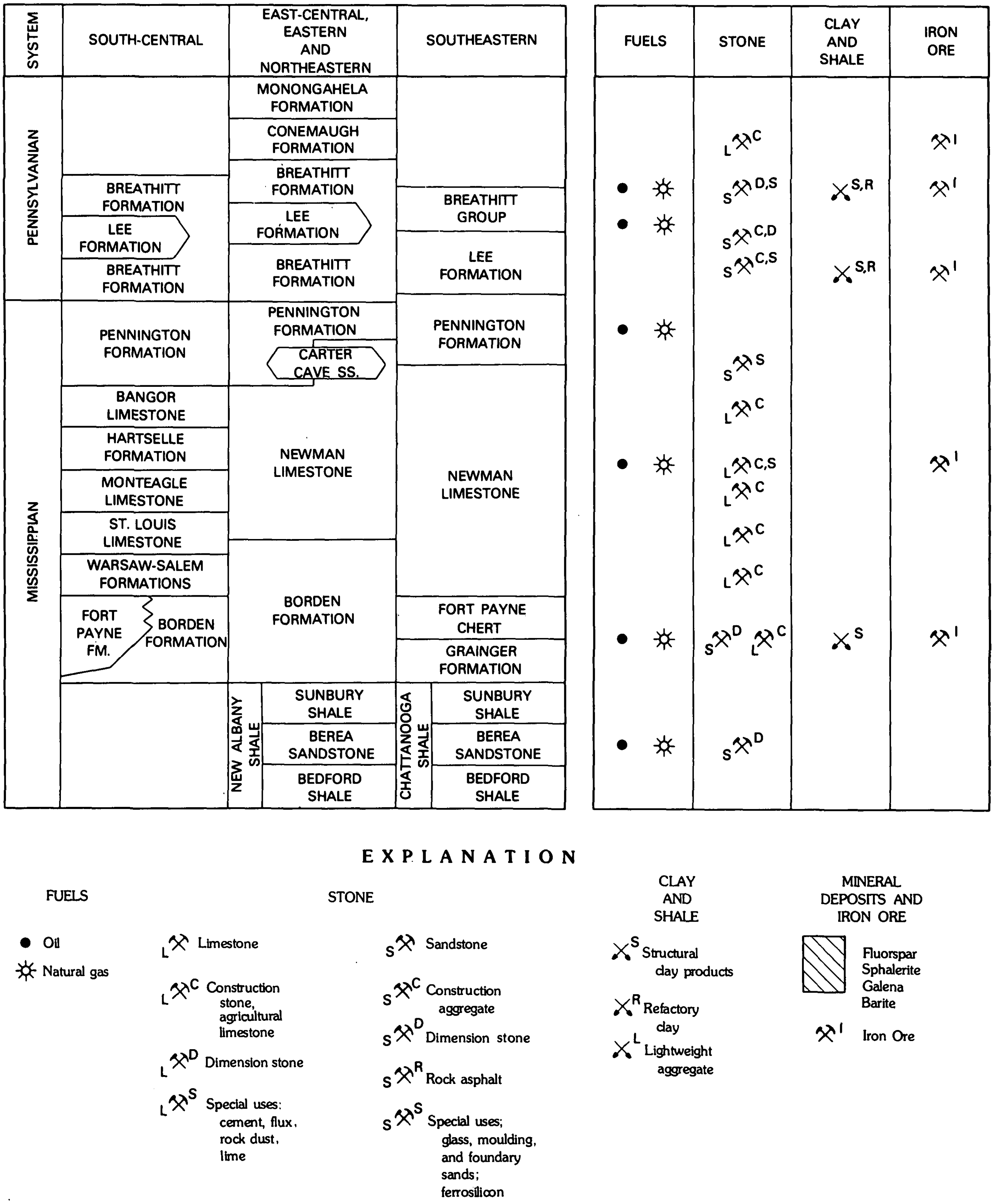

FIGURE 18.—Sources of oil, natural gas, and industrial and metallic minerals in Carboniferous rocks of eastern Kentucky.

Limonitic and sideritic iron ores in Carboniferous rocks were mined extensively during the 19th century for smelting in local furnaces. Deposits in the Breathitt and Conemaugh Formations (Pennsylvanian) and at the top of the Newman Limestone (Mississippian) were sources of ore for furnaces in northeastern and east-central Kentucky. Furnaces were built at several locations in west-central and western Kentucky to utilize ore from deposits in Mississippian and Pennsylvanian units.

Subsurface deposits of gypsum and anhydrite in the lower St. Louis Limestone (Mississippian) of west-central Kentucky may be a potential resource (McGrain and Helton, 1964).

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The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—Tennessee

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Historical review and summary of areal, stratigraphic, structural, and economic geology of Mississippian and Pennsylvanian rocks in Tennessee

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CONTENTS

ILLUSTRATIONS

TABLES

THE MISSISSIPPIAN AND PENNSYLVANIAN (CARBONIFEROUS) SYSTEMS IN THE UNITED STATES—TENNESSEE

By Robert C. Milici,[1] Garrett Briggs,[2] Larry M. Knox,[1] Preston D. Sitterly,[3] and Anthony T. Statler[4]

ABSTRACT

Carboniferous strata are distributed widely across Tennessee. In general, Mississppian deposits in eastern Tennessee are thick and are dominated by terrigenous clastic deposits in the Appalachian geosyncline; Mississippian deposits to the west are thin and are composed of limestone that was deposited on a carbonate platform. The geosyncline was filled, and the carbonate platform was ultmately overlapped by Upper Mississippian and Pennsylvanian terrigenous clastic deposits.

Geosyncline sequences are present in several isolated areas on Valley and Ridge thrust blocks, whereas carbonate platform deposits extend from the western Valley and Ridge, beneath the Cumberland Plateau, to the western Highland Rim. Stratigraphic nomenclature reflects regional changes in stratigraphic sequences from the geosyncline to the carbonate platform. The Carboniferous strata were deposited in marine, littoral, and delta-plain environments.

Tennessee produces petroleum from Mississippian strata, primarily in the northern part of the Cumberland Plateau. Pennsylvanian strata contain abundant coal beds, and five of these, the Sewanee, Coal Creek, Jellico, Big Mary, and Pewee, contain most of the reserves.

INTRODUCTION

Carboniferous strata underlie a great area of central and eastern Tennessee, extending westward from limited exposures on fault blocks in the Valley and Ridge across the Cumberland Plateau to the broad plateau of the Highland Rim (fig. 1). The lower part of the Mississippian section is preserved on the Highland Rim, which forms a crude ellipse around Ordovician and Silurian strata of the Central Basin (Nashville structural dome) of Tennessee. The most completely preserved section of Carboniferous strata in the State is beneath the Cumberland Plateau, where the stratigraphy of the older beds is known both from their extensive exposure along the linear Sequatchie Valley and from the many oil tests drilled in the region.

The lower part of the Carboniferous sequence in Tennessee is composed largely of carbonate rocks that were deposited on a relatively shallow stable platform to the west, and of terrigenous clastic and carbonate rocks that were deposited in a subsiding geosyncline to the east (fig. 2). The upper part of the sequence consists almost entirely of coal-bearing terrigenous clastic deposits, representing either coastal barrier island-lagoon depositional environments or the depositional environments diagnostic of deltaic sedimentation (fig. 3). The carbonate sequence is separated from the coal-bearing beds by a transitional unit, the Pennington Formation, a heterogeneous unit composed of many lithologies. In general, the lower carbonate rocks and the transitional Pennington Formation are Mississippian, whereas overlying terrigenous clastic rocks are Pennsylvanian.

Structurally, the Cumberland Plateau lies in a broad elongated downwarp between the Nashville dome and the thrusts of the Valley and Ridge. The synclinorium plunges gently northeastward from a broad, low, west-trending cross structure, a branch of the Nashville dome, that extends along the southern boundary of Tennessee west of Chattanooga. The southeastern regional dip from the Nashville dome, combined with the gentle northeastern regional plunge induced by the Chattanooga arch, accounts for the distribution of the coal-bearing strata of the plateau; only lowermost Pennsylvanian beds remain in the southern plateau, whereas younger beds are preserved in the Wartburg basin and on the Pine Mountain block to the northeast.

Historically, the Tennessee coal field has been divided into northern (Glenn, 1925) and southern Nelson, 1925) coal fields. The boundary generally follows the routes of the old Tennessee Central Railway and

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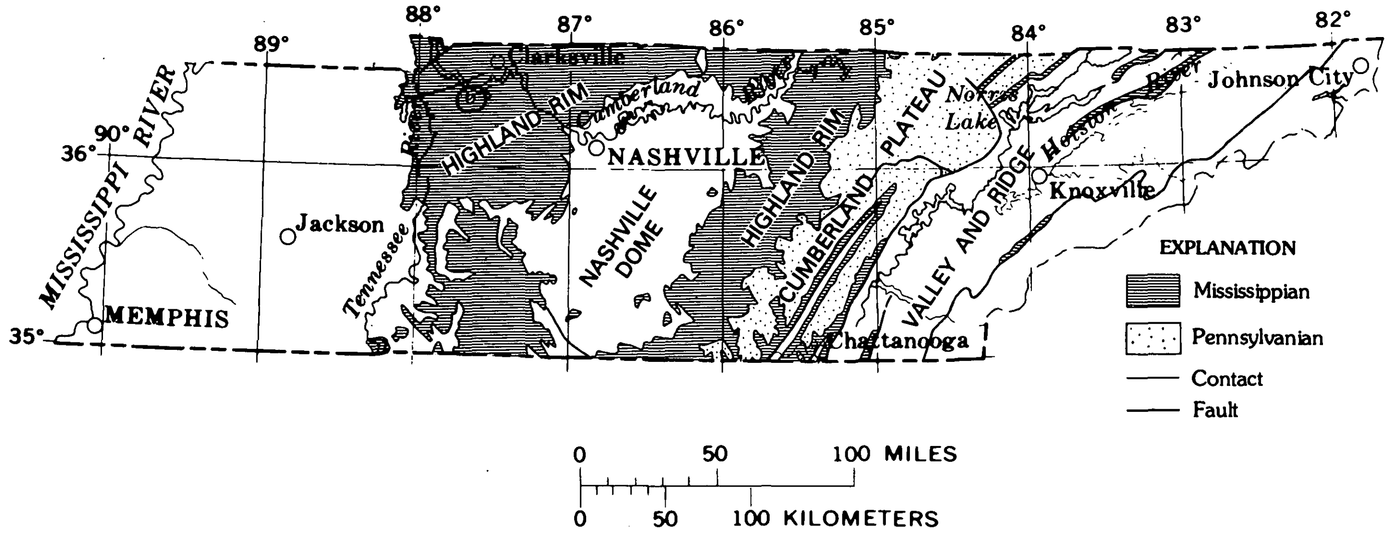

FIGURE 1.—Distribution of Carboniferous strata in Tennessee (from King and Beikman, 1974).

SERIES	WESTERN HIGHLAND RIM	CUMBERLAND PLATEAU AND EASTERN HIGHLAND RIM	PINE MOUNTAIN BLOCK (Englund, 1964, 1968)	NEWMAN RIDGE (Mixon and Harris, 1971)	BELT EAST OF CLINCH MOUNTAIN (Sanders, 1952, unpub. data; Hasson, 1973)	CHILHOWEE MOUNTAIN (Newman and Nelson, 1965)
CHESTERIAN		Gizzard Group (lower part)	Pennington Foramtion	Pennington Formation	Pennington Formation	
		Pennington Formation	Newman Limestone	Newman Limestone	Newman Limestone: Cove Creek Formation	
		Bangor Limestone			Fido Sandstone	
		Hartselle Sandstone			Fisher Creek Limestone	
MERAMECIAN	Ste. Genevieve Limestone	Monteagle Limestone			Gilliam Creek Limestone	
					Clifton Creek Limestone	
	St. Louis Limestone	St. Louis Limestone			Snowflake Formation	
					Laurel Branch Limestone	
	Warsaw Limestone	Warsaw Limestone			Pressmens Home Formation	Greasy Cove Formation
OSAGEAN	Fort Payne Formation	Fort Payne Formation	Fort Payne Chert / Grainger Formation	Grainger Formation	Maccrady Formation	Grainger Formation
					Grainger Formation	
KINDERHOOKIAN	Maury Shale	Maury Shale	Maury Shale	?	?	?
				Chattanooga Shale (upper part)	Chattanooga Shale (upper part)	Chattanooga Shale (upper part)

FIGURE 2.—Nomenclature of Mississippian strata in Tennessee.

SERIES	Wilson and others (1956)		Englund (1964, 1968) Wanless (1946, pl. 32)
ALLEGHENY	Cross Mountain Formation	Breathitt Group	Bryson Formation
ALLEGHENY	Grassy Spring coal bed	Breathitt Group	Red Spring coal bed ?
KANAWHA	Rock Spring coal bed	Breathitt Group	Hignite Formation
KANAWHA	Vowell Mountain Formation	Breathitt Group	Hignite Formation
KANAWHA	Pewee coal bed	Breathitt Group	Hignite Formation
KANAWHA	Readoak Mountain Formation	Breathitt Group	Sharp coal bed
KANAWHA	Readoak Mountain Formation	Breathitt Group	Catron Formation
KANAWHA	Windrock coal bed	Breathitt Group	Poplar Lick coal bed
KANAWHA	Graves Gap Formation	Breathitt Group	Mingo Formation
KANAWHA	Jordan coal bed	Breathitt Group	Mingo Formation
KANAWHA	Indian Bluff Formation	Breathitt Group	Mingo Formation
KANAWHA	Jellico coal bed	Breathitt Group	Harlan coal bed
KANAWHA	Slatestone Formation	Breathitt Group	Hance Formation

SERIES	Slighty modified from Wilson and others (1956)[1]		Englund(1964, 1968)[1]	
NEW RIVER	Crooked Fork Group	Poplar Creek coal bed	Breathitt Group	Hance Formation
NEW RIVER	Crooked Fork Group	Wartburg Sandstone	Breathitt Group	Hance Formation
NEW RIVER	Crooked Fork Group	Glenmary Shale	Breathitt Group	Hance Formation
NEW RIVER	Crooked Fork Group	Coalfield Sandstone	Breathitt Group	Hance Formation
NEW RIVER	Crooked Fork Group	Burnt Mill Shale	Breathitt Group	Hance Formation
NEW RIVER	Crooked Fork Group	Crossville Sandstone		Lee Formation
NEW RIVER	Crooked Fork Group	Dorton Shale		Lee Formation
NEW RIVER	Crab Orchard Mountains Group	Rockcastle Conglomerate		Lee Formation
NEW RIVER	Crab Orchard Mountains Group	Vandever Formation		Lee Formation
NEW RIVER	Crab Orchard Mountains Group	Newton Sandstone		Lee Formation
NEW RIVER	Crab Orchard Mountains Group	Whitwell Shale		Lee Formation
NEW RIVER	Crab Orchard Mountains Group	Sewanee Conglomerate		Lee Formation
				?
NEW RIVER	Gizzard Group	Signal Point Shale		Pennington Formation (upper member)
NEW RIVER	Gizzard Group	Warren Point Sandstone		Tongues of Lee Formation
?		?		
CHESTER	Gizzard Group	Raccoon Mountain Formation		Pennington Formation (lower member)

[1]Queried double lines show opinions concerning the Mississippian–Pennsylvanian boundary.

FIGURE 3.—Nomenclature of Pennsylvanian strata in eastern Tennessee and adjacent parts of Kentucky. Only coal beds that separate formations are shown.

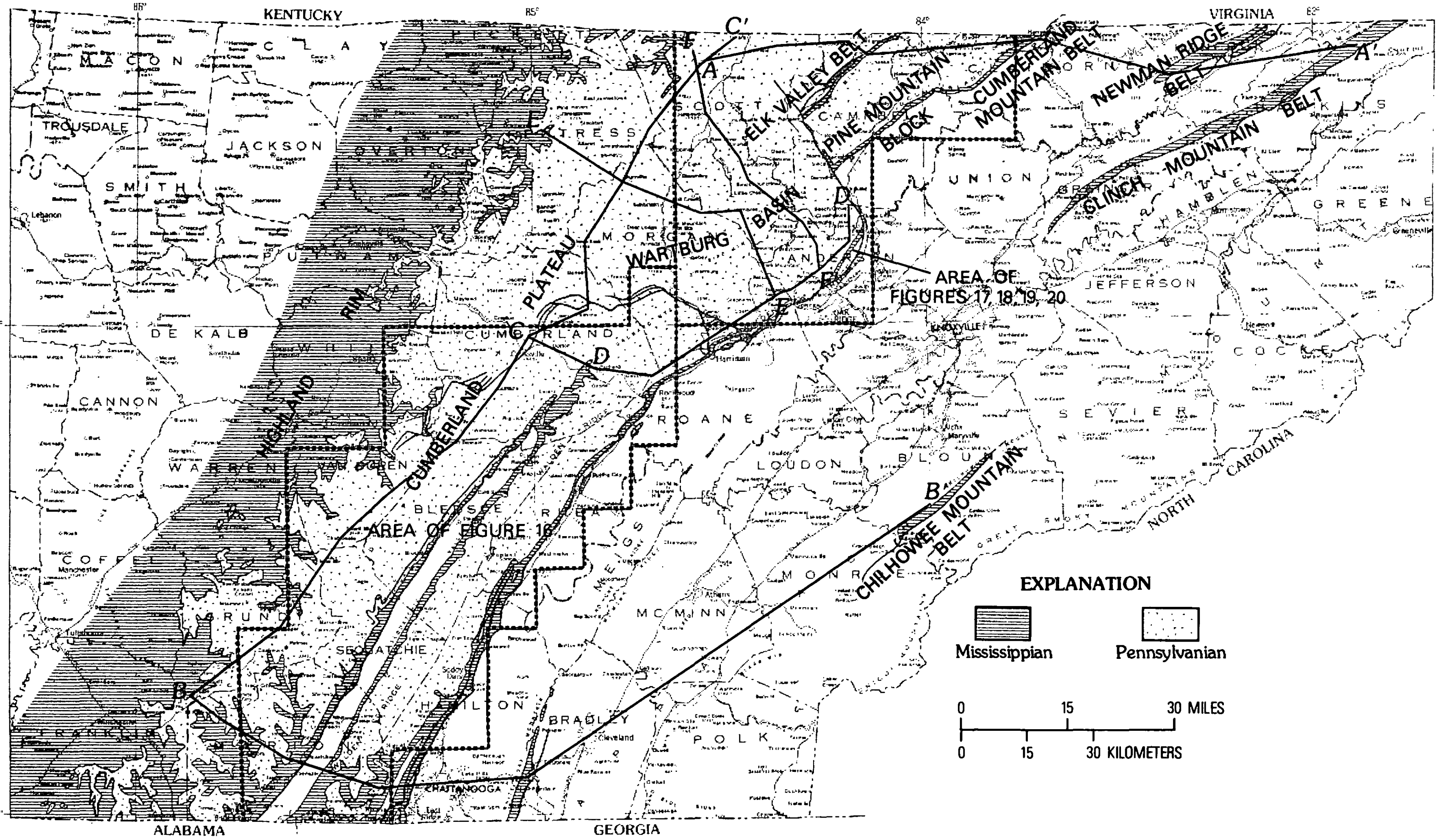

FIGURE 4.—Location of stratigraphic cross sections in eastern Tennessee.

the more recently constructed Interstate 40 between Harriman and Monterey. The southern Cumberland Plateau and the western part of the northern plateau consist of broad, moderately dissected uplands underlain by widespread thick orthoquartzites and interbedded shale units. In contrast, the higher mountains in the northeastern part of the Cumberland Plateau in Tennessee are underlain by units composed mostly of shale and siltstone and thinner sandstone beds; these sandstone beds are not nearly so widespread as the orthoquartzites and are generally subgraywackes. Carboniferous strata are exposed on the western half of the Pine Mountain thrust block; this part of the block is in the plateau.

Four major outcroppings of Carboniferous strata occur on the thrust blocks of the Valley and Ridge of Tennessee: on Whiteoak Mountain to the south, near Chilhowee Mountain along the toe of the Blue Ridge, and to the north near Clinch Mountain and on Newman Ridge. The outcrop along the Blue Ridge contains only the lower part of the Mississippian section; a little Pennsylvanian is preserved at the top of the section along Whiteoak Mountain; and the Pennington Formation caps the Mississippian sections in the Clinch Mountain strike belt and on Newman Ridge. Regional stratigraphic cross sections along lines shown in figure 4 are presented herein to illustrate Devonian to Pennsylvanian thickness and facies variations in eastern Tennessee.

The stratigraphic nomenclature used in this paper has not been reviewed by the Geologic Names Committee of the U.S. Geological Survey. The nomenclature used here conforms with the current usage of the Tennessee Department of Conservation, Division of Geology.

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STRATIGRAPHY

The final major cycle of Paleozoic sedimentation in Tennessee began with the Middle to Late Devonian submergence of an erosional surface that cut across beds ranging in age from Middle Ordovician to Early Devonian. Then, mud, silt, and sand of the Chattanooga Shale were deposited on this surface.

The Chattanooga Shale lies upon about 25 formations in central and eastern Tennessee (fig. 5). Basal beds of the Chattanooga range generally from Middle to Late Devonian in age .With minor exceptions, the Devonian-Mississippian boundary—the base of the Carboniferous system—is either within or at the top of the Chattanooga Shale. On the basis of studies of conodonts, plant fossils, and bones, Conant and Swanson (1961, p. 21) described the Chattanooga as being entirely Devonian in central Tennessee. However, conodonts studied by Roen and others (1964) and fossils described by Glover (1959) show that the upper part of the Chattanooga is Mississippian in the Valley and Ridge near Big Stone Gap in southwestern Virginia and near Chilhowee Mountain in eastern Tennessee.

CHATTANOOGA SHALE

The Chattanooga Shale (Hayes, 1891), which is a potential source of uranium and hydrocarbons,

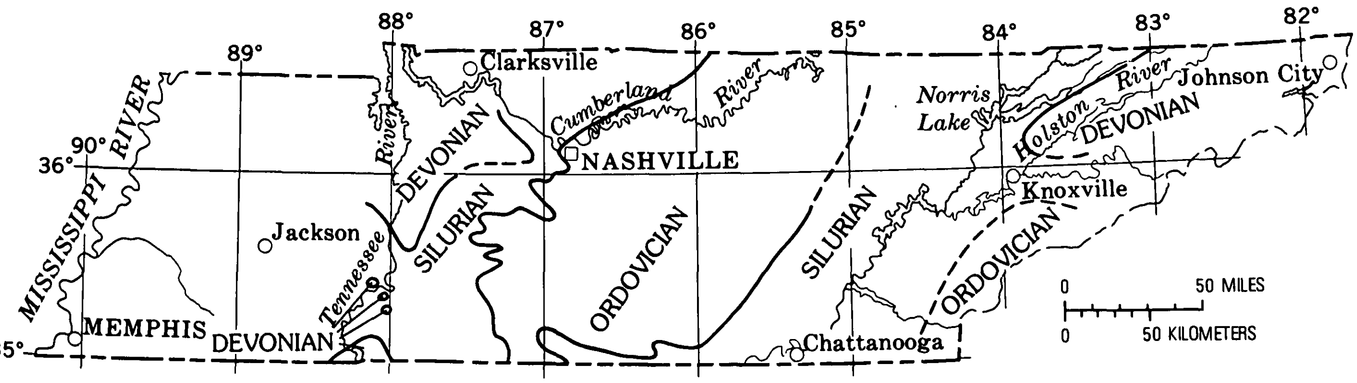

FIGURE 5.—Ages of pre-Chattanooga strata in eastern Tennessee.

varies greatly in thickness in Tennessee. In places in central Tennessee, the formation is absent altogether (Conant and Swanson, 1961, pl. 1; Wiethe and Sitterly, 1978). Elsewhere in central Tennessee it ranges from 3 to 10 m (10 to 33 ft) in thickness. The formation thickens greatly to the east and may be as much as 610 m (2,000 ft) thick in the Greendale syncline along Clinch Mountain (fig. 6).

Chilhowee Mountain belt.—The Chattanooga Shale is about 7.6 m (25 ft) thick along the northwest flank of Chilhowee Mountain (Neuman and Nelson, 1965, p. D40–D41). There the formation consists of dark gray carbonaceous shale and has several centimeters of fine-grained sandstone at its base. In the Chilhowee Mountain strike belt, the Chattanooga overlies the Bays Formation (Middle Ordovician) unconformably, in some places resting on quartzites and in other places on bentonitic volcanic ash within the Bays (Glover, 1959, p. 145).

Fossils collected by Neuman and Nelson (1965) and by Glover (1959) indicate that the Chattanooga along Chilhowee Mountain is of Late Devonion or Early Mississippian age.

Clinch Mountain belt.—The Paleozoic stratigraphy of the Greendale syncline along Clinch Mountain was studied in detail by Sanders (1952). The nomenclature of Devonian and Mississippian formations that was proposed by Sanders (1952) for that region has not been formally published but has been modified and adopted by the Tennessee Division of Geology for mapping purposes and is used in this report.

The Chattanooga Shale crops out along the southeastern flank of Clinch Mountain. The formation thickens markedly from about 122 m (400 ft) at the southern end of the outcrop belt in Grainger County to about 610 m (2,000 ft) in Hawkins County, and from this area thins northeastward into Virginia.

In the Greendale syncline strike belt, the Chattanooga rests on older Devonian beds that are commonly mapped with the Clinch Sandstone because they are so thin. Sanders (1952) recognized about 1.8 m (6 ft) of coarse-grained fossiliferous sandstone, which he correlated with the Ridgely Sandstone (Lower Devonian) of the central Appalachians. On Clinch Mountain, the Ridgely (or Oriskany) is in places overlain by about 0.3 m (1 ft) of yellowish-gray chert, which Sanders (1952) correlated with the Huntersville Chert of West Virginia.

Dennison and Boucot (1974) correlated the pre-Chattanooga Lower Devonian sequence at Little War Gap on Clinch Mountain with the Wildcat Valley Sandstone of Miller, Harris, and Roen (1964) and divided it into a lower Oriskany Member (2.9 m, 9.4 ft thick) and an upper Huntersville Member (2.4 m, 7.9 ft thick), which is composed of fine-grained glauconitic and phosphatic sandstone.

Sanders (1952) subdivided the Chattanooga Shale of the Greendale syncline into three units (classified as members by the Tennessee Division of Geology), the Little War Gap Shale Member at the base, the Klepper School Member in the middle, and the Salt Lick Gap Shale Member at the top. Hasson

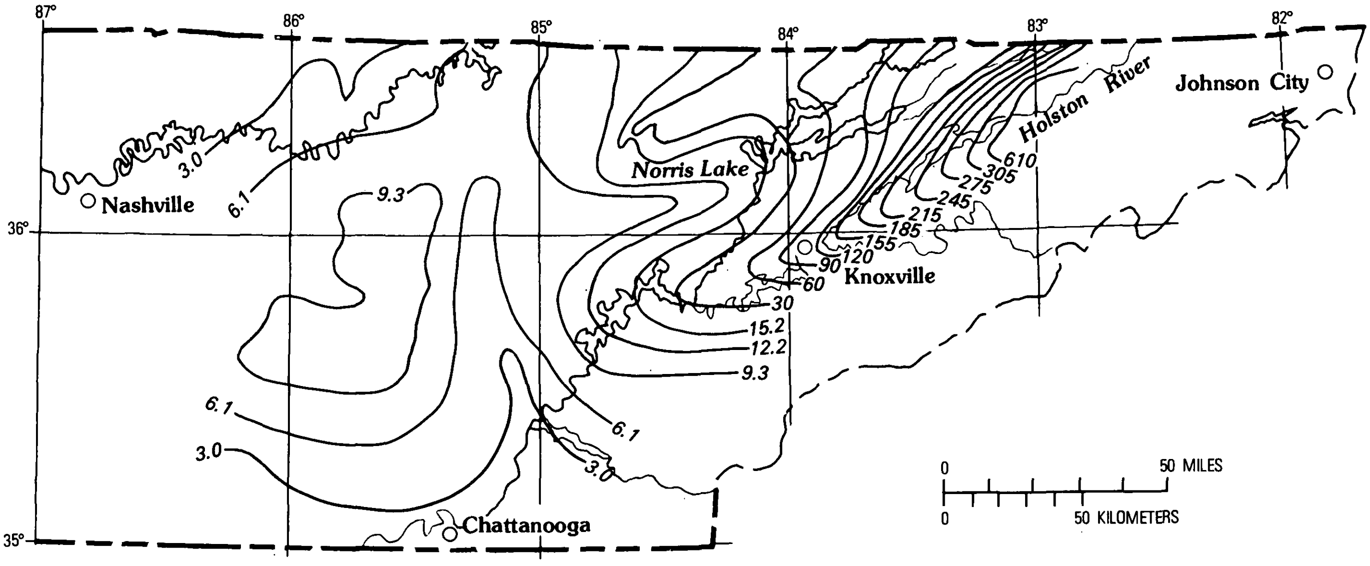

FIGURE 6.—Isopach map of the Chattanooga Shale in eastern Tennessee (in part from Conant and Swanson, 1961, pl. 15). Isopachs in meters.

(1972, 1973) and Dennison and Boucot (1974) placed the top of the Chattanooga Shale at a somewhat higher stratigraphic level than did Sanders (1952).

A detailed section of the Little War Gap Shale Member was measured along Tennessee Highway 70 near Little War Gap in Clinch Mountain by Dennison and Boucot (1974, p. 98–99). In this section, the member is 287 m (940 ft) thick and generally consists of fissile black shale and subsidiary amounts of gray shale.

The Klepper School Member consists generally of finely laminated dark-gray micaceous siltstone, dark-gray laminated silty shale, and interlaminated light-gray and dark carbonaceous siltstone and shale. Southwest of its type section on Tennessee Highway 70, the Klepper School contains beds of very fine grained light-gray sandstone that range in thickness from 15 to 61 cm (0.5–2 ft). Sanders (1952) estimated the unit to be about 244 m (800 ft) thick at its type section, thinning to 152 m (500 ft) or less to the southwest. Dennison and Boucot (1974) measured 327.4 m (1,074 ft) for the Klepper School Member at its type section.

Sanders (1952) mapped about 7.6 m (25 ft) of fissile black shale above the Klepper School Member as the Salt Lick Gap Shale Member, but exposures are too poor to designate and measure a type section. Correlation of the upper part of the Chattanooga Shale, including the Salt Lick Gap Shale Member, in the Greendale syncline in Tennessee with strata near Big Stone Gap in southwestern Virginia is in question. Hasson (1972) placed as much as 65.8 m (216 ft) of the basal beds of Sanders' (1952) Grainger Formation in the Chattanooga Shale and correlated this unit with the Big Stone Gap Member of the Chattanooga Shale (Roen and others, 1964). If Hasson (1972) is correct, then the Big Stone Gap, including the Salt Lick Gap Shale at its base, should be extended into Tennessee as the upper member of the Chattanooga Shale.

Newman Ridge and Pine Mountain block.—The Chattanooga Shale thins progressively to the northwest, and on Newman Ridge along the southeast side of Powell Mountain, it consists of about 122 m (400 ft) of grayish-black carbonaceous shale (fig. 7). The shale is commonly pyritic and contains small amounts of interbedded greenish-gray shale (Harris and Mixon, 1970; Mixon and Harris, 1971; Harris and others, 1962). On Newman Ridge, the Chattanooga overlies the Upper Silurian Hancock Dolomite (Sneedville Limestone of Hardeman and others, 1966).

On the Pine Mountain block near Cumberland Gap, the Chattanooga is 61–91 m (200–300 ft) thick and consists mostly of grayish-black carbonaceous and pyritic shale that lies unconformably on the Hancock Dolomite (Englund, 1964; Harris, 1965). Englund (1964) considered the 15.2 m (50 ft) of greenish-gray shale that in places is at the base of the Chattanooga to be part of that formation.

Central Tennessee.—Because of its potential as a low-grade uranium resource, the Chattanooga in central Tennessee and in nearby areas was extensively studied by the U.S. Geological Survey (Hass, 1956; Glover, 1959; Conant and Swanson, 1961). The Chattanooga lies on formations ranging in age from Middle Ordovician to Devonian in central Tennessee; the older beds are truncated over the crest of the Nashville dome (Wilson, 1949, pl. 2; Conant and Swanson, 1961, pl. 3). In central Tennessee, the Chattanooga is divided into three members, a basal Hardin Sandstone Member, a middle Dowelltown Member, and an upper Gassaway Member.

The Hardin Sandstone Member is generally present in several counties in central Tennessee, where it is as much as 4.9 m (16 ft) thick (Conant and Swanson, 1961, fig. 6). The member consists of massive fine-grained gray sandstone containing minor amounts of phosphate and bones. The Hardin Sandstone Member was regarded by Conant and Swanson (1961, p. 28) as a local overthickening of a widespread but very thin basal Chattanooga sandsone or conglomerate. They preferred to restrict the use of the name Hardin to the area where the unit is thick, is of Devonian age, and is fine grained and massively bedded. The Hardin Sandstone Member is Upper Devonian, but elsewhere the age of the thin basal sandstone or conglomerate varies as the age of the overlying shale varies and is, in different places, Late Devonian or possibly Mississippian (Conant and Swanson, 1961, p. 25).

The Dowelltown Member overlies either the Hardin Sandstone Member or the much older beds beneath the Chattanooga and consists of a lower black shale unit and an upper unit composed of interbedded light-gray claystone and dark-gray shale beds. The member is present around the northern and central parts of the Highland Rim, where it is commonly 4.6–6.1 m (15–20 ft) thick, but it is not very thick near the southern border of Tennessee.

The contact between the Dowelltown Member and overlying Gassaway Member was interpreted by Conant and Swanson (1961, p. 29) to be a diastem or slight unconformity within the Chattanooga. The

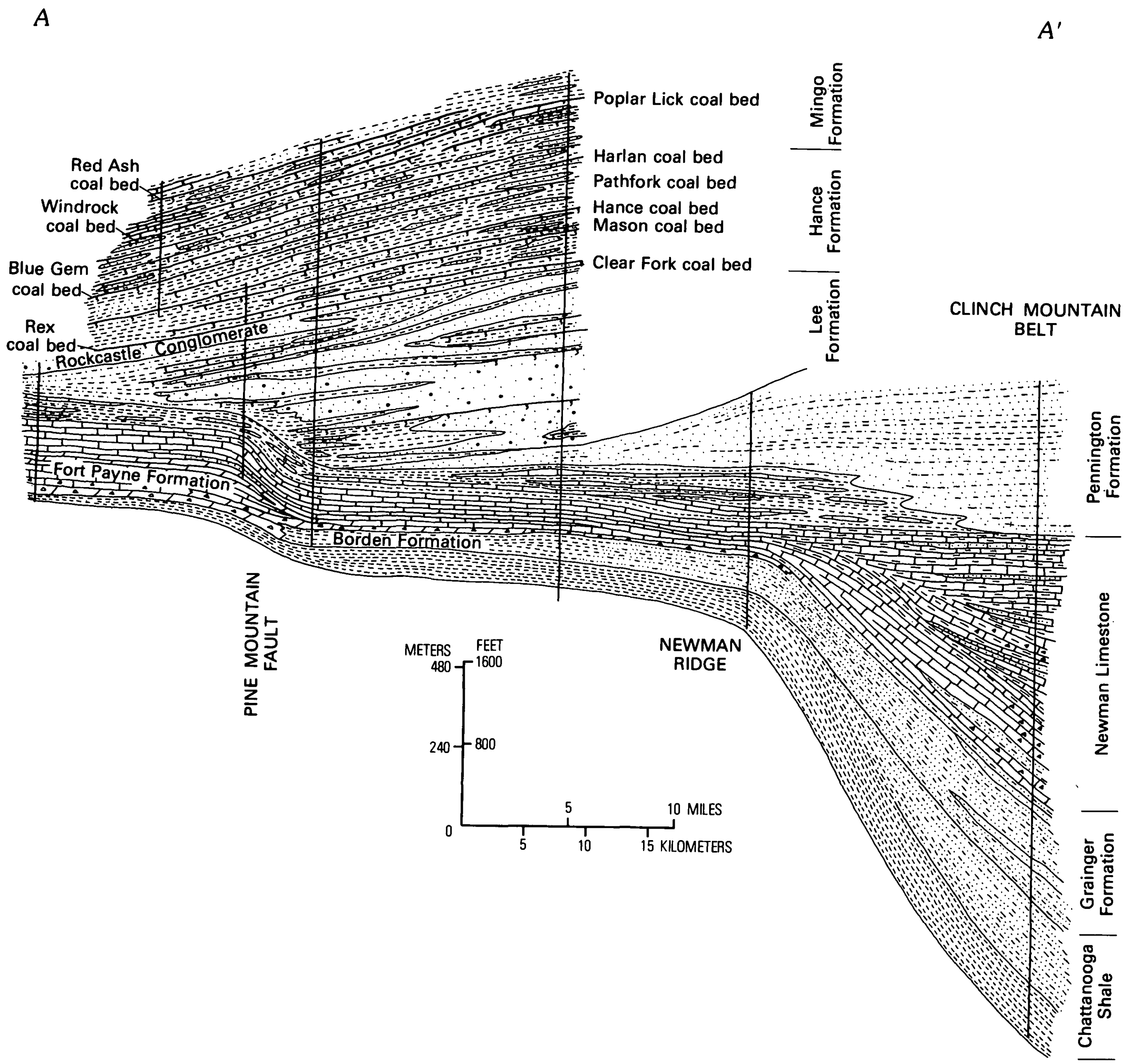

FIGURE 7.—Stragraphic cross section along line A–A'.

Gassaway Member is the most widespread of the three members of the Chattanooga Shale. Typically the unit consists of massive black bituminous shale. In Tennessee, the member is generally 4.6–6.1 m (15–20 ft) thick but thins to the south, and along the southern Tennessee border, it is less than 3 m (10 ft) thick.

GRAINGER FORMATION

The Grainger Formation (Keith, 1895) overlies the Chattanooga Shale in the Chilhowee Mountain, Clinch Mountain, and Newman Ridge strike belts and in exposures on the Pine Mountain block. The formation grades to the west and south into the Fort Payne Formation and to the north and northwest into the Borden Formation (figs. 7, 8). The Grainger reaches a maximum thickness of 320 m (1,050 ft); the thicker sections are near Chilhowee Mountain, and thinner ones are on the Pine Mountain block (fig. 9).

Chilhowee Mountain belt.—Neuman and Nelson (1965, p. D43) measured 320 m (1,050 ft) of

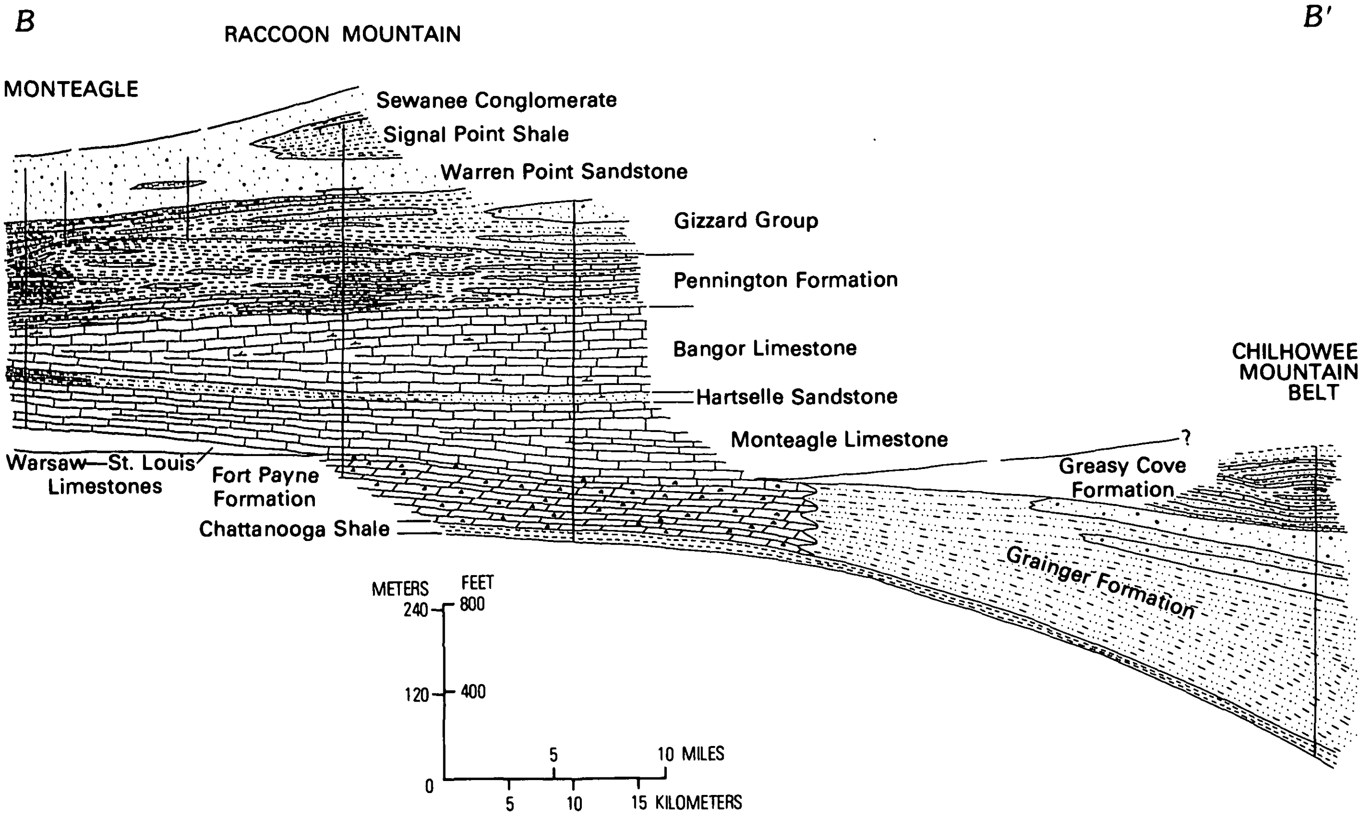

FIGURE 8.—Stratigraphic cross section along line B–B

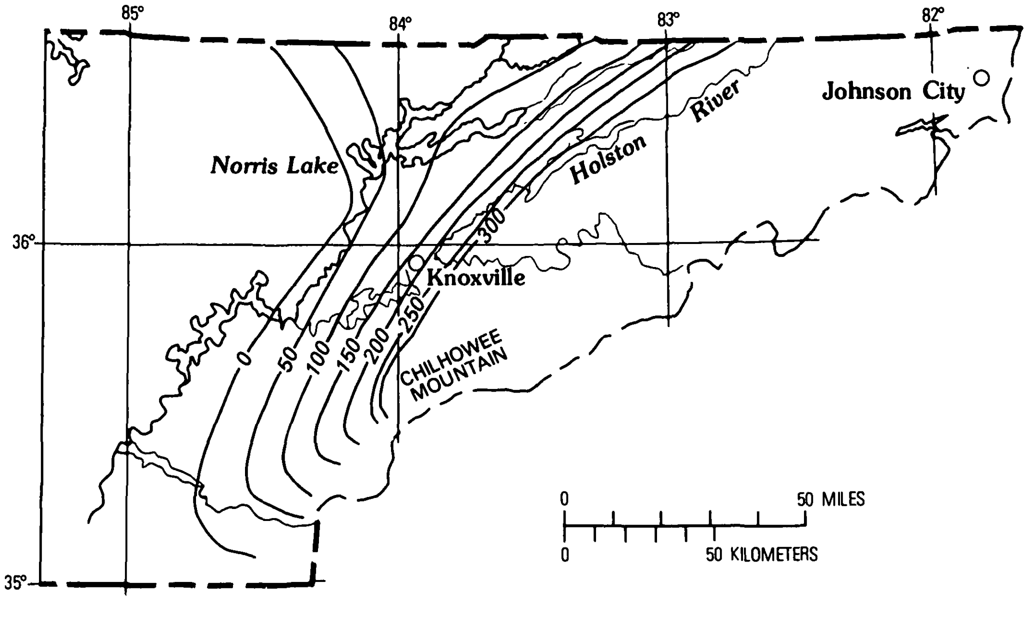

FIGURE 9.—Generalized isopach map of the Grainger Formation in eastern Tennessee. Isopach interval 50 meters.

Grainger near Chilhowee Mountain. The lower and middle parts of the formation consist of gray shale and sandy shale that is overlain by massive gray sandstone and siltstone. The upper part of the formation consists of coarser grained and conglomeratic sandstones containing quartz pebbles as much as 2.5 cm (1 in.) long. The formation contains a few beds of fossiliferous sandy limestone; the fossils suggest that the Grainger in this area is of Warsaw age.

Clinch Mountain belt.—The type area of the Grainger is in the Greendale syncline, along a low ridge called Pine Mountain which is east of Clinch Mountain. The Grainger was studied there by Sanders (1952) and by Hasson (1972, 1973). Sanders (1952) divided the Grainger into four lithologic members, a basal member, a lower sandstone member, a middle siltstone-shale member, and an upper sandstone member. The basal member, which is 61–91 m (200–300 ft) thick, consists of dark-gray argillaceous shale and olive-gray siltstone, thin beds of fine-grained sandstone, and a little limestone. The lower sandstone member ranges from 15.2 to 61 m (50 to 200 ft) in thickness along the Greendale syncline in Tennessee. The unit consists of very fine grained light-gray sandstone and some pebble conglomerate. The middle member of the Grainger consists of 122 to 152 m (400 to 500 ft) of gray shale and olive-gray siltstone; two glauconite zones are in the upper part. Except for the glauconite beds, the middle and basal members are lithologically similar. The upper sandstone member of the Grainger consists of as much as 45.7 m (150 ft) of very fine grained to coarse-grained feldspathic, medium-gray sandstone and some interbedded olive-gray silty shale. Cross bedding is common, and the upper part of the member contains pebble conglomerate of vein quartz, quartzite, feldspar, and slate.

Hasson (1972, 1973) restricted the Grainger Formation in the Greendale syncline to the upper three members of Sanders (1952) and correlated the basal member with most of the Big Stone Gap Member of the Chattanooga Shale in southwestern Virginia. Hasson (1973) provided two measured sections of the Grainger (restricted), one at the type section in Grainger County, and another in Hawkins County, which he designated as the standard reference section for the formation. Depending upon the assignment of the basal member of the Sanders (1952), the Grainger is either 168 or 234 m (552 or 768 ft) thick at the standard reference section. Hasson (1972, 1973) concluded that the Grainger was of Kinderhook-Osage age, on the basis of brachiopods, bryozoans, and crinoid columnals that he studied.

Newman Ridge.—In the Newman Ridge strike belt—the next belt northwest of the Greendale syncline—the Grainger Formation is considerably thinner than in the Greendale syncline. Near the south end of Newman Ridge, the Grainger, as mapped by Harris and Mixon (1970) and Harris and others (1962), consists of 107–122 m (350–400 ft) of greenish-gray shale and siltstone, some grayish-red shale is near the middle of the formation, and about 6.1 m (20 ft) of thin-bedded greenish-gray chert is at the top.

Pine Mountain block.—The Grainger thins and changes markedly to the northwest between its exposures on both sides of the Middlesboro syncline on the Pine Mountain block. Near Middlesboro, Ky., the formation consists of 91–99 m (300–325 ft) of greenish-gray and grayish-red shale containing abundant siderite nodules; about 6.1 m (20 ft) of Fort Payne Chert is at the top (Englund, 1964). On the northwest side of the Pine Mountain block, the Grainger consists of a maximum of 69 m (225 ft) of greenish-gray and grayish-red shale containing siderite nodules. The formation thins and intertongues with the Fort Payne to the southwest between Jellico and Pioneer, to where only about one-third meter (a foot) of shale (Maury Formation) is at the base of the Fort Payne (Englund, 1968, fig. 6). Fossils described by Englund (1968, p. 9) show that the Grainger is of early Osage age.

Paul Potter (oral commun., 1976) pointed out that the unit mapped as Grainger by Englund (1968) at Jellico is lithologically similar to the Borden Formation of eastern Kentucky. Like Potter, the present writers believe that the term Grainger should be used in eastern Tennessee where the formaton is thick, sandy, and silty and predominantly gray, whereas the term Borden is more appropriate for correlative thinner greenish-gray and grayish-red shale of the Jellico-Pioneer area. The change in facies from Grainger to Borden lithologies seems to be related to the tectonic setting in which the strata were deposited; the Borden was deposited on the stable shelf, and the Grainger on the shelf edge and in the basin.

FORT PAYNE FORMATION

The Grainger (or Borden) grades laterally into the Fort Payne Formation; where the two coexist, the Fort Payne overlies the Grainger (Smith, 1890). The Fort Payne Formation is widespread in Tennessee; it extends from the western part of the Valley and Ridge, passes beneath the Cumberland Plateau, where it crops out along the eastern side of Sequatchie Valley and in Elk Valley, to the Highland Rim. The boundary between the Fort Payne and Grainger or Borden is shown approximately by the zero isopach in figure 9. The formation ranges from about 30 to 91 m (100 to 300 ft) in thickness.

The base of the Fort Payne is marked almost everywhere by the thin (generally about a meter (3 ft) or less) Maury Formation (Stafford and Killebrew, 1900). The Maury is characteristically a greenish-gray to grayish-green shale, mudstone, siltstone, or claystone. Phosphate nodules are common and in some places, the formation is abundantly glauconitic. The Maury is too thin to map separately and is commonly included with the Fort Payne.

The Fort Payne Formation contains several lithologies and facies in Tennessee. The stratigraphy of the formation has not been studied in detail on a regional basis, and much of the description in this report was obtained from published geologic quadrangle maps. Wilson (in press) mapped about 76.2 m (250 ft) of cherty limestone and dolomite in the Whiteoak Mountain syncline. Englund (1968) described the Fort Payne as consisting of 30 to 53 m (100 to 175 ft) of finely crystalline bedded cherty dolomite containing greenish-gray shale partings in the area of its transition to the Borden Formation.

In northern Sequatchie Valley, the Fort Payne consists of about 61 m (200 ft) of siliceous and cherty limestone and dolomite. To the south, the formation is thinner and more deeply weathered so that outcrops consist of beds of crinoidal chert.

The Fort Payne of the Highland Rim is a heterogeneous mixture of carbonate and terrigenous clastic material and a rock described by the Tennessee Division of Geology on many geologic quadrangle maps as silicastone. Silicastone is defined by the Tennessee Division of Geology in its quadrangle mapping as "sedimentary rocks composed of fragmental (silt-size) and/or precipitated silica."

Calcareous shale and siltstone and cherty argillaceous limestone are the dominant lithologies of the eastern Highland Rim. However, Chowns and Elkins (1974, p. 887) noted that dolomite, which had not been reported by previous workers (see for example, Wilson and Barnes, 1968), was present in the Fort Payne in the area that they studied. The formation ranges from about 21.3 to 39.6 m (70 to 130 ft) in thickness in the southeastern Highland Rim and is 76.2 m (250 ft) or more thick to the northeast, near Kentucky. In places, the lower part of the formation consists of several meters of greenish-gray to light-olive-gray shale that encapsulates beds, bioherms, and lenses of crinoidal limestone as much as 9 m (30 ft) thick (fig. 10). Chert is abundant throughout the formation in carbonate rocks and calcareous siltstones as bands, beds, lenses, nodules, or irregularly shaped masses. Two silicastone-bearing areas of Fort Payne are in central Tennessee, one at the Kentucky line and a larger area that appears to extend from the central part of the eastern Highland Rim to the southwestern part of the western Highland Rim (fig. 10).

Geodes of quartz are common in the Fort Payne. Those studied by Chowns and Elkins (1974) appear to be pseudomorphs after anhydrite and are associated with tidal-flat and lagoonal sedimentary sequences. Chowns and Elkins (1974) identified siliceous sponge spicules and spiculite in the Fort Payne and Warsaw; these fossils may have been the source of the abundant silica in the formation.

In the southwestern Highland Rim, the Fort Payne can be divided into an upper cherty facies and a lower siltstone facies. The cherty facies consists of irregular rough plates and granules of brown, gray, or black chert in a matrix of calcareous brown to gray siltstone, and interbedded chert and siltstone. The lower siltstone facies consists of gray calcareous massively bedded siltstone containing siliceous and calcareous geodes and irregular beds of chert. Locally, the lower siltstone facies contains crinoidal and glauconitic limestone beds, and in places it is petroliferous. In this area, the Fort Payne ranges in thickness from 61 to 91 m (200 to 300 ft).

The lower siltstone facies gives way to the northeast so that the cherty facies overlies silicastone-bearing strata (fig. 10). The silicastone is generally gray to brownish gray and contains various amounts of calcite and dolomite. Chert and quartz geodes are common. Olive-gray to brownish- or greenish-gray shale is present beside and below the silicastone in this area, and crinoidal limestone is locally abundant within the shale.

In the northwestern part of the Highland Rim, the upper cherty facies is absent, and the Fort Payne is represented mostly by brownish-black, brownish-gray, and grayish-black calcareous siltstone. The siltstone in places is shaly, is cherty, or contains quartz geodes. In places, the upper part of the Fort Payne contains crossbedded calcarenite 15.2 m (50 ft) or more below the Fort Payne-Warsaw contact, the calcarenite is similar to that of the Warsaw Limestone.

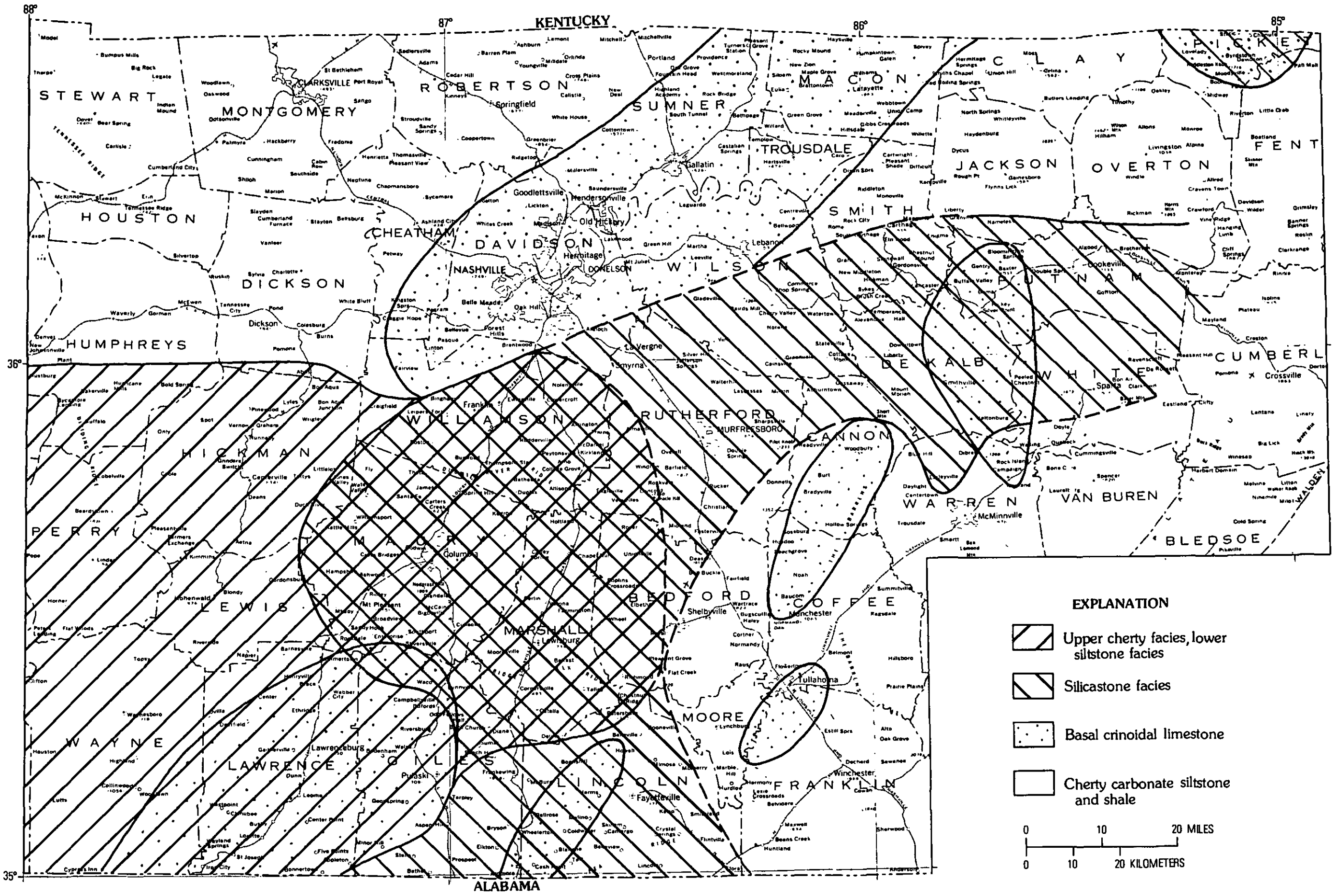

FIGURE 10.—Facies of the Fort Payne Formation in central Tennessee.

In the north-central Highland Rim, the formation consists of brownish-black to gray cherty calcareous or dolomitic siltstone and shale that is interbedded with gray cherty and silty dolomitic limestone. Lenticular masses and bioherms of crinoidal limestone as much as 7.6 m (25 ft) thick are present in the lower part of the Fort Payne in the western and northern Highland Rim (fig. 10).

In the western valleys of the Tennessee and Cumberland Rivers along the Kentucky line, the Fort Payne is represented by brown to black dense chert interbedded with siliceous shaly limestone and calcareous to dolomitic siltstone. Some of the chert is in rough irregular plates and granules in a siliceous or calcareous matrix. Small siliceous geodes are common. The New Providence Shale is a facies within the Fort Payne in places in this area and is represented by about 6.1 to 21.3 m (20 to 70 ft) of medium-gray to grayish-green calcareous and glauconitic shale and a few thin beds of silty nodular crinoidal limestone.

The Fort Payne Formation, as mapped by the Tennessee Division of Geology, includes all beds between the Maury Formation and Warsaw Limestone and is of Kinderhook or Kinderhook-Osage age (Conkin and Conkin, 1975).

NEWMAN LIMESTONE AND EQUIVALENTS

The Newman Limestone (Campbell, 1893, p. 38) consists of those beds between the top of the Fort Payne Formation and the base of the Pennington Formation (fig. 2). The unit is mapped as a formation on Newman Ridge and on the Pine Mountain block (Mixon and Harris, 1971; Englund, 1964, 1968). The Tennessee Division of Geology recognizes formations within the Newman in the Clinch Mountain strike belt east of Newman Ridge and uses a slight modification of the nomenclature proposed by Sanders (1952, and unpub. data in the files of the Tennessee Division of Geology). Strata equivalent to the lower part of the Newman were recognized by Neuman and Nelson (1965) in the Chilhowee Mountain belt. In the Cumberland Plateau and Highland Rim, Newman equivalents are divided into another set of formations that are mostly limestone but contain subordinate amounts of sandstone and shale.

CHILHOWEE MOUNTAIN BELT

Neuman and Nelson (1965) named the post-Grainger Mississippian beds near Chilhowee Mountain the Greasy Cove Formation. The unit consists of about 305 m (1,000 ft) of gray argillaceous limestone interbedded with red and gray fine-grained sandstone, siltstone, and shale (fig. 8). The top of the formation has been cut off by faulting, and younger beds are unknown in this area. Brachiopods in limestone beds suggest that the Greasy Cove is of Warsaw age.

CLINCH MOUNTAIN BELT

The Newman Limestone is estimated to be between 637 and 914 m (2,090 and 3,000 ft) thick in the strike belt east of Clinch Mountain (fig. 7), where it was subdivided by Sanders (1952), from base upward, into the: Maccrady Formation, Pressmens Home Formation, Laurel Branch Limestone, Snow Flake Formation, Clifton Creek Limestone, Gilliam Creek Limestone, Fisher Creek Formation, Fido Sandstone, and Cove Creek Formation.

The Maccrady Formation (Stose, 1913) consists of about 18.3–21.3 m (60–70 ft) of gray to grayish-red claystone, shale, calcareous siltstone, and sandstone. In places, grayish-red siltstone is gypsiferous, reflecting the equivalence of the Maccrady in Tennessee to the gypsum-bearing beds of the same age in southwestern Virginia.

The Pressmens Home Formation (J. E. Sanders, unpub. data in the files of the Tennessee Division of Geology) consists of about 45.7 m (150 ft) of calcareous siltstone, sandstone, limestone, and dolomite. In places, the limestone is cherty, and the unit locally contains 3 to 4.6 m (10 to 15 ft) of oolitic limestone near its top at the type section in the Pressmens Home quadrangle.

The Laurel Branch Limestone (Sanders, 1952) is composed of very fine grained dark-gray to black limestone that contains chert nodules and lenses and silicified corals, brachiopods, and bryozoans. The unit is about 24.4 m (80 ft) thick.

Sanders (1952) named the Snow Flake Formation for a siltstone unit 36.6 to 39.6 m (120 to 130 ft) thick between the Laurel Branch and Clifton Creek limestones. The unit is composed of silty shale and siltstone lithologically similar to the Grainger Formation. The base of the Snow Flake is marked by 0.3 m (1 ft) of calcareous sandstone. The sandstone is overlain by about 30 m (100 ft) of weathered silty shale and calcareous siltstone, and then by 2.4 m (8 ft) of fissile black limestone and 2.4 m (8 ft) of fissile black shale, and at the top by about 3 m (10 ft) of silty crystalline fossiliferous limestone.

The Clifton Creek Limestone (Sanders, 1952) is composed of about 39.6 m (130 ft) of dark-gray to black finely crystalline limestone containing small scattered nodules of black chart. Dark-gray oolitic limestone that is 0.3 m (1 ft) thick is about 7.6 m (25 ft) below the top.

The Gilliam Creek Limestone (Sanders, 1952) is about 122 m (400 ft) thick and consists typically of cherty gray to brownish-gray limestone, some argillaceous to silty, and some containing "porphyritic" crystals of calcite in a matrix of aphanitic rock. In general, the unit consists in its lower part of 40 m (130 ft) of medium crystalline limestone containing 0.6 m (2 ft) of oolitic limestone 12.2 m (40 ft) above the base. Next above is 18.3 m (60 ft), more or less, of silty aphanitic and cherty limestone, above which is 3.7 m (12 ft) of very coarsely crystalline calcarenite. The upper part of the formation is composed of interbedded cherty and silty limestone.

The Fisher Creek Formation (Sanders, 1952) consists of three members. The lower member is composed of about 152 m (500 ft) of coarse silty laminated gray limestone, gray crossbedded calcarenite, greenish-gray to yellowish-gray shaly and calcareous siltstone, and fine-grained gray limestone. The middle sandstone member of the Fisher Creek Formation consists of 15.2 m (50 ft) of medium-grained calcareous gray sandstone in beds 15–30 cm (0.5–1 ft) thick; in places, the sandstone grades laterally into calcarenite. The upper member of the Fisher Creek Formation consists of about 305 m (1,000 ft) of interlaminated gray limestone, coarser silty limestone, greenish-gray calcareous siltstone, and fine-grained gray limestone. Massive calcarenite beds are present in subordinate amounts.

The Fido Sandstone of Butts (1927) consists 6.1–15.2 m (20 to 50 ft) of very fine to medium-grained gray calcareous sandstone or grayish-red sandy calcarenite in the Clinch Mountain belt. The formation is commonly crossbedded and in places contains fossil fragments.

The Cove Creek Formation of Butts (1927) consists of three members in the Clinch Mountain belt in Tennessee, a lower limestone member, a middle sandstone member, and an upper limestone member. The lower member consists of 68.6–107 m (225–350 ft) of massive argillaceous limestone containing laminations, ribbons, and discontinuous lenses of quartz sand. The middle member is composed of about 15.2 m (50 ft) of fine- to medium-grained gray calcareous sandstone and sandy calcarenite. The upper member consists of gray argillaceous or shaly limestone interlaminated with siltstone. The member is about 30 m (100 ft) thick, and the total thickness of the Cove Creek Formation of Butts (1927) ranges from 122 to 152 m (400 to 500 ft) in Tennessee.

The names Cove Creek Limestone and Fido Sandstone were abandoned by the U.S. Geological Survey on the basis of a report by Wilpolt and Marden (1949). They replaced the name Cove Creek Limestone by the name Bluefield Formation, which has precedence, and the Fido was determined to be equivalent to the lower part of the Bluefield and the upper part of the Greenbrier Limestone (Keroher and others, 1966). For this reason, the Cove Creek and Fido should not be perpetuated in the stratigraphic nomenclature for Mississippian strata in Tennessee, and a set of local names should be proposed.

The great thickness and lithologic aspects of the Newman Limestone in the Greendale syncline suggest that it is largely a slope deposit marginal to the carbonate platform. However, detailed petrologic studies have not yet been made.

NEWMAN RIDGE AND PINE MOUNTAIN BLOCK

The Newman Limestone consists of a lower limestone member and an upper limestone and shale member on Newman Ridge and on the Pine Mountain block (Mixon and Harris, 1971; Harris and Mixon, 1970; Harris and others, 1962, Harris, 1965; Engund, 1964, 1968). The formation thins from 241 m (790 ft) on Newman Ridge to a maximum of 223 m (730 ft) along Cumberland Mountain to no more than 210 m (690 ft) in Elk Valley.

The formation is more calcareous to the northwest, primarily because of an increase in thickness of the lower limestone member. This member is composed of about 70 m (230 ft) of chert-bearing light-olive-gray calcilutite interbedded with bioclastic and oolitic limestones on Newman Ridge and of 79 m (260 ft) of similar lithologies along Cumberland Mountain; in Elk Valley, the lower member is 122–131 m (400–430 ft) thick and its lowest 6.1 m (20 ft) consists of finely crystalline olive-gray or dolomitic argillaceous limestone that contains lenses of coarse sand and jasper-bearing conglomerate. This basal unit is overlain by oolitic and bioclastic gray limestone that contains thin beds of greenish-gray or grayish-red shale.

The upper member is about 171 m (560 ft) thick on Newman Ridge and consists of greenish-gray shale and siltstone interbedded with olive-gray calcilutite, argillaceous calcilutite, and medium-grained oolite. In the Cumberland Mountain belt, the upper members consists of 99 m (325 ft) or more of medium-gray calcareous shale interbedded with medium-gray to olive-gray calcilutite and oolitic, bioclastic limestone. In Elk Valley, the correlative unit is composed principally of gray, greenish-gray, and grayish-red shale interbedded with fine- to coarse-grained limestone or argillaceous limestone and is 67.1–100.6 m (220–330 ft) thick.

The Mississippian section on I–75 south of Jellico was studied in detail by members of a Sedimentation Seminar at the University of Cincinnati, and a detailed report of the seminar is being published by the Tennessee Division of Geology (in press). Significantly, the seminar group was able to identify in the Newman at Jellico the formations typical of the Mississippian section in the Cumberland Plateau to the west and south, including a bit of the Warsaw, the St. Louis, Monteagle, Hartselle, and Bangor.

The Newman (or Bangor)-Pennington contact is picked differently by different workers. In the Elk Valley region, Englund (1968, p. 13) mapped the top of the Newman at the base of 6.1 m (20 ft) of massive sandstone, placing the considerable thickness of interbedded shale and limestone beds below in the upper member of the Newman. In Tennessee, other workers map the base of the Pennington lower in the section, selecting as a matter of convenience the base of yellowish-gray weathering silty dolomite beds a little above the solid limestone of the Bangor. The reader should be aware, therefore, that the upper member of the Newman Limestone, as mapped in Newman Ridge and on the Pine Mountain block, may include correlatives to beds mapped elsewhere within the lower part of the Pennington Formation.

CARBONATE PLATFORM DEPOSITS OF THE CUMBERLAND PLATEAU AND HIGHLAND RIM

Beneath the Cumberland Plateau and Highland Rim, the Fort Payne Formation is overlain by a carbonate sequence containing minor amounts of sandstone and shale. On the eastern side of the Nashville dome, the sequence is divided into the Warsaw, St. Louis, and Monteagle Limestones, the Hartselle Sandstone, and the Bangor Limestone (figs. 11 and 12). West of the dome, where the upper

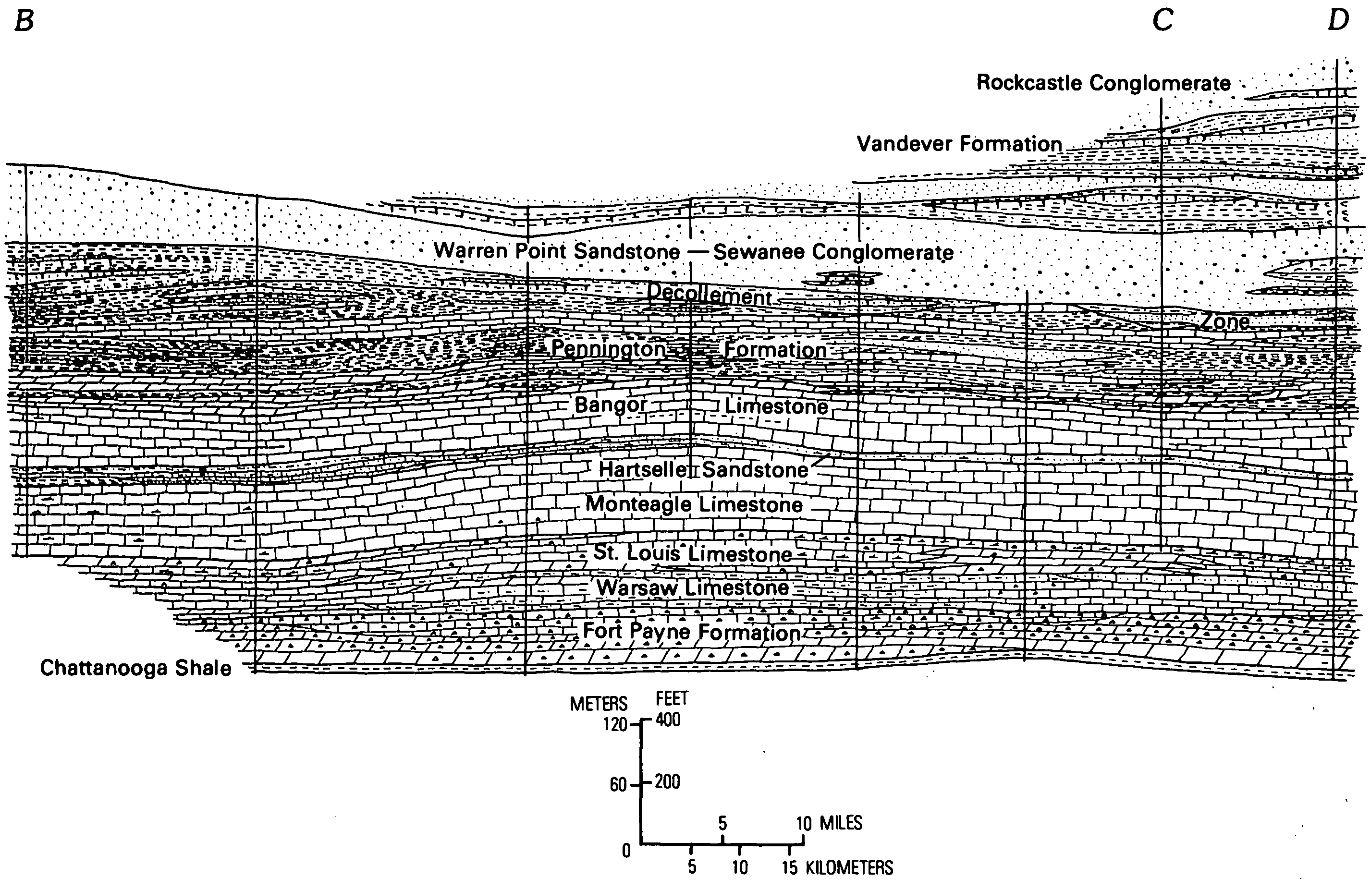

FIGURE 11.—Stratigraphic cross section along line B–C–D.

part of the section is removed by erosion, the Ste. Genevieve Limestone occupies the position of the Monteagle.

WARSAW LIMESTONE

The Warsaw Limestone (Hall, 1857) is 15–55 m (50 to 180 ft) thick on the eastern Highland Rim. It is distinguished from the Fort Payne and the St. Louis by the character of its chert; chert in the Warsaw is mostly porous or spongy, whereas chert in the adjacent formations is dense and hard.

In the southern part of the Cumberland Plateau and eastern Highland Rim, the Warsaw is composed of slightly cherty brown to gray, medium- to coarse-grained bioclastic limestone. In some places the formation is sandy, silty, or dolomitic.

Terrigenous clastic content increases generally to the north, so that the Warsaw in the east-central Highland Rim consists of dark-gray to brownish-gray sandy and silty limestone, which is bioclastic in part. In places, calcareous shale, siltstone, and argillaceous limestone are the dominant lithologies, and these are commonly interbedded with bioclastic calcarenite. Silicastone containing quartz geodes is common in the lower part of the formation in some places.

On the northeastern part of the Highland Rim along the Kentucky line, the Warsaw is composed mostly of calcareous crossbedded very fine to medium-grained sandstone that grades laterally within short distances into crossbedded silty or sandy bioclastic limestone.

On much of the western Highland Rim, the Mississippian limestones are weathered to a rubble of chert and clay. Where preserved in that area, the Warsaw is represented by 12–61 m (40–200 ft) of gray, yellowish-brown, brownish-gray, or olive-gray fine- to coarse-grained limestone. The limestone is commonly crossbedded and bioclastic and in places is glauconitic. Some is silty or dolomitic. Local oolitic limestone beds at the top of the Warsaw are regarded as possible equivalents to the Salem Limestone of nearby States. Chert is common in the formation as nodules, lenses, and large irregular masses. Dolomitic limestone, silty dolomite, and sandy siltstone are also common in the formation,

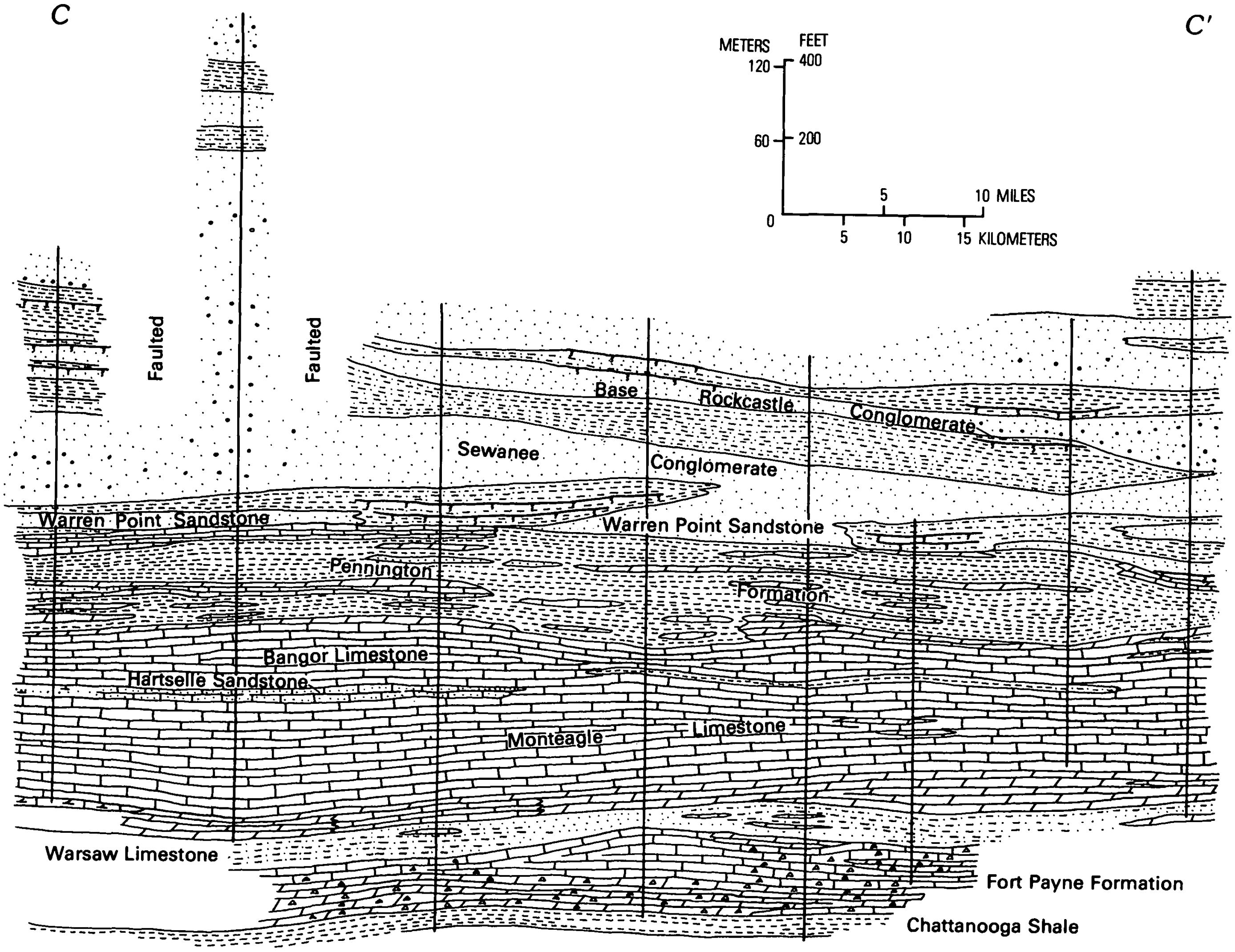

FIGURE 12.—Stratigraphic cross section along line C–C′.

and these generally are brownish gray to yellowish brown, are cherty, and contain small siliceous geodes.

ST. LOUIS LIMESTONE

The St. Louis Limestone (Engelmann, 1847) generally ranges from 12 to 55 m (40 to 180 ft) in thickness on the eastern Highland Rim. In the southeastern Highland Rim, the St. Louis is composed mostly of yellowish-gray, yellowish-brown, and gray very fine to medium-grained dolomitic limestone and dolomite containing balls and dolls of dense pale-blue to bluish-gray chert. Gray bioclastic limestone is common in some places and locally contains fragments of algae, crinoids, and brachiopods.

Northeastward along its outcrop the St. Louis consists of medium- to medium-dark-gray, brownish-gray, or light-olive-gray limestone, containing beds of brownish-gray to yellowish-brown, fine-grained dolomite and walnut- to baseball-sized spherical chert cannonballs. Quartz geodes are common in some places. Some beds contain calcite bird's eyes, and some are petroliferous. In places, the formation contains thin beds of greenish-gray shale. Foraminifera were observed in several places in the formation along the Kentucky line and on the western Highland Rim.

The St. Louis Limestone ranges from 45.7 to 108.2 m (150 to 355 ft) in thickness on the western Highland Rim but more commonly is about 61 m (200 ft) thick. There the formation consists of fine- to coarse-grained yellowish-gray, yellowish-brown, and gray limestone and silty or dolomitic limestone. Some is crossbedded and bioclastic, but more commonly beds are thick to massive. Thin oolitic zones are present locally within the unit. In places, the upper part of the St. Louis consists of fine- to medium-grained gray limestone that contains abundant rounded cannonballs of chert. These beds overlie poorly sorted calcarenites that are locally petroliferous. Elsewhere cherty calcareous siltstones or silty dolomite beds as much as 6.1 m (20 ft) thick mark the base of the formation.

The formation is characterized by more or less abundant *Lithostrotion proliferum* and *Lithostrotionella castelnaui,* and these fossils together with the cannonball cherts are the key to identification of the unit.

MONTEAGLE AND STE. GENEVIEVE LIMESTONES

The Monteagle Limestone (P. R. Vail, 1959, in Stearns, 1963, p. 4–8) consists of 45.7–115.8 m (150–380 ft), commonly about 76 m (250 ft), of light- to medium-gray and light-olive-gray bioclastic and oolitic limestone and some beds of light-gray to light-olive-gray, bird's-eye-bearing micrite. Greenish-gray to olive-gray shale and yellowish-gray dolomitic interbeds are common in some sections, but are only a small part of the formation. Medium- to dark-gray and bluish-gray chert is present locally in some beds but is generally not abundant. A yellowish-gray to yellowish-orange, porous bryozoan-bearing chert (Lost River Chert of Elrod, 1899) serves as a marker bed near the base of the formation. The porous chert is produced by weathering of siliceous limestone beds in a zone 1 m (3 ft) or less thick and is common as blocks or pieces in the soil overlying the zone. In some places, scattered sand grains are in limestone beds near the base of the formation.

The Ste. Genevieve Limestone (Shumard, 1860) on the northwestern Highland Rim is stratigraphically equivalent to the lower part of the Monteagle Limestone on the eastern Highland Rim and plateau. The Ste. Genevieve consists of about 61 m (200 ft) of rock lithologically similar to that of the Monteagle. The Lost River Chert of Elrod (1899) persists to the western Rim and serves there too as marker beds 3–6.1 m (10–20 ft) above the base of the formation. Only in the structurally deformed Wells Creek basin area of the northwestern Highland Rim have Mississippian beds younger than the Ste. Genevieve been preserved. In this area, a graben contains about 61 m (200 ft) of beds younger than the Ste. Genevieve; these beds have been tentatively correlated with the Renault, Bethel, and Paint Creek Formations of western Kentucky.

Depositional environments of carbonate sands near Monteagle, Tenn., ranged from shoals to the interior platform (Bergenback and others, 1972). Shoal deposits of crossbedded oolitic carbonate sands are separated by subaerial crusts, represented by micrites containing fenestral fabrics and laminae; the crusts formed during brief periods of emergence. Brecciated nodular beds of micrite and dololutite are interpreted to represent caliche paleosols. Oolitic sands of tidal and marine sand deposits grade into poorly sorted, burrowed, pelletal, and bioclastic sands that accumulated in interior platform environments.

HARTSELLE FORMATION

The Hartselle Formation (Smith, 1894), a persistent clastic unit in the predominantly carbonate sequence, is as much as 27.4 m (90 ft) thick. In general, the Hartselle consists of olive-gray to greenish-gray shale, silty shale, and rippled to crossbedded, grayish-orange, yellowish-brown, and gray sandy limestone and calcareous sandstone. In places where the clastic unit is absent, the stratigraphic interval is marked by yellowish-gray dolomite. Zones of oolitic and bioclastic limestone are near the base of the formation in some places. Where sandstone is the dominant lithology, the Hartselle forms a prominent topographic bench along the western Cumberland Escarpment between the surfaces of the Highland Rim and Cumberland Plateau. The Hartselle is generally thin or absent in southern Tennessee; where present, it is represented mostly by shale. The formation thickens and becomes more sandy along its outcrop to the north, but in the subsurface to the northeast it thins and grades into a shaly facies.

BANGOR LIMESTONE

The Bangor Limestone (Smith, 1890) consists of 24.4 to perhaps 152.4 m (80 to 500 ft) of medium-gray to medium-dark-gray, or brownish-gray limestone. The Bangor is commonly petroliferous and is generally darker and more argillaceous than the Monteagle. The formation generally contains oolitic and bioclastic beds. A few thin beds are dolomitic and pale yellowish brown; thin beds of greenish-gray to olive-gray shale are common. The formation generally contains lenses and nodules of medium-gray to medium-dark-gray chert. The Bangor is thickest in the southeastern part of the Cumberland Plateau, thinning generally to the west across the plateau and to the north into Kentucky.

PENNINGTON FORMATION

The Pennington Formation (Campbell, 1893) is a heterogeneous unit composed of dolomite; limestone; red, green, or gray shale; fine-grained sandstone; and conglomeratic sandstone. In general, the formation ranges in thickness from 30 to 152.4 m (100 to 500 ft). On the eastern side of the plateau, the Pennington is thicker and contains a greater proportion of terrigenous clastic deposits; to the west, it is thinner and more calcareous.

The Pennington may be divided into five stratigraphic units that have some lateral continuity (Vail, 1959). Silty, yellowish-gray and light-olive-gray to brownish-gray fine-grained dolomite beds in a zone ranging from 1 to 10 m (3.3–33 ft) in thickness commonly mark the base of the formation. In some places, the dolomite contains quartz-filled geodes, and less commonly it contains vugs filled with celestite or strontianite. Frazier (1975) concluded that celestite-bearing geodes in Fentress County are replacements of gypsum nodules that formed a little way beneath the surface of a sabkha-like environment. The basal dolomite zone is in many places overlain by limestone, succeeded by beds of red and green shale, fine-grained sandstone or quartz-pebble conglomerate, an upper limestone unit, and locally by some shale and sandstone at top. Limestone beds generally resemble those of the Bangor and are gray, oolitic to bioclastic, and, in places, shaly.

In Tennessee, the Pennington contains beds that were deposited in littoral (but nondeltaic) depositional environments. Bergenback, Horne, and Inden (1972) recognized that the Pennington near Monteagle contains units deposited in tidal flat, tidal channel, levee, and intertidal environments. Milici (1974) described fine-grained sandstones within the Pennington as representing offshore sandbars formed from fine sand and clay winnowed by waves and longshore currents from beach sands. A regional stratigraphic cross section (fig. 13) shows that quartz-pebble conglomerates on the northeast can be traced southwestward into fine-grained sandstone typical of the Pennington. According to Englund and Smith (1960) and Englund (1968), these conglomerates are tongues of Lee in the Pennington in northeastern Tennessee and adjacent parts of Virginia and Kentucky. As shown in the cross section (fig. 13), these tongues are in places overlain by red and green Pennington shale and appear to pass laterally below beds of limestone.

In southern Tennessee, similar beds of quartz-pebble conglomerate interbedded with olive-gray to dark-gray carbonaceous shale and siltstone and thin coal are called Gizzard and are considered to be of Mississippian or Pennsylvanian age (Milici, 1974). Englund (1968) classified strata similar to those in the Gizzard as Pennington and placed the top of the Pennington (base of Lee) at a higher stratigraphic level. The Pennington-Gizzard problem and its relation to the nature of the Mississippian-Pennsylvanian boundary was discussed by Milici (1974).

THE COAL MEASURES

The coal-bearing strata of Tennessee are mostly of Early and Middle Pennsylvanian age (fig. 3) and are divided generally into a lower sequence of thick orthoquartzite interbedded with shale and some coal, and an upper sequence dominated by shale but containing subsidiary amounts of sandstone and much more coal than the lower sequence. This basic division is apparent in the stratigraphic cross section of the northern Cumberland Plateau (figs. 7, 13–15). Wilson and Stearns (1960) recognized this dichotomy, referring to the orthoquartzites as blanket sandstones and to the upper sandstones as digitate. Ferm (1974) showed that on a regional basis, the progradational sequence from Pennington red and green shale, limestone and fine-grained argillaceous sandstone through the orthoquartzite to the section dominated by shale and many coal beds represented a transition from marine deposits to littoral deposits and then to delta-plain facies.

Units deposited in shoreline environments are evident in the Gizzard and Crab Orchard Mountains Groups and persist perhaps into the lower part of the Crooked Fork Group. Quartzose barrier sandstones (deposited in beaches, tidal deltas, tidal channels, washovers, and bars) are abundant in the Gizzard and Crab Orchard Mountains Groups (Ferm and others, 1972; Milici, 1974; this report, fig. 3). Sandstone formations vary widely in thickness, generally ranging from 10 to 100 m (33 to 328 ft), although composite sandstone bodies 91–122 m (300–400 ft) thick are known in a few places. Quartz-pebble conglomerate and conglomeratic sandstone characterize each of the blanket sandstones in some places. However, the Sewanee and Rockcastle Conglomerates almost everywhere contain at least a few quartz pebbles. Thick dark-gray shale associated with the orthoquartzite sandstone bodies is thought to have been deposited in back-barrier lagoons. In places, this shale is calcareous and contains marine fossils. Elsewhere, it grades through burrowed and flasered beds, interpreted to be tidal flats, into sandstone. Coal beds are associated with

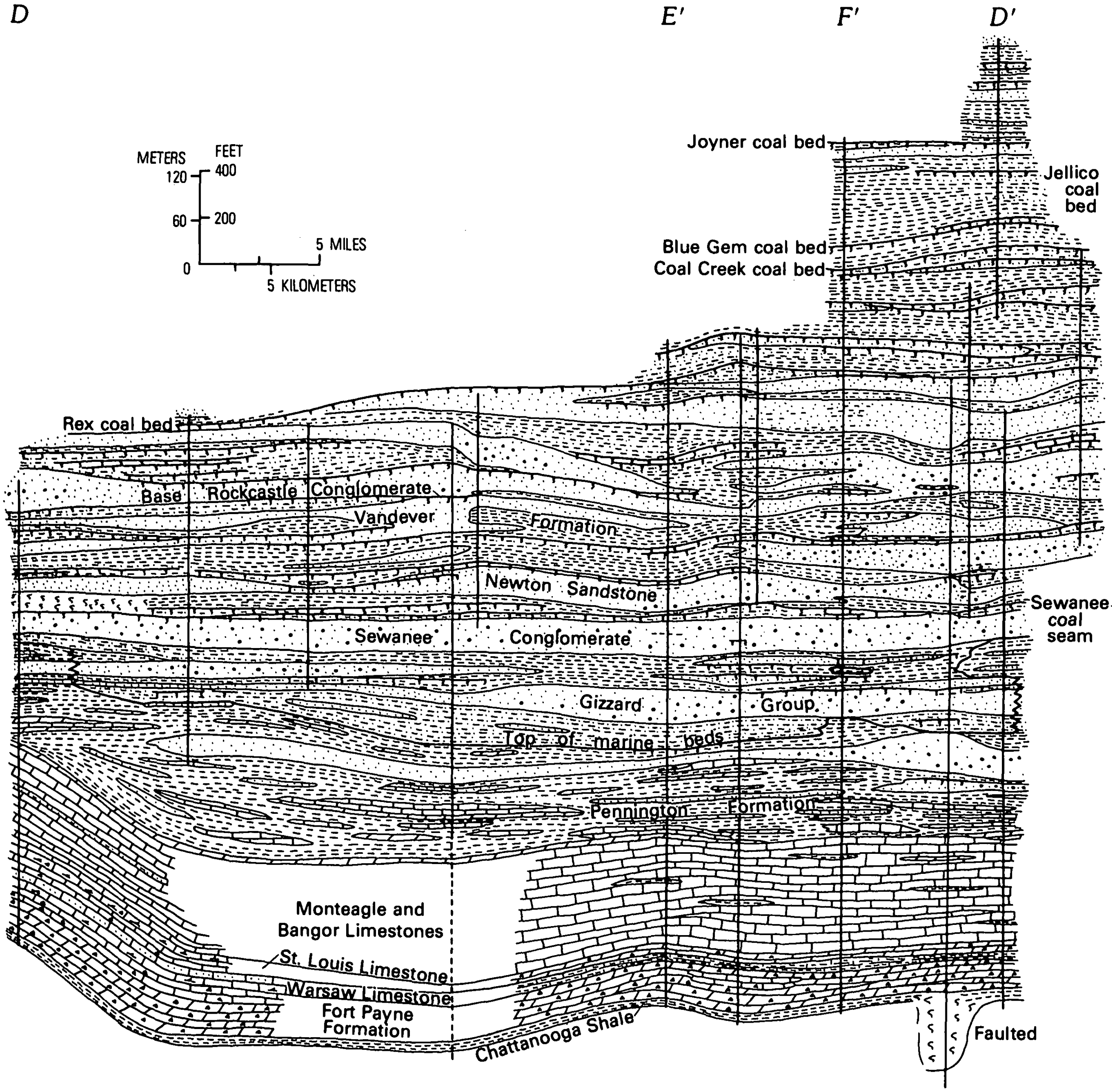

FIGURE 13.—Stratigraphic cross section along line D–E′–F′–D′

these back-barrier-fill sequences, and in places, marsh deposits are characterized by thick zones containing fossil roots and by anastomosing channel fills of sandstone, shale, and siltstone.

GIZZARD GROUP

The Gizzard Group (Safford, 1869) is composed of three formations, the Raccoon Mountain Formation, Warren Point Sandstone, and Signal Point Shale. In southern Tennessee, the boundary between the Raccoon Mountain and Pennington Formations is picked at the top of the highest red or green shale or limestone, and in a few places, at the top of recognizable Pennington Sandstone. This convention generally separates coal-bearing beds above from the main mass of marine strata below.

The convention used for selecting the top of the Pennington in southern Tennessee does not work well around the periphery of the Wartburg basin, where the stratigraphic reconstruction (fig. 13) illustrates a complex facies between the Pennington and the Gizzard, wherein quartz-pebble conglomer-

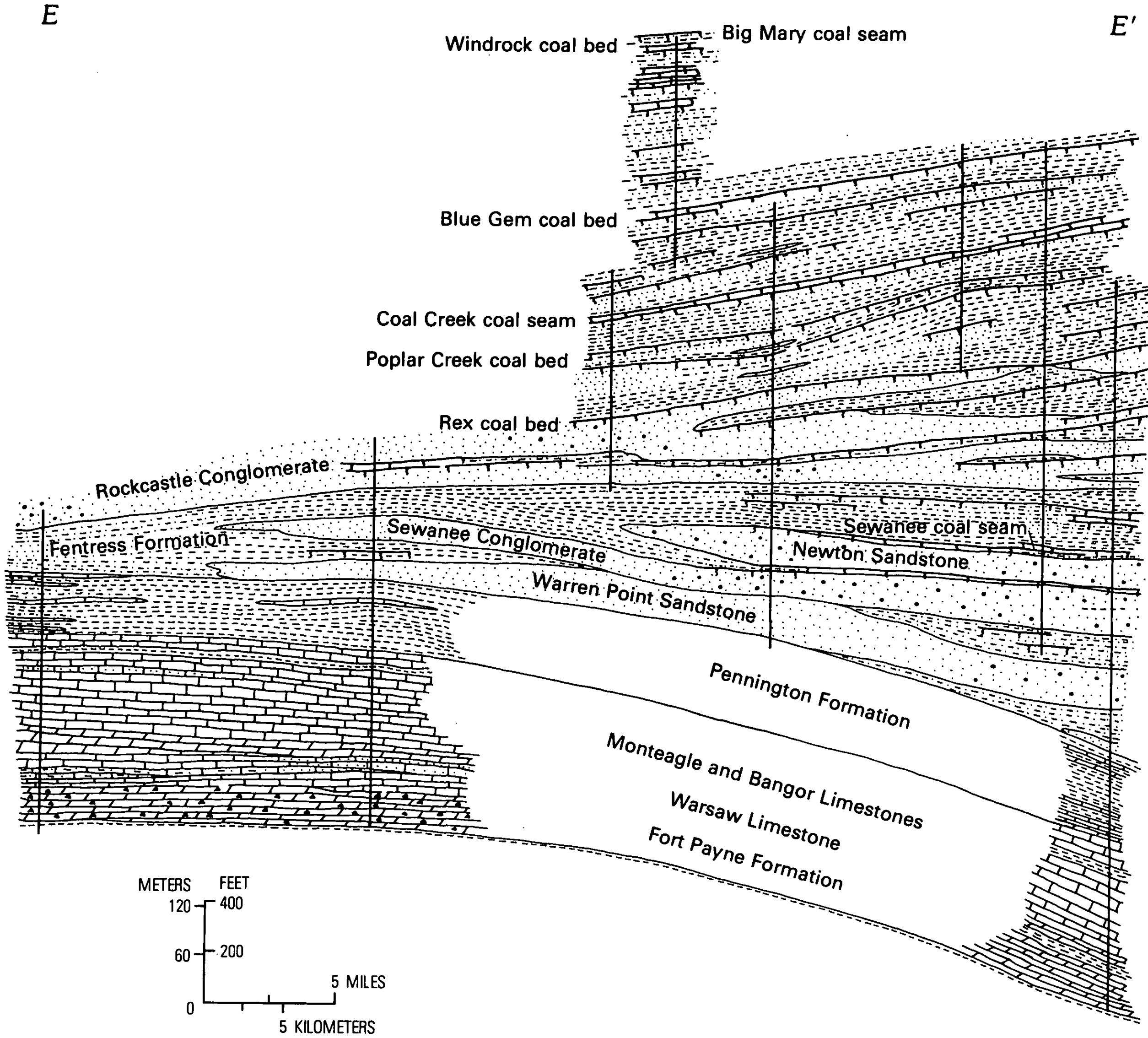

FIGURE 14.—Stratigraphic cross section along line E–E'.

ate, coal, carbonate deposits, and red beds intertongue both laterally and vertically. Similar facies variations were reported by Horne and others (1974) along the Mississippian-Pennsylvanian boundary in northeastern Kentucky and by Englund and Smith (1960) and Englund (1968) in northern Tennessee and adjacent States.

Raccoon Mountain Formation.—The Raccoon Mountain Formation (Wilson and others, 1956) consists of a few tens of meters to about 91 m (300 ft) of gray shale, siltstone, sandstone, and coal. In some places in southern Tennessee, the Raccoon Mountain Formation is thick, it contains as many as seven coal beds in the Sale Creek and Raccoon Mountain coal basins (Milici, 1974). These coal beds are mostly thin and discontinuous, although some are of good grade and were extensively mined at one time.

Warren Point Sandstone.—The Gizzard Group is divided by separating out the Warren Point Sandstone (Nelson, 1925), which is a persistent mappable unit in southern Tennessee. Where thick, the formation consists of 30–91 m (100–300 ft) of fine to coarse sandstone that in places contains abundant quartz pebbles. In places, thin shale and coal beds interrupt the sequence of massive sandstone. Where the Warren Point thins to several meters and is indistinguishable from the sand in the Raccoon Mountain, the Gizzard is divided into informal map units. Regionally, the Warren Point consists of a series of laterally discontinuous lenticular sand bodies, which

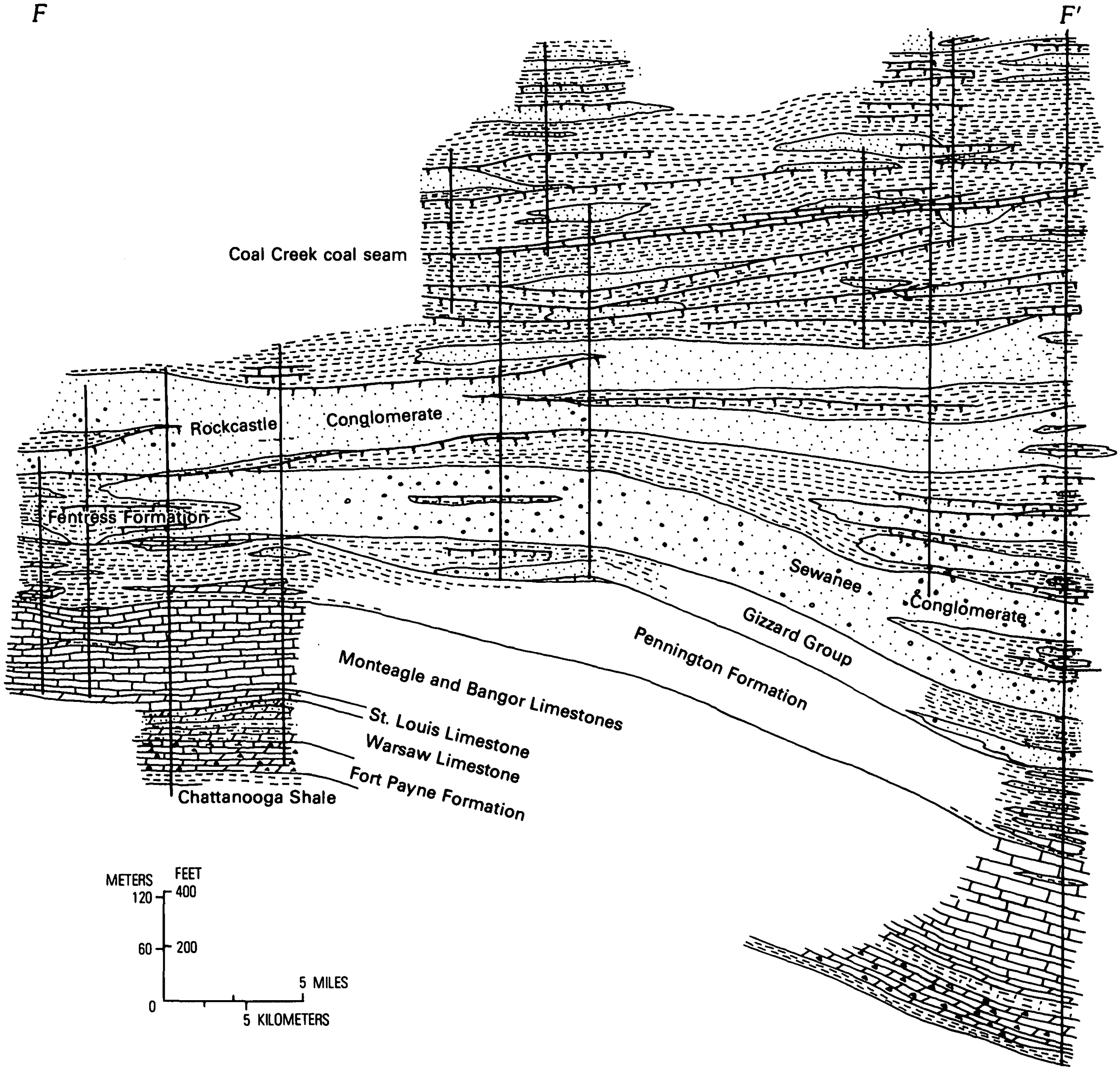

FIGURE 15.—Stratigraphic cross section along line F–F′

are correlated by position in sequence to the type area. In this way, Gizzard sandstone bodies in the subsurface of northern Tennessee are correlated with Warren Point Sandstone in southern Tennessee (figs. 11–14).

Signal Point Shale.—The Signal Point Shale (Wilson and others, 1956) consists generally of 20–55 m (66–180 ft) of gray shale, siltstone, thin sandstone, and a few thin coal beds. Where mappable, this fine-grained clastic unit separates the massive sandstone and conglomeratic sandstone of the Warren Point Sandstone from the Sewanee Conglomerate. In many places, the Signal Point is missing, and coarse quartz-pebble conglomerate and conglomeratic sandstone of the Sewanee lie upon the Warren Point. In a few places, the entire Gizzard is missing, and the Sewanee rests directly on the Pennington Formation. Where the Sewanee and Warren Point are lithologically similar, they are mapped together as a thick composite sand body. Coal beds within the Signal Point are mostly thin, discontinuous, and only locally important.

CRAB ORCHARD MOUNTAINS GROUP

The Crab Orchard Mountains Group (Wilson and others, 1956) includes the Sewanee Conglomerate, Whitwell Shale, Newton Sandstone, Vandever Formation, and Rockcastle Conglomerate. The group is represented by these five formations in the southern Cumberland Plateau and in the Crab Orchard Mountains. On the northwestern part of the plateau, the lower stratigraphic units grade laterally into the Fentress Formation, and only the Rockcastle persists as a mappable unit (Wilson, 1956).

Sewanee Conglomerate.—The Sewanee Conglomerate (Safford, 1893) is the most persistent stratigraphic unit in the Tennessee coal measures. The formation ranges generally from 24.4 to 27.4 m (80 to 90 ft) in thickness, but in some areas it is as much as 61 m (200 ft) thick. It is composed of fine- to coarse-grained sandstone and contains pebbles, which are locally abundant. In several places, the formation thins to several meters, and the quartz pebbles are absent. The Sewanee Conglomerate is exposed on much of the southern plateau, is easily recognizable in the subsurface of the Wartburg basin (fig. 13), but thins to the northwest where it grades into the Fentress Formation (figs. 14, 15).

Whitwell Shale.—The Whitwell Shale (Butts and Nelson, 1925) consists of about 10 m (33 ft) to as much as 61 m (200 ft) of gray shale, silty shale, sandstone, and coal. The formation contains most of the commercial coal in the southern plateau (fig. 16). The most widely prospected seam is the Sewanee, which is generally within the lower half or third of the formation. The Richland coal bed, which is at or near the base of the Whitwell, is also of commercial quality. As many as four seams are within the Whitwell in some areas, but there individual coal beds are too thin to be commercially expoitable.

In the past, most of the mining of the Sewanee and Richland coal beds was in the southern part of the plateau, near Whitwell and Tracy City, and this is still the area of greatest activity. The quadrangles northeast of the Whitwell-Tracy City district and the area west of Rockwood contain sizable coal reserves. Most of the Sewanee and Richland coal is marketed either as steam coal or, after being washed, as metallurgical coal. Although Whitwell coal is currently being prospected by deep core drilling, some areas in the southern plateau are relatively untested.

Newton Sandstone.—The Newton Sandstone (Nelson, 1925) consists generally of about 10 m (33 ft) to as much as 45.7 m (150 ft) of fine- to medium-grained sandstone. In some places, the formation is coarse grained, contains quartz pebbles, and is conglomeratic. The formation is generally persistent in the southern plateau, between the shale and siltstone of the Whitwell and Vandever. In a few places, the Whitwell Shale is absent, and the Newton rests directly upon the Sewanee. The Newton Sandstone is below drainage in the Wartburg basin, where it consists of sandstone, some of which contains quartz pebbles (figs. 13–15). Like other formations of the Crab Orchard Mountains Group, the Newton grades northwestward into shale and siltstone of the Fentress Formation.

Vandever Formation.—The Vandever Formation (Nelson, 1925) ranges generally from 61 to 137 m (200 to 450 ft) in thickness and consists mostly of shale and sandstone and some siltstone and coal beds. The formation is divided into three members in the southern plateau. The upper and lower members, which consist of shale, minor siltstone, thin sandstone, and coal beds, are separated by a middle sandstone member. Where the sandstone member is thick and conglomeratic, it is mapped as the Needleseye Conglomerate Member of the Vandever Formation (Luther and Swingle, 1963). The Vandever Formation contains two main coal beds, the Lantana seam in the lower member and the Morgan Springs near the top of the upper member. Both of these seams are generally suitable for steam coal.

In the subsurface of the Wartburg basin, the Vandever consists of anastomosing sandstone, conglomeratic sandstone, and shale containing beds of coal (fig. 13). The top of the Vandever is difficult to select in this region because of irregular facies variations in the formation.

Fentress Formation.—The Fentress Formation (Glenn, 1925) consists of the interlaminated and flasered shale and fine sandstone and thin beds of sandstone and coal between the top of the Pennington and the base of the Rockcastle Conglomerate along the northwestern side of the Cumberland Plateau. The Fentress Formation is as much as 76.2 m (250 ft) thick. Like the facies in the Gizzard, those in the Fentress are extremely variable, and both formations are overlain by blanket orthoquartzites.

Rockcastle Conglomerate.—The Rockcastle Conglomerate (Campbell, 1898) is a widespread blanket orthoquartzite throughout much of the central and northwestern parts of the Cumberland Plateau. In general, the formation ranges from 30 to 91 m (100

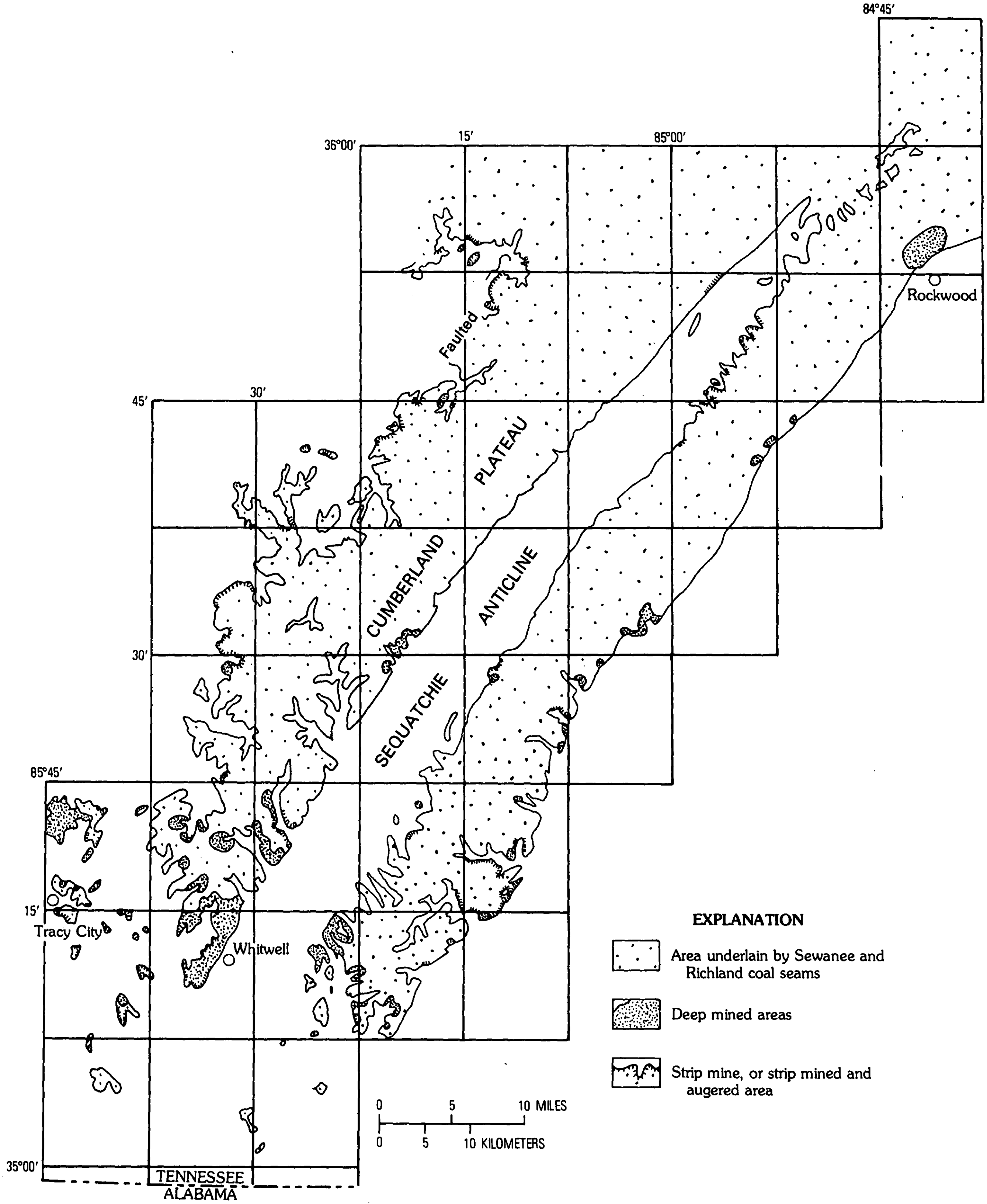

FIGURE 16.—Areas underlain by, and areas mined out of, the Sewanee and Richland coal seams in the southern Cumberland Plateau, Tennessee.

to 300 ft) in thickness and consists of fine- to coarse-grained, locally conglomeratic sandstone. The formation generally contains a widespread shale and coal bed (Nemo) near the middle. To the east, shale interbeds are more common and thicker and, like the Vandever, the formation consists of anastomosing shale and sandstone and thin coal beds (figs. 13–15). The Rockcastle can thus be divided regionally into a barrier phase consisting generally of orthoquartzite to the west, and a back barrier phase of orthoquartzite, shale, and coal to the east.

CROOKED FORK GROUP

The Crooked Fork Group consists of a succession of six shale and sandstone formations (fig. 3): the Dorton Shale (Wilson and others, 1956), the Crossville Sandstone (Wanless, 1946), the Burnt Mill Shale (Wilson and others, 1956), the Coalfield Sandstone (Wilson and others, 1956), the Glenmary Shale (Wilson and others, 1956), and the Wartburg Sandstone (Keith, 1896). The Crooked Fork Group crops out around the periphery of the Wartburg basin and in belts on either side of the Crab Orchard Mountains (Hardeman and others, 1966). The group ordinarily ranges from 91 to 122 m (300 to 400 ft) in thickness and is the uppermost to contain thick sandstone. However, the sandstone of the Crooked Fork is not nearly as thick or laterally persistent as that in the groups below.

The formations within the Crooked Fork range generally from 20 to 30 m (66 to 100 ft) in thickness, although locally several were mapped as 45.7 m (150 ft) thick. The shale is generally medium to dark gray and in places is interbedded with siltstone or thin sandstone. Sandstone is commonly fine to medium grained but in places may be coarser. Quartz pebbles are uncommon within the sandstone but are present in the Crossville and Wartburg sandstones in an area north of the New River. Although the depositional environments of the Crooked Fork Group have not been studied in detail, it is apparent that these beds are transitional between the littoral beach-barrier sequence below and the delta-plain sequence above.

The only coal bed of significance in the group is the Rex, which is at or near the base of the Dorton Shale. In places, the Rex is thick enough to be commercially exploitable and after washing may be suitable as a metallurgical grade coal. The Poplar Creek coal bed at the top of the group is of local commercial significance.

DELTA-PLAIN SEQUENCE

In Tennessee the beds above the Wartburg Sandstone are divided into six formations, all named by Wilson, Jewell, and Luther (1956): the Slatestone Formation, Indian Bluff Formation, Graves Gap Formation, Redoak Mountain Formation, Vowell Mountain Formation, and Cross Mountain Formation (fig. 3). Wilson, Jewell, and Luther (1956) originally described the thick units as groups, but when it became apparent that they could not be easily divided into mappable units, they were reduced in rank to formations (Hardeman and others, 1966).

Slatestone Formation.—The Slatestone Formation consists of 91 to 219 m (300 to 720 ft) of gray shale and subsidiary amounts of siltstone and silty sandstone. The formation includes the strata between the top of the Poplar Creek coal bed and the top of the Jellico coal bed. The formation consists of gray clayey to sandy shale that in places is separated into members by four mappable fine- to medium-grained sandstones, named by Wilson, Jewell, and Luther (1956) the Stephens, Petros, Sand Gap, and Newcomb sandstones. The sandstones are lenticular and commonly are 10 m (30 ft) or more thick but rarely are more than 30 m (100 ft) thick. Important coals within the formation are the Coal Creek, Petros, Blue Gem, and Jellico coals. The Coal Creek and the Jellico are the most extensively mined and have the largest reserves in the formation.

Coal Creek coal bed.—The Coal Creek coal bed underlies much of the northern Tennessee coal field (fig. 17). It is a high-quality steam coal (table 1). Thicknesses may be as much as 1.65 m (5.42 ft), but they vary greatly within short distances. A rider seam commonly is about 6.1 m (20 ft) above the coal. Recoverable reserves of the Coal Creek coal are in Anderson, Campbell, and Claiborne Counties. Additional reserves are in Morgan and Scott Counties in a coal seam that is variously correlated either with the Poplar Creek or with the Coal Creek. Because evidence is not available to resolve the correlation problem, the two areas are separated by a dashed line in figure 17. For convenience, however, the coal tonnage is included with the Coal Creek even though the correlation is uncertain. Total recoverable reserves of the Coal Creek coal are approximately 190 million short tons.

Extensive underground mining of the Coal Creek seam began in 1870 and continued into the 1950's in Anderson County near Oliver Springs, Briceville, Lake City, and Eagan (fig. 17). Today, the only

TABLE 1.—*Representative analyses and rank of selected Tennessee coal beds*

[Data from Luther, 1959, and Johnson and Luther, 1972]

Seam	Proximate percent: Moisture	Proximate percent: Volatile matter	Proximate percent: Fixed carbon	Proximate percent: Ash	Ultimate percent: Sulfur	Ultimate percent: Hydrogen	Ultimate percent: Carbon	Ultimate percent: Nitrogen	Ultimate percent: Oxygen	Heat value (btu)	Ash softening tempera-ture/°F	Rank average [1]
Sewanee	3.04	29.21	58.17	9.62	0.93	4.96	75.29	1.48	8.16	13,099	2,532	hvAb[2]
Coal Creek	3.47	36.44	55.49	4.67	1.34	5.42	76.26	1.86	9.64	13,760	2,030	hvBb
Jellico	3.06	36.79	53.53	6.68	2.20	5.54	77.06	1.89	8.6	13,509	2,304	hvBb
Big Mary	3.08	36.0	49.67	11.27	3.12	5.1	70.83	1.49	8.51	12,667	2,304	hvCb
Pewee	3.60	36.81	54.23	5.7	.68	5.55	78.73	1.65	10.18	13,571	2,421	hvBb

[1] Ranked according to Standard Specifications for Classification of Coals by Rank of the American Society for Testing and Materials, 1967.
[2] Abbreviations.
hvAb=high-volatile A bituminous.
hvBb=high-volatile B bituminous.
hvCb=high-volatile C bituminous.

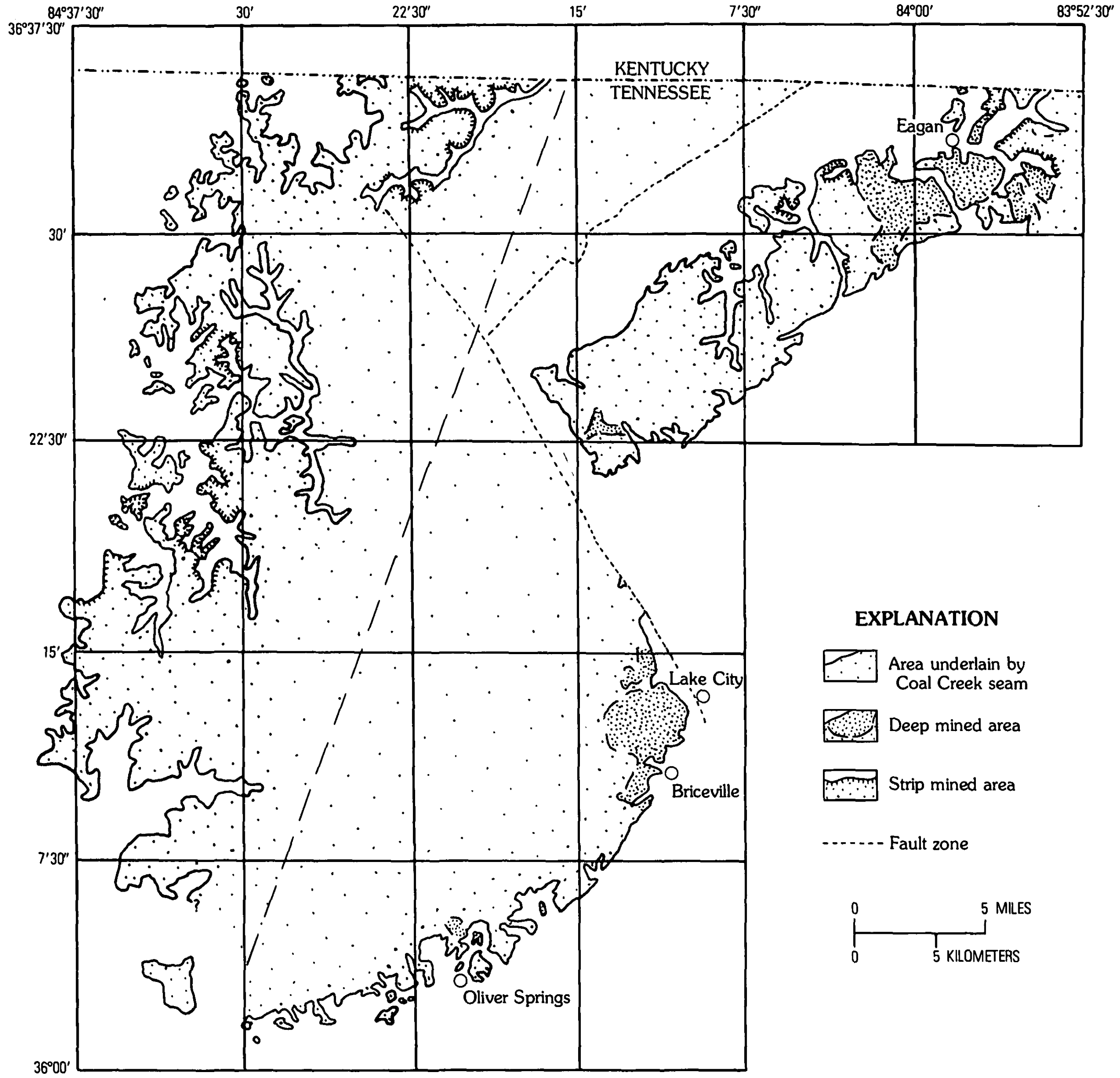

FIGURE 17.—Areas underlain by, and areas mined out of, the Coal Creek coal bed in northern Tennessee.

major underground mine on the Coal Creek coal is the Consolidation Coal Co. mine on Tackett Creek in Claiborne County. Less than 20 percent of the total Coal Creek surface trace has been surface mined.

Jellico coal bed.—Approximately 122 m (400 ft) above the Coal Creek coal is the Jellico coal (fig. 18). The Jellico coal is a medium-grade seam (table 1). Recoverable reserves are in Anderson, Campbell, Claiborne, Morgan, and Scott Counties. These reserves total approximately 54 million short tons.

Present deep mining of the Jellico coal is limited to a few relatively small mines. However, large old deep mines are near Petros, Jellico, and Log Mountain west of Bryson. Many of the surface mines on the Jellico seam are near the large old underground mines at Petros and Jellico. In addition to these, several strip mines are on the Jellico coal in Scott County. Less than 10 percent of the total surface trace of the Jellico coal is stripped.

Indian Bluff Formation.—The Indian Bluff Formation consists of 61 to 143 m (200 to 470 ft) of clayey to sandy gray shale and minor amounts of siltstone and sandstone. The formation includes the strata between the top of the the Jellico coal and the top of the Pioneer Sandstone Member, or Jordan coal bed where the Pioneer is absent. The Indian Bluff Formation is in places divided into members by the Seeber Flats (Wilson and others, 1956),

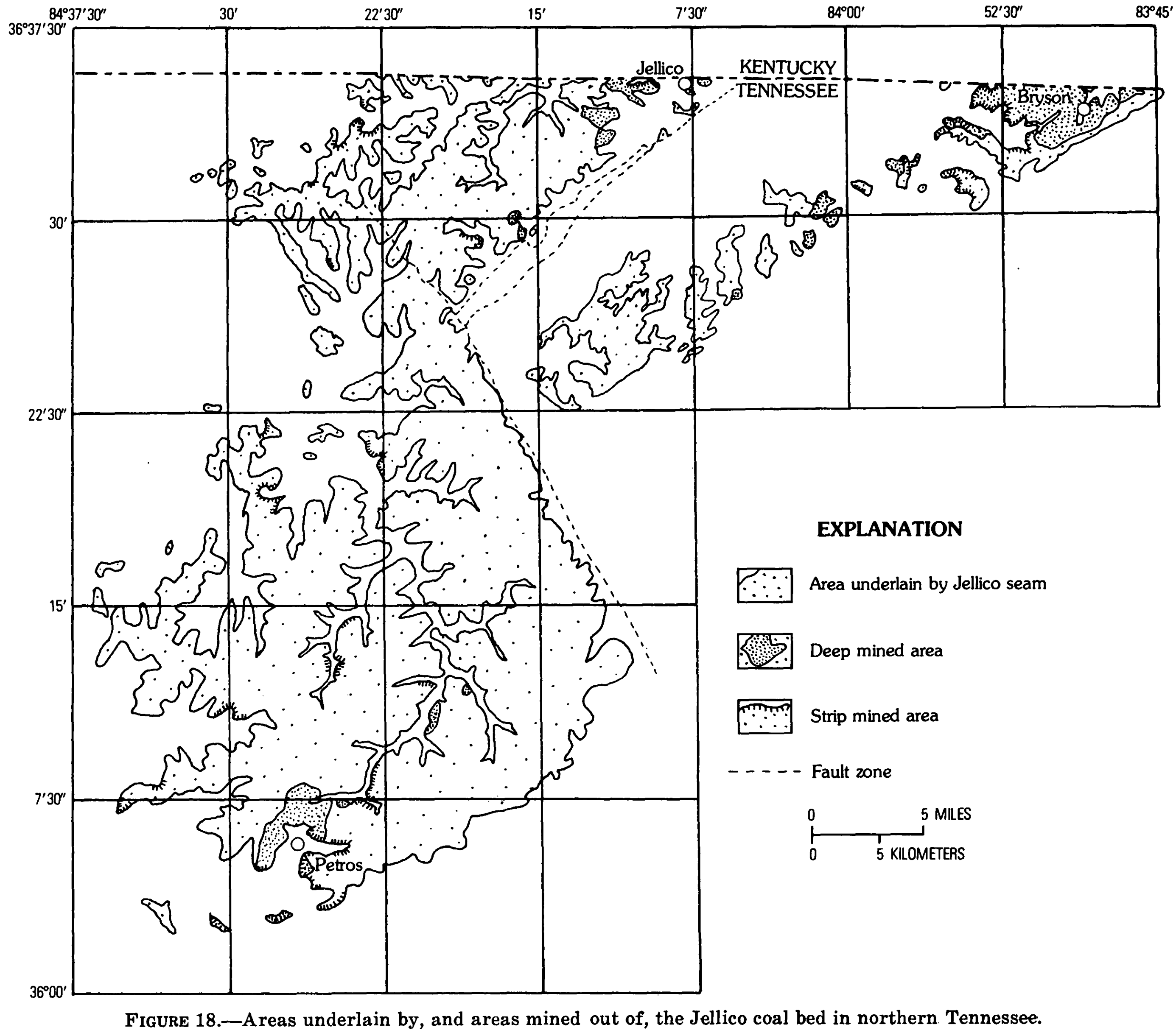

FIGURE 18.—Areas underlain by, and areas mined out of, the Jellico coal bed in northern Tennessee.

Stockstill (Wilson and others, 1956), and Pioneer Sandstones (Glenn, 1925). The sandstones are fine to medium grained and lenticular. Thicknesses of these sandstones are as much as about 24 m (80 ft), and of the three, the Pioneer Sandstone is the thickest and most widespread. The only coal bed of any economic significance within the Indian Bluff Formation is the Joyner seam.

Graves Gap Formation.—The Graves Gap Formation extends from the top of Pioneer Sandstone to the top of the Windrock coal bed. The formation consists of 55 to 122 m (180 to 400 ft) of clayey to sandy gray shale and minor amounts of siltstone and sandstone. In places, sandstone beds, named the Armes Gap Sandstone and Roach Creek Sandstone by Wilson, Jewell, and Luther (1956), are thick enough to divide the formation into members. The sandstones are generally fine to medium grained and lenticular. These sandstone members may be as thick as 21–24 m (70 to 80 ft). The Graves Gap Formation contains four economically important coal beds, the Jordan, Lower Pioneer, Upper Pioneer, and Windrock.

The Redoak Mountain Formation.—The Redoak Mountain Formation includes the strata between the top of the Windrock coal and the top of the Pewee coal. The formation consists of 91 to 140 m (300 to 460 ft) of gray clayey to sandy shale and minor amounts of sandstone and siltstone. In places, the formation is divided into members by lenticular sandstones named the Caryville, Fodderstack, and Silvey Gap Sandstones by Wilson, Jewell, and Luther (1956). The Silvey Gap and Caryville are as thick as 20 m (65 ft), but the Fodderstack is thinner and locally attains a thickness of 10 m (30 ft). Important coal beds in the Redoak Mountain Formation are the Big Mary, Beech Grove, Sharp, Red Ash, Walnut Mountain, and Pewee. Of these, the Big Mary (fig. 19) and the Pewee (fig. 20) are the most widely mined and contain the greatest reserves.

Big Mary coal bed.—Recoverable reserves of the Big Mary coal bed were 101,274,000 short tons in 1959 (Luther, 1959). The Big Mary seam ranges in thickness from 0.30 to 2.59 m (1 to 8.5 ft), including shale partings and beds that range generally from 0.05 to 1.2 m (0.17 to 4 ft). In a few places, the Big Mary is split by shale beds as much as 3 m (10 ft) thick, so that each split is too thin to mine. The Big Mary has been extensively strip mined, augered, and deep mined in Tennessee (fig. 19). Approximately 20 percent of the Big Mary cropline has been strip mined. The most extensively deep-mined areas are near Petros, Devonia, Rosedale, Turley, and Fork Ridge. The Big Mary seam is a low-grade steam coal because of its relatively high sulfur and ash contents (table 1). The Tennessee Valley Authority purchases most of the coal mined from the Big Mary seam.

Pewee coal bed.—The Pewee coal bed is at the top of the Redoak Mountain Formation approximately 116–122 m (380–400 ft) above the Big Mary coal bed. Recoverable reserves of the Pewee seam were 32,934,000 short tons in 1959 (Luther 1959). Since then, an undetermined amount has been mined. The Pewee seam ranges in thickness from approximately 0.3 to 2.1 m (1 to 7 ft) including partings that range from 5 to 76 cm (0.17 to 2.5 ft). At most places the coal is solid, or partings aggregate less than 15 cm (0.5 ft) in thickness. The Pewee has been extensively strip mined, augered, and deep mined in Tennessee (fig. 20). Approximately 35 percent of the Pewee cropline has been strip mined. The most extensively deep-mined areas are in the mountains surrounding Pewee and in the areas northwest of Petros, west of Fork Ridge, and north of Windrock. The Pewee is a high-grade steam coal (table 1).

Vowell Mountain Formation.—The Vowell Mountain Formation includes the strata between the top of the Pewee coal and the top of the Frozen Head Sandstone. The formation ranges from 70 to 128 m (230 to 420 ft) in thickness and consists of gray clayey to sandy shale and minor siltstone and some sandstone. A sandstone member in the middle of the formation was called the Pilot Mountain Sandstone by Wilson, Jewell, and Luther (1956). Glenn (1925) named the Frozen Head Sandstone at the top. Like other sandstones in the delta-plain sequence, these sandstones are fine to medium grained, are lenticular, and may be as much as 18–20 m (60–65 ft) thick. The coal beds in the Vowell Mountain Formation are the Split, Petree, Lower and Upper Pine Bald, and Rock Spring coals. Only the Lower Pine Bald coal and the Rock Spring coal have been mined, and the Rock Spring is the highest seam in Tennessee that has been mined underground on a large scale (Luther, 1959, p. 136). Barlow (1969) studied the plant fossils of the northern coal field and concluded that the Rock Springs coal bed was the base of the Allegheny Series in Tennessee.

Cross Mountain Formation.—The Cross Mountain Formation includes strata between the top of the Frozen Head Sandstone and the top of Cross Mountain and is 169 m (554 ft) thick at its type section. These are the youngest Pennsylvanian beds preserved in Tennessee. The formation is composed of sandstone and shale members lithologically similar

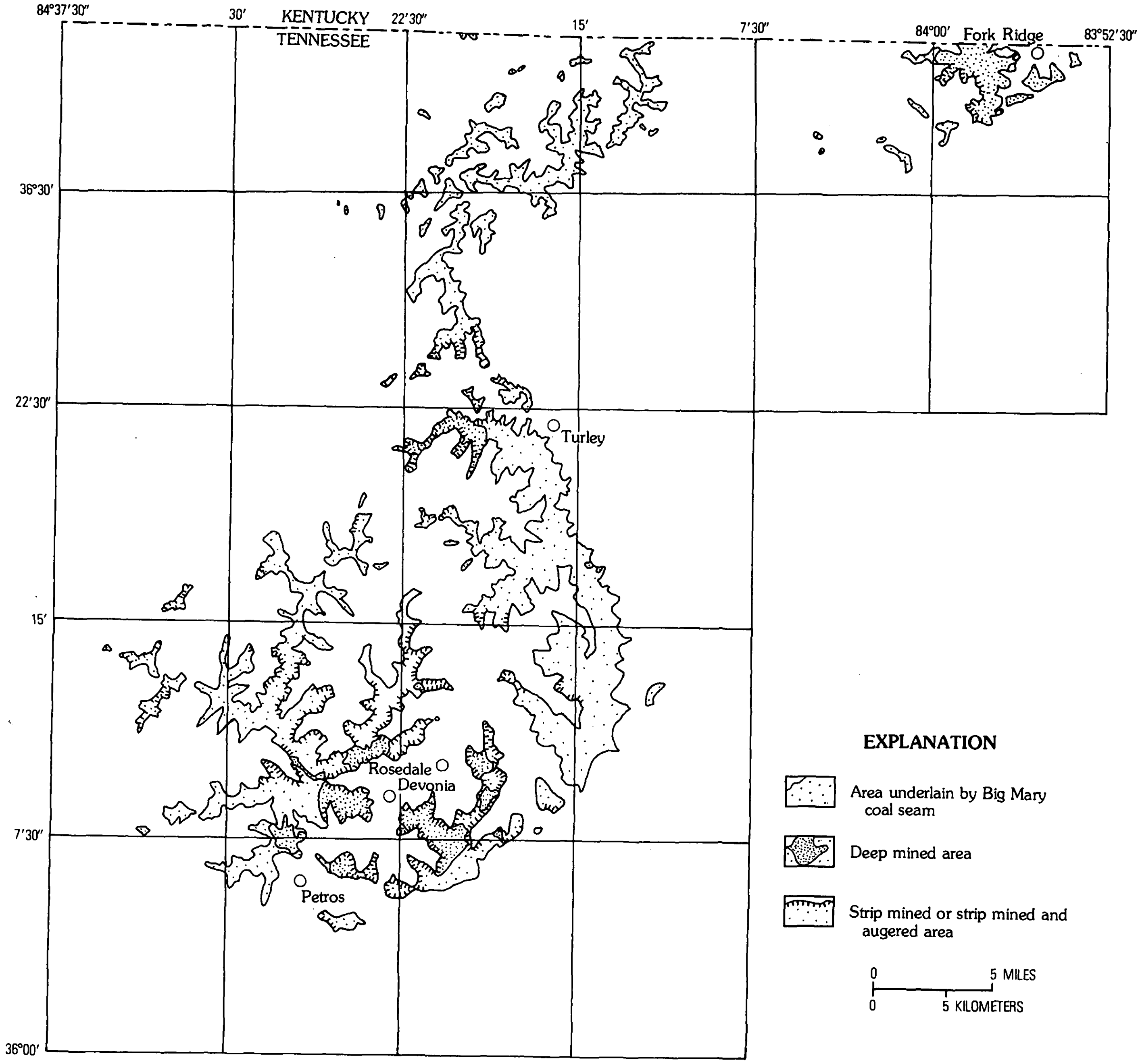

FIGURE 19.—Areas underlain by, and areas mined out of, the Big Mary coal bed in northern Tennessee.

to the strata below. Named sandstone members are the Low Gap and Tub Spring Sandstones. They are both lenticular and vary greatly in thickness; the Low Gap reaches a maximum of 21.3 m (70 ft), and the Tub Spring is as much as 15.2 m (50 ft) thick. The Cross Mountain contains six named coal seams in Tennessee, but only the Upper and Lower Grassy Spring coals, the Cold Gap coal, and the Lower Wild Cat coal have been mined (Johnson and Luther, 1972, p. 5).

INDICATORS OF DEPOSITIONAL ENVIRONMENTS IN THE UPPER-DELTA-PLAIN SEQUENCE

The sequence reviewed in this section includes the upper three (Redoak Mountain, Vowell Mountain, and Cross Mountain) of six formations generally assigned to the Middle Pennsylvanian in Tennessee. The interval, which is about 305 m (1,000 ft) thick, was selected for study because it was only recently strip mined, and the highwall exposures are largely

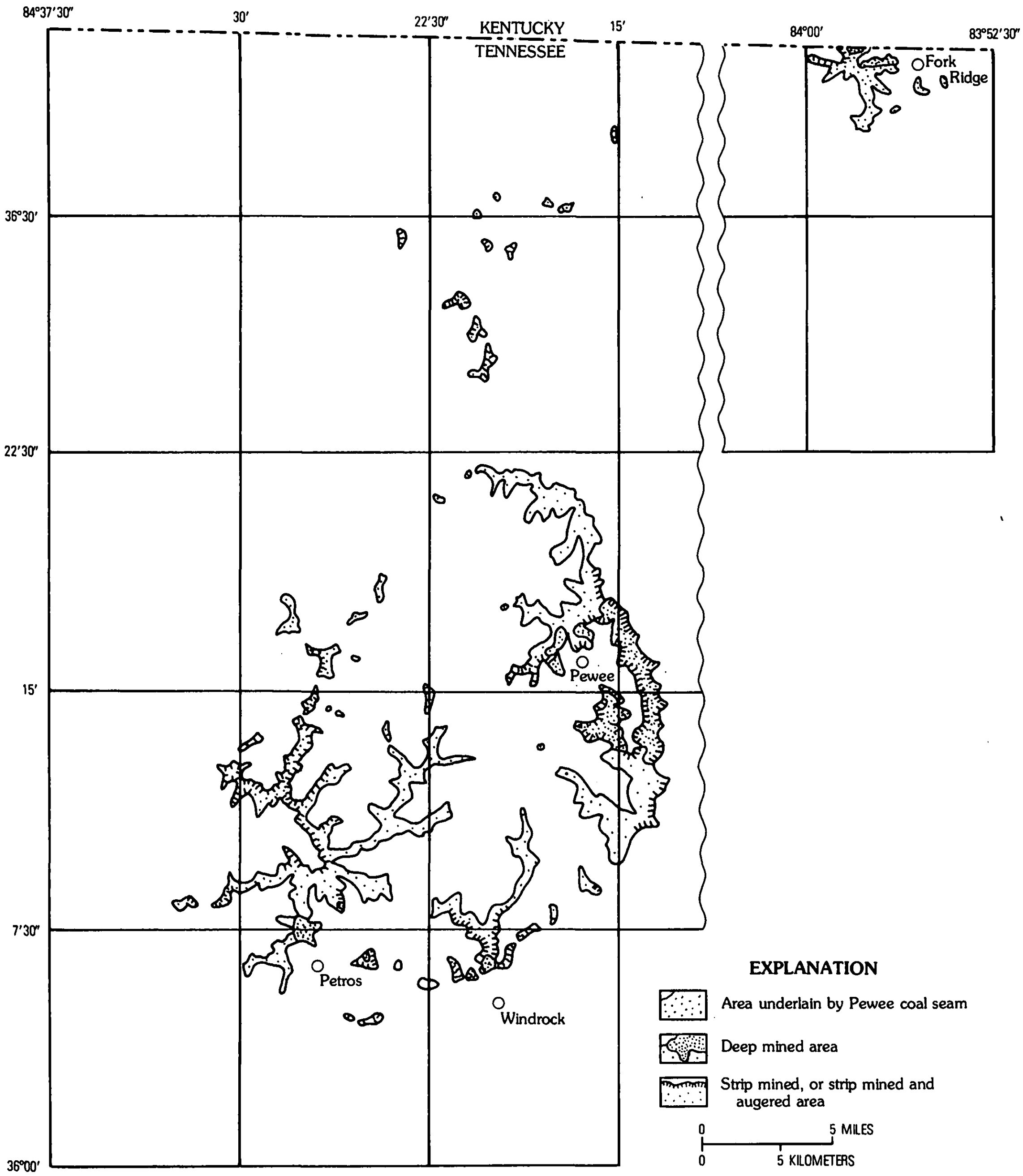

FIGURE 20.—Areas underlain by, and areas mined out of, the Pewee coal bed in northern Tennessee.

unreclaimed. The interval contains a dozen or more minable coal seams within the Wartburg basin, but only two or three (principally the Big Mary and Pewee coals) are laterally continuous and minable almost basinwide.

Figure 21 is a columnar section of the 305-m- (1,000-ft-) thick sequence, the width of which is designed to show both the primary lithology, and selected drawings of 50-m- (164-ft-) long sections of strip-mine highwalls. The lateral sections depict facies relationships seen in highwall exposures near the Scott-Anderson County line. The columnar section consists of several sequences that coarsen upward, each of which begins with dark-gray shale and fauna indicative of a marine or brackish-water incursion. Overlying channel, levee, and splay deposits reflect the progradation and reestablishment of the delta. The extent and duration of each episode is indicated by the thickness and extent of the facies. The establishment of a coal swamp signaled the end of each progradational phase, at which time the river system that maintained the complex was

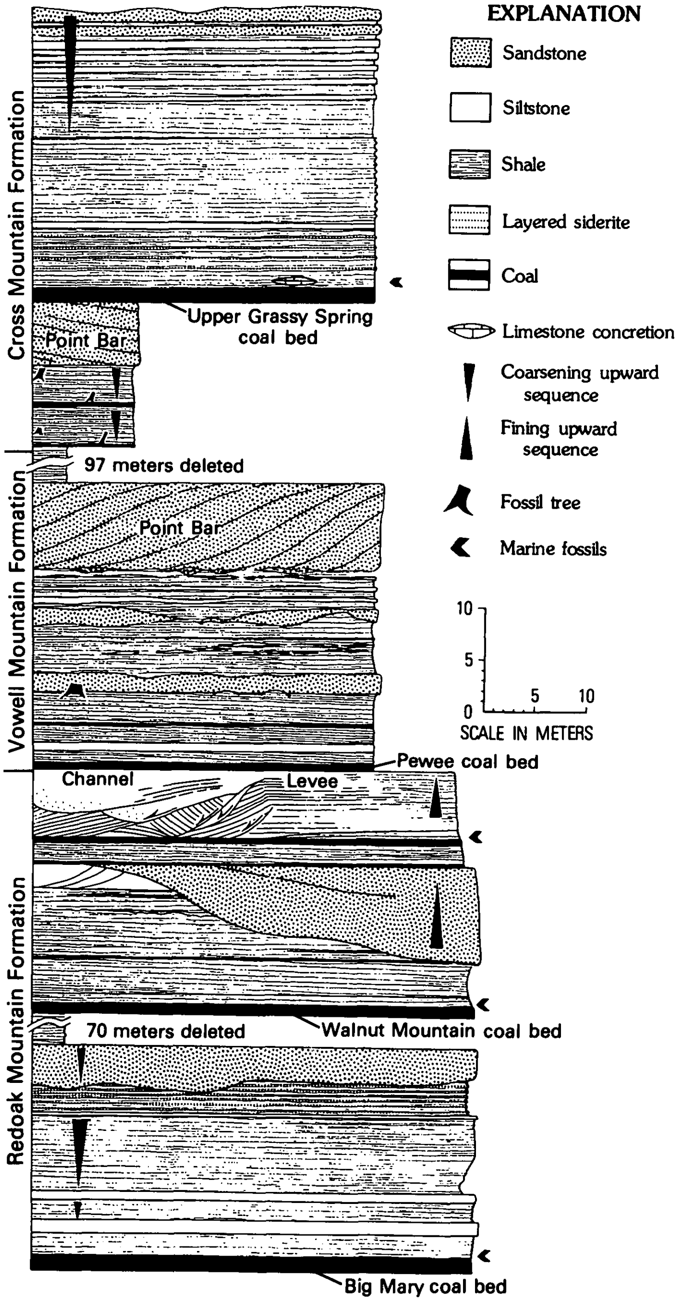

FIGURE 21.—Columnar section of upper Middle Pennsylvanian coal-bearing sequence, with drawings of strip-mine highwalls.

abandoned; then, when subsidence exceeded sedimentation, the delta plain was inundated.

The stage of delta development represented by the columnar section was principally that of the lower delta plain and was characterized by broad interdistributary bays and sluggish channels having low, barely emergent levees and numerous but localized crevasse splays. Although the sequence is generally one of progradation leading to the ultimate establishment of an upper-delta-plain/terrestrial environment, this progradation was intermittent and was punctuated by many reversals or lateral shifts in environment. The environments represented range from shallow-water marine to those of the upper delta plain including freshwater swamps and coalesced point-bar deposits.

The broad areal extent of the Big Mary coal bed within the Wartburg basin and the marine zone that typically overlies it testify to the abandonment and inundation of a widespread delta complex. At least seven marine incursions took place within the interval studied. The one that covered the Big Mary coal was relatively slow to retreat, as is evidenced by a sequence that is 17 m (55 ft) thick of medium- to dark-gray clay shale beds that contains a diverse marine fauna, rhythmically repetitious thin layers of siderite, and several tabular clayey siltstone beds interpreted to be delta-front sheet deposits. The marine zone is discontinuous and is locally absent eastward across the basin. This absence suggests that the sea invaded from the west (Thomas Roberts, oral commun., 1977). A second prominent marine zone covers the Upper Grassy Spring coal bed, but, because the Grassy Spring coals are confined to only the higher mountain tops, strip mines are few and far apart, and the associated marine zone is poorly described. Distributary-mouth bar sequences were observed in highwalls above both the Big Mary (White, 1975) and Upper Grassy Spring (top of section—fig. 21) coals.

When the delta complex grew substantially, channels formed and meandered broadly, forming extensive point-bar deposits such as those in the highwalls above the Pewee coal bed (fig. 21). Abundant fossil remains of large trees are preserved in growth position on levees and in interdistributary areas at several horizons but are best preserved in the interval overlying the Pewee coal bed. The presence of many large trees is interpreted to signify the establishment of a freshwater swamp similar in some ways to modern cypress swamps.

SIDERITE

Siderite is present throughout the entire study interval, in both marine and nonmarine beds. The nature of siderite occurrences varies within the sequence, however, and is considered useful in interpreting depositional environments. In sequences known to be marine by virtue of fossils and facies associations, siderite is present in thin (about 5 cm, 2 in.) persistent layers that alternate with the dark-gray silty shales. Above the marine deposits, these layers grade into segmented disk-shaped nodular masses as the sequence in which they are enclosed coarsens and becomes less marine. Occurrences of siderite in this layered form are typical both of the gray shale sequence overlying the Big Mary coal bed and of other marine intervals within the sequence studied.

The marine formation of siderite was not accepted by Berner (1971). He described siderite as a relatively common constituent of ancient nonmarine sediments, where it is normally found in association with coal beds and freshwater clay. He stated further that siderite is not stable in marine sediments and has never been observed forming in modern marine sediments.

Large lens-shaped concretions of siderite or limestone (micrite) as much as 2.4 m (8 ft) in diameter and 1 m (3.3 ft) in width are found within the marine to brackish intervals, especially above the Big Mary coal, but the concretions are not everywhere associated with layered siderites. That these concretions, called "flying saucers" by the miners, are clearly diagenetic is indicated by the fact that thin laminae of the enclosing shale pass undisturbed into the carbonate masses. Subsequent compaction caused draping of layers immediately above and beneath the concretions.

Where trees are preserved in growth position in carbonaceous shale of terrestrial origin, siderite is present in large irregularly shaped masses, some of boulder proportions. Unlike the conformable disk-shaped masses in the marine intervals, the irregularly shaped masses cut across the bedding as did the roots of ancient trees around which they nucleated. Less commonly, siderite masses filled in and preserved the trees themselves. Siderite masses of the irregularly shaped variety are most abundant where fossil trees are large and numerous; hence, they are believed to be useful in recognizing freshwater-swamp and upper-delta-plain environments.

Both nonmarine and marine siderite deposits are believed to have lithified quickly, whether they precipitated chemically as a primary sediment or formed diagenetically. As channels moved and the shales and their interbedded siderite layers were scoured, the lithified siderite formed large clasts in channel lag deposits.

FOSSIL TREES

Studies of the fossil trees preserved in growth position in the area around the Wartburg basin have provided a new understanding of depositional environments and rates of sedimentation. The transition from a lower-delta plain to an upper-delta plain environment is marked by a gradual change in flora. Following widespread marine incursions, such as the one that terminated the Big Mary coal swamp, the delta complex from lower to upper delta plain was slowly reestablished.

The lower delta plain is characterized by thin and areally restricted levees, splays, and bar deposits devoid of plants preserved in life position. Coincident with the growth in size and extent of the levees and splays is the appearance of the tree, *Calamites*. Because of the early appearance of *Calamites* in the reestablishment and progradation of the delta, *Calamites* is thought to have been more salinity tolerant than the larger *Lepidodendron* and *Sigillaria* found preserved in growth positions higher in the sequence and hence higher on the delta plain. Probably *Calamites* first became established on low, barely subaerial levees where pore waters were fresh to brackish but where salinity varied widely seasonally if not diurnally. Because *Calamites* had a wide range of salinity tolerance, it persisted on the delta plain in freshwater environments.

Upward in the section and in association with larger and coarser levee, splay, and point-bar deposits, the larger *Lepidodendron* and *Sigillaria* appear and become abundant. These larger trees probably had a low salinity tolerance and grew only in freshwater environments. The trees became established first on levees on the lower delta plain where pore waters were fresh; they spread onto the upper delta plain and into the freshwater interdistributary areas, became more abundant, and formed swamps. The presence of *Calamites* among *Lepidodendron* and *Sigillaria* indicates that the environments in which *Calamites* flourished included freshwater environments. *Sigillaria* and *Lepidodendron* are particularly abundant in the interval immediately overlying the Pewee coal.

In strip-mine highwalls, the sequence observed consists of interbedded, interdistributary silty gray shale and undulating distal levee or flood deposits. Fossil trees 1 m (3.3 ft) or more in diameter have roots in the gray shale, indicating that the trees grew in a shallow-water, highly carbonaceous swamp environment. The undulating fine sandstone and siltstone layers represent flood deposits, which periodically covered the swamps and buried the trees to depths of 0.5 m (1.6 ft) or more. Burial to such depths kills most modern trees, but these ancient trees were capable of generating new roots at the new sediment-water interface (fig. 22).

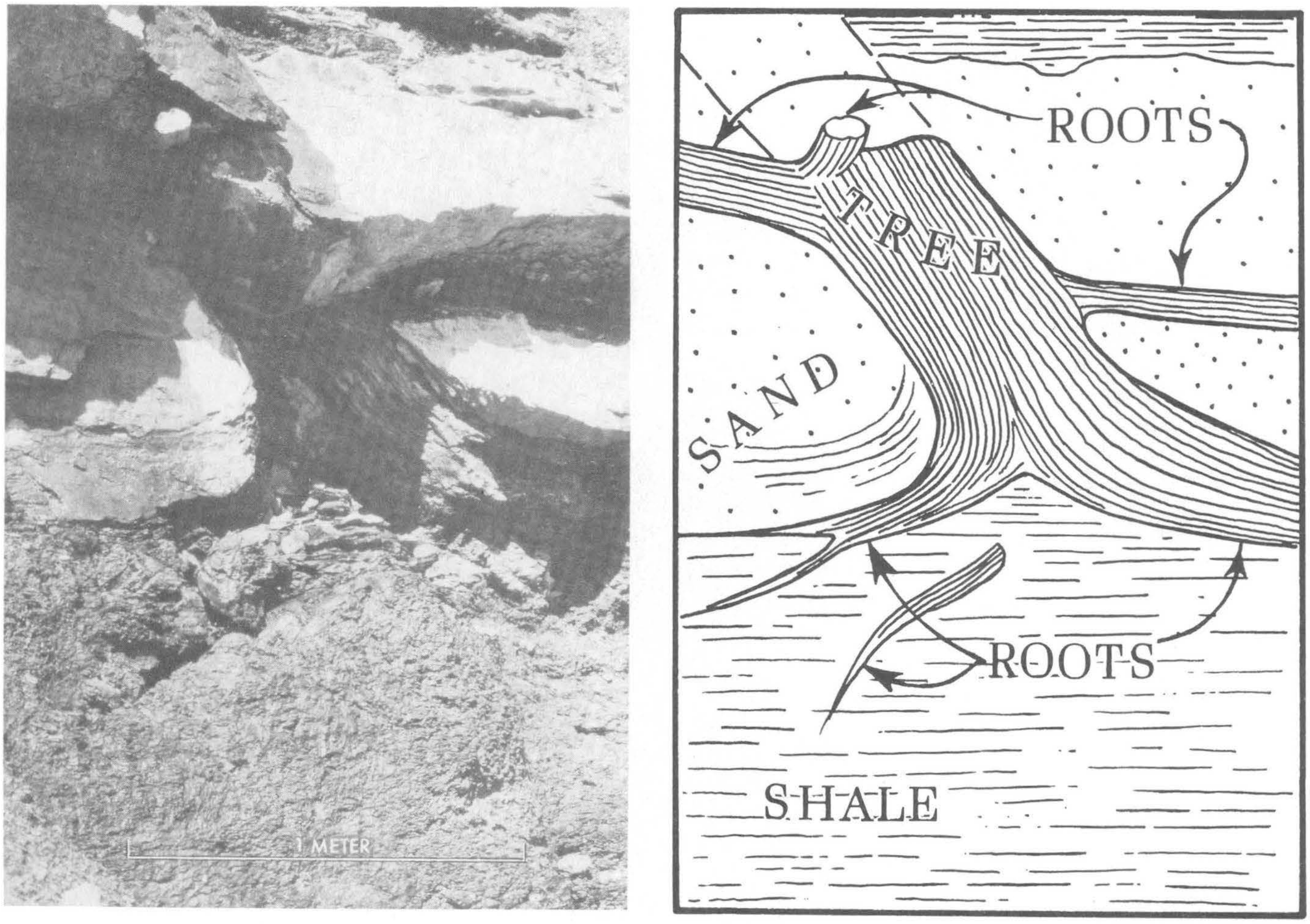

FIGURE 22.—Tree, showing generation of new roots at a higher sediment-water interface that formed when the base was buried by a flood deposit.

In several deposits, the base of a fossil tree is surrounded by a planar-convex body of sandstone as shown in figure 23. The sand collected in a depression produced by compaction of the swamp-floor mud by the increasing weight of the growing trees. During floods, the depressions around the bases of trees were filled with the coarser sediment carried by the moving water. Within the planar-convex bodies, numerous carbonaceous partings contain roots and conform to the curvature of the lower convex boundary of the sand body, indicating that tree growth, compaction, sand deposition, and the generation of new roots at each successive sediment-water interface were all parts of a gradual continuing process.

Figure 24 shows a tree that was buried to a depth of 4.6 m (15 ft). Because the tree is in growth position and shows no root regeneration, it probably was buried very quickly, certainly before it could decay. Probably the tree (and others like it) grew in a back swamp, the level of which was substantially below the water level of the adjacent levee-confined river. When crevasses formed in the natural levee, sediment-laden waters rushed into the back swamp, their velocity was quickly checked, and deposits were immediately laid down around the trees. Thus, a tree, rooted in mud, could be buried by 4.6 m (15 ft) of sediment without being knocked over by the transporting current. Minkin (1977) described several trees that were bent over, all at the same level and in the same direction during burial by such a flow. Moving sediment and water apparently continued to push against the upper parts of the trees after the lower parts of the trees had been buried and stabilized.

HEAVY METALS AND SULFUR

Franks (1976) and Thompson (1977) conducted studies of the heavy-metal content and associations of several depositional facies in the hope that these

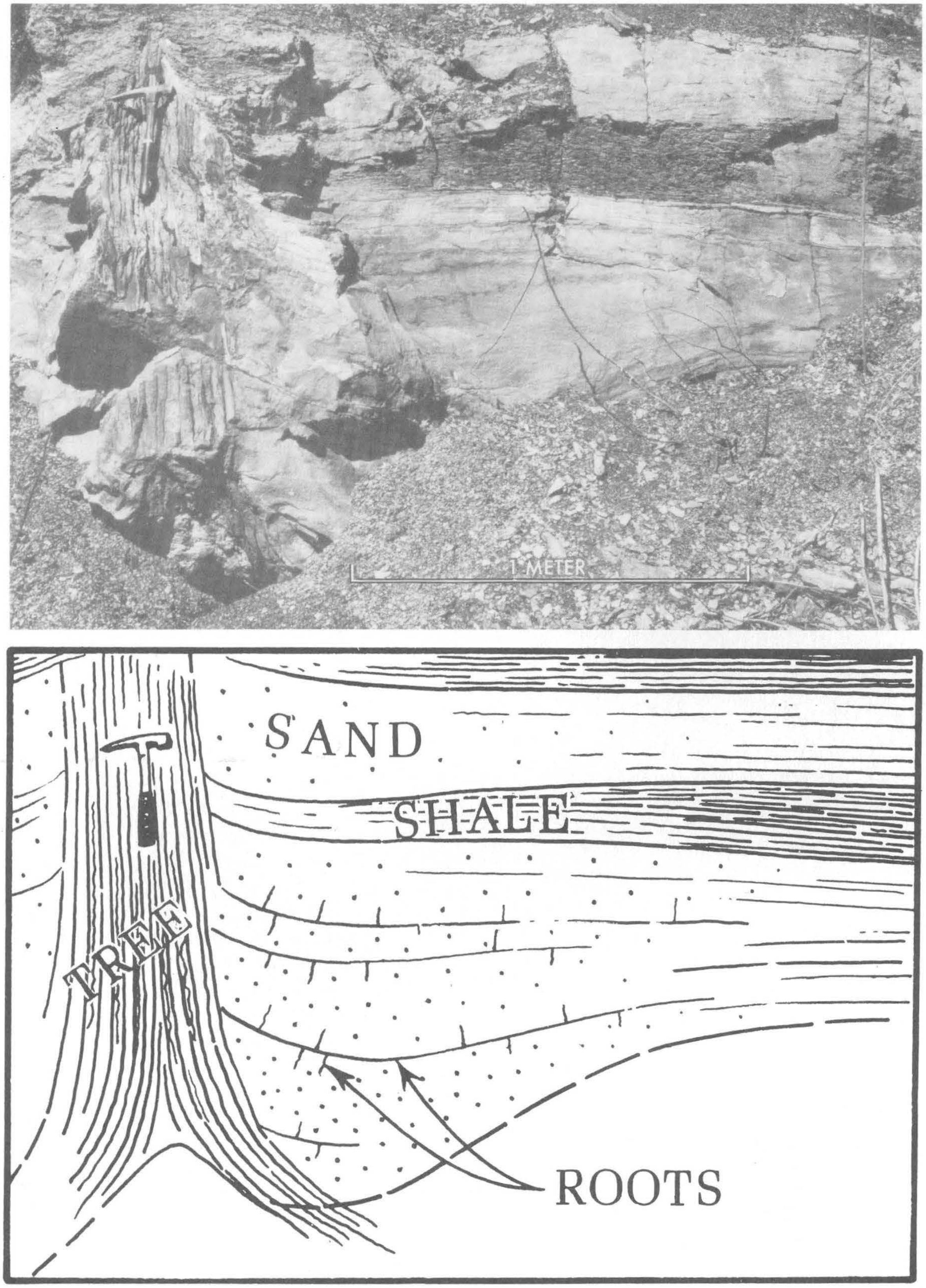

FIGURE 23.—Planar-convex sand bodies at the base of a fossil tree.

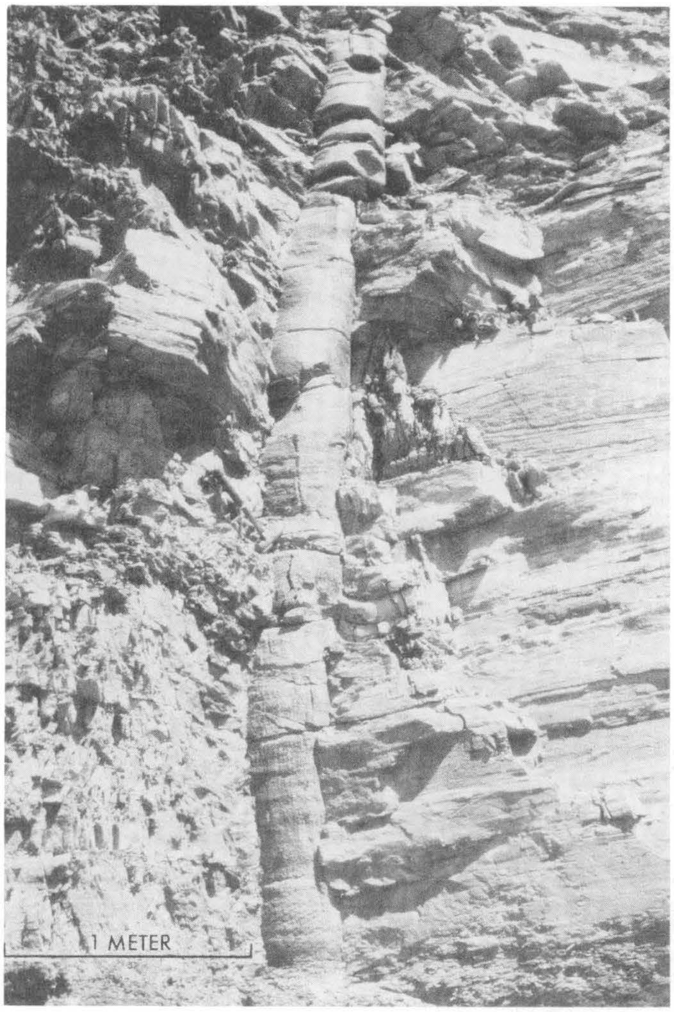

FIGURE 24.—*Lepidodendron* buried in growth position by shaly deposits to a depth of 4.6 m (15 ft).

would provide criteria for distinguishing marine from nonmarine sediments or marsh deposits from swamp deposits. The two studies focused on the Big Mary and Pewee coals and the sedimentary rocks, exposed above them in strip-mine highwalls. The Big Mary was selected because it is overlain by a marine sequence and the Pewee because it is overlain by freshwater swamp deposits. The elements investigated were As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Rb.

The studies were inconclusive about the value of these elements as environmental indicators. However, the studies did show that the concentration of heavy metals is primarily a function of grain size. Concentrations are high in the shale, particularly in the shale immediately overlying coal beds, but are relatively low in the coarser deposits. The coal beds themselves have low concentrations of the heavy metals.

The coal in the Middle Pennsylvanian sequence is typically high in sulfur and ash. In places, the Big Mary coal contains 2.8 percent sulfur and 9.5 percent ash, and the Pewee coal contains 1.1 percent sulfur and 10.9 percent ash (Garman and Jones, 1975). The ash content reflects proximity to a source of detrital sediment during peat accumulation, whereas sulfur content relates in some degree to the position on the delta-plain complex where the coal formed. The high sulfur content of the Big Mary supports the inference that it was formed on the lower delta plain in association with brackish or marine water. The moderate sulfur content of the Pewee coal supports the interpretation that it was deposited higher on the delta plain in association with fresh water in a depositional environment similar to that of the Eocene Wilcox lignite of Texas (Kaiser, 1974). The high sulfur and heavy-metal concentrations in these and other Middle Pennsylvanian coals indicate that the Tennessee area, like the area in West Virginia described by Horne and others [1] (1977), was slow to subside.

MISSISSIPPIAN OIL AND GAS FIELDS IN THE NORTHERN CUMBERLAND PLATEAU

Most of Tennessee's oil production has come from carbonate reservoirs of Mississippian age in Scott and Morgan Counties. Since 1969, more than 90 percent of the State's oil production has come from Fort Payne reservoirs found in these two counties. Although oil and gas production in this area dates from the early 1900's, the discovery of the Oneida West Fort Payne pool in 1969 initiated an active shallow play which is still continuing. Although the primary objective is limestone of the Fort Payne Formation, smaller oil and gas pools are in the Monteagle, Bangor, and Warsaw limestones and the Hartselle sandstone. To date, no significant discoveries have been made in the Pennsylvanian rocks, although several small oil wells and shut-in gas wells have been completed in Lower Pennsylvanian sandstone in Scott County.

Figure 25 shows the locations of the more important Fort Payne and Monteagle pools in Scott, northern Morgan, and eastern Fentress Counties. Table 2 lists selected pools, discovery dates, number

[1] Horne, J. C., Ferm, J. C., Caruccio, F. T., Cohen, A. D., Baganz, B. P., Cantrell, C. L., Corvinus, D. A., Geidel, G., Howell, D. J., Mathew, D., Melton, R. A., Pedlow, G. W., Sewel, J. M., and Staub, J. R., 1977, Depositional models in coal exploration and mine planning, unpublished manuscript on file with (1) Tennessee Div. Geology, Knoxville, Tenn., and (2) Carolina Coal Group, Dept. Geology, Univ. South Carolina, Columbia, S.C.

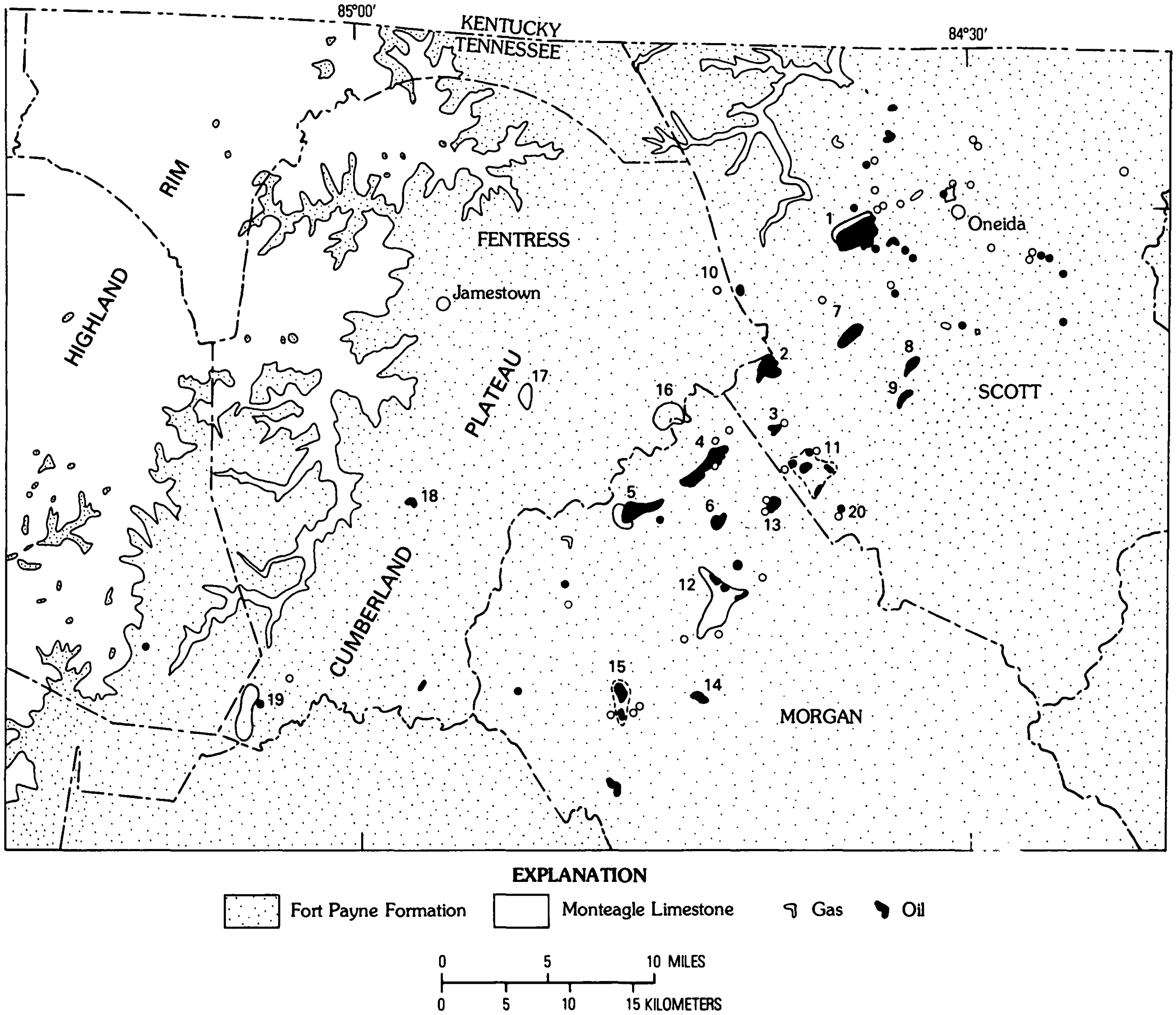

FIGURE 25.—Mississippian oil and gas pools in the northern Cumberland Plateau. Dashed line encloses a group of oil pools. Fort Payne production: 1. Oneida West, 2. Honey Creek So., 3. Gum Branch, 4. Indian Creek, 5. Burrville, 6. Boone Camp (abandoned), 7. Lick Branch unit, 8. Low Gap, 9, Reuben Hollow, 10. Hurricane Ridge. Monteagle production: 11. Glenmary, 12. Sunbright, 13. Union Hill, 14. Little Clear Creek, 15. Douglas Branch, 16. Shirley, 17. Big Branch, 18. Grimsley North, 19. Hurricane Creek, 20. Coal Hill.

of producing wells, and cumulative oil production. Fort Payne reservoirs have produced nearly 4 million bbl of oil in Scott and Morgan Counties, 3.8 million bbl since 1969. Data on gas-pool production are omitted from table 4 because production to date has been quite limited. Owing to lack of pipeline facilities, many of the gas wells in the trend are currently shut-in.

As presently known, the area of productive Fort Payne is about 32 km (20 mi) long, is 13–19 km (8–12 mi) wide, and trends northeast from Burrville in Morgan County to Oneida in Scott County. No major structural features are present in the area, which is west of the Pine Mountain fault block and north of the Cumberland Plateau overthrust. Regional dip is about 7.6 m/km (40 ft/mi) to the southeast. Mapping of the subsurface reveals only minor structural warping. Available data indicate that most Mississippian reservoirs are primarily stratigraphic traps having little or no relationship to observed structure.

Fort Payne reservoirs consist of one or more zones of vugular porosity found within local lenses or mounds of fossiliferous and fragmental limestone

TABLE 2.—*List of selected Mississippian oil and gas pools, Tennessee*

Number in figure 25	Field name, County	Year of discovery	Number of producing wells	Cumulative production to December 1977 (bbl)
	Fort Payne Pools			
6	Boone Camp, Morgan	1924	13	150,000 est.
1	Oneida West, Scott	1969	40	1,215,687
(Off fig. 25)	Broken Leg, Overton	1970	10	43,699
2	Honey Creek So., Scott	1972	15	239,586
3	Gum Branch, Scott	1973	6	71,509
4	Indian Creek, Morgan	1973	35	1,312,102
5	Burrville, Morgan	1974	39	321,700
7	Lick Branch Unit, Scott	1976	26	463,968
8	Low Gap, Scott	1976	18	100,863
9	Reuben Hollow, Scott	1977	10	37,456
	Monteagle Pools			
11	Glenmary, Scott	1916	20	206,500 est.
14	Little Clear Creek, Morgan	1928	4	79,050
20	Coal Hill, Scott	1950	1	38,567
15	Douglas Branch, Morgan	1972	12	47,288

[1] Abandoned.

that overlie the typical massive chert and siliceous carbonate rocks of the lower Fort Payne. These lenses are generally tabular or elongate, locally are as thick as 24 m (80 ft), and range in areal extent from 80–120 ha (200–300 acres) to 7–10 km^2 (3–4 mi^2). Studies of samples indicate that these lenses contain little or no chert and are in sharp contact with the underlying cherty carbonate. They are overlain by dark-gray, impermeable, dolomitic siltstones (upper part of the Fort Payne and lower part of the Warsaw) which serve as seals for the reservoirs. Structural mapping indicates that a surface of considerable relief is on the top of the cherty carbonates even within the limits of a single pool. Previous studies (Statler, 1971, 1975) suggest that the thickness and configuration of the cherty carbonate in the lower part of the Fort Payne may have an important bearing on the location and geometry of the productive limestone lenses.

Younger Mississippian oil and gas fields have been found in a wider area extending into western Fentress County, and several small fields have been found along the eastern edge of the Cumberland Plateau in Anderson and eastern Morgan Counties. The most important of these fields are in the Monteagle Limestone, which locally has good porosity and permeability in the massive oolitic and bioclastic limestone facies. Most of the Monteagle discoveries are gas reservoirs; they are apparently mainly stratigraphic traps, although structural warping may contribute fracture porosity locally. The fact that several gas-gathering systems are currently being constructed in the area should greatly stimulate interest in and drilling for these shallower gas reservoirs.

Outside of the area shown in figure 25, the Cumberland Plateau is only sparsely drilled. Although widely scattered wildcats in the southern and eastern parts of the plateau have not yet found commercial quantities of oil or gas, large areas remain virtually untested. Mississippian lithologies and drilling depths are comparable to those of the producing area in the northern plateau.

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The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States— Georgia

By WILLIAM A. THOMAS *and* HOWARD R. CRAMER

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Historical review and summary of areal, stratigraphic, structural, and economic geology of Mississippian and Pennsylvanian rocks in Georgia

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CONTENTS

ILLUSTRATIONS

TABLES

THE MISSISSIPPIAN AND PENNSYLVANIAN (CARBONIFEROUS) SYSTEMS IN THE UNITED STATES—GEORGIA

By WILLIAM A. THOMAS[1] and HOWARD R. CRAMER[2]

ABSTRACT

Mississippian and Pennsylvanian rocks are exposed in the Appalachian fold and thrust belt of northwest Georgia. The Mississippian System includes a carbonate facies on the northwest and a clastic facies on the southeast. The carbonate facies is characterized by high-energy shallow-marine limestones. The clastic facies is composed mainly of prodelta mud and includes minor delta-front sands. Intertonguing of the clastic and carbonate facies indicates that delta progradation alternated with transgression and delta destruction. Both facies of the Mississippian System grade upward through a sequence of fine clastic rocks to massive sandstone that has commonly been considered as Pennsylvanian. However, the Mississippian-Pennsylvanian boundary is not precisely defined. Early Pennsylvanian rocks (Pottsville) are the youngest Paleozoic rocks in northwest Georgia. The Pennsylvanian System is predominantly sandstone and shale, and contains subordinate amounts of conglomerate, coal, and siltstone. The lower coal-bearing rocks appear to have been deposited in a shoreline environment; bar, tidal-delta, and lagoonal deposits have been identified. The upper coal-bearing rocks appear to have been deposited in a lower-delta-plain environment; the sedimentary units are individually more widespread and less variable. Bituminous coal is the major economic resource, although the reserves are uncertain and may be somewhat less than 100 million tons. All the coal is medium- and low-volatile, low sulfur, and for the most part in beds much less than 1 m thick.

INTRODUCTION

Sedimentary rocks of the Mississippian and Pennsylvanian Systems are exposed in the Appalachian fold and thrust belt of northwest Georgia (fig. 1). The maximum thickness is more than 1,000 m. The Mississippian System includes a carbonate facies on the northwest and a clastic facies on the southeast. Both facies of the Mississippian System grade upward into a Pennsylvanian clastic sequence characterized by sandstone, shale, and coal.

In the Appalachian Piedmont of Georgia (fig. 1), some metamorphic and plutonic rocks yield radiometric dates indicating a Mississippian-Pennsylvanian age (Pinson and others, 1957; Smith and others, 1969; Hurst, 1970; Fullagar, 1971; Fullagar and Butler, 1974; Jones and others, 1974; Whitney and others, 1976). None of the metasedimentary rocks in the Appalachian Piedmont of Georgia has yet been shown to represent Mississippian-Pennsylvanian deposition. To the southwest, in the Piedmont of Alabama, metasedimentary rocks in the Talladega Slate belt include sedimentary deposits of Mississippian (Carrington, 1967, p. 26) and Pennsylvanian ages (Butts, 1926, p. 219). Parts of the Talladega have been traced from Alabama into northwest Georgia (Cressler, 1970, p. 51).

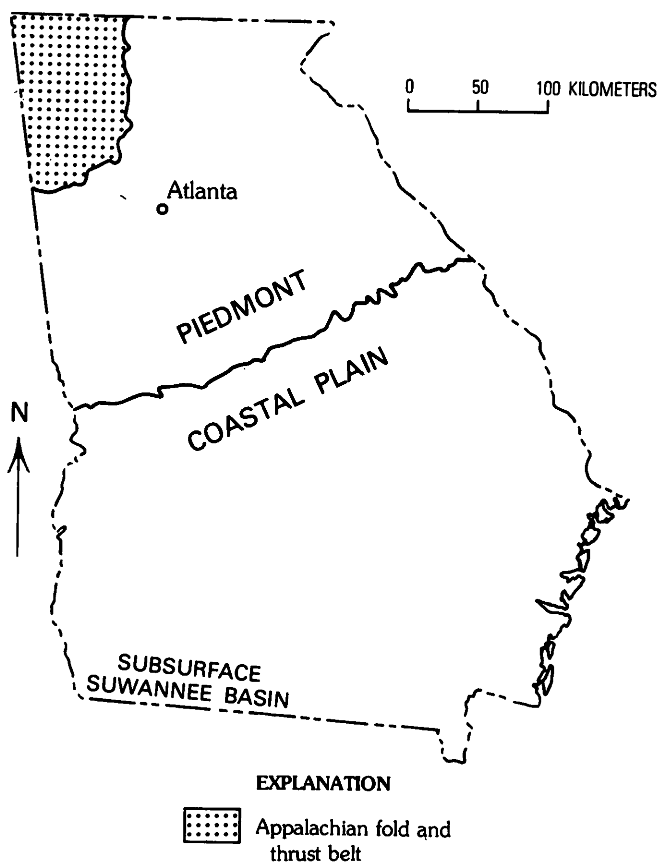

FIGURE 1.—Index map of Georgia.

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In south Georgia, beneath the Mesozoic-Cenozoic strata of the Gulf Coastal Plain, the Suwannee basin contains a thick sequence of Paleozoic clastic sedimentary rocks (fig. 1). Palynological studies of samples from one well (Anderson No. 1 Great Northern Paper Co.) indicate a Devonian age (McLaughlin, 1970). Studies of fossils in cores from another well (Warren No. 1 Chandler) yield conflicting results. Ostracodes suggest a Late Ordovician or Early Silurian age (Swartz, 1949, p. 320); however, Pennsylvanian pelecypods have been identified in slightly deeper beds (Palmer, 1970). Possibly Mississippian-Pennsylvanian strata will be documented by future work in the pre-Mesozoic basin.

The purpose of this paper is to review the Mississippian and Pennsylvanian sedimentary rocks in Georgia as they are presently understood. The scope of the paper is limited to consideration of known Mississippian-Pennsylvanian strata in the Appalachian fold and thrust belt of northwest Georgia. To facilitate organization, a twofold subdivision has been used; however, that subdivision is hampered by problems of identification of the Mississippian-Pennsylvanian boundary. In general, Thomas has gathered and interpreted data relative to Mississippian rocks, and Cramer has gathered and interpreted data relative to Pennsylvanian rocks. The Mississippian limestone is a distinct lithostratigraphic entity, but the overlying sequence of shales and sandstones evidently lacks persistent lithostratigraphic markers. Massive sandstone above the base of the shale-sandstone sequence forms a bluff that is topographically distinct; however, the bluff evidently is formed by different sandstone units at different places. In any local stratigraphic column, the top of the limestone and a bluff-forming sandstone are the most readily identified beds. In the following discussions, these beds are used loosely as reference horizons. Available biostratigraphic data suggest that the Mississippian-Pennsylvanian boundary is probably within the shale-sandstone sequence between the top of the limestone and the massive sandstone but may be as high as some of the massive sandstones.

The discussion and interpretations are based on data from publications, unpublished manuscripts, field notes, and core descriptions available for compilation in 1977. We acknowledge the assistance of many geologists in identifying data sources. Cores from the Rocky Mountain area, Floyd County, were described by H. D. Lowe and G. S. Grainger of the Southern Co.; data from cores and outcrops were provided by G. S. Grainger and W. V. Conn of Georgia Power Co. Cores from Pigeon and Lookout Mountains, Walker and Chattooga Counties, were described by Duane Jorgensen of the United States Gypsum Co. Core descriptions and measured section data were provided by Robert Bolding of West Georgia College, R. C. Milici of the Tennessee Division of Geology, B. J. Timmons of Florida Rock Industries, D. H. White, Jr., of the U.S. Bureau of Mines, and R. L. Wilson of the University of Tennessee at Chattanooga. Access to file data of the Georgia Geological Survey was provided by S. M. Pickering, Jr., and J. B. Murray. The manuscript has been read by J. B. Murray, D. E. Ogren, S. M. Pickering, Jr., Mark Rich, J. A. Waters, and E. L. Yochelson, and we appreciate their comments.

The stratigraphic nomenclature used in this paper has not been reviewed by the Geologic Names Committee of the U.S. Geological Survey. The nomenclature used here conforms with the current usage of the Georgia Department of Natural Resources, Geologic and Water Resources Division.

HISTORY OF THE STUDY OF THE CARBONIFEROUS ROCKS

Figure 2 shows the evolution of the classification schemes that have been used for the Carboniferous rocks of Georgia.

The period from 1809 to 1892 includes that time from when geology was first studied in the United States to when the Carboniferous rocks of Georgia were first investigated. During this period, the Carboniferous rocks of Georgia were examined only incidentally, as parts of larger regional studies. The nomenclature used did not originate in Georgia but was introduced from elsewhere. Williams (1891) provided a history of the nomenclature evolution of the Carboniferous rocks of Georgia and elsewhere.

The period from 1892 to 1904 encompasses the time when geologists, mostly from the U.S. Geological Survey, first investigated the rocks of Georgia and proposed names for the subdivisions. The period begins with the works of Hayes (1892; 1894; 1895; 1902) and ends with the summary work on the Carboniferous of the entire Appalachian chain by Stevenson (1903, 1904). Economic studies of the Carboniferous rocks of Georgia were made by Spencer (1893) and McCallie (1904). Many of the stratigraphic concepts developed during this period are in use today.

Between 1904 and 1942, little new information accrued about the Carboniferous of Georgia except that in individual reports on economic geology. In

CARBONIFEROUS ROCKS					AUTHOR AND DATE
Secondary					U.S. Map Maclure 1809
Transition	Appalachian Coal Field				Ga. State Map Williams, *in* White 1849
Carboniferous					U.S. Map Marcou 1853
Carbonifiere Inferiere ou Calcaire du Montagne	Carbonifiere Superieur ou Terrain Houiller				
Vespertine	Umbral	Seral			Rogers 1858
Carboniferous					U.S. Map Hitchcock and Blake 1874
Carboniferous					Ga. State Map Little 1876
Sub Carboniferous	Coal Measures				
Lower Sub Carboniferous	Upper Sub Carboniferous	Carboniferous			U.S. Census Map McCutcheon 1884
Carboniferous					Ga. State Map Spencer 1893
Fort Payne Chert	Floyd Shale	Mountain Limestone	Coal Measures		
Waverlyan	Tennesseean	Pennsylvanian			Ulrich 1911
Carboniferous (on map)					Ga. State Map Georgia Div. Mines, Mining, and Geology 1939
Mississippian (in legend)	Pennsylvanian (in legend)				
Mississippian	Pennsylvanian				Ga State Map Georgia Geological Survey 1976
Tournaisian	Visean	Namurian	Westphalian	Stephanian	European Stages

FIGURE 2.—Correlation chart showing the evolution of Carboniferous nomenclature in Georgia.

1939, the first modern geologic map of the State was published (Georgia Div. Mines, Mining, and Geology, 1939); this map included a summary of the Carboniferous stratigraphy to that date.

During, and just after the war years, from 1940 to about 1950, the need for mineral-resource development prompted geologists again to investigate the Carboniferous rocks of Georgia. Most of the resulting reports deal with the coal resources. The summary volume of Pennsylvanian stratigraphy of the southern Appalachians (Wanless, 1946) appeared at this time, and also the volume of the geology of northwest Georgia (Butts and Gildersleeve, 1948). Correlation charts prepared by committees of the Geological Society of America (Mississippian, Weller, chairman, 1948; Pennsylvanian, Moore, chairman, 1944) fixed the nomenclature of the Carboniferous of Georgia in relation to that of other States.

After 1950, geological education in Georgia flourished, and much data about the Carboniferous resulted from student research. Authors of theses mainly used the nomenclature recommended by Butts (*in* Butts and Gildersleeve 1948).

Expanded activity in geological mapping took place between 1960 and 1969, and much detail was uncovered by geologists from the U.S. Geological Survey and the Georgia Geological Survey (Cressler, 1963; 1964a, b; 1970; Croft, 1964). The work of Culbertson (1963) summarized the nomenclature of the Pennsylvanian rocks. The concepts of regional stratigraphic analysis emanating from the Northwestern University school of stratigraphy were applied to Georgia (Stearns and Mitchum, 1962). In this report the Pennsylvanian rocks of Georgia are shown on three-dimensional maps in a regional context.

Work by Hobday (1969) initiated another era of stratigraphic studies in the Carboniferous rocks of Georgia. Before this, Ferm and his associates (Ferm and others, 1967; Ferm, 1974) had begun to look at the Carboniferous rocks of the Appalachian region, not as layers as in a cake, but as a sequence of laterally discontinuous, time-transgressive sedimentary units that are a result of changing environments in the coastal, littoral, and deltaic regimes. The work of Hobday (1974) was the first published account of the Carboniferous rocks of Georgia that used such a sedimentologic model as the primary interpretation. Application of this kind of interpretation will require a reevaluation of all of the clastic rocks of the Carboniferous of Georgia.

The U.S. Geological Survey's paleotectonic study of the Pennsylvanian of the United States (McKee and others, 1975) summarizes all the available data. This and the most recently published geologic map of the State (Georgia Geological Survey, 1976) will serve as springboards for the reevaluation and future interpretations.

DISTRIBUTION AND STRUCTURAL SETTING OF THE CARBONIFEROUS ROCKS

Mississippian and Pennsylvanian strata in northwest Georgia are within the Appalachian fold and thrust belt (figs. 1, 3*A*). Pennsylvanian strata, the

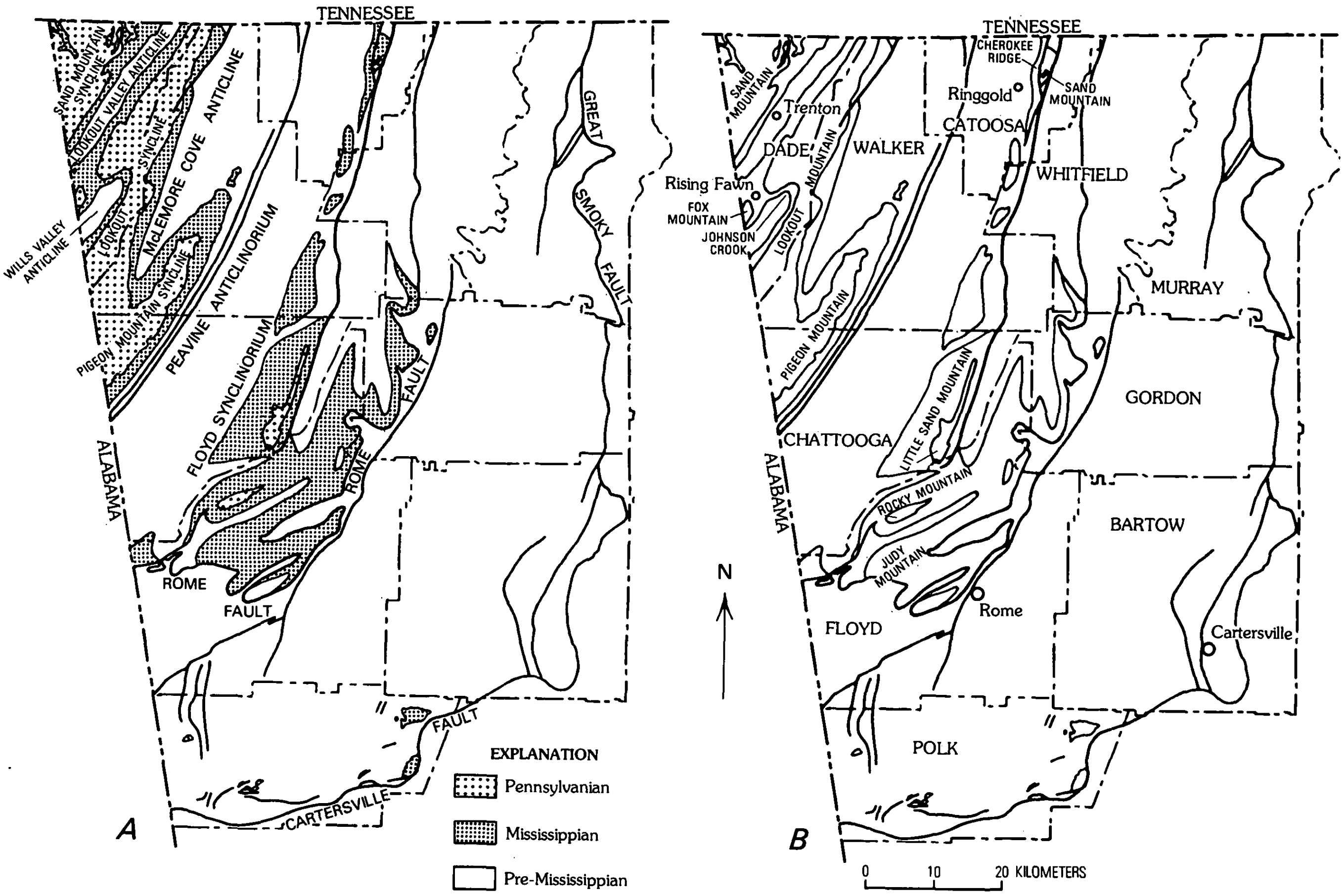


FIGURE 3.—Geologic map (*A*) of northwest Georgia and outline map (*B*) showing localities mentioned in text. Geologic map adapted from the geologic map of Georgia (Georgia Geological Survey, 1976).

youngest rocks exposed in northwest Georgia, cap flat-topped mountains. The Pennsylvanian beds are preserved in the troughs of synclines and commonly have gentle dips. Mississippian rocks are exposed along the mountain slopes and in adjacent valleys.

On the east and south, the Appalachian fold and thrust belt is bordered by metamorphic rocks of the Appalachian Piedmont along the Cartersville (Great Smoky) fault. The next major structure northwest of the Cartersville fault is the Rome fault, the sinuous trace of which reflects low dip and folding of the fault plane (fig. 3*A*). The Rome fault block is internally complicated by folds and faults and is composed of lower Paleozoic formations except for small areas of Mississippian rocks north of the Cartersville fault in Polk County. A regional structural recess in the Appalachian structural system in northwest Georgia is expressed by abrupt curves in strike of both the Cartersville and Rome faults.

Northwest of the Rome fault is the large, complex Floyd synclinorium which plunges into a depression northwest of Rome in Floyd County (fig. 3*B*). North of the depression, a complex south-plunging anticline divides the synclinorium into two branches; a thrust fault along the west limb of the anticline ends southward down the plunge. Southwest of the depression, northeast-trending anticlines plunge northeastward. An abrupt change in strike within the synclinorium at the depression outlines the regional structural recess (fig. 3*A*). Much of the surface area of the depression and synclinal branches of the Floyd synclinorium is formed on Mississippian rocks. Pennsylvanian rocks in synclinal troughs cap three isolated mountains: Rocky Mountain (shown as Rock Mountain on the 7½-min quadrangle map named for the mountain), northwest of Rome; Little Sand Mountain, north of Rome; and Sand Mountain[3], east of Ringgold (fig. 3*B*).

Northwest of the Floyd synclinorium on the Peavine anticlinorium, Cambrian and Ordovician

[3] Two separate topographic features in northwest Georgia are called Sand Mountain: (1) on the east, an areally small mountain east of Ringgold in Catoosa County, and (2) in the northwest corner of Georgia, in Dade County, a broad flat-topped mountain that extends into Alabama and Tennessee.

rocks are exposed, and the anticlinorium separates Mississippian-Pennsylvanian outcrops of northwest Georgia into two major parts (fig. 3*A*). On the southeast is the large outcrop area in the Floyd synclinorium. On the northwest is a large area of Mississippian and Pennsylvanian outcrops on Pigeon, Lookout, and Sand Mountains.

Northwest of the Peavine anticlinorium, the strata are broadly folded in the Pigeon Mountain and Lookout synclines (fig. 3*A*). The two synclines are separated by the southwest-plunging McLemore Cove anticline. The anticline flattens down plunge, and the Pigeon Mountain and Lookout synclines apparently merge southwestward into the more narrow Lookout syncline along Lookout Mountain in Alabama. The northwest limb of the Lookout syncline is formed by the en echelon Wills Valley and Lookout Valley anticlines (fig. 3*A*). Northwest of the en echelon anticlines, the broad flat-bottomed Sand Mountain syncline extends northwestward beyond the northwest corner of Georgia. The most northwesterly Appalachian anticline, the Sequatchie anticline, is farther northwest in Tennessee and Alabama.

Pennsylvanian rocks form a wide outcrop area on the flat mountain tops in the Pigeon Mountain and Lookout synclines. A continuous outcrop extends from the northern end of Lookout Mountain at Chattanooga, Tenn., across northwest Georgia, and southwestward into Alabama. Lower Pennsylvanian sandstones form a prominent bluff, or brow, around the top of Pigeon and Lookout Mountains. Mississippian formations, mainly limestones, are exposed along the slopes of Lookout and Pigeon Mountains. A similar arrangement of outcrops and rock types is found on Sand Mountain in the northwest corner of Georgia (fig. 3*B*).

MISSISSIPPIAN STRATIGRAPHY OF NORTHWEST GEORGIA

By William A. Thomas

LITHOFACIES

The Mississippian System of northwest Georgia includes two geographically and stratigraphically distinct facies. The facies on the northwest is mainly carbonate rock, and that to the southeast is mainly clastic rock (fig. 4). Areas of distribution of the two facies are divided roughly by the Peavine anticlinorium (fig. 3*A*).

The northwestern carbonate facies may be subdivided into three successive units. The lower unit is characterized by bedded chert and cherty carbonate. The middle and thickest unit is mainly noncherty limestone. The upper unit is characterized by maroon, green, and gray mudstones and shales. Boundaries between the three subdivisions are gradational. The shale unit at the top of the Mississippian System grades upward into a sequence of sandstone, shale, and coal that has been assigned to the Pennsylvanian System.

The southeastern clastic facies is mainly shale but also includes sandstone. The lower part of the southeastern clastic facies contains bedded chert similar to that in the bedded chert unit at the base of the northwestern carbonate facies. The clastic facies also contains interbeds of limestone similar to the limestone in the middle unit of the northwestern carbonate facies (fig. 4). The southeastern clastic facies of Mississippian rocks is overlain by sandstone of the Pennsylvanian System.

Limestone tongues within the southeastern clastic facies indicate a lateral transition characterized by intertonguing of the two facies; however, outcrop sections do not show the complete range of intermediate characteristics between the two facies. Along the Peavine anticlinorium, in the probable area of facies transition, Mississippian rocks have been removed by erosion. Interpretation of structure of the anticlinorium (Butts, *in* Butts and Gildersleeve, 1948, geologic map) suggests only minor structural telescoping of the sedimentary facies. Some possible transitional aspects can be seen where the section is mostly limestone on Sand Mountain (Catoosa County) in the western north-trending branch of the Floyd synclinorium (fig. 3*A*). To the south in the Floyd synclinorium, the Mississippian System is represented by the clastic facies. Evidently the clastic facies grades northward to the carbonate facies along the western branch of the Floyd synclinorium, but details are obscure because of poor exposure. Apparently the facies boundary roughly parallels structural strike along the Peavine anticlinorium, but it trends somewhat more easterly and extends into the Floyd synclinorium on the north.

Trends of major facies patterns are paralleled by major thickness trends in the Mississippian System (fig. 4). On the northwest, the carbonate facies ranges in thickness from approximately 360 to 460 m. The system thickens to the southeast, and in the depression of the Floyd synclinorium the clastic facies is as much as 775 m thick. Because of poor exposure, thickness data for the clastic facies are sparse. Complex structure precludes a thickness

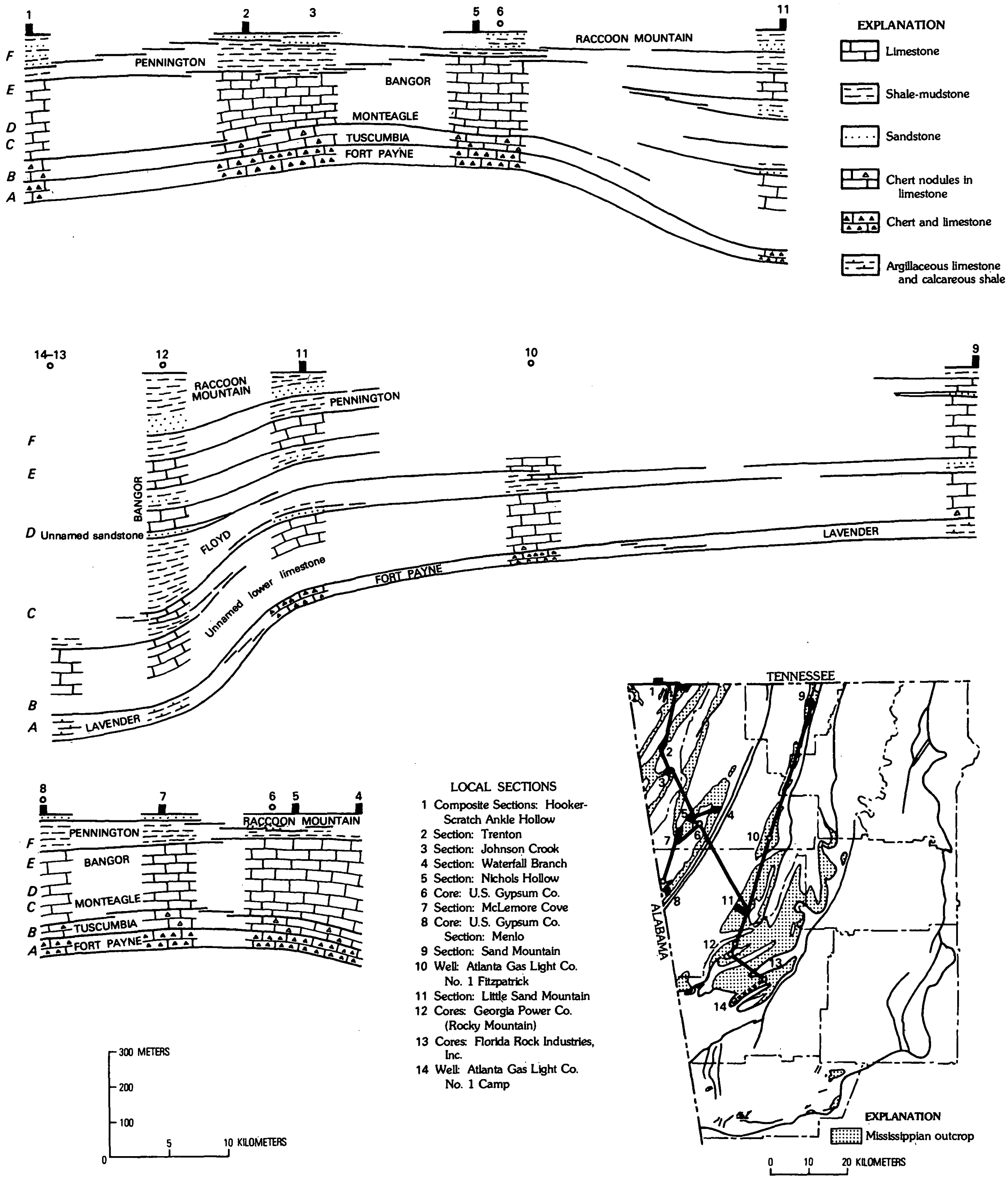


FIGURE 4.—Diagrammatic stratigraphic cross sections of Mississippian rocks in northwest Georgia. Top of each section is base of massive sandstone. Lithologic symbols on cross sections show the part of each local section that is included in available descriptive data. Letters A through F on cross sections show approximate stratigraphic positions of maps in figure 8. Data for local sections from Sullivan (1942) (section 3), Allen (1950) (section 9), Clement (1952) (section 3), Moore (1954) (section 2), Wheeler (1954) (sections 4, 5), Windham (1956) (section 9), Wilson (1965) (section 1), McLemore (1971) (sections 1–5, 7–9, 11), Florida Rock Industries, Inc. (section 13), Georgia Geological Survey (sections 10, 14), Georgia Power Co. (section 12), and U.S. Gypsum Co. (sections 6, 8).

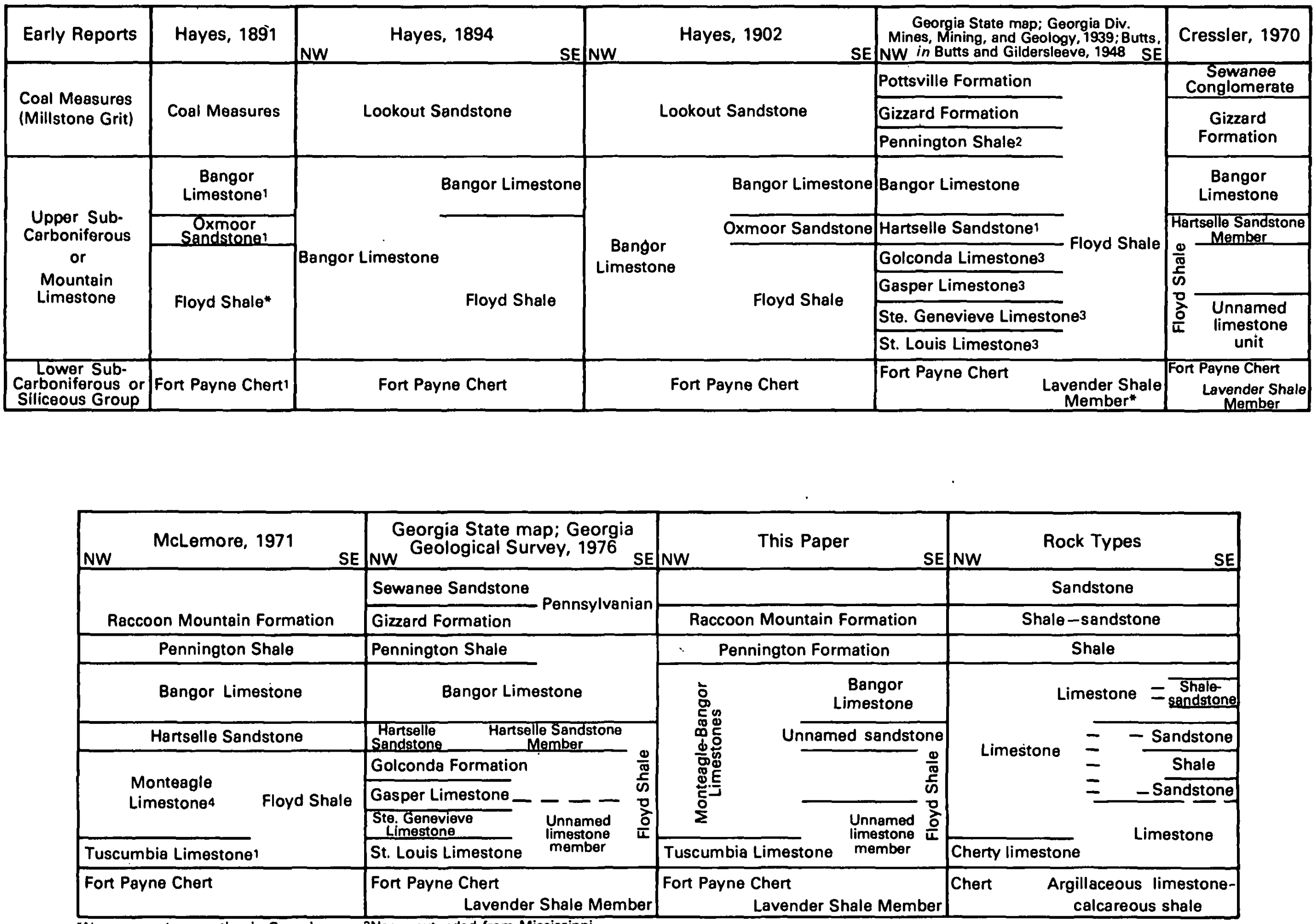
measurement of Mississippian rocks on the Rome fault block.

EVOLUTION OF STRATIGRAPHIC NOMENCLATURE

Pioneer stratigraphic work in Tennessee and Alabama led to the recognition of three major subdivisions of Carboniferous rocks (Safford, 1869; Smith, 1879). The Lower Sub-Carboniferous or Siliceous group included the cherty beds that make up the lower part of the Mississippian in Georgia. The Upper Sub-Carboniferous or Mountain Limestone included the carbonate sequence of northwest Georgia. The Coal Measures apparently included the shale at the top of the Mississippian as well as the overlying sandstone-shale-coal sequence of the Pennsylvanian.

The first identification of formation subdivisions in Georgia apparently is the work of Hayes (1891) who extended the stratigraphic names Fort Payne Chert, Oxmoor Sandstone, and Bangor Limestone from Alabama. Hayes first used the name Floyd Shale for the lower part of the clastic sequence in Georgia (fig. 5).

In quadrangle mapping at Ringgold and Rome, Hayes (1894; 1902) recognized the two geographically distinct sequences of Mississippian rocks in Georgia. He used the name Bangor for all carbonate rocks above the Fort Payne Chert on the northwest, and he used the names Floyd and Oxmoor for the shale and sandstone parts of the clastic sequence on the southeast (fig. 5). The name Bangor was also used for a limestone unit above the Floyd and Oxmoor of the clastic sequence. Hayes (1894) specifically recognized that the clastic facies changes northwestward into the carbonate facies and that the Floyd on the southeast is the same age as the lower part of the Bangor on the northwest.



*New name, type section in Georgia
1Name extended from Alabama
2Name extended from Virginia
3Name extended from Mississippi Valley by way of Alabama
4Name extended from Tennessee

FIGURE 5.—Chart showing the evolution of stratigraphic subdivision and nomenclature of Mississippian rocks in northwest Georgia.

On the 1939 State geologic map of Georgia and in a subsequent report by Butts (*in* Butts and Gildersleeve, 1948, p. 3–79), several formation names were extended into Georgia from the Mississippi Valley section (fig. 5). These subdivisions were based mainly on earlier work, in which Butts (1926) had extended the use of the Mississippi Valley units to Alabama. The same units were subsequently extended to Georgia from Alabama. Recognition of St. Louis, Ste. Genevieve, Gasper, and Golconda was based mainly upon the presence of certain distinctive faunal elements (Butts, *in* Butts and Gildersleeve, 1948, p. 45–48). Above the Golconda (of Butts, 1926) in Alabama is an extensive sandstone unit, the Hartselle Sandstone. Originally the name Bangor Limestone had been used in Alabama for the entire limestone sequence above the Fort Payne Chert (in that sense, Hayes, 1894, extended the use of Bangor into Georgia), and Hartselle Sandstone had been recognized as a member of the Bangor (Thomas, 1972a, fig. 2). Later, Butts (1926) restricted the Bangor to limestone beds above the Hartselle Sandstone and raised Hartselle to formation rank. In the latter sense, Butts (*in* Butts and Gildersleeve, 1948, p. 48). extended the use of Hartselle and Bangor into Georgia.

The Hartselle Sandstone in Alabama is a distinctive sandstone unit locally as much as 50 m thick (Thomas, 1972a, pl. 10), and a sandstone and sandy limestone approximately 3 m thick marks the position of the Hartselle at the north end of Lookout Mountain in Chattanooga, Tenn. (Butts, *in* Butts and Gildersleeve, 1948, p. 48). However, the limestone sequence in Georgia contains no persistent sandstone unit at the stratigraphic position of the Hartselle. Extension of the name Hartselle Sandstone from Alabama has led to a frustrating search for a rock unit to fit the stratigraphic name.

Butts (*in* Butts and Gildersleeve, 1948, p. 49) also extended the name Pennington from Alabama for the shale unit at the top of the Mississippian section (fig. 5). The name Pennington was defined in Virginia (Campbell, 1893, p. 28) and had been extended to Alabama by Butts (1910).

The clastic facies on the southeast in Georgia was assigned to the Floyd Shale (Butts, *in* Butts and Gildersleeve, 1948, p. 49–52). So defined, the Floyd included interbeds of limestone and sandstone, but stratigraphic names were not applied to any of these units (Butts *in* Butts and Gildersleeve, 1948, p. 50). Butts defined the Lavender Shale Member of the Fort Payne Chert as a dark-colored shale member (fig. 5). The Lavender Shale Member is restricted generally to the east of the area of the Fort Payne Chert.

Preparation of county maps by Cressler (1970) led to further subdivision of the clastic facies (fig. 5). A distinctive limestone tongue in the upper part of the clastic facies was identified as Bangor Limestone, following the usage of Hayes (1891). The clastic rocks below the Bangor and above the Fort Payne Chert were called Floyd Shale, and a sandstone unit near the top of the Floyd was designated the Hartselle Sandstone Member (Cressler, 1970, p. 48). The Hartselle Sandstone Member as mapped by Cressler (1970) is the same unit Hayes (1891; 1902) called Oxmoor Sandstone. Both names had been extended from Alabama, and the change introduced by Cressler reflected changes in subdivision and nomenclature of the Alabama section. The Hartselle Sandstone in Alabama occupies a well-defined stratigraphic position, and Cressler's (1970) work extended the use of the name into the clastic facies in Georgia. A limestone unit at the base of the Floyd Shale was mapped locally by Cressler (1970) as an unnamed limestone unit.

In a dissertation, McLemore (1971) proposed revisions of some of the stratigraphic nomenclature to recognize lithologically distinct units (fig. 5). The name Tuscumbia was extended from Alabama for the lower cherty part of the carbonate facies above the Fort Payne Chert. Overlying the Tuscumbia is a noncherty limestone unit for which the name Monteagle Limestone was extended to Georgia from Tennessee. McLemore (1971) continued the use of the name Hartselle for a shaly and locally sandy unit that he identified within the carbonate facies between Monteagle and Bangor. Although the thickness of the complete Monteagle-Bangor interval is relatively constant, the stratigraphic position of the unit assigned to the Hartselle seems to vary abruptly from section to section resulting in abrupt reciprocal changes in thickness of beds assigned to Monteagle and to Bangor. It appears likely that the rocks designated as Hartselle are not a continuous clastic unit but rather are several local clastic lenses at different stratigraphic positions. McLemore (1971) also used the name Hartselle Sandstone for a sandstone unit within the clastic facies.

Many of the formal stratigraphic names applied to Mississippian rocks in northwest Georgia have been extended from other areas, and subdivision of the Georgia succession has been designed to conform to a scheme of subdivision defined elsewhere. Some units have been identified on the basis of rock characteristics, but many of the formation names that have been extended into Georgia were applied to subdivisions that were identified on the basis of their fossil content. Such units are biostratigraphic units in terms of modern concepts and are not necessarily distinct as rock-stratigraphic units. This review of the evolution of stratigraphic nomenclature in Georgia provides the background for recognition of units that are distinct on the basis of rock type, in keeping with a modern definition of rock-stratigraphic units (fig. 5).

The rocks of the carbonate facies are divided herein into the Fort Payne Chert, Tuscumbia Limestone, Monteagle-Bangor Limestones undifferentiated, and Pennington Formation, in ascending order (fig. 5). The Fort Payne is characterized by bedded chert. The Tuscumbia is cherty limestone. The Monteagle-Bangor sequence is characterized by bioclastic and oolitic limestones that contain very little chert. Maroon and green mudstone is characteristic of the Pennington, and the formation grades upward into a sequence of gray shale, sandstone, and coal.

Because no persistent sandstone unit can be identified within the carbonate facies, the rock-stratigraphic unit called Hartselle cannot properly be identified in Georgia. The Hartselle Sandstone is a distinct rock-stratigraphic unit in Alabama, but isopach mapping shows that the Hartselle Sandstone pinches out eastward along an irregular north-trending line more than 65 km west of the Georgia-Alabama State line (Thomas, 1972a, pl. 10). Because the Hartselle Sandstone of Alabama does not continue eastward into Georgia, and because the beds that have been assigned to the Hartselle in Georgia do not constitute a distinct rock-stratigraphic unit, it is inappropriate to continue the use of the name Hartselle in Georgia. Lack of a mappable stratigraphic unit precludes the need for a separate unit between Monteagle and Bangor.

In northeastern Alabama the Monteagle and Bangor Limestones are differentiated because of the Hartselle Sandstone between them (Thomas, 1972a, p. 22). East of the pinch-out of Hartselle Sandstone in Alabama, a contact between Bangor and Monteagle cannot be reliably traced, and the carbonate sequence can be identified best as Monteagle-Bangor undifferentiated (Thomas, 1972a, p. 22). Use of Monteagle-Bangor undifferentiated is a practical approach to the present problem of subdivision of the carbonate facies in northwest Georgia.

On the southeast, the clastic facies contains several stratigraphic units that have not been precisely defined. The lower part of the sequence has been called Floyd Shale, and the Floyd rests on either Fort Payne Chert or its facies equivalent, the Lavender Shale Member. The Lavender does not constitute a single distinctive member within the Fort Payne; rather it appears to be a laterally equivalent facies that intertongues with the entire Fort Payne Chert.

In Floyd County, the Lavender or Fort Payne is overlain by a distinctive limestone unit that has been included within the Floyd Shale (Cressler, 1970, p. 47). Presumably the limestone unit in the lower part of the clastic facies is a tongue of the lower part of the carbonate facies. However, because the limestone unit cannot be traced or precisely correlated to the carbonate sequence, it should be referred to as an unnamed limestone member of the Floyd Shale or as a new formation, rather than as one of the named units of the carbonate sequence (fig. 5).

Above the limestone unit the Floyd Shale is mainly shale and contains a few thin beds of sandstone and limestone. The shale sequence grades upward into a sandstone unit that has been called Hartselle. However, the sandstone is not physically continuous with the Hartselle Sandstone of Alabama but is separated from the Hartselle by a wide area in the carbonate facies of northwest Georgia and northeast Alabama. Therefore, the name Hartselle is inappropriate for the sandstone in the clastic facies in Georgia; however, no formal name is presently available (fig. 5).

The sandstone unit is overlain by a tongue of the Bangor Limestone, and the Bangor is overlain by a shale unit in the stratigraphic position of the Pennington. Thus, the Pennington both on the northwest and southeast overlies Mississippian limestone and is overlain by sandstone and shale that are generally considered to be Pennsylvanian.

LITHOSTRATIGRAPHY

MAURY SHALE

The Maury Shale is a thin, extensive, distinctive unit at the base of the Mississippian System in Alabama, Tennessee, and Georgia (Hass, 1956, p. 23; Conant and Swanson, 1961, p. 66). The Maury consists of partly silty to sandy green and gray shale. The rocks are commonly glauconitic, and the formation characteristically contains phosphatic nodules (Wheeler, 1955; Conant and Swanson, 1961, p. 63). In Georgia, the formation is generally less than 2 m thick.

FORT PAYNE CHERT

In weathered outcrops the Fort Payne Chert typically consists of light-colored chert in nodular beds less than one-fourth meter thick. The formation in northwest Georgia has a maximum thickness of more than 60 m (fig. 4). Much of the bedded chert evidently has been concentrated by the present weathering cycle from siliceous carbonate rocks. Cherty dolostone and cherty limestone (microfacies 5, 6, and 8 of McLemore, 1971, p. 99; fig. 6) make up much of the formation. Parts of the formation include quartz geodes which contain relict anhydrite replaced by quartz and calcite (Chowns, 1972, p. 90). The weathered Fort Payne Chert commonly contains molds of echinoderm columnals and other fossils. The Fort Payne Chert of northwest Georgia is part of a regionally extensive cherty facies that extends westward through the Fort Payne Chert of northern Alabama and Mississippi and is possibly continuous farther west with the upper part of the Arkansas Novaculite of the Ouachita Mountains in Arkansas (Thomas, 1972b, p. 96; 1977a, p. 16). In Georgia, the Fort Payne grades eastward into the Lavender Shale Member.

TUSCUMBIA LIMESTONE

The Tuscumbia Limestone is characterized by bioclastic limestone that contains relatively abundant nodules of chert. Chert appears to be scattered randomly through the formation, and no persistent marker beds have been defined. Beds of lime mudstone and finely crystalline dolostone are common; dolomitic mudstones locally contain calcite pseudomorphs after gypsum (McLemore, 1971, p. 102). Argillaceous limestone and thin beds of calcareous shale are rare. The formation ranges from approximately 35 to 65 m in thickness (fig. 4).

The contacts of the Tuscumbia with the underlying Fort Payne Chert and the overlying Monteagle Limestone are gradational. The bedded chert of the Fort Payne contrasts with the nodular chert of the Tuscumbia. The contact between the Tuscumbia and Monteagle is a regional upward change from cherty limestone to generally noncherty oolitic limestone. The contact is arbitrarily placed above the highest cherty lime mudstone and below the lowest thick oolitic limestone (McLemore, 1971, p. 102). However, the sequence above the arbitrary contact includes some thin cherty limestone, and thin beds of

MICROFACIES DESCRIPTION	DEPOSITIONAL ENVIRONMENT
1 Echinoderm grainstone and sparry echinoderm packstone	Shallow marine, outer platform of carbonate bank High current energy
2 Sparry bryozoan packstone and muddy bryozoan packstone	Protected shallow marine, inside bars (barrier rim) Low current energy
3 Oolitic grainstone and sparry oolitic packstone	Shallow marine, shoals or bars High current energy
4 Skeletal wackestone	Shallow marine, protected lagoon Low current energy
5 Mudstone (lime mudstone)	Shallow marine, lagoon between oolite shoals Low current energy
6 Dolostone	Shallow marine shelf, supratidal
7 Muddy skeletal packstone	Shallow marine, protected lagoon Low current energy
8 Dolomitized limestone	Partial dolomitization of shallow marine limestone

FIGURE 6.—Chart showing microfacies of Mississippian carbonate rocks in George (modified from McLemore, 1971).

oolitic limestone are present in the Tuscumbia. The contact as defined may not be practical for detailed mapping.

MONTEAGLE-BANGOR LIMESTONES

In the absence of a traceable contact between subdivisions, the upper part of the carbonate facies in Georgia is herein considered as Monteagle-Bangor Limestones undifferentiated. The Monteagle-Bangor sequence ranges from 135 to 275 m in thickness (fig. 4) and is mainly oolitic and bioclastic limestone (microfacies 1, 2, and 3 of McLemore, 1971; fig. 6). Thick beds of oolitic limestone are commonly crossbedded. The sequence includes beds of lime mudstone. Thin beds of dolostone and dolomitic limestone make up a small part of the unit, and dolostone locally contains scattered gypsum crystals. Chert nodules in thin intervals are scattered throughout the Monteagle-Bangor. Some cherty zones apparently extend laterally for short distances, but none are so extensive as to provide stratigraphic markers.

The Monteagle-Bangor sequence includes a few beds of argillaceous limestone and calcareous shale. The shaly intervals commonly are no more than 10 m thick and include limestone interbeds. Shale interbeds appear to be randomly distributed throughout the sequence. Two shaly zones in the lower (Monteagle) part of the sequence apparently extend at least 25 km along the Pigeon Mountain syncline. In northeastern Alabama, a shaly zone marks the middle Monteagle (Thomas, 1972a, p. 21), but that zone cannot be traced into Georgia. Locally, east of the pinch-out of the Hartselle Sandstone in Alabama, a thin shale marks the same stratigraphic horizon; but, the shale unit has limited extent (Thomas, 1972a, p. 42). Most of the shaly intervals appear to have limited lateral extent in Georgia. Some shaly zones in the upper part of the succession locally contain thin beds of sandstone.

The upper part of the limestone sequence generally includes beds of gray calcareous shale and maroon and green mudstone, and the Monteagle-Bangor grades upward into the Pennington Formation. In southern Tennessee and northeastern Alabama, a distinctive dolostone unit marks the base of the Pennington (Ferguson and Stearns, 1967, p. 58; Thomas, 1972a, p. 84). Although the upper part of the Bangor in Georgia includes some dolostone beds, the marker unit has not been identified.

PENNINGTON FORMATION AND RACCOON MOUNTAIN FORMATION ABOVE NORTHWESTERN CARBONATE FACIES

Overlying the carbonate facies is a sequence of fine-grained clastic sediments approximately 65 to 130 m thick (fig. 4). The lower part of the sequence, the Pennington Formation, is characterized by maroon and green shale and mudstone. Impressions of fenestrate bryozoans are abundant. The maroon and green mudstone grades up into dark-gray shale. The upper part of the sequence includes beds of siltstone and fine-grained sandstone, but locally the upper part contains maroon mudstone like that of the lower part. The upper, characteristically dark-gray, sandstone-bearing part of the sequence evidently belongs to the Raccoon Mountain Formation as used in Tennessee (Culbertson, 1963, p. E56).

The Pennington-Raccoon Mountain contact is within a gradational sequence that includes a variety of vertical arrangements of rock types. The Tennessee Division of Geology defines the top of the Pennington as the top of the highest limestone or maroon and green mudstone (Milici, 1974, p. 118). The Raccoon Mountain Formation contains gray shale, sandstone, and coal. Sandstone units in the Raccoon Mountain appear to be laterally discontinuous. Siderite nodules are common in the shale units. On Sand Mountain (Dade County), the formation contains several coal beds. The overlying massive bluff-forming sandstone is formed by different stratigraphic units in different places (Wilson, 1965, p. 28).

LAVENDER SHALE MEMBER OF FORT PAYNE CHERT

The Lavender Shale Member of the Fort Payne Chert consists of dark-gray calcareous shale and dark-gray argillaceous lime mudstone. The calcareous rocks weather to light-gray, greenish-gray, and yellowish-gray shale and mudstone, and the type section of the member consists of weathered shale (Butts, *in* Butts and Gildersleeve, 1948, p. 44; Cressler, 1970, p. 45). Petrographic work shows that the typical rock of the Lavender, where unweathered, is as much as 75 percent carbonate (Hurst, 1953, p. 218).

The Lavender does not constitute a single unit within the Fort Payne, and beds of Lavender rock types are distributed randomly within the Fort Payne Chert interval (Cressler, 1970, p. 47). The Lavender includes discontinuous beds of chert. Thickness of the argillaceous rocks increases toward the east as the thickness of rocks typical of the Fort Payne Chert decreases. Beds of argillaceous rocks are rare in the Fort Payne west of the Peavine anticlinorium, but farther east, the Lavender replaces most of the Fort Payne. The facies boundary between Lavender and Fort Payne apparently is a very irregular north-trending line through the Floyd synclinorium. On the Rome fault block in Polk County, thin intervals of Fort Payne Chert are found in scattered small thrust slices, and the Fort Payne is replaced eastward across Polk County by the Lavender Shale Member (Cressler, 1970, p. 41).

Near the depression of the Floyd synclinorium, the Lavender Shale Member apparently is nearly 80 m thick (fig. 4). It is not clear whether the top of the Lavender is equivalent to the top of the Fort Payne or whether the Lavender also includes equivalents of some younger beds.

UNNAMED LOWER LIMESTONE OF CLASTIC FACIES

The lower part of the interval that commonly has been mapped as Floyd Shale is a limestone unit in the depression of the Floyd synclinorium. The limestone may be more than 180 m thick (fig. 4). The lower limestone unit is characterized by bioclastic limestone, some of which contains coarse bioclasts. The unit also includes gray-black, very argillaceous lime mudstones that are similar to the Lavender Shale Member. Some of the bioclastic limestone contains black nodular chert. The very argillaceous lime mudstone within the sequence of bioclastic limestones suggests intertonguing with the clastic facies. Farther south, on the Rome fault block in Polk County, the lower part of the Floyd is shale (slate), and evidently the limestone grades southward to shale.

FLOYD SHALE

The Floyd is characteristically dark-gray to black shale, part of which is calcareous and part of which is carbonaceous. The Floyd Shale above the unnamed lower limestone apparently is as much as 290 m thick (fig. 4). Locally the shale contains siderite nodules, and at one locality in northwestern Polk County pyritic nodules in the shale contain fossils (Cressler, 1970, p. 48). The Floyd includes thin beds of siltstone, sandstone, and limestone. Around Rocky Mountain, the unnamed lower limestone is overlain by calcareous shale; but, around Little Sand Mountain north of Rocky Mountain, the unnamed lower limestone member of the Floyd is overlain by a sandstone unit approximately 11 m thick (fig. 4). The sandstone is characteristically fine grained but the lower part commonly is very fine grained and argillaceous. The lower part of the sandstone consists of thin ripple-laminated sandstones that have thin clay partings. Small unidentified plant fragments lie on bed surfaces.

UNNAMED SANDSTONE AT TOP OF FLOYD SHALE

Most of the Floyd Shale sequence contains relatively little sandstone, but the shale grades upward into a sandstone unit. The sandstone is fine to very fine grained and commonly is interlaminated with clay. The sandstone unit throughout most of its extent appears to be less than 20 m thick (fig. 4); however, it is reported to be about 90 m thick on Judy Mountain west of Rome (Cressler, 1970, p. 48). Because the outcrop on Judy Mountain is isolated by erosion from other exposures of the sandstone, correlation of the much thicker sandstone on Judy Mountain with the thinner sandstone elsewhere is uncertain.

BANGOR LIMESTONE TONGUE OF SOUTHEASTERN CLASTIC FACIES

The limestone interval within the southeastern clastic facies is as much as 200 m thick, but that interval includes beds of shale and sandstone (fig. 4). The Bangor tongue includes bioclastic limestone and argillaceous lime mudstone. Part of the bioclastic limestone contains nodules of dark-colored chert. The argillaceous lime mudstone weathers to massive clay that contains numerous impressions of fenestrate bryozoans. Clastic beds within the Bangor tongue consist of dark-gray clay shale and fine-grained sandstone, generally in thin wavy beds having partings of shale. The limestone interval and the sandstone-shale interbeds indicate repeated intertonguing of the clastic and carbonate facies.

PENNINGTON FORMATION OF SOUTHEASTERN CLASTIC FACIES

Above the Bangor Limestone tongue is a dark-colored shale in the stratigraphic position of the Pennington Formation (fig. 4). The lower part of the Pennington includes thin beds of brown-weathered claystone which contains molds of brachiopods; the claystone may be weathered from argillaceous limestone. The upper part of the Pennington includes thinly bedded sandstone and shale in which sandstone generally increases in abundance upward. Some sandstone beds have micaceous, carbonaceous laminae on top. Siderite nodules are common in parts of the shale sequence. The Pennington Formation interval generally coarsens upward and grades upward into a sandstone unit. Although correlation of the sandstone unit above the shale is uncertain, it may be considered to mark the base of the Raccoon Mountain Formation.

RACCOON MOUNTAIN FORMATION OF SOUTHEASTERN CLASTIC FACIES

The sandstone at the base of the Raccoon Mountain Formation forms a prominent ledge on Rocky Mountain and Little Sand Mountain in Floyd and Chattooga Counties. The sandstone unit is locally more than 50 m thick (fig. 4) and consists of very fine to fine-grained slightly argillaceous sandstone. The beds are characteristically thin; some are ripple laminated. Carbonaceous, micaceous laminae mark the tops of sandstone beds, and clay partings are common. Toward the top of the unit, the sandstone is more quartzose. Echinoderm columnals, bryozoan fragments, and possible brachiopod fragments are preserved in one sandstone bed. The sandstone is overlain by dark-colored shale, similar to the dark-colored shale below the sandstone unit. The upper shale interval is as much as 120 m thick (fig. 4) and includes thin beds of sandstone and a few thin beds of limestone. Thin coaly beds are found in the lower part; siderite nodules are common in the upper part of the shale. The shale at the top of the Raccoon Mountain Formation is overlain by massive bluff-forming sandstone, part of which contains quartz pebbles.

POSSIBLE FACIES TRANSITION

The carbonate and clastic facies in Georgia are distinct, but details of the facies transition are obscure. However, a section exposed around Sand Mountain in Catoosa County east of Ringgold shows features that suggest the nature of the facies transition. Because of complicated structure in the area, different authors have reported different thicknesses and stratigraphic sequences for Mississippian rocks (Allen, 1950; Windham, 1956; McLemore, 1971). The problem is mainly one of recognizing stratigraphic units, particularly the sandstone or sandstones.

The section is mainly limestone, but the lower part is dominated by the Lavender Shale facies rather than the Fort Payne Chert (fig. 4). Above the Mississippian limestone sequence is a thin interval of maroon, green, and gray shale of the Pennington Formation. The Pennington is overlain by massive bluff-forming sandstone that contains quartz pebbles and that is considered to be Pennsylvanian. Between the Lavender and Pennington, most outcrops are limestone. On Sand Mountain, a sandstone unit is exposed within the east-dipping limestone sequence; and west of Sand Mountain on Cherokee Ridge, a sandstone is exposed within the east-dipping limestone sequence. On the assumption that the Hartselle Sandstone is the only sandstone within the limestone sequence in northwest Georgia, both the sandstone on Cherokee Ridge and the sandstone on Sand Mountain have been called Hartselle. That correlation requires that a thrust fault has duplicated the section between Sand Mountain and Cherokee Ridge and that the Mississippian section is 300 to 350 m thick (Windham, 1956; McLemore, 1971, p. 239).

The sandstone on Cherokee Ridge is a distinctive light-gray fine-grained quartzose sandstone that is thick bedded to massive. Where exposed on Cherokee Ridge, this sandstone appears to be at least 15 m thick. The sandstone on Cherokee Ridge is associated with an interval of shale and sandstone which is more than 30 m thick (Allen, 1950, p. 150). In contrast, the sandstone on Sand Mountain is a brown slightly argillaceous fine-grained sandstone characterized by thin, irregular beds, some of which are ripple laminated. Clay partings are common. The contacts between the sandstone on Sand Mountain and the adjacent limestones are not exposed, but the interval that contains the sandstone apparently is not more than 12 m thick.

Both lithologic characteristics and thickness distinguish the sandstone on Sand Mountain from that on Cherokee Ridge. Evidently the two sandstones are not the same but represent two different sandstone tongues within the carbonate facies. Following that interpretation, the amount of implied structural duplication is reduced. The thickness of Mississippian rocks may be nearly 500 m (fig. 4). Whereas a thickness of 300 to 350 m is anomalously thin for the Mississippian in Georgia, a thickness of 500 m is intermediate between that of the carbonate facies and the maximum for the clastic facies.

The possible relationship of the two clastic tongues in the limestone sequence to the Floyd Shale farther south in the Floyd synclinorium has not been established. The section on Sand Mountain east of Ringgold has some characteristics of the southeastern clastic facies but it is dominated (above the Lavender at least) by carbonate rocks similar to those of the northwestern carbonate facies. Regardless of interpretation of details, the section on Sand Mountain contains a large amount of carbonate rock and is more like the northwestern carbonate facies than the southeastern clastic facies. Facies strike, therefore, crosses structural strike along the western north-trending branch of the Floyd synclinorium where the clastic sequence of the depression grades northward into the intermediate or carbonate sequence on Sand Mountain.

PALEONTOLOGY

BIOSTRATIGRAPHY

The oldest formation in the Mississippian of northwest Georgia is the Maury Shale which overlies the Late Devonian Chattanooga Shale. Regional correlations based on conodont studies show that the Maury is of Kinderhook age and that the upper beds are probably Osage (Hass, 1956).

The Fort Payne Chert contains a fauna of corals and brachiopods characteristic of the Keokuk and Burlington Formations of the standard Mississippian section of the Mississippi Valley (Butts, *in* Butts and Gildersleeve, 1948, p. 44). Among the typical fossils reported from the Fort Payne are "*Hadrophyllum ovale, Zaphrentis* cf. *Z cliffordana, Z. compressa,* large crinoid stems, one-half inch or more in diameter, *Athyris lamellosa, Chonetes shumardanus, Linoproductus ovatus, Dictyoclostus* (*Productus*) cf. *D. crawfordsvillensis, D.* cf. *D. inflatus, D.* cf. *D. viminalis, Spirifer, leidyi* type, *Spirifer rostellatus*" (Butts, *in* Butts and Gildersleeve, 1948, p. 44). Cressler (1970, p. 42) collected *Torynifer* cf. *T. pseudolineata, Leptogonia* cf. *L. analoga Brachythyris* cf. *B. suborbicularis, Spirifer* sp., *Cleiothyridina*? sp., echinoderms, and corals from the Fort Payne of Polk County.

The Lavender Shale Member of the Fort Payne Chert contains a bryozoan and brachiopod fauna which also demonstrates equivalence to the Burlington-Keokuk (Butts, *in* Butts and Gildersleeve, 1948, p. 44). From the Lavender Shale Member, Butts (*in* Butts and Gildersleeve, 1948, p. 44) tentatively identified "*Dictyonema* sp., *Cystodictya linearis, Hemitrypa* near *H. nodosa, Fenestrellina burlingtonensis, Fenestralina* near *funicula, F. multispinosa, F. regalis, F.* near *F. rudis, Brachythyris subcardiformis*?, *Cleiothyridina glenparkensis, Dictyoclostus* (*Productus*) *burlingtonensis, Phaethonides spinosus.*" The Lavender Shale Member in Polk County has yielded *Brachythyris* sp., other brachiopods, *Cypricardella* or *Cypricardinia* sp., other pelecypods, *Sinuitina*? sp., other gastropods, and echinoderms (Cressler, 1970, p. 43). The trilobite, *Australosutura georgiana,* has been described from the Lavender Shale Member near Ringgold (Rich, 1966) and has been collected from the Fort Payne Chert in Alabama (McKinney, 1969).

The name Tuscumbia Limestone is now applied to the cherty limestone beds which Butts (*in* Butts and Gildersleeve, 1948, p. 45) referred to the St. Louis Limestone. Like most of the other formation names that Butts extended from the Mississippi Valley section into Alabama and Georgia, the St. Louis was recognized mainly on the basis of its fossil fauna. Thus, the unit was traced as a biostratigraphic zone rather than as a lithostratigraphic formation. The Tuscumbia (St. Louis) in Georgia is characterized by the presence of two species of corals, *Lithostrotionella castelnaui* and *Lithostrotion proliferum* (Butts, *in* Butts and Gildersleeve, 1948, p. 46). No fossils diagnostic of Warsaw and Salem have been reported from the section in Georgia, and Butts (*in* Butts and Gildersleeve, 1948, p. 42) concluded that a hiatus separates Fort Payne and St. Louis. However, the lower Tuscumbia in Alabama contains a Warsaw-Salem fauna (Drahovzal, 1967, p. 14). The lithologic succession in Georgia does not require an unconformity, and possibly the lack of Warsaw-Salem fossils is a result of factors other than a hiatus.

The Monteagle-Bangor Limestones contain a characteristic Genevievian-Chesterian fauna. Butts (*in* Butts and Gildersleeve, 1948, p. 3–79) listed fossils representative of the Ste. Genevieve, Gasper, Golconda, and Glen Dean from the sequence now assigned to the Monteagle-Bangor. The units Butts understood as formations are now defined as time-stratigraphic units in Illinois (Swann, 1963). The succession is divided into Genevievian (Ste. Genevieve), Gasperian (Gasper), Hombergian (Golconda-Glen Dean), and Elviran (post-Glen Dean) Stages (Swann, 1963, fig. 1). Because the definition of a formation used by Butts and others of his time was based on index fossils, the formations are directly comparable with time-stratigraphic subdivisions. Thus, Butts' work provides a time-stratigraphic correlation with the Mississippi Valley section.

The Monteagle contains the Ste. Genevieve guide fossil, *Platycrinus penicillus* (Butts, *in* Butts and Gildersleeve, 1948, p. 46; McLemore, 1971, p. 115). Gasper forms reported from Georgia include *Talarocrinus, Campophyllum gasperense, Pentremites pyriformis, P. godoni,* and *Agassizocrinus ovalis* (Butts, *in* Butts and Gildersleeve, 1948, p. 47). Lithostrotionoid corals, similar to the characteristic forms of the St. Louis, are found in association with Gasper faunas in the limestone sequence in northwest Georgia (Butts, *in* Butts and Gildersleeve, 1948, p. 47) and in the Floyd Shale (Broadhead, 1975, p. 33). The value of lithostrotionoids as guides to the Meramec may be questioned in light of these associations. Beds equivalent to the Golconda are marked by *Pterotocrinus capitalis* (Butts, *in* Butts and Gildersleeve, 1948, p. 47).

The Bangor contains a distinctive Glen Dean fauna including *Pentremites cherokeeus, P. spicatus, Archimedes communis, A. meekanus, A. swallovanus, Fenestrellina cestriensis, F. serrulata, F. tenax, Prismopora serrulata, Septopora subquadrans, Polypora cestriensis, Composita subquadrata,* and *Spiriferina transversa* (Butts, *in* Butts and Gildersleeve, 1948, p. 48). A collection from an outcrop of the Bangor Limestone and Pennington Formation northwest of Rising Fawn includes *Pterotocrinus tridecibrachiatus, P. edestus,* and *Pentremites gutschicki*; these forms indicate age equivalence of the upper Bangor to the Kinkaid Limestone of the Illinois basin (Waters and Chowns, 1977).

Fossils from the Floyd Shale include an age range of Meramec to Chester; index fossils are listed by Broadhead (1975, p. 30–31) as:

- Chester undifferentiated
  - *Cleiothyridina sublamellosa*
  - *Reticulariina spinosa*
  - *Spirifer leidyi*
  - *Pentremites* (*godoni* and *pyriformis* groups)
  - *Agassizocrinus*
  - *Zeacrinites*
- Middle Chester
  - *Cravenoceras*
  - *Tylonautilus*
- Lower Chester
  - *Talarocrinus*
  - *Lyrogoniatites*
  - *Neoglyphioceras*
- Meramec
  - *Cystelasma*
  - *Lithostrotionella*
  - *Lithostrotion proliferum*
  - *Perditocardinia dubia*
  - *Forbesiocrinus*

Some assemblages from the Floyd contain forms characteristic of two successive stages; for example, one assemblage contains both the Lower Chesterian goniatite *Lyrogoniatites* and the Middle Chesterian goniatite *Cravenoceras* (Broadhead, 1975, p. 32). Broadhead (p. 32) concludes that these assemblages are from beds very near the stage boundary. The oldest fauna in the Floyd Shale includes both *Cystelasma* and *Perditocardinia dubia* which have been reported from the Salem Limestone (Broadhead, 1975, p. 34). The limestone unit within the lower Floyd contains *Talarocrinus* which is distinctive of the Gasper (Butts, *in* Butts and Gildersleeve, 1948, p. 51). Butts (*in* Butts and Gildersleeve, 1948, p. 51) reported fossils distinctive of St. Louis and Gasper from the Floyd east of Ringgold; however, the section at that locality is mainly limestone like the Tuscumbia and Monteagle. Fossils collected from the Floyd Shale in western Polk County include *Lyrogoniatites newsomi georgiensis, Goniatites* cf. *G. kentuckiensis,* and *Neoglyphioceras georgiensis* which indicate an Early Chester age (Crawford, 1957, p. 46; Cressler, 1970, p. 49).

The youngest fossils from the Floyd are compatible with an age assignment that is equivalent to the Haney (upper Golconda) Limestone (Broadhead, 1975, p. 35). Within the clastic sequence, the sandstone at the top of the Floyd Shale has been assumed to be equivalent to the Hartselle Sandstone of Alabama, and the sandstone is overlain by a limestone that has been considered to be a tongue of the Bangor Limestone. The Bangor Limestone in the carbonate facies of northwest Georgia and Alabama contains a Glen Dean fauna; and, because of its position below the Bangor, the Hartselle Sandstone of Alabama has been assumed to be equivalent to the Hardinsburg Sandstone of the Mississippi Valley (Butts, 1926, p. 195). Limestone within the clastic sequence in northeastern Chattooga County has yielded specimens of *Pentremites robustus* which indicates age equivalence to Haney or Glen Dean (J. A. Waters, written commun., 1978).

PALEOECOLOGY

Fossil faunas indicate marine environments for Mississippian sediments in northwest Georgia. The carbonate facies of northwest Georgia is characterized by a brachiopod-bryozoan-echinoderm-coral fauna that indicates an open-marine-shelf environment. Echinoderm fragments are associated with rock types that denote high current energy. (McLemore, 1971, p. 49). Rock types that suggest low current energy contain relatively large concentrations of bryozoans (McLemore, 1971, p. 104). Reeflike clusters of corals are less than 1 m in height and width (Owen, 1955).

Broadhead (1975, 1976) has defined and characterized five communities of marine benthic organisms within the Floyd Shale (fig. 7). Definition of the communities has been based on the recognition of a few groups of animals, and each of the communities may show much faunal diversity (Broadhead, 1975, p. 42; 1976, p. 268). Communi-

COMMUNITY	CHARACTERISTICS	ROCK TYPES	INTERPRETATION
(1) *Lingula*	Low faunal diversity; *Lingula*; bryozoans, articulate brachiopods; fragments of terrestrial plants	Bioturbated sandy siltstone and silty shale	Prodelta or distal delta front
(2) Bivalvia-Spiriferida-Productidina	High faunal diversity; *Inflatia, Spirifer, Phestia, Aviculopecten*; bryozoans, echinoderms, gastropods; fragments of terrestrial plants	Silty shale to argillaceous limestone	Restricted bays
(3) Fenestellidae	Low faunal diversity; *Fenestella, Archimedes*; brachiopods	Calcareous shale to siltstone	Bay, distal prodelta, mudbank
(4) *Pentremites*-Spiriferida-Fenestellidae	High faunal diversity; *Pentremites, Composita, Cleiothyridina, Spirifer, Reticulariina, Inflatia, Michelinia*; crinoids, gastropods, pelecypods, bryozoans	Calcareous shale to lime mudstone	Open marine shelf
(5) *Michelinia*-Rugosa	Low faunal diversity; *Michelinia, Pentremites*; crinoids, brachiopods	Lime mudstone to bioclastic and oolitic limestone	Carbonate bank

FIGURE 7.—Chart showing marine benthic communities in the Floyd Shale (modified from Broadhead, 1975, 1976).

ties 1, 2, and 3 reflect various components of a prograding delta, whereas communities 4 and 5 are associated with transgressive carbonate units that suggest delta destruction. Although understanding of the distribution of communities is complicated by complex structure and some uncertainty in stratigraphic position, communities 1 and 2 are most common on the south and east, and community 5 is restricted to the north and west (Broadhead, 1976, p. 272). Community 4 is widely distributed, but community 3 is relatively uncommon (Broadhead, 1976, p. 272). The evident distribution pattern suggests that a delta system prograded northward and (or) westward onto a marine shelf and that episodically delta lobes were abandoned and reworked. At a locality in Catoosa County, east of Ringgold, an oolitic and skeletal limestone containing community 5 is overlain by about 1 m of silty limestone and siltstone that contains fragments of a terrestrial plant (Broadhead, 1975, p. 60; 1976, p. 271). The plant-bearing beds are overlain by calcareous shale and limestone containing community 4. This locality is in the probable area of facies transition and apparently is indicative of numerous, abruptly bounded tongues of the southeastern clastic facies within the carbonate facies.

DEPOSITIONAL AND TECTONIC FRAMEWORK

The major facies of Mississippian rocks in northwest Georgia were deposited in two different depositional regimes. On the northwest is a carbonate-shelf sequence and on the southeast is a fine-clastic sequence of prodelta and delta-front sediments. Intertonguing of the carbonate and clastic facies results from migration of the prograding delta front and episodic transgression of the carbonate shelf facies over the deltaic sediments (fig. 4). The northwestern corner of Georgia remained in the carbonate-shelf regime throughout most of the Mississippian. In latest Mississippian an extensive complex of clastic sediments prograded over the carbonate facies.

The thinness and mineralogy of the Maury Shale suggest very slow accumulation of clastic sediments (McLemore, 1971, p. 99), and the Fort Payne Chert indicates the initial deposition of Mississippian carbonate sediments on the shallow-marine shelf. The association of dolostone and relict evaporites in the Fort Payne reflects a sabkha environment (Chowns, 1972, p. 90). On the east, the argillaceous limestone and calcareous shale of the Lavender Shale Member are evidently the most distal part of a sediment dispersal system and probably were deposited in deeper water off the shallow shelf (fig. 8*A*). The broad area of mixing of carbonate and clastic sediments in the Lavender suggests that no abrupt shelf edge had formed.

The Tuscumbia cherty limestones were deposited in an open-marine-shelf environment (fig. 8*B*). The Tuscumbia probably is correlative with at least the lower part of the lower limestone member of the Floyd Shale. If we assume that correlation, the Tuscumbia and related limestones extend farther east than part of the Fort Payne Chert and represent a

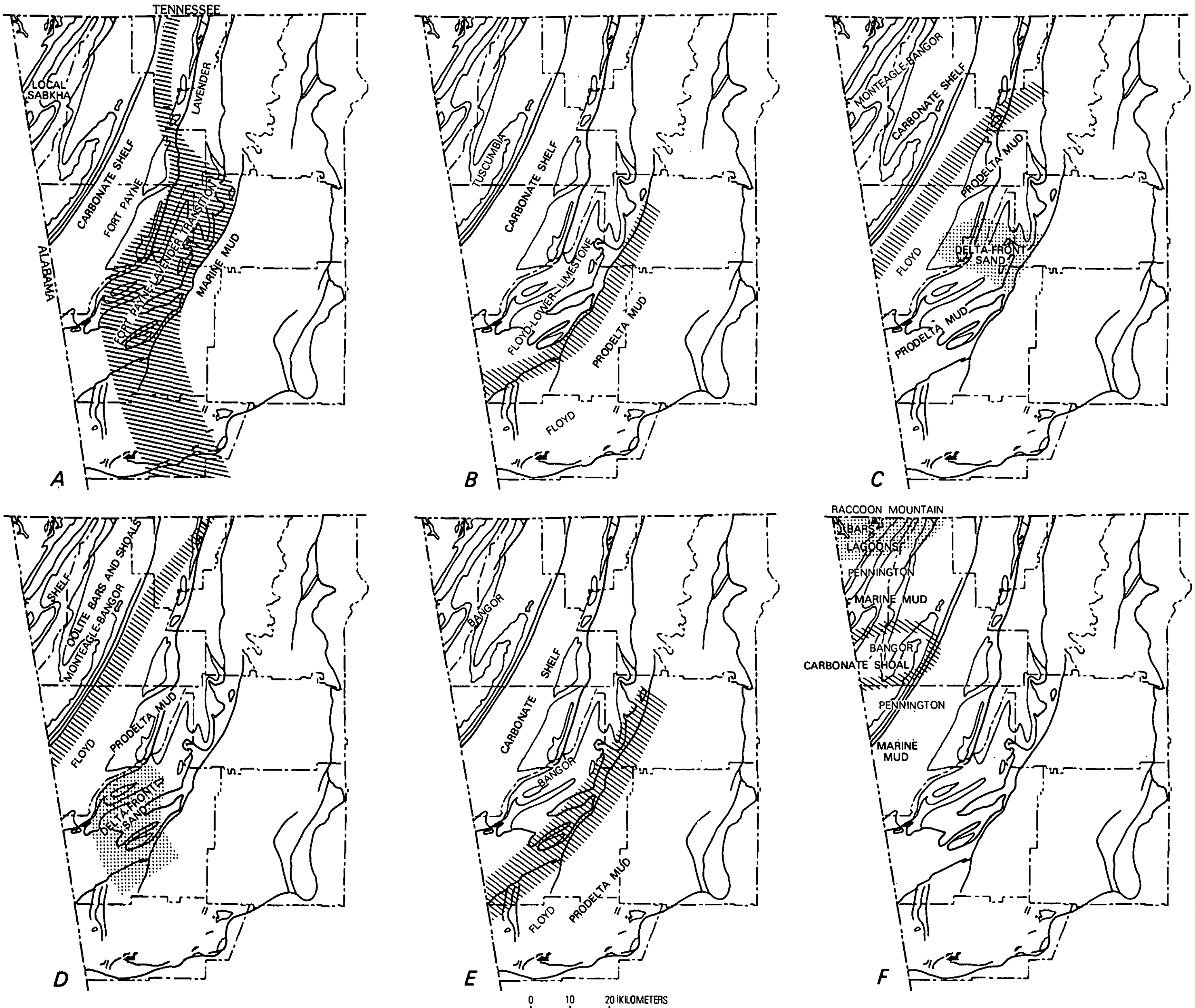


FIGURE 8.—Generalized lithofacies and paleogeographic maps of Mississippian rocks in northwest Georgia. Approximate stratigraphic position of each map is shown by letter on cross sections in figure 4. Line pattern indicates approximate area of facies transition. *A*. Fort Payne Chert/Lavender Shale Member. *B*. Tuscumbia Limestone/unnamed lower limestone/Floyd Shale. *C*. Lower part of Monteagle-Bangor Limestones/Floyd Shale. *D*. Middle part of Monteagle-Bangor Limestones/unnamed sandstone/Floyd Shale. *E*. Upper part of Monteagle-Bangor Limestones/Bangor Limestone tongue in clastic facies/Floyd Shale. *F*. Pennington Formation/Raccoon Mountain Formation/top of Bangor Limestone.

transgression of the shallow-marine shelf over the muddy sediments of the Lavender.

The Monteagle-Bangor sequence demonstrates persistence of the carbonate shelf (fig. 8*C*, 8*D*, and 8*E*). The sequence is mainly composed of oolitic and bioclastic limestones that indicate high-current energy on shoals and bars of a carbonate bank (McLemore, 1971; fig. 6). Lime mudstones and muddy bioclastic limestones indicate deposition on the shelf in protected lagoons between oolite shoals. Rare dolostones suggest local supratidal areas on the shelf. Rare beds of shale represent the most distal outwash from laterally equivalent clastic facies.

On the southeast, the fine clastic sequence of the Floyd Shale consists mainly of prodelta muds (fig. 8*C*). Benthic faunal communities in the Floyd suggest distal prodelta, delta front, and marine-bay environments (Broadhead, 1975; 1976; fig. 7). On the Rome fault block, prodelta shales rest directly on Fort Payne Chert (compare fig. 8*A* with fig. 8*B*). Farther northwest, the prodelta shales overlie the lower limestone member of the Floyd (compare fig. 8*B* with fig. 8*C*). The lower limestone is evidently equivalent to the lower part of the carbonate facies, presumably Tuscumbia and part or all of Monteagle. These relations indicate northwestward progradation of the prodelta sediments onto the carbonate shelf. Argillaceous zones within the lower limestone indicate pulses in the general progradation.

Sandstone units in the Floyd Shale are delta-front sands (fig. 8*C* and 8*D*). The sequence locally coarsens upward from shale into sand through a fine-grained ripple-laminated sand. The upper part of each sand unit is generally more thick bedded and quartzose. At least two different sandstone units are present: one just above the lower limestone unit, the other at the top of the Floyd (fig. 4).

Because of the small outcrop area and poor exposures, insufficient data are available to define the extent of the sandstone units, and details of geometry of the delta-front facies are unknown. The deltaic sediments locally prograded northwestward, and distribution of facies demonstrates that clastic sediment was transported into the area south and east of the carbonate facies. Presumably the preserved delta-front sediments were supplied through a fluvial system, but the orientation of the fluvial system and the location of the source of the sediment presently cannot be defined.

Other Mississippian clastic facies in the region indicate similar deltaic deposition, and for some of these the directions of progradation are better defined. On the west in Alabama, a deltaic sandstone-shale sequence in the Parkwood Formation progrades northeastward onto the western part of the Bangor Limestone (Thomas, 1972a, p. 81; 1974, p. 196). Along Appalachian synclines in Alabama the Parkwood deltaic sandstones reach their maximum eastward extent but apparently are limited to the west of the Georgia-Alabama State line. Thus, the sandstone units in the Floyd Shale of Georgia evidently are not continuous with the Parkwood sandstones presently exposed in Alabama. Furthermore, the most extensive Parkwood sandstones are in the upper part of the Mississippian section in Alabama, and the most extensive sandstones in the section in Georgia appear to be older.

To the north in Tennessee, a clastic sequence of Pennington, Raccoon Mountain, and younger units progrades southwestward over the Mississippian carbonate facies (Ferm and others, 1972, fig. 3). However, that clastic wedge progrades over the Bangor Limestone in Georgia and is younger than the deltaic sandstones of the Floyd (fig. 4). Older Mississippian clastic rocks are preserved locally in the Greasy Cove Formation in eastern Tennessee (Neuman and Wilson, 1960); but, because of limited exposure, the original extent of that unit is unknown.

Possibly the fluvial system that fed the deltaic facies in Georgia originated in the same provenance as did the Parkwood system of Alabama or in the same provenance as did the Greasy Cove clastic rocks on the north in Tennessee. Either source requires a long fluvial system outside (on the south or east) the limits of presently preserved Mississippian strata in Georgia. Alternatively, the sandstones in Georgia may have had local sources to the south or east. Regardless of the location of the sediment source, preserved rocks in Georgia are in the prodelta and delta-front facies (fig. 8*C* and 8*D*). No sediments of the delta plain have been recognized.

An extensive tongue of Bangor Limestone indicates marine transgression over the deltaic sandstone facies (fig. 8*E*). The contact between the sandstone and overlying transgressive limestone is not exposed, and details of destructional reworking of the abandoned delta lobe cannot be defined on the basis of available data. Within the limestone tongue another shale-sandstone unit indicates another pulse of delta progradation that was followed by delta destruction and deposition of the upper part of the limestone.

The Bangor grades upward into marine shale of the Pennington, and the Pennington grades upward from maroon and green mudstone to gray shale. The upper part of the shale sequence contains siderite nodules and carbonaceous beds as well as sandstone interbeds. The Pennington-Raccoon Mountain sequence represents the transition from marginal marine to bay and lagoonal sediments (fig. 8*F*). A few local bar sands are included. The fine-grained clastic sequence is overlain by massive sandstone of a barrier complex (Ferm and others, 1972). The clastic sediments in the upper part of the Mississippian in Georgia are part of a large-scale clastic wedge that prograded southwestward over the Mississippian carbonate facies (Thomas, 1974, p. 205; 1977b, p. 1258).

PENNSYLVANIAN STRATIGRAPHY OF NORTHWEST GEORGIA

By Howard R. Cramer

LITHOFACIES

Pennsylvanian sedimentary rocks are confined to Chattooga, Dade, Walker, Catoosa, and Floyd Counties (figs. 3 and 9), and have been summarized in three major regional studies (Wanless, 1946; Stearns and Mitchum, 1962; McKee and others, 1975). The rocks are almost entirely clastic and are, in approximate order of abundance: sandstone, siltstone, shale, coal, clay (as underclay), and siderite (also called ironstone). Some of the clastic rocks are cemented by carbonate. Very little limestone is known.

Coal is the major economic resource of the Pennsylvanian rocks, and has been the subject of many reports. The works of McCallie (1904) and Johnson (1946) remain the most comprehensive studies of the coal and enclosing rocks to date, although much detail can be gleaned from the publications of the U.S. Geological Survey and the U.S. Bureau of Mines.

EVOLUTION OF STRATIGRAPHIC NOMENCLATURE

Coal-bearing rocks have long been known from Georgia. Maclure's map (1809) showed the rocks to be Secondary in age (following the Wernerian scheme), and his text alluded to coal. Williams' map (*in* White, 1849) showed the rocks to be Transition in age (still following the Wernerian scheme) and outlined two distinct coal terranes, one in Dade County and the other in Walker County. Hayes (1892) was the first to subdivide the Pennsylvanian rocks of Georgia. He recognized two distinct units, the Lookout Sandstone below and the Walden Sandstone above.

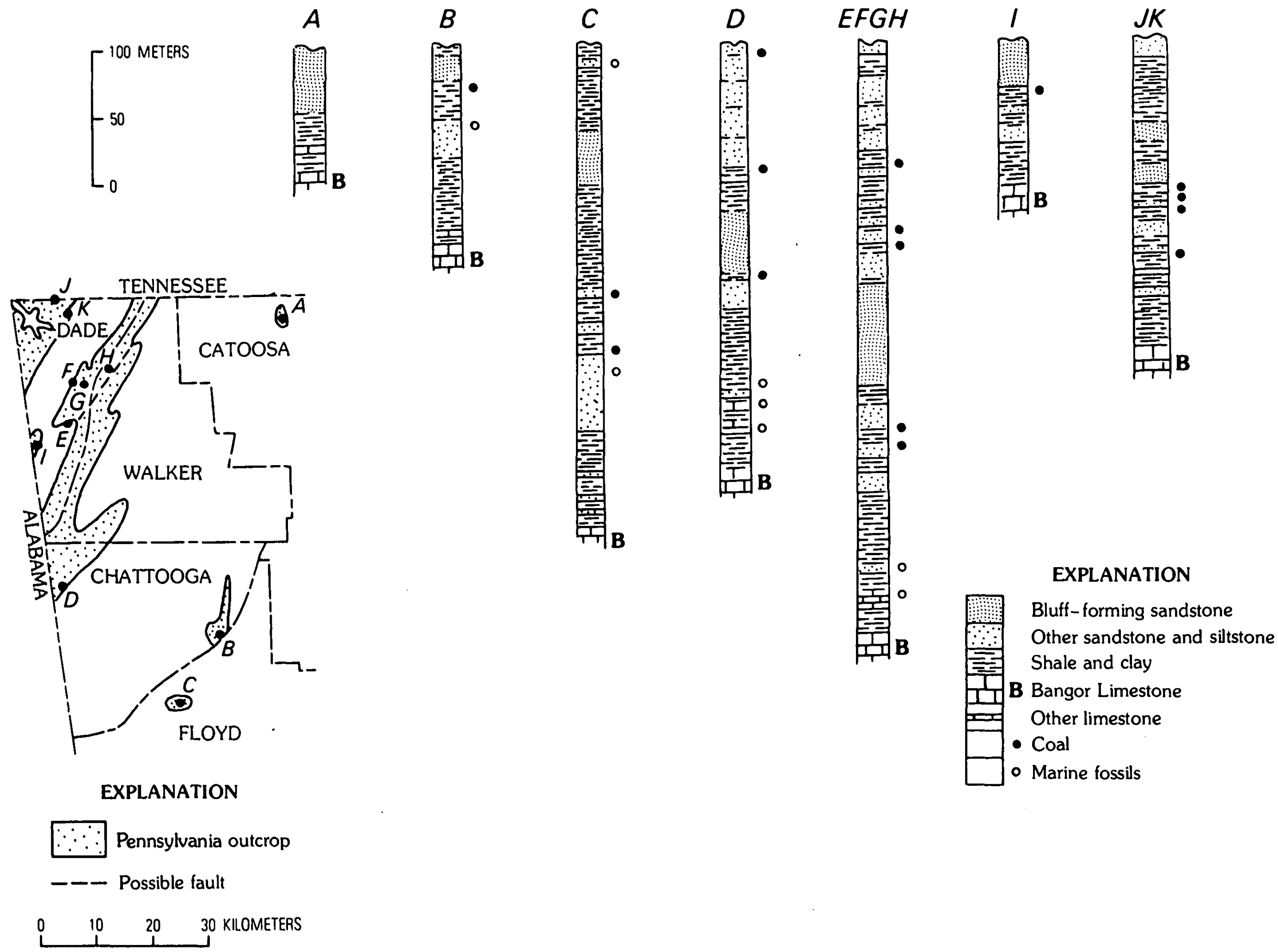


FIGURE 9.—Generalized columnar sections showing Pennsylvanian and Mississippian rocks above the Bangor Limestone.

Other studies of Pennsylvanian rocks in nearby States, notably Alabama and Tennessee, have resulted in nomenclature which has been later introduced for the rocks of Georgia. Culbertson (1963) summarized the history of Pennsylvanian nomenclature in Georgia.

More recently, the U.S. Geological Survey Pennsylvanian paleotectonic study (McKee and others, 1975) included much data about the Pennsylvanian of Georgia; the rocks are included in the stratigraphic category of Interval A. The stratigraphic nomenclature has been deliberately simplified for regional comprehension.

Most recently, the geologic map of Georgia (Georgia Geological Survey, 1976) has been revised, and the twofold subdivision of the rocks proposed by Hayes (1892) has been retained. Figure 10 shows the nomenclature that has been used for the Pennsylvanian rocks of Georgia. Because the rock succession consists of alternating units of sandstones and gray shales and siltstones, the identification and tracing of a common reference unit is difficult, causing much confusion in the nomenclature. The figure shows: (a) That there have been numerous interpretations for the same rocks, (b) that uncertainties exist even in the most recent interpretations, and (c) why the nomenclature used in this report has been simplified.

In order to avoid introducing any new names into what is intended to be a summary, no formal stratigraphic nomenclature is used in this report; all of the rocks are Early Pennsylvanian, or Pottsvillian in age.

Generally, the Pennsylvanian of Georgia is exposed in sandstone-capped plateaus and mountain tops, and these topographic features can be used for reference. Three categories of Pennsylvanian rocks can be recognized: (a) Massive bluff-forming sandstone on the brow of the plateaus at the top of steep slopes. Massive sandstone may be found in the rocks below the bluff-forming sandstone, giving the impression of two sandstone bluffs. In these places, notably near Cloudland, the upper one is considered the bluff-forming sandstone. (b) Rocks stratigraphically, and general topographically, above the bluff-forming sandstone. (c) Rocks below the bluff-forming sandstone exposed in the steep slopes of the plateaus and above the Mississippian Monteagle-Bangor Limestones.

This threefold subdivision is used entirely for reference, and no stratigraphic correlation is intended. For instance, the bluff-forming sandstone is probably not everywhere the same continuous stratigraphic unit. It has been called by different researchers in different places, the Flat Rock Sandstone, the Warren Point Sandstone, the Sewanee Conglomerate, the Lookout Sandstone, or the Bon Air Sandstone.

LITHOSTRATIGRAPHY

Correlation problems result from many factors, economic, topographic, and stratigraphic.

During the years when the stratigraphy of the area was being defined, coal mining was not extensive, and was entirely underground, providing few or no maps of value to the modern stratigrapher. Now strip mining is taking place, although only in very limited areas.

Topographically, problems result from the generally poor exposures on the talus-covered steep slopes of the plateaus and on the flat terrane of the plateau surfaces. Sandstone or conglomerate forms the brow of the plateaus, and as many similar-appearing sandstones and conglomerates are in the section, visual tracing is the only way to correlate one rock unit with another.

Stratigraphically, correlation is difficult because: (a) Measured sections taken from the literature are often incomplete because of the topographic difficulties cited, or are very old and not sufficiently detailed for modern stratigraphic interpretation. (b) Sections often encompass several miles of horizontal traverse to include but a few hundred feet of vertical section. In view of the rapid horizontal facies changes known, such sections, if presented vertically, would be misleading. (c) Almost all of the previous correlations have been based upon the assumption that the rocks are in continuous blankets, especially the coal seams. The rocks are now suspected to be of deltaic or littoral origin, and as such would have very limited horizontal continuation. (d) The common occurrence of sedimentation features such as pebble beds and zones, crossbedding, flaser bedding, and so on, both in horizontal and vertical context, make the use of these features extremely sensitive for correlation over any but immediate outcrop distances. (e) Almost no paleontological data are available except for a few floral lists from uncertain stratigraphic and geographic localities (just enough to show the rock to be Early Pennsylvanian). (f) Uncertain, but probable, structural complexities in the region may have juxtaposed distinctly different stratigraphic or sedimentologic units.

Another correlation problem relates to the base of the Pennsylvanian System, at its contact with the

UNDERLYING ROCKS	PENNSYLVANIAN ROCKS	AUTHOR AND DATE
Upper Sub-Carboniferous	Coal Measures	Little 1876
Bangor Limestone	Lookout Sandstone; Walden Sandstone	Hayes 1892
Pennington Formation	Pottsville Formation	Georgia Div. of Mines, Mining and Geology 1939
Pennington Formation	Lookout Formation: Unnamed; Lower Conglomerate; Unnamed; Upper Conglomerate — Walden Formation	Moore and others 1944
Pennington Formation	Lookout Formation: Gizzard Member; Sewanee Member — Whitwell Shale; Bonair Sandstone; Vandever Shale; Rockcastle Sandstone	Johnson 1946
Pennington Formation	Lee Group: Unnamed; Warren Point Sandstone; Gizzard Formation; Sewanee Conglomerate; Whitwell Shale; Eastland Sandstone; Newton Sandstone	Wanless 1946
Pennington Formation	Carboniferous (on map) Pennsylvanian (in legend) Pottsville Formation (in text)	Butts and Gildersleeve 1948
Pennington Formation	Pottsville Series New River Group	Stearns and Mitchum 1962
Pennington Formation	Gizzard Formation: Raccoon Mountain Formation; Warren Point Sandstone; Signal Point Shale — Crab Orchard Mountains Group: Sewanee Conglomerate; Whitwell Shale; Newton Sandstone; Vandever Shale; Rockcastle Sandstone	Culbertson 1963
Pennington Formation	Gizzard Group: Norwood Cove Formation; Flat Rock; Warren Point Sandstone; Signal Point Shale — Crab Orchard Mountains Group: Sewanee Conglomerate	Wilson 1965
Pennington Formation	Interval A_2	McKee and others 1975
Pennington Formation	Lookout Sandstone: Gizzard Formation; Sewanee Conglomerate — Pennsylvanian undifferentiated	Georgia Geological Survey 1976
Rocks below bluff-forming sandstone	Bluff-forming sandstone — Rocks above bluff-forming sandstone	This paper

FIGURE 10.—Correlation chart showing the evolution of Pennsylvanian nomenclature in Georgia.

underlying Mississippian System. The actual level of the contact in the succession of rocks below the bluff-forming sandstone is unclear, and has been much discussed in the literature; in some places the bluff-forming sandstone may be Mississippian.

The rocks below the bluff-forming sandstone are predominantly shale containing bedded sandstone and coal (fig. 9). The sandstones may be well developed and several meters thick. A small amount of nodular and laminar siderite is found in some localities. The paleobotanical data are sparse; only a few plants and no palynomorphs have been described. Only recently have marine invertebrates been discovered in these rocks immediately below the bluff-forming sandstone, and these have not yet been evaluated. These rocks have been called the Raccoon Mountain Formation, the Gizzard Formation, and the lower part of the Lookout Sandstone.

Underlying this sandstone and shale sequence is another sequence of clastic rocks, mainly shale, but including limestone, a little sandstone, and a small amount of coal and siderite. These clastic beds contain, in some localities, unquestioned Mississippian marine fossils, and are generally included in the Pennington Formation. These rest upon unquestioned marine limestones of the Monteagle-Bangor sequence.

The contact between the clastic Pennington rocks and the clastic rocks overlying them is not obvious in the field. Some geologists separate the two sequences on the basis of unconformity, but because of the nature of the sedimentation, there are several unconformities within them. Other geologists separate the two sequences on the basis of lithology, but it can be shown that the lithology of each formation is not unique, and the exposures are generally poor. Still other geologists would separate the two sequences on the basis of fossils, but fossils are sparse.

Accordingly, in the following discussion, and on figure 9, these rocks are not separated, but are included together in the clastic sequence known as the "rocks below the bluff-forming sandstone" and above the Monteagle-Bangor Limestones.

For the above reasons, it seems prudent to describe the Pennsylvanian rocks of Georgia purely as vertical lithologic successions and to avoid any horizontal correlation. Cores are important because they show the true vertical sequence and lithology of the sediments. Unfortunately, some of the more important sedimentary characteristics needed for correlation are not recovered from cores, particularly sedimentary structures and their orientation. Core data are used wherever possible in the following discussions, and are supplemented by data from nearby outcrops where possible.

The following discussions of Pennsylvanian rocks are taken from the most recently-published geologic map of Georgia (Georgia Geological Survey, 1976), from the published accounts from which the map was prepared, and from fieldwork by the authors.

PENNSYLVANIAN ROCKS ON SAND MOUNTAIN, CATOOSA COUNTY

Sand Mountain in Catoosa County (fig. 9, locality A) contains a small outlier of Pennsylvanian rocks preserved in a syncline at the northern part of the Floyd synclinorium. Pennsylvanian rocks underlie only a few hundred square meters at the crest of the mountain.

No cores are known. The section illustrated in figure 9 is taken from two sources. The upper part, the bluff-forming sandstone, is taken from Allen (1950, p. 158), and the lower part, rocks below the bluff-forming sandstone, are from McLemore (1971, p. 239). The section is at the crest of the mountain.

The bluff-forming sandstone consists entirely of massively bedded, crossbedded, conglomeratic quartz sandstone, 46 m thick. It has been called the Pottsville by Allen (1950), the Lookout Sandstone by Hayes (1894) and Cressler (1963), and on the present geologic map of the State (Georgia Geological Survey, 1976). McLemore (1971) called these rocks the Raccoon Mountain Formation.

The rocks below the bluff-forming sandstone are poorly exposed, but are entirely shale, 29 m thick. In this area, the rocks were called the Pennington Formation by Allen (1950) and Mc Lemore (1971) and were considered Mississippian in age.

No coals are known, and the basis for considering the bluff-forming sandstone Pennsylvanian is entirely its stratigraphic position. No fossils are reported from the Pennington Formation at this locality, and its age is considered Mississippian on the basis of its regional distribution and stratigraphic position.

PENNSYLVANIAN ROCKS ON LITTLE SAND MOUNTAIN, CHATTOOGA COUNTY

Pennsylvanian rocks are mapped as constituting the entire mountain, and are preserved in the Floyd synclinorium (fig. 9, locality B). These are among the least known Pennsylvanian rocks in Georgia, and to this date, no measured section has been published. A brief description by Spencer (1893, p. 127) is the only published account:

> a remnant of the Coal Measures occurs on Little Sand Mountain, which rises from 300 to 500 feet above the valley.

The lower part of the mountain consists of shale succeeded by sandstone, which are massive, but in layers of moderate thickness. The surface of the southern end of the mountain forms a basin, drained by Mill Creek, which cascades over a ledge of sandstone 15 or 20 feet thick. Descending the little chasm of the horse-shoe falls, there is a layer of rock, more or less shaly, having a thickness of 15 inches, through which a dozen seams of coal are scattered, each with a thickness of a quarter or half an inch. From this plateau a ridge extends some miles northward, composed of the same rock. No other coal is known upon it other than that just described.

The section illustrated in figure 9 has been compiled from field reconnaissance, topographic maps and aerial photographs, and from a generalized description of part of it given by Mc Lemore (1971, p. 246). All the rocks described are from the southern part of the mountain.

The beds overlying the Monteagle-Bangor Limestones and below the bluff-forming sandstone consist of about 121 m of clastic rocks, the lower 56 m of which are mainly gray and green shale containing siderite nodules and fenestrate bryozoans. Overlying this shale sequence is about 30 m of thin-bedded, flaggy, fine-grained sandstone which contains a marine fauna of fenestrate bryozoans, echinoderm columnals, and possibly brachiopods; this fauna has not yet been evaluated.

Overlying this sandstone is a poorly exposed section of about 35 m of gray shale.

The bluff-forming sandstone apparently rests unconformably upon the gray shale, is about 15 m thick, is massively bedded at the base, and more thinly bedded toward the top. The quartz sandstone contains discrete beds of conglomerate containing quartz pebbles as much as 1 cm in diameter.

The bluff-forming sandstone is overlain by an unknown thickness of gray shale that fills the bowl of the basin at the southern end of the mountain; the sandstone forms the rim. The shale is at least 10 m thick.

Mc Lemore (1971, p. 246) considered the clastic rocks above the Bangor Limestone and below the thin-bedded, fine-grained sandstone to be the Mississippian Pennington Formation, and the thin-bedded, fine-grained sandstone to be the basal sandstone in the Raccoon Mountain Formation. The 1939 geologic map of the State (Georgia Div. Mines, Mining, and Geology, 1939) showed all the rocks above the shale to be Pottsville as did Cressler (1970). The most recent geologic map of the State (Georgia Geological Survey, 1976) has the rocks mapped as Pennsylvanian undifferentiated.

For this report, the lowermost clastic rocks are considered Mississippian on the basis of regional facies considerations and paleontology. The bluff-forming sandstone is considered Pennsylvanian only on the basis of its stratigraphic position.

PENNSYLVANIAN ROCKS ON ROCKY [ROCK] MOUNTAIN, FLOYD COUNTY

Rocky Mountain, called Rock Mountain on the 7½-minute quadrangle, contains an outlier of Pennsylvanian rocks preserved in a syncline within the Floyd synclinorium (fig. 9, locality C).

Natural exposures on the rugged slopes are extremely poor, resulting in very limited and incomplete knowledge of the section from surface exposures. Recently, however, the Georgia Power Co. has investigated the mountain in regard to construction of a pump-storage facility, and has taken numerous cores. The section illustrated in figure 9 is prepared from several of these cores which overlap to form a complete section. The top of the section is within a few feet of the top of the mountain, both topographically and stratigraphically.

The lowermost 75 m of rocks, those above the Bangor Limestone, are mainly shale containing beds of limestone and carbonatic sandstone, with a few thin seams of coal near the top. Above these beds are about 55 m of thin-bedded, fine-grained sandstone which forms ledges or steps on the slope of the mountain, and which contains marine fossils.

This ledge-forming, thin-bedded, fine-grained sandstone is overlain by 120 m of gray shale containing a few beds of sandstone, some of which are fossiliferous.

Above this shaly sequence is about 40 m of bluff-forming sandstone which is massively bedded, cross-bedded, channeled, and medium to coarse grained; it is somewhat thinner bedded toward the top, and conglomeratic throughout. This unit forms the prominent scarp around the top of the mountain.

Over the bluff-forming sandstone is a gray shale sequence, 63 m thick, which contains a few beds of carbonatic, medium-grained, arkosic sandstone, and a marine fauna of gastropods, pelecypods, orthoconic nautiloids, fenestrate bryozoans and brachiopods.

Published accounts of the rocks on Rocky Mountain are unclear about the nomenclature used for the rocks below the bluff-forming sandstone. The lower, shaly part regionally resembles the Pennington Formation of Mississippian age, but no basis exists for an age assignment for the fine-grained sandstone nor for the bluff-forming sandstone and the rocks above it except for the marine fossils which have not yet been evaluated. No coals other than the thin seams mentioned are known. The bluff-forming sandstone is generally considered to be Pottsville on the basis of its lithology and stratigraphic position.

PENNSYLVANIAN ROCKS ON PIGEON MOUNTAIN AND ON THE SOUTHERN PART OF LOOKOUT MOUNTAIN, CHATTOOGA, DADE, AND WALKER COUNTIES

Lookout Mountain and Pigeon Mountain together form a sigmoidal-shaped, flat-topped plateau west of the Peavine anticlinorium. Because the section on the southern part of Lookout Mountain is different from the section on the northern part, and because a structural discontinuity may be between them, it seems practical to discuss the two parts of the mountain separately; the rocks on Pigeon Mountain are continuous with the rocks on the southern part of Lookout Mountain. The line of distinction between the northern and southern parts of Lookout Mountain appears to trend northeastward (figs. 3 and 9) from the narrow constriction between the two to the place where the fault intersects the eastern brow of the mountain.

The well-known coal deposits on Lookout Mountain have been much studied in the past, and numerous sections have been measured, but none is complete because of the poor exposures everywhere except on the brow of the plateau. Fortunately the U.S. Gypsum Co. has drilled some cores on the mountain for the purpose of finding evaporites in the underlying Mississippian limestone, and these holes pass through the entire Pennsylvanian section in that locality.

The most complete of these cores, and the one used for figure 9, locality D, is near the community of Cloudland, at an altitude of 443 m.

The beds between the Monteagle-Bangor Limestones and the bluff-forming sandstone are 150 m thick. The lower 110 m are mainly shale containing some fossiliferous limestone beds near the base. The upper 40 m are mainly quartz sandstones with interbedded shale; the sandstones form ledges, some very pronounced on the steep slopes, so that two bluffs are present. Coal is associated with the uppermost sandstone and shale.

Hobday (1974, p. 217–218) provided a measured section of some of these strata from the brow of the plateau nearby. He described the bluff-forming sandstone and the sandstone-shale interval immediately below, and provided an interpretation of the sedimentary environment. From his description, the presence of two potential bluff-forming sandstones can be deduced:

> *** The lower 300 feet of this outcrop consists of upward coarsening sequences, between 8 and 40 feet thick, composed of shale and siltstones with minor sandstones. Overlying these is a vertical sequence of eight orthoquartzite bodies averaging 10 feet in thickness, separated by siltstone averaging one foot in thickness. The sandstones are both massive and low-angle planar cross-bedded and are cut into their upper part by channels up to 15 feet deep, which contain bedding types similar to those in the unchanneled portions. . . . Separated from the top of these sandstones by 50 feet of silty shale are two superimposed orthoquartzite complexes which clearly illustrate the mutually perpendicular relation between the trough cross beds and the long, low-angle planar cross beds. The overlying upward-coarsening "bay-fill" sequence of siltstone, with horizontally bedded sandstones and a highly carbonaceous shale on top, is capped by low-angle planar cross-bedded sandstones ***

The bluff-forming sandstone, at the top of the steep slope, is 47 m thick, massive conglomeratic, crossbedded, and contains a few thin shale lenses.

The rocks over the bluff-forming sandstone are mainly sandstone containing shale beds and are about 110 m thick. Immediately over the bluff-forming sandstone one of the shale sequences is about 12 m thick.

The beds below the bluff-forming sandstone, and immediately above the Bangor Limestone, are generally mapped as the Pennington Formation, and the beds above these, but still below the bluff-forming sandstone, are mapped as the Gizzard Formation or the lower part of the Lookout Formation.

The bluff-forming sandstone has been mapped as the Sewanee Conglomerate and the Lookout Sandstone; it has been mapped as Pennsylvanian undifferentiated on the present State geologic map, and the rocks above the bluff-forming sandstone have been mapped as Walden Sandstone or as Pennsylvanian undifferentiated.

Several well-developed coal seams are in this section; two are above the bluff-forming sandstone, called the Tatum and Sewanee seams. The one below the bluff-forming sandstone is known as the Cliff seam. All have been mined sporadically, but all are discontinuous.

PENNSYLVANIAN ROCKS ON THE NORTHERN PART OF LOOKOUT MOUNTAIN, DADE AND WALKER COUNTIES

This part of Lookout Mountain is northwest of the line running northeastward from the narrow constriction of Lookout Mountain (figs. 3 and 9). These rocks contain immense reserves of coal and have been extensively investigated. Because of the incomplete exposures, however, no continuous section is known; the section in figure 9 is a composite, from four different localities.

The lowermost rocks were described by Sullivan (1942, p. 26) from Johnson Crook (fig. 9, locality E); they rest upon Bangor Limestone, are mainly shale, are 123 m thick, and contain some limestone beds. They are generally mapped as the Pennington Formation.

Above these are some rocks described by Wanless (1946, p. 24) from the west brow of Lookout Mountain just east of Trenton (fig. 9, locality F). They are 43 m thick, are mainly gray shales containing, ledge-forming sandstone beds, some very pronounced, and have a discontinuous coal seam near the top. These have been mapped as the Gizzard Formation, as part of the Lookout Sandstone, and as Pennsylvanian undifferentiated on the current State geologic map.

The bluff-forming sandstone rests upon these. Part of this section described above (Wanless, 1946, p. 24) fig. 9, locality F) can be seen in the core described by Johnson (1946) from nearby. The bluff-forming sandstone is very massive, crossbedded, channeled, conglomeratic, and coarse-grained quartzose; it is 70 m thick. It has been mapped as the Warren Point Sandstone, the Sewanee Conglomerate, the Lookout Sandstone, the Bon Air Sandstone, and as Pennsylvanian undifferentiated on the current State geologic map.

Above the bluff-forming sandstone are 182 m of shale containing beds of sandstone and coal. The sandstones are finer grained and are more evenly bedded and widespread than those below. The illustrated section is from a core described by Johnson (1946) and from a section measured by Wanless (1946, p. 31). The individual sandstone and shale units have been given different names by different workers, but they have been collectively called the Walden Formation or Pennsylvanian undifferentiated (fig. 9, localities G and H).

The rocks above the bluff-forming sandstone have been dated as Medial Pottsville on the basis of paleobotany. No fossils are known from the bluff-forming sandstone nor from the beds immediately below; the beds called the Pennington Formation have been dated as Late Mississippian on the basis of marine fossils and regional considerations.

PENNSYLVANIAN ROCKS ON FOX MOUNTAIN, DADE COUNTY

Fox Mountain, the northeastern part of which is in Dade County, is a small outlier of the much larger Sand or Raccoon Mountain. The rocks are preserved in the trough of a syncline, and are the least known of the Pennsylvanian rocks of northwest Georgia.

The section illustrated (fig. 9, locality I), is taken from McCallie (1904, p. 73) and from a field reconnaissance. The rocks above the Monteagle-Bangor Limestones are poorly exposed, but appear to be about 69 m of varicolored shale at the base and gray shale toward the top. Limestones are interbedded toward the base, and sandstones are interbedded toward the top. A thin, relatively persistent coal seam is at the top, immediately under the bluff-forming sandstone.

The bluff-forming sandstone forms the top of the plateau. It is medium to coarse grained, very conglomeratic, massive to thin bedded, channeled, and crossbedded. It is at least 33 m thick, though the top is nowhere exposed.

No fossils are known. The age of the rocks below the bluff-forming sandstone are probably Mississippian on the basis of regional considerations and stratigraphic position. The bluff-forming sandstone is probably Pennsylvanian.

PENNSYLVANIAN ROCKS ON SAND MOUNTAIN, DADE COUNTY

Sand Mountain in Georgia is a part of a much larger feature known as Sand or Raccoon Mountain in Alabama and Tennessee. The rocks are preserved as the trough of a broad syncline, forming a plateau, into which obsequent streams have incised deep valleys.

The section in figure 9 is composite, from two different localities. Most of the section is from Scratch Ankle Hollow (fig. 9, locality J), actually in Tennessee, measured by Wilson (1965, p. 36–38), and the lowermost part of the section is from an uncertain location identified only as Hooker (fig. 9, locality K) by McLemore (1971, p. 221). The Scratch Ankle Hollow section contains the type sec-much resemble the upper beds of the Bangor Lime-tion of the Raccoon Mountain Formation as identified by Wilson, Jewell, and Luther (1956).

The lowermost 32 m of gray shale in the composite section rests upon Bangor Limestone, and McLemore referred to these beds as being within what he called the Pennington Formation. What McLemore considered to be the lower part of the Pennington Formation contains beds which very much resemble the upper beds of the Bangor limestone of this report.

Above the 32 m of gray shale are shale and sandstone beds 106 m thick (Wilson, 1965, p. 36–38) which contain several commercial coal seams. Mc-

Lemore (1971) included some of these rocks within what he called the upper part of the Pennington Formation in the section which he measured. These rocks have been called by others the Lookout Sandstone, Gizzard Formation, Raccoon Mountain Formation (the type section), and the Norwood Cove and Flat Rock Formations. One of the sandstones in this part of the section thickens and becomes the bluff-forming sandstone elsewhere on Sand Mountain (Wilson, 1965, p. 28).

The composite nature of this part of the section results in uncertainty about the thickness; the Hooker section has an uncertain top, and the Scratch Ankle Hollow section has an uncertain base. This results in an uncertain amount of overlap in the two measurements. Reference to other published sections from nearby (McCallie, 1904; Spencer, 1893; Troxell 1946) show the irregularity of deposition of the beds and why the correlations have been so chaotic. Ferm and others (1972) described the sedimentary circumstances under which these beds could have been deposited, if true, would explain why the problems are present.

The bluff-forming sandstone is 39 m thick, massively bedded, conglomeratic, crossbedded, quartz sandstone. This has been called the Flat Rock Sandstone, part of the Gizzard Formation, the Warren Point Sandstone, the Lookout Sandstone, the Sewanee Conglomerate, and Pennsylvanian undifferentiated.

The beds above the bluff-forming sandstone constitute a shale sequence about 30 m thick, overlain by a conglomeratic sandstone about 3 m thick. The sandstone caps the highest hills on Sand Mountain, and is the youngest formation on the mountain in Georgia. These rocks have been called the Walden Formation, the Signal Point Shale, and the Sewanee Conglomerate, respectively.

Paleobotanically, the coal beds below the bluff-forming sandstone contain a flora that is Medial Pottsville in age; the beds below these, which rest upon the Bangor Limestone, contain Mississippian fossils. No fossils are in the rocks above the bluff-forming sandstone.

The coal resources on Sand Mountain are in beds below the bluff-forming sandstone, whereas the coals on the northern part of Lookout Mountain are in beds above the bluff-forming sandstone, yet the coals are the same age, Medial Pottsville.

CORRELATION OF PENNSYLVANIAN ROCKS

It is easy to understand how the twofold subdivision of Pennsylvanian rocks originated (fig. 10). Everywhere a similar-appearing, conglomeratic, bluff-forming sandstone can be seen at the edges of the plateaus, with shale, sandstone and coal underneath, with a distinctly irregular sedimentation pattern, whereas the rocks over the bluff-forming sandstone are clearly more widespread and continuous in distribution, and can be traced with more assurance.

The bluff-forming sandstone and the irregularly disposed rocks below were called the Lookout Sandstone, and the more uniform rocks above the bluff-forming sandstone were called the Walden Sandstone. Later, the rocks below the bluff-forming sandstones were identified as the Gizzard Formation, which contained one sandstone known as the Warren Point; the bluff-forming sandstone was called the Sewanee Conglomerate. The Walden Sandstone was subdivided into three shale and three sandstone formations.

As more data were gathered, the bluff-forming sandstone was found not to be the same unit everywhere; the bluffs were being formed by whichever sandstone happened to be at the level of erosion. Therefore, if different sandstones were found to be the bluff-forming sandstone, then the correlations of the rocks above and below would have to be altered; this accounts for the plethora of terms which have been used for the same rocks. An appreciation of the lateral variation in the rocks below the bluff-forming sandstone would also influence any decision about the correlation of these rocks over long distances.

Furthermore, correlations in the past have been predicated upon the "layer cake" philosophy of stratigraphy, that the units are formed as widespread blankets and can be correlated on the basis of superposition. Results of modern studies show that this concept, particularly for the Pennsylvanian of Georgia, is not valid, for the rocks are distinctly interfingered and not blanketlike.

Correlations in the past have been based partly on the assumption that the coal beds are widespread and that correlation by superposition and (or) lithology was possible. Detailed studies show that the coal beds are very irregularly disposed and distributed. Caution should be exercised when correlating the coal seams.

BIOSTRATIGRAPHY

Little paleontological investigation of the Pennsylvanian rocks of Georgia has been carried out because most of the rocks are nonmarine and fossils are sparse. Most investigations have been paleobotanical.

The first published report of fossil plants was by Lesquereux (1880–84, p. 852) who listed a flora of 27 species from an uncertain locality and stratigraphic position in Dade County. Inasmuch as mining activity at that time was confined to the Etna and Dade coal seams, the flora was probably from the rocks below the bluff-forming sandstone. He correlated this flora with that of the No. XI zone in Pennsylvania, which is now called the Mauch Chunk Formation, of Late Mississippian age.

White (1900, p. 817), on the other hand, noted that the flora of the roof shale of the Dade coal (below the bluff-forming sandstone, and from where Lesquereux's flora may have come) was similar to the flora of the *Mariopteris pottsvillea* zone of elsewhere in the Appalachians; he considered the age of this zone to be Early Pottsville, but not the earliest.

White later (1943), identified *Mariopteris pottsvillea* from rocks over the Castle Rock coal seam (also known as the Etna seam), immediately below the bluff-forming sandstone in Dade County; the Castle Rock seam is a few tens of feet above the Dade coal seam, which also contains the *M. pottsvillea* zone flora in the roof shale.

In the same reference, White (1943) noted *Aneimites tenuifolia difoliatis* and *A. pottsvillensis* var. *intermedia* in the roof shale over the Durham No. 5 coal seam, above the bluff-forming sandstone on the northern part of Lookout Mountain in Walker County. These are also Early Pottsville in age, although not the earliest.

Allen and Lester (1954, p. 131–149) listed and illustrated a curious flora of 23 species from coalmine dumps of uncertain stratigraphic and geographic position, although clearly in rocks above the bluff-forming sandstone. This flora contains species that have much older and much younger ages than the Early Pottsville.

Read and Mamay (1964), in their work on the floral zones of the upper Paleozoic, identified the *Mariopteris pottsvillea-Aneimites* spp. zone as the No. 5 zone in their classification. Zone 5 was according to them, Medial Pottsville, or Early New River in the terms of Appalachian stratigraphers.

Wilson (1965, p. 49) suggested that a coal seam at the base of the Norwood Cove Formation, the base of which he was calling Pennsylvanian, in rocks below the bluff-forming sandstone, contained spores having definite Chesterian (Late Mississippian) affinities.

Wanless (1975, p. 32) concluded that the Pennsylvanian rocks in Georgia are entirely within zones 5 and 6 of Read and Mamay. He noted the presence of elements of floral zone 6 from shale "just above the Sewanee coal on Lookout Mountain". Which coal he meant by the Sewanee is not clear, although in an earlier report (Wanless, 1946), he meant that coal which is in the shale immediately over the bluff-forming sandstone on the southern part of Lookout Mountain. In a later report (Wanless, 1961), he implied that all of the coals above the bluff-forming sandstone in the northern part of Lookout Mountain are the Sewanee, in the sense of the Sewanee coal basin. If this is so, it would include the Durham No. 5 seam, the same seam which contained the species of *Aneimites* noted by White (1943) which were included in floral zone 5 by Read and Mamay (1964).

Detailed biostratigraphic correlations based on paleobotany cannot be made with certainty at this time, but generally the presence of zone 5 and possibly of zone 6 of Read and Mamay seems reasonable. Zones 5 and 6 are entirely in the Pottsville Series, Lower Pennsylvanian, although not the lowest. These correlate with rocks of Morrowan age of the midcontinent region and with rocks of Westphalian-A age of Europe.

Invertebrates from the Pennsylvanian rocks of Georgia are rare. Wanless (1946, p. 32–33) reported a *Lingula*-bearing shale from the rocks overlying the bluff-forming sandstone on the northern part of Lookout Mountain.

Molds of imbricated pelecypod shapes are found in one of the sandstones exposed in a strip mine on Sand Mountain, Dade County, but identification other than the suggestion of beach-environment deposition is not possible.

Brachiopods, fenestrate bryozoans, and crinoid columnals have been found in the thin-bedded, finegrained sandstone unit below the bluff-forming sandstone on Little Sand Mountain in Chattooga County, above beds commonly considered Pennington Formation, but these fossils have not yet been analyzed.

Brachiopods, pelecypods, gastropods, orthoconic cephalopods, and fenestrate bryozoans have been found in a carbonatic, arkosic sandstone from rocks above the bluff-forming sandstone on Rocky Mountain, but these are not well enough preserved for positive identification.

Limestones, which, if present, would not only be a potential source of marine invertebrates, but would make splendid marker beds for the maps in this otherwise clastic-rock terrane, are rare. Only two have been identified, and neither investigated; both are thin and apparently not widespread. Spencer (1893, p. 252) noted a seam of limestone in the shale unit 3.07 to 5.2 m above a coal bed, later to be known as the No. 4 coal, on Lookout Mountain, Walker County. McCallie (1904, p. 41) failed to find this rock, and Wanless (1946, p. 32) reported a covered interval which included the limestone at that part of his measured section.

Another limestone, at least 0.6 m thick, was reported in one of the cores made by the Georgia Power Co. on Rocky Mountain. It is in the rocks above the bluff-forming sandstone; this has not been investigated.

DEPOSITIONAL AND TECTONIC FRAMEWORK

PAST INTERPRETATIONS

The first comprehensive study of Pennsylvanian rocks in Georgia, that of McCallie (1904), does not contain any geological background for the origin of the rocks or of the coals.

The first discussions of the rocks and coals were included in the report of Wanless (1946, p. 129) in which the Pennsylvanian rocks of the entire southern Appalachian Mountains were described. He speculated upon cyclothemic deposition, so common in the rocks of the midcontinent area, and concluded that:

> *** a sort of rhythmic sequence is frequently repeated *** This begins with a massive basal siltstone or sandstone, unconformable on underlying strata. The sandstone grades up into siltstone or sandy shale, and the shale may contain sandstone partings and fossil plants. The siltstone is followed by an underclay which is often divided by shale or siltstone and may have siltstone or sandstone at the top. The coal zone follows, and often includes several benches of coal spread through an interval of as much as 20 feet. The coal zone is overlain by shale which is generally plant bearing in the immediate roof and which may contain ironstone or occasionally impure limestone bands or concretions and may yield fresh- or brackish water fauna and rarely a marine fauna. This may grade up into sandy shale and siltstone to the next higher sandstone, or the sandstone may cut out part or all of the shale and rest on the coal, or even cut out the coal.
>
> There are many resemblances between the rhythms *** here and the cyclothems *** the differences being the obvious results of differences in environment and rates of sedimentation.
>
> *** The Warren Point, Sewanee, Herbert, Newton, Rockcastle *** sandstones are all basal members of such sequences *** at least a considerable part of the sediment was derived from the east or southeast.
>
> Certain districts seem to have been near the points of discharge of large rivers carrying sandy or gravelly sediment.

He further noted (Wanless, 1946, p. 131):

> The sediments all seem to have formed in aqueous environments which include piedmont, valley flat, marsh, lake, delta, lagoon, and shallow sea-floor environments. Even the coarsest sediments are too well sorted with too nearly horizontal bedding surfaces and are too extensive to suggest a piedmont environment adjacent to high uplands *** The coals are evidently of a marsh environment ***
>
> *** A widespread delta plain fronting the sea, with a network of delta lakes, marshes, and lagoons and shifting channels of discharge for the streams seems the most likely type of environment.

As regards the tectonic setting, Wanless concluded (1946, p. 132):

> Adequate sedimentation prevailed during the deposition of the coal measures of the southern Appalachian field. *** [excess sediment was bypassed to a more distant locality] *** If this assumption is correct, the amount of sediment deposited during a particular interval is a measure of the amount of downwarping. The southeastern border of the coal field [including northwest Georgia] was downwarped several thousand feet more than the region of Ohio *** and the rate of downwarping increased southeastward at a uniform rate.

He showed that the basins of deposition formed during the Pottsville, and that great changes in thickness take place within short distances, such as that between the rocks under the bluff-forming sandstone in Sand Mountain and the northern part of Lookout Mountain. Milici (1974) named the Raccoon Mountain basin as the depositional center for the thick section of rocks under the bluff-forming sandstone on Sand Mountain.

Wanless' pioneer work was followed by many studies and interpretations of the sedimentary petrology of the sandstones, mostly of those on the northern part of Lookout Mountain. Renshaw (1951) recognized deltaic and beach sedimentation, and Allen (1955) and Albritton (1955) identified tidal-flat sediments. The latter writer also speculated upon a southeastern source for the sediments. Shotts (1957) showed that the coals on the southern part of Lookout Mountain are in discrete basins, and that they are separated from one another by what he called deltaic variations in sedimentation.

Tanner (1959) first noted, from crossbedding studies, that Pennsylvanian rocks were deposited by currents that were more toward the south than toward the north; he suggested a shoreline toward the north-northeast. Schlee (1963), also, after crossbedding studies, concluded that the Pennsylvanian sandstones are mainly from a fluviatile environment and that the predominant transport direction was toward the southwest. He suggested that the sandstones are from sands deposited on flood plains or in estuaries, and that they are the result of sheets of anastomosing linear sand bodies.

Chen and Goodell (1964) studied the petrography of the bluff-forming sandstone on both parts of Lookout Mountain. They found provenance to have been mainly a crystalline-rock terrane, and the direction of regional transport to have been to the southwest. They suggested a paludal or marginal-continental environment for the sandstones.

Wilson (1965) believed that the Pennsylvanian rocks on Sand Mountain were of terrestrial origin, and saw no clear evidence for the marine origin suggested by Wilson and Stearns (1960). He interpreted provenance as having been highlands to the east or northeast, with small amounts of the sediments possibly having come from as far away as the Canadian Shield. The coals are from freshwater swamps. Boron-trace studies support this interpretation.

The volume on Pennsylvanian paleotectonics of the United States (McKee and others, 1975), the summation of Pennsylvanian stratigraphy to that date, includes much data about the rocks in Georgia. They were deposited in a basin with the source of the sediments having been to the east and northeast, and with the provenance having been a series of welts of mountainous islands, like those which flank the Pacific basin today. The conglomerates, sandstones, and mudstones form a series of detrital wedges. In some areas, sand and mud accumulated without much interruption, but elsewhere, deposition of detritus ceased periodically, and coal beds resulted. The sea is believed to have transgressed periodically from the southwest. Cyclic sedimentation is plainly evident, but cyclothemic conditions are less uniform regionally.

Coarse sediment entered the Appalachian basin, including Georgia, several times during the deposition of Pottsville sediments, a result of erosion and sedimentation caused by contemporaneous tectonism. Whether the alternations between the coarse, conglomeratic sandstones, clay, and coal beds resulted from intermittant renewal of tectonism or from climatic changes cannot be determined from the exposures in Georgia.

The above review of the data and the interpretation shows no unequivocable explanation for the sedimentary environment or tectonic setting for the Pennsylvanian rocks of Georgia. The rocks are neither unquestionably marine nor unquestionably terrestrial.

CURRENT INTERPRETATIONS

More recent investigations of the Pennsylvanian rocks in the Appalachian Mountains in general, and in Alabama and Tennessee in particular, have allowed for interpretations which take into account the uncertainties outlined above—an environment between the marine and the terrestrial, that of the littoral zone, the barrier-island complex, and the lower-delta plain.

During the time that the Pennsylvanian paleotectonics volume was being prepared, new ideas regarding the interpretations of the Appalachians around Georgia were fermenting. John Ferm and his associates and students identified possible depositional environments for the Pennsylvanian rocks of Georgia and vicinity.

The current interpretations were initiated by Stearns and Mitchum (1962) who applied isopach and lithofacies studies to a regional stratigraphic analysis of the Pennsylvanian of the southeastern United States. They noted a belt of high-sand ratios which passed through Georgia, subparallel to the present outcrop patterns, and trended northeast. They suggested no explanation, but it is possible that these belts of high-sand ratios were roughly parallel to the paleoshorelines and that they could have resulted from barrier-island complexes. Considerable evidence now supports this interpretation.

In many places, particularly along the western brow of the northern part of Lookout Mountain, the bluff-forming sandstone is massively bedded, crossbedded, conglomeratic, channeled, and quartzose. The crossbedding is in channels, planar, and trough-like, such as would be expected in a barrier-island complex environment.

In other places, the bluff-forming sandstones are not as massive or conglomeratic; these could be preserved from other parts of the barrier-island complex, such as tidal deltas, washover fans, or dunes. The dark-gray shales and bedded sandstones which accompany the more massive sandstones could be from barrier-island marshes, which were occasionally invaded by the sea or from washover fans or tidal fans from the seaward side, or from terrestrially-derived detritus from the landward side, such as flood plains. Coal could form when these marshes were filled to sea level and a soil could form; if the environment would not support vegetation, ironstone could precipitate. An environment such as this would explain the irregular distribution of the coal and the sandstones, and the frequent intimate mixing of them.

Milici (1974) and Ferm and others (1972) recognized, for instance, from nearby Tennessee and Alabama, rocks from the littoral environment. The coal-bearing sandstone and shale (the Racoon Mountain Formation), from beneath the bluff-forming sandstone are from lagoon complexes that formed behind barrier bars. Tidal deltas, washover fans, and beach deposits are also part of this complex, and the sandstones from these features are interdigitated with the coal-bearing, shaly, lagoon deposits. The shifting of the strand line, whether tectonic or eustatic, resulted in blanket-sandstone deposits (the bluff-forming sandstone) as the bars migrated over the marsh deposits to follow the strand line.

The interpretation that these rocks were deposited in a littoral environment provides an explanation for the correlation chaos; the various units, sandstone, conglomerate, shale, coal, and others, are all interfingered rather than being superimposed. The coals and siderite layers result from a stillstand of the sea when the lagoons were filled to sea level so that they could support the coal-producing vegetation or ironstone-forming conditions.

Thomas (1972a), in a report on the Mississippian rocks of Alabama, recognized that the rocks lying athwart the Mississippian-Pennsylvanian boundary, in part those below the bluff-forming sandstone, are the result of similar depositional environments. The littoral environment prograded southwestward, bringing clastic sediments into and onto the carbonate shelf. Although his discussion does not include Georgia, it could clearly be extrapolated to include the State. Marine rocks are overlain by intercalated clastic rocks of marine and littoral origin. The alternation of marine and littoral environments resulted from strand-line fluctuations throughout the interval.

Thomas' thesis, of a southwestward-prograding clastic lithosome, was supported by the observations of Ferm (1974) who, in speculating about the sedimentary similarities between the Carboniferous rocks of eastern North America, western Europe and Africa, suggested that a landmass somewhere in the North Carolina area shed sediments outward in all directions. Sediments coming to the Georgia area would have been from a metamorphic terrane, as indicated by the petrologic studies, and from the northeast, as suggested by the textural and structural studies.

Hobday (1974) believed that some of the Pennsylvanian rocks of Georgia were deposited in a littoral environment. His studies of one of the orthoquartzite bodies in the section near Cloudland, the one forming the lower bluffs (fig. 9, locality D) on the southern part of Lookout Mountain, show it to be a deposit of a barrier island. The associated shale and coal originated in relation to this feature.

The sedimentary features that distinguish the rocks over the bluff-forming sandstone from those under it on the northern part of Lookout Mountain and on Sand Mountain, Dade County, were noted as early as 1892 by Hayes (1892, p. 50) who used this distinction to create the first subdivision of the Pennsylvanian rocks of Georgia. He noted:

"These upper rocks [those over the bluff-forming sandstone], embraced under the name Walden, are more homogeneous than the Lookout [the bluff-forming sandstone and the rocks under it] and show marks of fewer abrupt changes in conditions of sedimentation."

This same difference was noted by Wanless (1961) when he discussed what he called the Sewanee coal basin. Although his text did not clearly indicate which coal he meant, the environment of deposition that he discussed for the basin was clearly for rocks overlying the bluff-forming sandstone on the northern part of Lookout Mountain. He noted the persistency of these units over large areas, and showed the relations of these deposits to deltaic sedimentation. The regional correlations were based on the flora of the roof shales of some of the coals. He suggested that the basin persisted for the time that several of the coals were deposited, and not just one of them.

The coal deposits on the northern part of Lookout Mountain, those above the bluff-forming sandstone, seem to have a different character from those below the bluff-forming sandstone elsewhere. The coal seams themselves, and the enclosing shales and sandstones, are much more laterally continuous, reflecting a greater geographic area for the depositional environment, and one which was more stable over a longer time than one closer to sea level, where strand-line fluctuations would be reflected in the changes in sedimentation. The thickness of the coals also support the interpretation of a more stable long-lived environment. Such an environment would be found on the delta plain, behind and inland to the littoral, offshore-bar environment.

Therefore, if the tectonic-sedimentation regime which began in the Mississippian, of deltaic progradation over a carbonate sequence, were to have continued into the Pennsylvanian, the resulting vertical sequence of rocks to be expected over the open-marine rocks would be prodelta and delta-front clastic rocks, which in turn would be overlain by deposits of barrier-bar complexes and bar-marsh deposits, which in turn would be overlain by delta-plain deposits in which the coal seams would be thicker and more widespread.

As this appears to be true in Georgia, the systemic boundary between the Mississippian and Pennsylvanian must be in the complex of clastic rocks between the Monteagle-Bangor Limestones of unquestioned Mississippian age and the overlying clastic rocks that contain a Pennsylvanian flora.

MISSISSIPPIAN-PENNSYLVANIAN BOUNDARY PROBLEM

The boundary between Mississippian and Pennsylvanian rocks in Georgia has commonly been assigned to designated marker beds of some description such as at the top of the highest maroon mudstone, below the lowest coal bed, at the base of the massive bluff-forming sandstone, or at the base of the lowest quartz-pebble-bearing sandstone. Although the Mississippian-Pennsylvanian systemic boundary is by definition a time-stratigraphic horizon, the criteria by which it has been identified in Georgia have been rock-stratigraphic.

Fossils in the limestone sequence establish a Mississippian age, and plant fossils demonstrate a Pennsylvanian age in the coal above the massive sandstone. The horizon of the Mississippian-Pennsylvanian boundary must be within the lithofacies transition beds between the limestone and the coal-bearing sequence, and the systemic boundary has commonly been placed at the contact between the Pennington and Raccoon Mountain Formations (Culbertson, 1963; Wilson, 1965, p. 47; Milici, 1974, p. 118). That contact traditionally has been considered to be a regional unconformity (Culbertson, 1963, p. E56), but recent work indicates that the succession is gradational except locally where sandstone at the base of the Raccoon Mountain rests on a scoured surface (Milici, 1974, p. 121). Lack of detailed biostratigraphic data from this part of the section precludes precise identification of the boundary. Spores from a coal bed in the Raccoon Mountain Formation of Alabama have "definite Chesterian affinities" (Wilson, 1965, p. 49), and invertebrate fossils from Raccoon Mountain equivalents in Alabama are Mississippian (Milici, 1974, p. 118). Possibly the systemic boundary is within the Raccoon Mountain Formation.

The rock succession in Georgia suggests continuous sedimentation during deposition of a prograding clastic sequence (fig. 11). The succession above the Mississippian carbonate sequence grades upward from marine and near-shore mudstone to massive barrier and (or) delta-front sandstones. The interpretation that the strata reflect prograding sedimentation implies the identification of time-stratigraphic planes across temporally equivalent facies (fig. 11). Identification of the systemic boundary awaits resolution of a maze of biostratigraphic and lithostratigraphic details.

MINERAL RESOURCES OF THE CARBONIFEROUS ROCKS

COAL

The most valuable mineral deposit in the Carboniferous rocks of Georgia is bituminous coal; it is still being mined after more than 100 years. The first mining took place in Dade County in 1854. In 1891, the first coal was taken from Walker County on Lookout Mountain, and after 1892, when the railroad arrived at Durham, production increased dramatically. By 1900, all of the coal from Georgia was coming from the Lookout Mountain field in Walker County except for one mine still operating on Sand Mountain, in Dade County. The peak year of production was 1903, when 417,000 short tons were taken, mostly from the Durham No. 5 coal.

In 1920, strip mining was introduced to Georgia, and sporadic production continued. Production again increased during World War II, but declined steadily after that, and has been negligible for many years. Currently, production has again increased dramatically.

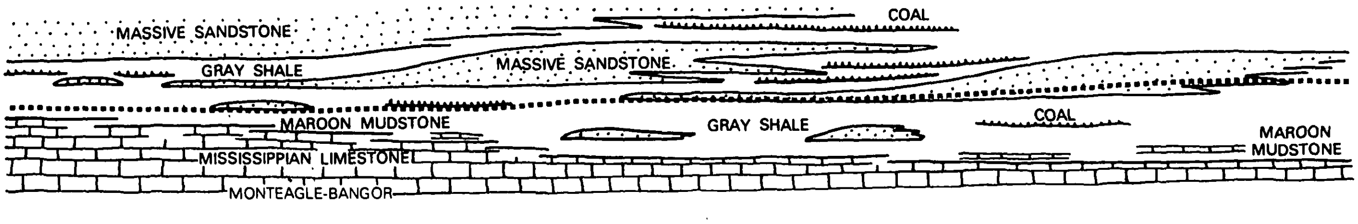


FIGURE 11.—Hypothetical stratigraphic cross section of rocks near the Mississippian-Pennsylvanian boundary in northwest Georgia. Heavy dashed line shows interpreted position of a time-stratigraphic line.

Production of coal from Georgia, by quintade, is shown in figure 12, and the reports of McCallie (1904) and Johnson (1946) remain the most complete sources of information to date.

Coal seams.—Many seams of coal have been mined, and there is much confusion about the correlation of the various seams. The same name has been given to clearly different seams, and the same seam has been given different names. As a result, the information derived from the literature is hard to evaluate.

On Sand Mountain, all of the coals from Georgia are in the rocks below the bluff-forming sandstone; those above have not yet been developed if they exist. Two well-known seams are the Castle Rock, or Etna seam, and the Dade seam. The name Etna is generally used for the coal immediately under the bluff-forming sandstone and the Dade seam is about 10 m below the Etna. The other seams—Rattlesnake, Red Ash, Mill Creek, Cliff, and New England, are irregular and discontinuous, and all are subject to miscorrelation. The seams reach thicknesses of more than 2 m, but most are much thinner than 1 m.

The coals on the northern part of Lookout Mountain are much better known and have been more fully exploited than those on Sand Mountain. Three prominent coal seams are an uppermost A seam, the Durham No. 5 seam a few tens of meters below the A seam, and the Durham No. 4, or Tatum seam, about 15 m below the Durham No. 5. All are above the bluff-forming sandstone. A thin, discontinuous coal seam is immediately below the bluff-forming sandstone called the Cliff, or Castle Rock seam. All the coals have been mined at one time or another, with the No. 5 being the biggest single producer. All have been called the Sewanee coal seam in the literature.

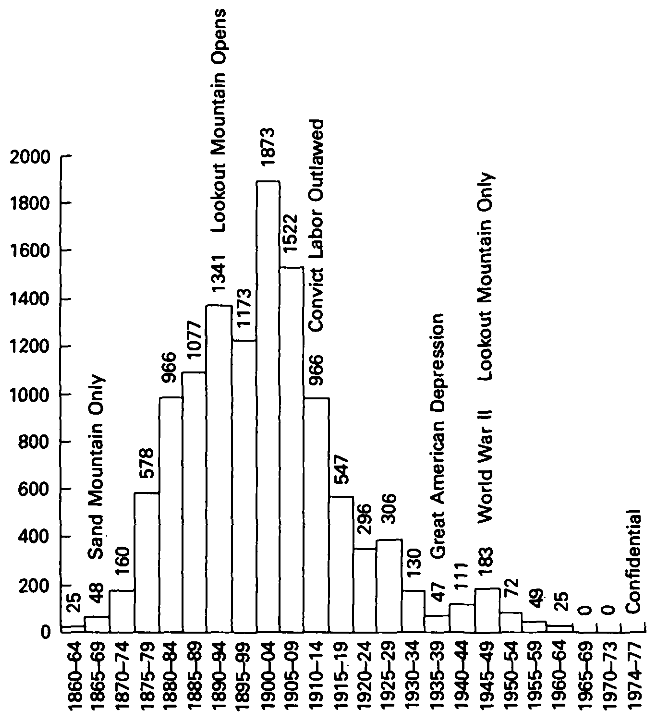


FIGURE 12.—Graph showing coal production (given in thousands of short tons) in Georgia for 5-year intervals from 1860 to 1977.

On the southern part of Lookout Mountain above the bluff-forming sandstone are two coals seams which have been extensively mined. The uppermost one is the Tatum seam, with the Sewanee seam a few tens of meters below it. The Sewanee seam is known to be as much as 2 m thick, but is usually less than a meter. A thin, discontinuous zone of coals is immediately below the bluff-forming sandstone. These coals are called the Cliff seams No. 1 and No. 2, or the upper and lower Cliff coals. They have also been called the Etna and (or) Castle Rock seams. All of the coals on the southern part of Lookout Mountain are being mined today in one place or another; none is everywhere present, however.

Coal reserves.—The figures for the reserves of coal in Georgia have varied considerably. The differences in the figures reflect not only changes in the techniques of reserve calculations, but differing interpretations of the correlations of the coals. Table 1 shows the reserves as calculated in different years.

TABLE 1.—*Coal reserves, Georgia, 1907–74*

Date	Source	Original reserves (millions of short tons)	Remaining res-rves (millions of short tons)	Remarks
1907	Campbell, 1908	933	921	
1942	Peyton, 1942	---	400	Unpublished data.
1942	Sullivan, 1942	188	184	Sand Mountain only.
1946	Johnson, 1946	24	---	
1948	Gildersleeve, 1948	206	120	*In* Butts and Gildersleeve, 1948.
1948	Peyton, 1948	---	115	Unpublished data.
1960	Averitt, 1961	100	76	Average of others.
1967	Averitt, 1969	24	18	
1974	Averitt, 1975	84	78	Includes hypothetical possibilities.
1974	Averitt, 1975	---	1	Demonstrated reserve base.

The figure of 1 million tons, currently quoted, is a product of a conservative formula, the Demonstrated Reserve Base, designed to allow comparison of coal reserves from different areas. It is based upon the reserves in beds 24 or more inches thick, less than 1,000 feet deep, and economically exploitable in 1974. Not much Georgia coal falls into this tightly restricted category, hence the low figure.

Coal rank and chemistry.—Table 2 shows published cumulative analyses of Georgia coals. All the coals are medium-volatile bituminous on the table, but individual coal analyses include much low-volatile bituminous coal.

Because of the problems of coal-seam correlation, much confusion probably exists in the identity of the coals cited in the table. Also, the variation in the analytical quality is considerable. Some are the averages of a few tens of analyses, and some are average for as few as three.

All the coals, except for a few that have very distinctly different analyses, are low in sulfur. Many other trace-element studies have been made on Georgia coals, the results of which may be found in Stadnichenko and others (1961), Walker and Hartner (1966), and in Zubovic and others (1966).

CLAY AND SHALE

Clay and shale are actual and potential mineral resources from the Carboniferous rocks of Georgia. The underclays of the Pennsylvanian terrane have been tested for their fire-brick potential, and none is useful for that, although they test well for general ceramic properties. Inacessibility prevents their being developed at this time.

Shale in the Pennington and Floyd formations of Mississippian age is being used for ceramic products and portland cement; most comes from the Floyd formation. None that has been tested is suitable for whitewear or bloating. Smith (1931) and McLemore (1971) provide numerous analyses and descriptions of clay and shale deposits from the Carboniferous rocks of Georgia.

TABLE 2.—*Proximate analyses and sulfur content of Georgia coals, in percent*

Coal	H_2O	Volatile matter	Fixed carbon	Ash	Sulfur
Cliff	1.7	21.1	70.5	8.1	2.0
Dade	2.5	23.9	63.4	11.4	.9
Red Ash	4.8	23.9	70.2	4.4	1.3
Etna	2.6	26.3	66.8	5.3	1.8
Rattlesnake	3.8	24.6	65.0	9.3	1.1
Durham 4	2.8	20.2	72.1	5.4	.7
Durham 5	2.4	20.0	72.5	5.5	.9
A	2.6	20.2	61.6	18.1	2.1
Sewanee	2.9	18.1	65.6	13.5	1.0

BUILDING STONE

Some crossbedded sandstones in the Pennsylvanian have been used for flagstone (Sullivan, 1942), as has the so-called Hartselle Sandstone on Lookout Mountain (U.S. Geol. Survey and U.S. Bur. Mines, 1968, p. 200–201). This latter unit is more likely a Pennsylvanian sandstone.

Burns (1892, p. 899) wrote of the Millstone Grit on Lookout Mountain, presumably the bluff-forming sandstone, and pointed out its value as a potential source of millstones. The market for these is depressed at the moment.

LIMESTONE AND DOLOSTONE

All the limestone and dolostone resources of the Carboniferous rocks of Georgia are from the Mississippian. Cement limestone is taken from parts of the Monteagle-Bangor facies and from one of the limestone tongues in the Floyd Shale. Numerous other quarries provide limestone for aggregate, most of which also comes from the Monteagle-Bangor; a little comes from the cherty Tuscumbia Limestone. A small amount of Mississippian limestone is used for aglime, and one quarry provides fluxstone. McLemore (1971) provides a review of the limestone and dolostone resources of the Mississippian rocks.

CHERT

Chert is found in great abundance in the weathered parts of the Fort Payne and Tuscumbia terranes, and is used for aggregate and road metal locally.

SLATE

In Polk County, the Floyd Shale has been metamorphosed to slate and is exposed in a few of the slices in the overthrust belt. It has been taken in the past along with the much more abundant Rockmart Slate, of Ordovician age. Cressler (1970) gives the details.

GROUND WATER

Northwest Georgia in general has a good supply of ground water, sufficient for most domestic needs, but the rugged topography of the Carboniferous terrane precludes the possibility of obtaining large supplies for commercial development (Schneider and others, 1965). Precipitation is between 132 and

152 cm per year, and Wyrick (1968) shows groundwater flows of 0–73,000 liters per day per square kilometer. The maximum yield of ground water, in liters per minute per day is 379 to 1,137 for Sand Mountain, and 1,137 to 2,274 for Lookout and Pigeon Mountains. Croft (1964) and Cressler (1963; 1964a b; 1970) provide the details about the ground water, of the Carboniferous terrane.

SCENIC FEATURES

Many scenic features have already been set aside for public enjoyment and recreation on the Carboniferous terrane, and even more are possible candidates for such development. The sandstone-capped plateaus have deep canyons cut into them by the obsequent streams draining them. Cloudland Canyon State Park is one such feature (just north of locality G, fig. 9). DeSoto Falls State Park, southward on the same mountain in Alabama, is a similar feature, and many others could also be developed as parks and scenic areas.

Rock City is an attraction formed from joint-separated blocks of the bluff-forming sandstone on the northeastern bluff of Lookout Mountain.

Many caves have been formed in the Mississippian limestone below the bluff-forming sandstone that forms the cap rock of the plateaus; some of the caves may be developed commercially. Included in these is Ellison's Cave, on the eastern flank of Pigeon Mountain; this cave is the largest in Georgia and contains one of the largest vertical pits in the world.

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The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—Alabama and Mississippi

Mississippian Stratigraphy of Alabama
By WILLIAM A. THOMAS

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By W. EVERETT SMITH

Carboniferous Outcrops of Mississippi
By ALVIN R. BICKER, JR.

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MISSISSIPPIAN STRATIGRAPHY OF ALABAMA

CONTENTS

ILLUSTRATIONS

THE MISSISSIPPIAN AND PENNSYLVANIAN (CARBONIFEROUS) SYSTEMS IN THE UNITED STATES—ALABAMA AND MISSISSIPPI

MISSISSIPPIAN STRATIGRAPHY OF ALABAMA

By WILLIAM A. THOMAS [1]

ABSTRACT

Mississippian rocks in Alabama are exposed along the Appalachian fold and thrust belt and extend through the Black Warrior basin and East Warrior platform northwest of the Appalachians. The lower part of the Mississippian System is an extensive unit of chert and cherty carbonate (Fort Payne and Tuscumbia); the upper part includes three different facies. In north-central Alabama, the upper part of the Mississippian is a shallow-marine limestone facies (Monteagle and Bangor). On the southwest, the carbonate facies is bordered by a northeast-prograding sequence of prodelta mud and deltaic sand and mud (Floyd and Parkwood). Tongues of the clastic facies pinch out northeastward into the carbonate facies. The most extensive tongue of shale and sandstone (Pride Mountain and Hartselle) extends from the lower part of the clastic facies and grades northeastward into the Monteagle Limestone on the East Warrior platform. The upper part of the clastic facies grades northeastward into the Bangor Limestone near the southwest edge of the East Warrior platform. The Mississippian System thickens southwestward in the clastic facies off the East Warrior platform and is thicker in Appalachian synclines southeast of the platform. Where the section is thick in Appalachian synclines, the clastic facies (Floyd and Parkwood) progrades over the Bangor Limestone and extends much farther northeast than on the East Warrior platform. In northeastern Alabama, a southwest-prograding clastic facies (Pennington) grades southwestward into the upper part of the Bangor Limestone. Both the northeast-prograding Floyd-Parkwood clastic facies and the southwest-prograding Pennington Formation grade upward into massive sandstones of the Pottsville Formation, and the Pottsville extends over the Bangor Limestone in north-central Alabama. Although the Mississippian-Pennsylvanian boundary is not precisely defined, the Pottsville is commonly considered to be Pennsylvanian.

Distribution of thickness and facies of Mississippian rocks in Alabama define the Black Warrior basin and East Warrior platform. Greater thickness and extent of the northeast-prograding clastic facies indicate contemporaneous Appalachian synclines southeast of the East Warrior platform. On a more regional scale, the northeast-prograding Floyd-Parkwood sequence is at the eastern limit of a major clastic wedge centered on the Ouachita structural salient, and the southwest-prograding Pennington sequence is at the southwestern fringe of a clastic wedge centered on the Tennessee Appalachian structural salient. The large-scale clastic wedges converged on the Mississippian carbonate facies in the Alabama Appalachian structural recess.

INTRODUCTION

In northern Alabama, Mississippian rocks are exposed in a wide outcrop area along the north limb of the Black Warrior basin and have been drilled in the subsurface beneath Pennsylvanian rocks throughout the basin (fig. 1). The north limb of the Black Warrior basin is a homocline of low dip, and the basin is bordered on the southeast by the Appalachian fold and thrust belt. The eastern part of the Black Warrior basin is defined as the East Warrior platform (Thomas, 1972a, p. 5).

In the Appalachian fold and thrust belt, Mississippian rocks are exposed in narrow linear outcrops along Appalachian structures, including both limbs of the Sequatchie anticline; the northwest limbs of the Birmingham anticlinorium, Murphree Valley anticline, and Wills Valley anticline; both limbs of the Blount Mountain and Lookout synclines; the northwest limb of the Cahaba syncline (southeast limb of Birmingham anticlinorium); the northwest limb of the Coosa synclinorium; and the Coosa deformed belt along the southeast limb of the Coosa synclinorium (fig. 1). Farther southeast in the Piedmont province of Alabama, some metasedimentary rocks are of Mississippian age (Carrington, 1967, p. 26; 1972, p. 1–18).

Toward the west and southwest both in the Black Warrior basin and along Appalachian structures, Paleozoic rocks plunge southwest beneath the cover of Mesozoic strata in the Gulf Coastal Plain (fig. 1). In the subsurface (below Mesozoic coastal-plain beds) of western Alabama, the northwesternmost

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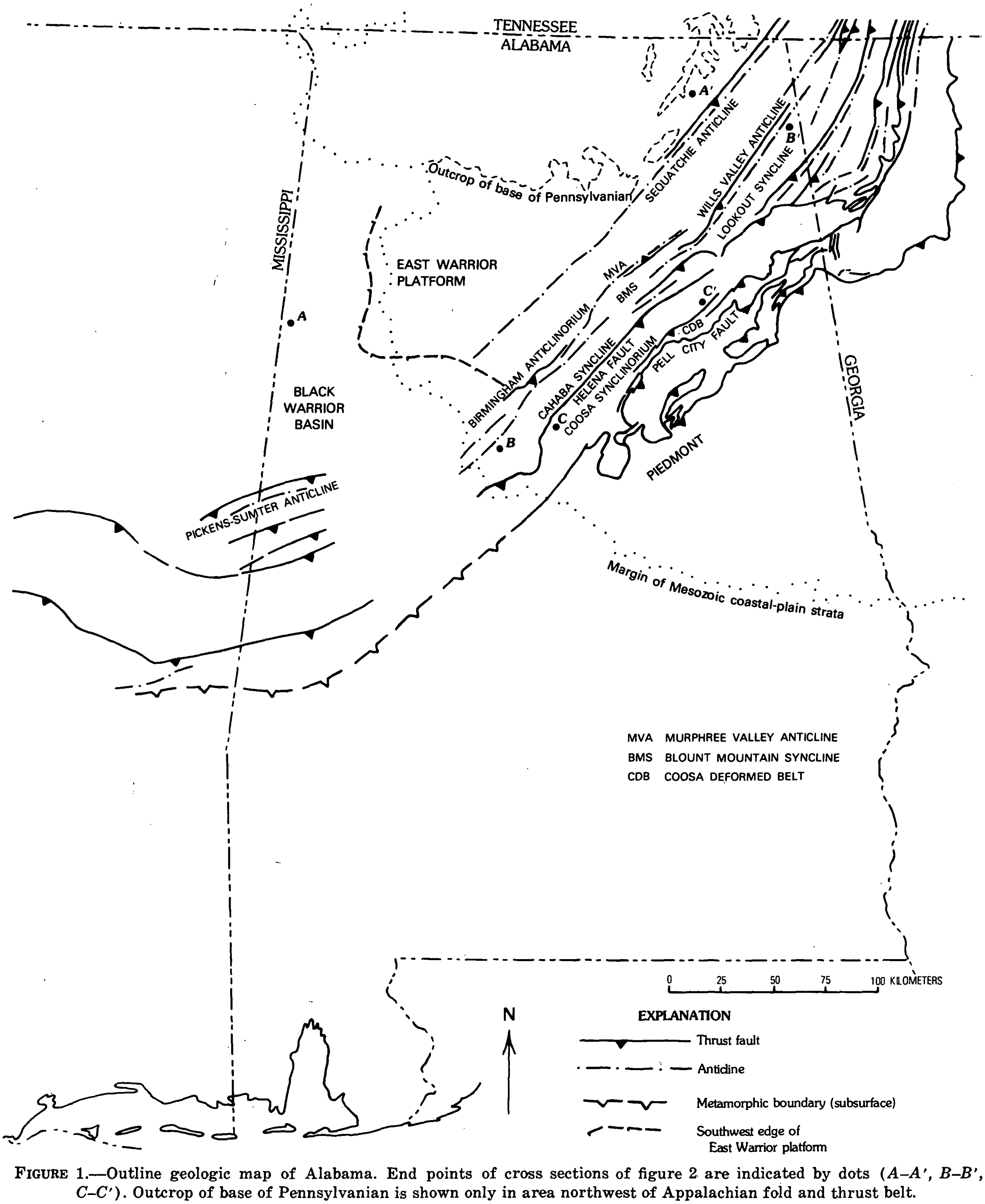


FIGURE 1.—Outline geologic map of Alabama. End points of cross sections of figure 2 are indicated by dots (*A–A'*, *B–B'*, *C–C'*). Outcrop of base of Pennsylvanian is shown only in area northwest of Appalachian fold and thrust belt.

Appalachian structure is the Pickens-Sumter anticline (fig. 1), and the subsurface fold and thrust belt includes at least two other major structures (Thomas, 1973).

The descriptions and interpretations summarized here are based on measured outcrop sections from each of the outcrop belts and on data (sample descriptions and geophysical logs) from wells in the Black Warrior basin (Thomas, 1972a). More detailed descriptions, as well as detailed stratigraphic cross sections and maps, have been published in Monograph 12 of the Geological Survey of Alabama (Thomas, 1972a). The regional setting of Mississippian rocks in Alabama has been discussed in the context of stratigraphic cross sections and maps (Thomas, 1974).

This paper summarizes published descriptive data available in 1977 and reviews the evolution of stratigraphic subdivision and correlation in Alabama. The data and conclusions are summarized in a discussion of depositional and tectonic framework. The manuscript has been reviewed by J. A. Drahovzal and G. H. Mack.

The stratigraphic nomenclature used in this paper has not been reviewed by the Geologic Names Committee of the U.S. Geological Survey. The nomenclature used here conforms with the current usage of the Geological Survey of Alabama.

MISSISSIPPIAN LITHOFACIES

The Mississippian System of Alabama may be divided into two general units (fig. 2). The lower unit is a regionally extensive interval of cherty limestone and chert (Fort Payne and Tuscumbia formations). The Fort Payne Chert is underlain by a thin widespread green shale (Maury Shale) that marks the base of the Mississippian System in Alabama. The upper part of the Mississippian (above Tuscumbia) encompasses three different laterally equivalent facies. In north-central Alabama, the upper part of the Mississippian is almost entirely limestone (Monteagle and Bangor Limestones). The carbonate facies grades southwestward into a succession of shale and sandstone (Floyd and Parkwood formations). Toward the northeast, the upper part of the carbonate facies grades into another succession of shale and sandstone (Pennington Formation). All three facies of the upper part of the Mississippian are overlain by massive sandstone and quartz-pebble conglomerate of the Pennsylvanian Pottsville Formation.

The Fort Payne-Tuscumbia interval is more than 100 m thick in north-central Alabama on the East Warrior platform, but toward the southwest, the cherty carbonate interval thins gradually to less than 50 m in the Black Warrior basin (figs. 2, 3). Similarly, toward the southeast in Appalachian synclines, the Fort Payne-Tuscumbia interval thins to less than 50 m and pinches out locally.

The thickness of Mississippian rocks between the top of the Tuscumbia and the base of the Pottsville ranges from a minimum of about 200 m on the East Warrior platform in north-central Alabama to more than 1,000 m in the Coosa synclinorium (figs. 2, 3). The thickness of the upper part of the Mississippian is less than 300 m across the East Warrior platform, which encompasses the eastern end of the Black Warrior basin and the northwestern part of the Appalachian fold and thrust belt, including the Sequatchie anticline. The southwestern edge of the East Warrior platform is marked by an abrupt southwestward increase in thickness of the upper part of the Mississippian; in the Black Warrior basin, the thickness increases to more than 500 m. The East Warrior platform is bounded on the southeast by thicker sections in Appalachian synclines. Maximum thickness is more than 400 m in the Blount Mountain and Lookout synclines, more than 800 m in the Cahaba syncline, and more than 1,000 m in the Coosa synclinorium.

The Floyd-Parkwood clastic facies thickens southwestward in the Black Warrior basin and is also relatively thick in the Cahaba and Coosa synclines (fig. 2). The clastic facies grades northeastward into the carbonate facies along a boundary that trends southeastward across the Black Warrior basin, diagonally across the East Warrior platform, and into the northwestern part of the Appalachian fold and thrust belt, where the facies boundary is approximately perpendicular to Appalachian structural strike. Tongues of clastic rocks extend northeastward from the clastic facies and pinch out toward the northeast within the carbonate facies on the East Warrior platform. The most extensive tongue of the clastic facies (Pride Mountain Formation and Hartselle Sandstone) extends from the lower part of the Floyd Shale and underlies the Bangor Limestone in north-central Alabama (fig. 2). Farther northeast, the Pride Mountain-Hartselle clastic tongue grades northeastward into the Monteagle Limestone and pinches out between the Monteagle and Bangor Limestones (figs. 2, 3). The upper part of the clastic facies grades northeastward into the Bangor Limestone across the south-

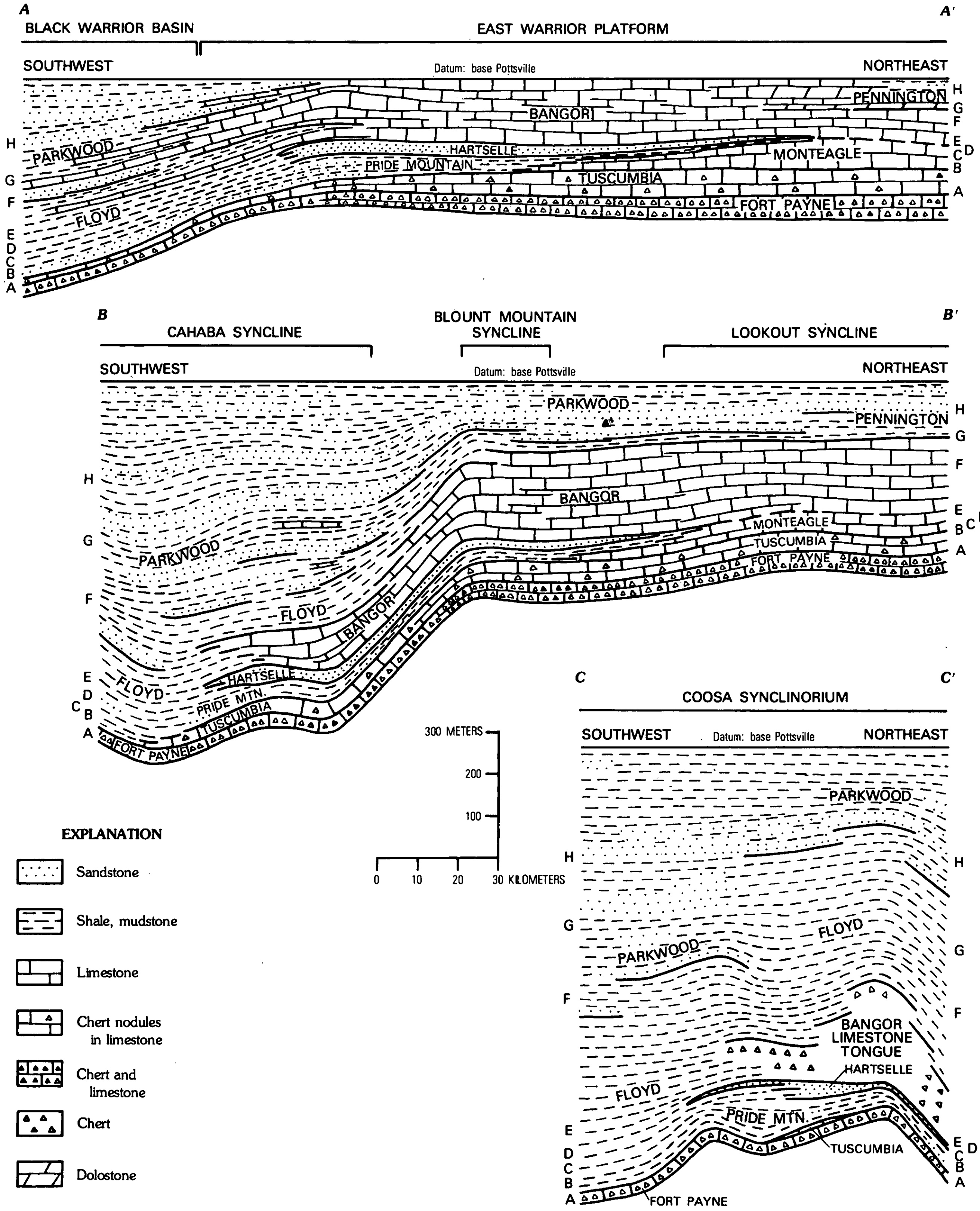


FIGURE 2.—Diagrammatic stratigraphic cross sections of Mississippian rocks in Alabama. End points of cross sections are shown on map in figure 1. Letters A through H on cross sections show approximate stratigraphic positions of maps in figure 5.

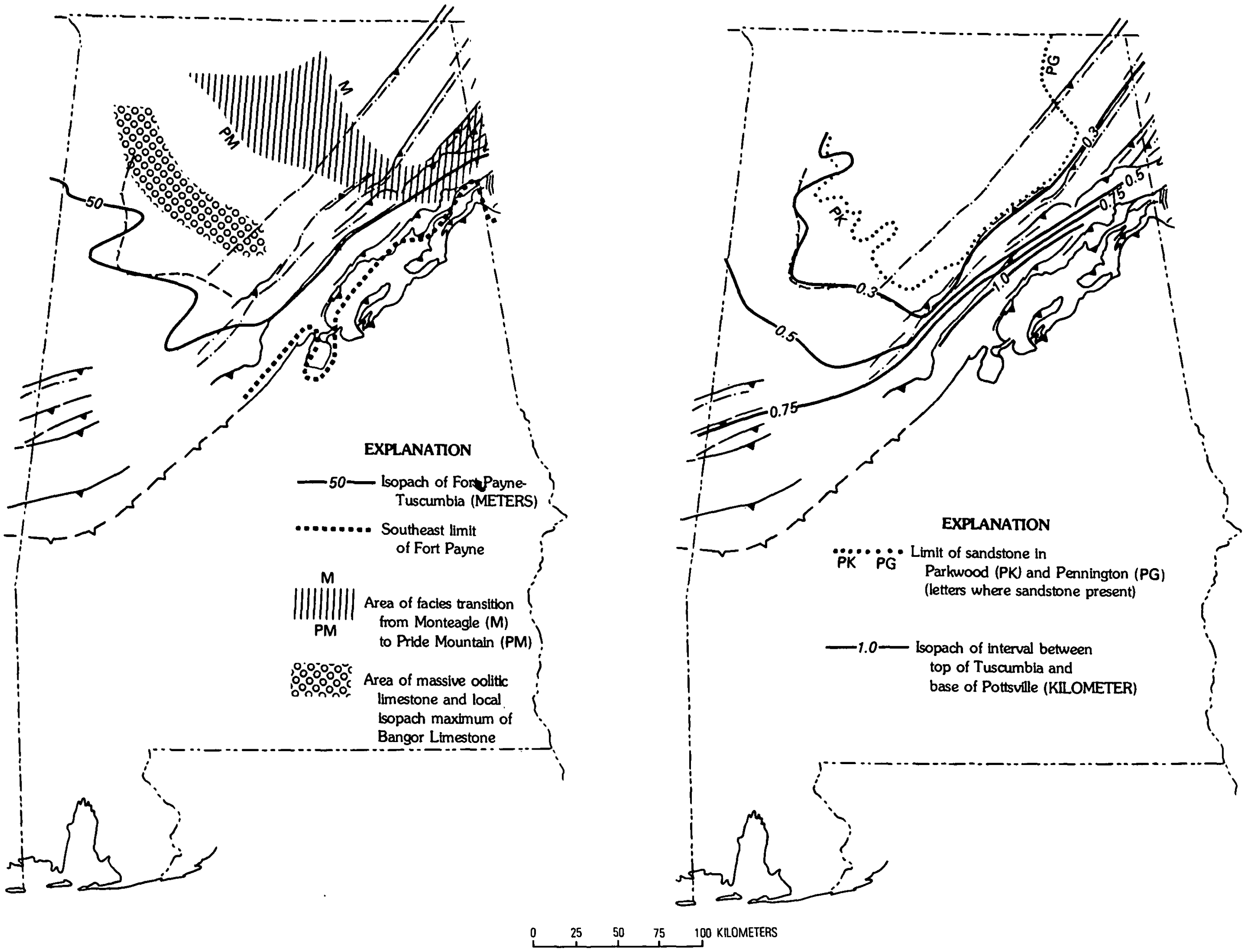


FIGURE 3.—Generalized isopach and facies maps of parts of Mississippian System in Alabama.

western part of the East Warrior platform. Similar patterns of distribution of the major facies prevail along Appalachian synclines; however, the clastic facies is thicker and extends much farther northeast along the more southeasterly structures. In the relatively thicker sections along Appalachian synclines, the upper part of the clastic facies extends far to the northeast above the Bangor Limestone (fig. 2). In the Coosa synclinorium, the clastic facies extends to the northeast end of the outcrop, and the carbonate facies is represented only by a southwest-thinning tongue of limestone and chert (fig. 2). Distribution of the Floyd-Parkwood clastic facies indicates that the rocks in Alabama are at the eastern fringe of a regionally extensive clastic wedge that includes the very thick Mississippian clastic rocks of the Ouachita Mountains (Thomas, 1974, p. 201; 1977, p. 1259).

The Pennington Formation is restricted to the northeastern corner of Alabama and grades westward into the upper part of the Bangor Limestone (fig. 2). The Pennington Formation of Alabama evidently is only the distal fringe of a regionally extensive clastic wedge centered farther northeast (Thomas, 1974, p. 205; 1977, p. 1258).

EVOLUTION OF STRATIGRAPHIC NOMENCLATURE

In 1879, Smith established a threefold division of Carboniferous rocks in Alabama and identified regional equivalents (fig. 4). The Lower Sub-Carboniferous was divided into Lower Siliceous (equivalent to Keokuk and Burlington) and Upper Siliceous (equivalent to St. Louis). The Upper Sub-Carboniferous or Mountain Limestone (equivalent to Chester) contained the entire carbonate sequence

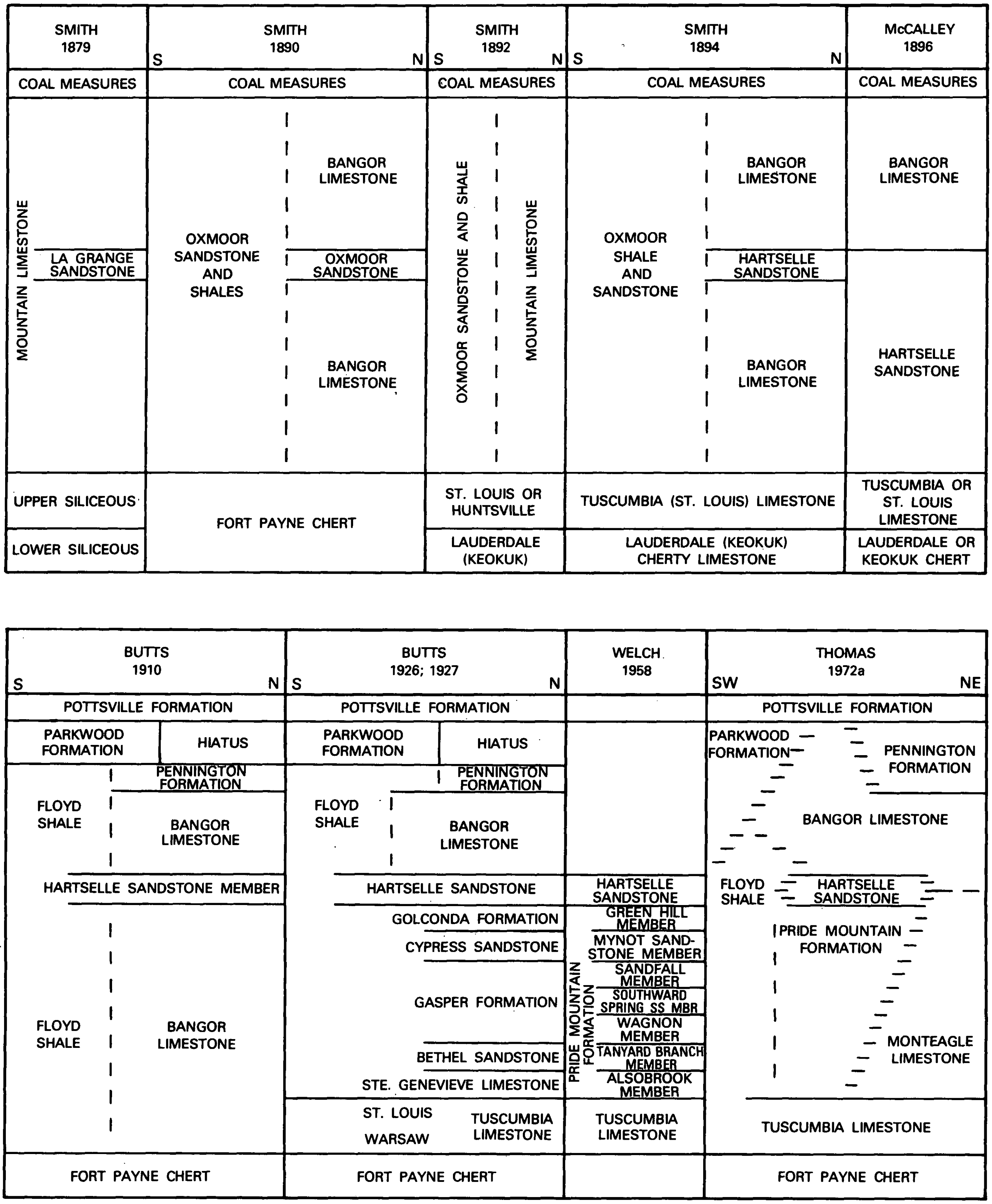


FIGURE 4.—Evolution of stratigraphic subdivision and namenclature of Mississippian rocks in Alabama.

above the lower cherty unit. Smith (1879, p. 17) designated the local name, LaGrange Sandstone, for a persistent sandstone within the Mountain Limestone. The Coal Measures included the coal-bearing sequence later assigned to the Pennsylvanian System.

Later, Smith (1890) applied local formation names to Mississippian stratigraphic units (fig. 4). The Fort Payne Chert encompassed all the cherty limestones in the siliceous Lower Sub-Carboniferous. The carbonate sequence above the Fort Payne Chert was called the Bangor Limestone. Toward the south in Alabama, the Bangor Limestone is replaced by a sandstone and shale succession called Oxmoor Sandstone and Shales (Smith, 1890, p. 155). The name Oxmoor was extended to replace Lagrange for the sandstone within the limestone sequence. The Oxmoor included the entire southwestern clastic sequence.

In summary reports, Smith (1892, 1894) defined two divisions of the beds originally called Fort Payne Chert (fig. 4). The upper cherty limestone unit was referred to as St. Louis or Huntsville in 1892 and as the Tuscumbia (St. Louis) Limestone in 1894. The lower subdivision was called Lauderdale (Keokuk) in 1892 and Lauderdale (Keokuk) cherty limestone in 1894. Smith (1894) used the name Hartselle Sandstone to replace Lagrange and Oxmoor for the sandstone unit within the Bangor Limestone.

McCalley (1896, p. 40) restricted Bangor to the limestone above the Hartselle Sandstone and extended the Hartselle Sandstone downward to include a succession of sandstone and shale beds below the Bangor Limestone and above the Tuscumbia (fig. 4). McCalley (1896, p. 40) recognized a prominent sandstone (Hartselle of earlier and later use) at the top of his Hartselle and described the westward or southwestward thickening of the sandstone-shale unit.

Butts (1910, p. 7) recognized equivalence of the carbonate sequence of northern Alabama to part of the clastic sequence to the south and modified the stratigraphic nomenclature to reflect that interpretation (fig. 4). Fort Payne Chert was restricted to the bedded chert previously called Lauderdale cherty limestone. Butts (1910, p. 7) extended Bangor Limestone downward to the top of the redefined Fort Payne and recognized a gradational contact between the Fort Payne and cherty limestone of the lower Bangor. Following Smith (1894), Hartselle Sandstone was defined as a member of the Bangor. Butts (1910, p. 8) extended use of Floyd Shale from northwest Georgia as the shaly lower part of the clastic sequence and defined a new name, Parkwood Formation, for the sandstone-shale succession of the upper part. Floyd and Parkwood replaced Oxmoor (fig. 4). The name Pennington Formation was extended from Virginia for shale above the Bangor Limestone (fig. 4). Butts (1910, p. 7) described the Pennington as being overlain by the Pottsville Formation on the north and by the Parkwood Formation on the south. Butts (1910, p. 7) concluded that the Bangor and Pennington are contemporaneous with the Floyd and are older than the Parkwood. He (1910, p. 8) suggested that where Parkwood is present, sedimentation was continuous from Mississippian into Pennsylvanian. Absence of Parkwood below the Pottsville north of Birmingham was regarded as an indication of regional unconformity between Mississippian and Pennsylvanian rocks (Butts, 1910, p. 8).

In the classic report on the geology of Alabama, Butts (1926) retained the use of local stratigraphic names for several units and extended names from the Mississippi Valley for other stratigraphic subdivisions in Alabama (fig. 4). Tuscumbia Limestone was used interchangeably with Warsaw and St. Louis for the cherty limestone above the Fort Payne Chert. Formation names extended from the Mississippi Valley were applied to the succession of shale, limestone, and sandstone between the Tuscumbia and the Hartselle (fig. 4). Bangor Limestone was restricted to beds above the Hartselle Sandstone (Butts, 1926, p. 195), and Hartselle was raised to formation rank (Butts, 1926, p. 192). The Pennington Formation apparently was described only for beds between Bangor and Pottsville in northern Alabama (Butts, 1926, p. 199); later, Butts (1927, p. 12) considered the shale between Bangor and Parkwood south of Birmingham (Pennington of Butts, 1910, p. 7) as part of the Floyd Shale.

Recognizing the impracticality of identification of the Mississippi Valley units for the beds between Tuscumbia and Hartselle in northwestern Alabama, Welch (1958) defined the entire succession of shale, limestone, and sandstone as the Pride Mountain Formation. Welch (1958) provided member definition for each part of the formation, which is described as consisting "of relatively thick units of shale that alternate with thinner units of limestone, sandstone, and siltstone" (fig. 4). The Pride Mountain Formation constitutes a clastic tongue in the lower part of the Mississippian carbonate sequence;

it grades northeastward into the limestone sequence in northeastern Alabama.

Stratigraphic subdivisions currently used for Mississippian rocks by the Geological Survey of Alabama (fig. 4) were outlined in a comprehensive review of Mississippian stratigraphy of Alabama (Thomas, 1972a). The southwestern clastic facies is divided into the Floyd Shale and the Parkwood Formation. Generally, the Floyd Shale overlies the Tuscumbia Limestone. The Tuscumbia evidently grades southeastward into shale, and where the Tuscumbia is absent, Floyd Shale rests directly on the Fort Payne Chert. A tongue of the lower part of the clastic sequence extends northeastward into the carbonate facies and is divided into the Pride Mountain Formation (shale, sandstone, and limestone) and the Hartselle Sandstone at the top. The Hartselle Sandstone pinches out both to the southwest within the shale unit in the lower part of the clastic facies and to the northeast within the carbonate facies. Southwest of the pinchout of the Hartselle Sandstone, the Pride Mountain Formation below is not distinct from the Floyd Shale above, and the Floyd Shale extends down to the top of the Tuscumbia Limestone. Toward the northeast, in northeastern Alabama, the Pride Mountain Formation grades into a limestone unit between the Tuscumbia and Hartselle. The name Monteagle Limestone was extended from southern Tennessee for the limestone above the Tuscumbia and below the Hartselle Sandstone or Bangor Limestone (Thomas, 1972a, p. 19), and Monteagle replaced the names Butts (1926) had extended from the Mississippi Valley. The upper part of the Mississippian carbonate sequence in Alabama is the Bangor Limestone. The Bangor overlies the Hartselle Sandstone, and toward the northeast where the Hartselle pinches out, the Bangor rests directly on Monteagle Limestone. East of the pinchout of the Hartselle Sandstone, the Monteagle and Bangor Limestones are not differentiated. In northeastern Alabama, the upper part of the Bangor grades northeastward into a clastic facies of shale, mudstone, sandstone, dolostone, and limestone. The name Pennington Formation has been restricted to the clastic facies on the northeast (Thomas, 1972a, p. 83).

LITHOSTRATIGRAPHY

MAURY SHALE

The Maury Shale is a thin persistent unit of green clay shale characterized by phosphatic nodules. In northern Alabama, the Maury is generally less than 2 m thick; however, the formation provides a distinctive lithologic marker at the base of the Mississippian System.

FORT PAYNE CHERT

The Fort Payne Chert in Alabama is typified by buff-weathered chert in irregular nodular beds. Commonly, the weathered chert contains abundant molds of echinoderm columnals and brachiopods, and the texture of some of the weathered chert suggests decalcified siliceous limestone. In unweathered exposures and in the subsurface, the Fort Payne is dark-gray to light-gray siliceous micrite and blue-gray to smoky chert in irregular beds and nodules. The formation locally includes light-gray coarse bioclastic limestone in lenses less than 3 m thick. The Fort Payne Chert includes some dark shale in northwestern Alabama (Butts, 1926, p. 164) and shaly beds in eastern Alabama. In northern Alabama, the formation contains geodes.

The Fort Payne ranges in thickness from more than 50 m on the East Warrior platform to less than 20 m on the southwest in the Black Warrior basin. The formation also thins southeastward across the Appalachian fold and thrust belt. Apparently the Fort Payne Chert pinches out southeastward along an irregular line along the Coosa deformed belt and the upplunge southwest end of the Coosa synclinorium (fig. 3).

The contact between the Fort Payne Chert and Tuscumbia Limestone is gradational from the siliceous micrite and bedded chert typical of the Fort Payne upward to a succession of light-colored bioclastic limestone and micrite containing abundant nodules of light-colored chert (Thomas, 1972a, p. 12). Differentiation of the two units is progressively less distinct westward in the Black Warrior basin. Where the Tuscumbia Limestone is absent along the southeastern Appalachian structures, the Fort Payne is overlain by dark clay shale and argillaceous limestone of the Pride Mountain Formation-Floyd Shale.

TUSCUMBIA LIMESTONE

The Tuscumbia Limestone consists mainly of light-gray micrite and bioclastic limestone in thick beds. Crossbedded, coarse crinoidal limestone beds are locally as much as 3 m thick. Oolitic limestone is rare. In northeastern Alabama, thin lenses and beds of finely crystalline dolostone and dolomitic limestone are scattered randomly throughout the Tuscumbia; dolostone is more common in equivalent beds in southern Tennessee (Ferguson and Stearns, 1967, p. 56). Light-gray and white chert nodules are common throughout the formation; dark-gray chert is less common. Part of the chert contains fossil molds. Fenestrate bryozoans are locally abundant. Concentrically banded, concretionary chert is abundant locally.

The Tuscumbia Limestone is more than 50 m thick on the East Warrior platform in north-central Alabama; it thins gradually southwestward in the Black Warrior basin to less than 15 m (fig. 2). Along Appalachian synclines, the formation thins and pinches out to the southeast and southwest, and it is absent at the southwest end of the Cahaba syncline and along the Coosa synclinorium, except locally on the northwest limb (fig. 2).

Where the Tuscumbia is overlain by the clastic facies, the basal beds of the Pride Mountain Formation-Floyd Shale commonly are shaly, oolitic, and (or) sandy limestone that suggests an upward gradation into the shale succession. The pinchout of the Tuscumbia along Appalachian synclines may be a result of lateral gradation into the lower part of the clastic facies (Thomas, 1972a, p. 17). Alternatively, thinning of the Tuscumbia in the Black Warrior basin has been attributed to an unconformity at the top of the formation (Welch, 1958; 1959). In northeastern Alabama, the contact between the Tuscumbia and overlying Monteagle Limestone is gradational; the Monteagle is characterized by light-colored massive oolitic limestone and contains significantly less chert, dolostone, and micrite than does the Tuscumbia.

MONTEAGLE LIMESTONE

The Monteagle Limestone is characterized by light-gray oolitic limestone in crossbedded, massive beds more than 3 m thick. Thick-bedded bioclastic limestones are common. Interbeds of micrite are less common. Interbeds of finely crystalline dolostone and dolomitic limestone are rare and are randomly distributed. Nodules of gray and black chert are rare. The Lost River Chert, a marker in the lower Monteagle of Tennessee (Ferguson and Stearns, 1967, p. 57), does not appear to be laterally persistent in Alabama. In the northeastern corner of Alabama, the middle part of the Monteagle contains a distinctive unit of interbedded limestone and shale about 8 m thick (Thomas, 1972a, p. 21).

In northeastern Alabama, the Monteagle is approximately 65 m thick and is almost entirely limestone. Toward the southwest on the East Warrior platform, the Monteagle grades southwestward to clay shale of the Pride Mountain Formation (figs. 2, 3). The facies boundary between the Monteagle and Pride Mountain rises stratigraphically northeastward, and a thin tongue of clay shale of the upper Pride Mountain extends northeastward above the Monteagle and below the eastward-pinching Hartselle Sandstone. East of the pinchout of both Pride Mountain and Hartselle, the Monteagle is overlain by the Bangor Limestone in a continuous succession of limestone beds. Although a Monteagle-Bangor contact may be projected eastward, the two formations are clearly separable only where the Hartselle and (or) Pride Mountain intervene, and the undifferentiated Monteagle-Bangor cannot be reliably subdivided farther east (Thomas, 1972a, p. 22).

The Monteagle Limestone extends southeastward into Lookout syncline and grades southwestward to the Pride Mountain Formation near the southwest end of the syncline, just as it does on the East Warrior platform (figs. 2, 3). Southeast of the Lookout syncline, the Monteagle grades into the clastic facies (Pride Mountain-Floyd).

BANGOR LIMESTONE

The Bangor Limestone is mainly bioclastic limestone and oolitic limestone. The formation also includes micrite and thin beds of shaly argillaceous limestone and calcareous shale. Thin laterally discontinuous beds of maroon and green blocky mudstone are scattered through the upper half of the formation. Chert is generally restricted to the upper part of the Bangor. A few small masses of coral are scattered widely. In northeastern Alabama, a dolostone unit extends from the basal Pennington Formation into the Bangor Limestone.

The Bangor Limestone ranges approximately from 130 to 180 m in thickness on the East Warrior platform. A linear isopach and limestone isolith maximum is alined approximately with the southwestern edge of the East Warrior platform in northwestern Alabama and trends southeastward diagonally across the platform northeast of the edge (Thomas, 1972a, pl. 11; 1974, fig. 6). Southwest of the linear isopach-isolith maximum, thickness of limestone decreases where the Bangor grades southwestward into the clastic facies (Thomas, 1972a, p. 50). Similarly, the Bangor thins northeastward where the upper part grades laterally into the Pennington Formation (fig. 2).

The Bangor thickens southeastward to more than 180 m along the Sequatchie anticline and Blount Mountain and Lookout synclines. Farther southeast in the Appalachian fold and thrust belt, the Bangor generally is less than 150 m thick, but there, much of the Bangor-equivalent interval is in the Floyd-Parkwood clastic facies (fig. 2). However, the Bangor Limestone also thins southwestward and grades to clastic rocks along strike of the Cahaba syncline. A similar pattern prevails along the Coosa synclinorium (fig. 2), where the southwest-thinning Bangor Limestone Tongue of the Floyd Shale is mostly weathered chert on the northwest limb and mostly limestone along the Coosa deformed belt.

Oolitic limestone is most abundant along the linear isopach maximum across the southwestern part of the East Warrior platform (fig. 3); along the same area, the formation contains three separate massive oolitic limestone units, each as much as 12 m thick (Jones, 1928, p. 13; Thomas, 1972a, p. 49). Farther northeast on the East Warrior platform, oolitic limestone units appear thinner and less extensive, and both oolitic and bioclastic limestones are generally in thick beds or large lenses, which are crossbedded.

On the East Warrior platform, the Bangor is overlain by the Pottsville Formation. The contact is within a succession that includes (in ascending order) limestone, maroon and green mudstone, carbonaceous shale and thin-bedded sandstone, and the characteristic thick massive sandstone of the lower Pottsville. Thickness of fine clastic rocks between the top of the limestone succession and the massive sandstone is generally less than 20 m but varies locally. Various components of the gradational succession are not everywhere present, and locally the massive sandstone appears to rest directly on the limestone. The succession indicates that the Bangor-Pottsville contact is gradational, but channels are suggested where the massive sandstone rests on limestone. However, the possible channels appear to be local, and the contact apparently is not a regional unconformity (Thomas 1972a, p. 94).

FLOYD SHALE

The Floyd Shale is a dark-gray clay shale that constitutes the lower part of the southwestern Mississippian clastic sequence. In the Black Warrior basin, the Floyd grades upward into the Parkwood Formation, and the upper part of the Floyd grades northeastward into the Bangor Limestone (fig. 2). The Floyd and Parkwood grade northeastward into the Bangor along an irregular southeast-trending line near the southwestern edge of the East Warrior platform; however, an extensive tongue of the lower part of the Floyd Shale extends far northeast beneath the Hartselle Sandstone as the Pride Mountain Formation. Sandstone units characteristic of the Pride Mountain extend southwest into the lower Floyd. Along Appalachian synclines, where the Mississippian System is thicker than it is in the Black Warrior basin, the Floyd-Parkwood contact rises northeastward above the most extensive Bangor Limestone, and the Floyd Shale intervenes between the Parkwood and the Bangor (fig. 2). The clastic facies extends much farther northeast along Appalachian synclines than it does on the East Warrior platform. In the Coosa synclinorium, the Floyd includes a southwest-thinning tongue of Bangor Limestone, as well as the northeast, southeast, and southwest limits of the Hartselle Sandstone (fig. 2). The Floyd Shale extends northeast to the end of exposures in the Coosa synclinorium.

The Floyd Shale is predominantly dark-gray clay shale. Siderite nodules are scattered through the sequence. Parts of the shale sequence are calcareous and include shaly, argillaceous limestone beds. Within the Floyd in the Black Warrior basin, a limestone tongue of the lower Bangor contains dark-gray chert.

Around the southwest end of the Coosa synclinorium, the lower Floyd Shale includes beds less than 3 m thick of dark-gray argillaceous limestone that contains abundant fenestrate bryozoans, echinoderm columnals, and brachiopods. Farther southwest, south of the Black Warrior basin on the Pickens-Sumter anticline, the lower part of the Floyd contains limestone units that attain an aggregate thickness of about 60 m. At the northeast end of the Coosa deformed belt and southeast of Lookout syncline, the Floyd contains relatively thick limestone units; however, complex structure obscures the stratigraphic position of the limestones. To the east in Georgia, the lower part of the Floyd Shale contains a limestone tongue equivalent to the Tuscumbia and (or) Monteagle, and the Floyd is overlain by a tongue of the Bangor Limestone. The limestones in the Floyd of eastern Alabama may be equivalent to either or both limestone tongues within the clastic sequence in Georgia.

PRIDE MOUNTAIN FORMATION AND HARTSELLE SANDSTONE

The Pride Mountain Formation and Hartselle Sandstone constitute a laterally extensive tongue of shale and sandstone that extends from the lower part the Floyd Shale and pinches out northeastward into the carbonate facies between the Monteagle and Bangor Limestones (figs. 2, 3). Thickness of the tongue is generally less than 110 m. The clastic tongue contains four separate sandstone units, of which the lower three are in the Pride Mountain Formation and the upper is the Hartselle Sandstone. Each of the four sandstone units is broadly linear in distribution and trends southeast, parallel with the major facies boundaries across the southwestern part of the East Warrior platform. Each of the linear sandstones pinches out southeastward along trend. The Pride Mountain sandstone units are thin or absent in the Appalachian fold and thrust belt southeast of the Birmingham anticlinorium. The Hartselle Sandstone extends as far southeast as the northwest limb of the Coosa synclinorium.

The southwest and southeast limits of the four sandstones are within the gray shale of the lower part of the clastic facies. By definition, the Pride Mountain includes the shale and sandstone succession below the Hartselle Sandstone; beyond the limit of Hartselle Sandstone, beds equivalent to the Pride Mountain are included in the lower part of the Floyd Shale (fig. 2). Sandstone units of the Pride Mountain extend farther southwest than the Hartselle and are, therefore, included in the Floyd Shale. The area of the lower sandstone unit is relatively wide and extends from the East Warrior platform southwestward into the Black Warrior basin. The middle and upper units are confined to narrow areas on the platform; however, northwest along trend, both extend across the platform edge into the Black Warrior basin. Farther west in the Black Warrior basin in Mississippi, the sandstones have a more blanketlike distribution (Thomas, 1972b, p. 98; 1974, p. 196). The three sandstone units in the Pride Mountain pinch out northeastward into a shale succession that, farther northeast, grades into the Monteagle Limestone beneath the Hartselle Sandstone.

The Pride Mountain (lower Floyd) sandstones are characteristically quartzose; however, the sandstone units commonly contain beds of partly sandy bioclastic limestone. Locally the sandstone grades laterally to limestone. The lower beds of the Pride Mountain (lower Floyd) are generally shaly and (or) oolitic limestone, and locally the lower sandstone unit is interbedded with the basal limestone. The sandstone units grade laterally to thin-bedded or shaly argillaceous sandstone and shale. The units locally consist of very fine grained sandstone in ripple-laminated beds and lenses less than 5 cm thick. Clay laminae and beds of shale alternate with the thin sandstone beds. In some places, the laminae are disrupted by abundant burrows, and the bed surfaces are marked by numerous trails. Locally, channel-filling conglomerate at the base of a sandstone unit contains clasts of limestone, claystone, and sandstone as much as 10 cm in diameter and fragments of corals, bryozoans, and brachiopods (Thomas, 1972a, fig. 13). Near the northeast limit of each sandstone, lithology and thickness vary locally.

Apart from the sandstone units, the Pride Mountain Formation consists of gray clay shale and includes calcareous shale and shaly argillaceous limestone. The calcareous rocks generally contain abundant fossils of bryozoans and brachiopods. Parts of the shale succession contain abundant siderite nodules. Plant fragments are scattered in some of the shale beds (Butts, 1927, p. 12).

The Hartselle Sandstone is the thickest and most extensive of the sandstone units on the East Warrior platform. Maximum thickness of the formation is more than 45 m along a narrow southeast-trending area across the southwestern part of the East Warrior platform. The linear area of maximum thickness is parallel with and only 18 km northeast of the southwest limit of the sandstone. Northeast of the well-defined linear thick sandstone, the formation thins irregularly eastward. Limited data suggest other discontinuous southeast-trending isolith maxima separated by broad areas of thinner sandstone (Beavers and Boone, 1976, p. 11). Farther east, the sandstone thins gradually and pinches out eastward between the Monteagle and Bangor Limestones. Near the east limit of sandstone, the Hartselle includes lenses of alternating thin laminae of quartzose sandstone and oolitic bioclastic limestone. Where the Hartselle overlies the thin east-pinching tongue of Pride Mountain shale, sandstone fills channels nearly 1 m deep, and where the Hartselle overlies the Monteagle Limestone, the upper limestone beds are sandy. Thickness of sandstone varies abruptly near the east limit; possibly, some sandstone lenses are isolated farther east within the carbonate facies. Eastward beyond the limit of sandstone, the Hartselle horizon within the limestone succession may be marked by a thin bed of shale and (or) locally by crossbedded lenses and channeled limestone beds. In north-central Alabama, the Hartselle Sandstone grades upward to the Bangor Limestone through a few meters of calcareous clay shale and argillaceous limestone.

The Hartselle Sandstone is generally a light-colored fine-grained quartzose sandstone. In northwestern Alabama, the formation includes two major facies: thick-bedded crosslaminated matrix-free sandstone and thin-bedded ripple-laminated sandstone that has a terrigenous matrix and mudstone interbeds (Beavers and Boone, 1976, p. 11). The Hartselle is characterized generally by thick-bedded crossbedded sandstone. Some beds are ripple marked, and thin-bedded ripple-laminated sandstone locally is marked by trails. Flat clay pebbles less than 3 cm in diameter are scattered in the sandstone beds at some localities. Beds of shale and shaly sandstone make up a small proportion of the formation. Whole and fragmented fossils of brachiopods, bryozoans, and blastoids are common locally. Plant fossils, including tree segments as much as 60 cm long and 15 cm across, are imprinted on sandstone and shale beds. Large tree fragments, including a stump, were collected from the Hartselle of northwestern Alabama (McCalley, 1896, p. 171–176).

Near the southwest end of the Lookout syncline and in the area farther north, the Pride Mountain Formation grades northeastward to the Monteagle Limestone, and the Hartselle pinches out northeastward within the carbonate facies. Along the Coosa synclinorium, where the clastic facies extends farther northeast, the Hartselle Sandstone pinches out northeastward within the shale succession in the lower part of the clastic facies.

PARKWOOD FORMATION

The Parkwood Formation is a succession of alternating units of shale and sandstone and is divisible into four cyclic intervals. Part of each cycle is dominated by sandstone; however, shale interbeds are common. Generally, the sandstone grades up into a dominantly shale unit, which grades up into a higher sandstone. Where the formation is thick, each cycle commonly includes more than 100 m of beds. Some sandstone units are locally more than 30 m thick, and sandstone generally constitutes 15–40 percent of the formation. The base of the formation is defined as the base of the lowest sandstone unit, and because the lower sandstone units successively pinch out northeastward, the base of the formation ascends stratigraphically in that direction. Aggregate thickness of sandstone and total thickness of the formation generally increase southwestward.

The Parkwood Formation pinches out northeastward along an irregular, southeast-trending line that extends across the East Warrior platform and into the Appalachian fold and thrust belt (figs. 2, 3). Along the Appalachian synclines, where the clastic facies is thickest, the Parkwood extends much farther northeast than on the East Warrier platform (figs. 2, 3). On the southeast limb of the Sand Mountain syncline and in Lookout syncline, Parkwood strata blend northeastward with clastic rocks of the southwest-thinning Pennington Formation, and the northeastern limit of Parkwood clastic sediments is obscure. The Parkwood extends northeast to the up-plunge end of the Coosa synclinorium and the northeast end of the Coosa deformed belt.

The sandstones are characteristically very fine to fine grained, argillaceous, and micaceous, but some are more quartzose. Flattened clay pebbles less than 3 cm in diameter are locally abundant. Beds range from thin and shaly to thick bedded and from planar to lens shaped. Ripple marks are relatively common, and some of the sandstones are crossbedded. Some beds and lenses are characterized by flaser bedding. Burrows and trails mark some beds. Thin clay partings and clay shale beds are common.

Between the sandstone units are intervals of gray clay shale, silty clay shale, and mudstone. Nodules and thin nodular beds of siderite are common throughout but apparently are most abundant in the lower part of the formation. Silty laminae within the shales are locally interrupted by abundant burrows.

Contacts of sandstone units with underlying and overlying clay shales are commonly gradational. Locally, sandstone units rest on scoured basal contacts, and sandstone fills shallow channels in the underlying shale. Lenses of clay-pebble and limonite-concretion conglomerate mark the bases of some sandstones, but other channel-filling sandstones are not conglomeratic.

Extensive tongues of limestone extend from the Bangor Limestone southwest into the shale-dominated parts of the Parkwood. Argillaceous, bioclastic, and cherty limestones and rare oolitic limestone compose the tongues. Calcareous mudstone and maroon and green mudstone beds are associated with the limestone beds.

Marine fossils are abundant locally. The limestone beds contain abundant brachiopods, bryozoans, and echinoderms. Shale units locally contain abundant molds of brachiopods, pelecypods, and bryozoans. Poorly preserved molds of brachiopods and bryozoans are included in some of the sandstone beds, and molds of echinoderm columnals are widely scattered.

Carbonaceous shale and sandstone containing small plant fragments are common in the upper part of the formation. Large plant fossils are preserved locally in sandstone. Carbonaceous shale near the top of the formation contains thin beds of clayey coal. The coal beds and the greatest concentration of carbonaceous sandstone and shale are in the upper 75 m of the Parkwood in the Cahaba syncline.

Across the Black Warrior basin and southwest edge of the East Warrior platform, the Parkwood grades northeastward laterally into the Bangor Limestone. Along the Appalachian synclines, the lower Parkwood grades northeastward into the Floyd Shale, which constitutes a transitional facies between the Parkwood and the Bangor. The Parkwood is overlain by a thick massive unit of quartzose sandstone, quartz-pebble conglomerate, and carbonaceous sandstone, which marks the base of the Pottsville Formation. In some places, the basal Pottsville sandstone fills erosional channels cut several meters into the underlying Parkwood beds, but at other localities, the contact is planar and appears conformable.

PENNINGTON FORMATION

The Pennington Formation is a succession of shale, mudstone, sandstone, dolostone, and limestone that overlies part of the Bangor Limestone in northeastern Alabama (figs. 2, 3). In the area northwest of the Wills Valley anticline, the clastic succession grades westward to limestone of the upper Bangor, but farther south along Appalachian structures, the Pennington merges southwestward with the northeast-wedging Parkwood clastic sequence. Along and northwest of the Sequatchie anticline, the base of the Pennington is marked by dull-gray, micrograined dolostone interbedded with maroon, green, and gray mudstone. The distinctive dolostone interval is virtually coextensive with the succeeding clastic rocks, but the dolostone extends farther west into the limestone sequence. Southeast of the Sequatchie anticline, the dolostone is not commonly exposed and the lower part of the Pennington is gray shale and maroon and green mudstone.

The Pennington Formation is predominantly gray clay shale. Maroon and green mudstones generally make up less than 10 percent of the total thickness. The formation contains beds of bioclastic, oolitic, and micritic limestones, typical of the Bangor Limestone, and the proportion of limestone increases westward. Toward the east, beds of very fine to fine-grained generally argillaceous sandstone are common in the upper part of the Pennington. The sandstone beds generally are complexly overlapped lenses or crossbeds; and, in part, the sandstone grades laterally to mudstone. The sandstone is generally carbonaceous, and plant fragments are common. The sandstone-bearing succession commonly includes carbonaceous shale and thin shaly coal beds, which are generally less than 30 cm thick. In eastern Alabama, one coal bed apparently grades laterally within a few tens of meters to a nodular bed of siderite that contains brachiopods and gastropods. Thickness of coal beds is greater to the northeast in Georgia and Tennessee, and some beds in the same stratigraphic position have been mined. The interval of sandy carbonaceous beds thickens eastward in Alabama to more than 30 m, and farther northeast, the equivalent succession is separated from the Pennington as the Raccoon Mountain Formation in Tennessee.

The Pennington Formation overlies the lower part of the Bangor Limestone and grades laterally westward into the upper Bangor. The Pennington is overlain by massive sandstone of the lower Pottsville Formation. The coal-bearing upper Pennington (or Raccoon Mountain) appears to be gradational upward to the Pottsville. Probably no major unconformity separates the Pennington and the Pottsville, although channel filling marks the base of the Pottsville sandstone in a few places.

BIOSTRATIGRAPHY

The Maury Shale contains abundant conodonts. The formation evidently encompasses three assemblage zones (*Siphonodella isosticha-S. cooperi* zone, *Gnathodus semiglaber-Pseudopolygnathus multistriata* zone, and *Bactrognathus-Polygnathus communis* zone) of the late Kinderhookian and early Valmeyeran (Drahovzal, 1967, p. 12).

The Fort Payne Chert of northern Alabama contains the characteristic Keokuk forms, *Spirifer logani* and *Brachythyris suborbicularis,* and thus is correlative with at least the Keokuk of the Mississippi Valley (Drahovzal, 1967, p. 14). Fossils representative of Kinderhook, Fern Glen, Burlington, and Keokuk have been collected from the Fort Payne Chert at several places in Alabama (Butts, 1926, p. 166–167). Butts (1926) evidently included the Maury Shale with the Fort Payne, and, exclusive of the basal shale and associated limestone beds, the

Fort Payne is equivalent to Keokuk (Drahovzal, 1967, p. 14).

The Tuscumbia Limestone in Alabama is equivalent to the Warsaw, Salem, and St. Louis of the Mississippi Valley (Drahovzal, 1967, p. 14). The lower Tuscumbia in northern Alabama contains a Warsaw-Salem fauna, including *Marginirugus magnus, Reticularia setigera,* and *Spirifer bifurcatus*; the upper part of the Tuscumbia contains a St. Louis fauna, characterized by *Lithostrotionella castelnaui* and *Lithostrotion proliferum* (Drahovzal, 1967, p. 14). In northwestern Alabama, the St. Louis coral fauna is found only in small areas, and Butts (1926, p. 175) concluded that the St. Louis is absent except locally.

The Pride Mountain Formation includes the units for which Butts (1926), on the basis of fossil faunas, extended the identification of the Ste. Genevieve, Bethel, Gasper, Cypress, and Golconda formations from the Mississippi Valley to Alabama (Thomas, 1972a, p. 26). The lower limestone unit of the Pride Mountain is recognized as equivalent to Ste. Genevieve because it locally contains abundant *Inflatia inflata* (*Productus inflatus*) (Drahovzal, 1967, p. 16). Butts (1926, p. 187–189) identified the Gasper by the presence of *Campophyllum gasperense, Chonetes chesterensis, Talarocrinus,* and other forms. Butts (1926, p. 184) correlated the underlying sandstone (now the lower sandstone unit of the Pride Mountain) with the Bethel Sandstone because it is overlain by limestone containing fossils "of lower Gasper age." However, the characteristics of *Talarocrinus* above the sandstone in Alabama are more like those of the Renault than those of the Paint Creek in the Mississippi Valley, and the sandstone may be as old as Aux Vases (Drahovzal, 1967, p. 16). Butts (1926, p. 192) identified the Golconda on the basis of *Camarophoria explanata,* and he (p. 189) correlated the underlying sandstone (now the upper sandstone unit of the Pride Mountain) with the Cypress Sandstone on the basis of stratigraphic position. A goniatite fauna from the lower part of the Pride Mountain Formation in northwestern Alabama includes *Goniatites granosus, Neoglyphioceras subcirculare, Girtyoceras limatum,* and *Lyrogoniatites* sp. cf. *L. utahensis* (Drahovzal, 1972, p. 34–35); comparison with sparse goniatites from the Illinois section and with conodont ranges suggests a Hombergian age (J. A. Drohovzal, oral commun., 1978).

The lower part of the Monteagle Limestone of northeastern Alabama contains a Ste. Genevieve fauna, characterized by *Platycrinites penicillus* (*Platycrinus huntsvillae*) (Butts, 1926, p. 182; Drahovzal, 1967, p. 16). The upper part of the Monteagle contains a Gasperian fauna, including *Chonetes chesterensis* (Drahovzal, 1967, p. 18). Golconda equivalents have not been found in the Monteagle in Alabama (Drahovzal, 1967, p. 19); however, Butts (1926, p. 191) reported *Pterotocrinus capitalis* from the section farther northeast in Tennessee.

The Hartselle Sandstone has been correlated with the Hardinsburg Sandstone of Illinois on the basis of stratigraphic position between beds containing Golconda and Glen Dean faunas (Butts, 1926, p. 195).

The lower part of the Bangor Limestone contains a Glen Dean fauna, including *Prismopora serrulata, Pentremites pyramidatus,* and *Pentremites brevis* (Butts, 1926, p. 199). More recent work has confirmed the correlation of lower Bangor with Glen Dean on the basis of *Pterotocrinus depressus* and *Pentremites robustus-maccalliei* (Drahovzal, 1967, p. 20) as well as nonfenestrate bryozoans (McKinney, 1972). The age of the upper part of the Bangor is less well established. *Pterotocrinus tridecbrachiatus* from near the top of the Bangor in north-central Alabama indicates correlation with the Kinkaid Limestone of Illinois (Drahovzal, 1967, p. 21). Drahovzal (1967, p. 21) reported a blastoid fauna, tentatively identified as *Pentremites laminatus,* that by correlation with conodont zones in Arkansas suggests correlation of the highest Mississippian beds in Alabama with the Grove Church Formation of the Mississippi Valley.

The Floyd Shale contains fossils at few places. Butts (1926, p. 204) reported brachiopod-bryozoan faunas that indicate an age range of at least Gasper to Glen Dean. Rock-stratigraphic correlations show that the Floyd grades laterally into units of the carbonate facies between the Tuscumbia and the lower part of the Bangor.

Fossils have been collected from several outcrops of the Parkwood Formation in the Appalachian fold and thrust belt. Butts (1926, p. 206) reported a collection from the Parkwood Formation that was "a mixture of Pennsylvanian and Mississippian fossils" and listed *Derbya kaskaskiensis* and *Hustedia mormoni,* Pennsylvanian forms, and *Spirifer leidyi* and *Reticularia setigera,* Mississippian forms. The lower part of the Parkwood contains Mississippian fossils such as *Archimedes* and *Fenestella tenax* (Butts, 1926, p. 206). A collection from a sandstone in the upper part of the Parkwood is probably of Pennsylvanian age, but G. H. Girty (in a communication quoted by Butts, 1927, p. 13) expressed caution about the age assignment. The collection includes such forms as *Spirifer rockymontanus*, *Composita subtilita*, and *Deltopecten occidentalis* (Butts, 1926, p. 206; 1927, p. 13). Fossil plants of Pocahontas age have been reported from the upper part of the Parkwood (Moore and others, 1944, p. 686). On the basis of these data from outcrops along Appalachian structures, the lower part of the Parkwood has been considered Mississippian and the upper part, Pennsylvanian (Butts, 1927, p. 13; Culbertson, 1963a, p. E49; Wanless, 1975, p. 23).

The Parkwood clastic facies grades laterally into the Bangor Limestone, and the two facies intertongue across a wide area. The rock-stratigraphic relationship suggests that the Parkwood and Bangor are temporally equivalent. However, the Bangor contains a well-documented Mississippian fauna, and time equivalence of Bangor and Parkwood is incompatible with the reported Pennsylvanian fossils of the upper Parkwood along Appalachian synclines. Possibly, differences in faunas of the Parkwood and Bangor reflect paleoecologic controls rather than time-stratigraphic controls.

On the basis of rock-stratigraphic relationship, the Pennington Formation is considered to be equivalent to the upper part of the Bangor Limestone (Thomas, 1972a, p. 89).

In a detailed investigation of crinoids in Mississippian rocks in Alabama, Burdick (1971) recognized three successive crinoid zones, in ascending order, the *Platycrinites penicillus* zone, *Talarocrinus* zone, and *Agassizocrinus* cf. *A. conicus* zone. The *Platycrinites penicillus* zone is distinctive of Ste. Genevieve; *Talarocrinus*, of lower Chesterian; and *Agassizocrinus* cf. *A. conicus*, of middle and upper Chesterian. The crinoid zones have been defined for the Mississippi Valley region, and Burdick (1971) found that in the Alabama section, the three zones are mutually exclusive. In Alabama, the *Platycrinites penicillus* zone is in the lower part of the Monteagle Limestone in northeastern Alabama and in the Pride Mountain Formation of northwestern Alabama (Burdick, 1971, p. 19). The *Talarocrinus* zone is recognized in the upper part of the Monteagle and in the Pride Mountain (Burdick, 1971, p. 20). The *Agassizocrinus* cf. *A. conicus* zone in Alabama is found as low as the base of the Hartselle Sandstone and extends through the stratigraphically higher beds of the Hartselle, Bangor, and Pennington formations (Burdick, 1971, p. 21–22).

BASE OF POTTSVILLE AND PROBLEM OF MISSISSIPPIAN-PENNSYLVANIAN BOUNDARY

The lower part of the Pottsville Formation in northern Alabama is a massive quartzose sandstone and quartz-pebble conglomerate. Conglomeratic beds locally include carbonized plant fragments and siderite pebbles. The sandstone unit is as much as 200 m thick but that includes a persistent middle shale interval (Culbertson, 1963a, fig. 193.1).

Traditionally, the base of the Pottsville in Alabama has been regarded as part of a regional unconformity beneath the massive sandstone. The upward succession from prodelta shales of the Floyd, to distributary-front and marine-bay sandstones and shales of the Parkwood, and to delta-plain and barrier sandstones of the Pottsville suggests continuous sedimentation rather than a major unconformity. Channel fillings at the base of the massive sandstone may reflect local channels within the delta plain. The Pennington-Pottsville contact may be interpreted similarly. Where the Pottsville overlies the Bangor Limestone, the gradational interval is relatively thin, but the succession commonly includes components of an upward transition from shallow-marine limestone to deltaic and coastal clastic sediments. The geographic extent of the Bangor Limestone is limited by Mississippian clastic facies that prograded onto the carbonate shelf from the southwest (Parkwood) and northeast (Pennington). Continuation of those processes evidently resulted in more widespread progradation of the overlying Pottsville sediments to completely cover the area of Bangor Limestone deposition in north-central Alabama. Thus, the contact of the Pottsville with the underlying Mississippian System can be regarded as part of a depositional continuum rather than as part of a regional unconformity.

The base of the massive sandstone at the base of the Pottsville commonly has been considered to mark the approximate position of the Mississippian-Pennsylvanian boundary. In part, that age assignment is based on the assumption of a regional unconformity coincident with a systemic boundary. In Alabama, Mississippian rocks are clearly documented by biostratigraphic data. Beds above the base of the massive sandstone of the lower Pottsville contain plant fossils, palynomorphs, and some invertebrate fossils that are of Pennsylvanian age (Butts, 1926, p. 213; Upshaw, 1967). However, available biostratigraphic

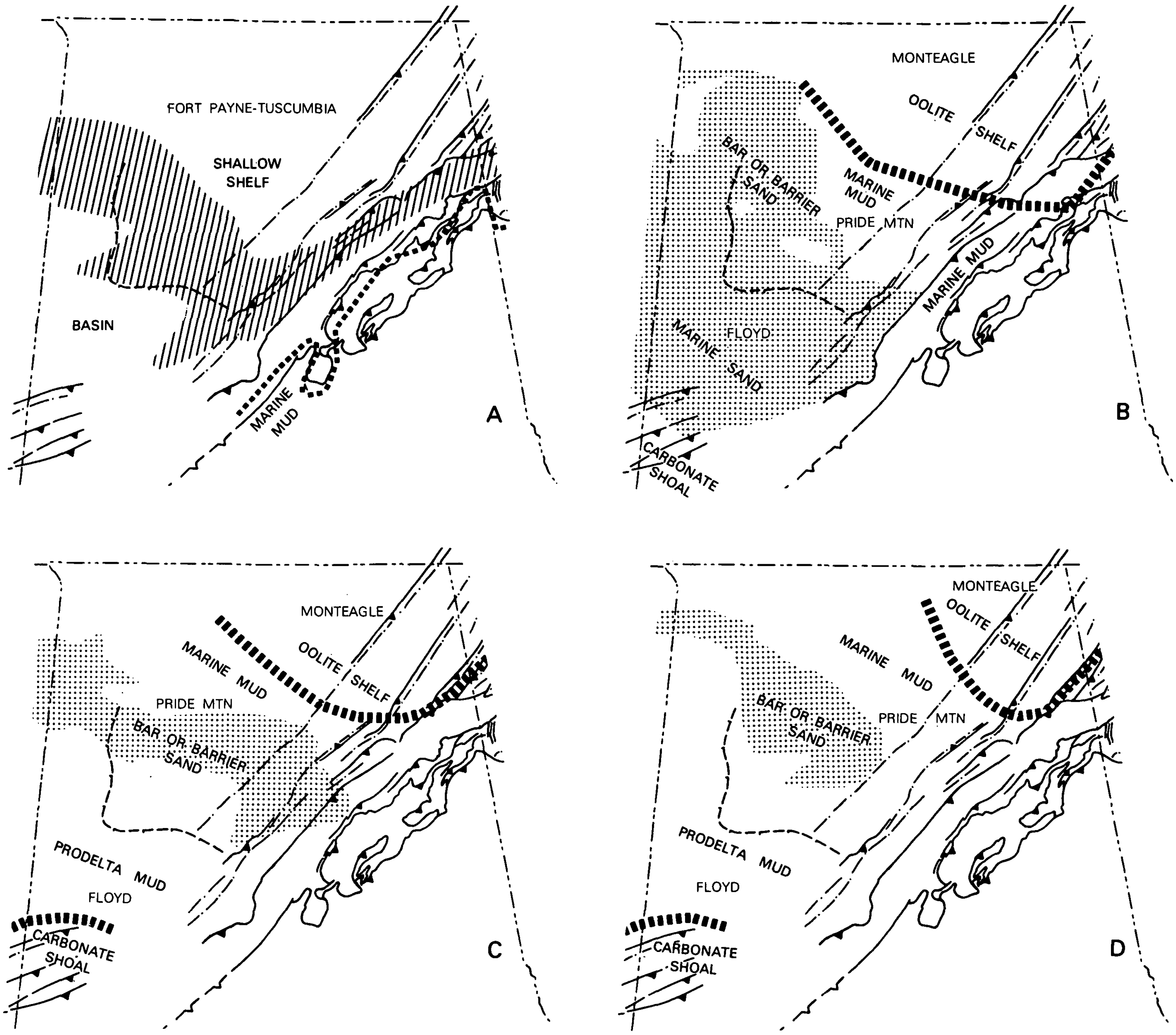
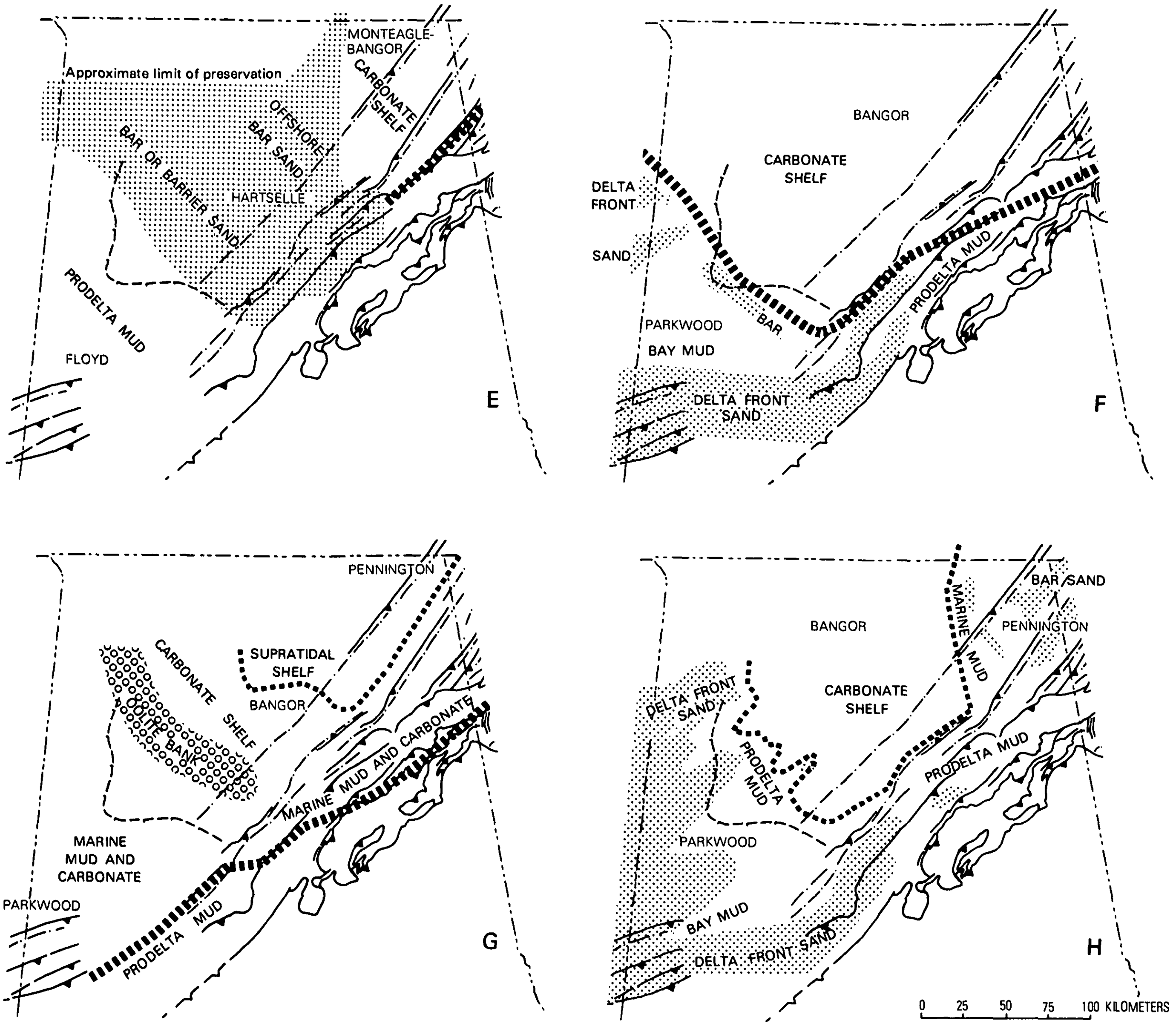


FIGURE 5.—Generalized lithofacies and paleogeographic maps of Mississippian rocks in Alabama. Approximate stratigraphic position of each map is shown by letter on cross sections in figure 2.

data do not precisely define the Mississippian-Pennsylvanian boundary.

Available data indicate that the stratigraphically highest part of the Bangor is of Mississippian age. In northeastern Alabama, the Pennington Formation grades into the upper part of the Bangor and thus appears to be equivalent to the Bangor. Farther northeast, the upper part of the Pennington apparently is continuous with the Raccoon Mountain Formation in Tennessee, and the Raccoon Mountain Formation commonly is considered to be Pennsylvanian (Culbertson, 1963b; Milici, 1974, p. 118). These correlations do not conform to a single time-stratigraphic surface at the systemic boundary. Spores from a coal bed in the Raccoon Mountain Formation of Alabama have "definite Chesterian affinities" (Wilson, 1965, p. 49), and invertebrate fossils from equivalents of the Raccoon Mountain Formation in the northeast corner of Alabama are Mississippian (Milici, 1974, p. 118).

Faunas of the Bangor Limestone are characteristic Mississippian forms; however, Butts (1926, p. 206; 1927, p. 13) reported both Mississippian and Pennsylvanian fossils from the Parkwood. A Mississippian fauna in the Bangor and the reported Pennsylvanian fossils in the Parkwood seem incompatible with the observation that the Parkwood and Bangor formations intertongue both in the Black Warrior basin and in Appalachian synclines. Possibly the differences in the faunas reflect the dif-



A. Fort Payne-Tuscumbia, B. Floyd/lower Pride Mountain/Monteagle. C. Floyd/middle Pride Mountain/Monteagle. D. Floyd/upper Pride Mountain/Monteagle. E. Floyd/Hartselle/Monteagle-Bangor. F. Lower Parkwood (example of prograding sandstone)/Bangor. G. Parkwood (example of limestone tongue)/Bangor/lower Pennington. H. Upper Parkwood (example of prograding sandstone)/Bangor/upper Pennington.

ferent sedimentary environments. Outcrops along the Cahaba syncline offer the best opportunity for detailed study of the relative importance of paleoecology and biostratigraphic position in controlling variations in local fossil faunas of the Bangor and Parkwood. Fossilferous units include the limestone of the Bangor as well as both shale and sandstone of the Parkwood. Along the Cahaba syncline, stratigraphic positions of the different faunas may be mapped accurately with respect to both vertical succession and facies boundaries. Detailed studies could provide understanding of time-dependent variations in the faunas of both the carbonate and clastic facies as well as time correlation between the faunas of the two intertonguing facies. The problem of biostratigraphic identification of the Mississippian-Pennsylvanian boundary is a common one, and the outcrops along the Cahaba syncline provide an opportunity for a significant contribution to understanding of that problem.

DEPOSITIONAL AND TECTONIC FRAMEWORK

The Fort Payne-Tuscumbia chert and cherty limestone succession reflects deposition on a broad shallow-marine shelf on the East Warrior platform (fig. 5A). On the southwest in the Black Warrior basin, the Fort Payne-Tuscumbia is thinner, and vertical differentiation of two rock types is indistinct. Thinning off the platform may be a result of less rapid accumulation of bioclastic sediment in lower energy environments, and possibly the thinner section in the basin represents the same time span as the thicker section on the platform. Alternatively thinning may be a result of lateral gradation of the upper part of the Tuscumbia into the northeast-prograding clastic facies. Another suggested alternative is that thinning results from an unconformity at the top of the Tuscumbia (Welch, 1959). Toward the southeast, the Fort Payne-Tuscumbia thins off the East Warrior platform into Appalachian synclines, and the entire cherty unit pinches out locally. Interbeds of limestone in the Floyd Shale suggest that the Fort Payne-Tuscumbia grades vertically and laterally southeastward into the clastic facies. Higher on the East Warrior platform toward the northeast, dolostone interbeds are more common. In northwest Georgia, the dolostone is associated with quartz geodes containing relict anhydrite (Chowns, 1972, p. 90). The suggested sabkha environment (Chowns, 1972, p. 90) is on the presumably highest supratidal part of the platform.

The oolitic and bioclastic limestones of the Monteagle and Bangor indicate high-energy environments on a shallow-marine shelf (fig. 5). The massive crossbedded units are laterally discontinuous, and interbeds of lime mudstone and shaly limestone suggest deposition in protected areas between carbonate bars. The prolific marine invertebrate fauna includes corals, echinoderms, brachiopods, and bryozoans. Thick units of oolitic limestone in the Monteagle are limited to northeastern Alabama, but in the Bangor, massive linear units of oolitic limestone across the southwestern part of the East Warrior platform suggest a high-energy shelf-edge system (fig. 5G). Southwest of the oolite shelf, the Bangor Limestone tongues reflect lower energy environments in the Black Warrior basin, and components of a shelf, ramp, and basin sequence can be identified (Scott, 1976, p. 720). The southwestward gradation from carbonate to clastic facies extends into the Appalachian synclines, but the limestones suggest lower energy environments, presumably in deeper water in contemporaneous synclines off the southeastern edge of the shelf.

The clastic facies on the southwest is composed of a prograding succession of prodelta shales (Floyd) and delta-front sandstones (Parkwood). The clastic facies makes up most of the Mississippian System in the Black Warrior basin and along the deeper Appalachian synclines. A tongue of shale and sandstone (Pride Mountain and Hartselle) extends from the lower part of the clastic facies northeastward onto the East Warrior platform, where the Mississippian is otherwise dominated by the carbonate facies.

The Pride Mountain and Hartselle include four sandstone units that are broadly linear in distribution and that trend southeast across the southwestern part of the East Warrior platform (figs. 5B, 5C, 5D, and 5E). The sandstone units in the Pride Mountain contain limestone beds and locally grade laterally to limestone. Toward the northeast, the Pride Mountain sandstones grade into marine shales that, farther northeast, are replaced by oolite bars of the Monteagle (figs. 5B, 5C, and 5D). In contrast, the Hartselle Sandstone extends eastward and pinches out within the carbonate facies. Toward the southwest, the linear sandstones pinch out into gray shale of the Floyd. Northwestward along trend, the linear sandstones extend across the platform edge and into the Black Warrior basin in Mississippi, where the sandstones are more blanketlike (Thomas, 1972b, p. 98; 1974, p. 196). The linear sandstones end southeastward along trend in the Appalachian fold and thrust belt (figs. 5B, 5C, 5D, and 5E). Although that aspect of sand distribution may be a function of the sediment-dispersal system, evidently the linear sandstones were limited mainly to the shallow platform and did not extend far southeast into the contemporaneously subsiding Appalachian synclines. Contemporaneous slump faults in the basal beds of the Hartselle Sandstone indicate paleoslopes in the direction of structural dip on both limbs of the Birmingham anticlinorium (Thomas, 1968).

Sedimentary structures in the Pride Mountain-Hartselle sandstones indicate a variety of depositional processes characterized by high-energy environments. Tidal channels are indicated by local rock-clast conglomerate. Lateral and vertical associations of rock types and sedimentary structures in the Hartselle of northwestern Alabama indicate the effects of both longshore and tidal currents (Beavers and Boone, 1976, p. 12). Tree fossils, especially the stump reported from the Hartselle (McCalley, 1896, p. 171–176), suggest partly forested areas. Shells of marine organisms are concentrated locally in the high-energy sands. Near the eastern limit of Hartselle Sandstone, sandstone and oolitic bioclastic limestone are interlaminated in crossbedded high-energy bar deposits.

The linear shapes of the Pride Mountain-Hartselle sandstone units and distribution of the sandstone relative to that of the major carbonate and clastic facies suggest deposition as a succession of bar or barrier sand complexes (Thomas, 1972a, p. 105; 1974, p. 200). The linear sandstones are within a clastic tongue that extends northeastward from the lower part of the Floyd Shale, and the Floyd is overlain by the Parkwood Formation, which contains northeastwardly prograding deltaic sandstones. However, the Parkwood sandstones are evidently younger than the Pride Mountain and Hartselle sandstones, and the source of the Pride Mountain and Hartselle sands is not conclusively established. Swann (1964, p. 653) suggested that sand supplied through the Illinois basin by the Michigan River system prograded as far south as the Black Warrior basin. Regardless of the source of sand, the Pride Mountain-Hartselle sandstones are distributed along the boundary between the regional carbonate and clastic facies, and the orientation of the linear sandstones suggests a high-energy environment near the southwestern edge of the East Warrior platform. The more blanketlike sandstones in the Black Warrior basin in Mississippi are interpreted to be marine sands. More precise definition of environments represented by the linear sandstones will result from better understanding of their relation to facies in the Floyd Shale on the southwest, of the system of sand supply, and of sedimentary features within the sandstones.

Along the Coosa synclinorium, the Bangor Limestone Tongue in the Floyd Shale demonstrates intertonguing of the clastic and carbonate facies. Farther east in Georgia, the clastic sequence contains two limestone tongues—a tongue of Bangor Limestone and a lower limestone tongue in the Floyd Shale in the stratigraphic position of the Tuscumbia and (or) Monteagle. The lower limestone may extend southwest as far as the northeast end of the Coosa deformed belt, but there it evidently grades southwestward to the shale facies in a pattern similar to the southwestward gradation from Monteagle Limestone to shale on the East Warrior platform.

Along the Pickens-Sumter anticline south of the Black Warrior basin in the subsurface in west-central Alabama, the lower part of the Floyd Shale includes limestone beds (figs. 5B, 5C, and 5D) that are in the same stratigraphic position as the sandstone units in the Floyd and Pride Mountain on the East Warrior platform, but no genetic relationship is apparent. Possibly the limestones denote a local carbonate shoal associated with a contemporaneous Pickens-Sumter anticline; alternatively, they may mark the northern edge of a more extensive carbonate shelf that extends farther south into the fold and thrust belt.

The Floyd Shale constitutes a prodelta mud deposit that grades upward into deltaic sediments of the Parkwood Formation. Parkwood sandstones are interpreted to be delta-front and distributary sediments that are interbedded with marine-bay shale and mudstone (figs. 5F, 5G, and 5H). Distribution of the sandstones suggests northeastward prograding from a sediment source southwest of the Black Warrior basin of western Alabama and eastern Mississippi. The more sandy part of each of the Parkwood cycles reflects a major episode of delta prograding. The shaly parts of the Parkwood include interdistributary-bay sediments and contain extensive tongues of the Bangor Limestone which denote transgression and delta destruction. Bay-fill fine clastic sediments generally grade upward to distributary-front sandstones. A few of the sandstones were deposited on scoured surfaces evidently in small distributary channels. Most Parkwood sediments are in the marine-delta front and interdistributary-bay facies; little of the succession suggests delta-plain deposits. Sedimentary features and fossil faunas of the Parkwood suggest a near-shore marine environment (Whisonant, 1970, p. 141). Interdistributary marsh deposits in the locally carbonaceous uppermost beds of the Parkwood represent the highest preserved part of the delta complex. Later Parkwood sandstones are more extensive than older ones, and the upper part of the Parkwood progrades northeastward onto the southwestern edge of the East Warrior platform. The Parkwood grades upward into conglomerate, sandstone, shale, and coal of the Pottsville Formation, which progrades northeastward farther than the Parkwood and overlies the Bangor Limestone on the East Warrior platform.

The Floyd-Parkwood clastic facies is much thicker and extends farther northeast along the Appalachian synclines than in the Black Warrior basin and East Warrior platform. The same general pattern of cyclical delta progradation and transgression is recognizable within the Parkwood Formation in the synclines. The greater thickness and extent of the clastic facies suggest that the synclines subsided contemporaneously with Mississippian deposition and that the structural troughs provided channels along which sediment was selectively transported northeastward. Distribution of sandstone in the Parkwood in the Cahaba syncline does not parallel that in the Coosa synclinorium. Sections in the Cahaba syncline generally contain about 50 percent more sandstone than sections across strike in the Coosa synclinorium; however, the total thickness of the section in the Coosa synclinorium averages 25 percent greater than that in the Cahaba syncline. These distribution patterns suggest contemporaneous downwarp of two separate synclines. Northeastward prograding of the Parkwood, northeastward decrease in sandstone, and southwestward thinning of the Bangor Limestone are compatible with the interpretation that the clastic sediment was transported longitudinally northeastward along the synclines from a source on the southwest. Thus, a regionally consistent pattern of northeastward progradation and a provenance on the southwest are indicated for the Floyd-Parkwood clastic sediments in both the Black Warrior basin and the Appalachian synclines (Thomas, 1972a; 1974, p. 203).

Other interpretations have been proposed for location of the provenance and dispersal system of Parkwood clastic sediments. Crossbedding in Parkwood sandstones in the Cahaba and Coosa synclines shows significant modes toward both the north-northwest and the south-southwest (Whisonant, 1967, p. 1871). Citing the interpretation of crossbedding and heavy-mineral data indicative of a metasedimentary provenance, Whisonant (1967, p. 1872) postulated possible northwestward transport from a sediment source on the southeast in the Appalachian Piedmont. However, that provenance location and transport direction are not supported by the regional distribution of the Parkwood clastic facies and the equivalent carbonate facies. Furthermore, Carrington (1967, 1972) concluded that some metasedimentary rocks in the Piedmont represent Parkwood-equivalent sediments.

Another alternative for the Parkwood dispersal system is derived from regional studies of the Michigan River system deltaic sediments in the Illinois basin (Swann, 1964). Swann (1964, p. 653) suggested that at some times the Michigan River system prograded southward from the Illinois basin and transported sediment to the northeastern edge of the Ouachita trough and the western part of the Black Warrior basin. Welch (1971) concluded that Mississippian sandstones in the Black Warrior basin were supplied from the north, probably through the Illinois basin. That interpretation requires that Parkwood deltaic sediments prograded southward or southeastward into the Black Warrior basin.

In northeastern Alabama, the Pennington Formation constitutes a clastic facies that prograded southwestward onto the carbonate-shelf sediments of the Bangor Limestone (figs. 5G, 5H). Evidently the location of the facies boundary was not influenced by a shelf edge. The dolostone unit in the lower Pennington suggests a supratidal shelf that was subsequently covered by shallow-marine fine clastic sediments (fig. 5G). The shallow-marine mudstone and limestone are supplanted farther east by sandstone, shale, and carbonaceous beds that represent marine bays, small bars, and coastal lagoons and marshes (fig. 5H). Lateral gradation of a coal bed to brachiopod-bearing siderite, and interfingering of bar sandstone with marine shale, suggest small-scale environmental features on a plain nearly at sea level. The Pennington is overlain by massive sandstones of the Pottsville Formation which constitute a coarser fraction of the southwest-prograding clastic complex. The Pottsville extends beyond the Pennington clastic succession and overlies the Bangor Limestone farther west.

Provenance and dispersal studies of Pottsville sandstones in Alabama have implications for interpretations of underlying Mississippian clastic sediments. Crossbedding in the basal Pottsville sandstones of northeastern Alabama indicates transport toward the west or southwest (Tanner, 1959, p. 224; Schlee, 1963, p. 1446; Chen and Goodell, 1964, p. 70; Metzger, 1965, p. 27). This direction is most persistent in northeastern Alabama, where the Pottsville overlies the Pennington clastic facies, and beyond the western limit of the Pennington, where the Pottsville progrades over the Bangor Limestone. In Northwestern Alabama, crossbedding orientation is more diverse (Schlee, 1963, pl. 1; Metzger, 1965, p. 27). On the basis of geometry of beach and barrier-island sandstones of the basal Pottsville, Hobday (1974, p. 223) concluded that two sediment supply systems (from the northeast and from the south) merged in north-central Alabama. Compositional variation in Pottsville sandstones of central Alabama indicates a source on the south (Davis and Ehrlich, 1974, p. 177). These interpretations may be assembled to suggest that the Pottsville of Alabama includes two components that converged on the East Warrior platform from the northeast and from the south. Thus, the northeast-prograding Parkwood continues upward into one component of the Pottsville and the southwest-prograding Pennington continues upward into the other component.

Mississippian clastic rocks in Alabama are parts of two regional clastic wedges in the Appalachian-Ouachita structural system (Thomas, 1974, p. 206; 1977). The Floyd-Parkwood-Pottsville clastic sequence is part of a large-scale clastic wedge centered on the Ouachita structural salient. The Mississippian-Pennsylvanian clastic sequence extends from Alabama westward in the subsurface across the Black Warrior basin in Mississippi toward the Ouachita Mountains, where the thickness is much greater than that in the Black Warrior basin. The wedge includes a lower unit of shale (Stanley of Ouachita Mountains; Floyd of Black Warrior basin) and an overlying succession of sandstone and shale (Jackfork-Atoka of Ouachita Mountains; Parkwood-Pottsville of Black Warrior basin). Depositional features of the Ouachita sediments indicate a deep-water flysch environment (Cline, 1960, p. 100; 1970, p. 100), whereas the thinner sequence on the east in the Black Warrior basin comprises a prograding delta system (Thomas, 1974, p. 200). The indicated dispersal pattern suggests a common source area southeast of the Ouachitas and southwest of the Black Warrior basin (Thomas, 1974, p. 202; 1976, p. 337).

Similarly, the southwest prograding Pennington clastic facies in northeastern Alabama is evidently at the southwestern fringe of a large-scale clastic wedge centered farther northeast (Thomas, 1977, p. 1258). The center of that wedge appears to be within the Tennessee structural salient, probably in southwestern Virginia, where the Pennington is much thicker and coarser than it is in Alabama. Regional facies relations indicate that Upper Mississippian clastic sediments prograded southwestward along the Appalachians in Tennessee (Ferm and others, 1972, fig. 3). In Alabama, the Pennington at the fringe of the wedge grades southwestward into the carbonate facies. The overlying southwest-prograding Pottsville clastic sequence extends farther west and southwest above the Bangor Limestone.

Mississippian-Pennsylvanian clastic wedges prograde from southwest and northeast onto the shallow-marine carbonate facies in the Bangor Limestone in north-central Alabama. Each of the two converging clastic wedges is centered on a regional structural salient (Ouachita and Tennessee salients), and the intervening carbonate facies is within a regional structural recess in Alabama (Thomas, 1977).

The Black Warrior basin and East Warrior platform are reflected in distributions of thickness and facies throughout the Mississippian System. However, the Fort Payne-Tuscumbia rocks show gradual southwestward change, whereas the younger Bangor and Parkwood facies reflect a relatively abrupt change at the platform edge. Possibly the East Warrior platform and the western edge of the platform became more pronounced in the later Mississippian. Facies and thickness of the Mississippian System indicate contemporaneous subsidence of the Appalachian synclines southeast of the East Warrior platform.

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PENNSYLVANIAN STRATIGRAPHY OF ALABAMA

CONTENTS

ILLUSTRATIONS

TABLE

THE MISSISSIPPIAN AND PENNSYLVANIAN (CARBONIFEROUS) SYSTEMS IN THE UNITED STATES—ALABAMA AND MISSISSIPPI

PENNSYLVANIAN STRATIGRAPHY OF ALABAMA[1]

By W. Everett Smith [2]

ABSTRACT

Pennsylvanian strata crop out in the northern half of Alabama and underlie much of the State at depth. Folding and faulting and subsequent erosion of the southern Appalachians have resulted in isolation of several outcrop areas termed the Warrior, Coosa, Cahaba, and Plateau coal fields.

General subdivisions of the rock sequence have been made on the basis of coal groups, floral zones, and lithology. The most recent classification system was proposed by H. R. Wanless, who used the terminology subinterval A_1, and subinterval A_2 and interval B (youngest). Major rock types include sandstone, siltstone, shale, mudstone, underclay, and bituminous coal. The coal is generally ranked as high volatile A to low volatile and ranges from 3 to 15 percent of ash and less than 2 percent of sulfur. Estimates of State coal reserves range from 13.9 billion short tons to 35.5 billion short tons. The several coal fields are generally considered to have been part of a major depositional basin during Pennsylvanian time; however, the fields vary greatly in sediment thickness and lithologic patterns, and most coal beds have not been correlated with certainty between the fields. Most of the Pennsylvanian rocks in Alabama probably are early (Pocahontas) and middle (New River) Pottsville in age. Time transgression of lithologic units in a northeastern direction appears likely, sediment sources being primarily to the south and east.

INTRODUCTION

This paper summarizes basic geologic information and concepts thus far acquired on Pennsylvanian rocks in Alabama. Because of its summary nature, the paper makes all too brief reference to the geologic data and only passing comment or inference on many fundamental concepts and issues. The published information on the Alabama Pennsylvanian System is relatively sparse, and important published reports are now practically inaccessable to many investigators. The writer wishes to call attention early in this discussion to the recently published comprehensive work on the Pennsylvanian System in the United States by McKee, Crosby, and others (1975) which includes discussions of Pennsylvanian rocks in the southern Appalachians by Wanless (1975).

Few geologists have given sufficient attention to Pennsylvanian rocks in Alabama to acquire insight to the whole system. It was only in the 1870's that interest in the coal beds in the Pennsylvanian focused attention on these rocks, and from this early period until the early 1900's, geologic investigations of the Pennsylvanian rocks were essentially descriptions of the coal-bearing horizons. In this respect, Henry McCalley (1891, 1898, 1900) did much of the first field investigations and prepared descriptive reports. Prouty (1912) and Butts (1907, 1910, 1911, 1926, 1927, 1940) were also early contributors. In recent years, Rothrock (1949), Culbertson (1964), Ferm (Ferm and Ehrlich, 1967; Horne, Ferm, and others, 1976), Metzger (1961, 1965), and Thomas (1972) have contributed information on stratigraphy, paleoecology, and tectonism. Recently, many geologists again have given attention to local stratigraphy of Pennsylvanian rocks in connection with exploration for and development of coal.

The stratigraphic nomenclature used in this paper has not been reviewed by the Geologic Names Committee of the U.S. Geological Survey. The nomenclature used here conforms with the current usage of the Geological Survey of Alabama.

DISTRIBUTION

Rocks of Pennsylvanian age crop out in northern Alabama and underlie much of the State at depth. Folding and faulting and subsequent erosion of the southern Appalachians have resulted in isolation of several different outcrop areas which are herein referred to as coal fields.[3] Four major fields are the

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[3] Some geologists now refer to these areas as coal basins or use the term "basin" synonymously with the term "field," although it should be recognized that the two terms in the strictest sense carry different connotations.

Warrior, Plateau, Coosa, and Cahaba.

The Warrior field (Mellen, 1947; McCalley, 1898, 1900; Metzger, 1965; Wanless, 1975) is the largest outcrop area of Pennsylvanian rocks in Alabama, comprising approximately 12,680 km² in the northwestern quarter of the State. Mellen (1947) proposed that the Warrior basin be defined as a triangular area of approximately 35,000 sq mi of normal Paleozoic sediments bounded on the north by Tennessee, on the southeast by the southwest-plunging Appalachian Mountains of Alabama, and on the southwest by the buried Ouachita Mountains of eastern Arkansas and northern Mississippi. Mellen (1947) noted that this area, whether or not correctly described as a basin, has been one of great negative epeirogenic tendency.

Physiographically, the area of the Warrior field not covered by Coastal Plain sediments is part of the Cumberland Plateau. The field is bounded on the north by the southern flank of the Nashville dome and on the southeast by folds and thrust faults of the Sequatchie Valley anticline and faulted anticlines of the Bessemer-Birmingham valley. On the southwest, in the subsurface the field may be limited by concealed thrust faults (Wanless, 1975; Kidd, 1976). Strata of the Warrior field dip south and thicken in the same direction. The field is structurally less complex than other areas in the State, but gentle folds, large-scale joint features, and normal and reverse faults of significant magnitude are found in the field. Sediments in the Warrior field include eight[4] coal groups having more than 20 minable beds in some part of the field. Gas is being produced from Mississippian horizons underlying the field in northwestern Alabama.

The Plateau field is the name given to several coal-bearing plateau areas in northeast Alabama similarly divided by eroded anticlines. The field includes more than 11,660 km² including Lookout Mountain, Blount Mountain, Altoona Mountain, Sand Mountain (Raccoon Mountain), West Sand Mountain, and many small remnant mountains in extreme northeastern Alabama. Some geologists also include in the Plateau field certain areas that other geologists consider the northern part of the Warrior field, particularly those outcrop areas of coal beds below the Black Creek coal bed. The Pennsylvanian rocks in the Plateau region contain more than 25 coal beds.

The Coosa field is a folded and faulted synclinorium, which includes approximately 725 km². It is about 96 km long, about 8 km wide and contains more than 15 coal beds of mineable thickness. The Cahaba field southeast of Birmingham includes an area of approximately 906 km² and contains about 60 coal beds. The several coal fields are considered to have been more or less continuous during Pennsylvanian time; however, the fields vary greatly in rock thickness and lithologic patterns, and most coal beds have not been correlated with certainty between the fields.

In the subsurface, Pennsylvanian rocks in Alabama have been identified as far south as Marengo County (Kidd, 1976). South of central Marengo County, these rocks have not been identified; they are apparently covered by thrust-faulted older rocks (Kidd, 1976). This thrust faulting is hypothesized to have been generally toward the northwest and generally along a line extended from southern Bibb County through southern Sumter County and into Mississippi. Kidd (1976) also indicated thrust faulting of older sedimentary rocks over Pennsylvanian rocks in southern Greene and northern Sumter Counties. Kidd's map of the configuration of the top of the Pennsylvanian rocks in west-central Alabama (Kidd, 1976) shows a dip to the southwest into Missisipi.

South of the Appalachian Valley and Ridge province in Alabama, Pennsylvanian-age rocks appear to be terminated, possibly by thrust-faulted older sedimentary rocks or by metamorphic rocks.

STRATIGRAPHY

White, as reported by Butts (1927), showed that the lower-middle Pottsville boundary in West Virginia is approximately at the horizon of the Black Creek coal in the Alabama Warrior coal field. Read, as reported by Metzger (1965), identified and determined the ages of plant remains in the uppermost exposed beds of the Warrior field (above the guide coal seams) to be latest early New River. Thus, most of the Pennsylvanian rocks in Alabama probably are early (Pocahontas) and middle (New River) Pottsville in age. Palynology studies by Upshaw (1967) are in accord with these age assignments, although Upshaw (1967) pointed out that precise age equivalents cannot be established because detailed palynological studies of Pocahontas and New River type sections have not been made. Upshaw

[4] Six coal groups were recognized by McCalley (1900), including the Brookwood, Gwin, Cobb, Pratt, Horse Creek (including the Mary Lee coal), and Black Creek. In recent years, the Utley coal group has been recognized. In addition, the term "J group" has been used by some geologists and miners, in reference to the J, K, L, and M beds which are below the Black Creek coal group in the Blue Creek basin.

further suggested that beds older than the lowest Pottsville of the type area (and older than the lowest Morowan of Arkansas) may be included in the Pottsville Formation of Alabama. West of Alabama, in the subsurface of Mississippi, beds of Kanawha age are included with the Pottsville unit and contain abundant *Laevigatosporites ovalis* in association with *Endosporites globifermis* (Upshaw, 1967, p. 18). The studies by Upshaw show time transgression of lithologic units to be all in a northeastern direction. Ferm and Ehrlich (1967) supported this concept of time transgression of lithologic units.

Butts (1926, p. 206) assigned all Pennsylvanian rocks in Alabama (except those of the Erin Shale) to the Pottsville Formation. He considered the Parkwood to be part of the Mississippian sequence and placed the base of the Pennsylvanian in Alabama at the base of the Brock coal bed, which he judged to be at a horizon in the lower Pottsville Formation as low as the lowest Pennsylvanian throughout the Appalachian coal fields. He noted however that the upper Parkwood may include a mixture of Pennsylvanian and Mississippian fossils, and that no sharp line of division appears within the Parkwood that would serve as a division line between the Mississippian and Pennsylvanian (See discussion by Thomas, this chapter for detailed discussions of Mississippian-Pennsylvanian boundary.) Culbertson (1963, p. 49; 1964) defined the top of the Parkwood as being at the base of sandstone members at the base of the Pottsville Formation, including the Shades Sandstone Member in the Cahaba and Coosa fields, the Boyles Sandstone Member in the Warrior field, and the Lower Conglomerate (McCalley, 1891) in the Plateau field (fig. 6).

Wanless (1975) considered the upper part of the Parkwood Formation to be within the Lower Pennsylvanian. According to Butts (1926) and Wanless, the Erin Shale (phyllite in the metamorphic Talladega Series) is apparently of Pennsylvanian age, although its relationship to other Pennsylvanian rocks is undetermined.

The Pennsylvanian Subcommittee, R. C. Moore, Chairman (Moore and others, 1944), has assigned most of the Pennsylvanian rocks in Alabama to the Morrow Series (Lower Pennsylvanian) which includes Read's (according to Moore, and others, 1944) floral zone of *Neuropteris pocahontas* and *Mariopteris eremopteroides*, floral zone of *Mariopteris Pottsvillea* and *Aneimites*, and floral zone of *Mariopteris pygmaea*. The subcommittee assigned uppermost Pennsylvanian rocks in the Cahaba and Warrior fields to the Kanawha Series (which include Read's (according to Moore and others, 1944) floral zone of *Cannophyllites* and floral zone of *Neuropteris tenuifolia*).

McCalley (1900) proposed a classification of the Pennsylvanian rocks of Alabama based on six coal groups, using the lowest coal within each group as the base. Metzger (1965) proposed a similar system of subdivision but suggested that the most persistent coal bed in each group rather than the lowermost bed be used as the group market. Neither McCalley or Metzger assigned specific names to the various subdivisions, although Metzger, to facilitate discussion of the sediments, designated the units from oldest to youngest as stratigraphic intervals A, B, C, D, E, F, and G.

Wanless' (1975) discussion of the Alabama Pennsylvanian, which is a part of a comprehensive discussion of the Pennsylvanian System of the United States (McKee, Crosby, and others, 1975) uses the classification system set up in that report and classifies Alabama's Pennsylvanian rocks as interval A (containing subintervals A_1 and A_2) and interval B (youngest). This classification system has been used in the present discussion.

Fossils in the Pennsylvanian sequence of Alabama are relatively abundant. Fossil flora are the most abundant, but zones of marine invertebrates also are found. Butts (1926) reported at least four fossiliferous horizons (presumably excluding fossil flora associated with many of the coal beds) in the Warrior field and listed the more common forms (as identified by G. H. Girty) as follows:

Lingula carbonaria
Schizophoria n. sp. (very common)
Derbya crassa
Productus cora semireticulatus
Marginifera muricata
Spirifer rockymontanus
Hustedia mormoni
Composita subtilita
Solenopsis solenoides?
Aviculopecten hertzeri rectilateralis
Deltopecten occidentalis
Myalina swallowi
Pleurophorus tropidophorus
Schizodus aff. *symmetricus*
Edmondia aff. *E. gibbosa*
Leda bellistriata

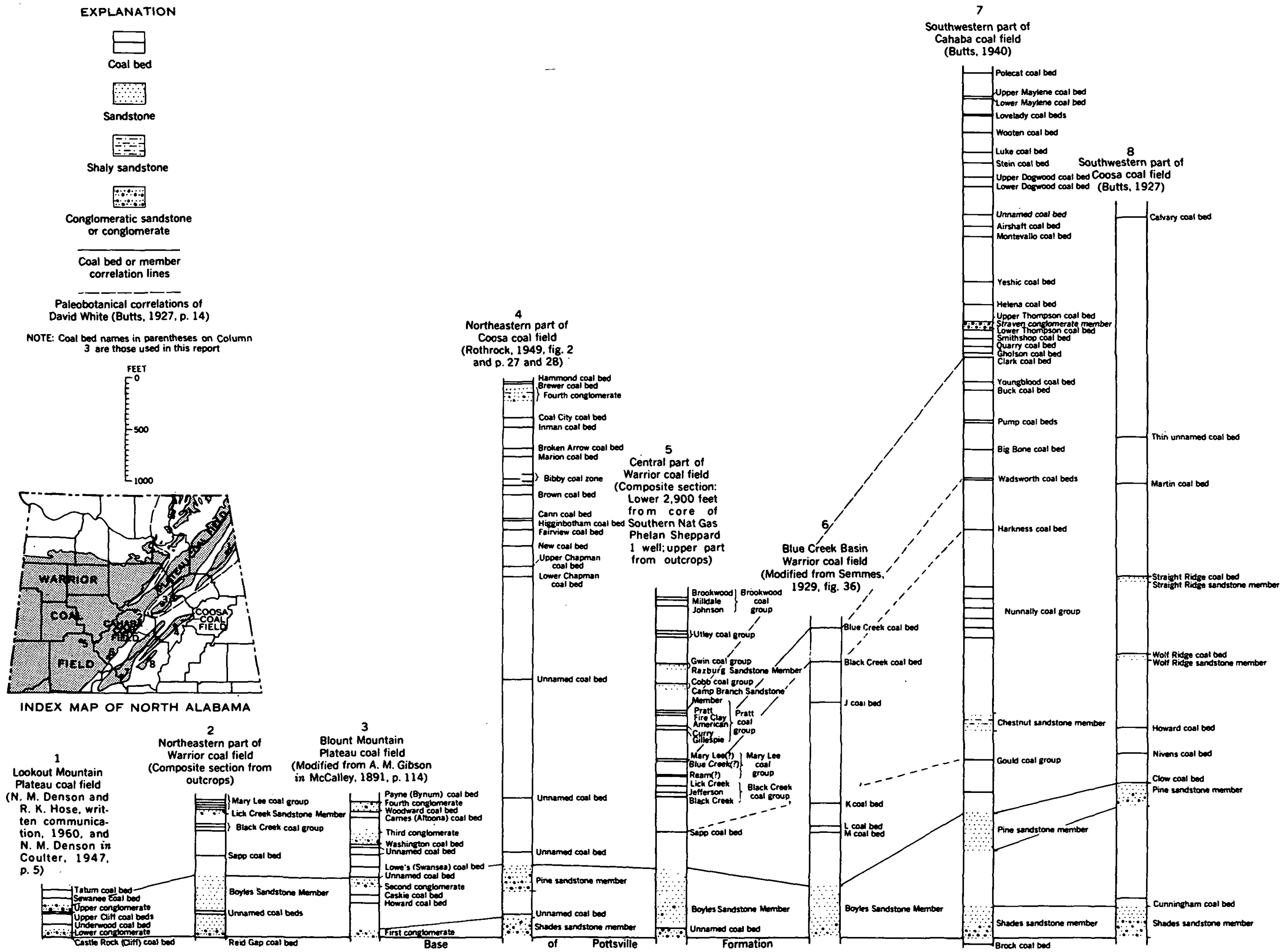

FIGURE 6.—Columnar sections showing position of coal beds and sandstone members of the Pottsville formation in Alabama (from Culbertson, 1964).

Yoldia oweni
Anthracomya (Naiadites) elongata
Estheria dawsoni

Butts (1926) noted that except for the last two fossils, most of the species seem to range through the full thickness of the Pennsylvanian sequence, although they are not restricted to the Pennsylvanian elsewhere in the United States.

Metzger (1965, p. 13) listed the following forms from an exposure in the Warrior field:

Stereostylus sp.
Fenestrellina
Lingula carbonaria Swallow
Orbiculoidea capuliformis (McChesney)
Chonetes choteauensis Mather
Desmoinesia nana (Meek and Worthen)
Dictyoclostus sp.
Juresania ovalis Dunbar and Condra
Linoproductus insinuatus? (Girty)
Schizophoria oklahomae Dunbar and Condra
resupinoides (Cox)
sp.
Spirifer occidentalis Girty
Wellerella osagensis (Swallow)
Dentalium sp.
Plagioglypta sp.
Bellerophon crassus Meek and Worthen
Euphemites carbonarius (Cox)
Phymatopleura nodosus (Girty)
Pseudozygopleura rothi Knight
Straparolus (Amphis capha) reedsi Knight
Trepospira depressa Cox
Worthenia sp.
Gastrioceras sp.
Liroceras liratum (Girty)
Pseudorthoceras sp.
Astartella newberryi Meek
Aviculopinna sp.
Cypricardinia carbonaria Meek
Dunbarella knighti Newell
Edmondia gibbosa (McCoy)?
Nucula anadontoides Meek
subrotunda Girty
Nuculana meekana (Mark)
sp.
Parallelodon tenuistriatus (Meek and Worthen)
Pteria sp.
Schizodus affinis Herrick
cuneatus? Meek
Paladin sp.
Crinoid stems
Thuroholia sp.
Fish teeth, undetermined

Butts (1926) listed fossil flora as *Lepidodendron* sp., *Lepidodendron obovotum, sigillaria mamilloris calamites suckowii, Neuropteris smithii, Pecopteris buttsii*, and *Alethopteris lonchitica*.

McKee (1975) studied Pennsylvanian sedimentary rock-fossil relationships in part of the Warrior field. Several unpublished studies by major oil companies reportedly have been made of Pennsylvanian palynology in the Warrior field. Upshaw (1967) recognized more than 90 species of palynomorphs in the Pennsylvanian sedimentary rocks of the Warrior field and found species of *Lycospora* and *Densosporites* to be numerically dominant in most samples. In addition, he provided a partial list of forms from several stratigraphic positions within the Pottsville sequence (table 1).

TABLE 1.—*A list of selected taxa from Pennsylvanian strata of the Warrior basin, Alabama*
[From Upshaw, 1967]

Taxa	Sample locality[1] (1)	(2)	(3)
Knoxisporites dissidius Neves	×		
Proprisporites laevigatus Neves	×		
Trinidulus diamphidios Felix and Paden	×		
Tricidarisporites fasciculatus (Love) Sullivan and Marshall	×		
Convolutispora florida Hoffmeister, Staplin and Malloy	×	×	
Reinschospora speciosa (Loose) Schopf, Wilson and Bentall	×	×	
Bellispores nitidus (Horst) Sullivan	×	×	
Densosporites irregularis Hacquebard and Barss	×	×	
Crassispora kosankei (Potonio and Kremp) Bhardwaj	×	×	
Knoxisporites triradiatus Hoffmeister, Staplin and Malloy	×	×	
Knoxisporites stephanephorus Love	×	×	
Lycospora uber (Hoffmeister, Staplin and Malloy) Staplin	×	×	×
Lycospora noctuina Butterworth and Williams	×	×	×
Savitrisporites nux (Butterworth and Williams) Sullivan	×	×	×
Florinites visendus (Ibrahim) Schopf, Wilson and Bentall	×	×	×
Wilsonites sp. (100–160 microns)	×	×	×
Cirratriradites saturni (Ibrahim) Schopf, Wilson, and Bentall	×	×	×
Tantillus triquetrus Felix and Burbridge	×	×	×
Ahrensisporites querickei (Horst) Potonie and Kremp	×	×	×
Cristatisporites indignabundus (Loose) Potonie and Kremp	×	×	×
Schulzospora rara Kosanke	×	×	×
Camptotriletes superbus Neves	×	×	×
Discernisporites irregularis Neves	--	×	
Reinschospora triangularis Kosanke	--	×	×
Apiculatisporis variocorneus Sullivan	--	×	×
Laevigatosporites ovalis Kosanke	--	--	×
Dictyotriletes bireticulatus Ibrahim	--	--	×

[1] (1) Below the Black Creek coal including some units assigned to the Parkwood Formation by Culbertson (1963); (2) Black Creek coal to Brookwood coal; and (3) above the Brookwood coal.

SUBINTERVAL A_1

Rocks included in subinterval A_1 are those of the upper part of the Parkwood Formation and those of the lower part of the Pottsville Formation. The upper boundary of subinterval A_1 is considered by Wanless (1975) to be at the base of the Black Creek coal group or the equivalent Harkness coal bed. Culbertson (in Wanless, 1975, p. 29) gives reasons why subinterval A_1 is equivalent to floral zones 4 and 5. According to Culbertson (in Wanless, 1975, p. 29), some workers have mistakenly assumed that the lower part of the Pottsville Formation, as defined by White (according to Butts, 1927), below the Black Creek coal group or the equivalent Harkness coal bed, includes only floral zone 4. No well-established floral-zone fossils mark the top or the base of subinterval A_1 (Wanless, 1975). Wanless has discussed distribution and thickness of strata in subinterval A_1, the northern extent of which may have been in the general vicinity of the present Tennessee River.

Sedimentary rocks of subinterval A_1 are considered to occur in all the coal fields in Alabama and may be represented by the Erin Shale (Wanless, 1975) within the metamorphic Talladega Series. Subinterval A_1 strata are absent on the Plateau remnants in northeastern Alabama but are present south of the Tennessee River. Thomas (1972) has measured approximately 44 m of Parkwood sediment at Isbell quarry in Franklin County, northwest Alabama, but the thickness of Parkwood strata here that can be assigned to subinterval A_1 is unknown. From northern Alabama, subinterval A_1 sedimentary rocks thicken southeastward to a maximum of more than 510 m near Birmingham. Subinterval A_1 sedimentary rocks range in thickness from 900 m to more than 1,500 m in the Cahaba coal field; in the Coosa coal field, they are about 1,500 m thick. In Sumter County in the southern part of the Warrior field, a thickness of 489 m has been reported (Wanless, 1975). Metzger (1965, p. 10) called attention to thinning of the rocks in subinterval A_1 and suggested that inasmuch as the area of thinning is directly in line with the later formed Blountsville or Sequatchie anticline, the sedimentation might have been controlled by local tectonic activity even in early Pottsville time.

Subinterval A_1 strata consist of mudstone, claystone, siltstone, sandstone, conglomerate, and thin coal beds. Sandstone generally is more abundant than the other types of sedimentary rocks in north-central Alabama and is generally less abundant in basins that include thousands of feet of strata (Wanless, 1975). The Parkwood Formation includes both orthoquartzitic sandstone and graywacke sandstone as well as a considerable volume of gray slightly silty shale. Rocks herein referred to as belonging to subinterval A_1 have often been referred to informally as "the lower unproductive zone" in reference to the relatively few thin coal beds within the sequence.

Ferm (Ferm and Ehrlich, 1967), in discussing the general petrology of Pennsylvanian sedimentary rock in Alabama, classified most of the coarser sediments as lower rank graywacke and reported varying proportions of strained and sheared (metamorphic) quartz, sodic feldspar, a great variety of low-grade micaceous metamorphic rock fragments, and some detrital volcanic fragments. Heavy minerals include staurolite, kyanite, epidote, garnet, muscovite, chlorite, tourmaline, and zircon. Studies by Ferm (Ferm and Ehrlich, 1967) also show that components of finer grained sedimentary rocks are similar to those of the coarser grained rocks but include a considerable amount of illite and lesser kaolinite. Ferm (Ferm and Ehrlich, 1967) also stated that quartz content of the low-rank graywackes diminishes from north to south.

The number of coal beds in subinterval A_1 is greatest in the southern Plateau field (Blount Mountain) and in the Coosa and Cahaba fields. These fields contain as many as 15 coal beds, but maximum cumulative thickness is only 4.5 to 5.8 m (Wanless, 1975). The number of beds decreases to the west and northwest. Wanless (1975) pointed out that the average thickness of coal beds in Alabama is remarkedly less than the average thickness of similar-age sediments in the Pocahontas field of Virginia, although the environments of coal deposition were similar. Culbertson (1964) showed stratigraphic position of the coal beds and sandstone members in the lower Pottsville (fig. 1).

Wanless (1975) suggested an easterly or southeasterly sources for subinterval A_1 sediments, citing pattern of grain-size distribution and crossbedding (Schlee, 1963, p. 1448). Metzger (1965) interpreted crossbedding data to indicate that the predominant flow of sedimentary detritus in the Warrior field was from northeast to southwest, that flow direction in the northeastern part of the Warrior field was to the southwest, and that flow direction in the western part of the field was to the west. Wanless (1975) gave the opinion that the moderately coarse grained rock in north-central Alabama suggests there was a nearby land area, probably east or southeast of present outcrops, and that the pattern of grain size distribution is consistent with an easterly source for sediments, as inferred by cross-bedding measurements (Schlee, 1963, p. 1448). Ehrlich (1965; Davis and Ehrlich, 1974, p. 177) postulated a southern source on the basis of distribution of unstable minerals, an apparent increase from south to north in relative percentage of quartz in the low-rank graywackes, and a southward thickening and increasing proportion of sandstone in the sedimentary sequence. Ferm (Ferm and Ehrlich, 1967) observed that this source area may have extended into the Ouachita orogenic belt. Hobday (1974, p. 223) on the basis of geometry of basal Pottsville beach and barrier-island facies, concluded that two distinct sources may have existed in the lower Pennsylvanian clastic rocks in northern Alabama, one in the northeast and the other to the south.

Individual beds or lithologic units in the Pottsville sequence are laterally discontinuous, and, at present, data are insufficient to delineate accurately the lateral distribution of even major lithologic units. Many workers now accept, as a working hypothesis, the concept of prograding delta systems to explain the variations in lithology and distribution patterns. Ferm and Ehrlich (1967) suggested that lower Pottsville and Parkwood orthoquartzites can be attributed to a beach-barrier system, which separated deltaic from offshore facies and became much broader as progradation proceeded from the "geosynclne" on to the "shelf"; they further suggested that some of the Parkwood graywacke sandstone apparently represents local overriding of the barrier system by rapidly prograding deltaic deposits, whereas other Parkwood graywackes probably represent sediment that was transported through barrier passes to accumulate in offshore bars below the zone of intensive wave action.

PLATEAU FIELD

Insufficient work has been done to define boundaries of subintervals A_1, A_2 and interval B in the Plateau field; Wanless (1975) noted, however, that subinterval A_1 strata are absent in the Plateau field north of the Tennessee River but appear in the field south of the river. Because of this lack of stratigraphic detail, the description of the Plateau field in this paper is given here under discussion of subinterval A_1 strata.

Strata on Blount Mountain in the Plateau field consists of four principal conglomerate members: the First, Second, Third, and Fourth Conglomerates (Gibson, 1891, 1893). Although Gibson has provided considerable detail on strata of the Plateau field, his two reports, as Culbertson (1964) observed, are often in conflict or are inconsistent with regard to thickness of strata. In brief, the stratigraphic sequence in the Plateau field may be described as follows: the First conglomerate, correlated by Butts (1910) as the equivalent of the Boyles Sandstone Member in the Warrior field, lies at the base of the Pottsville sequence and is estimated to be as much as 30 m thick. The First Conglomerate is overlain by a shale, sandstone, and coal sequence estimated to be about 70 m thick. This variable sequence is overlain by the Second Conglomerate, estimated to be as much as 45 m thick. stone, and coal beds, reported by Gibson to be either The Second Conglomerate is overlain by shale, sand- 240 m thick and containing 11 coal beds (Gibson, 1891, p. 114) or 728 m thick and containing 25 coal beds (1893, p. 29). This coal-bearing sequence is overlain by the Third Conglomerate, which may be as much as 45 m thick. The Third Conglomerate is overlain by shale, sandstone, and coal beds reported by Gibson to be either 67 m thick and containing 4 coal beds (Gibson, 1891, p. 114), or 342 m thick and containing 15 coal beds (Gibson, 1891, p. 29). This sequence is overlain by the Fourth Conglomerate, which was reported by Gibson (1893, p. 22) to consist of an upper section 3 to 4.5 m thick, a second section about 12 m thick, and a lower section about 30 m thick. The Fourth Conglomerate is reported to be about 15 m beneath the highest strata exposed on Blount Mountain. Gibson (1893, p. 29) reported this strata in T. 12 S., R. 3 E., to consist of shale, thin- and thick-bedded sandstone, clay, ironstone, underclay, and coal beds.

Many of the coal beds are thin and discontinuous on Blount Mountain. The Howard and Caskie coal beds are between the First and Second Conglomerates. The Swansea, Washington, and several unnamed coal beds lie between the Second and Third Conglomerates. According to Culbertson (1964), the Swansea is also know as the "Inland" and "Jagger" coal beds. The Swansea is reported to be as much as 1 m thick and has been mined along the northwest edge of Blount Mountain (Culbertson, 1964). The Altoona or "Underwood" and Woodward coal beds are between the Tihrd and Fourth Conglomerates, the Woodward being immediately underneath the Fourth Conglomerate. The Altoona is about 76 cm thick and has been mined on the surface as well as underground. The Bynum coal bed directly overlies the Fourth Conglomerate in a small area on Blount Mountain in T. 12 S., R. 3 W., but is generally too thin to be mined independently (Culbertson, 1964, p. 315).

The section on Lookout Mountain in the Plateau field, as described by Culbertson (1964), includes the Lower Conglomerate, overlain by a thin sequence (about 30 m thick) of shale, sandstone, and coal beds, including the Underwood coal bed and Upper Cliff coal beds. These units are overlain by the Upper Conglomerate, which is overlain by a series of shale, sandstone, and coal beds, including the Sewanee coal bed and the Tatum coal bed. Culbertson (1964) noted that a coal bed termed the Castle Rock (Cliff) coal bed underlies the Lower Conglomerate.

WARRIOR FIELD

The Boyles Sandstone Member is a basal conglomeratic orthoquartzite sandstone in the Warrior field; it ranges from 60 to 213 m in thickness, as indicated from oil and gas test-hole logs. This unit is interbedded with varying amounts of gray shale, thin-bedded micaceous sandstone, and locally, one or more thin coal beds (Culbertson, 1964). The lower part of the Boyles Sandstone Member is generally conglomeratic and the upper part, nonconglomeratic, although conglomeratic lenses are reported in the upper part in a few localities. The Boyles forms steep bluffs along the northern edge of the Warrior field, prominent ridges along the southeastern edge of the field, and the ridges bordering the Sequatchee Valley. The unit is thinnest along the southeast margin of the Warrior field and reportedly thickens westward and southwestward in the subsurface. The Boyles Sandstone Member usually includes a predominantly shaly unit, which has been used by some workers to divide the Boyles into two unnamed sandstone units. According to Culbertson (1964), the Boyles can be divided into a third sandstone unit at a few places in the Warrior field, such as along the southeast edge of the Blue Creek basin. In several other places in the Warrior field, Culbertson (1964) observed that the intervening shaly unit either has graded to sandstone, has been cut out by the overlying sandstone bed, or is insignificantly thin. The upper boundary of the Boyles Sandstone Member in the Warrior field is indistinct at some localities where the orthoquartzite beds grade upward to dark micaceous sandstone beds.

In the Blue Creek basin of the Warrior field, approximately 600 m of strata beneath the Black Creek coal group includes several coal beds. A coal bed locally called the Polecat in Marion and Winston Counties may be equivalent to the Sapp (Culbertson, 1964). The J, K, L, and M beds are reported to be persistent throughout the basin. The J bed is reported to be about 90 m below the Black Creek coal bed and to have an average thickness across the basin of 76 cm (Culbertson, 1964, p. B21).

CAHABA FIELD

Subinterval A_1 in the Cahaba field includes the Shades Sandstone Member at the bottom and extends upward to the bottom of the Harkness coal bed. The Shades Sandstone Member is considered the equivalent of the Boyles Sandstone Member of the Warrior field and is generally overlain by a shale sequence, which separates it from the Pine Sandstone Member. Culberton (1964) correlated the Pine Sandstone Member with sandstone sequences in the upper part of the Boyles Sandstone Member of the Warrior field. Two sandstone units, the Chestnut Sandstone Member and the Rocky Ridge Sandstone Member and several coal beds occur in the interval between the Pine Sandstone Member and the upper boundary (base of Harkness coal bed) of subinterval A_1 in the Cahaba field, (Culbertson, 1964, p. B36). The Chestnut ranges from 30 to 60 m in thickness and is a quartzose sandstone that makes a prominent ridge along the entire Cahaba field (Culbertson, 1964). The Chestnut is separated from the underlying Pine Sandstone Member by 150 to 240 m of strata, which is mostly shale and which contains the Gould coal bed (Butts, 1927, p. 14; 1940, p. 11). The Rocky Ridge Sandstone Member is a thick-bedded conglomeratic quartzose sandstone about 15 to 30 m thick that lies about 730 m above the Chestnut Sandstone Member in the interval between the Buck and Pump coal beds (Culbertson, 1964, p. B36).

COOSA FIELD

The Shades and Pine Sandstone Members constitute the lower part of the Pennsylvanian sequence in the Coosa field. The Shades is a sparsely conglomeratic quartzose sandstone about 60 m thick separated from the Pine Sandstone Member by about 60 to 90 m of shale and fine-grained sandstone (Rothrock, 1949). About 1,450 m of strata overlies the Pine, and no specific upper boundary of subinterval A_1 sediments has been identified.

SUBINTERVAL A_2

In Alabama, the middle part of the Pottsville Formation is considered to be subinterval A_2. In the Plateau field, only the lower part of subinterval A_2 is recognized, although the lower boundary in this field is ill defined. Subinterval A_2 in Alabama may include floral zone 5 fossils in its lower part near the Black Creek coal group (Wanless, 1975), as inferred by occurrence of floral zone 5 near the Battle Creek coal bed in the Gizzard Formation in Tennessee, a unit apparently correlative with Alabama subinterval A_2 sedimentary rocks. Wanless (1975) stated that floral zone 6, characterized by *Marecopteris pygmaea* and *Neuropteris tennesseana* was reported above the Mary Lee coal in the Warrior field by White (according to Butts, 1927, p. 15). In addition, the Wadsworth coal in the Cahaba field (Butts, 1927) has yielded this flora. The Erin Shale (phyllite), in the Talladega metamorphic series in Clay County may include strata of subinterval A_2, according to Wanless (1975). Wanless (1975) observed that in the Alabama coal basins, the sandstones of subinterval A_2 are less easily distinguished from those overlying them than they are in Tennessee and northward.

The upper part of the Pottsville Formation in Alabama is mostly strata of subinterval A_2 and is characterized by sandstone, siltstone, mudstone, underclay, coal beds, shale, and zones of marine and brackish-water fossils. Culbertson (1964) described the rocks as a somewhat rythmical sequence; however, Wanless suggested that although a semblance of cyclic sedimentation may appear in a given stratigraphic section, such cycles are only apparent when the patterns of lateral and vertical distribution of the sedimentary rocks are studied. Shale is the predominant rock type, ranging from medium gray and silty to grayish black and carbonaceous. Shale may grade vertically and laterally to argillaceous gray siltstone and gray to tan very fine grained sandstone. Ripple marks are commonly preserved in the siltstone and fine-grained sandstone. Interbeds of shale, siltstone, and sandstone are common. Siderite or ankerite concretions, usually less than 7 cm in maximum diameter are common in the shale. Siderite may occur as a lens as much as 30 cm thick and more than a meter in diameter, and at some localities, layers of siderite less than 2.5 cm thick are interbedded with the shale (Culbertson, 1964). Sandstones frequently have sedimentary structures (crossbedding, ripple and current marks) and are massive to thick bedded, fine to coarse grained, and well indurated. Thickness of the sandstones varies laterally and is as much as 30 m. Culbertson (1964) pointed out that the sandstones differ from the orthoquartzite sandstone beds of the Boyles Sandstone Member (within subinterval A_1) in that they are darker gray and contain mica, clay, and carbonaceous material, including coalified plant fragments.

WARRIOR FIELD

Subinterval A_2 strata in the Warrior field includes the Black Creek coal bed at the bottom and the Brookwood coal group at the top. As noted earlier, the thin succession of rocks capping Plateau regions north of the Tennessee River (northern part of the Plateau field in northeastern Alabama) consists largely or entirely of the lower part of subinterval A_2 (Wanless, 1975). From this outcrop area, these strata thicken southward. From west-central Walker County to northern Tuscaloosa County, the sequence thickens in a distance of 30 km from 153 m to 646 m (Wanless, 1975). Wanless noted that the sparse well data in Pickens and Sumter Counties indicate that south of the belt of rapid thickness change, subinterval A_2 strata appear to be uniform in thickness.

The more prominent sandstone beds in subinterval A_2 rocks in the Warrior field have been named as sandstone members and include, from oldest to youngest, the Bremen, Lick Creek, Camp Branch, and Razburg. Many linear channel-fill sandstones occur in the Pottsville, and Culbertson (1964) has provided some general information on distribution of one of the channels within the Pratt group. New stratigraphic and lithologic data are being rapidly accumulated from the Warrior field through ongoing coal exploration and coal mining and through exploration for gas and petroleum. In the near future it may be possible to begin studies of the distribution of some of the lithologic units within the Pottsville.

Subinterval A_2 rocks in the Warrior field include the major coal beds of that field. These beds are grouped into seven coal groups, which are, from oldest to youngest: Black Creek, Mary Lee, Pratt, Cobb, Gwin, Utley and Brookwood. Of the more than 25 coal beds within these groups, not all are persistent or of sufficient average thickness to be mined. Bituminous coal beds and underclays are regionally more persistent in the Warrior field than are most of the other lithologic units. Clay, siltstone, and siderite partings in the coal range from a few centimeters to as much as 3 m in thickness (Culbertson, 1964). The individual coal beds may pinch out, coalesce, or split. The coal underclay generally lacks bedding features, is light gray, and frequently shows root marks (stigmaria) (Culbertson, 1964).

CAHABA FIELD

Wanless (1975) places subinterval A_2 strata in the Cahaba field from the base of the Harkness coal bed to the base of the Yeshic coal bed. Pennsylvanian strata reach a maximum thickness of 2,740 m and are described by Culbertson (1964) as consisting of a lower part (Shades Sandstone Member and Pine Sandstone Member previously mentioned as belonging to subinterval A_1 strata), a middle part consisting of shale, sandstone, and commercial coal beds, and an upper part consisting of thick conglomerate beds and commercial coal beds. Culbertson (1964) defined the middle part as lying between the Pine Sandstone Member and the Straven conglomerate (fig. 6, locality 7).

A unique conglomerate member, the Straven, occurs in the upper part of subinterval A_2 sedimentary rocks in the Cahaba field. The Straven Conglomerate Member is characterized by large pebbles and cobbles as much as 20.3 cm in diameter and a higher portion of pebbles to matrix. Culbertson (1964) gave thickness of this conglomerate as 9 to 32 m in the Montevallo and Maylene basins of the Cahaba field. Butts (1910, p. 10) indicated that the Straven thins to the north, and suggested (Butts, 1940, p. 13) that the pebbles were derived from erosion of the Waxahatchee Slate, Brewer Phyllite, Wash Creek Slate, Weisner Quartzite, and Copper Ridge Dolomite, exposures of which are a few kilometers southeast of the Cahaba field. Culbertson (1964) reported that more than 35 coal beds occur in the 1,950 m-thick "productive" part of the sequence, which he defines as lying above the Gould coal bed. Of these, more than 22 beds are between the Harkness and Yeshic coal beds. Coal beds included in this interval are, in order of decreasing age: Wadsworth, Big Bone, Pump, Buck, Youngblood, Clark, Gholson, Quarry, Smithshop, Lower Thompson, Upper Thompson (Upper and Lower Thompson separated by Straven Conglomerate), and Helena.

NORTHEASTERN COOSA FIELD

Wanless (1975) did not specify the lower boundary of subinterval A_2 strata in the Coosa field; he designated the top of subinterval A_2 as the bottom of the Brewer coal bed. A specific upper boundary of the "middle barren part" was not suggested by Culbertson (1964).

In northeastern Coosa field, Culbertson (1964), p. B45) described the strata as being divisible into three parts—a lower part consisting of the Shades and Pine Sandstone Members, a middle barren part, and an upper coal-bearing part. Culbertson's "middle barren part" is not the exact equivalent of subinterval A_2 strata as defined by Wanless (1975). In the Wattsville basin of northeastern Coosa County, Rothrock (1949) estimated a total thickness of Pennsylvanian strata of about 1,650 m. Here, Rothrock (1949) reported Pennsylvanian strata above the Pine Sandstone Member as being 1,440 m thick, including in the lower 840 m, lenticular beds of sandstone, siltstone, and claystone that locally contain three nonpersistent coal beds generally less than 30 cm thick. Overlying this sequence (Rothrock, 1949, p. 23) is 600 m of coal-bearing strata which consists chiefly of fine- to medium-grain sandstone, carbonaceous claystone, and siltstone interbedded with coal beds.

Culbertson (1964) recognized 14 named beds of bituminous coal in northeastern Coosa County (fig. 6, locality 4), which vary in areal extent. Within this sequence of coal-bearing strata, about 60 m above the Coal City coal bed, is a 45-m-thick sandstone bed containing scattered quartz pebbles. This is the Fourth or upper conglomerate of Gibson (1895, p. 79). The Brewer coal bed, the bottom of which marks the top of subinterval A_2 strata, lies above the Fourth Conglomerate.

SOUTHWESTERN COOSA FIELD

Butts (1927) reported Pennsylvanian strata in the Yellow Leaf Basin of southwestern Coosa field as 2,220 m thick, of which 1,740 m consists of strata overlying the Pine Sandstone Member. Of this 1,740 m, the lower 1,140 m is composed of shale and sandstone and contains two main sandstone members—the Wolf Ridge and Straight Ridge—and seven coal beds. The remaining 600 m (an undetermined thickness of which probably includes interval B strata) consists of shale and thin sandstone. The Wolf Ridge Sandstone Member is about 360 m above the Pine Sandstone Member and is 15 to 30 m thick. The Straight Ridge Sandstone Member is about 244 m above the Wolf Ridge Sandstone Member. Of the seven coal beds, most are thin. Prouty (1912) measured a section in Yellow Leaf Basin of southwestern Coosa basin and gave the following data on the coal beds observed above the second conglomerate (Pine Sandstone): Clow, 15 to 76 cm; Double Ridge, 7 to 40 cm; Straight Ridge, 20 to 60 cm; Martin, 15 to 365 cm; Marker, 0 to 15 cm; and unnamed coal bed, 7 to 30 cm. In addition, Butts (1927, p. 19) reported a coal bed named the Cunningham as 2 m thick. Culbertson (1964) is of the opinion that this thickness is confined to a very small area.

INTERVAL B

Wanless (1975) noted that rocks of Interval B are characterized by extraordinary lithologic complexity in the Appalachian region and that the sandstones within the interval are generally less conglomeratic, finer grained, and less quartzose than those of Interval A. Interval B strata have not been adequately defined in the Warrior, Coosa, and Chahaba basins, although Wanless (1975), p. 35) suggested some lower boundaries of rocks in these regions. Interval B is considered to include floral zones 7 and 8 of Read and Mamay (1964). Zone 7 is characterized by *Megalopteris spp.*, which are found in the basal part of Interval B. Zone 8 is charaterized by *Neuropteris tenuifolia* (Wanless, 1975).

During Interval B time, according to Wanless (1975, p. 39), the Appalachian and Black Warrior basins were bordered on the southeast by tectonically deformed highlands that probably extended from Philadelphia, Pa., to Georgia and were the probable principal source of the detrital sediments. Wanless (1975, p. 40) suggested that, in general, Interval B in the Appalachian area consists largely of fluviatile and deltaic deposits that accumulated on a surface of very low relief. In Alabama, however, coarser detrital sediment appears to have been derived from nearby elevated land areas south of the Cahaba and Coosa fields. The southern Cahaba field is among the few areas in the Appalachians that show much conglomerate in upper Pennsylvanian strata (Wanless, 1975, p. 40). This conglomerate was described by Butts (1940).

WARRIOR FIELD

In the Warrior field, Wanless (1975) considers all Pennsylvanian rocks above the Brookwood coal group to be within Interval B and has tentatively traced these rocks in western Alabama and Mississippi on the basis of electric logs. These strata occur only in the subsurface, as the Brookwood coal group is the highest outcropping unit in the Warrior field. Interval B strata in the Warrior field have not been studied sufficiently to permit their classification. Upshaw (1967, p. 18) noted that to the west in the subsurface of Mississippi, beneath the Cretaceous overlap, beds of Kanawha age are included with the Pottsville Formation. The upper boundary of Interval B in the Warrior field is considered to be the unconformable Cretaceous contact.

CAHABA FIELD

White (quoted by Butts, 1927, p. 14) suggested a boundary between middle and upper Pottsville strata in the Cahaba field, and Wanless (1975) referred to the rocks containing White's upper Pottsville as Interval B. In this field, Wanless (1975) considers all Pennsylvanian strata, including and younger than the Yeshic coal, to be within Interval B (Wanless, 1975, p. 35). The upper boundary of Interval B in the Cahaba field is the contact with unconformably overlying Cretaceous rocks (Wanless, 1975).

Butts (1940) showed approximately 725 m of sandstone and shale interbedded with coal beds overlying the Yeshic coal in the Cahaba field. Culbertson (1964, p. B–37) called attention to the many test holes drilled during 1957 in the Montevallo and Maylene basins of the Cahaba field and estimated that 10 to 20 percent of the upper Pottsville sequence consists of fine-grained, thin-bedded micaceous sandstone, shale, underclay, and about 20 coal beds. In addition, Culbertson (1964, p. B37) estimated that more than 50 percent of the upper Pottsville sequence consists of fine- to coarse-grained sandstone in beds as much as 30 m thick, a remaining 25 percent consisting of conglomerate and conglomeratic sandstone. Several coal beds, including the Yeshic, Montevallo, and Maylene, and some thin coal beds occur in the interval of the Cahaba field strata considered by Wanless to be Interval B. Culbertson (1964) has provided a general description of the stratigraphy of this interval. The Montevallo coal bed is 115 to 131 m above the Yeshic bed (the bottom of which is considered to be the lower boundary of Interval B) in the Maylene, Dry Creek, and Montevallo basins. Between the Montevallo and Maylene coal beds in the Maylene basin is a sequence of sandstone, conglomerate, and shale that averages about 390 m in thickness and in places contains as many as 15 coal beds. Wanless (1975, p. 39) stated that nearly twice this number of coal beds could be shown in southern Cahaba field if all the seperate benches are considered. Many of these coal beds are reported to be 35 cm thick and locally as much as 1.2 m thick. Butts (1927, fig. 5) named seven beds in the interval between the Montevallo and Maylene coal beds, including, in ascending order, the Airshaft, Dogwood (upper and lower), Stein, Luke, Wooten, and Lovelady. The Maylene coal consists of an upper and lower bed, the lower bed being 2 to 12 m below the upper. A coal bed called the Polecat is about 60 to 75 m above the Maylene and is the highest coal bed in the Pennsylvanian sequence in the Cahaba field (Culbertson, 1964).

COOSA FIELD

In the Coosa field, Pennsylvanian strata including the Brewer coal bed and rocks above it, is considered by Wanless (1975, p. 35) as Interval B. The upper boundary of the interval is considered to be the unconformable contact between the overlying Cretaceous sedimentary rocks. Culbertson (1964) termed the upper 600 m of the Pennsylvanian sequence in northeastern Coosa field as the "upper coal bearing part," near the top of which is the Brewer coal. The thickness of Interval B strata in the northeastern Coosa field, as inferred from the work of Rothrock (1949, p. 3) may be slightly more than 30 m, although Wanless (1975, p. 38) has interpreted the thick sequence of strata in the Wattsville basin in northeastern Coosa field as being entirely in Interval A. Within the Interval B sequence in northeastern Coosa County is the Hammond coal, which reaches a maximum thickness of 231 cm (Culbertson, 1964, p. B49).

Studies sufficient to delineate the lower boundary of Interval B have not been made in southwestern Coosa County. Wanless (1975, p. 38) referred to a thickness of 115 m of strata in the southern part of the Coosa field as Interval B strata.

COAL RESOURCES

The Pennsylvanian-age coal in Alabama is generally high-grade banded "bright" bituminous that is ranked as high volatile A to low volatile. Most of the coal is high volatile A bituminous. Ash content generally ranges from 3 to 15 percent, and sulfur content is usually less than 2 percent (Culbertson, 1964, p. B51). Culbertson (1964, p. B53) stated that the rank of Alabama coals increases generally from northwest to southeast and suggested that the probable cause for this is such interacting factors as the variation of amount of horizontal compression, composition of the coal, and weight of overlying beds during maximum depth of burial of the coal.

Many studies, based on field exploration programs have been made of Alabama coal resources. Most of these studies have been restricted to relatively small properties or to a small part of a coal field and are, for the most part, unpublished. Segments of the coal fields have been dealt with on a larger scale by the Geological Survey of Alabama (Daniel, 1969a, 1969b; Daniel and Fies 1971; Neathery and others, 1969a, 1969b). Various studies have been made of coal reserves, notably those by McCalley (1886), Warrior coal field; Campbell (1913, 1929), Warrior, Cahaba, and Coosa fields; Squire (1890, p. 13), Cahaba field; Butts (1907, p. 113; 1911, p. 143), Cahaba field; Prouty (1909, p. 923), Coosa field; Jones (1929, p. 25), Coosa field; Rothrock (1949, p. 88), Coosa field; Culbertson (1964) and Ward and Evans (1977), Warrior field. The various investigators have used a wide range of criteria in making their estimates of reserves, and the comparison of estimates is, therefore, difficult. Campbell (1929) estimated that the original reserves of coal in Alabama total 67,570 million short tons in beds that are 35 cm or more thick and that are under less than 3,000 feet of overburden. Culbertson (1964) estimated that coal reserves remaining in Alabama total 13,753.8 million short tons in beds that are 35 cm or more thick and that are under less than 914 m of overburden. Culbertson gave figures for the separate fields as follows: Warrior field, 11,904.6 million short tons or 86 percent of the State coal; Cahaba field, 1,766.3 million short tons or 13 percent of the State total; Coosa field, 41.4 million short tons or about 0.3 percent of the State total; Plateau field, 41.5 million short tons or about 0.3 percent of the State total. Culbertson (1964) noted that his estimates are considerably lower than those made by Campbell because: (1) reserves were not calculated for large areas where data were not available; (2) test-hole data from the Warrior field indicate a westward thinning of minable coal; and (3) assumptions (made by Culbertson) concerning thicknesses of coal away from areas of proved thickness are conservative. Ward and Evans (1977) have estimated total remaining reserves at 35 billion short tons with a recoverable reserve estimate of 18.4 billion short tons. At the time of this writing, the Geological Survey of Alabama is preparing estimates of the total State reserves based on latest available coal data.

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CARBONIFEROUS OUTCROPS OF MISSISSIPPI

CONTENTS

ILLUSTRATIONS

THE MISSISSIPPIAN AND PENNSYLVANIAN (CARBONIFEROUS) SYSTEMS IN THE UNITED STATES—ALABAMA AND MISSISSIPPI

CARBONIFEROUS OUTCROPS OF MISSISSIPPI

By Alvin R. Bicker, Jr.[1]

ABSTRACT

Carboniferous outcrops in Mississippi are restricted both in areal extent and stratigraphic content. Outcrops of Paleozoic rocks are present only in Tishomingo County in the northeastern corner of the State. The Carboniferous outcrops include rocks of the Kinderhook, Osage, Meramec, and Chester Series of Mississippian age. Although Pennsylvanian rocks are present in the subsurface approximately 25 miles to the south, none are exposed.

INTRODUCTION

The Carboniferous outcrops of Mississippi are restricted to strata of Mississippian age. Late Carboniferous- or Pennsylvanian-age sedimentary rocks are present only in the subsurface. Mississippian outcrops are limited to Tishomingo County in the northeastern corner of the State, adjacent to Alabama and Tennessee (fig. 7). Tishomingo County is rectangular, its long axis trending north. It is approximately 37 miles long and approximately 15 miles wide. The county is bounded on the north by the State of Tennessee and the Tennessee River. The eastern boundary is the Mississippi-Alabama State line.

Most of the Carboniferous outcrops are in the northern and eastern parts of the county, along the Tennessee River and its tributaries, where overlying Cretaceous-age sediments or more recent terraces have been eroded. Major tributaries where Carboniferous strata are exposed are Yellow Creek, Indian Creek, Bear Creek, and tributaries of Bear Creek, mainly Little Bear, Pennywinkle, and Cripple Deer Creeks. A few isolated exposures are present in the southwestern part of Tishomingo County in the drainage system of Mackeys Creek and its tributaries. Mackeys Creek is a tributary of the Tombigbee River, which drains south. Mackeys Creek valley will be the route of the Tennessee-Tombigbee Waterway in this part of Tishomingo County.

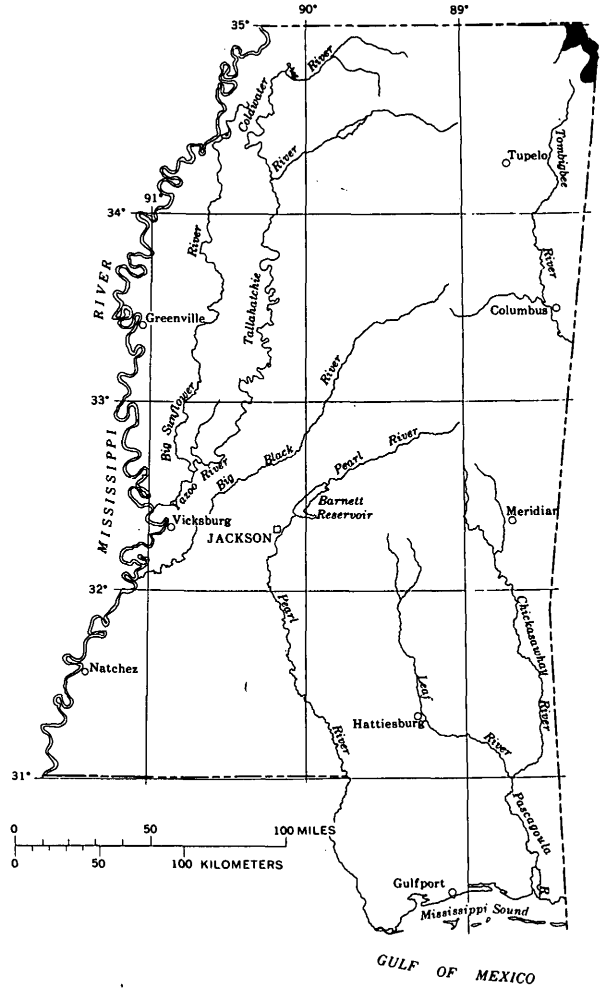

FIGURE 7.—Distribution of Mississippian outcrops in Mississippi.

The stratigraphic nomenclature used in this paper has not been reviewed by the Geologic Names Committee of the U.S. Geological Survey. The nomen-

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clature used here conforms with the current usage of the Mississippi Geological, Economic, and Topographical Survey.

HISTORY

Although previous writers had briefly referenced Paleozoic strata as being present in Mississippi, Harper (1857) was the first to specifically discuss the Paleozoic beds in the State. He reported Carboniferous strata in Tishomingo and Itawamba Counties as extending into the State from neighboring Alabama. The only part of the Carboniferous that Harper recognized, he designated Mountain Limestone; he considered that this unit consisted of limestone, sandstone, chert (hornstone), and clay. Harper recognized and labeled some faunal species contained in the limestone and clay.

Hilgard (1860) (fig. 8) more correctly delineated the stratigraphic horizon of the Carboniferous strata. He stated that, on the basis of faunal identification, the greater part of the Mississippian outcrops were within the limits of the Warsaw and Keokuk Limestones. He further stated that observations were insufficient to separate those beds belonging to each group. Hilgard, as Harper had earlier, did not indicate specific locations of Mississippian outcrops as far south as Itawamba County; however, both authors indicated Mississippian strata within the county on their respective charts or geologic maps. Hilgard believed that the Orange Sand overlay the Carboniferous in most places; the Tuscaloosa Group had not been designated at that time. However, he pointed out that data from water wells suggested that the Eutaw Group overlay the Carboniferous at certain localities in Tishomingo County. In his introductory paragraph, Hilgard noted diverse dips of the Mississippian strata and contemplated the probability of folds extending into Mississippi from Alabama and Tennessee.

Between 1860 and 1905, the area of Paleozoic outcrops must have been observed by other geologists, but records of their visits are difficult to find. During a visit to northeast Mississippi in the year 1884, Johnson (Smith and Johnson, 1887) noted the presence of gravel, lignite, and clay, which he assigned to a formation below the Eutaw. These beds of gravel, clay, and lignite were identified by Smith and Johnson (1887) as belonging to the Tuscaloosa Formation of Cretaceous age.

Crider (1906), in a paper on the geology and mineral resources of the State, described some of the Paleozoic outcrops. Crider may not have observed outcrops in the entire area he designated as containing Paleozoic. As Harper and Hilgard had shown earlier, Crider indicated that Paleozoic outcrops extended far south in Itawamba County. The idea of Paleozoic rocks being present at the surface in Itawamba County persisted until 1930, when Morse restricted the Paleozoic outcrops to Tishomingo County. Crider differentiated more of the Paleozoic strata than had previous writers. On the basis of faunal evidence collected along Yellow Creek in secs. 15 and 22, T. 1 S., R. 10 E., in northern Tishomingo County and identified by Charles Schuchert and E. M. Kindle, Crider was able to identify the oldest Paleozoic strata as lower Devonian, correlative with the New Scotland of New York. Crider's description of an outcrop on Whetstone Creek indicates that he recognized other beds that he considered to be Devonian in age, but he did not identify the formation. Although Crider was influenced by McCalley (1896) in his assignment of Mississippian strata, he neglected or chose not to recognize the upper beds as the Devonian black shale. Crider identified the lowest Carboniferous strata as the Tullahoma Formation and correlated it with the Tullahoma or Lauderdale chert, as had McCalley of the Alabama Survey. He identified the principal materials of the formation as highly siliceous fragmental chert, pulverized silica, and residual clay. Overlying the Tullahoma Formation, Crider recognized a highly fossiliferous limestone as the St. Louis Limestone. He suggested that a member of the upper part of this interval is equivalent to the Ste. Genevieve of Missouri. Crider identified the Chester Formation as the uppermost Carboniferous in Mississippi. The formation is represented by limestone, sandstone and shale. The one section described is near Mingo in southern Tishomingo County.

Lowe (1919), in a report on the general geology of the State, briefly discussed the Paleozoic strata. Lowe assigned the name Yellow Creek beds to the Devonian strata underlying the Mississippian. He stated that the beds at certain levels consisted of dark limestone containing fauna of Devonian age that are correlative with those of the New Scotland. Immediately overlying the Devonian, Lowe identified the Carboniferous strata as the Lauderdale Chert. General locations of outcrops were given. Lowe was the first to report the use of the name Tuscumbia for those beds overlying the Lauderdale chert that are correlative with the St. Louis. For the strata in the Chester series, Lowe used the name Hartselle Sandstone, as had the Alabama Survey. In this report is the only indication of the Carbonifer-

SYSTEM	SERIES	HILGARD 1860	CRIDER 1906	LOWE 1915	MORSE 1930	WELCH 1959	ALABAMA BUTTS 1926	ALABAMA THOMAS 1972	MC NAIRY COUNTY TENNESSEE RUSSELL 1972	THIS PAPER
MISSISSIPPIAN	CHESTERIAN		CHESTER FORMATION	HARTSELLE SANDSTONE	FOREST GROVE FORMATION HIGHLAND CHURCH MEMBER SOUTHWARD BRIDGE FORMATION SOUTHWARD SPRINGS SANDSTONE SOUTHWARD POND FORMATION ALLSBORO SANDSTONE ALSOBROOK FORMATION	FLOYD SHALE	PARKWOOD FORMATION PENNINGTON FORMATION HARTSELLE SANDSTONE GOLCONDA FORMATION CYPRESS SANDSTONE GASPER FORMATION BETHEL SANDSTONE STE. GENEVIEVE LIMESTONE FLOYD SHALE	PARKWOOD FORMATION PENNINGTON FORMATION BANGOR LIMESTONE HARTSELLE SANDSTONE PRIDE MOUNTAIN FORMATION MONTEAGLE LIMESTONE FLOYD SHALE		FOREST GROVE FORMATION HIGHLAND CHURCH MEMBER SOUTHWARD BRIDGE FORMATION SOUTHWARD SPRINGS SANDSTONE SOUTHWARD POND FORMATION ALLSBORO SANDSTONE ALSOBROOK FORMATION
	MERAMECIAN	WARSAW LIMESTONE	ST. LOUIS LIMESTONE	TUSCUMBIA LIMESTONE	IUKA FORMATION	TUSCUMBIA LIMESTONE	TUSCUMBIA LIMESTONE	TUSCUMBIA LIMESTONE		TUSCUMBIA LIMESTONE
	OSAGEAN	KEOKUK LIMESTONE	TULLAHOMA FORMATION	LAUDERDALE CHERT			FORT PAYNE CHERT	FORT PAYNE CHERT	FORT PAYNE FORMATION UPPER	IUKA FORMATION
	KINDERHOOKIAN				CARMACK LIMESTONE WHETSTONE BRANCH SHALE	FORT PAYNE CHERT MAURY SHALE CHATTANOOGA SHALE	CHATTANOOGA SHALE	MAURY SHALE	FORT PAYNE FORMATION LOWER CHATTANOOGA SHALE	CARMACK LIMESTONE CHATTANOOGA SHALE

FIGURE 8.—Correlation chart of the Mississippian rocks of Mississippi.

ous strata that supposedly crop out in southern Itawamba County; Lowe stated that a sandstone member crops out on Bull Mountain Creek in northern Monroe County and adjacent regions.

The most complete record of Paleozoic rocks that crop out within Mississippi was given by Morse (1930). Many of the outcrops that Morse reported have since been partly or entirely inundated by the water of Pickwick Lake. Most of those that are partly inundated are so isolated that they are best reached by water. Most of the Devonian outcrops have been completely inundated; only a few feet of Devonian strata is visible above water level at isolated locations. Morse named the upper part of the Devonian the Whetstone Branch. The type locality is a small stream by the same name in sec. 31, T. 1 S., R. 11 E. Although Morse considered the Whetstone Branch to be in part correlative with the Chattanooga and to be Devonian in age, he reported the presence of fauna indicative of early Mississippian age in the upper section of the formation. He was skeptical of assigning the upper section to the Mississipian because he could not recognize a stratigraphic break between the upper and lower sections; therefore, he assigned the section to the Devonian.

Morse gave the lower part of the Mississippian the name Carmack, stating that the formation is largely Kinderhookian in age. He recognized pronounced unconformities at the base and top of the Carmack. He included all strata overlying the Carmack, between the Carmack and the base of the Chester, in the Iuka Terrane (now Iuka Formation), a unit consisting mostly of residual material in the form of clay and chert fragments. Outcrops included by Morse in the Iuka that contain unleached material are present only in western Alabama near the Mississippi State line. In Mississippi, strata of both the Fort Payne and Tuscumbia Formations were included in the Iuka Terrane by Morse. That part of the Iuka which Morse described in the south wall of Cripple Deer Creek, contained faunal evidence that indicated a St. Louis age. Other writers used the name Tuscumbia for correlative strata in Alabama and the subsurface of Mississippi.

Overlying his Iuka Terrane, Morse (1930) identified strata of the Chester Group, which he divided into six formations and to which he assigned names. In ascending order, these formations were the Alsobrook, Allsboro, Southward Pond, Southward Springs, Southward Bridge, and Forest Grove. Some of the formations are restricted, both at the outcrop and in the subsurface, and the names proposed by Morse are used only locally by few geologists. The uppermost Mississippian outcrops described by Morse were of the Highland Church Sandstone Member of the Forest Grove Formation. The most southerly outcrops of Highland Church that Morse described are in T. 7 S., R. 9 E., in the southwest part of Tishomingo County. The Highland Church is correlative with the Hartselle of Alabama; many geologists working in both areas prefer the name Hartselle when describing the strata in Mississippi.

Russell, during geological investigations for a proposed nuclear generating plant site for the Tennessee Valley Authority (1977), mapped an area in cooperation with TVA geologists in northern Tishomingo County. The area was designated as the Yellow Creek Plant Site. The site encompasses an area within a 5-mile radius centered in sec. 35, T. 1 S., R. 10 E. Russell and others (1972) previously had mapped quadrangles immediately to the north in Tennessee and had retained formational names in use in that State for strata present at the Yellow Creek Site. Russell showed the Chattanooga to be Devonian and Mississippian in age. The Mississippian section overlying the Chattanooga had been designated the Fort Payne Formation. Russell divided this section into the Lower Fort Payne and the Upper Fort Payne. The Lower Fort Payne is correlative with the strata that Morse designated as the Carmack; the Upper Fort Payne is equivalent to the lower part of Morse's Iuka Terrane.

This paper is presented as a guide to those who may have some interest in the Carboniferous outcrops within the State of Mississippi. It does not attempt to alter the nomenclature of the Mississippian strata or to resolve differences in nomenclature as used by different investigators. Formational names used herein are those deemed most satisfactory for the facies that appear at the surface in Mississippi.

GEOLOGICAL SETTING

Most geologists assign a Devonian and Mississippian age to the Chattanooga Shale. Morse (1930) gave the name Whetstone Branch to these sedimentary rocks and stated that faunal evidence indicated the lower part of the section to be undoubtedly Devonian. Although at some localities, the upper part of the formation appears to be closely associated with the Mississippian, Morse could not identify an unconformity within the section; therefore, he included the whole section in the Devonian.

The Carmack Limestone, as named by Morse is the lowermost Mississippian strata. It unconformably overlies the Chattanooga in some areas of outcrop. At several localities along the west bank of Pickwick Lake between Yellow Creek and Indian Creek in sec. 30, T. 1 S., R. 11 E., gently dipping thin-bedded Carmack Limestone can be seen above highly contorted more steeply dipping Chattanooga strata. The unconformable relationship between the Carmack and the Chattanooga is not as apparent at the few outcrops that are visible at other localities This is due in part to the small thickness of Chattanooga that is exposed above the water level of Pickwick Lake. In the most extreme northern outcrops, the Carmack Limestone overlies strata of Early Devonian age. In his cliff section, in sec. 22, T. 1 S., R. 10 E., Morse (1930, p. 21) showed the Carmack Limestone to overlie Devonian strata to which he assigned the name Island Hill. TVA geologists (1977) assigned the same Devonian strata to the Ross Formation and showed that the Lower Fort Payne of Mississippian age overlies the Devonian unconformably.

The Mississippian is overlain by rocks of Cretaceous age or by Quaternary terrace materials. Cretaceous strata overlap the Mississippian and are present at the outcrop except in those localities where erosion has removed the Cretaceous strata and fluvial Quaternary sediments have been deposited. In the northernmost outcrops, sediments of the Eutaw Group of Cretaceous age overlie the Carmack Limestone. Southward, succeedingly older Cretaceous sediments are in contact with progressively younger Mississippian beds. At the southernmost outcrops, strata of the Tuscaloosa Group overlie the Hartselle or Highland Church Sandstone Member of the Chester Series.

The Mississippian outcrops are near the eastern edge of the Mississippi Embayment, a southward-plunging structural trough that formed in Late Cretaceous-early Tertiary time. The axis of the trough coincides roughly with the present course of the Mississippi River. Post-Paleozoic tectonics and the overlying younger sediments obscured much of the evidence of late Paleozoic structural movement.

Lower Mississippian rock types suggest deposition on a broad relatively stable shelf. Regional dip of the outcrops is to the south and southeast, showing a homoclinal feature having minor undulations. This feature may have been a broad shelf south of the Pascola arch, a positive feature between the Ozark and Nashville domes. Northward updip thinning of pre-Mississippian strata suggests a positive feature to the north, on which the Mississippian strata onlapped, and indicates the presence of the Pascola arch at the time of Mississippian deposition.

Although faults have not been mapped in the outcrop area, the location and attitude of some of the Mississippian strata is highly suggestive of faulting. In addition, meager subsurface control indicates faulting involving Mississippian strata in the south-central part of Tishomingo County. This interpreted faulting is probably post-Mississippian; however, additional information is needed before a more accurate date can be assigned.

CARMACK LIMESTONE

The name Carmack Limestone was introduced by Morse (1930) for that strata overlying the Devonian-age Chattanooga (Whetstone Branch). The strata are correlative with the basal Fort Payne of Alabama (Butts, 1926; Thomas, 1972a) and the Lower Fort Payne of Tennessee (Russell and others, 1972). Also correlative, in part, is the St. Joe Formation, the basal member of the Iowa Series, which is downdip in the subsurface (Welch, 1959). The name Fort Payne has been used in the oil industry. Carmack Limestone is preferred herein because of the lithologic difference between these strata and those of the basal Fort Payne of Alabama. Thomas reported the Fort Payne of Alabama to consist of finely crystalline to microcrystalline siliceous limestone and smoky chert (the chert content of fresh rock being 50 percent), whereas the Carmack is predominantly a thin-bedded fine-grained, shaly limestone. When fresh, the limestone is usually gray to dark gray, weathering to brownish gray.

At the surface, the formation has a maximum thickness of 100 feet. Morse (1930) described 81.5 feet of Carmack at the cliff section before its inundation by Pickwick Lake. Other outcrops contain intervals that are covered by colluvial material, and the entire thickness of the Carmack section cannot be observed. Data from test wells within the outcrop area substantiate the maximum thickness assigned to the outcrop sections. Apparently the formation thins southward in the subsurface. Data from a test well in sec. 23, T. 3 S., R. 10 E., shows the formation to be 50 feet thick.

Outcrops of Carmack are numerous along the shoreline of the main body of Pickwick Lake, the Yellow Creek Embayment, and in the valleys of streams that drain into the lake. Outcrops of the

Carmack are not visible south of the latitude of sec. 16, T. 2 S., R. 11 E.

IUKA FORMATION

The name Iuka Terrane was introduced by Morse (1930) to include that section of Mississippian strata between the underlying Carmack Limestone and the base of the overlying rocks of the Chester series. The unit is now called the Iuka Formation. The section is correlative with the Fort Payne Chert and the Tuscumbia Limestone of Alabama (Thomas, 1972a) and, in part, with the Upper Fort Payne of Tennessee (Russell and others, 1972). In Mississippi, the formation consists of small to large blocks of residual chert interbedded with residual clay; in some localities, it contains beds of amorphous silica. The residual chert is the result of leaching of the calcium carbonate fraction of the original formation. In the northern outcrops, the formation is the residual material resulting from leaching of the truncated Fort Payne. To the south, the material present in the outcrops is progressively younger. In the latitude of sec. 15, T. 4 S., R. 11 E., the formation contains residual material whose faunal content identifies this part of the Iuka as being correlative with the Tuscumbia Limestone. Because of the lithologic similarities and insufficient faunal content, the two formations cannot be differentiated at the surface where they are present in their residual state.

Morse (1930) stated that at a few outcrops, evidence of pre-Chester erosion at the top of the Iuka indicates an unconformity. Subsurface data from oil test wells in secs. 15 and 21, T. 4 S., R. 11 E., suggest the presence of the unconformity. The southernmost well, in sec. 21, has competent bedded material that can be differentiated into the respective Fort Payne and Tuscumbia Formations. Other well data in the vicinity include a stratigraphic section that contains residual Iuka material (probably Tuscumbia equivalent) underlying Chester beds, suggesting possible pre-Chester leaching.

Thickness of the Iuka in the northern area of outcrop is approximately 100 feet. Near the southern edge of the outcrop, the formation has a thickness of 200 feet.

TUSCUMBIA LIMESTONE

Morse (1930) chose not to differentiate the Tuscumbia Limestone from the Iuka Terrane, although he recognized a few thin limestone beds present at the surface in the southern part of the Iuka outcrop. Even though Morse identified the materials as correlative with the Tuscumbia or St. Louis Limestone, he included it with the Iuka.

In 1970, a limestone quarry was opened in sec. 22, T. 4 S., R. 11 E., in the area of outcrop of chystalline limestone that Morse (1930) included in the Iuka. The quarry shows a competent section of crystalline limestone that should be correlative with the Tuscumbia Limestone.

The limestone is light gray, medium to coarse crystalline, and contains many fossil imprints and light-gray chert. Scattered joints and small void spaces are filled with asphaltic material.

The full thickness of the limestone has not been exposed, nor has the underlying contact been reached. However, test-hole data indicate that the Tuscumbia in this area is more than 100 feet thick. The formation dips to the south, and in the latitude of the Tishomingo-Itawamba County boundary, subsurface data show the Tuscumbia section to be 70 feet thick.

Surface exposures that can be identified as Tuscumbia Limestone are restricted to the valley of Cripple Deer Creek.

ALSOBROOK FORMATION

Morse (1930) assigned the basal 85 feet of the Chester Series to the Alsobrook Formation. The formation is correlative with the St. Genevieve of Alabama (Butts, 1926) or the basal section of the Pride Mountain of Alabama (Thomas, 1972a). The type locality and most exposures are east of the Mississippi-Alabama State line near the small village of Allsboro.

The formation, as described by Morse (1930), consists of 8 feet of highly fossiliferous limestone overlain by 44 feet of green clay shale. Overlying the shale is a sandstone bed 36 feet thick, which in turn is overlain by a 5-foot bed of clay shale. Faunal content of the limestone clearly indicates a Chester age for the basal limestone.

In Mississippi, outcrops of the Alsobrook Formation are restricted to the valley of Cripple Deer Creek, where widely scattered small outcrops of thin beds of limestone are overlain by green shale. The limestone does not contain faunal evidence that would definitely indicate the age of the strata; however, the stratigraphic position of the limestone relative to the nearby Tuscumbia Limestone strongly suggests a basal Chester section. The sandstone designated the Cripple Deer Sandstone Member is not present at the surface in Mississippi. Subsurface data from a test well on the divide immediately south of Cripple Deer Creek, includes a sandstone section at the stratigraphic position of the Cripple Deer. This sandstone member appears to be correlative with the Lewis Sandstone, which produces hydrocarbons to the south in Monroe County, Miss.

ALLSBORO SANDSTONE

The 3-foot section of sandstone above the Alsobrook Formation at the type locality was designated the Allsboro Sandstone by Morse (1930). The Allsboro, together with the Cripple Deer Sandstone Member, is correlative with the Bethel of Alabama (Butts, 1926) and with the lower sandstone member of the Pride Mountain of Alabama (Thomas, 1972a). The type locality in Alabama is the same as that given for the Alsobrook Formation; other outcrops of Allsboro Sandstone described are also in Alabama. Isolated outcrops of sandstone within the valley of Cripple Deer Creek may be Allsboro, but exact stratigraphic position of these outcrops is undetermined. Most of the Paleozoic beds are covered by Cretaceous sand and gravel, which prevents an accurate assessment of their position.

Morse described the Allsboro Sandstone at the type locality as being dark gray, coarse grained, and containing a petroleum residue. Other descriptions indicate that the sandstone varies in thickness and character at different localities. Although this variation was noted by Morse (1930, p. 131), he still chose to separate the Allsboro Sandstone from the Cripple Deer Sandstone Member. The variation suggests a facies change, which may indicate that perhaps the Allsboro and the Cripple Deer should have been included in the same unit.

SOUTHWARD POND FORMATION

Overlying the Allsboro Sandstone is a shale sequence separated by thin beds of limestone. The entire sequence is approximately 75 feet thick; the intervening limestone beds are 9, 1, and 3 feet thick. Morse (1930) designated this section as the Southward Pond Formation and assigned the limestone beds the designations A, B, and C. The section is correlative with the Gasper Formation of Alabama (Butts, 1926) and with that part of the Pride Mountain between the lower sandstone unit and the middle sandstone unit (Thomas, 1972a).

Both the limestone and shale are extremely fossiliferous and at different localities afford the best collecting of Paleozoic fauna of all the Mississippian strata. The basal limestone is a dark-gray, very oolitic, highly fossiliferous, slightly asphaltic unit that is distinctive and easily recognized. The middle and upper limestone beds are dark-gray crystalline fossiliferous units but are not as easily recognizable as the lower limestone unit. The shale units are usually green, fossiliferous, and at some localities very limy.

The type locality is near the northwest part of Cypress Pond, a low swampy area that was an old meander of Bear Creek, in sec. 17, T. 5 S., R. 11 E. At the time of Morse's investigation, the low area was named Southward Pond. Other outcrops of the Southward Pond Formation are in the valley of Pennywinkle Creek and at several scattered outcrops in McDougle Creek in the western part of Tishomingo County. The outcrops in Pennywinkle Creek afford the best fossil-collecting area in the Paleozoic outcrop belt.

SOUTHWARD SPRINGS FORMATION

Overlying the Southward Pond Formation is a sandstone section that Morse (1930) designated the Southward Springs Sandstone and that is now called the Southward Springs Formation. The Southward Springs is correlative with the Cypress of Alabama (Butts, 1926) and with the middle sandstone unit of the Pride Mountain Formation (Thomas, 1972a). Outcrops of the Southward Springs are restricted to the area north and south of Cypress Pond. Outcrops north of the pond are in the southwest quarter of sec. 8, T. 5 S., R. 11 E.; outcrops south of the pond are in sec. 18.

The northern exposure consists of 26 feet of shaly sandstone and sandy shale, yellowish buff, weathering to yellowish red. The upper part of the section is calcareous and fossiliferous. At the southern exposure, only about 15 feet of the section can be observed. Both exposures are covered partly by colluvium, and the entire section cannot be seen. Fossils from both exposures are mainly brachiopods.

The stratigraphic position of the Southward Springs Formation suggests that the sandstone is correlative with the Evans sand, which produces hydrocarbons in Itawamba and Monroe Counties, south of the outcrop area.

SOUTHWARD BRIDGE FORMATION

South of Cypress Pond, near the abandoned bridge crossing Bear Creek, in the valley wall of the creek, is an exposure of alternating shale, sandy shale, and limestone, which Morse (1930) designated the Southward Bridge Formation. The Southward Bridge Formation is correlative with the Golconda of Alabama (Butts, 1926) and with the upper part of the Pride Mountain Formation (Thomas, 1972a).

The whole interval is not exposed at Southward Bridge. The upper limestone member is missing here but is present a short distance upstream in the Bear Creek valley. The basal shale section is black, carbonaceous, and contains thin limestone beds. Upper shale intervals are blue-gray, calcareous, sandy, and fossiliferous. The limestone members are bluish gray, massive, fine crystalline, and fossiliferous. Thickness of the entire interval is approximately 90 feet. The limestone members are 4 to 6 feet thick, and the intervening shale beds are as much as 40 feet thick.

The larger outcrops of the Southward Bridge Formation are in the valley of Bear Creek in T. 5 S., R. 10 and 11 E. However, in western Tishomingo County, small outcrops are present in the bed of McDougle Creek in sec. 5, T. 5 S., R. 10 E. At this location, greenish-gray shale and brown crystalline fossiliferous limestone can be observed in the bed of the creek. Colluvial material covers much of the area, and only thin beds of Paleozoic rocks are visible.

FOREST GROVE FORMATION

HIGHLAND CHURCH SANDSTONE MEMBER

The section of shale, shaly sandstone, and sandstone overlying the uppermost limestone member of the Southward Bridge Formation was named the Forest Grove Formation by Morse (1930). A persistent massive sandstone at the top of the interval has been designated as the Highland Church Sandstone Member. The basal part of the Forest Grove Formation has been correlated with the Golconda of Alabama (Butts, 1926) or with the upper part of the Pride Mountain (Thomas, 1972a). The massive Highland Church is correlative with the Hartselle Sandstone of Alabama (Butts, 1926, Thomas, 1972a).

The basal section below the massive Highland Church contains alternating beds of gray to dark-gray, sandy, slightly calcareous shale and thin beds of fine-grained sandstone. Both the shale and sandstone may contain fossils at some localities. Lithology of the massive Highland Church is generally consistent throughout its outcrop area. The sandstone is generally light colored, well sorted, fine to medium-grained, locally calcareous, and fossiliferous.

Outcrops of the Highland Church and the underlying shale of the Forest Grove are numerous in the valley of Bear Creek in T. 5 and 6 S., R. 10 and 11 E. Outcrops of the Highland Church are present also in the valley of Mackeys Creek in southwestern Tishomingo County in S. 26, T. 6 S., R. 9 E. The outcrops of Highland Church in Mackeys Creek are the most southerly and the youngest Mississippian strata present at the surface.

Thickness of the combined interval of the basal Forest Grove and the overlying Highland Church is approximately 125 feet. At the outcrop, only 25 to 30 feet of Highland Church and as much as about 50 feet of the basal Forest Grove can be observed. Data from core holes in the area of Mackeys Creek show the Highland Church to be 47 feet thick and the basal Forest Grove to be 77 feet thick.

Toward the south in the subsurface, the Highland Church and Forest Grove, like much of the Chester-age strata, pinch out or are not identifiable because of facies changes. In the latitude of central Itawamba County, the Highland Church-Forest Grove section probably grades into the marine carbonate, the Bangor limestone, and is not present as a separate identifiable unit.

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The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—Michigan

By GARLAND D. ELLS

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Geological Survey Division
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Historical review and summary of areal, stratigraphic, structural, and economic geology of Mississippian and Pennsylvanian rocks in Michigan

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CONTENTS

ILLUSTRATIONS

TABLES

THE MISSISSIPPIAN AND PENNSYLVANIAN (CARBONIFEROUS) SYSTEMS IN THE UNITED STATES—MICHIGAN

By GARLAND D. ELLS[1]

ABSTRACT

The Michigan basin covers about 315,968 km^2. (122,000 sq mi). On the west it is bounded by the Wisconsin arch and Wisconsin dome, and to the north by the Canadian shield. To the southwest it is separated from the Indiana-Illinois basin by the Kankakee arch, and to the southeast it is cutoff from the Appalachian basin by the Findley and Algonquin arches. The basin contains Cambrian, Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, and remnant Jurassic sediments. Pleistocene glacial drift, as much as 366 m (1,200 ft) thick, blankets virtually all bedrock.

Carboniferous rocks, generally separated into Mississippian and Pennsylvanian in Michigan, form most of the bedrock surface. The combined thickness of these rocks is about 1,158 m (3,800 ft). Because of limited outcrops and the fact that the complete sequence cannot be studied in outcrop, Carboniferous rocks are best known from subsurface investigations made possible from thousands of well records. Though formation names have been derived from outcrop localities, the thickness and characteristics of the rock units have been determined by subsurface studies.

Studies have shown that Mississippian rocks are of marine origin, were deposited under different environments of deposition, and that an erosional unconformity of considerable magnitude separates Mississippian strata from those of the overlying Pennsylvanian system. Pennsylvanian rocks are terrestrial and marine and were deposited under several modes of environment. The original extent and thickness of Pennsylvanian rocks in Michigan is unkown. Also dissected and partly eroded before Pleistocene glaciation, they are now confirmed to the basin interior and cutoff from correlative rocks in other basins. Before Pleistocene glaciation, Jurrassic sediments were deposited over part of the eroded surface.

Most of Michigan's Carboniferous studies have been made with the objective being the exploitation of the contained resources. The nomenclature applied to these rocks has been guided to a considerable extent by the needs of industry rather than from an academic point of view. Regional and inter-basin correlations have been made on the basis of fossil assemblages and similar lithologies. Terms such as "Red Rock," "Triple Gypsum," "Stray Sandstone," serve a useful purpose in the search for economic products. Economic products currently extracted from Michigan's Mississippian rocks include shales, limestone, sandstone, gypsum, natural brines, oil and natural gas, and in some areas, freshwater. In the past Pennsylvanian rocks have provided bituminous coal and small amounts of natural brines. Current economic products are shales and freshwater supplies.

INTRODUCTION

The basin-shaped characteristics of the depositional province known as the Michigan basin have been recognized for nearly 140 years. The basin, as generally defined, includes the Southern Peninsula and eastern part of the Northern Peninsula, eastern Wisconsin, northeastern Illinois, northern Indiana, northeastern Ohio, and western Ontario. The basin covers about 315,968 km^2 (122,000 sq mi), part of which is covered by Lakes Michigan, Huron, St. Clair, and the Michigan part of Lake Erie. The basin is flanked on the west by the Wisconsin arch in central Wisconsin and its northern extension the Wisconsin dome; on the north and northeast by the Canadian shield; on the east and southeast by the Algonquin arch in Ontario and the Findlay arch in northern Ohio; and on the southwest by the Kankakee arch in northern Indiana and northeastern Illinois.

Nearly all Paleozoic systems are present in the basin as well as an area of remnant Mesozoic rock. Except for small scattered outcrops, the bedrock surface of the basin is covered with glacial drift deposited during the Wisconsin stage of the Pleistocene. The drift is as much as 366 m (1,200 ft) thick in some areas, especially where parts of thick terminal moraines may overlie preglacial valleys. Mississippian, Pennsylvanian, and Jurassic sediments form most of the truncated bedrock surface of the Southern Peninsula. Not all formations outcrop. Those that do are of small extent, are widely scattered, and limited to areas of thin drift.

The stratigraphic succession of rocks in the Michigan basin is best known from subsurface studies made possible from the records of thousands of oil- and gas-well borings and other types of wells drilled over the years. Because of limited outcrops which seldom expose more than a few meters of vertical

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section, even in manmade openings such as quarries, most of the Mississippian and Pennsylvanian rock units have been measured from well-record studies. The formation names were derived from localities where the rocks were first noted and studied.

Complete sections of Mississippian and Pennsylvanian rocks are not found in outcrop, nor are the contacts between formations visible at the surface. The combined thickness of these rocks is about 1,158 m (3,800 ft). Because of shifting depocenters during several periods of sedimentation, erosional unconformities between Mississippian, Pennsylvanian, and Jurassic rock, and erosion before Pleistocene time, the combined thickness is not found in any one locale. The distribution of Carboniferous and Jurassic bedrock beneath unconsolidated Pleistocene glacial deposits is shown in figure 1.

Because of the mantle of glacial drift, the events following deposition of Carboniferous rocks are not well known. Subsurface investigations show that a major unconformity exists at the top of Mississippian rocks, at the top of Pennsylvanian rocks that overlie the Mississippian, and at the top of a small area of Jurassic sediments that immediately overlie a part of the eroded Pennsylvanian section. The truncated bedrock surface was scoured and modified by continental glaciers during the Pleistocene Epoch. Studies show that the preglacial bedrock surface was greatly incised by valley systems whose major tributaries led to larger preglacial valleys now occupied by Lakes Michigan and Huron. Bedrock elevations suggest two stages of uplift as evidenced by peneplained surfaces. On the basis of deformation of the Lake Algonquin shoreline, one of several ancient Great Lakes shorelines, an unwarp has been postulated for much of the northeastern part of the Southern Peninsula. The upwarp of the land took place in response to withdrawal of the Pleistocene ice sheet (Stanley, 1945, pp. 11–13). Present-day stream channels are incised in glacial drift and follow a haphazard pattern which may be influenced by glacial features such as moraines. In a few areas, where drift is thin, streams cut through bedrock and may be channeled through part of their course in preglacial valleys.

The stratigraphic nomenclature used in this paper has not been reviewed by the Geologic Names Committee of the U.S. Geological Survey. The nomenclature used here conforms with the current usage of the Geological Survey Division, Michigan Department of Natural Resources.

EARLY GEOLOGICAL WORK

The Geological Survey of Michigan was instituted by legislative act in 1838. Douglass Houghton, Michigan's first State Geologist, made his first report to the Legislature in 1838. The sequence of Carboniferous rock which he was able to identify was simply referred to as Upper Sandstones and Coal Measures. With the discovery of coal in 1835 (Cohee and others, 1950) and the drilling of wells for brine to be used in the salt-making process, a considerable nomenclature soon began to develop for Carboniferous formations. A prominent and later State Geologist, Alexander Winchell, introduced in 1869 the term "Mississippian group" for the Carboniferous limestones of the Mississippi River Valley. Not until 1901, however, was the term Mississippian used to designate a part of Carboniferous rocks in Michigan. In 1901, Alfred Lane, another State Geologist, introduced the terms Pennsylvanian and Mississippian and referred both to the Carboniferous. But in Lane's 1904 report, both terms were dropped in favor of Carboniferous, only to reappear again in 1908. The term Carboniferous remained in general Survey usage until 1933. It was then considered obsolete and finally replaced by Mississippian and Pennsylvanian designations.

Rocks now defined as Mississippian and Pennsylvanian have been variously subdivided and grouped by the Survey. Until 1901, most rock divisions now classified as Mississippian were classified as Devonian. After that date, the stratigraphic boundary between Devonian and Mississippian rocks became better defined and has remained virtually the same since then. The stratigraphic nomenclature applied to Mississippian and Pennsylvanian rocks from 1837 to 1956 has been documented in chart form (Martin and Straight, 1956).

MISSISSIPPIAN SYSTEM

Early and Late Mississippian rocks are recognized in the Michigan basin. Early Mississippian rocks of Kinderhookian age include most of the Bedford Shale, the Berea Sandstone, Sunbury Shale, and Coldwater Shale. The Coldwater Shale grades upward into the Marshall Sandstone without an apparent time break, and is considered to be of Osagian age. The remaining Mississippian rocks include the Michigan Formation and the overlying Bayport Limestone. The Michigan Formation, which overlies the Marshall Sandstone, appears to grade upward from the Marshall without a break in sedimentation. The Bayport Limestone, the stratigraph-

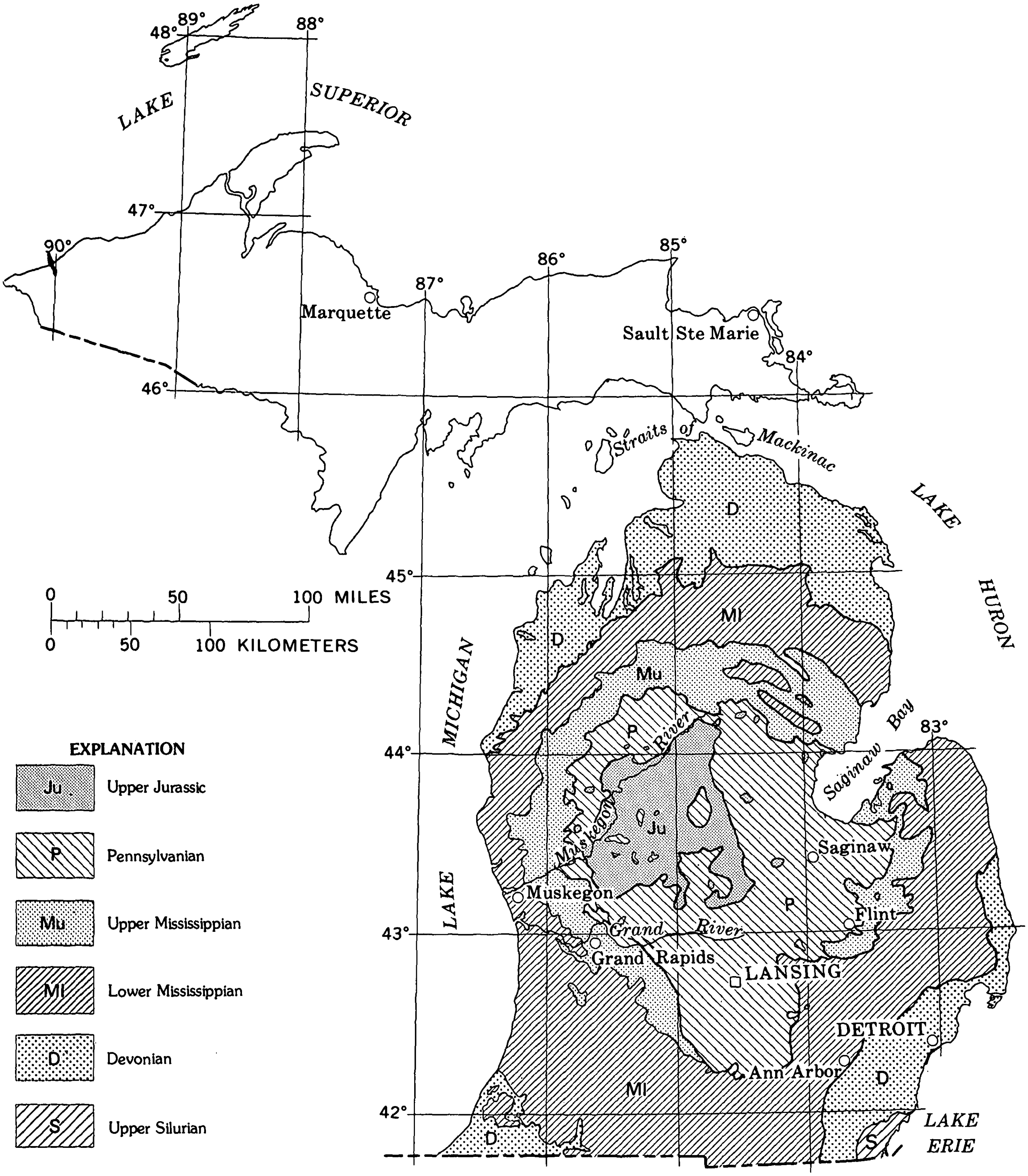

FIGURE 1.—Distribution of Mississippian, Pennsylvanian, and remnant Jurassic bedrock in the Southern Peninsula of Michigan. Jurassic rocks overlie a part of the Pennsylvanian section and are limited to the basin interior. Outermost bedrock areas of the Southern Peninsula are Devonian except for a small area of Upper Silurian strata near the western end of Lake Erie. Distribution of bedrock units adapted from Kelley (1968).

TABLE 1.—*Mississippian nomenclature, 1947–64*

1956 Martin and Straight			1964 Ells and others			
Series	**Group**	**Formation**	**Series**	**Group**	**Formation**	**Member**
Iowan	Meramec Osage	Bayport-Au Gres Limestone Michigan "Michigan Stray"	Meramecian	Grand Rapids	Bayport Limestone Michigan	"Triple Gypsum" Brown Limestone "Stray Sandstone"
Iowan	Kinderhook: Marshall	Napoleon Sandstone Lower Marshall Sandstone	Osagian	Marshall	Marshall Sandstone	Napoleon (Stray Sandstone Member)
Iowan	Kinderhook: Coldwater	Coldwater Shale Richmondville Sandstone Coldwater Limestone "Red Rock"	Kinderhookian	Coldwater	Coldwater Shale	Coldwater Limestone Weir Sandstone "Red Rock"
Iowan	Kinderhook	Sunbury Berea Bedford Ellsworth	Kinderhookian		Sunbury Shale Berea Sandstone Bedford Shale Ellsworth Shale	

ically highest Mississippian rock identified in Michigan, likewise appears to lie conformably on the Michigan Formation. Both are classified as Meramecian or Late Mississippian.

No break in sedimentation is apparent from Devonian into Mississippian time (Cohee and others, 1951); thus the boundary between the two systems is obscure and not well defined lithologically. The boundary is believed to be within the basal few feet of the Bedford Shale in eastern Michigan and the upper part of the Ellsworth Shale of western Michigan. An unconformity of considerable magnitude cuts across Mississippian formations in Michigan. Pennsylvanian sediments were deposited on this eroded surface and were in turn eroded. Table 1 shows the nomenclature commonly applied to Mississippian rocks in Michigan from 1947 to present.

Contact with underlying rocks.—In the Appalachian basin the Devonian-Mississippian boundary is in the basal few feet of the Bedford Shale. The Bedford Shale, Berea Sandstone, and Sunbury Shale of the Appalachian region can be projected into the Michigan basin with considerable confidence, although these formations no longer connect with the Michigan basin. On this basis, and because of the lack of evidence to the contrary, the boundary in Michigan is also placed in the basal few feet of the Bedford (DeWitt, 1970, p. G 10).

In the eastern sector of the Southern Peninsula, the Bedford Shale, the overlying Berea Sandstone, and the Sunbury Shale subcrop in a narrow band beneath the glacial drift and then offshore in Lake Huron. North of Saginaw Bay (fig. 1) they turn inland and again subcrop beneath glacial drift. No outcrops of these rocks are found in the Michigan basin.

In eastern Michigan the gray Bedford Shale lies directly on the black, radioactive Antrim Shale of Devonian age (Chautauquan). The Antrim as defined in eastern Michigan is a facies of most of the greenish-gray Ellsworth Shale of western Michigan. The Bedford and the Berea and Sunbury formations above it thin in a westward direction and merge laterally into the upper approximately 30 m (100 ft) of the Ellsworth Shale.

Contact with overlying rocks.—In the central part of the basin, Mississippian rocks are overlain by sedimentary rocks of Pennsylvanian age which were deposited on an erosion surface. A sizable area of remnant Jurassic rock overlies a part of the Pennsylvanian (fig. 1). According to Cohee (1965), part of these Jurassic sedimentary rocks overlap onto Mississippian strata. Where not immediately overlain by Pennsylvanian or Jurassic rock, Mississippian strata are immediately overlain by Pleistocene glacial deposits. The extent of pre-Pennsylvanian erosion and the amount of sediments that may have been removed is unknown. Though now isolated within the Michigan basin, the continuation of certain Lower and Upper Mississippian rocks into adjacent regions outside the defined limits of the Michigan basin is well established (Cohee and others, 1951).

To the northwest, in the western part of the Upper Peninsula, small outliers of Middle and Upper Ordovician, Middle Silurian, and Middle Devonian rocks are found at Limestone Mountain in Houghton County (Case and Robinson, 1915). Now completely surrounded by Precambrian rock, these outliers show that Paleozoic sediments extended far to the north of their present limits in the Michigan basin. Though Mississippian rocks are now found only in the Southern Peninsula, possibly they, too, once extended far north of their present limits. Devonian and Mississippian strata were deposited in northeastern Illinois as shown by their preservation in fault blocks in the Des Plaines Disturbance, an area north of Chicago, Ill. (Willman, 1962). Except for such isolated locales, these strata were largely truncated during erosion of the pre-Pennsylvanian surface.

According to subsurface data, several hundred feet of Mississippian rocks were eroded from anticlines in the vicinity of Saginaw Bay before deposition of Pennsylvanian rocks. The erosional episodes before Pleistocene glaciation were no doubt complex. The preglacial drainage systems that carried sediments away from the central part of the Michigan basin are not well established in some areas as well control is lacking. In areas of abundant well control, preglacial valleys lead into the valleys now occupied by the Great Lakes.

Structural events involving Carboniferous rocks.—Throughout most of the Michigan basin, anticlines trend in a northwest direction. Early recognition of this fact was useful in the development of the State's oil and gas industry. Oilfield studies show that most anticlines in Michigan were developed during several stages of folding beginning in Middle Ordovician time and continuing, intermittently, into Mississippian. Structure mapping of numerous Mississippian formations and marker beds show similar folding. Michigan's stratigraphically youngest Mississippian formation, the Bayport Limestone, varies in thickness because of the erosional unconformity which separates it from the overlying Pennsylvanian rock. Presumably the Bayport Limestone, and other Mississippian strata which may have been deposited above it but later eroded, was also folded.

Faults have been observed in Pennsylvanian rocks and must also occur in Mississippian rocks. Subsurface investigations show that faulting has taken place along the flanks of such structures as the Howell-Northville anticlines and others included in the Washtenaw anticlinorium (Ells, 1969); Fractures, brecciation, and steep dips which may suggest faulting, have been observed in Ordovician, Silurian, and Devonian rocks, but have not been reported in Mississippian sediments associated with these structures.

Along the Howell anticline near the Howell gas storage field, more than 305 m (1,000 ft) of structural movement has taken place. Over the crest and higher part of the structure, in certain areas, the Berea Sandstone is eroded and found immediately beneath the glacial drift (Ells, 1969). At the northern end of the structure, Pennsylvanian strata are found on both sides of the feature, and it is likely that they, too, were folded and later eroded. The Howell anticline is the most prominent structure in this area of en echelon folds. Recent studies (Wanless and Shideler, 1975) suggest that at the beginning of Morrow time, the anticlinal areas stood above the surrounding depositional plain as a monadnock several hundred feet high, but was buried by the end of Morrow time.

Upper Silurian (Cayugan) salt beds have been dissolved in places along the west edge of the Howell anticline. Solution of salt and subsidence of certain formations appear to have taken place mainly during Devonian time. Solution channels are probably related to fractures associated with the fault zone. Some evidence exists that Mississippian rocks as high in the sequence as the Sunbury Shale were affected in areas of greater subsidence. Contours on the top of this formation show closed depressions over areas of probable salt removal.

Igneous and metamorphic rocks.—There is no evidence in the Michigan basin of igneous actiivty during Mississippian and Pennsylvanian time. A

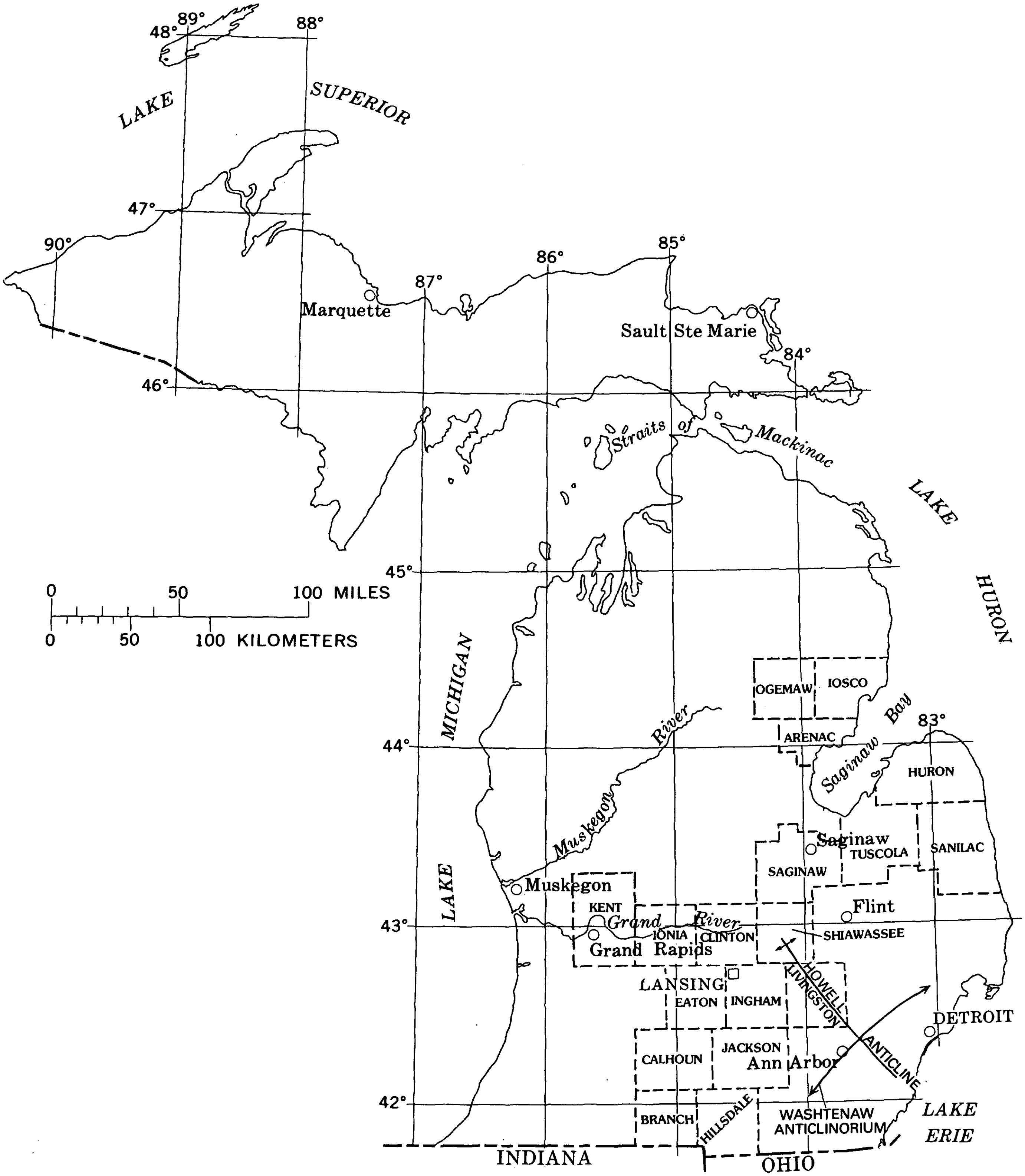

FIGURE 2.—The northwest-trending Howell anticline is one of the most prominent structures associated with the Washtenaw anticlinorium, a region containing several similar-trending structural features that plunge basinward. See figure 1 for areal bedrock geology associated with this feature. Counties having outcrops of Mississippian or Pennsylvanian rock are outlined.

bentonite zone has been noted in Middle Devonian rocks in the basin (Baltrusaitis, 1974) but no ash beds have been found in Mississippian or Pennsylvanian rocks. Rocks of both systems show no signs of alteration that might be related to metamorphism.

MISSISSIPPIAN FORMATIONS

As mentioned earlier, no break in sedimentation is apparent from Late Devonian into Mississippian time. The boundary between the two systems is within the basal part of the Bedford Shale which immediately overlies the Antrim Shale of Devonian age (Chautauquan) in eastern Michigan and the upper part of its correlative, the Ellsworth Shale of western Michigan.

Bedford Shale.—The Bedford Shale and the overlying Berea Sandstone were first identified in Michigan from a well in southeastern Michigan (Rominger, 1876). These formations subcrop beneath the glacial drift and have not been identified at the surface in Michigan. They are correlated with the Bedford, Berea, and Sunbury of Ohio on the basis of lithology and stratigraphic position. They are not continuous from Michigan into Ohio, having been eroded from the Findlay arch in northwestern Ohio and in Ontario, Canada. The Bedford is a silty, gray shale containing numerous stringers of Berea-type sandstone. The upper part of the Berea contains Bedford-type shale stringers; thus the Bedford and Berea are frequently treated as a single formation. Gamma ray-neutron logs show these features but also show a definite separation between the two formations. The Bedford is as much as 61 m (200 ft) thick in eastern Michigan but thins westward and merges into the upper part of the Ellsworth Shale.

Berea Sandstone.—The Berea Sandstone in Michigan has been divided into three lithologic units (Cohee and others, 1951). The lower unit is light gray, fine grained, dolomitic sandstone which is silty and shaly, cemented with silica and dolomite, and is micaceous and pyritic. The middle unit is friable, fine grained sandstone composed of angular quartz grains. The upper unit is lithologically similar to the lower unit but is less shaly and pyritic. The Berea is thickest around Saginaw Bay. Like the underlying Bedford Shale, the Berea thins westward, and about mid-basin it merges into the upper part of the Ellsworth Shale. The thin facies found in the upper part of the Ellsworth is sometimes referred to as "Berea."

The Bedford Shale and Berea Sandstone of northeastern Ohio and northwestern Pennsylvania are associated with deltaic deposition (DeWitt, 1970). As the same formations are correlated with similar rocks occupying the same stratigraphic position in Michigan, the inference is that they are also a part of the same deltaic system. According to Cohee (1965), the clastic materials making up the Bedford and Berea formations came from Ontario and the Canadian shield and were carried into the eastern side of the Michigan basin as deltaic deposits. The name commonly applied to the part of the Southern Peninsula east of Saginaw Bay, where these rocks are thickest and best formed, is "the thumb." Accordingly, Cohee named the Bedford-Berea deltaic deposits the Thumb Delta. The Sunbury Shale, normally not considered a part of the deltaic deposits, lies immediately above the Berea Sandstone.

Sunbury Shale.—The Sunbury Shale is more widespread within the basin and is thickest in the same general area of the basin as the Bedford and Berea formations. More than 30 m (100 ft) thick in the Saginaw Bay region near Lake Huron, the Sunbury is a black to dark-brown shale lithologically similar to the Antrim of Devonian age. First identified by Lane in 1909 from well cuttings, it is known in Michigan only from subsurface studies. It extends over most of the Southern Peninsula, but thins and grades into gray and greenish-gray shales in the top part of the Ellsworth Shale in places in the western and southwestern part of the State.

Coldwater Shale.—The Coldwater Shale is one of the most widespread and thickest of Mississippian formations. Predominantly a gray to bluish-gray shale, it is about 396 m (1,300 ft) thick in the central part of the basin. Named by Lane in 1895 from small exposures along the Coldwater River near Coldwater, Mich., other small outcrops are found at places in Branch and Hillsdale Counties and along the shores of Lake Huron in Huron and Sanilac Counties. The Coldwater Shale extends beneath the drift into northern Indiana and northwestern Ohio. It is correlated with the Borden Group of Indiana and Illinois and the Cuyahoga Group of Ohio.

In the western part of the basin, the Coldwater Shale is similar to upper parts of the underlying Ellsworth Shale. The two formations are separated by a useful marker bed referred to as Coldwater "Red Rock." From 3–6 m (10–20 ft) thick, it consists of red limestone, red shale, dolomite, and glauconitic dolomite. It can be traced eastward above the black Sunbury Shale but does not extend everywhere within the eastern part of the basin. The Coldwater "Red Rock" may be equivalent to the

Rockford Limestone of Indiana and Illinois (Cohee and others, 1951). But according to Lineback (1970, p. 35) the Rockford Limestone is not found in the Michigan basin.

Several facies have been identified within the Coldwater Shale sequence but cannot be traced across the basin. In an area of western Michigan, an argillaceous dolomite zone commonly referred to as the "Coldwater Lime" or "Speckled Dolomite" is about 91 m (300 ft) above the base of the shale (Hale, 1941). This zone grades eastward into shale. On the eastern side of the basin several sandstone beds are found in the upper part of the Coldwater Shale and may correlate with scattered surface exposures near Richmondville in Sanilac County. A silty sandstone interval near the base has been called the Weir Sandstone, but like most of these lenticular sandstone beds, it does not extend for any great distance in the subsurface. The small exposures of Coldwater Shale are not representative of the sequence as known in the subsurface. In the subsurface the Coldwater grades upward into the Marshall Sandstone, thus making the contact between the two formations difficult to define in most areas.

Marshall Sandstone.—The Marshall Sandstone, which overlies the Coldwater Shale, is frequently divided into two members: the lower Marshall and the Napoleon Sandstone. The Marshall Sandstone was named by Winchell in 1861 from outcrops around Marshall, Calhoun County, Mich. At an earlier date (1838), Douglass Houghton, Michigan's first State Geologist, had named the upper part of the Marshall, the Napoleon Sandstone, from exposures around Napoleon, Jackson County, Mich. In 1900, Lane designated these rocks as the upper Marshall Sandstone. The Napoleon persists as a member bed, though there is little need for such a designation.

Because of the indefinite contact between the Marshall and underlying Coldwater Shale in most parts of the basin, thickness values assigned to the entire Marshall section range from 46 to 122 m (150 to 400 ft). Electric-log studies show better definition of the Coldwater Shale-Marshall Sandstone contact than ordinary well-cutting investigations. The Marshall also has silty shale beds that can be best traced by use of electric logs of the gamma-ray type.

The Marshall Sandstone also has affinities with the overlying Michigan Formation. The basal part of the Michigan Formation intergrades with the upper Marshall, particularly in the central part of the basin. A sandstone, most frequently referred to as the "Stray Sandstone" and assigned to the basal part of the Michigan Formation, overlies and interfingers with the lithologically similar sandstone, the Marshall. The boundary between the two sandstones is not easily determined. In the past the "Stray," which produces gas, has been compared with "shoestring sands," or sandbars, such as those in Oklahoma and Kansas (Ball and others, 1941). Modern logging techniques and more abundant well control suggests a variable but blanket-type deposit rather than isolated, linear sandbars. The underlying Marshall, which also produces gas in a few fields, is a blanket-type sandstone body. The so-called "Stray" can be traced into the Napoleon Sandstone of the outcrop area. Evidently there was little, if any, break in deposition from Marshall time into Michigan Formation time.

The Marshall Sandstone is confined to the Southern Peninsula and apparently was removed from a much larger area by pre-Pleistocene erosion. According to Cohee and others (1951), the Marshall Sandstone overlying the Coldwater Shale is probably the time equivalent to the upper part of the Borden Group (Osage) of northern and southern Indiana.

Michigan Formation.—The Michigan Formation, now cut off from correlative rocks in other States, consists of gray to dark-gray and greenish-gray shale, thin beds of limestone, dolomite, sandstone, and anhydrite and gypsum. Originally called Michigan Salt Group by Winchell (1861), the formation was described from exposures at Grand Rapids, Kent County, and from exposures along the shore of Tawas Bay on the west side of Saginaw Bay. Although brines are found in the porous parts of the formation, no bedded halite has been found in the thousands of wells which have now penetrated the section. The name was eventually changed to Michigan Formation.

As previously noted, the basal sandstone of the Michigan Formation intergrades with the upper Marshall in the central basin. Some geologists have described these basal sandstones as reworked Marshall (Newcombe, 1933) thus implying an erosion surface between the "Stray" sandstone and the upper Marshall, or Napoleon Sandstone. The Michigan Formation, now confined to the central part of the basin and cut off from correlative strata in adjacent basins, is believed to be lower Meramac in age. The thickness of this formation is about 183 m (600 ft).

Facies changes are evident within the Michigan Formation. Depositional pinchout of shale beds or merging of shale beds into sandstones is common. However, several key beds show widespread continuity and are useful in mapping subsurface structures. The stratigraphically lowest marker bed, referred to as "brown lime" or "brown dolomite," is about 4.5 m (15 ft) thick and is found from 30 to 46 m (100 to 150 ft) above the "Stray Sandstone" in the central basin areas. Another marker, referred to as "Triple Gyp zone" (Wolcott, unpub. data, 1948) consists of three anhydrite beds separated by thin shale stringers. This zone, about 9 m (30 ft) thick and about 12 m (40 ft) above the "brown lime," is especially evident in electric logs of the gamma ray-neutron type. Other anhydrite beds may be traced for considerable distances.

Bayport Limestone.—The Bayport Limestone is the youngest Mississippian rock identified in Michigan. Originally called Point Au Gres Limestone from small outcrops on the west shore of Saginaw Bay (Douglass, 1841), better exposures were found around Bayport, Huron County, Mich., so the name was changed to Bayport Limestone in 1899 by Lane. Scattered outcrops are found in several areas of the basin but the best exposures are found in quarries in Eaton, Huron, and Arenac Counties.

The Bayport is light buff to brown and contains chert, frequently in spherical-shaped forms along certain bedding planes. The basal part may be arenaceous or may contain thin sandstone beds in some regions. The thickness is variable and generally less than 30 m (100 ft). According to thickness maps (Cohee and others, 1951), the Bayport has been completely removed by pre-Pennsylvanian erosion from several areas of the central part of the basin.

The Bayport is considered to be conformable on the Michigan Formation and is treated as a formation of the Grand Rapids Group. The fauna indicates correlation of the Bayport Limestone with the upper part of the St. Louis Limestone and the Ste. Genevieve Limestone of the Mississippi Valley (Newcombe, 1933). Newcombe also states that the beds can be compared approximately with the Maxville Limestone of Ohio. The Bayport is now isolated and cut off from its correlative sections in adjacent basins.

PENNSYLVANIAN SYSTEM

Pennsylvanian rocks cover an area of approximately 29,784 km^2 (11,500 sq mi) in the central basin (fig. 1). The sequence has been variously divided by different geologists since the coal-bearing measures were first discovered near Jackson, Jackson County, in 1835. The most extensive nomenclature was formulated by Lane in 1901, 1905, and 1908 when Michigan coal was an important resource. Studies were made by Kelly (1933, 1936) in which the cyclothemic nature of the strata was recognized. A more recent evaluation of Michigan's Pennsylvanian sequence was made by Wanless and Shideler (1975) who derived most of the thickness and lithology data from logs of oil-well borings. The nomenclature used in 1861 and at various times through 1975 is shown in table 2. Because Michigan coal measures have little economic import at this time, and records of wells that penetrate these rocks are not definitive in detail, Pennsylvanian rocks are commonly divided into a Saginaw Formation (Pottsville Series) and an overlying Grand River Formation (Conemaugh Series). The Parma Sandstone, long considered the basal formation of the Pennsylvanian section, cannot be traced throughout the basin. Because of its very restricted occurrence, it is treated as an unnamed unit of the Saginaw Formation.

Outcrops of Pennsylvanian strata are extremely limited in the Michigan basin because of the thick cover of Pleistocene glacial drift. A concentration of outcrops is found along the Grand River near the town of Grand Ledge, Eaton County, and along the Grand River valley in the City of Jackson, Jackson County. Most of the knowledge of Michigans' Pennsylvanian section has come from study of coal borings (Andrews and Huddle, 1948; Cohee and others, 1950), from data gathered from coal mines and open pits when they were in operation, and from a large number of oil-well borings. These studies concentrated on the coal resource.

Subsurface studies show erosional unconformities at the top and base of the Pennsylvanian section, so the thickness values vary over different parts of the basin. Thicknesses range from as much as 91 to 152 m (300 to 500 ft) in the Saginaw Bay region to more than 213 m (700 ft) farther west in the basin (Cohee and others, 1951). Thickness determinations are complicated by similar lithologies of sedimentary rocks of Jurassic age which overlie part of the Pennsylvanian section and by the Michigian Formation-Bayport Limestone of Mississippian age which underlies the section.

PENNSYLVANIAN FORMATIONS

The most definitive stratigraphic studies of Michigan's Pennsylvanian system are probably those by Kelly (1930, 1931, 1933, 1936). Kelly recognized the cyclical nature of the many strata and the unconformities which separate many of them. He referred to the coal-bearing interval as the Saginaw Group and presented evidence that the Verne Limestone was a comparatively persistent member and a convenient place to divide the Saginaw Group into pre- and post-Verne cyclical formations (table 2). Occasionally the Verne Limestone can be recognized in well cuttings obtained by cable-tool drilling, but in general pre-Verne and post-Verne cyclical formations are difficult to correlate for any distance. Therefore the Saginaw is treated as a single formation. The Parma Sandstone, long considered the basal formation of the Pennsylvanian, is now treated as an unnamed unit of the Saginaw Formation because of its restricted occurrence and doubtful correlation from region to region. The uppermost division of the Pennsylvanian referred to by Kelly (1936) as the Grand River Group, is mainly a sandstone interval and is treated as a single formation.

Saginaw Formation.—The aggregate thickness of Pennsylvanian rocks is probably 213–229 m (700–750 ft). Most of this thickness is assigned to the Saginaw Formation. The Saginaw is composed of material of freshwater, brackish water, and marine origin. It consists of sandstones, shales, coal, and limestones. According to Kelly (1936, p. 165), and others, individual strata vary in character and thickness within relatively short distances. Numerous unconformities have disrupted cyclothem sequences and in places the complete sequence appears to have been removed by erosion. Coal beds are thin and discontinuous. Recent investigations (Kalliokoski and Welch, 1976), using primarily water-well and oil-well records, show that very few coal occurrences are outside of the six-county area surrounding the tip of Saginaw Bay. This six-county region represents less than half of the areal distribution of Pennsylvanian rocks shown in figure 1.

TABLE 2.—*Pennsylvanian nomenclature in Michigan, 1861–1975*

1861 Winchell	1876 Rominger	1895 Lane	1901 Lane	1905 Cooper	1908 Cooper	1909 Lane	1912 Smith	1931 Newcombe	1933 Kelly
Woodville	Coal measures	Woodville		Woodville absent in Bay County	Woodville absent in Tuscola County	Woodville Ionia suggested	Woodville	"Red Beds" Woodville	Grand River Group: "Red Beds" Ionia Sandstone Eaton Sandstone Woodville Sandstone
Coal measures		Jackson Coal Group	SAGINAW SERIES: Upper Rider Lower Verne Coal Upper Verne Coal Middle Rider Saginaw Coal Lower Rider Lower Coal	SAGINAW: Salzburg Rider Salzburg Coal Upper Rider Upper Verne Coal Lower Verne Rider Lower Verne Coal Middle Rider Saginaw Coal Lower Rider Lower Coal Bangor Rider Bangor Coal	SAGINAW: Reese Coal Unionville Coal Salzburg Rider Salzburg Coal Upper 1 Rider Lower Verne Rider Lower Verne Coal Middle Rider Saginaw Coal Lower Rider Lower Coal Bangor Rider Bangor Coal	Saginaw	Saginaw	Saginaw	SAGINAW GROUP: Post-Verne Cyclical Formations Verne Pre-Verne Cyclical Formations
Parma		Parma	Parma	Parma	Parma doubtfully represented in Tuscola County	Parma	Parma	Parma	Parma probably restricted to southern area

Grand River Formation.—The Saginaw Formation is considered to be overlain in most areas by sandstones referred to as the Grand River Formation. Grand River sandstones, thought of as a group, include in ascending order the Woodville (Winchell, 1861), Eaton (Kelly, 1936), and Ionia (Lane, 1909). These sandstones are very similar. Little evidence exists to show that they represent a vertical succession of strata as used in the group sense. Laterally, they do not yield to precise correlation.

The Grand River Formation consists predominantly of coarse sandstones with conglomeratic beds near the base. The sandstones are chiefly quartz cemented by siliceous or ferruginous material. Small amounts of feldspar and heavy minerals such as zircon and tourmaline are present. The formation is as much as 30 m (100 ft) thick. Red and brown colors and in some places purplish coloration are characteristic of the beds. According to Kelly (1936, p. 210) the various characteristics of the Grand River sandstones indicate that it was of freshwater origin, that much of the formation was due to river deposition, and that some of the beds are channel sandstones.

Contact with underlying rocks.—The basin was uplifted and eroded in Late Mississippian time. The Coldwater Shale (Kinderhook) and Marshall Sandstone (Osage)of Early Mississippian age, and the Michigan Formation and Bayport Limestone (Meramac) of Late Mississippian age were eroded from some of the more prominent anticlinal folds. In most areas, Pennsylvanian strata lie on the eroded surface of the Michigan Formation or the Bayport Limestone. In areas where these Late Mississippian rocks were completely removed, Pennsylvanian strata may lie directly on the eroded surface of the Marshall Sandstone. According to Cohee and others (1951) the last folding took place after deposition of Pennsylvanian sediments had ceased. A buff limestone in the lower part of the Saginaw Formation in the central part of the basin (Isabella County) is said to be well enough defined on electric logs of that area to indicate that structure of the Pennsylvanian rocks in general conforms to the underlying Mississippian strata (Cohee and others, 1951).

The Howell anticline, one of the major structures in the Michigan basin, is a complex, faulted, structural feature which plunges to the northwest (fig. 2). It was elevated and the crest stripped of Mississippian strata down to the Berea Sandstone (Kinderhook) in the Howell region, Livingston County (Ells, 1969). Along the southeasterly strike of the structure, successively older strata subcrop beneath Pleistocene glacial drift. Pennsylvanian rocks are not recognized over the crestal part of the structure except at its northern terminus in Livingston County. Presumably Pennsylvanian rocks extended over at least most of the anticlinal area but were removed by erosion. According to Wanless and Shideler (1975, p. 64), the Coldwater Shale of Early Mississippian age underlies the central part of the Howell structure. They state that this elevated area apparently stood above the depositional plain as a monadnock several hundred feet high and was not buried until about 122 m (400 ft) of Lower Pennsylvanian sediment (table 2, interval A) had accumulated around it. By the end of interval A time the monadnock was buried.

Michigan's Pennsylvanian rocks are restricted to the interior of the basin and isolated from the coal basins of Ohio and Illinois. Because of post-Pennsylvanian erosion, the total thickness and original areal distribution of these rocks within the basin is unknown. An extensive study was made by Kelly

TABLE 2.—Continued

1964 Ells and others		1975 Wanless and Shideler		
		Interval	Formation	Named Unit
Grand River Formation	Ionia Sandstone Eaton Sandstone Woodville Sandstone	C	Grand River Formation	
SAGINAW FORMATION	Verne Limestone	B	Saginaw Formation	Verne Limestone Member Verne Coal
		A		Saginaw Coal
			Parma Sandstone Member	

(1936, pp 172–76) of Michigan's Pennsylvanian marine fauna, most of which is found in the Verne Limestone. He concluded that the embayment in which the Verne marine member was deposited originally extended from at least the vicinity of Bay City southwestward in a direction approximating the long axis of Saginaw Bay (fig. 1). The extension of the embayment outside the State of Michigan was said to be toward Indiana, Illinois, and Iowa rather than toward Ohio. According to Wanless and Shideler (1975, p. 68), during the time that the Verne Limestone was being deposited in the Michigan basin, the Seville of northern Illinois and the Mercer of northern Ohio were being deposited. The exact positions of the seaways are not known. Pennsylvanian clays are found in solution cavities in Silurian strata near Kankakee and Joilet in northeastern Illinois (Willman, 1962, p. 63). The presence of these clays would seem to support the concept of an embayment which once extended northeastward across the present Kankakee arch and into the Michigan basin.

Contact with overlying rocks.—A sizable area of pre-Pleistocene but post-Pennsylvanian sediments immediately overlies part of the beveled Pennsylvanian surface. Largely confined to the western and northern Pennsylvanian subcrop region (fig. 1), these sediments consist of poorly consolidated red mudstones, greenish-gray mudstones, sandstones, and gypsum, frequently of the selenite variety. These rocks apparently do not crop out anywhere in the Michigan basin so are known only from subsurface studies. Once classified as "Permo-Carboniferous Red Beds" (Newcombe, 1931) and then as Pennsylvanian (Kelly, 1936), they are now classified as Late Jurassic (Kimmeridgian) age (A. T. Cross, oral commun., 1964) on the basis of spores collected from well cuttings. A formal nomenclature has not been established for these Jurassic sedimentary rocks; they are simply referred to as "red beds." The red beds contain spores shown by Cross (1966) to be similar to those in the Fort Dodge Gypsum of Iowa.

The original extent and thickness of the "red beds" in the Michigan basin is unknown. Though mainly overlying Pennsylvanian strata, red-bed sediments directly overlie the eroded surface of the Michigan Formation in some peripheral areas, and are thus confused with these Mississippian strata. Red mudstones and gypsum have also been included in the upper part of the Pennsylvanian section in the subsurface (Kelly, 1936; Wanless and Shidler, 1975, pp 68–69). The base or contact of these Jurassic sedimentary rocks with underlying Mississippian and Pennsylvanian rocks is not everywhere easily identified. Rocks assigned to the "red bed" interval are poorly consolidated and frequently subject to caving and lost circulation problems in drilling. Because of these conditions, well cuttings are few and do not necessarily reflect an accurate vertical succession of strata. They may include a mixture of Mississippian or Pennsylvanian sediments.

A study by Cohee and others (1951) of well logs and samples in the area of "red beds" showed much variation in thickness and an uneven distribution. This suggested that "red bed" sediments were deposited in topographic depressions, possibly under conditions of subaerial erosion, after deposition of Pennsylvanian rocks in Michigan had ceased. He reported thicknesses of 91–122 m (300–400 ft) in some subcrop sectors. Cohee and others (1951) also reported that investigations for water supplies in certain areas in Michigan showed that "red beds" were limited to topographic lows in the bedrock surface. There is some indication that the source of information was unintentionally misquoted and that "red beds" are confined to topographic highs rather than lows.

Except for small, widely scattered outcrops of various age assignments, the bedrock surface of the Michigan basin is covered by Pleistocene glacial drift. The glacial drift directly overlies Pennsylvanian rocks except for those areas directly overlain by remnant Jurassic sedimentary rocks which, in turn, are also covered.

MISSISSIPPIAN-PENNSYLVANIAN ENVIRONMENT OF DEPOSITION

All of Michigan's Mississippian rocks were accumulated in a marine environment. Largely shales and sandstones, they are about 914 m (3,000 ft) thick. At different times, sediments appear to have been supplied from eastern, western, and northern sources, causing intertonguing of sediments or lateral blending of them. No obvious break in sedimentation is apparent from Late Devonian (Chautauquan) time through Late Mississippian (Meramecian) time, although Middle Mississippian rocks have not been identified. Mississippian strata were apparently subject to a variety of depositional environments while they were accumulating in the basin.

On the eastern side of the Michigan basin, the Bedford Shale and overlying Berea Sandstone are invariably interpreted as deltaic deposits which merge westward into the Ellsworth Shale. The Ellsworth Shale was probably derived from a western source. The Sunbury Shale, immediately overlying the Berea Sandstone, is dark brown to black and is thickest in eastern Michigan. This shale, of either shallow or deep-water deposition, represents a different depositional environment from that of the underlying Berea and Bedford formations. The thinning of the Sunbury formation in a general east to west direction across the basin, provides some evidence that the unit represents a transgressive-regressive depositional cycle within Michigan.

The Coldwater Shale, about 396 m (1,300 ft) thick in the central part of the basin, contains thin lenticular siltstones and sandstones, thin limestones, and thin beds of limonite nodules. Several lateral facies within the sequence suggest probable transgressive-regressive episodes. Over much of the basin the upper part of the Coldwater is characterized by an increasing number of thin siltstone or sandstone beds separated by thin shale beds. The alternating nature of these beds foreshadows the deposition of the Marshall Sandstone.

The Marshall Sandstone, which grades upward from the Coldwater Shale formation, also contains Coldwater-type shales in parts of the basin. Shales and silty shales pinch out within the sandstone sequence or merge with sandstone strata. Some beds within the Marshall contain shell coquinas which may be indicative of shallow-water or shoreline deposition. In some areas where the Marshall grades into the overlying Michigan Formation, a thin sandy dolomite or limestone is found at the top of the Marshall.

Following deposition of the Marshall Sandstone, the basin continued to receive clastic material but became more restricted. During this phase, sediments now assigned to the Michigan Formation were deposited. The formation, about 183 m (600 ft) thick is made up of shale beds, anhydrite beds, and lesser numbers of sandstone, dolomite, and limestone beds. Several of the anhydrite beds and at least one of the limestone beds within the formation have widespread lateral continuity within the basin. The youngest Mississippian unit, the Bayport Limestone, is conformable with the underlying Michigan Formation and represents a return to more normal marine conditions. The Bayport is very irregular in thickness and distribution because of erosion during post-Bayport pre-Pennsylvanian uplift near the close of Mississippian time.

Pennsylvanian rocks in the Michigan basin are primary clastics deposited upon an eroded surface of Mississippian rocks. Sediments were deposited under deltaic and swamp conditions, some of which resulted in thin coal beds. Cyclic deposition is evident within the coal-bearing interval, and marine inundations are evident as shown by fossiliferous limestones. Unconformities which cut out parts of cyclothems appear to be frequent. Channel sandstones which suggest deposition by river systems have been identified. Red and green shales and gypsum have been identified as Pennsylvanian in parts of the basin. But as similar rock assemblages are found in the Michigan Formation which underlies parts of the Pennsylvanian sequence, the age of these rocks may be misidentified. The upper non-coal bearing part of the Pennsylvanian is mainly sandstone. The source area for these and the underlying clastics is considered to be eastern and northern highlands.

The original thickness and extent of Pennsylvanian rocks once covering Michigan is unknown. The Verne Limestone, which is carbonaceous and has an abundant marine fauna, has been correlated with the Seville Limestone of Illinois and a part of the Mercer Formation of Ohio. A seaway of unknown dimensions undoubtably connected the Michigan, Illinois, and Appalachian basins. Following deposition of Pennsylvanian rocks in the Michigan basin, the region was uplifted and eroded. Erosion was severe and the Pennsylvanian surface was heavily dissected by stream valleys. The thickest sections of Pennsylvanian rock with a maximum of about 229 m (750 ft) are found in the central part of the basin. The entire Pennsylvanian section is now confined to the interior of the basin and isolated from correlative rocks in other depositional basins. A remnant section of Jurassic-age rocks overlies a part of the Pennsylvanian sequence. These rocks are overlain by Pleistocene glacial drift.

The presence of Mesozoic rocks in Michigan is of special interest. Now remote from other Mesozoic strata, these remnant Late Jurassic sedimentary rocks overlie a part of the eroded Pennsylvanian surface and overlap onto parts of the eroded Mississippian rocks. In turn, they were apparently eroded before Pleistocene glaciation and burial beneath Pleistocene glacial deposits. Formerly classfied as "Permo-carboniferous Red Beds" and later as Pennsylvanian "Red Beds," they have now been identified on the basis of palynologic evidence. The lithology of these red beds, possibly as much as 122 m (400 ft) thick, consists of poorly consolidated red and green clays and shales, sandstones, and some gypsum. The stratigraphic order of these different lithologies is uncertain. The lower boundary is also uncertain because similar lithologies have been, or are, included in underlying Mississippian or Pennsylvanian formations. Palynologic studies do confirm their age assignment at least down to the controversial lower boundary. Whether these sediments accumulated in depressions as valley fill or in playa lakes as suggested by Cohee (1965), or are confined to Pennsylvanian topographic highs, or covered a much larger part of the Michigan basin, awaits further research.

ECONOMIC PRODUCTS

Valuable resources have been extracted from Michigan's Mississippian and Pennsylvanian rocks for many years. Though no metallic ores are found in either system, certain Mississippian formations have supplied shales suitable for use in cement and brick and tile manufacture; sandstones and limestones for construction and aggregate use; natural saline brines used in salt and chemical manufacture; and gypsum for use in various gypsum-based products. Mississippian rocks, primarily the sandstones, have also produced significant volumes of natural gas and petroleum. In certain areas of the State, Mississippian sandstones also are valuable and important sources of freshwater. Michigan's Pennsylvanian rocks, have fewer usable mineral resources, but were once important as a source of coal. In the early days of salt production (1860) from the evaporation of brines, brines from basal Pennsylvanian formations were used along with those from Upper Mississippian sandstones. The Pennsylvanian brines were subsequently abandoned in favor of the more concentrated salines of the underlying Mississippian sandstones. Pennsylvanian rocks are also the source of shales for brick and tile manufacture. In years past, sandstones were quarried at a few locales for building stone. In certain areas of the State, the upper part of the Pennsylvanian section serves as an important source of freshwater. The economic products currently extracted from Carboniferous rocks and other informative data are summarized.[2]

Sandstones.—Mississippian sandstones (Napoleon Sandstone member of the Marshall Sandstone) are quarried at three locations near Napoleon, Jackson County, Mich. The product is rough and dressed dimension stone which is used in various construction projects. Current production has averaged about 5,000 short tons (4,500 t) per year over the past 3 years. Historically, a number of quarries have been operated in the past throughout the outcrop area of the Marshall-Napoleon Sandstone in the southern part of the State. Small amounts of Pennsylvanian sandstone (Ionia Sandstone-Grand River Formation) were once quarried at Ionia, Ionia County, and possibly at other areas.

Shale.—Pennsylvanian shales from the Saginaw Formation are quarried in three locations. The shale mined in Clinton and Eaton County is ground and used in the manufacture of vitrified field and sewer tile. That produced in Shiawassee County is ground and used to manufacture bricks. The annual production from these operations in both 1974 and 1975 amounted to 100,000 short tons (90,000 t). In the past, Pennsylvanian shales were also quarried in Ingham and Jackson counties for use in brick and tile manufacturing.

Limestones.—Mississippian Bayport Limestone has been quarried for many years in several parts of the State. Currently seven quarries are in operation. From quarries in Arenac, Eaton, Huron, and Jackson Counties, limestone production in 1974, 1975 and 1976 ranged from more than 1.1 to nearly 1.4 million short tons (1.26 million t). Most of the limestone is used as construction aggregate but some of high purity is used in the beet-sugar refining process.

Gypsum.—Gypsum beds of the Michigan Formation (Late Mississippian) have been mined for more than 100 years. Presently five gypsum mines are in operation; two shallow underground mines in Kent County and three open-pit operations in Iosco County. Annual production figures have been kept since 1868. Before 1868, 146,528 short tons (131,875 t) were mined. Total gypsum mined in Michigan through 1975 is 66,162,294 tons (59,546,065 t). The largest recorded annual tonnage was produced in 1973 when 1,882,257 tons (1,694,032 t) were mined. Most of the gypsum is exported out of the State for processing. Michigan has ranked in first place in the United States in the production of gypsum in all but 7 years since 1945, and in at least second place since 1926.

Petroleum and natural gas.—Mississippian rocks have produced significant amounts of petroleum and natural gas. The State's first commercial oil field was discovered in Berea Sandstone reservoir rocks at Saginaw, Mich. in 1925. In 1925 and 1926, 100 percent of the State's oil production, 98,000 barrels, came from this field. In 1927, production from the

[2] Information on economic products other than petroleum and natural gas supplied by Milton Gere, Economic Geologist, Geological Survey Division, Michigan Department of Natural Resources.

Berea Sandstone was 434,000 barrels. In the same year, however, oil was discovered in Devonian formations, and exploration for Mississippian Berea Sandstone accumulations became less important. Since 1927, other Berea reservoirs have been found. Annual oil production from these rocks continues to decrease and amounted to only 22,921 barrels in 1976. Total cumulative Mississippian oil production through 1976 amounted to 2,546,556 barrels.

Until recent years, the Michigan Stray-Napoleon-Marshall sandstones were the principal Mississippian gas-producing reservoir rocks. The first recorded gas production was in 1931 when 46,232 Mcf (thousand cubic feet) was reported. By 1947, annual production was recorded as 19,817,437 Mcf. Since that year, production has declined each year and amounted to only 169,433 Mcf in 1976. Total cumulative Mississippian gas production through 1976 amounts to 213,538,591 Mcf. Though most of the larger Mississippian gas traps appear to have been found, smaller accumulations, are occasionally found.

Most of the larger Mississippian, Michigan Stray-Napoleon-Marshall gas pools have been converted to underground gas-storage reservoirs. Owned and operated by gas utility companies, Michigan utilities have pioneered the conversion of suitable oil and gas traps to natural gas storage. Fifteen Mississippian gas pools, yielding from more than a billion to as much as nearly 52 billion cubic feet of native gas before conversion, are now in active use.

Freshwater reservoirs.—Where Mississippian and Pennsylvanian rocks have been flushed of naturally occurring brines, the sandstones serve as freshwater reservoirs or aquifers. Covered by varying thicknesses of glacial drift, these areas are found mainly around the subcrop margins in the southern part of the basin. Down-dip toward the center of the basin they become progressively saline.

Natural brines.—Natural brines from Mississippian rocks, primarily the Marshall Sandstone, were once extensively used for the manufacture of salt (NaCl) and other chemical products. Whereas most brines used in Michigan's extensive chemical industry are now produced from Devonian or Silurian rocks, virtually all Marshall Sandstone brine wells have been abandoned and plugged.

Coal.—Bituminous coal, though not now produced, was mined from various coal beds in the Saginaw Formation for more than 100 years. As many as 38 coal mines were in operation at one time during the years 1905, 1906, and 1908. Volume of coal production fluctuated; the largest annual tonnage was produced from 37 mines which were in operation in 1907. The tonnage that year was 2,035,855 tons (1,832,270 t). Coal production figures exist for 1860 through 1953 and for the year 1975. From 1947 through 1952 only one mine was in operation and this was closed in 1952. Total Michigan coal production has amounted to 46,316,580 short tons (41,684,922 t). Production data for the year 1975 relate to the reopening of a small open-pit mine where a small amount of cannel coal was removed and sold locally for fireplace fuel. Currently no coal is actively mined in the State.

There has been some renewed interest in Michigan's coal reserves. A recent U.S. Bureau of Mines open-file report (Kalliokoski and Welch, 1976, p. 30) places Michigan coal reserves at approximately 126.5 million short tons (113.9 million t). The bulk of Michigan's coal is only accessible through underground mining. Coal seams are thin, generally less than 1 m (3 ft), and frequently discontinuous. Water problems and possible hazards associated with oil- and gas-test borings throughout many parts of the coal-bearing region impose additional limitations to underground mining. Near-surface coal seams usually require the removal of large volumes of glacial drift and rock overburden. Present-day economics and environmental considerations do not favor the revival of Michigan's coal industry.

OUTCROP LOCALITIES

A blanket of Pleistocene glacial drift covers all the bedrock surface of Michigan. Mississippian and Pennsylvanian rocks are exposed at the surface in a few locales, but the outcrops are small in vertical and lateral extent. Exposures of Mississippian rocks are found in 12 of the 68 Southern Peninsula Counties, namely: Arenac, Branch, Calhoun, Eaton, Hillsdale, Huron, Iosco, Jackson, Kent, Ogemaw, Sanilac, and Tuscola. Pennsylvanian outcrops are found in Arenac, Calhoun, Clinton, Huron, Ingham, Ionia, Jackson, Saginaw, and Shiawassee Counties. A list of reported exposures and type localities of Michigan's Mississippian and Pennsylvanian rocks in the aforementioned counties has been documented by Martin and Straight (1956, pp. 198–243). The location of these counties is shown in figure 2.

Quarries or mines afford the best opportunity to view partial sections of Michigan's Mississippian and Pennsylvanian rocks and to collect fossils. A selected list of quarries and possible fossil-collecting localities follows[3]:

Coldwater Shale (Mississippian):

1. Old abandoned Wolverine Portland Cement Co. shale pit. Located approximately 2 miles south and 2 miles west of Coldwater, Mich., in the C NW¼ sec. 32, T. 6 S., R. 6 W., Branch County.
2. Old abandoned Peerless Portland Cement Co. shale pit. Located approximately 2 miles south and 0.7 miles east of Union City, Mich., in the SE¼ NE¼ NE¼ sec. 16, T. 5 S., R. 7 W., Branch County.
3. Old abandoned grindstone quarries in and about the community of Grindstone City, Mich., in sec. 25, T. 19 N., R. 13 E., Huron County.

Marshall Sandstone (Mississippian):

1. Long abandoned Hanover quarry, approximately 1 mile south and 1.6 miles west of Hanover, Mich. Located in the NE¼ NW¼ sec. 31, T. 4 S., R. 2 W., Jackson County.
2. Active quarry located approximately 0.5 miles east of Napoleon, Mich. in the NW¼ NE¼ sec. 6, T. 4 S., R. 2 E., Jackson County.

Michigan Formation (Mississippian):

1. Gypsum quarries of the Michigan Gypsum Co. Located approximately 4 miles south and 2 miles east of Whittemore, Mich. in the C SW¼ sec. 25, T. 21 N., R. 5 E.; C N½ NW¼ and C S½ sec. 31, T. 21 N., R. 6 E., Iosco County.
2. Gypsum quarry of National Gypsum Co. Located approximately 2 miles east and 1.1 mile north of National City, Mich., in sec. 35, T. 22 N., R. 6 E., Iosco County.
3. Gypsum quarry of the United States Gypsum Co. Located just west of Alabaster, Mich. in sec. 27, T. 21 N., R. 7 E., Iosco County.

Bayport Limestone (Mississippian):

1. Limestone quarry of Wallace Stone Co. Located approximately 2.5 miles east and 1 mile south of Bayport, Mich. in secs. 5 and 6, T. 16 N., R. 10 E., Huron County.
2. Limestone quarry of Arenac County Road Commission. Located approximately 2.5 miles and 2 miles east of AuGres, Mich. Located in the NW¼, Sec. 5, T. 19 N., R. 7 E., Arenac County.
3. Limestone quarry of Cheney Limestone Co. Located approximately 1 mile west and 0.1 mile north of Bellevue, Mich., in the SE¼ NE¼ sec. 29, T. 1 N., R. 6 W., Eaton County.

Saginaw Formation (Pennsylvanian):

1. Shale pits of the Grand Ledge Clay Products Co. One pit is located about 1.5 miles northwest of Grand Ledge, Mich. in the SW¼ NE¼ sec. 3, T. 4 N., R. 4 W., Eaton County. Another pit is located about 2.5 miles northwest of Grand Ledge in the NE¼ SW¼ sec. 34, T. 5 N., R. 4 W., Clinton County.
2. Shale pits of Michigan Brick Inc. Located about 1.5 miles northeast of Corunna, Mich. in the E½ of sec. 22, T. 7 N., R. 3 E., Shiawassee County.

[3] Selection of quarry sites prepared by H. O. Sorensen, Economic Geologist, Geological Survey Division, Michigan Department of Natural Resources.

Grand River Formation (Pennsylvanian):

1. Exposures of Eaton Sandstone are found along the north bank of the Grand River in the northwest part of the town of Grand Ledge. Also in the immediate vicinity are abandoned pits and quarries showing exposures of Eaton Sandstone, several thin coal seams, Verne Limestone, underclays, and shales assigned to the Saginaw Formation or Saginaw Group of Kelly (1936).
2. Exposures of Ionia Sandstone, also a part of the Grand River Formation are found in old abandoned quarries, approximately 3.5 miles east of Ionia, Mich., near the south banks of the Grand River in the SW¼ NW¼ sec. 23, T. 7 N., R. 6 W., Ionia County.

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The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States— Indiana

By HENRY H. GRAY

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1110-K

Prepared in cooperation with the Indiana Geological Survey, Department of Natural Resources

Historical review and summary of areal, stratigraphic, structural, and economic geology of Mississippian and Pennsylvanian rocks in Indiana

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CONTENTS

ILLUSTRATIONS

THE MISSISSIPPIAN AND PENNSYLVANIAN (CARBONIFEROUS) SYSTEMS IN THE UNITED STATES—INDIANA[1]

By HENRY H. GRAY[2]

ABSTRACT

Rocks of the Mississippian System are widespread in southwestern Indiana, where they reach a maximum exposed thickness of about 600 m. All parts of the period are represented, but the lowest series, the Kinderhookian, is very thin. Early Valmeyeran rocks consist of shale and siltstone; later Valmeyeran rocks are a sequence of limestone formations. Rocks of the Chesterian Series contain repeated alternations of limestone, sandstone, and shale.

The lower boundary of the Mississippian System is in a black shale sequence, is faunally determined, and has no physical expression. The upper boundary is a disconformity which has relief as great as 100 m. Mississippian rocks were uplifted, tilted, and erosionally beveled before deposition of Pennsylvanian sediments, so that Pennsylvanian rocks rest on youngest Mississippian rocks at the southern border of Indiana and on progressively older rocks northward.

Rocks of the Pennsylvanian System are widespread in southwestern Indiana, where they reach a maximum thickness of 500 m. Repeated cyclic sequences of sandstone, shale, coal, and limestone characterize the entire system, but subtle vertical distinctions may be perceived. In rocks of the Morrowan and Atokan Series, sandstone is the prominent rock type, and beds of coal are thin and local. The Desmoinesian Series, in which shale is dominant, contains five major commercial beds of coal. The Missourian Series also consists mainly of shale, but beds of coal are scattered and thin. Rocks of latest Pennsylvanian (Virgilian) age are not represented in Indiana.

INTRODUCTION

SOME BASIC FACTS

From the time of the first systematic geologic investigations in Indiana (Owen, 1838, 1839), it has been clear that rocks which in many other parts of the world are assigned to a single geologic system, the Carboniferous, here are divided into two lithologically distinct parts by a locally and regionally conspicuous unconformity. Classic study areas from which evolved the concept of the Mississippian System for the lower of these divisions are not far to the west; classic study areas from which evolved the concept of the Pennsylvanian System for the upper of these divisions are not far to the east. These two systemic terms have had increasingly common usage in Indiana for nearly 100 years, and they will be used in this report.

Rocks of the Pennsylvanian System underlie an area of nearly 19,000 km^2 in southwestern Indiana, or about one-fifth of the State's total area (fig. 1). The rocks constitute a dominantly clastic sequence of shale, siltstone, and sandstone, and intercalated thin but widespread beds of clay, coal, black shale, and limestone. Their maximum thickness is about 500 m near the southwest corner of the State; their mean thickness, however, is about half that figure, so that these rocks have a total volume of about 5,000 km^3. From these rocks is produced a large share of the State's mineral wealth. The total value of raw-mineral commodities produced from Pennsylvanian rocks in Indiana in 1976 was about $300 million (Indiana Geological Survey, 1977). Nearly all this value was derived from coal, which was mined mostly by stripping; of lesser value were oil, clay and shale, sandstone, and limestone.

Most of the area underlain by Pennsylvanian rocks is covered by residual soil or by younger unconsolidated deposits, which include till of Wisconsinan and Illinoian (late Pleistocene) ages and associated outwash sand and gravel, glacial lake silt and clay, loess, dune sand, and Holocene alluvium. Thickness of this cover is as much as 45 m in buried valleys near the confluence of the Wabash and Ohio Rivers, but over large areas the cover is less than a meter to a few meters thick. Scattered exposures of the bedrock are distributed throughout the area, but most of the larger exposures are found in the upland along the eastern margin of the outcrop belt and in strip mines that follow the crop line of the

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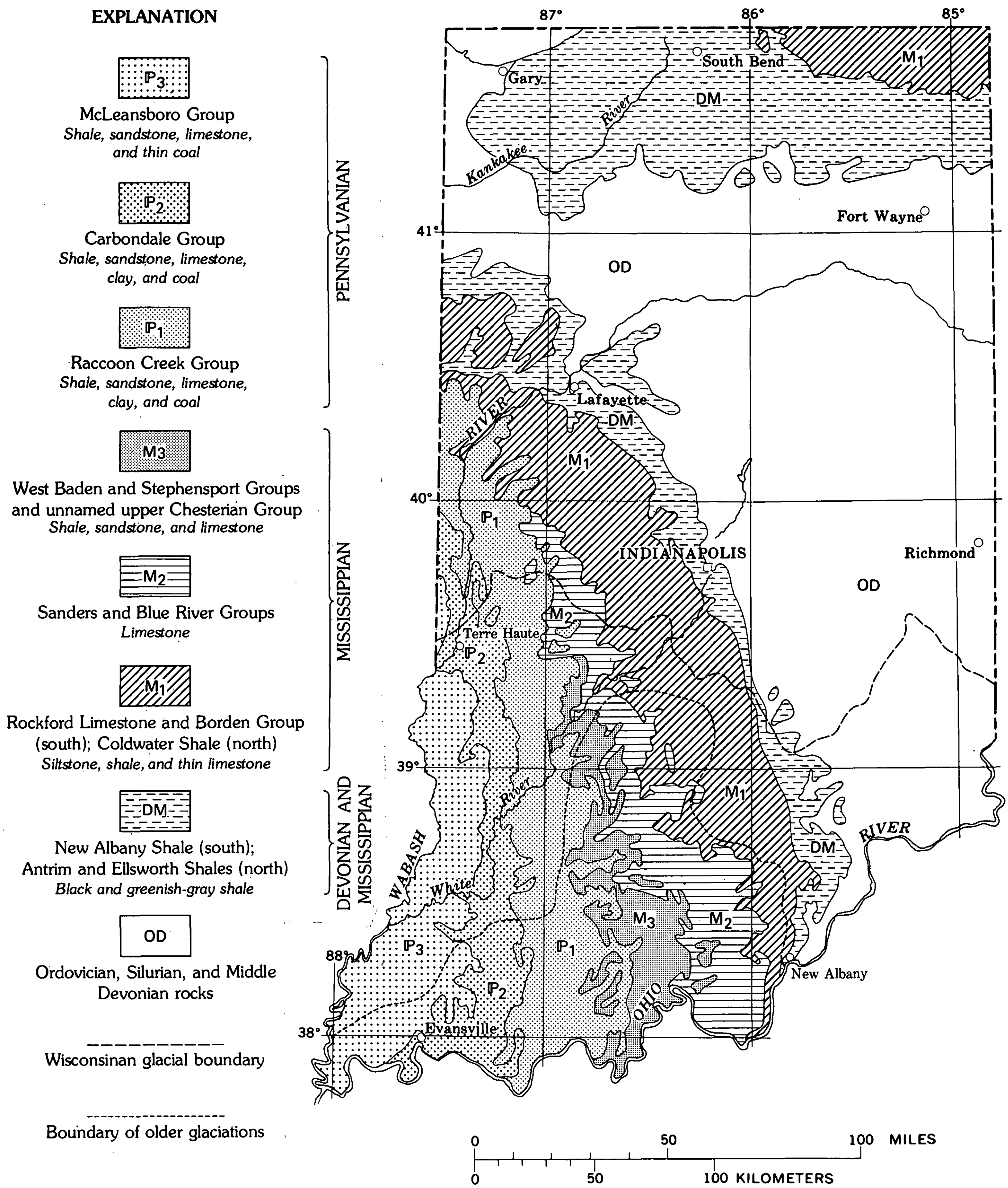

FIGURE 1.—Map of Indiana showing distribution of Mississippian and Pennsylvanian rocks.

major beds of coal in a north-northwest trend across the midsection of the belt.

The contact between rocks of the Pennsylvanian System and underlying rocks is a well-defined unconformity whose surface, as reconstructed from outcrop and subsurface data, has the aspect of a southwest-sloping plateau entrenched as much as 50 to 100 m by integrated systems of southwest-trending consequent stream valleys. Because of local relief on the unconformity, Pennsylvanian rocks in any given area may rest on several older formations, but a regional trend also exists because the older rocks were slightly tilted and erosionally beveled before deposition of basal Pennsylvanian sediments. As a result, Pennsylvanian rocks rest on youngest Mississippian rocks at the southern extremity of the outcrop area and on progressively older rocks northward. Along the main outcrop belt, the unconformity truncates almost the entire Mississippian System; in scattered outliers to the northeast, Pennsylvanian rocks lie on black shale of late Devonian age.

Rocks of the Mississippian System are at the bedrock surface in southwestern Indiana in an area of about 18,000 km^2 (fig. 1). They underlie Pennsylvanian rocks in the area previously described, and in northern Indiana they are at the bedrock surface in an additional area of nearly 4,000 km^2. Thus, in all they underlie slightly more than 40,000 km^2, or a little more than two-fifths of the State. These rocks are divisible into three lithologically distinct parts. The upper part, which comprises repeated cyclic sequences of sandstone, shale, and limestone, and the middle part, which consists principally of limestone of many textural varieties, are restricted to southwestern Indiana. The lower part, a clastic sequence of siltstone and shale, is present in both northern and southwestern Indiana.

In the southwestern outcrop area, Mississippian rocks are thickest near the Ohio River, where they attain a thickness of 600 m. They thin progressively northward, mainly as a result of the truncation earlier described, so that in west-central Indiana they are only about 100 m thick. In northernmost Indiana, their maximum thickness is about 200 m. The total volume of Mississippian rocks in Indiana is about 11,000 km^3, and the total value of raw-mineral commodities produced from these rocks in 1976 was about $60 million (Indiana Geological Survey, 1977). Mississippian rocks are the major source of oil in Indiana (Carpenter and others, 1975, p. 43). Also of importance are limestone (used principally for crushed stone, cement, and dimension stone), gypsum, shale, and sandstone.

In their northern area of occurrence (fig. 1), Mississippian rocks are entirely covered by glacial deposits; not a single exposure is known. Much of the southwestern area also is covered, although more thinly, by the same kinds of unconsolidated deposits that cover adjacent areas of Pennsylvanian rocks. In much of south-central Indiana, however, Mississippian rocks underlie only thin residual deposits and loess. Exposures thus are rather common, especially in large quarries in the limestone belt that trends northwestward from the Ohio River to central western Indiana.

Rocks in southwestern Indiana dip west-southwest at the rate of about 5 m/km away from the crest of the Cincinnati arch near the eastern border of the State and toward the axis of the Illinois basin. A few normal faults that have displacements as great as 60 m are known, mostly along the Wabash River near the southwest corner of the State. Rocks in northern Indiana dip northward at a similar rate toward the center of the Michigan basin.

HISTORY OF GEOLOGIC WORK AND EVOLUTION OF NOMENCLATURE

The history of geologic study of these rocks is long, and only a few of the works on which the present overview is based may be mentioned. Some of the important schemes of stratigraphic classification that have been used in this area are outlined in figures 2 and 3. Evolution of the nomenclature was discussed in detail by Cumings (1922), and more recently a brief review and an updating were presented in Shaver and others (1970).

Serious original research into Indiana geology began in 1837, when pioneer geologist David Dale Owen was appointed State Geologist and was instructed to make a 1-year survey that later was extended for an additional year (Owen, 1838, 1839). Owen's reports were printed many times; the most widely available version, which was considerably revised from earlier printings, is the 1859 printing (Owen, 1859a, b). Cumings (1922, p. 475) credited Owen as being the first geologist in American to recognize the twofold nature of the Carboniferous System, although, in a sense, Owen's classification was merely derived from the Mountain Limestone-Coal Measures scheme that had come into use in Europe, where Owen had been schooled. By 1859, Owen had refined and restated the definition of his "sub-carboniferous group" so that it almost exactly

Owen, 1859 a,b		Hopkins, 1904	Cumings, 1922; Logan, 1932	Current usage modified from Shaver and others, 1970: Group	Current usage modified from Shaver and others, 1970: Formation	Series	
Sub-carboniferous Group	Archimedes and Pentremital Limestones	Huron Limestone, Sandstone, and Shale	Negli Creek Limestone	——	——	Chesterian	Namurian
			——				
			Siberia ——				
			—— Limestone				
			——				
			Tar Springs Sandstone		Tar Springs Formation		
			Glen Dean Limestone	Stephensport	Glen Dean Limestone		
			Hardinsburg Sandstone		Hardinsburg Formation		Visean
			Golconda Limestone		Haney Limestone		
			Indian Springs Shale		Big Clifty Formation		
			Cypress Sandstone				
			Beech Creek Limestone		Beech Creek Limestone		
			Elwren Formation	West Baden	Elwren Formation		
			Reelsville Limestone		Reelsville Limestone		
			Sample Sandstone		Sample Formation		
			Beaver Bend Limestone		Beaver Bend Limestone		
			Mooretown Sandstone		Bethel Formation		
	Barren Limestone	Mitchell Limestone	Paoli Limestone	Blue River	Paoli Limestone		
			Ste. Genevieve Limestone		Ste. Genevieve Limestone	Valmeyeran	
			St. Louis Limestone		St. Louis Limestone		
		Bedford Oolitic Limestone	Salem Limestone	Sanders	Salem Limestone		
		Harrodsburg Limestone	Harrodsburg Limestone		Harrodsburg Limestone		
					Ramp Creek Formation		Tournaisian
	Knobstone or Sub-carboniferous Sandstone	Knobstone Shale	Edwardsville Formation	Borden	Edwardsville Formation ——		
			Floyds Knob Formation				
			——		——		
			New Providence Formation		New Providence Shale		
	——	Rockford Goniatite Limestone	Rockford Limestone	——	Rockford Limestone	Kind.	
Black Bituminous Aluminous Slate		New Albany Shale	New Albany Shale		New Albany Shale	Chaut.	Fam.

FIGURE 2.—Evolution of Mississippian rock-unit nomenclature in southwestern Indiana. Minor boundary changes are not indicated. Units marked—either received no name or received names that have been shown to be not useful. Kind.=Kinderhookian, earliest Mississippian. Chaut.=Chautauquan, Fam.=Famennian, latest Devonian.

included what now constitutes the Mississippian System (fig. 2). He further recognized and described (Owen, 1859a, p. 20–23) a threefold lithologic division of the "sub-carboniferous group."

D. D. Owen embarked on another survey in 1859, but he died before the work was finished, and it was completed by his brother Richard (Owen, 1862). This report includes a section by Leo Lesquereux (1862) specifically describing the Coal Measures of Indiana. A few years later, a State geological survey was established as a continuing organization that has functioned, though the name has changed several times, until the present. Much of the research on the stratigraphy of Mississippian and Pennsylvanian rocks in Indiana has been done under the aegis of this organization.

In the early years, the Indiana Geological Survey concentrated on preparation of areal reports. In 1895, however, a new State Geologist, W. S. Blatchley, brought with him a "plan for taking up each of the great natural resources of the State" (Blatchley, 1897, p. 6). Backed by a corps of able assistants, many of whom later became nationally known, he produced a series of reports that remained definitive for many years. Worthy of mention in the present context are studies of the Carboniferous sandstones (Hopkins, 1896; Kindle, 1896), the famous dimension limestone (Hopkins and Siebenthal, 1897; Cumings and others, 1906), coal (Ashley, 1899, 1909), the lower Carboniferous (Ashley and Kindle, 1903), and the first detailed geologic map of the State, toward which many of the earlier studies were directed (Hopkins, 1904). Also during this period, two folio reports on the coal-bearing area were prepared by the U.S. Geological Survey to add to the then rapidly expanding Geologic Atlas of the

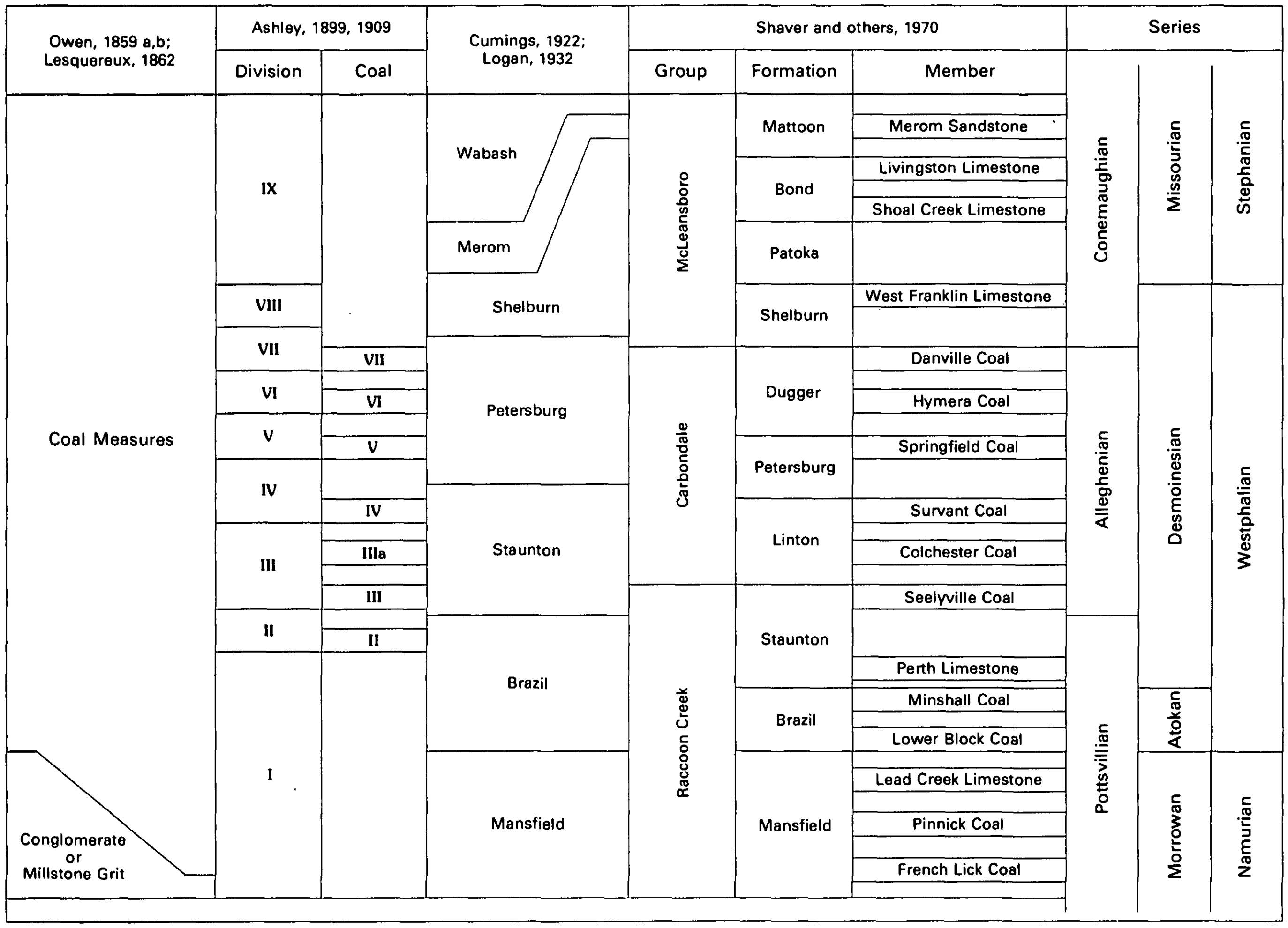

FIGURE 3.—Evolution of Pennsylvanian rock-unit nomenclature in Indiana.

United States (Fuller and Ashley, 1902; Fuller and Clapp, 1904).

The impetus of the Blatchley organization was not maintained, however, and the focus of geologic research shifted to Indiana University. Perhaps because the Ashley reports on coal were so thorough, faculty and students turned their attention mainly to the Mississippian rocks. Notable among these studies were those of Malott (1915, 1919, 1925, 1952) and Stockdale (1931, 1939). The present era of activity in the study of Indiana geology began when C. F. Deiss became State Geologist in 1946. In addition to renewed emphasis on mapping (Perry and Smith, 1958; Melhorn and Smith, 1959; Gray and others, 1960; Hutchison, 1960, 1976; Sunderman, 1968), interest has been extended into the vast store of subsurface data (Pinsak, 1957; Sullivan, 1972), and a series of Coal Investigations Maps has been prepared in cooperation with the U.S. Geological Survey (Friedman, 1961; Hutchison, 1958; Kottlowski, 1954, 1959, 1960; Waddell, 1954; Wier, 1950, 1951, 1954a).

The current definitive statewide geologic maps of Indiana consist of a series of Regional Geologic Maps published by the Indiana Geological Survey with the cooperation of geologists in adjacent States. Each of these maps covers an area of 1° in latitude by 2° in longitude and shows both bedrock and unconsolidated deposits on a scale of 1:250,000 Principal areas of outcropping Mississippian and Pennsylvanian rocks are shown on the Danville (Wayne, Johnson, and Keller, 1966), Indianapolis (Wier and Gray, (1961), Vincennes (Gray, Wayne, and Wier, 1970), and Louisville (Gray, 1972) quadrangles.

GEOLOGIC SETTING

Indiana lies astride the northwestward extension of the Cincinnati arch, a broad, gentle structural rise that divides the basins adjoining on the north, east, and west. Mississippian rocks in the Michigan basin are no closer to their Illinois basin counterparts than 150 km; Pennsylvanian rocks are separated by twice that distance. The early Paleozoic history of this structural feature is elusive, but by mid-Paleozoic time an arch in this general geographic position clearly was influencing sedimentation. In the late Paleozoic, this feature dominated the paleogeographic and paleotectonic patterns. During Mississippian and Pennsylvanian time, an arch separated the Michigan and Illinois basins so effectively that their depositional histories are quite distinct. Since the Pennsylvanian, these areas have been relatively stable tectonically so that the present structure fairly adequately portrays the tectonic framework that influenced late Paleozoic sedimentation.

In southwestern Indiana, the Devonian-Mississippian transition is placed near the top of a black shale, the New Albany Shale (fig. 2; Lineback, 1970, fig. 16). In northern Indiana, the transition is near the top of the Ellsworth Shale, which itself is transitional from the underlying black Antrim Shale to the overlying greenish-gray Coldwater Shale. Thus, the close of the Devonian Period is not marked by any obvious tectonic event in this area—yet there was a change in the character of the sediment, from black mud indicative of stagnant bottom conditions to greenish-gray mud that represents more oxygenated bottom conditions; this change marks the beginning of a prograding deltaic sequence that in turn reflect uplift of a source area far to the north and east. During earliest Mississippian time, however, the sedimentation rate remained exceedingly slow, so that the entire Kinderhookian Epoch is represented by scarcely more than a meter of shale and limestone (fig. 4).

Early in Valmeyeran time, a great delta composed mainly of silt was built along the eastern margin of the Illinois basin, but the prograding deltaic wedge failed to fill the basin. Carbonate-rock units not represented at the surface in Indiana succeeded the deltaic silt in deeper parts of the basin (Lineback, 1969), and it was not until middle Valmeyeran time that the deep basin was filled to overflowing. For the later half of Valmeyeran time, normal shelf-type shallow-water carbonate sedimentation was dominant.

A strong terrigenous influence again prevailed as the Chesterian Epoch began. Clastic materials poured into the Illinois basin from the northeast (Potter and others, 1958, Swann, 1964). These sediments appear to have bypassed the Michigan basin, which may have been full to the brim at the time. Vaccilating shorelines, deltas, and shallow seas are recorded by the deposits, in which terrigenous clastic and indigenous carbonate deposits alternate to form a pattern that has been called rhythmic (Swann, 1964). Clearly, at this time an approximate balance had been achieved between the rates of sedimentation and of subsidence. At the very end of Mississippian time or during earliest Pennsylvanian, the recently deposited sediments were slightly uplifted and tilted gently toward the west. Erosion shaped the newly emergent land into a surface of gently rolling uplands that here and there were rather sharply entrenched by consequent streams.

As the Illinois basin subsided slightly, deposition once more began about middle Morrowan time (fig. 5). A cyclic sedimentation pattern again is evident, but sediments are more continental than before; thus, few sediments represent offshore marine conditions and more are typical of deltaic and fluvial conditions (Wanless and others, 1970). Notable, though volumetrically minor, are deposits associated with coal-swamp environments. Beds of coal, underclay, and black roof shale are distributed throughout the Pennsylvanian rocks of Indiana, but the principal beds of coal are of Desmoinesian age.

Rocks of the Pennsylvanian System constitute the youngest bedrock in Indiana. Permian rocks have not been identified in the Illinois basin; Cretaceous rocks are known in southern and western Illinois (Willman and others, 1975, p. 205–206) but have not been found in Indiana. Some scattered occurrences of chert gravel are provisionally assigned to the Miocene or Pliocene (Lafayette Gravel, Shaver and others, 1970, p. 86–87; Luce Gravel, Ray, 1965, p. 17–21), but the geologic materials that overlie Pennsylvanian rocks in most areas are glacially related deposits of late Pleistocene age.

The stratigraphic nomenclature used in this paper has not been reviewed by the Geologic Names Committee of the U.S. Geological Survey. The nomenclature used here conforms with the current usage of the Indiana Geological Survey.

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THE DEVONIAN-MISSISSIPPIAN BOUNDARY AND EARLIEST MISSISSIPPIAN ROCKS

In southern and western Indiana, the Devonian-Mississippian boundary is recognized within and near the top of the New Albany Shale (fig. 4). This formation consists predominantly of brownish-black partly dolomitic shale that contains as much as 20 percent by weight organic matter. Greenish-gray shale and mudstone that contain very little organic matter make up a lesser part of the formation. Rather uniformly about 35 m thick in the outcrop belt (fig. 1), the New Albany Shale thickens westward in the subsurface (Lineback, 1970).

Deposition of the Albany Shale began late in middle Devonian time and ended in middle Kinderhookian (early Mississippian) time. Conodont assemblages representative of two of the six zones of the standard upper Devonian sequence of Germany (Zones toI and toIII) are recognized in the lower and middle parts of the New Albany Shale, and assemblages indicative of early Mississippian age (Zones cuI and cuII) are known from the uppermost 0.5 m of the formation. From this and other faunal evidence, the Devonian-Mississippian boundary in southern Indiana can be placed about 0.6 to 1.8 m below the top of the New Albany Shale, but the boundary has no physical expression and cannot be more precisely located because definitive faunas do not occur at critical stratigraphic positions (Lineback, 1970, p. 39).

In northernmost Indiana, rocks equivalent to the New Albany Shale include the Antrim Shale, a brownish-black shale that is much like the New Albany, and the overlying Ellsworth Shale, a greenish-gray shale that has a transitional zone of interbedded brownish-black and greenish-gray shale at the base. Together, these two formations are about 60 m thick near the margin of the Michigan basin. Because of the thick glacial cover, these rocks are nowhere exposed. Sparse subsurface data suggest that the upper part of the Ellsworth Shale can be traced eastward into rocks in Ohio that are assigned to the Bedford Shale and the Berea Sandstone, and therefore is Mississippian in age.

Earliest Mississippian rocks in southern Indiana constitute many thin named beds in the uppermost part of the New Albany Shale. These include, in ascending order, a 6-cm bed of phosphatic nodules, the Falling Run Bed; a 12-cm bed of greenish-gray shale, the Underwood Bed; a 25-cm bed of black fissile shale, the Henryville Bed; and a 12-cm bed of greenish-gray glauconitic mudstone, the Jacobs Chapel Bed (Lineback, 1970, p. 27–29). None of these units is geographically extensive, but they are of interest because of the shifting environments that they suggest and because of the rich and varied faunas that they contain. Included are conodonts, scolecodonts, bryozoans, crinoids, brachiopods, gastropods, pelecypods, arthropods, fish, plants, and associated ichnofossils. An especially diverse conodont fauna has been found in the Jacobs Chapel Bed (Rexroad, 1969). All faunas indicate a Kinderhookian age.

Overlying the New Albany Shale, and forming a distinctive marker bed that separates the New Albany from the Borden Group above, is the Rockford Limestone (fig. 4). This formation, which commonly is about a meter thick, is a greenish-gray micritic dolomite (Lineback, 1970, p. 35). It has a fairly abundant and varied conodont fauna from which a latest Kinderhookian to earliest Valmeyeran (Osagean) age has been determined (Rexroad and Scott, 1964), but possibly the most interesting elements in the otherwise sparse fauna are the several species of goniatites and nautiloids that have been known since the time of Verneuil (1847). Recent collections from sites in two widely separated areas have also been described (Gutschick and Treckman, 1957; Lineback, 1963).

The Rockford Limestone is overlain by the New Providence Shale (fig. 4). The contact is a disconformity of very low relief, so that in some places the Rockford is missing and the New Providence rests directly on uppermost parts of the New Albany Shale (Lineback, 1970, p. 35–37).

THE MISSISSIPPIAN SYSTEM

Earliest Mississippian rocks, which represent Kinderhookian and part of Valmeyeran time, are very thin and have for convenience been discussed in connection with the Devonian-Mississippian boundary. The greater thickness of the Mississippian System in Indiana comprises three nearly equal parts: a clastic sequence (Borden Group) that is Valmeyeran in age a carbonate rock sequence (Sanders and Blue River Groups) that is Valmeyeran and earliest Chesterian in age and a mixed clastic-carbonate cyclic sequence (West Baden and Stephensport Groups and an unnamed group) that is Chesterian in age (fig. 4).

BORDEN GROUP

The most comprehensive study of the Borden Group is that of Stockdale (1931) who identified

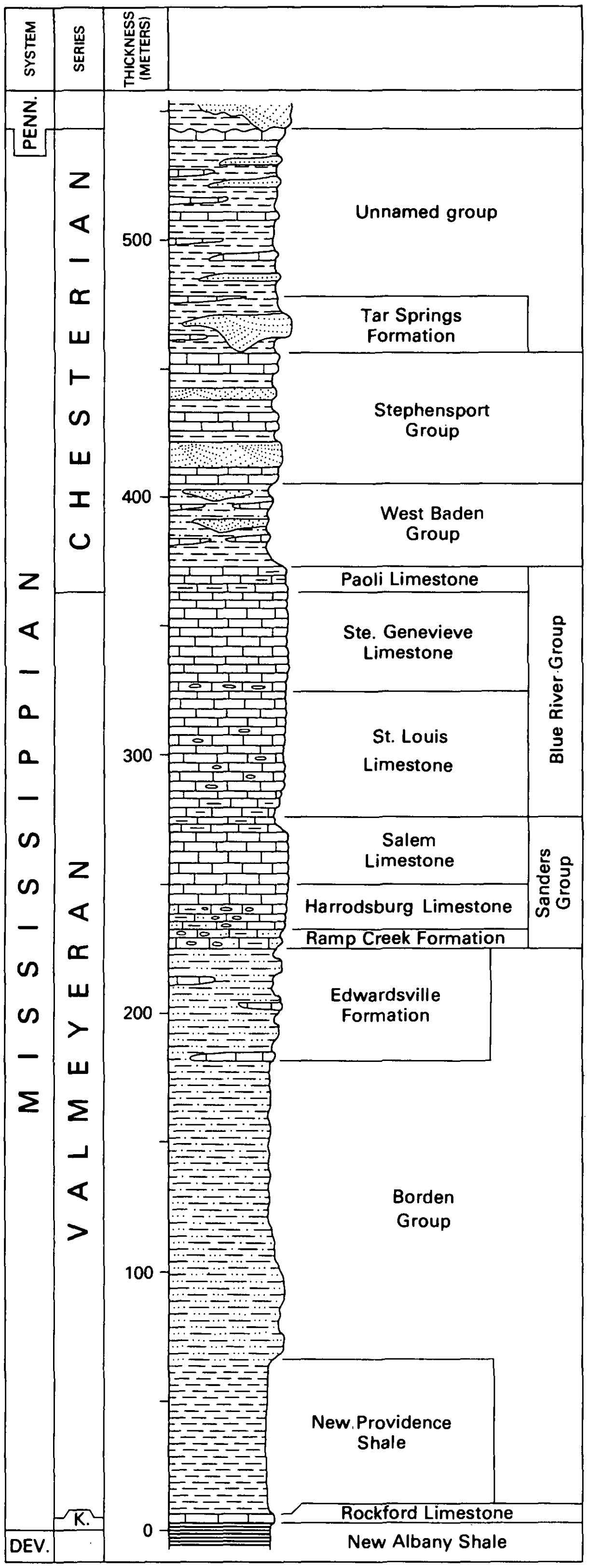

FIGURE 4.—Columnar section showing exposed Mississippian Rocks in Indiana. K.=Kinderhookian.

in the group five formations and a large number of lithic units that he designated facies and within which he recognized many members. Only a few of his names are still in use but his study remains a repository of factual data. The Borden Group represents a late and distal tongue of the great Catskill-Mauch Chunk delta system of the northern Appalachians but most of the sediment that was deposited in the Illinois basin probably had a northeastern source (Swann and others 1965).

The Borden Group comprises a rather straightforward prodelta-delta sequence. The green-gray and red-brown soft New Providence Shale represents the prodelta deposits; the overlying sequence of siltstones (fig. 4) varies from clay poor and sandstonelike to clay rich and shalelike and is regarded as deltaic. Kepferle (1977), in a recent study of a siltstone member in the lower part of the group, concluded that the siltstone is a turbidite that was deposited by west-southwest currents in relatively deep water at the base of a deltaic slope. Higher members of the group represent associated slope and platform deposits.

Toward the top of the Borden Group are a few thin and discontinuous beds of coarsely crinoidal limestone. In some places, similar rocks form small reefy masses as much as 3 km across and 20 m thick. These masses were referred to as bioherms by Stockdale (1931) in what was one of the earliest applications of the term. Bioherms near Crawfordsville have been known for many years because of the abundance and variety of crinoids and other fossils that they contain (Lane, 1973).

Maximum thickness of Borden rocks is about 250 m near the center of the State, which was an apparent major locus of sediment influx into the Illinois basin. The deltaic siltstone beds which constitute the greater part of the group, dip westward at a rate that is significantly greater than the true regional dip. In this way, the siltstones record initial dip of at least 3 m/km, which is consistent with an abrupt westward depositional thinning shown by the group. The Borden delta, therefore, is restricted to the margin of the basin; in the central part of the basin, only about 20 m of prodelta shale represents the Borden Group. This classic example of a sediment-starved basin, in which off-delta water depths may have reached 300 m, was documented by Lineback (1969), who also described the sequence of partial basin fills of successive limestone units that followed the close of Borden deposition.

The clay-poor siltstone beds of the Borden Group, particularly those in the upper part of the group, are resistant to erosion, so that the group is expressed physiographically as scenic uplands of considerable relief, thorough dissection, and steep slopes that have many exposures. Equivalent rocks in northern Indiana are referred to the Coldwater Shale, a greenish-gray slightly silty shale similar to the New Providence Shale. This formation is 150 m thick at the northeast corner of the State and is the youngest bedrock in the Indiana part of the Michigan basin.

SANDERS AND BLUE RIVER GROUPS

The mid-Mississippian limestone sequence—the "Barren Limestones" of Owen (1859a)—begins at the base with a complex succession of microrudites and biosparites that gradually give way upward to packstones and grainstones.[3]

These, in turn, are overlain by a thick series of micrites that in part are fossiliferous and pelletiferous. Low among the micrites are beds of gypsum, anhydrite, and micritic dolomite. Higher, some oolites appear, and toward the top of the sequence are thin beds of calcareous sandstone and siltstone that presage clastic depositional conditions to follow.

The Sanders Group (fig. 4) is at the base of this sequence and includes mainly coarsely textured types of limestone; some geode-bearing silty dolomite is interbedded near the base. This group ranges in exposed thickness from about 50 m near the Ohio River to a wedge edge in west-central Indiana (Nicoll and Rexroad, 1975). The thinning is partly depositional but ultimately is due to truncation beneath Pennsylvanian rocks. Downdip into the subsurface, the group thickens abruptly as a complement to the thinning of the underlying rocks that belong to the Borden delta. Thickness as great as 140 m has been recorded near the southwest corner of the State, where the group includes additional rock units that are not present at the outcrop.

At the top of the Sanders Group is the famous Salem Limestone. This formation is not, as is sometimes stated, an oolite; instead, it is a packstone to grainstone composed of sand-sized lime-coated fossil fragments. The prominent cross-stratification and lack of terrigenous detritus suggest deposition as a shallow shoal remote from shore (Carr and others, 1966). The texture and composition of this rock make it ideal for cutting and carving, and for many years it has been one of the premier building stones of the world (Rooney, 1970). Abundant among the microfauna of the Salem is the guide fossil *Endothyra (Globoendothyra) baileyi* (Hall), and in many places a diversified but diminutive megafauna is found. Especially notably is the Spergen Hill locality, which has been known for more than 100 years. Early monographic treatments of this fauna are those of Whitfield (1882) and Cumings and others (1906).

The Blue River Group (fig. 4) crops out from the southern boundary of the State, where the group is 150 m thick, northwestward about 200 km into west-central Indiana where it is truncated by the Mansfield Formation. In the subsurface the group is somewhat thicker. It consists mainly of micritic limestone, but oolite, sandy limestone (calcarenite), and chert of several types are prominent. Associated with gypsum and anhydrite in the lower part of the group are micritic dolomite and thin beds of black, gray, and green-gray shale. The evaporite deposits are economically important in the subsurface (French and Rooney, 1969), but they are poorly represented on the outcrop. In places in the northern part of the outcrop area, beds of limestone breccia occur at the evaporite position.

The gypsum-bearing rocks indirectly give rise to a group of mineral springs that center on French Lick and West Baden, towns that retain vestiges of the era when "taking the waters" was a popular pastime. Many other mineral spring localities are known, but the major sulfate water springs in Indiana lie nearly on a north-northwest line within about 40 km of French Lick. Along this line the gypsum beds lie at a depth of about 100 m. Gypsum and anhydrite are of wide extent downdip from the springs, but are thin and sporadic updip. The interface between the gypsum and the sulfate-water system is irregular and deeply embayed. Probably it is slowly progressing westward because of the constant removal of gypsum by solution.

In the upper part of the Blue River Group, true oolite is the subdominant lithology. As described by Carr (1973), this rock type commonly occurs as lenticular bodies about 2 km wide by 6 km long by 5 m thick. Inner parts of these bodies are composed of moderately porous grain-supported oolite; outer parts are of less porous oolite that is cemented by sparry calcite. Chemically, the rock is an exceedingly pure limestone that assays more than 98 percent calcium carbonate. In the subsurface, these oolitic

[3] Because no scheme of classification yet proposed is fully satisfactory for the wide variety of carbonate rock types in the Mississippian System of Indiana, selected terms from the classifications of Folk (1959) and Dunham (1962) have been used.

bodies are important reservoirs for petroleum; at the surface they are quarried for use as an industrial chemical. As modern analogs, Carr (1973) suggested the carbonate sand bodies of shallow marine shelf areas in the Bahamas banks.

WEST BADEN AND STEPHENSPORT GROUPS AND UNNAMED UPPER CHESTERIAN GROUP

Three groups in the upper part of the Mississippian System consist principally of terrigenous clastic rocks, and thus they are distinct from the underlying mid-Mississippian limestone sequence. The lowermost, the West Baden Group (fig .4), is about 35 m thick in the outcrop area (Gray and others, 1960). It consists of five formations, three of which are clastic and include sandstone, shale, siltstone, and mudstone, and two of which are biomicritic to oomicritic limestone. Near the base of the group in the Bethel Formation are beds of shaly coal as much as 5 cm thick, the oldest coal in Indiana.

Although the limestone formations of the West Baden Group are of normal marine origin, they are less continuous laterally than might be expected of such rocks. Gray and Perry (1956) found that in places the Reelsville Limestone is absent as the result of facies change. Hrabar and Potter (1969) and Sullivan (1972) related similar anomalies to the West Baden clastic belt, a branching, irregularly linear area 3 to 10 km wide that can be traced from the outcrop southwestward for about 80 km and in which the limestone formations are replaced laterally by sandstone and other clastic rocks. In a few places the transition is abrupt, but more commonly it is gradual and is accompanied by thickening of the limestone bed along with increasing content of noncarbonate material toward the clastic belt. Strips of sandy shale a kilometer or so in width normally separate the limestone bed laterally from the axial sandstone body.

The West Baden clastic belt is a distributary of Swann's (1963) Michigan River, an important feature of late Paleozoic geography. The belt marks the locus of virtually continuous clastic sedimentation that took place contemporaneously with deposition of the alternating clastic and carbonate rock units that typically are recognized in the West Baden Group. The limestone formations were deposited when the rate of clastic supply was regionally diminished, so that clastic deposition was limited to the distributary belt; the clastic formations represent times when terrigenous sediment was introduced in greater quantity and dispersed more widely. The geographic position of the clastic belt remained stable throughout West Baden time.

The Stephensport Group (fig. 4) is about 45 m thick in the outcrop area (Gray and others, 1960) and consists of five formations. The limestone formations, which are more continuous and more prominent in this group than in the West Baden Group, include biomicrite, oomicrite, biosparite, and oosparite. Among the abundant and varied faunas are pentremites (Galloway and Kaska, 1957), crinoids (Horowitz, 1965), bryozoans (Utgaard and Perry, 1960; Perry and Horowitz, 1963), and conodonts (Rexroad, 1958; Rexroad and Jarrell, 1961). The clastic formations consist of gray shale, siltstone, mudstone, and evenly stratified fine-grained sandstone. The sandstone beds also are more continuous than those of the West Baden Group and are notable cliff formers, so that the outcrop area of the Stephensport Group includes some of the most rugged terrain in southern Indiana.

The cyclic alterations of clastic- and limestone-dominated rock units that typify Chesterian deposition are best shown in the Stephensport Group. In general, the clastic units represent marine regressions and the limestone units represent transgressions. The Big Clifty Formation and the overlying Haney Limestone in the middle of the Stephensport Group make up such a regressive-transgressive couple. The lower two-thirds of the Big Clifty is an evenly stratified fine-grained sandstone of remarkable lateral extent along the outcrop (it is less continuous in the subsurface). It has a wavy upper contact that resembles megaripples and is succeeded upward in turn by thin marly mudstone, olive-gray and red-brown mudstone and shale, and gray shale that toward the top contains increasing numbers of fenestrate bryozoans and conularids. This sequence suggests a beach and barrier sand followed by a lagoonal mud that finally becomes fully marine. The biomicrites, biosparites, and oosparites of the overlying Haney Limestone represent a set of closely related shallow marine shelf and shoal environments (Vincent, 1975). Other comparable couples among the Chesterian rocks may be similarly, though not identically, interpreted.

Uppermost Chesterian rocks in southern Indiana have been described by Malott (1925) but have received no formal group name.[4] They are here con-

[4] After this paper was submitted for publication, these upper Chesterian rocks were described and their nomenclature was discussed in H. H. Gray, 1978, Buffalo Wallow Group—Upper Chesterian (Mississippian) of southern Indiana: Indiana Geol. Survey Occasional Paper 25, 28 p.

sidered an unnamed group that consists mainly of shale and that reaches a maximum thickness of 80 m near the Ohio River. About 70 km to the north, however, the group is truncated by the disconformity at the base of the Pennsylvanian System, so that areally this is the most restricted of the Mississippian groups.

This group consists predominantly of blue-gray, green-gray, and olive-gray shale and mudstone in which are interspersed a few beds of sandstone and many beds of limestone (fig. 4). Some of the limestone beds, which rarely are as much as a meter thick, represent tongues of much thicker limestone formations to the west. A thick and local sandstone member near the base of the group forms prominent cliffs and box canyons, but for the most part the group is topographically expressed as steep, smooth slopes beneath caprock ledges of Pennsylvanian-age sandstone. Formational terminology that is used for equivalent rocks in most of the Illinois basin (Swann, 1963) is not applicable here. For a discussion of some of the problems raised thereby, see Shaver and others (1970, p. 175–176).

Among the limestones of the unnamed group are thin beds of micritic dolomite that may indicate a sterile penesaline environment, but normal marine carbonate and shaly carbonate deposits containing bryozoan-brachiopod faunas that have not been studied are widely present. Conodont faunas of some of the limestones have been described by Rexroad and Nicoll (1965).

AGE AND CORRELATION OF MISSISSIPPIAN ROCKS

Many schemes have existed for the subdivision of Mississippian rocks by age; the Indiana Geological Survey follows the Illinois State Geological Survey in the usage (from oldest to youngest) of Kinderhookian, Valmeyeran (formerly Osagean and Meramecian), and Chesterian for epoch and series terms. The Kinderhookian-Valmeyeran boundary is about midway in the thin Rockford Limestone, as shown by conodont zonation (Rexroad and Scott, 1964). The Valmeyeran-Chesterian boundary is placed at the base of the Paoli Limestone (fig, 4), following the reasoning presented by Swann (1963, p. 17–20), who based his determination in part on the distribution of *Platycrinites penicillus*, a guide fossil found in the Ste. Genevieve Limestone, and *Talarocrinus*, which occurs in the Paoli Limestone and in younger Chesterian rocks.

Only a few paleontologic studies of Mississippian rocks in Indiana have attempted correlation with the European standard sections. Horowitz and Perry (1961) concluded, on the basic of crinoid faunas, that the Glen Dean Limestone probably is close to the Visean-Namurian boundary; from studies elsewhere, Mamet and Skipp (1971), on the basis of calcareous Foraminifera, would place this boundary between the Haney and Glen Dean Limestones. In parts of Europe, the Tournaisian-Visean boundary is placed within the zone of *Syringothyris*. In Indiana, this form is found in the Borden Group just below the Edwardsville Formation (Cumings, 1922, p. 493; Stockdale, 1931, p. 191), but on the basis of Mamet and Skipp's (1971) criteria, this boundary should be placed somewhat higher, probably at the base of the Harrodsburg Limestone.

THE MISSISSIPPIAN-PENNSYLVANIAN UNCONFORMITY

In the Midwestern United States, rocks of the Pennsylvanian System overlie older rocks at an unconformable contact that is second in regional importance only to the unconformity that separates Paleozoic from Precambrian rocks. In Indiana, this surface is a disconformity—that is, the uneven surface of contact is prominent but the strata above and below are virtually parallel. The crenelated line of outcrop of this disconformity trends from the Ohio River in a north-northwest direction some 300 km to west-central Indiana (fig. 1). The disconformity surface extends from this line southwestward across an area of nearly 19,000 km^2.

This disconformity has long been recognized as a buried ancient land surface that is mostly gently rolling, but that is entrenched, in some places quite deeply, by a set of subparallel valleys that trend southwestward entirely across the Illinois basin. The shape of this surface in part of Illinois was documented by Siever (1951). Similar documentation for Indiana does not exist, but Bristol and Howard (1971) prepared a so-called sub-Pennsylvanian paleogeologic map that covers much of the Illinois basin and that strikingly portrays the major valleys on the disconformity surface.

The full scope of the disconformity cannot be appreciated except through subsurface studies, but many aspects of it are well displayed on the outcrop. In a railroad cut near Shoals (Gray and others, 1957, p. 14–16), the disconformity is almost continuously exposed for nearly 300 m and clearly shows a small valley with relief of at least 20 m. Basal Pennsylvanian rocks here include sedimentary iron ore and sandstone, and rest on three formations of the Stephensport Group. Similar though less striking exposures may be observed at other places nearby (Gray and others, 1960, p. 29–35). In most places, however, the disconformity must be visualized on the basis of scattered data. For example, a valley about 35 m deep, 2 to 3 km wide, and more than 5 km long was mapped by Malott (1931), using only outcrop data. Quartz pebble conglomerate is an important part of the fill in this valley. Some of the deepest entrenchment is implied by isolated outliers 10 to 20 km from the main outcrop area (Malott, 1946). These outliers commonly are very porous sandstone, and where they rest on limestone they probably have been solutionally lowered, mostly during Cenozoic time, as has a sandstone channel-fill associated with the Bethel Formation in Kentucky (Indiana University, 1969).

North of the Wisconsinan drift boundary (fig. 1), the crop line of the Mississippian-Pennsylvanian disconformity is mostly covered, but there also the disconformity is a surface of considerable relief (Esarey and others, 1950). The valleys of Sugar Creek, Raccoon Creek, and their tributaries, most of which have been superimposed from a late Wisconsinan (late Pleistocene) drift surface and so have created many young valleys having extensive rock exposures, show the disconformity well. On a very local scale, in walking up the beds of some of these creeks, one can cross and recross the Mississippian-Pennsylvanian contact every few steps. Exposures in Shades State Park and just downstream along Sugar Creek show basal sandstone of the Mansfield Formation in contact with the Harrodsburg Limestone and siltstone of the Borden Group. Fifteen kilometers downdip to the west is a small inlier of the St. Louis Limestone that represents a hill about 75 m high on the disconformity surface.

Also observable at the outcrop is the regional truncation of the Mississippian rocks by those of the basal Pennsylvanian. Youngest Mississippian rocks underlie the Pennsylvanian near the Ohio River, but northward the disconformity gradually slices through 400 m of section. In scattered outliers to the northeast of the north end of the main Pennsylvanian outcrop, the entire Mississippian column is missing, and Pennsylvanian rocks rest on the New Albany Shale.

Although the disconformity is a profound and striking feature wherever it is well exposed, many of the rocks of the two systems are not readily identifiable with one system or another on a lithologic basis alone. Coal of respectable thickness, sedimentary iron ore, and nonstratified gray mudstone and clay are indicative of the Pennsylvanian System and biomicrite, biosparite, and red-brown and green-gray shale and mudstone are indicative of the Mississippian, but the more common kinds of shale and sandstone of the two systems are less distinct. In many shales of Pennsylvanian age, however, micas, carbonaceous materials, carbonized plant impressions, and siderite nodules are somewhat abundant than in otherwise similar rocks of Mississippian age. Many Pennslyvanian sandstones are somewhat coarser grained and more micaceous, and contain more abundant plant molds than do most Mississippian sandstones. Quartz pebbles, which in places are scattered through the basal sandstone beds of the Pennsylvanian System, also are useful indicators. These and other criteria were discussed by Atherton and others (1960) and Gray (1962).

The fauna of the youngest Mississippian rocks in Indiana clearly indicates an age very close to the end of Mississippian time. Somewhat younger Chesterian rocks are known from southern Illinois (Swann, 1963, p. 42–45; Collinson, Rexroad, and Thompson, 1971, p. 387–388). In contrast, the oldest identified Pennsylvanian florule from Indiana is from beds about 30 m above the base of the system and is placed by Read and Mamay (1964, p. K6–7) at their Zone 4-Zone 5 transition, below which in the central Appalachians there is a considerable section of Pennsylvanian rocks. Thus, it appears that basal Pennslyvanian rocks in Indiana are somewhat to considerably younger than oldest known Pennsylvanian rocks, and that the greater part of the hiatus represented by the unconformity belongs to Pennsylvanian time.

THE PENNSYLVANIAN SYSTEM

Coal constitutes only about 1 percent of the Pennsylvanian System in Indiana, but its economic impact has caused it to dominate stratigraphic work on these rocks since the earliest days of geologic research. The three nearly equal parts into which the system may be divided, principally on the basis of coal content, are more subtle than those of the Mississippian, and geologists have not generally found it useful to erect a semiformal classification such as that once used in the northern Appalachians in which "productive" and "barren" measures alternate. Nevertheless, a "productive" part of the system, which is Desmoinesian in age and which includes the thickest and most extensive beds of coal and widespread beds of limestone as well, may rather readily be identified (fig. 5). Below this, in rocks of Morrowan and Atokan age, sandstone is somewhat more prominent than in the rest of the

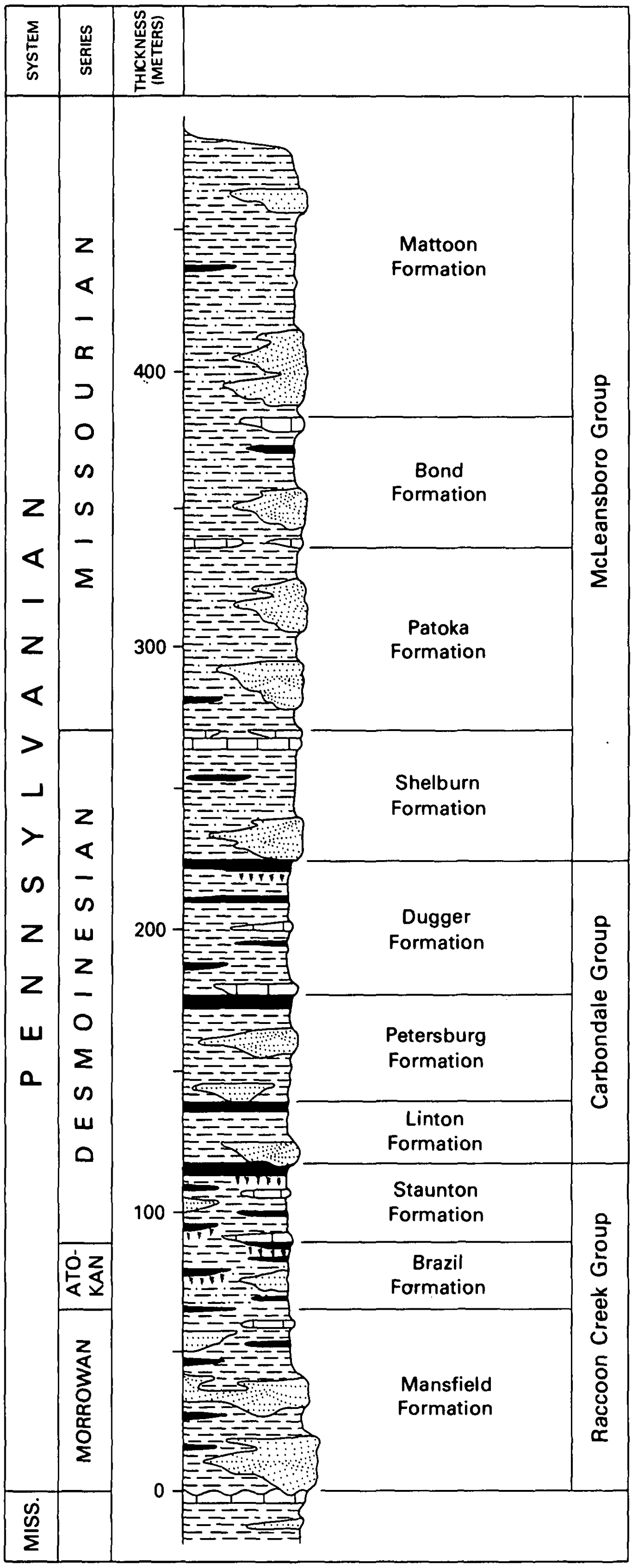

FIGURE 5.—Columnar section showing exposed Pennsylvanian rocks in Indiana.

system, and beds of coal and limestone are relatively thin and discontinuous. Above, in rocks of late Desmoinesian and Missourian age, shale is the dominant rock type, and only thin and local beds of coal and limestone are found. Rocks of latest Missourian and Virgilian age are not found in Indiana.

Formational nomenclature was slow to be applied to the Pennsylvanian rocks of Indiana (fig. 3), and even today is not applied strictly in accord with the precepts set forth in the Code of Stratigraphic Nomenclature, which calls for successive formations to be lithologically homogeneous and distinct one from another (American Commission, 1970, Art. 6). Contributing to this state of affairs are the following factors. First, by far the greater part of the Pennsylvanian System consists of a somewhat limited variety of common clastic rock-types—a few kinds each of sandstone, siltstone, shale, and clay. Truly distinctive lithologies are few. Second, the clastic rocks are interspersed with coal, limestone, chert, and sedimentary iron ore in repetitive cyclic sequences. Sequences that are seemingly identical may in fact be far apart stratigraphically. Third, lateral facies changes may be abrupt. Within short distances, individual beds and whole cyclic sequences may change in character so completely that they are scarcely recognizable. In consequence, formations in the Pennsylvanian System in Indiana are defined with reference to thin beds of coal and limestone used as key beds. As a further complication to traditional stratigraphic study, floral and faunal distributions are strongly facies controlled, so that fossil sequences that are effective for age determination or interregional correlation are sparse. These difficulties are shared with equivalent rocks both in the Appalachians, where the Pennsylvanian System has a more continental aspect, and in the midcontinent, where marine sequences are better developed.

RACCOON CREEK GROUP

Rocks that constitute approximately the lower one-quarter of the Pennsylvanian System in Indiana are assigned to the Racoon Creek Group (fig. 5). This group is extremely variable in thickness, primarily as a result of the disconformable relationship at its base. In the northern part of the outcrop area (fig. 1), the Raccoon Creek Group is 30 to 100 m thick (Hutchison, 1961); at the southern edge of the outcrop belt it is 150 to 200 m thick (Hutchison, 1959, 1971a); and in the subsurface at the southwest corner of the State, it is 300 m thick (Shaver and others, 1970, p. 137). Most of the increased thickness results from additional beds at the base of the group. Thus, beds in the lower part of the group in the southern outcrop area are not found to the north, and beds near the base of the group in the subsurface are not represented on the outcrop.

The lower part of the Raccoon Creek Group is designated the Mansfield Formation (fig. 5). Most of the variation in thickness shown by the group is assignable to this formation. As described from outcrop data (Gray, 1962), about 60 percent of the Mansfield Formation is sandstone, mostly evenly stratified to cross stratified; 22 percent is gray shale, and 14 percent is siltstone, mudstone, and clay. The rest includes small amounts of black shale, coal, limestone, chert, and sedimentary iron ore. Many of the sandstones are somewhat coarser grained and texturally less mature than those in the Mississippian formations. They contain significant, though small, amounts of clay as grain coatings, as matrix, and as discrete sand-size grains, some of which appear to be clots or aggregates and some of which probably are degraded shale fragments. Many of the sandstone beds are prominent cliff-formers, but most of the other rocks are less well exposed.

In the lower part of the Mansfield Formation near French Lick are beds of clay-bonded, slightly friable siltstone that are characterized by an exceptional smooth and uniform stratification. These rocks, which are used to make sharpening stones and are known as the Hindostan Whetstone Beds, cleave so perfectly that in quarrying they commonly are lifted out, by wedging, in sheets about 0.5 m wide by 2 m long by 2 cm thick. From their earliest use in 1821, some whetstones were exported to Europe (Carr and Hatfield, 1975, p. 11), but production now has almost ceased, and stratigraphic interest in the whetstones overshadows their economic value. Extending over an area of 20 km along strike by 5 km wide, in a zone about 15 m thick and marked above and below by thin but traceable beds of coal (Gray and others, 1960, p. 24–27), this unique lithology long has invited environmental interpretation as a lacustrine, lagoonal, or flood-plain deposit. In addition to the varvelike stratification, evidence includes a variety of delicate tracks and trails (Owen, 1859b, p. 17; Gray, 1962, p. 14), an assemblage of fossil plants (Kindle, 1896, p. 354–355), and large standing stumps of *Lepidodendron* (Kindle, 1896, p. 349–350).

Maps and other regional interpretations by Wanless (1955; 1975, p. 75) imply that the Hindostan Whetstone Beds constitute an isolated unit that is older than any other Pennsylvanian deposit in the Illinois basin. Although these beds contain a flora that apparently is older than any other Pennsylvanian flora yet studied in the basin, the beds are not an isolated occurrence. Rocks stratigraphically equivalent to the whetstone and to the marker beds of coal above and below have been traced northward for a few kilometers to where they are terminated by a facies change, and southward about 60 km to the Ohio River (Gray, 1962, p. 31). In the subsurface, where equivalent beds have been widely recognized (Hutchison, 1964, 1967, 1971b), they are underlain by 40 m or more of Pennsylvanian rocks. Included among these older rocks are a few beds of coal. The floras of this part of the Pennsylvanian System have not been studied, and probably among them are floras as old as the flora of the Hindostan Whetstone Beds, or older.

The principal producing beds of coal in the Raccoon Creek Group are those of the Brazil and Staunton Formations (fig. 5). Although local in extent and commonly no more than a meter thick, these have been mined by both underground and stripping methods. The Lower and Upper Block Coal Members of the Brazil Formation are of special interest. These are nonagglomerating and low in sulfur content, and their ash has a high fusion point. These properties placed them in demand for blacksmithing from the time of their discovery, about 1850. By 1870, the Block coals were being used as a direct charge in six Indiana blast furnaces, but by 1895 the last of these had ceased operation (Wayne, 1970) and these coals were then relegated mainly to domestic use. Also in the Brazil Formation, a waxy cuticular "paper coal" has been reported (Neavel and Guennel, 1960).

Many of the coal beds in the Staunton Formation are associated with marine deposits and characteristically have a relatively high sulfur content (Wier, 1973, fig. 9). The bed that marks the top of this formation and of the Raccoon Creek Group, the Seelyville Coal Member (fig. 5), is the lowest of the five most continuous and most productive beds of coal in Indiana.

CARBONDALE GROUP

Four of the five most productive beds of coal in Indiana are included in the Carbondale Group (fig. 5). Along the outcrop this group does not vary much from its average thickness of about 100 m, although the three formations that make up the group are themselves quite variable. These formations are, in ascending order, the Linton, Petersburg, and Dugger Formations. Each is bounded at the top by a widespread and thick bed of coal that is stratigraphically defined as a member (fig. 3). A few of the less extensive beds that are of stratigraphic importance also are defined as members.

The Carbondale Group extends across southwestern Indiana from the Ohio River north-northwestward to the Illinois State line just north of Terre Haute (fig. 1). This belt of outcrop fairly well defines the area of intensive strip mining (Powell, 1972); areas of underground mining lie within and west of the outcrop belt. Of the 1.3×10^9 metric tons of coal that has been produced in Indiana through 1970, nearly 90 percent has come from the Carbondale Group (Wier, 1973).

The Linton Formation ranges from 15 to 40 m in thickness, and averages about 25 m (fig. 5). This variation is due partly to sandstone lenses, which in places are as thick as 20 m, near the base of the formation. Closely overlying the sandstone, or overlying gray shale or clay where the sandstone is absent, is the Colchester Coal Member (fig. 3), a thin but widespread bed that is an important stratigraphic marker both in Illinois and in Indiana. Other major Indiana coals, notably the Seelyville and Survant Coal Members (fig. 3), are absent or are less well represented in Illinois.

Just above the Colchester Coal Member is one of two thin black shale beds that have been the object of probably the most intensive study of Pennsylvanian paleoenvironmental conditions in the Illnois basin. Zangerl and Richardson (1963), primarily in search of exquisitely preserved vertebrate remains (notably sharks), painstakingly excavated three sites, stratum by stratum. One of these sites was in the black shale overlying the Colchester Coal Member; the other two were in an older black shale in the Staunton Formation. These authors perceived the black shale environment as mainly shallow-water lagoonal, influenced by adjacent delta and shoreline sedimentation, and toxic, not as much a result of salinity variations (from marine to brackish to fresh) as it was a result of the presence of a flotant, a floating mat of vegetation that inhibited wave action and that contributed to anaerobic conditions in the water beneath it. The varied faunas appear to be death assemblages; animals floated or swam from more favorable environments associated with open water west of the studied sites into the restricted environments, where they died. Decay was slight and burial was swift.

The Petersburg Formation (fig. 5) is 25 to 50 m thick and averages about 35 m. It consists principally of shale and sandstone and includes at its top the Springfield Coal Member, from which for many years has come about half of the coal produced in Indiana (Wier, 1973, p. 28). Commonly, this member is 1 to 2 m thick, but it attains 4 m in one small area (Shaver and others, 1970, p. 170). Like most Indiana coals, it is bright-banded high-volatile bituminous coal. Its heating value on an as-received basis typically is about 6,400 calories per gram, and its ash content is about 10 percent. Because its average sulfur content is just over 3 percent (Wier, 1973, p. 14), recent exploratory effort has been directed toward defining areas of lower sulfur. The Springfield Coal Member commonly has a marine shale roof, but where the roof rock is nonmarine, the sulfur content of the coal is relatively low. Coal balls from this member contain beautifully preserved plant materials (Benninghoff, 1943); some also contain a marine invertebrate fauna (Boneham, 1976).

The Dugger Formation (fig. 5), which ranges from 25 to 50 m and averages 40 m in thickness, includes four named limestone members and four named coal members (Shaver and others, 1970, p. 49). The Alum Cave Limestone Member near the base of the formation is a widely traceable marine marker bed, but the other limestones appear to be of limited areal extent. Near the middle of the formation are two thin coal members, one of which probably is equivalent to the Herrin Coal, a principal mined coal in Illinois; neither of these beds is presently commercial in Indiana, however. The Hymera and Danville Coal Members in the upper part of the formation are widely recognized in the northern part of the Indiana coalfield and are thought to be equivalent to two beds, locally called the Lower and Upper Millersburg Coals, in the southern part of the field (Shaver and others, 1970, p. 41–42, 74–75). The correlation is uncertain because continuity of the beds is interrupted by a belt of clastic sediments that probably is contemporaneous with coal deposition. Some of the underlying beds, notably the Springfield Coal Member, also are discontinuous in the same area, and thus the clastic belt may represent a persistent route of sediment transport into the Illinois basin. The margins of the clastic belt are marked by splits, cutouts, and changes in the character of the coals.

McLEANSBORO GROUP

The upper part of the Pennsylvanian System in Indiana, constituting more than half of the system in rock thickness, has been something of an enigma to stratigraphers. The area of outcrop in southwestern Indiana is thickly loess covered, so that exposures are few and far apart; faulting and rapid southward thickening of the formations complicate geologic interpretation; and the rocks are not productive of coal or other economic minerals that would provide impetus for study. In earlier work, serious miscorrelations were made, notably in respect to the Merom Sandstone Member (fig. 3). The definitive study of these rocks is a doctoral dissertation (Wier, 1955) that has not been published, but conclusions from this study have been incorporated, with emendations as required by newer data, into the current "Compendium of Rock-Unit Stratigraphy in Indiana" (Shaver and others, 1970), and that volume is the basis for much of the discussion presented here.

All the rocks in the Pennsylvanian System above the top of the Danville Coal Member of the Dugger Formation are assigned to the McLeansboro Group (fig. 5), which consists, in ascending order, of the Shelburn, Patoka, Bond, and Mattoon Formations. The full thickness of the group in the central part of the Illinois basin is about 400 m, but in Indiana its maximum known thickness is 250 m.

The Shelburn Formation (fig. 5) is the most widely present and best known formation in the McLeansboro Group. It can be traced from near Evansville on the Ohio River to the Illinois State line a little north of Terre Haute (fig. 1). Its thickness ranges from 20 to 80 m and averages about 45 m. A thick sandstone member is present in places near its base; the rest of the formation consists principally of shale and siltstone and includes thin and discontinuous beds of coal. The West Franklin Limestone Member at the top of the formation is an important marker bed in Indiana and consists of one to three thin beds of limestone separated by shale. Total thickness of this member is about 5 m. In Illinois, according to Willman and others (1975, p. 167, 194), the West Franklin member is represented by three or more named members that span the lower half of the Modesto Formation.

The Patoka Formation is recognized in six counties in southwestern Indiana, but in most of this area it is the youngest Pennsylvanian formation and is not present in its full thickness. Where the entire formation is found, it is 30 to 50 m thick. Bounded at the bottom by the top of the West Franklin Limestone Member and at the top by the base of the Shoal Creek Limestone Member (fig. 3), the Patoka Formation consists principally of shale but includes several named sandstone, limestone, and coal members. Earlier miscorrelations of some of these members now have been corrected (Wier, 1955; Wier and Girdley, 1962). Most of these members are of limited areal extent; only one, the Inglefield Sandstone Member near the base of the formation, is recognized in Illinois (Willman and others, 1975, p. 196), where rocks equivalent to the Patoka Formation are assigned to the upper part of the Modesto Formation.

The Bond Formation (fig. 5) includes rocks between the base of the Shoal Creek Limestone Member and the top of the Livingston Limestone Member (fig. 3), both of which are important marker beds throughout much of the Illinois basin. This formation consists principally of shale and siltstone but includes one named sandstone member near its base and also contains one thin coal member and one limestone member. Because of faulting and erosion, the entire formation is present in Indiana in only two rather limited and widely separated areas. Its thickness is about 45 m (Shaver and others, 1970, p. 20). The formation has a wide distribution in Illinois, where many members are recognized that have not been identified in Indiana.

All Pennsylvanian rocks in Indiana above the top of the Livingston Limestone Member are assigned to the Mattoon Formation. Near the base of this formation is a prominent sandstone, the Merom Sandstone Member (fig. 3). Nearly all the thick sandstone members in the McLeansboro Group have at one time or another been identified as the Merom (see, for example, Malott, 1948); this member is now known to be present in Indiana only near the type locality in western Sullivan County and in the Mumford Hills area in northwestern Posey County (Wier, 1960; Shaver and others, 1970, p. 109). In the former area only about 12 m of the Mattoon Formation is present; in the latter area the formation reaches its maximum thickness in Indiana of about 45 m. These are the youngest Pennsylvanian rocks, and the youngest bedrock, in Indiana; somewhat younger rocks are present in Illinois where the Mattoon Formation reaches its maximum thickness of nearly 200 m near the center of the Illinois basin (Willman and others, 1975, p. 198).

AGE AND CORRELATION OF PENNSYLVANIAN ROCKS

Although plant megafossils have been reported from Pennsylvanian rocks in Indiana since the days of Owen (1859a, p. 43), few definitive studies have been made. Collections reported by Lesquereux (1880), C. D. White (in Kindle, 1896, p. 354–355), Jackson (1917), and Benninghoff (1943) constitute nearly all the earlier work. An overview by Canright 1959) summarized the earlier studies and briefly listed genera recognized from 93 collecting sites. In the most thorough study yet published, Wood (1963) reported 86 species in a single flora from the Brazil Formation; both late Pottsvillian and Alleghenian forms were included, however, and after extensive discussion of the distribution of many of the taxa elsewhere, Wood concluded (p. 28–30) that the flora cannot be used for precise age determination. Similarly, Read and Mamay (1964, p. K7) indicated that the flora of the Hindostan Whetstone Beds is transitional between their floral zones 4 and 5. Thus, the value of plant megafossils for precise age determination has not yet been established in the Pennsylvanian System of Indiana. Miospores from the coal beds were studied by Guennel (1952, 1958), who was convinced of their value in correlation, at least on a local basis, and who also suggested some regional correlations. He did not, however, attempt to design a zonal scheme or to assign standard age designations.

Whereas floral studies look eastward to the Appalachian area, faunal studies look westward to the midcontinent. Fifteen limestone members are named in the Pennsylvanian System of Indiana, and nearly all these contain marine invertebrate macrofossils or microfossils. Again, however, definitive studies are few, but some success in age determination and interregional correlation has been achieved through study of the microfauna of some of the older limestones. St. Jean (1957), on the basis of a foraminiferal faunule, established an early Desmoinesian age for a limestone in the Staunton Formation. Thompson and Shaver (1964), considering both fusulinids and ostracodes, suggested a correlation with type Morrowan rocks for several limestone beds in the upper part of the Mansfield Formation. Shaver and Smith (1974) confirmed both the above correlations and assigned the Brazil Formation, mostly by default of definitive faunas, to the Atokan Series. Microfossils from higher Pennsylvanian limestone beds have not been studied, but megafossils were listed by Wier (1955), who concluded (p. 64) that the West Franklin Limestone Member probably is latest Desmoinesian in age.

No definitive studies relating the Pennsylvanian rocks of Indiana to European standard sections have been made. The age assignments in European terms shown in figure 3 follow the provisional correlations presented by McKee (1975, p. 2).

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The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—Illinois

By ELWOOD ATHERTON *and* JAMES E. PALMER

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Historical review and summary of areal, stratigraphic, structural, and economic geology of Mississippian and Pennsylvanian rocks in Illinois

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CONTENTS

ILLUSTRATIONS

THE MISSISSIPPIAN AND PENNSYLVANIAN (CARBONIFEROUS) SYSTEMS IN THE UNITED STATES—ILLINOIS

By ELWOOD ATHERTON[1] and JAMES E. PALMER[1]

ABSTRACT

The Carboniferous equivalents in Illinois consist of two systems separated by an angular unconformity. The Mississippian System includes 40 formations grouped into 3 series. It is more than 975 m thick in southern Illinois and thins northward. Limestone is the dominant rock type. During formation of the sub-Pennsylvanian unconformity, valleys as deep as 140 m were cut in the top of the Mississippian. The Pennsylvanian System includes about 140 named members, grouped into 7 formations and 5 series, and is about 760 m thick, it has a maximum composite thickness of more than 1,000 meters. About half of the system is shale and two-fifths is sandstone and siltstone; extensive coal seams are a distinctive feature. A great thickness of rock was eroded during formation of the unconformity on the top of the Pennsylvanian. In the Mississippian, invertebrate fossils abound in most of the limestone and calcareous shale; in the Pennsylvanian, plant fossils are abundant in the coal and shale, and marine invertebrate fossils in the limestone. The Mississippian includes a siltstone delta built out into fairly deep water (about 300 m), but most of the strata were deposited in relatively shallow water. During the Pennsylvanian, the surface fluctuated above and below sea level, and extensive coal swamps formed at a number of horizons. The major tectonic event during the Carboniferous in Illinois was the subsidence of the autogeosynclinal Illinois basin; the maximum subsidence centered near the southern tip of the State. Oil in the Mississippian and coal in the Pennsylvanian are the major economic products.

INTRODUCTION

The Carboniferous equivalents in Illinois consist of the Mississippian and Pennsylvanian Systems. The Mississippian is estimated to consist of about 35 percent shale and siltstone, 10 percent sandstone, and 55 percent limestone and dolomite, nearly all deposited in a shallow marine environment. The Pennsylvanian is estimated to consist of about 50 percent shale, 40 percent sandstone and siltstone, 5 percent limestone, 1 to 2 percent coal, and the remainder, including siderite and chert, less than 1 percent. The environment alternated from marine to nonmarine in many cycles, and extensive coal swamps are a distinctive feature, particularly during the Pennsylvanian. The two systems are differentiated in Illinois not only by the overall character of their sediments and fossils, but also by the angular unconformity that separates them.

Illinois, an area of 146,020 km^2, is divided into 102 counties (fig. 1), surveyed on a rectangular grid system of townships. The stratigraphy of Illinois is summarized in Willman and others (1975), which is the source of most of the information and illustrations given here. The literature of Illinois geology through 1965 is indexed in Willman and others (1968).

The stratigraphic nomenclature used in this paper has not been reviewed by the Geologic Names Committee of the U.S. Geological Survey. The nomenclature used here conforms with the current usage of the Illinois State Geological Survey.

THE MISSISSIPPIAN SYSTEM

The Mississippian System is named for exposures that extend for about 650 km in the Mississippi River valley along the western margin of Illinois. Mississippian rocks occur in the subsurface over the southern two-thirds of the State, where they are overlain mostly by Pennsylvanian rocks. In the western part of the State, the Mississippian rocks are covered by glacial till, and in southernmost Illinois, they are concealed by Cretaceous gravel and sand. Outcrops occur mainly in the bluffs of the Mississippi, Illinois, and Ohio Rivers that border and bisect the State.

The Mississippian System attains a thickness of a little more than 975 m in southern Illinois (fig. 2). Northward thinning is partly due to deposition and is partly the result of erosional truncation during formation of a prominent sub-Pennsylvanian unconformity. During Mississippian time, the Illinois basin was open southward between the Ozark and Nashville positive areas so that many forma-

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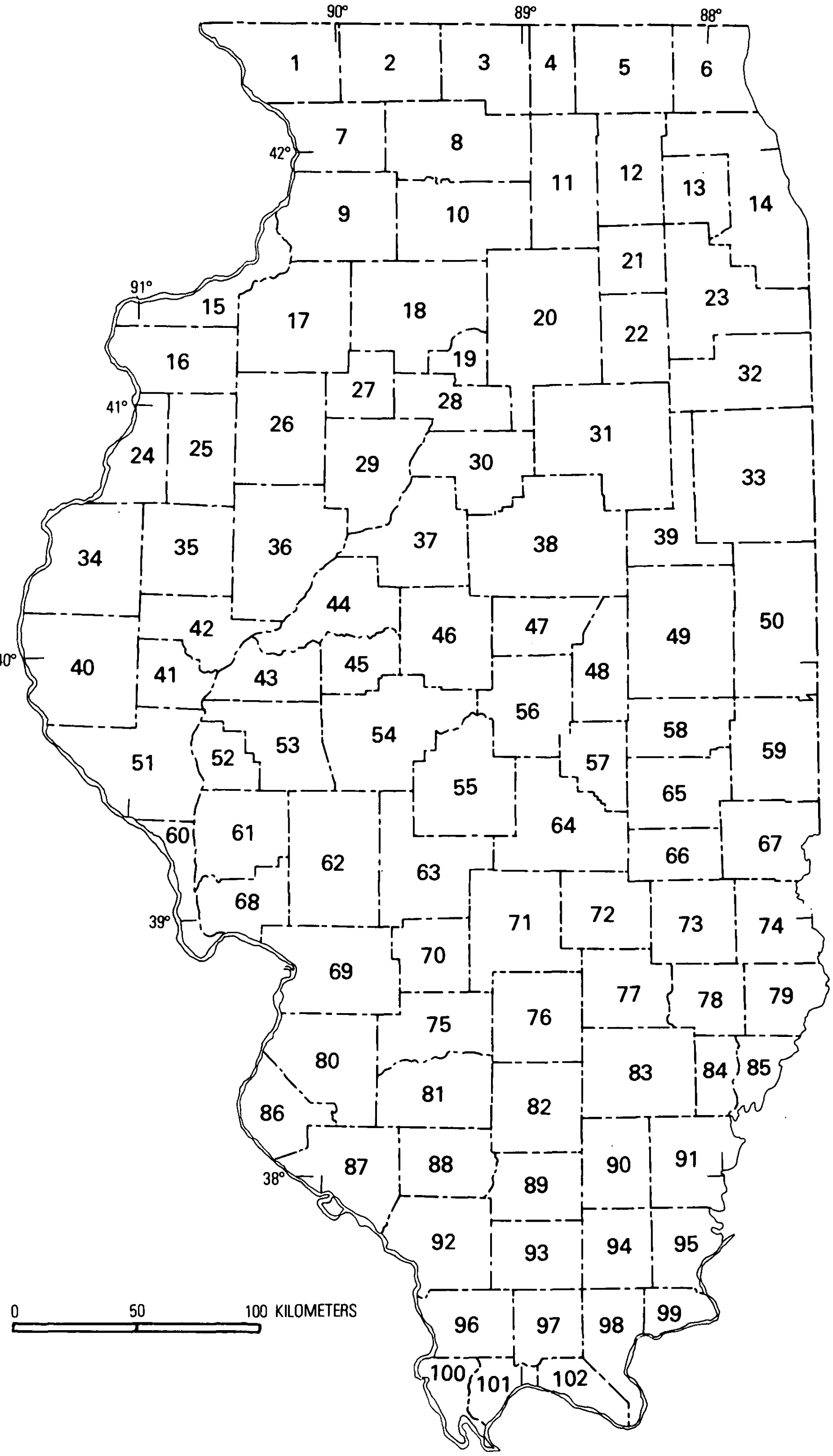

Adams	40	Lee	10
Alexander	100	Livingston	31
Bond	70	Logan	46
Boone	4	McDonough	35
Brown	41	McHenry	5
Bureau	18	McLean	38
Calhoun	60	Macon	56
Carroll	7	Macoupin	62
Cass	43	Madison	69
Champaign	49	Marion	76
Christian	55	Marshall	28
Clark	67	Mason	44
Clay	77	Massac	102
Clinton	75	Menard	45
Coles	65	Mercer	16
Cook	14	Monroe	86
Crawford	74	Montgomery	63
Cumberland	66	Morgan	53
De Kalb	11	Moultrie	57
De Witt	47	Ogle	8
Douglas	58	Peoria	29
Du Page	13	Perry	88
Edgar	59	Piatt	48
Edwards	84	Pike	51
Effingham	72	Pope	98
Fayette	71	Pulaski	101
Ford	39	Putnam	19
Franklin	89	Randolph	87
Fulton	36	Richland	78
Gallatin	95	Rock Island	15
Greene	61	St. Clair	80
Grundy	22	Saline	94
Hamilton	90	Sangamon	54
Hancock	34	Schuyler	42
Hardin	99	Scott	52
Henderson	24	Shelby	64
Henry	17	Stark	27
Iroquois	33	Stephenson	2
Jackson	92	Tazewell	37
Jasper	73	Union	96
Jefferson	82	Vermilion	50
Jersey	68	Wabash	85
Jo Daviess	1	Warren	25
Johnson	97	Washington	81
Kane	12	Wayne	83
Kankakee	32	White	91
Kendall	21	Whiteside	9
Knox	26	Will	23
Lake	6	Williamson	93
La Salle	20	Winnebago	3
Lawrence	79	Woodford	30

FIGURE 1.—Counties of Illinois.

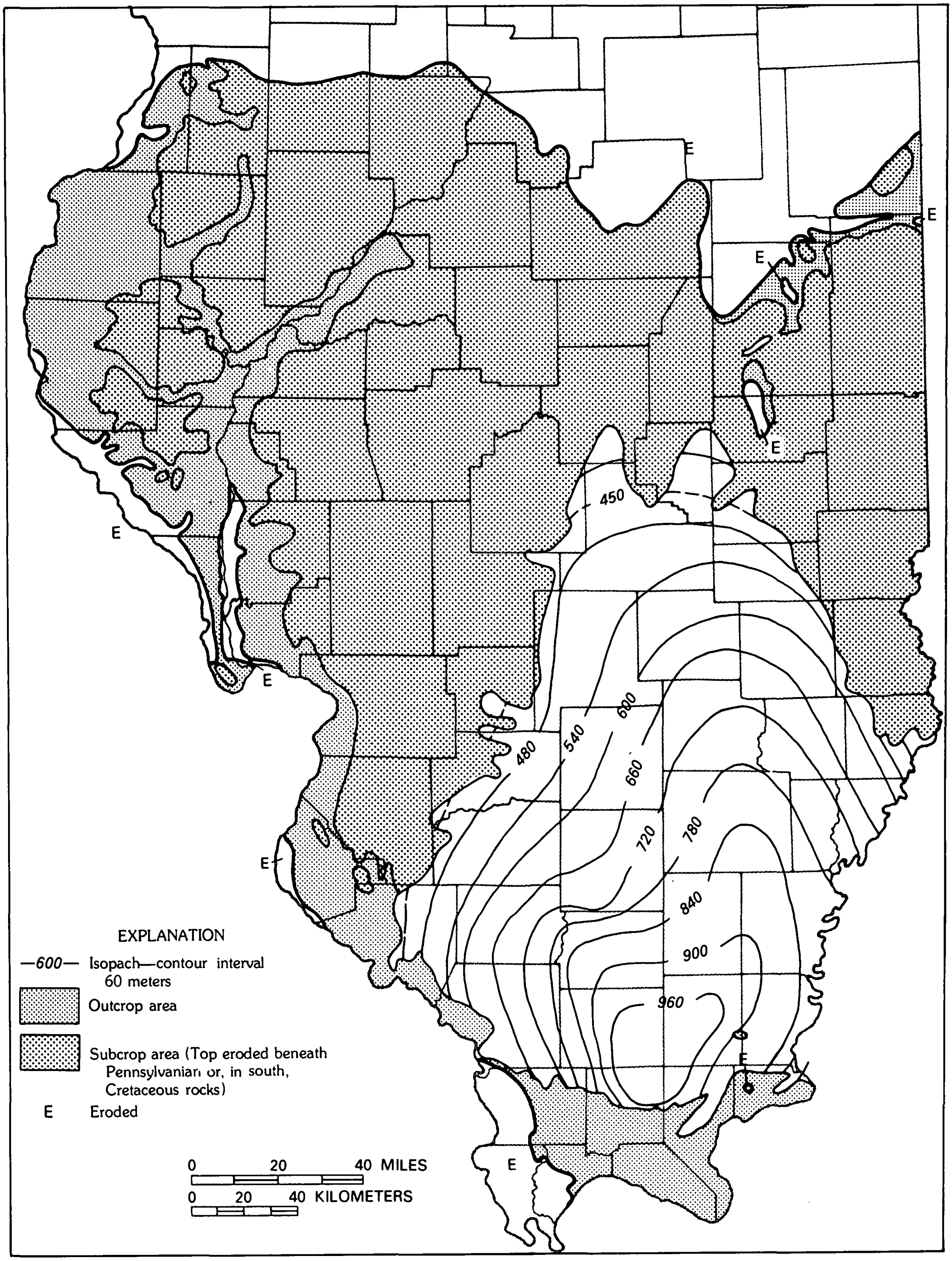

FIGURE 2.—Areal extent of the Mississippian System in Illinois. Thickness is shown where upper Chesterian strata are present (Willman and others, 1975).

tions originally thickened southward well beyond their present extent. Post-Mississippian uplift closed off the Illinois basin on the south, however, and erosion truncated the uptilted strata in southernmost Illinois.

In Illinois, the system is divided into three series. The lowermost, the Kinderhookian, consists mainly of normal marine fine-grained clastic sedimentary rocks. The relatively thick Valmeyeran, in the middle, includes biogenic limestone along the outer edges of the basin in western and northwestern Illinois but is represented by a thick siltstone delta in southwestern and central-eastern Illinois. The Chesterian Series, at the top, is thick and consists of limestone-shale and sandstone-shale formations that represent deltaic sediments deposited in patterns that are transitional to the cyclothems of the Pennsylvanian. Between the Mississippian and the Pennsylvanian is a major unconformity where valleys as deep as 135 m have been cut into Chesterian sedimentary rocks.

Fossils are abundant in the Mississippian. Productid and spiriferid brachiopods are useful for biostratigraphic zonation of much of the system. Blastoids, crinoids, and calcareous foraminifers provide a practical basis for correlation of Valmeyeran and Chesterian strata, and conodonts are the basis for biostratigraphic zonation throughout the system.

Tectonic activity, associated mainly with the Ozark uplift, controlled depositional patterns of the Kinderhookian and closed the epoch with broad uplift in western Illinois. Shallowing of the seas during Valmeyeran and Chesterian time culminated with widespread post-Mississippian erosion.

STRATIGRAPHY

KINDERHOOKIAN SERIES

The Kinderhookian Series consists mainly of silty marine shale overlain by the widespread Chouteau Limestone (fig. 3). The series, only 50 m thick at its maximum in western Illinois, is very thin in the eastern and southern parts of the Illinois basin (fig. 4). The shale of the Kinderhookian is combined with that of the underlying Devonian to constitute the New Albany Group. The base of the series commonly occurs within the shale sequence and can be identified only by paleontological means.

"Glen Park" Formation.—The "Glen Park" Formation of Illinois was at one time called the "Hamburg Oolite."[1] It is not the same age as the type Glen Park of Missouri, the former being Mississippian and the latter Devonian, but a new name has not yet been introduced. It occurs only in western

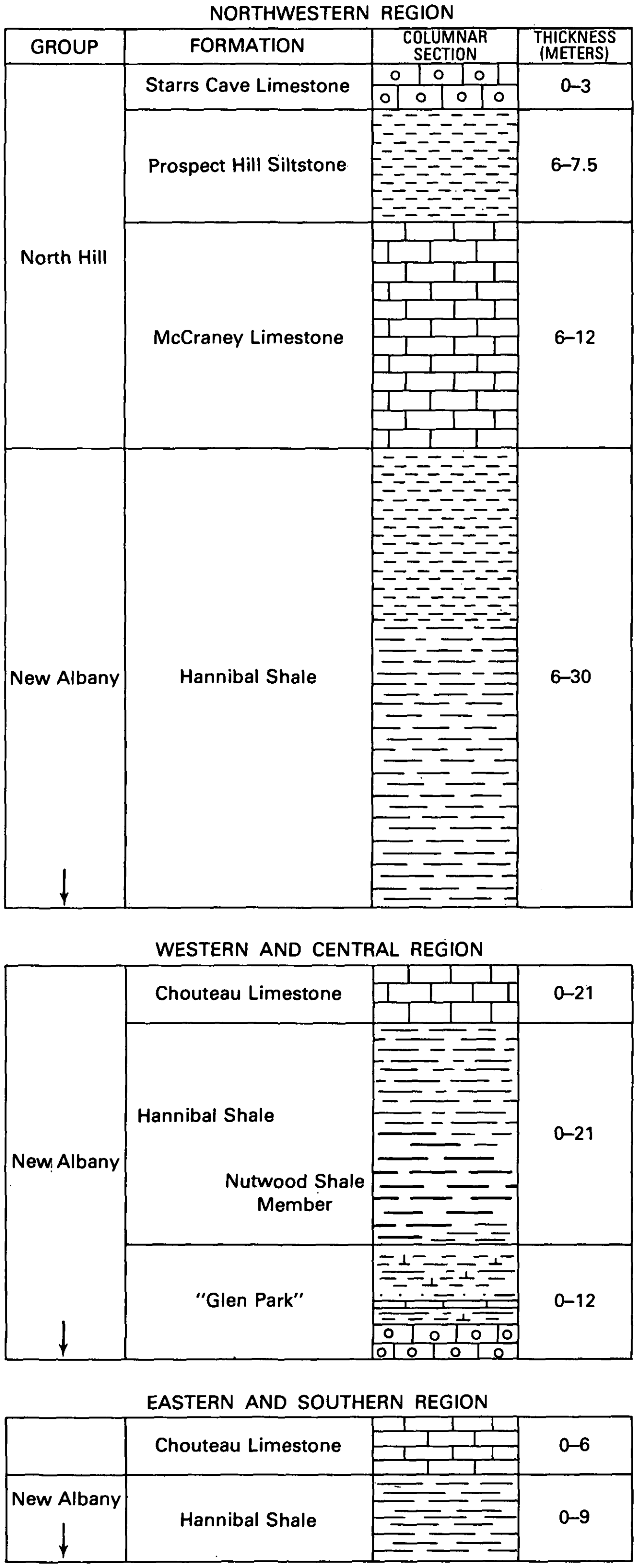

FIGURE 3.—Columnar section of the Kinderhookian Series (Willman and others, 1975).

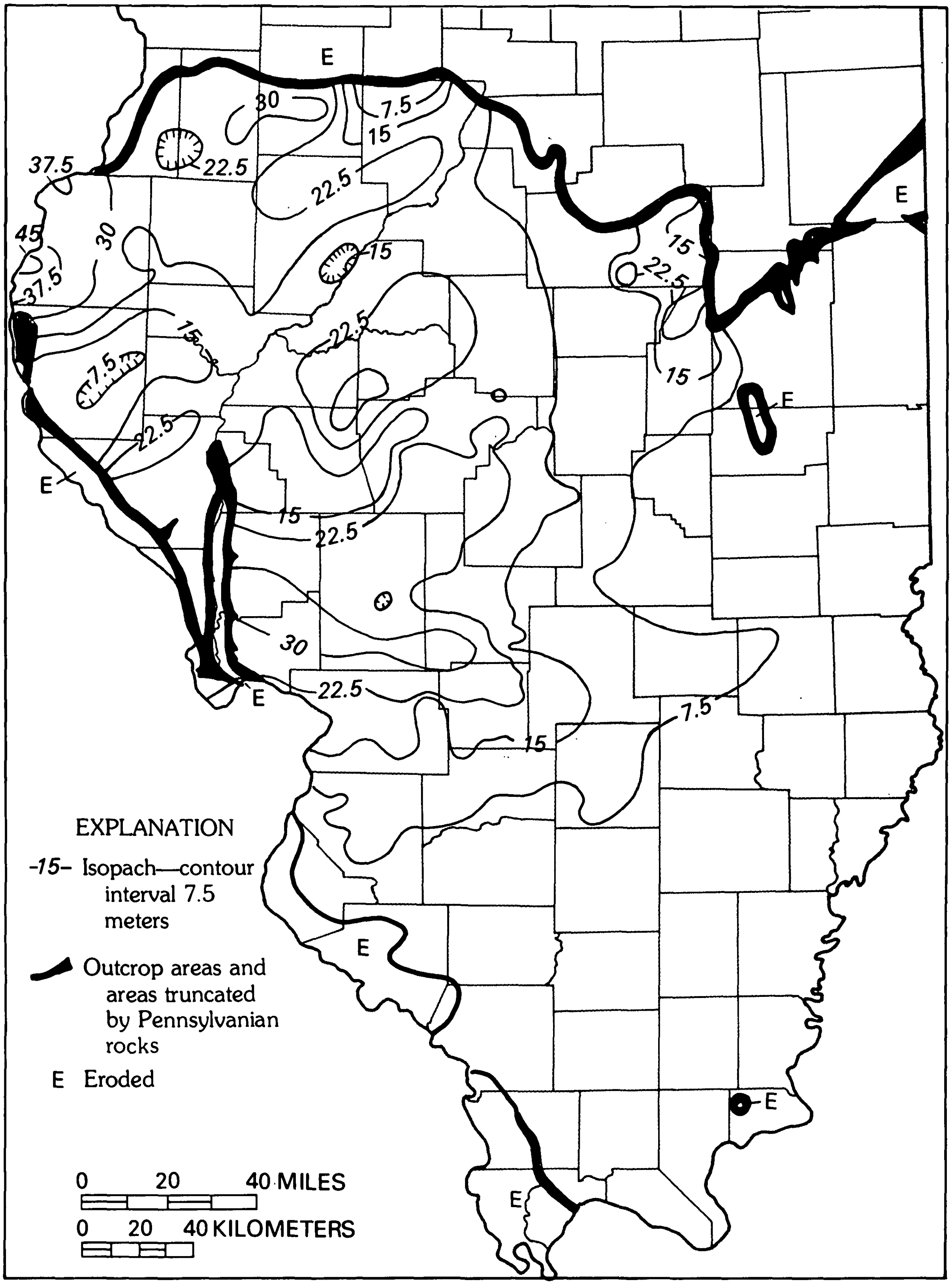

FIGURE 4.—Thickness of the Kinderhookian Series (Willman and others, 1975).

and central Illinois and is exposed in bluffs along the Mississippi and lower Illinois Rivers, where its thickness is less than 8 m. It is a highly variable unit, and conglomerate, sandstone, fine-grained limestone, oolite, siltstone, and shale represent nearshore facies. The contact with the underlying Devonian appears to be erosional.

Hannibal Shale.—The Hannibal Shale is a green to gray argillaceous siltstone grading to silty shale. In western Illinois, a siltstone facies about 12 m thick was once differentiated as the English River Formation, but the name has been dropped. In the southern part of the outcrop area, a lens of black shale is differentiated as the Nutwood Member. The Hannibal thins eastward from a maximum thickness of about 30 m in western Illinois. In eastern Illinois it is very thin or absent and is difficult to distinguish from the underlying Devonian Saverton Shale.

Chouteau Limestone.—The Chouteau Limestone is light brownish to greenish gray and lithographic to very fine grained. Locally, it is a fine-grained dolomite, and in a narrow belt it is red or pink. It is widespread across central and southern Illinois. Generally, it is 3 to 6 m thick, but it thickens to nearly 24 m locally in western Illinois. Its extensive occurrence, contact with overlying and underlying shale, and distinctive "kick" on electric logs make it an excellent marker bed in subsurface studies. Normally, it is conformable on the Hannibal Shale, but in southwestern Illinois locally it overlaps the Hannibal and lies unconformably on Devonian to Ordovician formations. The name "Rockford," applied to the formation in Indiana, was used for a while in southeastern Illinois, but the older name, "Chouteau," is now accepted for all Illinois.

North Hill Group.—The North Hill Group includes the McCraney Limestone at the base, the Prospect Hill Siltstone, and the Starrs Cave Limestone. It is extensive in Iowa, but in Illinois it is confined to a narrow belt east of the Mississippi River. It correlates with the Chouteau Limestone and is conformable on the Hannibal Shale, but it is unconformably overlain by the Burlington Limestone.

VALMEYERAN SERIES

The Valmeyeran Series is the thickest of the three Mississippian series (fig. 5). It includes rocks contemporaneous with the section from the base of the Meppen Limestone to the top of the Levias Member of the Renault Limestone (fig. 6). The Valmeyeran, especially the lower part, shows important facies changes (fig. 7) described later in the section "Environment of Deposition."

Meppen Limestone Formation. — The Meppen Limestone is dolomitic limestone, or calcareous dolomite that commonly contains many calcite geodes. It occurs in western Illinois from Calhoun County to Monroe County and has a maximum thickness of about 7 m. It is unconformable on the Chouteau, and is conformably overlain by the Fern Glen Formation. It was formerly called Sedalia in Illinois because of lithologic similarity to the Sedalia of Missouri, but the conodont faunas show that the Missouri Sedalia is Kinderhookian, whereas the Illinois Meppen is Valmeyeran.

Fern Glen Formation.—The Fern Glen Formation consists of red and green calcareous shale and of gray, green, and red limestone and dolomite that is partly argillaceous. Occurring in southwestern Illinois from Randolph County north to Jersey County and northeastward to Champaign County, the formation generally is less than 15 m thick, but in a few small areas it approaches 30 m. It overlaps the Meppen to rest on rocks as old as the Ordovician Maquoketa Shale Group and grades laterally and vertically into the Burlington Limestone.

Burlington Limestone Formation.—The Burlington Limestone occupies an irregular triangular area in western Illinois from Henderson County on the northwest to Jackson County on the south and Iroquois County on the east. Cropping out in the Mississippi River bluffs from Quincy to near Alton, Ill., the Burlington commonly is 30 to 45 m thick, but locally is as much as 60 m. To the southeast, it thins abruptly against the Borden Siltstone. In northwestern Illinois, the Burlington is very pure, coarsely crystalline, light-gray limestone containing a few beds of dolomitic limestone. Chert is common, especially in the middle and upper parts of the formation. Large crinoid stems are abundant, and some beds are almost entirely crinoid debris. Farther south, the Burlington becomes more cherty, crystalline limestone becomes less abundant, and fine-grained beds are more common. In the southern part of its extent, the Burlington and the overlying Keokuk are difficult to discriminate, except by their fossils; thus, they are generally referred to as the Burlington-Keokuk Limestone. The Burlington is conformable on the Fern Glen and Meppen and overlaps them to lie unconformably on older strata.

Keokuk Limestone Formation.—The Keokuk Limestone occupies much the same area as the Burlington and is 18 to 24 m thick over most of its extent. It is fossiliferous cherty limestone interbedded

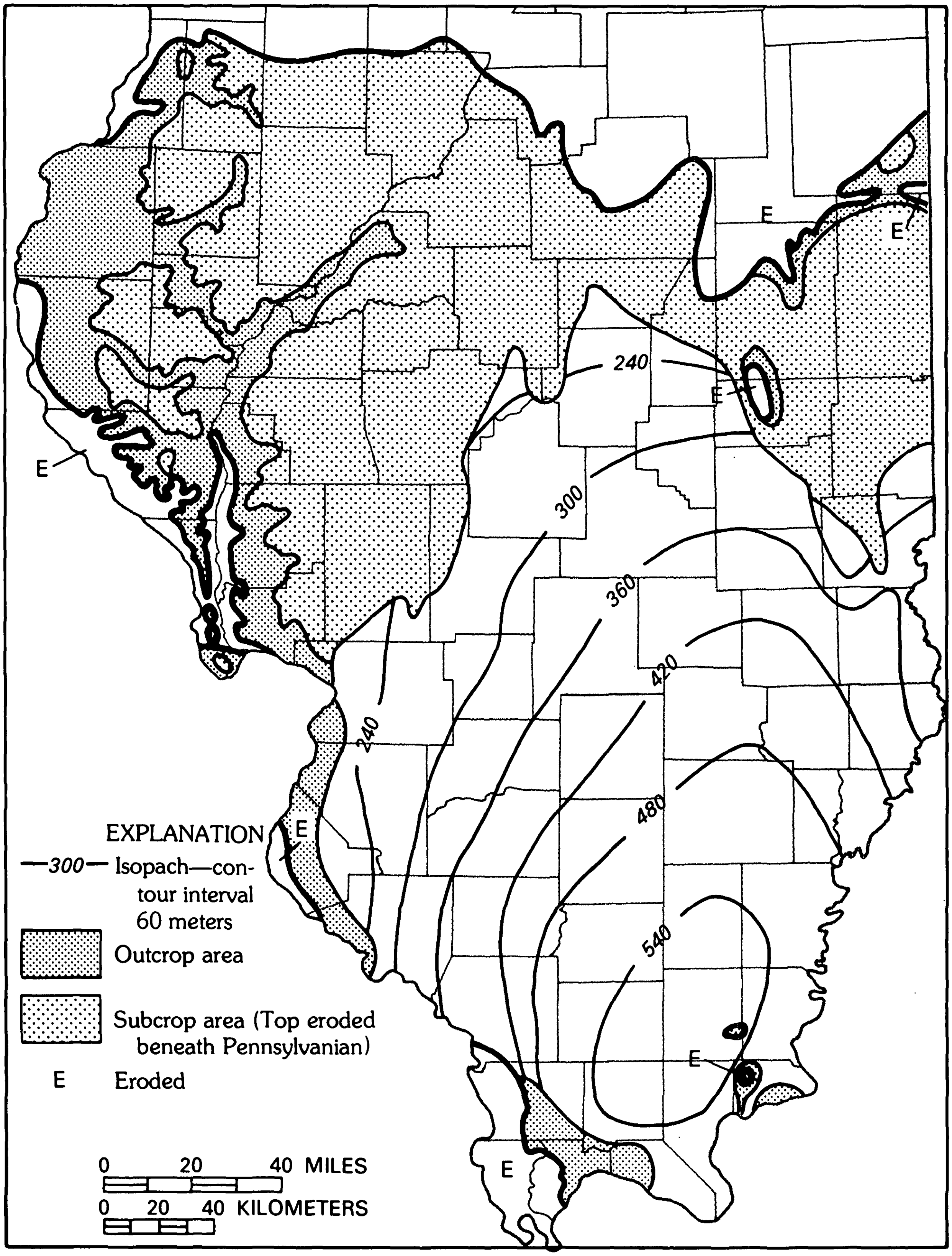

FIGURE 5.—Thickness of the Valmeyeran Series. Thickness is shown where Chesterian strata are present (Willman and others, 1975).

with fine-grained limestone, argillaceous dolomite, and calcareous gray shale. The Keokuk is generally thinner bedded and darker than limestone of the Burlington, and the shale partings are more numerous. Both formations are mainly biocalcarenites. In the type region, the lower 9 m of the Keokuk is very cherty and is differentiated as the Montrose Chert Member.

Borden Siltstone Formation.—The Borden Siltstone is gray to greenish-gray siltstone, glauconitic in part, grading to silty shale. The maximum thickness is about 200 m. The siltstone was deposited in a delta that enters Illinois in the vicinity of Edgar County in east-central Illinois and extends almost to the southwest border. Lenses of coarse siltstone and very fine sandstone near the base of the Borden are informally called the "Carper sand." A similar lens in central Illinois centering on Christian County is differentiated as the Bilyeu Member. The Bilyeu reaches a thickness of 45 m; a part extends westward beyond the Borden and into the Warsaw Shale as a member of the Warsaw. To the northwest, the Borden is separated from the Warsaw Shale by a vertical cutoff at the edge of the Burlington-Keokuk. To the south and east, the Borden is separated from the equivalent Springville Shale by a vertical cutoff along the line where the siltstone thins to less than 30 m.

Springville Shale Formation.—The Springville Shale is greenish-gray to dark brownish clayey shale. Locally, it is mottled red and green and has been informally called the "calico shale." The Springville is equivalent to the Borden but was deposited in deeper water. Near Jonesboro in Union County, the basal part of the Springville is differentiated as the State Pond Member. The member is a greenish-gray, soft, glauconitic shale containing phosphate nodules and is only about 40 cm thick. The member is a deepwater equivalent of the Fern Glen, Burlington, and Keokuk Limestones.

Fort Payne Formation.—The Fort Payne Formation is dark, very fine grained, siliceous, cherty limestone. Extending from the Ohio River to southwestern Clark County, the formation occurs only in southeastern Illinois and is rarely exposed. Slightly more than 180 m thick at the southern end of Pope County on the Ohio River, it thins northward and westward. The Fort Payne was deposited in a deepwater basin bordered by the foreset slopes of the Borden Siltstone delta in southern Illinois and overlies the Springville Shale, the Chouteau Limestone, or the lower part of the foreset slope of the Borden delta.

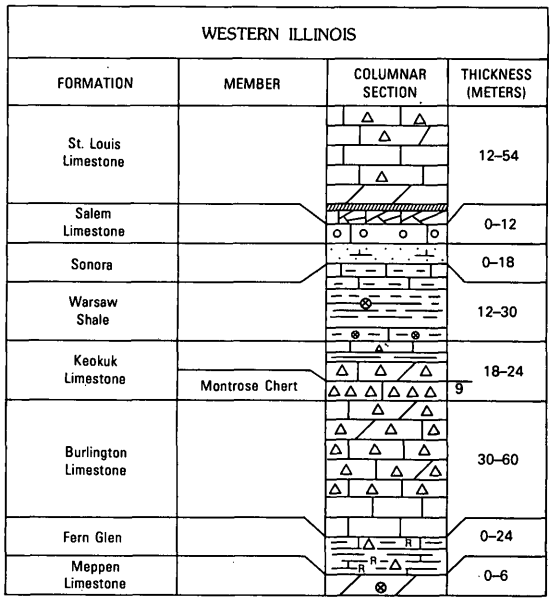

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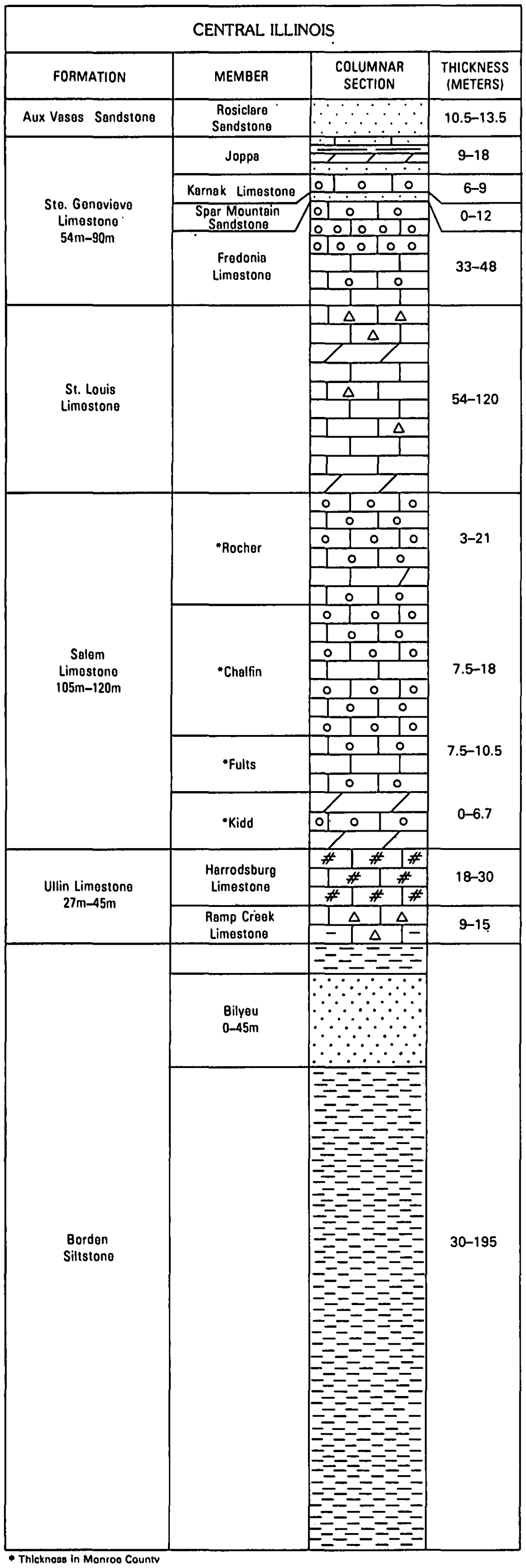
FIGURE 6.—Columnar section of the Valmeyeran Series in Illinois (Willman and others, 1975).

Ullin Limestone Formation.—The Ullin Limestone is mainly a light-colored bryozoan and crinoidal limestone. In southern Illinois, its maximum thickness is slightly more than 240 m in northern Hamilton County, and it is generally thick in a belt running northeast and southeast of that location. It thins away from this belt and pinches out to the northwest along an irregular line running from Jersey County to Champaign County. The Ullin overlies the Fort Payne Formation, but where the Fort Payne is absent it overlies the Borden, Springville, Warsaw, or Chouteau Formations. Generally, it can be divided into two members, the Ramp Creek Limestone Member, which is cherty, argillaceous limestone 0 to 150 m thick, and the Harrodsburg Limestone Member, which consists of light-colored bryozoan and crinoidal debris that is generally lighter colored, coarser grained, less cherty, and less argillaceous than the underlying Ramp Creek. More than 240 m thick in Hamilton County, the Harrodsburg thins northward and pinches out at the margin of the Ullin. The two members are similar in many places, and, in about one-third of the extent of the Ullin, they cannot be differentiated. The Ullin filled deepwater trenches between the foreset slope of the Borden delta and the depositional slope of the Fort Payne Formation.

Warsaw Shale Formation.—The Warsaw Shale consists of fossiliferous gray shale containing interbedded argillaceous limestone. Quartz geodes are common and locally abundant. The Warsaw grades



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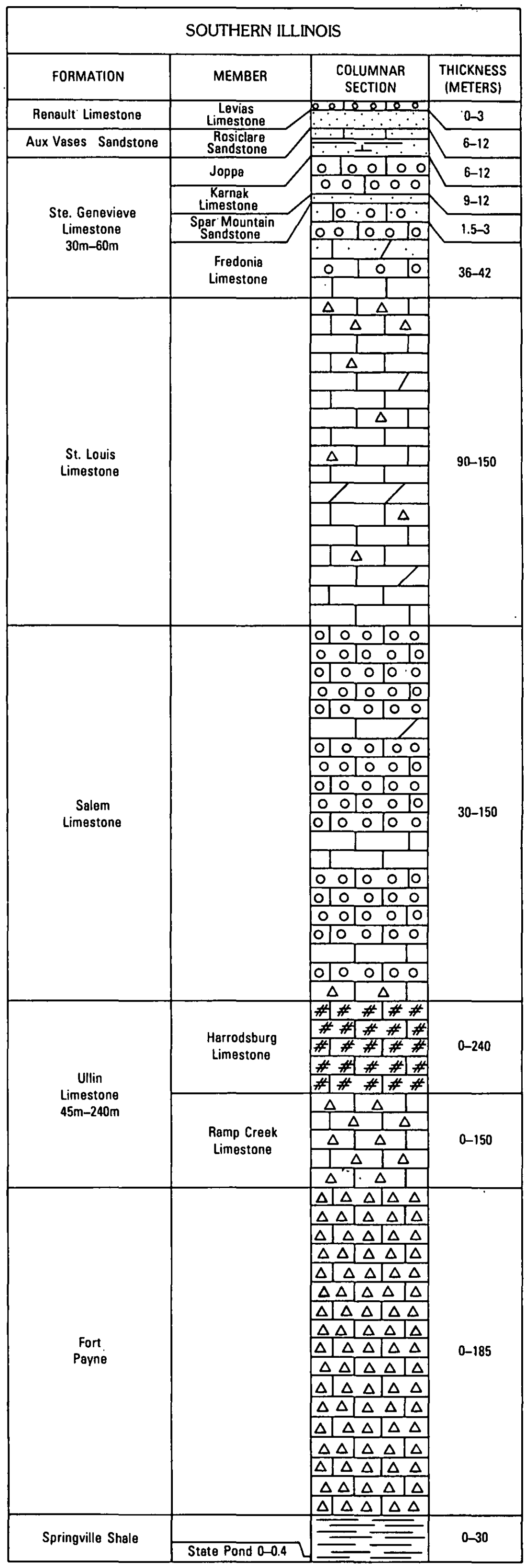

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FIGURE 6.—Continued.

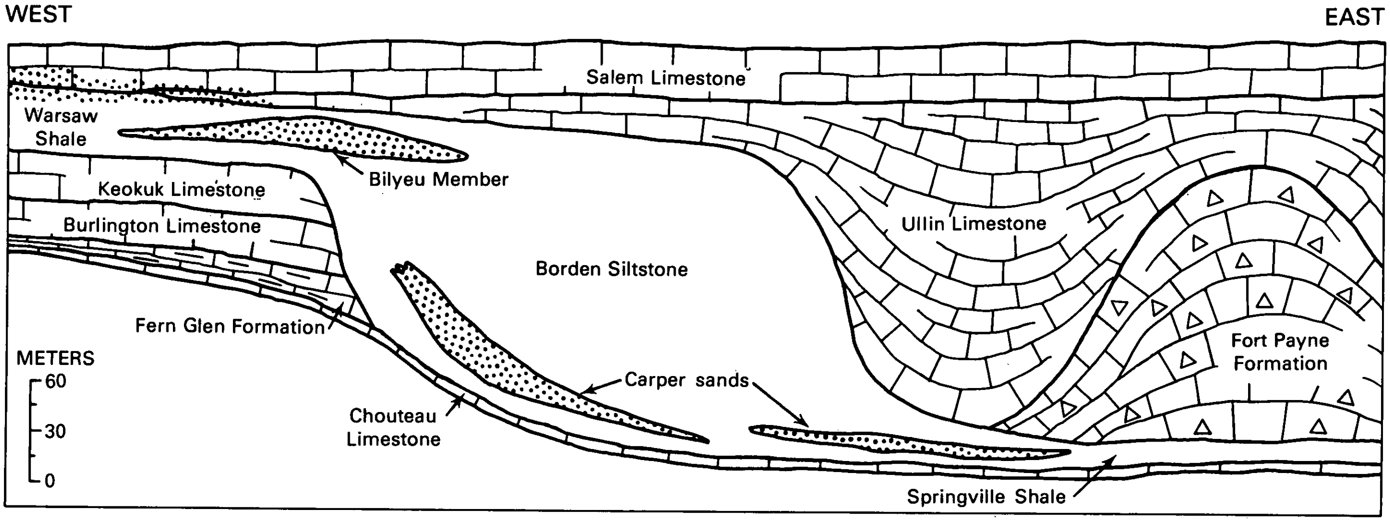

FIGURE 7.—Diagrammatic east-west cross section across central Illinois showing the Borden Siltstone delta (from Lineback, 1968).

eastward into the Borden Siltstone, from which it is separated by a vertical cutoff. It is nearly 30 m thick in western Illinois, where it crops out in the bluffs along the Mississippi and Illinois valleys and thickens to about 90 m in east-central Illinois. The corkscrew-like axes of *Archimedes* are very abundant. The Warsaw is overlain by the Sonora Formation or by the Ullin, Salem, or St. Louis Limestones.

Sonora Formation.—The Sonora Formation includes: sandstone, generally light buff, dolomitic, argillaceous, and fine grained; shale, generally greenish gray and sandy; dolomite, sandy to argillaceous, and sparsely fossiliferous. The lithology varies laterally and vertically, and is characteristically sandy. The Sonora is about 0.6 to 6 m thick and crops out in the bluffs of the Mississippi and its tributaries in Adams and Hancock Counties. Both Salem and St. Louis overlie the Sonora, and the latter contact varies from conformable to erosional. The Sonora grades laterally into the Salem Limestone and the upper part of the Warsaw Shale.

Salem Limestone Formation.—The Salem Limestone is mainly crossbedded biocalcarenite composed of fossil fragments, endothyrid foraminifers and other small fossils, and oolites or oolitic-like overgrowths. Minor components include sucrosic dolomite, dolomitic limestone, chert, sandstone, anhydrite, and gypsum. More than 150 m thick in northern White County, it thins to a line running from Jersey to Douglas County with only patches of Salem northwest of this zero line. The Salem overlaps the Ullin to lie on the Warsaw Shale or Sonora Formation. The upper part of the Salem grades laterally into the overlying St. Louis Limestone. In the outcrop area in western Randolph, Monroe, and St. Clair Counties the Salem is divided into four members: the Kidd (at the base), the Fults, the Chalfin, and the Rocher.

St. Louis Limestone Formation.—The St. Louis Limestone is typically a micritic to lithographic, cherty limestone, light to dark gray and brownish gray. It also includes beds of dolomite and evaporite deposits. One to three beds of gypsum and anhydrite occur extensively in the northern part of the subsurface St. Louis. Limestone breccias in the outcrop areas are regarded as indicating the former presence of evaporite layers. The St. Louis is about 150 m thick in southeastern Illinois, but it thins to the north and northwest to less than 60 m before being truncated by pre-Pennsylvanian erosion along a line running west from Edgar County to Mason and Cass Counties and then south along the Illinois River to Alton. Several large outliers are in the area from Fulton to Hancock and Adams Counties. The St. Louis is well exposed at Alton and north along the Illinois Valley and the Mississippi Valley south of St. Louis from St. Clair through Monroe to western Randolph Counties. Another good exposure is along the Ohio River in Hardin County in southeastern Illinois. Abundant sinkholes usually characterize the outcrop area of the St. Louis. In general, the St. Louis is darker, more cherty, finer grained, and much less oolitic than the overlying Ste. Genevieve Limestone. Locally, at the top of the formation, strata of St. Louis-type lithology are interbedded and intergrade with strata of Ste. Genevieve-type lithology, so that placement of the formation boundary is somewhat arbitrary. The contact is placed below the lowest prominent oolitic bed.

Ste. Genevieve Limestone Formation.—The Ste. Genevieve Limestone is mainly limestone in massive beds, much of which is oolitic and crossbedded. Some of the oolite is coarse and notably porous. In some oil fields, it is a reservoir rock and is informally called "McClosky lime." The limestone is generally light gray or light olive gray, but some oolitic rock is nearly white, and some of the lower part of the formation is gray or brownish gray. Chert is less abundant than in the St. Louis Limestone. Thin beds and lenses of sandstone and sandy limestone, some of which are widely traceable, occur mainly in the upper half of the formation. Locally, the limestone at the base of the formation is sandy, and near its western border the base is conglomeratic and rests unconformably on the eroded top of the St. Louis Limestone. The Ste. Genevieve is about 91 m thick in southern Illinois and is more than 61 m thick in south-central Illinois, thinning to the north and west to less than 30 m. It crops out from near Alton and St. Louis south along the Mississippi Valley and from Union County eastward across southern Illinois to Hardin County. Much of the formation is abundantly fossiliferous. The contact with the overlying Aux Vases Sandstone is conformable, but is marked by a series of downward steps to the west as limestone beds in the upper part of the Ste. Genevieve grade westward into sandstone of the Aux Vases. The Ste. Genevieve is divided into four members.

The Fredonia Limestone Member is mainly light gray, oolitic, crossbedded, and crinoidal limestone, but it includes some darker, lithographic limestone beds like those in the St. Louis. The Fredonia is generally 24 to 30 m thick, but north of Effingham County it thins rapidly to 6 m or less. The Spar Mountain Sandstone Member consists of sandstone and siltstone that grade to sandy or silty limestone. Locally, in the northern part of its extent, the sandstone is coarser than elsewhere and the sand grains are better rounded. The member extends throughout most of the area of the Ste. Genevieve. Its thickness is erratic, ranging from about 3 to 12 m, and the greater thicknesses are generally in the north. In the western part of the basin, where the overlying Karnak Member thins out, the Spar Mountain grades laterally into the Aux Vases Sandstone and is separated from it by a vertical cutoff. The Karnak Limestone Member is a persistent unit about 3 to 11 m thick, except that in western Washington County it wedges out into the Aux Vases Sandstone. The Joppa Member has a varied lithology, including beds of limestone, dolomite, sandstone, and shale, in part red and hematitic. It is 6 to 15 m thick. The Joppa is recognized in southeastern Illinois where limestone beds are present in the interval, but to the north and west the limestone beds thin out into sandstone regarded as Aux Vases.

Aux Vases Sandstone Formation.—The Aux Vases Sandstone consists of sandstone, siltstone, minor amounts of shale, and, locally, a little dolomite and limestone. The sandstone is light gray to greenish gray, calcareous, and grades to coarse siltstone. Locally, it is pink or red and hematitic. In southern Illinois, where the Joppa Member is recognized, the Aux Vases is commonly 6 to 12 m thick. To the north and west of this area, the Aux Vases includes Joppa equivalents and is correspondingly thicker, being about 18 to 24 m. In a small area where the Karnak is absent, the Aux Vases includes Spar Mountain equivalents and is 40 to 49 m thick. The thickness map of the Aux Vases shows discontinuities that reflect the areas where the base of the Aux Vases is stepped down. The Rosiclare Sandstone Member is the main body of the Aux Vases in southeastern Illinois where it overlies the Joppa Member of the Ste. Genevieve.

Renault Limestone Formation.—The Renault Limestone is a relatively thin but extensive formation. It averages about 2.5 m thick, thickening southward to 6 to 9 m and reaching slightly more than 12 m in Johnson County. The Renault consists of two members: the Levias Limestone Member, a relatively pure limestone, Valmeyeran in age; and the Shetlerville Limestone Member, a more or less sandy limestone, Chesterian in age. The Levias is a medium- to coarse-grained, white, oolitic limestone, containing some pink and light green ooliths. The basal 1 or 2 m are sandy. It is best developed in Hardin County in southeastern Illinois, where it commonly is 3 to 8 m thick, but it is less easily distinguished outside Hardin County and is recognized only sporadically north of Lawrence County and west of Franklin County. It contains *Platycrinites penicillus*, a fossil crinoid marking the uppermost part of the Valmeyeran Series. The Shetlerville Member is mostly brownish-gray or dark-gray limestone, partly oolitic, and somewhat sandy. The basal contact is sharp and may be unconformable. The member is about 5 to 6 m thick in the vicinity of Hardin County, and it makes up most, or all, of the Renault outside that area. The crinoid *Talarocrinus* is present, and marks the lower part of the Chesterian Series. The Popcorn Sandstone Bed in the base of the Shetlerville is dominantly sandstone. It has some shale and impure limestone and is about a meter thick. It occurs locally in Hardin County but is rarely found in Illinois outside that area.

CHESTERIAN SERIES

The Chesterian Series occupies the Illinois basin (fig. 8) from De Witt County on the north to the northern part of Johnson County on the south, and from Indiana on the east to within a few miles of the Mississippi River on the west. The series thickens southward to about 450 m in northern Johnson County. Nearly all the formations thicken southward to their truncated edges. The series is beveled by the sub-Pennsylvanian erosion surface. The outcrop belt extends along the Mississippi Valley from near Alton in western Madison County, southward to Union County, and thence eastward to Hardin County and the Ohio River. To the north and east of the vicinity of Alton, the margin of the Chesterian is overlapped by the Pennsylvanian System. The Chesterian includes 19 named formations plus the Shetlerville Member of the Renault Formation at the base (fig. 9). The Aux Vases Sandstone, long considered the basal formation of the Chesterian, is excluded, because it is below the top of the Valmeyeran *Platycrinites penicillus* Zone.

Yankeetown Sandstone Formation.—The Yankeetown Sandstone is chert and cherty sandstone at the type section, but in the subsurface in western Illinois it is a sandstone and shale unit. To the northeast, in Washington County, it becomes a thick sandstone, and to the southeast it changes to a limestone and shale unit. Although only about 6 m thick in the outcrop area, the Yankeetown thickens to about 30 m in southwestern Illinois but is only about 18 m thick over much of its extent.

Paint Creek Group.—The Paint Creek Group consists of the Downeys Bluff, Bethel, and Ridenhower Formations. The name is used in western Illinois where the Bethel, normally a sandstone, is a shale.

Downeys Bluff Limestone Formation.—The Downeys Bluff Limestone is white to light-brownish gray and crinoidal. Pink chert replaces many of the crinoid segments, especially in western Illinois. In southernmost Illinois, the Downeys Bluff consists of two benches separated by a thin shale, and generally is 6 to 9 m thick. The upper bench is typically cherty and the lower is slightly silty or very finely sandy. Farther north, the Downeys Bluff consists of only the upper of the two benches, generally is 2 to 3 m thick, but locally is 3 to 6 m thick.

West Baden Group.—The West Baden Group consists of the Bethel, Ridenhower, and Cypress Formations. The name is used in part of southeastern Illinois, where the Ridenhower is dominantly sandstone and difficult to separate from the sandstone formations above and below.

Bethel Sandstone Formation.—The Bethel Sandstone generally is 6 to 12 m thick in the northern and western part of its extent and thickens southeastward to about 30 m in northeastern Gallatin County. Dominantly sandstone, the Bethel grades to shale in western Illinois. The sandstone generally is slightly coarser grained than the other Chesterian sandstones. Locally, it includes a few small quartz pebbles and a basal conglomerate of limestone and shale pebbles. A prominent 5-m bed of red clay occurs along the outcrop belt in southwestern Illinois.

Ridenhower Formation.—The Ridenhower Formation is mainly shale, but also includes beds of limestone and sandstone that locally are thick. The limestone is diversified and has sandy, oolitic, crinoidal, and lithographic varieties. The proportion of limestone in the formation is greatest in western Illinois, and the proportion of sandstone is greatest in southeastern Illinois. The formation generally is 6 to 12 m thick, but at several places it is more than 24 m. In some parts of central and eastern Illinois, the formation divides into three members—the Beaver Bend Limestone (below), the Sample Sandstone, and the Reelsville Limestone—but in most of Illinois, these members cannot be recognized.

Cypress Sandstone Formation. — The Cypress Sandstone in western Illinois is generally less than 24 m thick, but in eastern Illinois it is more than 37 m thick and locally more than 61 m thick. Typically, the lower half to three-fourths of the formation consists of one or two bodies of massive sandstone. The upper part of the Cypress is more shaly than the lower; typically it is shale interbedded with thin to moderately thick sandstone and siltstone lenses. A fairly extensive red shale occurs about 3 m below the top of the Cypress. A thin coal occurs near the top of the Cypress in extreme southern Illinois. In northern and western Illinois, where the Cypress is relatively thin, the formation is nearly all shale, and has a high proportion of red and green shale.

Golconda Group.—The Golconda Group is a limestone-shale unit, consisting of the Beech Creek Limestone (below), the Fraileys Shale, and the Haney Limestone. A sandstone member is locally present in the Fraileys Shale.

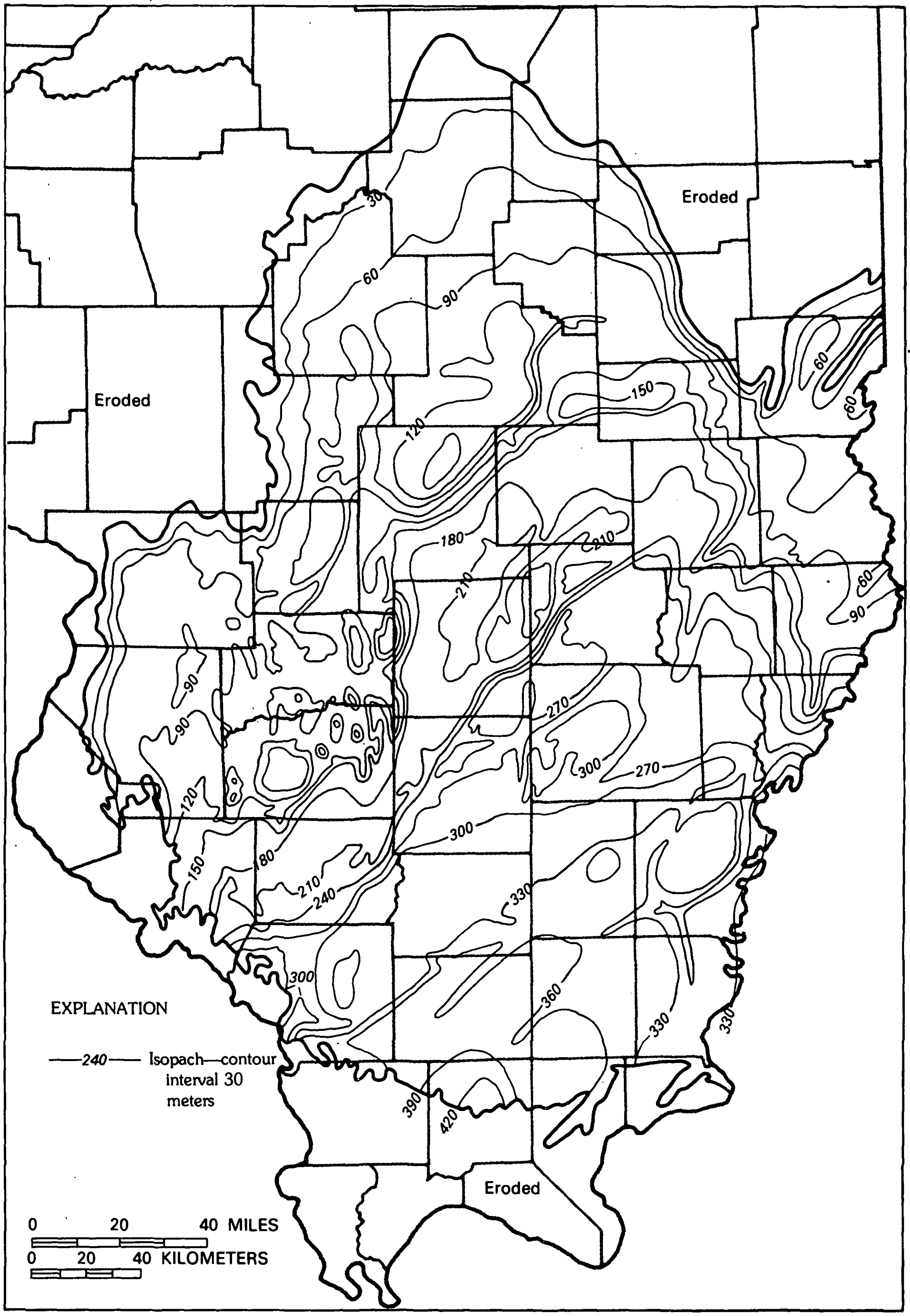

FIGURE 8.—Thickness of the Chesterian Series (Willman and others, 1975).

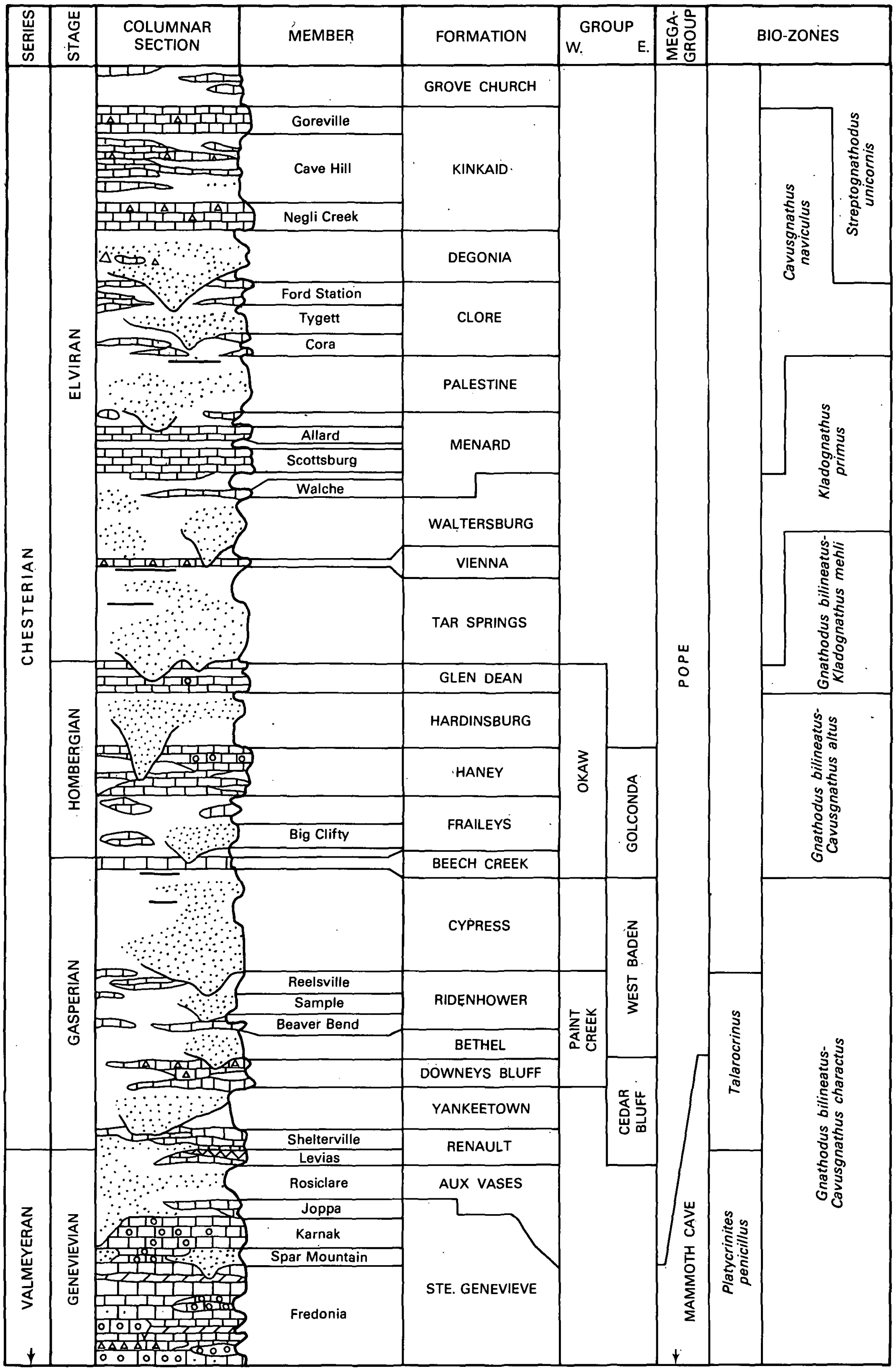

FIGURE 9.—Columnar section of the Chesterian Series (from Swann, 1963) showing biozones (from Collinson and others, 1971). In the columnar section, the blank areas are shale.

Okaw Group.—The Okaw Group consists of five formations from the Beech Creek through the Glen Dean Limestone. The Okaw is used only in western Illinois in an area having small limestone outcrops that are Haney or Glen Dean but that are difficult to differentiate.

Beech Creek Limestone Formation.—The Beech Creek Limestone is a relatively thin but persistent unit, commonly called the "Barlow lime." The lower part is argillaceous, dark brownish gray, dense to sublithographic limestone. The upper part is light brownish gray, fossiliferous, and oolitic in part. The Beech Creek thickens northward in contrast with the other Chesterian formations, which thicken southward. It is as much as 12 m thick in the north, but in Hardin County, in the south, it is shaly and locally absent or too thin to identify.

Fraileys Shale Formation.—The Fraileys Shale is as much as 30 m thick in Williamson County and thins northward to about 9 or 12 m thick before being beveled by the sub-Pennsylvanian erosion surface. It is dominantly shale, has sporadic limestone beds and, locally, a sandstone member. Most of the shale is dark gray; however, in the southern part of the Illinois basin, a persistent red shale occurs 1 or 2 m below the top of the Fraileys. Much of the limestone consists of lenses of fossil detritus, in part containing abundant red, orange, or green fossil fragments. The Big Clifty Sandstone Member enters Illinois from the east and thins out westward within a few tens of kilometers. The member is usually about 5 to 6 m thick and occurs near the middle of the Fraileys, or less commonly near the base.

Haney Limestone Formation.—Haney Limestone is about 30 m thick in southern Illinois and thins northward to less than 5 m. It is mainly limestone and some interbedded shale. The limestone is coarse grained, fossiliferous, and much of it is oolitic. In Randolph County, a 6-m bed of white oolite is informally named the "Marigold Oolite." To the northwest the Haney grades to a shale that is difficult to differentiate from the Fraileys or the Hardinsburg.

Hardinsburg Sandstone Formation.—Hardinsburg Sandstone has a thick-bedded sandstone facies and a thin-bedded shale and shaly sandstone facies. Much of the sandstone is light gray and very fine grained. In the thick bodies, the sandstone may be white and fine grained; in the thin bodies it may be gray or green and finer grained, in places grading to siltstone. About 10 m of red, green, and dark gray shale containing thin beds and nodules of red and brown, lithographic limestone and dolomite lie at the base of the Hardinsburg. Locally, this shale is cut out by an erosional surface that commonly separates it from the overlying sandstone facies so that sandstone rests directly on the Haney Limestone. In southeastern Illinois, the Hardinsburg is 18 to 25 m thick; to the northwest it thins to about 6 to 12 m.

Glen Dean Limestone Formation.—Shale separates the Glen Dean Limestone in the south into upper and lower limestone units. In the north only the lower unit generally persists, and the formation is correspondingly thinner. The limestone is coarse grained and fossiliferous; parts are oolitic, and some strata are cherty. In the south, the Glen Dean is 20 to 25 m thick. In the north, where only the lower limestone unit is present, the formation thins to only 2 to 6 m.

Tar Springs Sandstone Formation.—The Tar Springs Sandstone is nearly all sandstone, white to light gray, very fine to fine grained, and mostly friable but containing some well-cemented layers. Also present are: shale, dark gray and slightly carbonaceous; siltstone, medium to dark olive gray; and shaly sandstone, light to dark olive gray. Near the southern border of the Tar Springs, thin beds of coal occur locally near the top and middle of the formation. The thickness of the Tar Springs generally ranges from 23 to 40 m in thickness, but the maximum is more than 45 m. Near its northwestern border it thins to about 15 m.

Vienna Limestone Formation.—The Vienna Limestone is a thin limestone, mainly dark brownish gray and very fossiliferous. Much chocolate-brown chert is present in the outcrop, but chert is rare in the subsurface. The maximum thickness of the Vienna is about 9 m near its southern edge. About 48 km to the north, it thins to about 3 m; over most of its extent, it is about 1 m thick.

Waltersburg Formation.—The Waltersburg Formation is mainly dark gray, slightly carbonaceous shale, in part silty and sandy. A thin seam of coal is present locally near the top of the formation close to its southern border. Sandstone strata in the outcrop are characteristically well jointed. The Waltersburg generally is 15 to 23 m thick, but at the west it thins to less than 12 m and thickens to 36 m in a small area in Wayne County.

Menard Limestone Formation.—The Menard Limestone generally is 30 to 45 m thick in the southern, 24 to 30 m in the central, and 14 to 18 m in the northern and northwestern parts of its extent. The limestone is argillaceous, dark brownish gray to brown and buff, fine grained to lithographic, oolitic in part, and cherty in part. Fine-to-coarse dark rounded grains give many beds a characteristic speckled appearance. The shale is calcareous, dark gray, and fossiliferous.

The Menard is readily divided into three limestone members. The Walche at the base is 1 to 3 m thick and occurs only in the southern part of the basin. The Scottsburg overlaps the Walche to the north, is 9 to 12 m thick in the south, and thins northward to about 2 m. The Allard thins from about 9 m in the south to 3 m in the north. The shale strata separating these members, and overlying the Allard, are not named units. The shale above the Allard is about 6 to 9 m thick in the south and 3 to 6 m in the north. Locally, especially in the north, the sub-Palestine erosion surface cuts into this shale and in places entirely through it.

Palestine Sandstone Formation.—The Palestine Sandstone includes sandstone, shale, and siltstone. Much of the sandstone is gray, very fine grained, and more or less shaly. The sandstone in the thicker bodies is light gray to white and coarser grained. The shale is dark gray and generally silty to sandy. Much of this rock is slightly carbonaceous. In western Illinois, a thin coal is at the top of the Palestine at several localities. The Palestine tends to thicken slightly southward. Commonly it is 15 to 18 m thick, and it is thickest where massive, channel-phase sandstone bodies are present.

Clore Formation.—The Clore Formation is mainly shale throughout most of its extent, but the proportion of limestone increases southward. About 12 to 18 m thick near its northern and northwestern borders, it thickens southward to about 36 m in northern Johnson County. In many places the Clore is thinned by sub-Degonia channels; in some areas sub-Pennsylvanian channels cut into, or through, the Clore.

The Clore includes three members. The Cora Limestone Member (below), which consists of interbedded limestone and shale containing locally, sandstone lenses, is about 4 to 13 m thick. The Tygett Sandstone Member, which is sandstone containing minor amounts of shale, is 6 to 9 m thick over much of its extent. The Ford Station Limestone Member, which is limestone interbedded with shale and rare lenses of sandstone, is 6 to 15 m thick.

Degonia Sandstone Formation.—The Degonia Sandstone typically includes two beds of massive sandstone. The upper overlaps the lower, and locally both are absent. The shale in the Degonia is gray to dark gray, but red at the top of the formation. Thin seams of coal occur locally near the top and middle of the Degonia in southwestern Illinois. The thickness of the formation ranges from 45 m in western Illinois to as little as 6 m in the southeast. Sub-Pennsylvanian channels cut the Degonia into two large and many small areas.

Kinkaid Limestone Formation.—The Kinkaid Limestone is about 30 m thick in the north, thickening southward to about 51 m near its southern edge. Pre-Pennsylvanian erosion has cut the Kinkaid into many isolated areas. The thick upper and lower limestone members apparently were highly resistant to erosion because they cap the Chesterian over fairly large areas. Many slump blocks of the limestone are known to occur in the subsurface on the slopes of steep-walled sub-Pennsylvanian valleys.

The Kinkaid is divided into three members. The Negli Creek Limestone Member (at the base) is a massive limestone, cherty, brownish gray, containing scattered coarse fossil grains. The member is 11 m thick in Franklin County in the south and 5 m thick in Effingham County in the north. The Cave Hill Shale Member is a limestone and shale unit in which the proportion of limestone increases southward. The basal part is shale, dark gray, and locally black. The lower third of the member contains some silty shale, a little siltstone, and locally shaly sandstone. The middle part of the member contains a variety of carbonate rocks interbedded with a little shale. The upper part consists of calcareous dark gray and greenish gray shale above and red and green shale below. The Goreville Limestone Member is massive and resistant to erosion like the Negli Creek, but it is less extensive and is more dissected by pre-Pennsylvanian erosion. Average thickness of the Goreville is about 9 m, and thickness ranges from about 8 m in the north to nearly 15 m in the south.

Grove Church Shale Formation.—The Grove Church Shale, the uppermost formation in the Chesterian Series in Illinois, occurs only in patches in southern Illinois in Johnson, Pope, and Saline Counties. An unknown, but probably large, part was eroded before the Pennsylvanian was deposited in the area. The Grove Church is a gray, fossiliferous shale containing interbedded fossiliferous limestone. The maximum thickness known is about 20 m in northern Johnson County.

PALEONTOLOGY

The Mississippian System is named for exposures along the western margin of Illinois, and its fossils in this State have been intensively studied. The shale of the Kinderhookian Series is relatively unfossiliferous, except for spores and conodonts, but the Chouteau Limestone (=Rockford of Indiana) at the top of the series is famous for its cephalopod fauna; part of this fauna is earliest Valmeyeran in age. Fossils are abundant and varied in most of the limestone and calcareous shale of the Valmeyeran and Chesterian Series. Brachiopods are numerous, and some formations consist mainly of crinoidal debris. Fenestrate bryozoan debris is abundant in some beds. *Archimedes* with its corkscrewlike axes is so common in some strata that the term "*Archimedes* limestone" was applied to several stratigraphic units in some early reports. *Composita trinuclea* is the commonest Mississippian brachiopod of southern Illinois. Endothyrids are abundant in the Salem Limestone. The coral assemblage zone *Lithostrotionella castelnaui* (="*Lithostrotion canadensis*") and *L. proliferum* is generally equivalent to the St. Louis Limestone. Conodonts are common to abundant and provide a basis for biostratigraphic zonation. More than 20 characteristic conodont faunas have been recognized in North American Mississippian rocks. In the Chesterian, plant megafossils are found in parts of the sandstones, and spores have been described from the thin coals and carbonaceous layers.

ENVIRONMENT OF DEPOSITION

The Kinderhookian Series thickens westward, and the siltstone component is thickest in western Illinois, suggesting that the main source of sediment was west of Illinois. At the base of the series, a local erosional unconformity that has about half a meter of relief on the top of the Devonian suggests a relatively short interval of emergence. Oolitic limestone of the "Glen Park" at the base of the series in central Illinois and oolitic limestone of the thin Starrs Cave at the top of the series in extreme western Illinois indicate shallow water at these times and places. The water may have been deeper to the south and east where the series is thinner. Here the amount of sediment going into the basin may have lead to the "starved" condition that developed later. The close of the Kinderhookian is marked by a minor erosional unconformity at the base of the Burlington Limestone in northwestern Illinois.

Early in Valmeyeran time, as the Illinois basin sank, important facies differences developed in the sediments (fig. 7). In western and northern Illinois where the water was shallow, fossiliferous limestone (Burlington-Keokuk) was deposited that built up a thick carbonate bank. To the south and east, mud was slowly deposited in the deepening basin (Springville Shale and basal Borden). A siltstone delta (Borden Siltstone) encroached from the northeast into this sediment-starved basin where water depths are estimated to have been from 183 to 305 m (Lineback, 1968). The deep-water basin, marginal to the delta on the southeast and south, was filled by the cherty, very siliceous Fort Payne Formation and the bryozoan-rich Ullin Limestone. After the delta had built up to about the level of the top of the Burlington-Keokuk bank, mud and silt swept westward across the surface of the Keokuk to be deposited in western Illinois as the Warsaw Shale.

Carbonate deposition prevailed during the rest of Valmeyeran time. The water was generally shallower than before, the shoreline was to the north, and water was deeper to the south. At times, the environment approached the sabkha-type, and evaporites and oolites were deposited. This was a time of extensive deposition of thick limestone formations.

Of the several types of rock composing the Salem, the most abundant and characteristic are fine- to coarse-grained calcarenite and fossil-fragmental limestone. Coiled Foraminifera, such as *Globoendothyra,* and other small fossils are abundant. Oolites and oolitic overgrowths are locally common. The former presence of local evaporite deposits is suggested by the brecciation of the overlying St. Louis Limestone. Beds of extra fine grained dolomite in the Salem also suggest a shallow-water environment.

The St. Louis Limestone also was deposited in shallow water. Typically, the limestone is very fine grained to lithographic and is locally brecciated; the dolomite is extra fine grained. Oolitic rock is much less common, and the carbonate is generally darker and more cherty in the St. Louis than in the underlying Salem or overlying Ste. Genevieve Limestone. Disseminated anhydrite and some fairly thick beds of gypsum and anhydrite occur. The transition from gypsum to anhydrite is related to depths of burial; below 450 m the evaporite is principally anhydrite.

The Ste. Genevieve Limestone was deposited in a shallow-water environment that favored the deposition of oolitic limestone in lenticular or barlike bodies at several levels. A few thin strata of sandy limestone, sandy calcarenite, or sandstone are fairly widely traceable, foreshadowing the alternation of sandstone and limestone characteristic of the Chesterian.

The Aux Vases Sandstone shows a facies relation with the upper part of the Ste. Genevieve Limestone in southwestern Illinois. Limestone strata in the upper part of the Ste. Genevieve thin and grade into sandstone in this area, so that the base of the Aux Vases is stepped down to include the thicker sand. The sand in the Aux Vases probably came from the north or northeast rather than from the Ozark area itself.

The Levias Limestone Member in southeastern Illinois was deposited in clear, shallow water. Except for the basal few centimeters that are sandy, the limestone is a relatively pure, coarse-grained oolite. The break with the overlying Chesterian is minor and is marked by an erosional surface of very slight relief and sandy beds at the base of the Shetlerville Member.

The Chesterian Series is characterized by an alternation of sand-shale formations and limestone-shale formations in an irregularly cyclical succession. This cyclicity is explained as resulting from the shifts of an east-southeast to west-northwest trending shoreline (fig. 10). When the sea transgressed northward, limestone was laid down in the Illinois basin; when the sea retreated, sand was deposited. The location of major sand bodies is a consequence of lateral shifts in the position of the distributaries of the river that carried sediment into the basin from the north. This river has been named the Michigan River (Swann, 1963); it may have brought sediment from northeastern Canada, but the location of the source is not definitely known. This picture of the paleogeography during Chesterian time developed from a study of features in the sandstone that indicate the direction of paleocurrents. Detailed mapping of the thickness of sandstone in several of the Chesterian formations has shown the position of the distributaries of the Michigan River (Potter, 1963). Changes in the rate of sediment supply have been attributed (Swann, 1964) to climatic control rather than tectonic control, and sediment yield has been controlled mainly by rainfall in the source area. Shoreline position was dependent on the shifting balance between the rate of sedimentation and the rate of sinking of the basin.

In general, the Chesterian formations, except for the Beech Creek Limestone, thicken southward to their truncated edges in southern Illinois; the proportion and thickness of the limestone in the limestone-shale formations also increase southward. The limestone strata in the lower part of the Chesterian (Glen Dean and older) are generally lighter colored

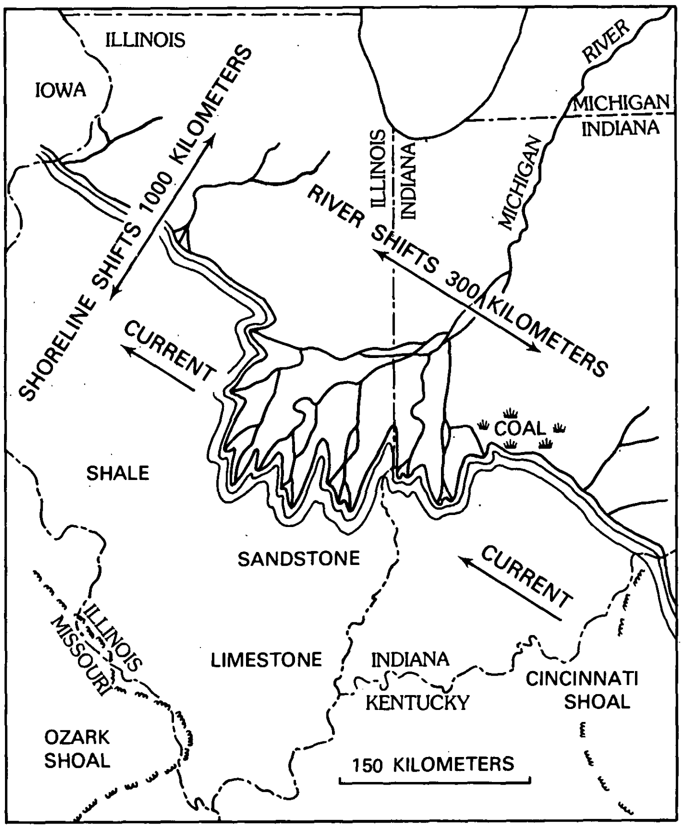

FIGURE 10.—Paleogeography at an intermediate stage during Chesterian sedimentation (from Swann, 1963).

and purer than the limestone in the upper part (Vienna and younger), and the amount of oolitic rock is much greater in the older formations. A coal swamp environment developed several times during the Chesterian. Thin coals occur in Jackson and Hardin Counties at the top of the Palestine Sandstone; in Johnson, Pope, and Hardin Counties at the top of the Waltersburg Sandstone; and in the southern part of the Illinois basin, at the top and near the middle of the Tar Springs and Cypress Sandstones.

TECTONIC DEVELOPMENT

The major tectonic event in Illinois during the Mississippian Period was the sinking of the Illinois basin which was greatest in southermost Illinois. During this period (and until the post-Pennsylvanian development of the Pascola arch) the Illinois basin was open to the south, and the maximum sinking during this time is southwest of the deepest part of the present basin.

At the close of the Devonian Period, the tectonic break was very minor, and local emergence was indicated by an erosional surface on the top of the

Louisiana Limestone (uppermost Devonian). A slight break between Kinderhookian and Valmeyeran Series is recorded along the western edge of the Illinois basin, where the Meppen Limestone (basal Valmeyeran) rests unconformably on the Chouteau Limestone (Kinderhookian). Absence of the Chouteau north of a line running from Calhoun County to the northeast may be a result of a slight upwarping of the Sangamon arch (fig. 11) at the close of the Kinderhookian, accompanied by truncation of the Chouteau. Slight doming of the Ozark region at this time was followed by overlap of the Valmeyeran onto rocks as old as Ordovician.

During the earlier part of Valmeyeran time in western Illinois, where the sea was shallower than it was farther south and east, buildup of the Burlington-Keokuk carbonate bank kept in balance with the sinking basin. Sinking outpaced sedimentation in eastern and southern Illinois, and that part of the basin became sediment-starved until the Borden Siltstone Delta was built out into the basin from the northeast. Near the close of the Valmeyeran, slight warping of the Ozark region is suggested by local erosion surfaces and by overlaps near the top and base of the Ste. Genevieve Limestone at the southwest edge of the Illinois basin.

The base of the Chesterian is marked by local erosion surfaces and by sandy beds. The base of the Cypress Sandstone tends more nearly to parallel the bedding of older units than it does the overlying Beech Creek Limestone, suggesting slight warping of parts of the basin during Cypress time. This, and similar, very minor nonparallelism of older and younger strata in the Chesterian, may be attributable to the differential compaction and draping of younger beds over thick sandstones. However, an abrupt thinning from west to east of the interval between the Downeys Bluff and the Beech Creek Limestones in the southern part of Crawford County in southeastern Illinois is more probably a result of local upwarping than of differential compaction. This monoclinal feature may be an early indication of the La Salle anticlinal belt. Other than this monocline, thickness maps of individual Chesterian and older Mississippian formations show no indication of contemporaneous development of the La Salle anticlinal belt. This major structural feature of Illinois mainly began during the interval of erosion that followed Chesterian deposition in the area.

ECONOMIC PRODUCTS

Oil.—As of December 31, 1976, the estimated original oil-in-place in Illinois was 8,968,692,000 barrels (1,220 million metric tons); the estimated ultimate recovery was 3,205,329,000 barrels (437 million metric tons). Of this Illinois oil, all Paleozoic, 6,766,392,000 barrels (922 million metric tons), or 75.4 percent of the original oil-in-place, and 2,582,443,000 barrels (352 million metric tons), or 80.6 percent of the estimated ultimate recovery, is from reservoirs in Mississippian strata.

A little more than 60 percent of the cumulative production of Mississippian oil is from sandstones in the Chesterian Series, and nearly half this production is contributed by the Cypress Sandstone. Of the other Chesterian sandstones, the Yankeetown ("Benoist"), Bethel, Tar Springs, and Waltersburg are the most important contributors. A little less than 40 percent of the cumulative production is from the Valmeyeran Series, and almost all this is from near the top of the series. Of this oil from the Valmeyeran, the Aux Vases Sandstone contributes about one-third, and the Ste. Genevieve Limestone about three-fifths. The most important reservoirs are in lenses of coarse oolitic limestone (McClosky lime) at several levels in the Fredonia Member of the Ste. Genevieve. Relatively small amounts of oil come from the Spar Mountain Sandstone Member of the Ste. Genevieve and from the Salem and Ullin Limestones.

Gas.—Production of natural gas in Illinois in 1976 was 1,556 million cubic feet (44 million cubic meters), of which only about one-sixth was from the Mississippian. Almost all the Mississippian gas production was from Chesterian sandstones. Eight of 39 active underground natural gas storage projects in Illinois use reservoirs in Mississippian rocks, but none of these 8 are among the relatively large projects in Illinois.

Fluorspar.—Illinois leads the other States in the production of fluorspar. In 1976, production was 129,000 metric tons. All the ore mined came from Hardin and Pope Counties in southern Illinois. The ore occurs in fissure veins and bedded replacement deposits in strata near the base of the Chesterian and near the top of the Valmeyeran Series.

Lead, zinc, and silver.—The fluorspar ore mined in Hardin and Pope Counties is treated to recover zinc, lead, and silver. In 1974, 3,720 metric tons of zinc, 447 metric tons of lead, and a small amount of silver were recovered.

Stone.—Stone production in Illinois in 1976 was 55,100,000 metric tons. Of this total, almost all

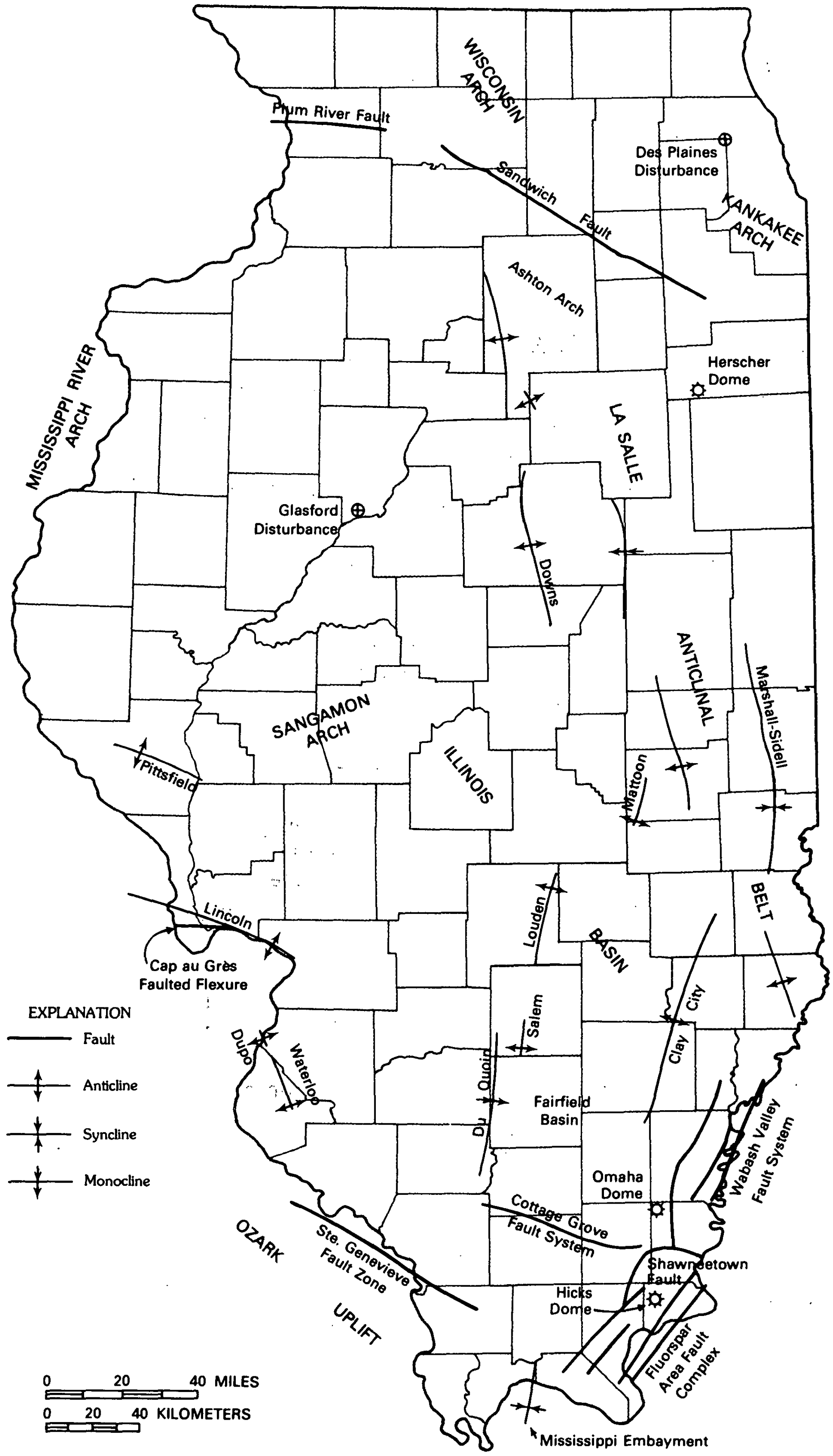

FIGURE 11.—Major tectonic features of Illinois. The Sangamon arch was a Paleozoic structure obscured by later structural movement.

crushed and broken limestone and dolomite, about one-sixth is from the Mississippian, and most of this is from the Valmeyeran. The middle part of the Mississippian System—from the top of the New Albany Shale Group, or the Borden Siltstone where present, up to the lowest sandstone or shale of Chesterian or late Valmeyeran age—is sometimes called the "Mississippi lime," or, more formally, the "Mammoth Cave Limestone Megagroup." This megagroup is an important source of limestone in Illinois, where it crops out along the western and southern borders of the State.

THE PENNSYLVANIAN SYSTEM

INTRODUCTION

The name "Pennsylvanian" was used in 1906 in the first report of the present Illinois State Geological Survey. The terms "Coal Measures" and "Upper Carboniferous," which were used before 1906, were gradually abandoned in later reports (fig. 12) The Pennsylvanian was classified as a series until it was recognized as a system in about 1925. Rock strata of the Pennsylvanian System lie at or near the surface in 86 of the 102 counties in Illinois, or in about two-thirds of the total area (95,291 of a total 146,020 km²).

Although Pennsylvanian strata of Illinois are commonly covered by unconsolidated Pleistocene glacial deposits, they are well exposed in various parts of the State in river valleys, stream valleys, and artificial cuts made during mining and construction of highways or railroads. Pennsylvanian strata are also exposed along the Illinois, Kaskaskia, Wabash, Sangamon, Spoon, and Embarras Rivers, and other smaller rivers and their tributaries. Erosion by streams emptying into the Mississippi and Illinois Rivers in western Illinois has produced numerous exposures. Many excellent exposures also occur in southern Illinois beyond the limits of Pleistocene glaciation. However, the single most important source of information concerning the Pennsylvanian System is the samples, records, and data at the Illinois State Geological Survey of many thousands of coal, oil, and water test holes.

Worthen 1875		S. Weller 1906		DeWolf 1910	Shaw and Savage 1912	Wanless 1929, 1931a	Wanless and J. M. Weller 1932	Wanless 1939 J. M. Weller 1940	Kosanke and others 1960 Willman and others 1975	
COAL MEASURES	Upper	PENNSYLVANIAN	Upper	McLeansboro Formation	McLeansboro Formation	Formations subdivided into cyclical units called "Suites"; later called "Cyclical Formations" McLeansboro Formation	Cyclical units called "Cyclothems" McLeansboro Formation	McLeansboro Group	Mattoon Formation	McLeansboro Group
									Millersville Limestone Member Bond Formation *Shoal Creek Limestone Member*	
	Shoal Creek Limestone		*Shoal Creek Limestone*						Modesto Formation	
								Anvil Rock Sandstone		
				No. 6 coal Petersburg Formation	Carbondale Formation	Carbondale Formation	Carbondale Formation	Carbondale Group	*Danville (No. 7) Coal Member* Carbondale Formation	Kewanee Group
				No. 5 coal LaSalle Formation *No. 2 coal*					*Colchester (No. 2) Coal Member*	
	Lower		Lower	Pottsville Formation	Pottsville Formation	Pottsville Formation	Pottsville Formation	*Palzo Sandstone*	Spoon Formation	
								Tradewater Group *Grindstaff Sandstone*	*Bernadotte Sandstone Member* Abbott Formation	McCormick Group
								Caseyville Group	*Pounds Sandstone Member* Caseyville Formation	

FIGURE 12.—Development of the classification of the Pennsylvanian System in Illinois (from Kosanka and others, (1960). In Wanless (1939) and Weller (1940), the McLeansboro and Carbondale Groups were divided into cyclothems, and the Caseyville and Tradewater Groups in southern Illinois were divided into seven formations. In several reports from 1940 to 1950, the base of the McLeansboro was put at the top of the No. 6 Coal. Cyclothems are retained in a separate cyclical classifications. Units bounding the groups and formations are in italics (Willman and others, 1975).

BOUNDARIES OF THE PENNSYLVANIAN SYSTEM

A major angular unconformity separates the Mississippian System from the Pennsylvanian System in Illinois. The configuration of the erosion surface separating the two systems has been studied extensively by workers at the Illinois State Geological Survey (Siever, 1951; Wanless, 1955; and Bristol and Howard, 1971). They identified a series of broad southwestward-trending valleys as much as 140 m deep and commonly several kilometers wide that evidently were formed by subaerial erosion (fig. 13).

A post-Pennsylvanian, pre-Pleistocene erosion surface that defines the upper limit of Pennsylvanian deposits in Illinois was formed by pre-Pleistocene stream erosion and later was modified by Pleistocene glaciation and Holocene stream erosion. Gulfian (Upper Cretaceous) rocks overlie Pennsylvanian strata in a small area in Adams, Pike, and Brown Counties in western Illinois.

GENERAL CHARACTERISTICS OF PENNSYLVANIAN STRATA

Pennsylvanian strata attain a maximum thickness of about 760 m in Wayne County, southeastern Illinois (fig. 14). If thickest sections are considered for each formation, the composite thickness of strata is about 1,000 m. The formations are generally thickest in southeastern Illinois and become thinner toward northern and northwestern Illinois.

Some lower strata of the Pennsylvanian System are present only in southern and central Illinois and are overlapped by younger formations in the north. At some locations on the La Salle anticline, the three lowest formations (Caseyville, Abbott, and Spoon) are absent and the St. Peter Sandstone (Middle Ordovician) directly underlies the Colchester (No. 2) Coal, which is at the base of the Carbondale Formation. In the area of Rock Island and Mercer Counties in extreme northwestern Illinois, however, the three lowest formations of the Pennsylvanian System are well developed.

About 90 to 95 percent of the Pennsylvanian System in Illinois consists of clastic rocks. Siltstone, shale, and underclay constitute about 40 percent of the lower part of the system and 65 to 70 percent of the middle and upper parts. In the lower part, sandstone constitutes about 60 percent of the strata; in the middle and upper parts, it constitutes only about 25 percent of the strata. Limestone is rare in lowermost Pennsylvanian strata but in some areas constitutes as much as 5 to 10 percent of the upper two-thirds of the system. Limestone is especially common in the Bond Formation, where individual beds as much 15 m thick have been recognized. Coal, one of the least abundant lithic units of the Pennsylvanian System, constitutes no more than 2 percent of rock strata in most areas.

More than 500 units of sandstone, siltstone, shale, limestone, coal, and clay are distinguishable in the Pennsylvanian strata of Illinois (Willman and others, 1975). The abruptness and great number of vertical changes in lithology indicate that changes in depositional environment were rapid. Some of the coal, underclay, and limestone, although rather thin, are the most persistent lateral units of the Pennsylvanian System. If Indiana and Kentucky are included, several coal and limestone beds can readily be correlated over a distance of about 560 km in the Illinois basin. On the basis of these marker beds, intervening strata that show substantial lateral variations can also be correlated over considerable distances.

STRATIGRAPHY

ABSAROKA SEQUENCE

The Absaroka Sequence, which was named for the Absaroka Mountains in northeastern Wyoming and southern Montana, includes the Pennsylvanian System of Illinois. The base of the sequence is the major unconformity at the base of the Pennsylvanian System in Illinois, and the top of the sequence is the major unconformity at the base of the Cretaceous System (Willman and others, 1975). The Absaroka Sequence, represented only by Pennsylvanian-age strata in Illinois, consists predominantly of clastic sediments and contains numerous minor unconformities produced through erosion by deeply entrenched valley systems and by entrenchment of river distributaries in deltaic sediments.

MORROWAN SERIES

The type exposure of the Morrowan Series is on Hale Mountain, Washington County, Ark., near the community of Morrow, for which the series was named. Both nonmarine and marine strata are included in the series. In Illinois, the Morrowan Series includes only the Caseyville Formation (Willman and others, 1975) (fig. 15).

McCormick Group.—The McCormick Group in Illinois includes strata of the Caseyville and Abbott Formations, which extend from the base of the Pennsylvanian to the top of the Bernadotte Sandstone Member. The group derives its name from exposures near McCormick, Pope County, in southern Illinois. The McCormick Group has a maximum

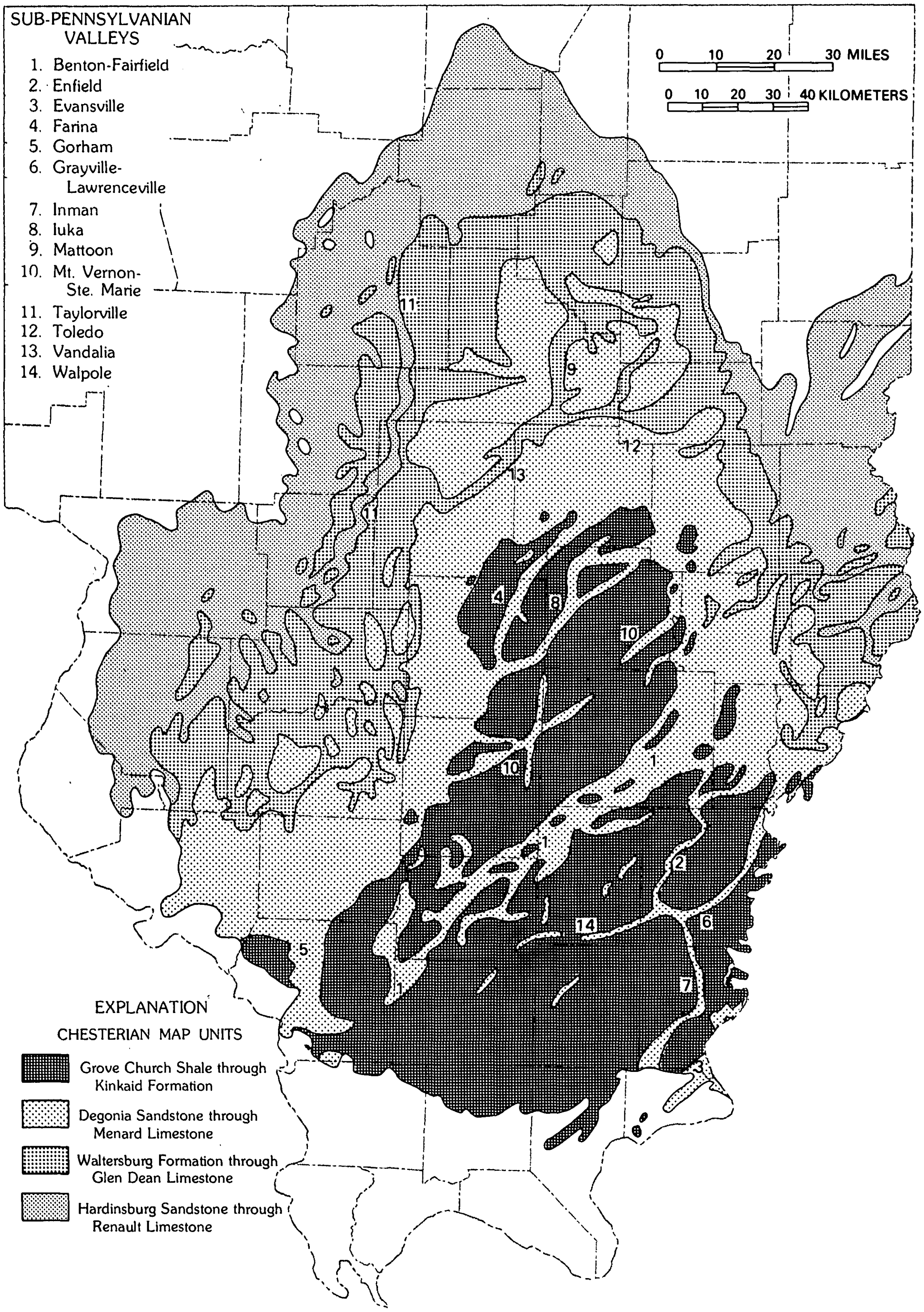

FIGURE 13.—Paleogeologic map of sub-Pennsylvanian Chesterian surface in Illinois (from Howard, in press).

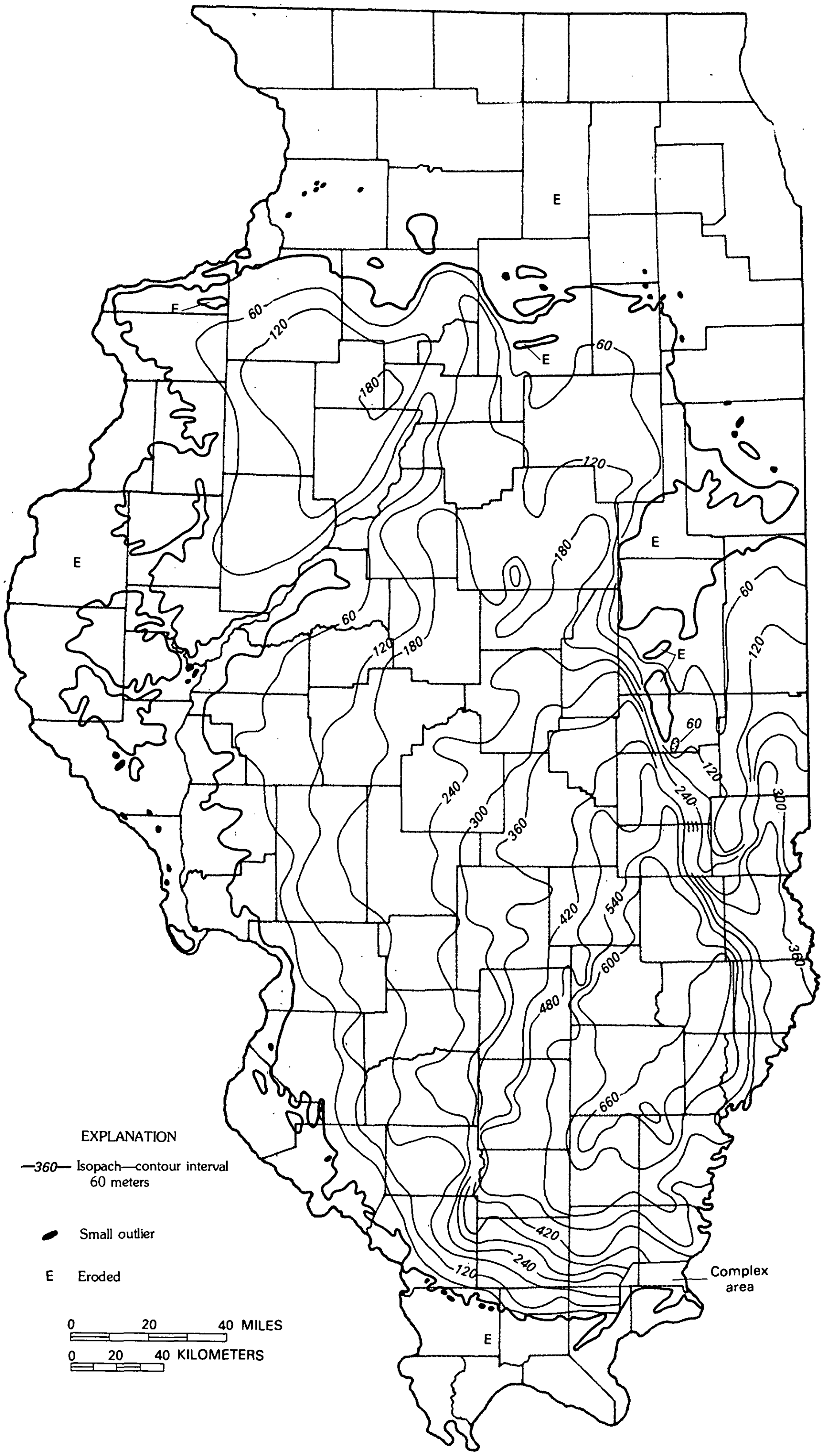

FIGURE 14.—Thickness of the Pennsylvanian System.

thickness of at least 180 m in southern Illinois, but it thins northward to about 60 m and is absent in large areas of western and northern Illinois. The McCormick Group consists of about 50 to 60 percent sandstone, about 40 percent or more sandy shale, and a few thin nonpersistent limestones and coals. The sandstones commonly form cliffs, are extensively cross bedded, and contain a high percentage of quartz.

The McCormick Group is predominantly devoid of animal fossils, although a few calcareous sandstones and shale zones and one limestone member that contain marine invertebrate fossils have been recognized. Log casts of *Lepidodendron* sp., *Calamites* sp., and *Sigillaria* sp. are common in fine-grained sandstone of the lower part of the McCormick Group.

Caseyville Formation.—The Caseyville Formation was named by Owen (1856, p. 48) for the community of Caseyville on the Ohio River in southwestern Union County, Ky., which is near the site of the type locality. Rock sections for definition of the formation were "measured from outcrops on the Illinois shore of the Ohio River between the mouth of the Saline River and Gentry's Landing below Battery Rock" in Hardin County (Lee, 1916, p. 15–16). Strata from the base of the Pennsylvanian System to the top of the Pounds Sandstone Member are included in the Caseyville Formation.

The Caseyville Formation is commonly about 100 m thick in southern Illinois. Where the formation has filled pre-Pennsylvanian bedrock valleys, it may be as much as 150 m thick. The Caseyville Formation was deposited only in southern and southeastern Illinois and in parts of Mercer and Rock Island Counties in northwestern Illinois, where it locally attains a thickness of more than 30 m (fig. 16). It is overlapped by the Abbott Formation; maximum combined thickness of the Caseyville, Abbott, and Spoon Formations in southern Illinois is more than 360 m (fig. 17).

Sandstone is the most common constituent of the Caseyville Formation, but the formation also contains abundant siltstone and shale. Because of local variations in lithology, individual beds of the formation can usually be traced only for short distances. The sandstones are predominantly quartzose and contain very little clay or mica. Quartz granules and pebbles, usually less than 12 mm in diameter, are scattered throughout the sandstones and may be in local deposits of conglomerate. Individual sandstones may be as much as 30 m thick and commonly display prominent, rather uniform cross-bedding with dip to the west, south, or southwest, parallel to the direction of elongation of the sand bodies (Willman and others, 1975).

Shale, silt shale, and siltstone beds are common in the Caseyville Formation. Most are medium to dark gray where unweathered and orange brown on weathered surfaces. Coarse siltstone and fine-grained sandstone beds are commonly ripple bedded. Shale associated with the coals is usually dark. In northwestern Illinois, the Caseyville is composed of medium-gray to dark-gray brittle shale interbedded with silty shale and, in a few places, a clean quartz sandstone.

Although several thin and lenticular coals are present in the Caseyville Formation, only the Gentry Coal Member of southeastern Illinois has been named. At least seven impure coals that are individually as much as 60 cm thick have been recognized in the Caseyville Formation of Rock Island and Mercer Counties.

The Caseyville Formation, in contrast with younger Pennsylvanian strata, contains almost no limestone beds. The Sellers Limestone Member, which is known from only one exposure near Sellers Landing, Hardin County, Ill., on the west bank of the Ohio River, is the only named limestone member; it contains a variety of invertebrate marine fossils. Other recognized members of the Caseyville Formation are the Lusk Shale, the Wayside Sandstone, the Battery Park Sandstone, the Drury Shale, and the Pounds Sandstone.

The Caseyville Formation of Illinois is correlative with the lower part of the Mansfield Formation of Indiana and all but the upper 1 or 2 m of the Caseyville Formation of Kentucky. Three State parks in southern Illinois and several parks in western Kentucky and Indiana are in Caseyville outcrop areas of outstanding natural beauty. The high sandstone cliffs and associated rugged topography form some of the most scenic areas of the Midwest.

ATOKAN SERIES

The Atokan Series in Illinois includes only strata of the Abbott Formation of the McCormick Group. The lower and upper boundaries of the series are established at the top of the Pounds Sandstone Member and the top of the Bernadotte Sandstone Member, respectively. Although fossil-bearing strata are present in the Atokan Series in Illinois, they are not used to define its boundaries (Willman and others, 1975).

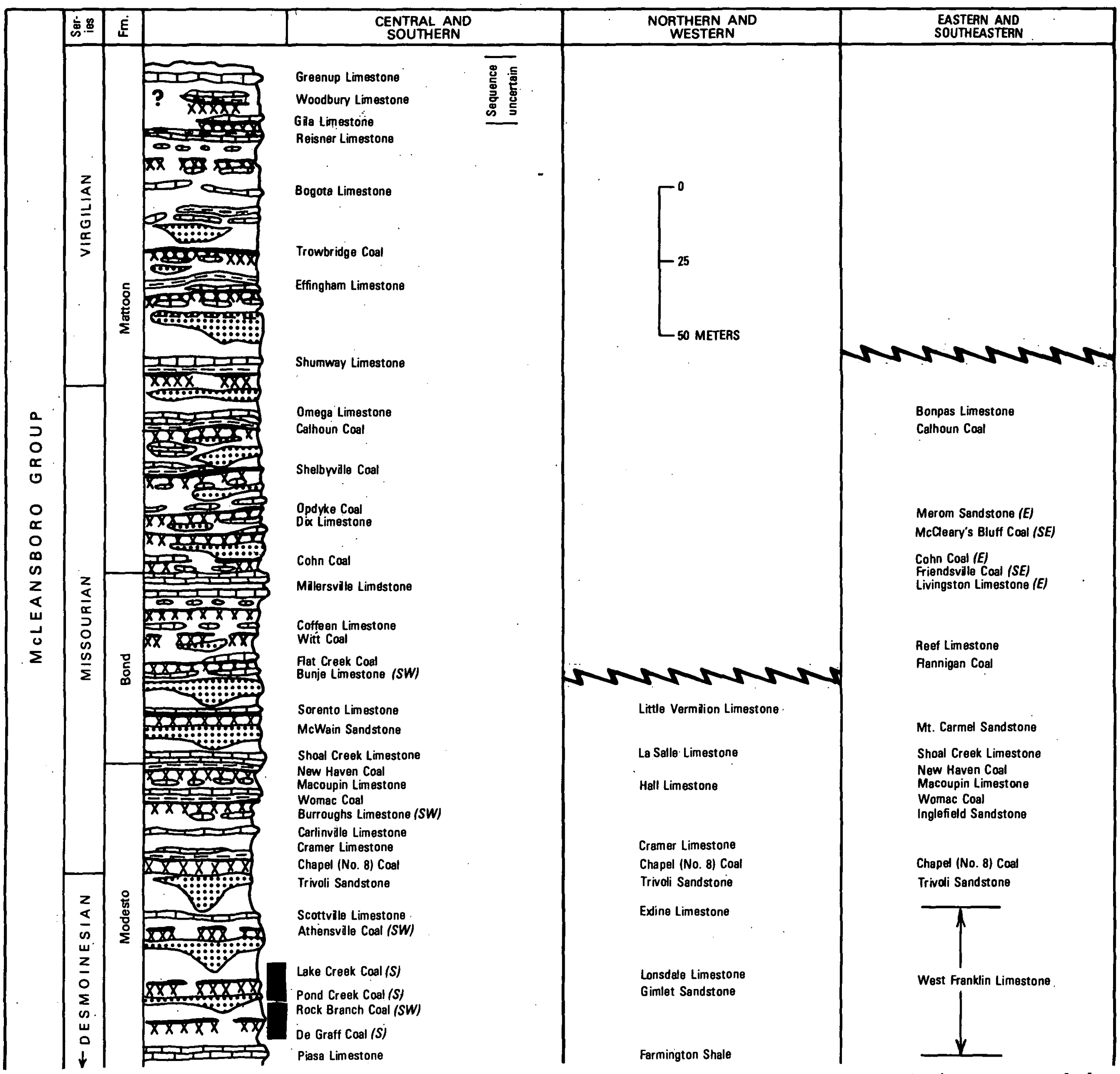

FIGURE 15.—Classification of the Pennsylvanian System. In the graphic column, blank space indicates gray shale. Named members are listed to the right of the graphic column.

Abbott Formation.—The type section of the Abbott Formation of the McCormick Group is defined from exposures near Abbott Station on the Illinois Central Gulf Railroad, Pope County, Ill. Only the prominent sandstones and some coals of the Abbott Formation have been named. Because the bordering sandstone members may be missing locally, both the top and the base of the Abbott Formation are commonly difficult to identify in the subsurface.

The Abbott Formation overlaps the Caseyville Formation and is the basal Pennsylvanian formation throughout much of Illinois. The Abbott is overlapped by the Spoon Formation in northern and northeastern Illinois and on some prominent anticlinal structures. Thickness of the Abbott Formation ranges from a maximum of 100 m in southern Illinois to less than 30 m in western Illinois.

The Abbott Formation is a transitional unit between the underlying Caseyville Formation and younger strata. Basal sandstones of the Abbott closely resemble those of the Caseyville Formation, whereas middle and upper Abbott sandstones are generally thinner, contain more interstitial clay and mica, and contain no more than a few quartz

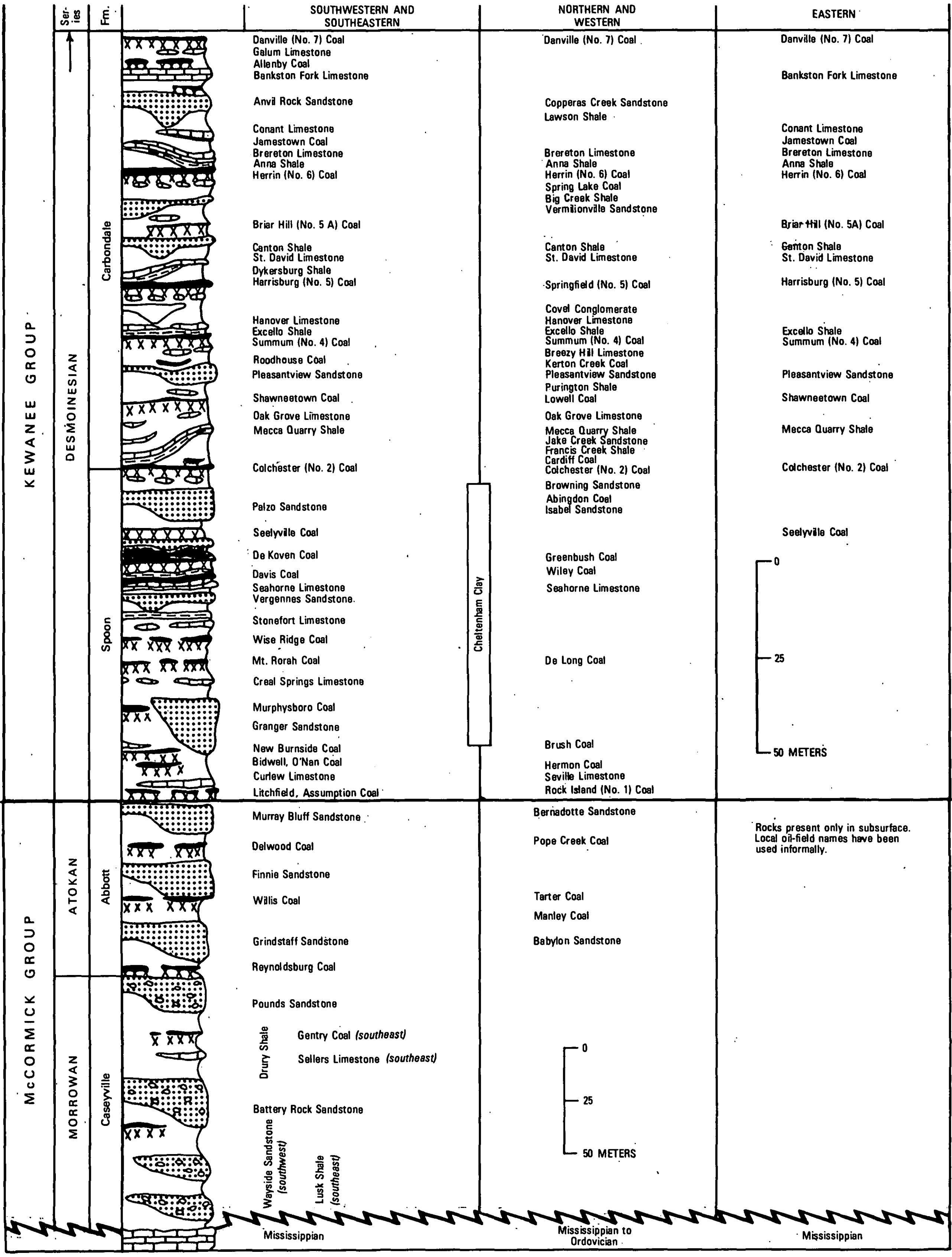

FIGURE 15.—Continued.

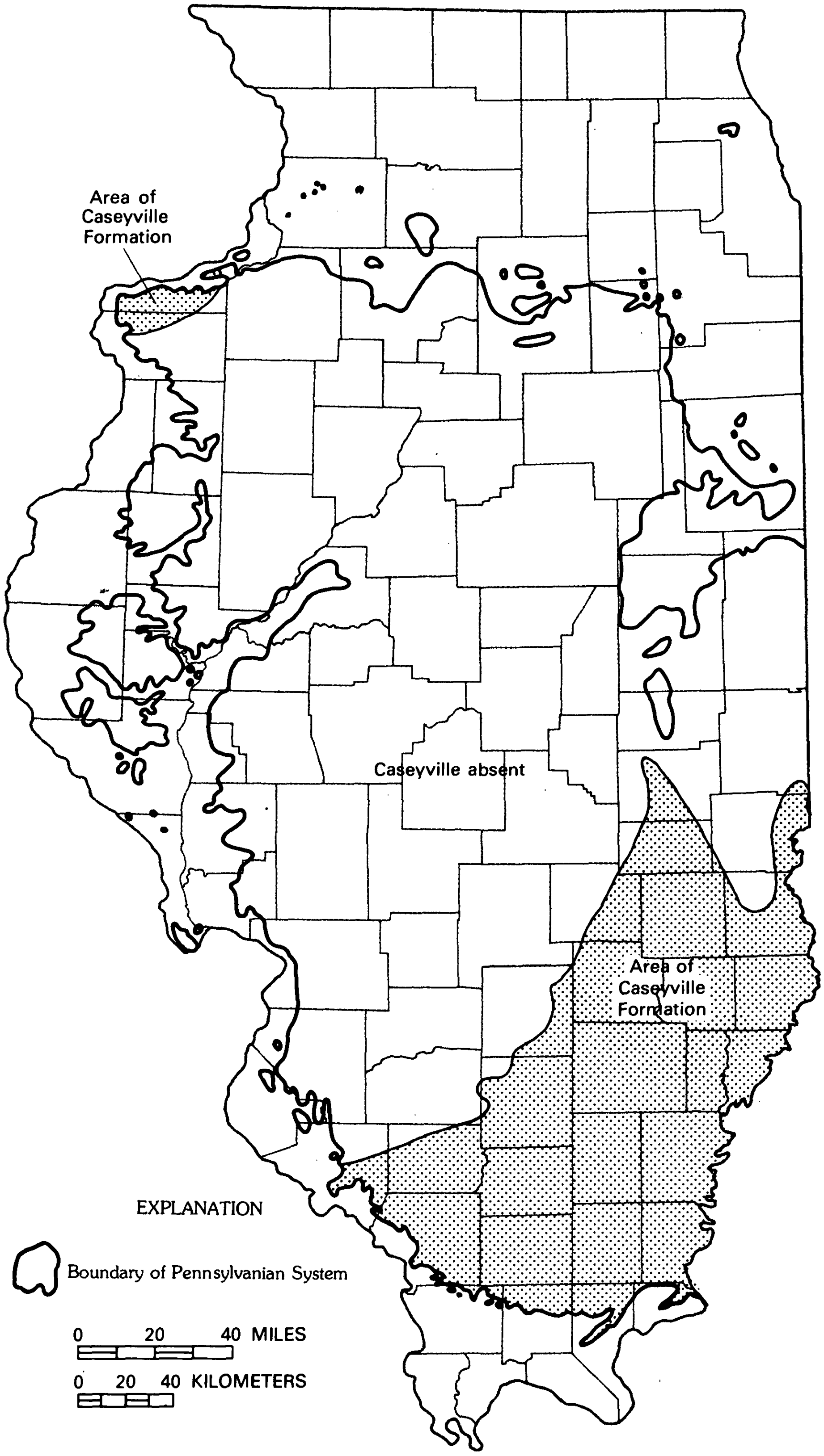

FIGURE 16.—Extent of the Caseyville Formation (from Wanless, 1955).

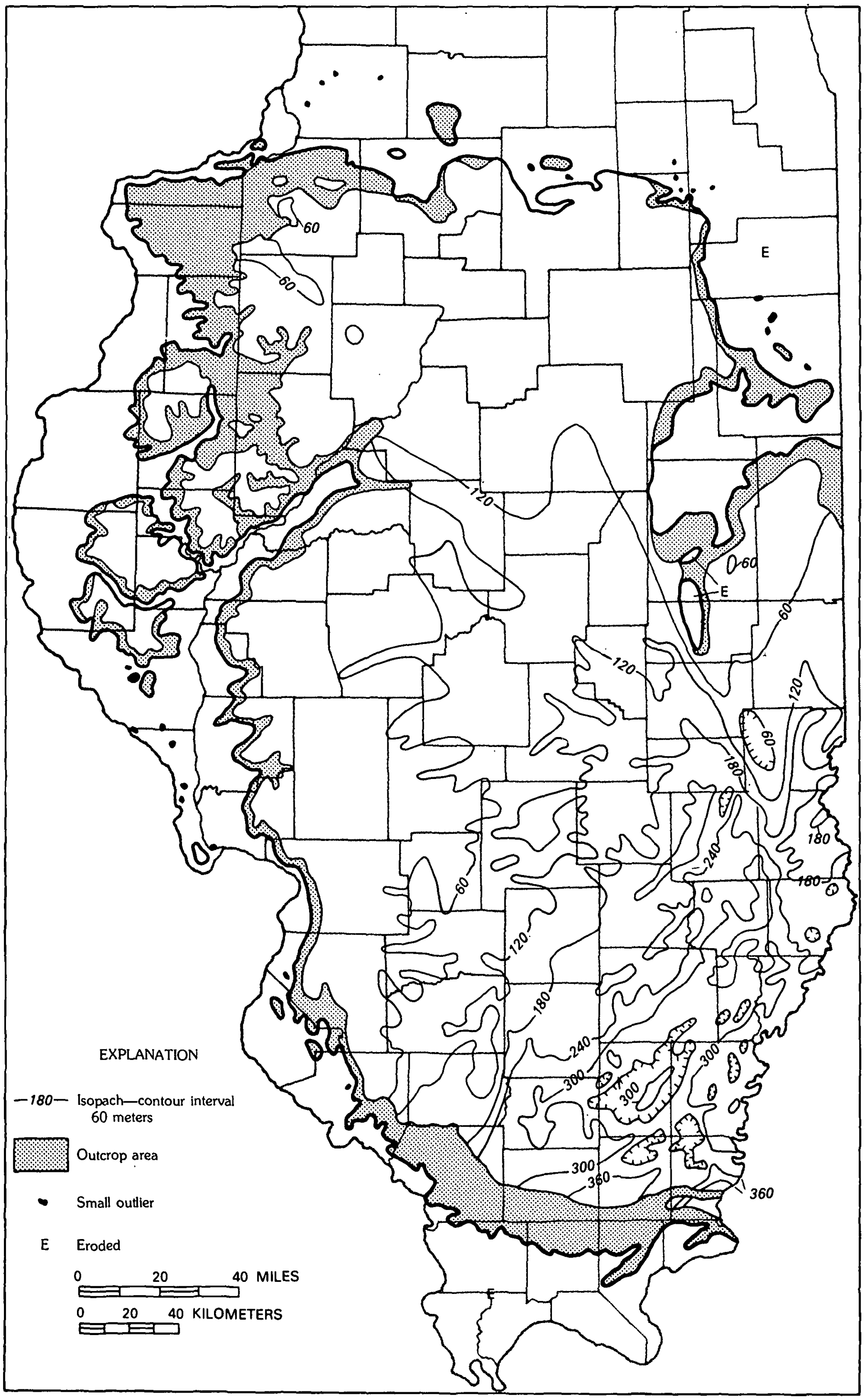

FIGURE 17.—Combined thickness of the Caseyville Formation (from Wanless, 1955).

granules and pebbles. Coals are generally thicker and more persistent in the Abbott Formation than in the underlying Caseyville but not as well developed or extensive as in younger formations. The uppermost sandstones of the Abbott Formation are similar to the relatively impure sandstones of the overlying Spoon Formation.

Named members of the Abbott Formation are the Reynoldsburg Coal, Grindstaff Sandstone, Babylon Sandstone, Manley Coal, Willis Coal, Tarter Coal, Finnie Sandstone, Delwood Coal, and Pope Creek Coal. The Abbott Formation is equivalent to the upper part of the Mansfield and virtually all the Brazil Formation of Indiana, and to the upper 1 or 2 m of the Caseyville Formation and the lower part of the Tradewater Formation in western Kentucky.

DESMOINESIAN SERIES

The Desmoinesian Series comprises the Spoon and Carbondale Formations of the Kewanee Group and the lower part of the Modesto Formation of the McLeansboro Group.

Kewanee Group.—The Kewanee Group consists of the Spoon and Carbondale Formations and is named for Kewanee, Henry County, in western Illinois, where the two formations are well exposed. The Kewanee Group overlies the Abbott Formation in normal sequence, but in northern and northeastern Illinois, where the Abbott is missing, the unit lies on strata ranging in age from Valmeyeran (Middle Mississippian) to Champlainian (Middle Ordovician).

More than 99 percent of the mapped coal reserves of Illinois are contained in the Kewanee Group. The well-developed cyclothems and the broad extent of many relatively thin lithologic units (marine limestone, black fissile shale, coal, and underclay) are distinctive of the Kewanee Group.

Spoon Formation.—The Spoon Formation of the Kewanee Group is defined from exposures in a road and railroad cut in western Fulton County, Ill. (NW¼ sec. 22, T. 6 N., R. 1 E.), near the Spoon River, from which the name of the formation is derived. The base of the formation is defined as the top of the Bernadotte Sandstone of western Illinois or the Murray Bluff Sandstone of southern Illinois. The upper boundary of the formation is the base of the Colchester (No. 2) Coal (fig. 12). The formation is as much as 100 m thick in southern Illinois, but it thins substantially in northern and western Illinois, where it ranges from 1 or 2 m to less than 30 m in thickness. The lowermost extensive limestones and coals of the Pennsylvanian System are in the Spoon Formation, but they are generally thinner than similar units of overlying Pennsylvanian strata. The sandstone of the Spoon Formation contains more mica and clay than the sandstone of the underlying Abbott Formation and reflects a gradual decrease in sediment maturity that is continued in younger Pennsylvanian strata. The coals are neither as thick nor as persistent as those of the Carbondale Formation but are markedly thicker and more extensive than those of the Abbott Formation. The Spoon Formation correlates with the uppermost part of the Linton Formation in Indiana and with the upper part of the Tradewater Formation and the lower part of the Carbondale Formation in western Kentucky. The named members of the formation include 18 coals, 5 limestones, and 5 sandstones (fig. 15).

Carbondale Formation.—The Carbondale Formation of the Kewanee Group is named for Carbondale, Jackson County, Ill., which is near outcrops of the formation in southern Illinois. Three outcrops in Fulton County, western Illinois (SE¼NE¼ sec. 1, T. 7 N., R. 4 E.; NW¼NE¼NW¼ sec. 20, T. 8 N., R. 3 E.; and SW. cor. sec. 21, T. 8 N., R. 3 E.) were established by Kosanke and others (1960, p. 34 and 46) as the type sections for the formation. The base of the Colchester (No. 2) Coal is defined as the base of the Carbondale Formation, and the top of the Danville (No. 7) Coal marks the upper boundary.

The gray silty shales and sandstones display abrupt lateral variations in thickness and are largely responsible for variations in thickness of strata between the coals and other persistent units. The formation is more than 120 m thick near outcrop areas in southern Illinois but is less than 45 m thick in western and northeastern Illinois (fig. 18).

Sandstones of the Carbondale Formation commonly are deposited in elongated channel systems and may be as much as 30 m thick. Thinner sheet-type deposits are also common. The sandstones, which are slightly more argillaceous than sandstones of the Spoon Formation, are classified as subgraywackes. Gray silty shale is the most abundant rock unit in the Carbondale Formation. Sideritic nodules and bands are abundant in the shales. The relatively thin but widespread marine limestones are gray to dark gray, argillaceous, and fossiliferous. Black fissile shales, usually less than 60 cm thick, are associated with the marine limestones and commonly contain a marine- to brackish-water invertebrate fauna similar to that in the limestones. A light gray, nodular limestone, usually devoid of

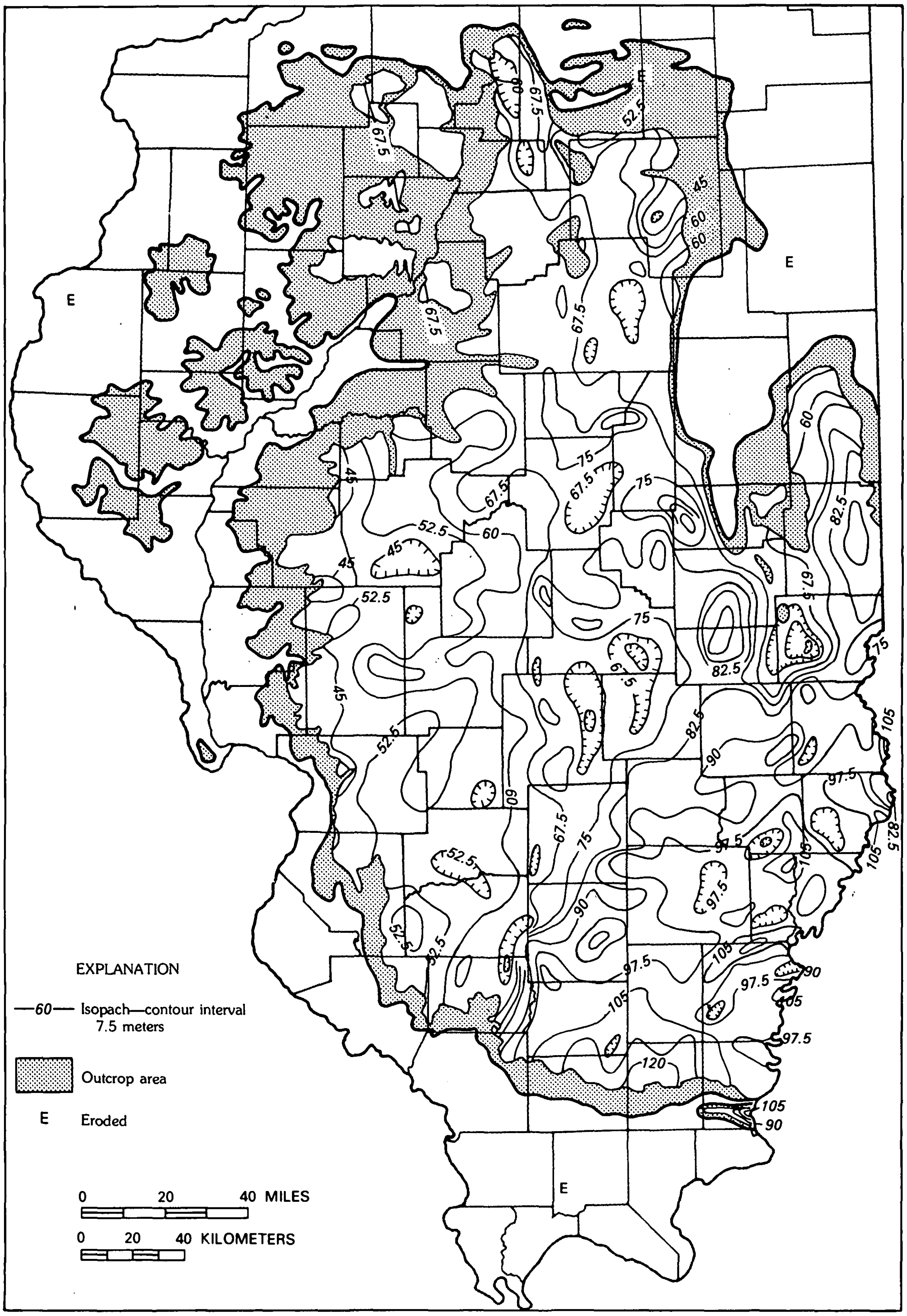

FIGURE 18.—Thickness of the Carbondale Formation (Willman and others, 1975).

marine fossils, occurs in the basal part of the widespread underclays.

The principal coals of Illinois, the Herrin (No. 6), the Springfield-Harrisburg (No. 5), the Colchester (No. 2), and the Danville (No. 7), listed in order of economic importance, are within the Carbondale Formation. The lower 15 m of the Sturgis Formation and the upper part of the Carbondale Formation of western Kentucky correlate with the Carbondale Formation. In Indiana, approximately the same interval of strata as in Illinois is assigned to the Carbondale Formation. The named members of the formation in Illinois include 14 coals, 9 limestones, 9 shales, 5 sandstones, and 1 conglomerate (fig. 15).

McLeansboro Group.—The McLeansboro Group consists of three formations—the Modesto, Bond, and Mattoon—and includes all Pennsylvanian strata in Illinois above the top of the Danville (No. 7) Coal, which is the base of the group. The group is named for the city of McLeansboro, Hamilton County. The type section consists of 247 m of Pennsylvanian strata in a diamond drill core from a test hole near McLeansboro (SE¼SW¼SW¼NE¼ sec. 25, T. 4 S., R. 5 E.). An additional 120 m of strata younger than those in the type section drill hole have been recognized in the deeper part of the Illinois basin in Jasper County, and still younger strata have been identified in western Kentucky.

Coals of the McLeansboro Group are generally thinner and less extensive than those of the Kewanee Group. Coals as thick as 1 m have been reported, although most are less than 30 cm thick. Limestones are generally thicker, more numerous, more predominantly marine, and less argillaceous than those of the Kewanee Group. Rock strata of the McLeansboro Group are also known by the same name in Indiana and correlate with all but the lowest part of the Sturgis Formation of Kentucky.

Modesto Formation.—The type locality for the Modesto Formation comprises four outcrops described by Payne (1942) and Ball (1952) near Modesto, Macoupin County, where nearly all of the formation is exposed. The base of the Modesto Formation is the top of the Danville (No. 7) Coal, and the formation extends to the base of the Shoal Creek Limestone Member or La Salle Limestone Member. The Modesto Formation is about 140 m thick in southern Illinois but thins to about 60 m in northern Illinois and to less than 40 m in the vicinity of the La Salle anticline in east-central Illinois (fig. 19). The coals of the Modesto Formation are generally thinner than those of the underlying Carbondale Formation, but are widespread. The limestones are generally thicker and less argillaceous, and some are commonly associated with red claystone and shale. Much of the Modesto Formation consists of gray shale, although channel sandstone deposits are as much as 24 m thick in some areas. The Modesto Formation correlates with part of the Sturgis Formation of western Kentucky and the Patoka Formation of Indiana. The named members of the formation include 8 coals, 10 limestones, 3 sandstones, and 1 shale (fig. 15).

MISSOURIAN SERIES

The Missourian Series of the Pennsylvanian System is named for the State of Missouri and includes rocks in Illinois from the top of the Trivoli Sandstone Member to a position 1 or 2 m below a coal that underlies the Shumway Limestone Member. The upper part of the Modesto Formation, all the Bond Formation, and about half of the Mattoon Formation are included in the Missourian Series.

Bond Formation.—The Bond Formation of the McLeansboro Group is named for Bond County in southwestern Illinois. Seven separate outcrops in Bond, Christian, and Montgomery Counties constitute the type section. The Bond Formation averages about 75 m thick; it ranges in thickness from less than 45 m in eastern Illinois to more than 90 m in southeastern Illinois (fig. 20). The base of the Bond Formation is defined at the base of Shoal Creek Limestone Member, or the La Salle Limestone Member, and its upper boundary is the top of the Millersville or Livingston Limestone Member. Substantial parts of the formation consist of calcareous clays and limestone. The bounding limestone members are the thickest and include the purest limestones in the Pennsylvanian System of Illinois. The upper limestone is as much as 15 m thick and the lower limestone is locally as much as 9 m thick; both are extensively quarried. Gray shale is the most abundant lithic constituent of the formation, but thick channel sandstones are also abundant locally. Red claystones and shales occur in the Bond Formation and are best developed in northern Illinois. The formation correlates with a part of the Sturgis Formation in western Kentucky and is also called "Bond" in Indiana. The named members of the formation include nine limestones, three coals, and two sandstones (fig. 15).

VIRGILIAN SERIES

The Virgilian Series of the Pennsylvanian System consists of all strata above a position 1 or 2 m below

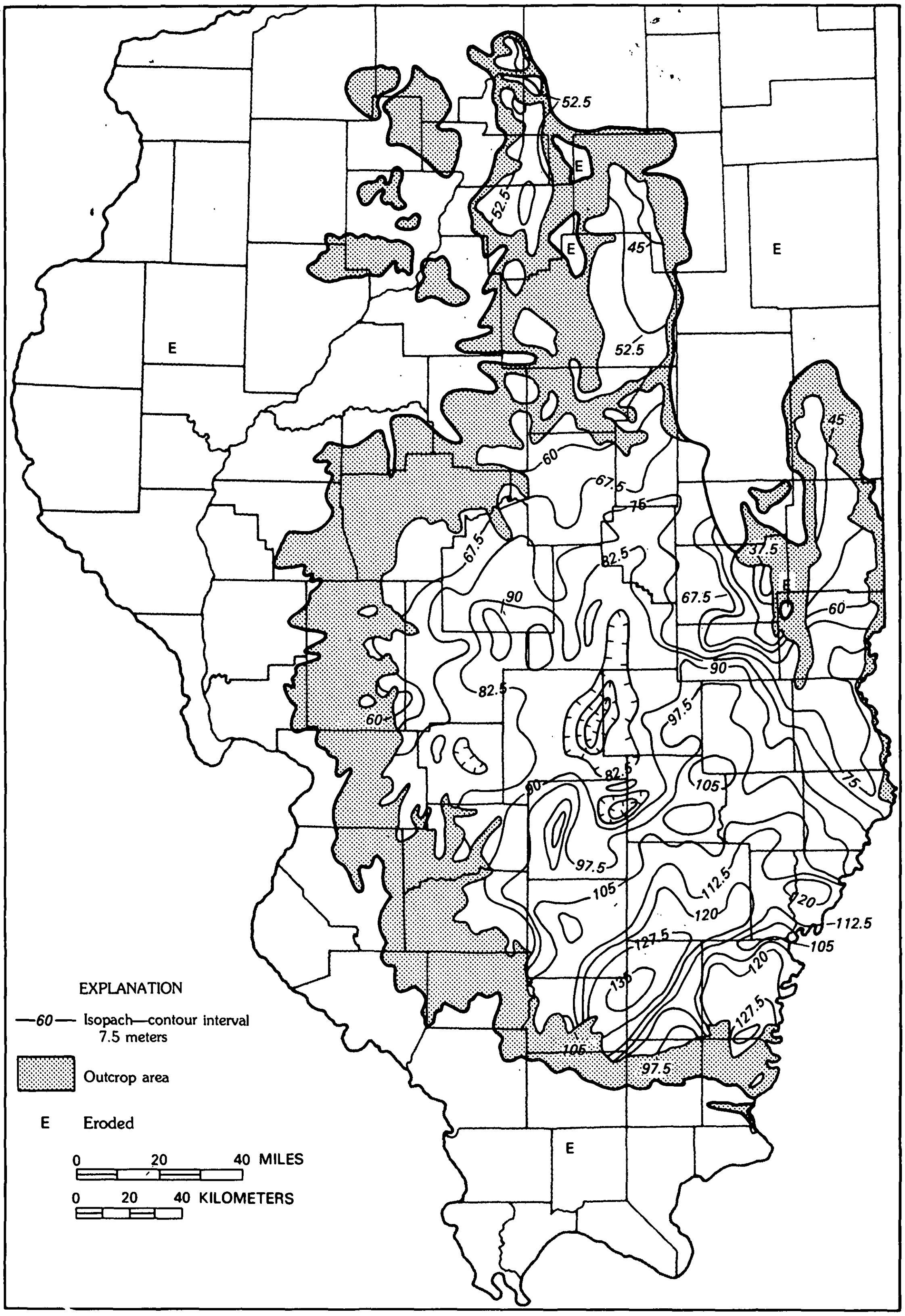

FIGURE 19.—Thickness of the Modesto Formation (Willman and others, 1975).

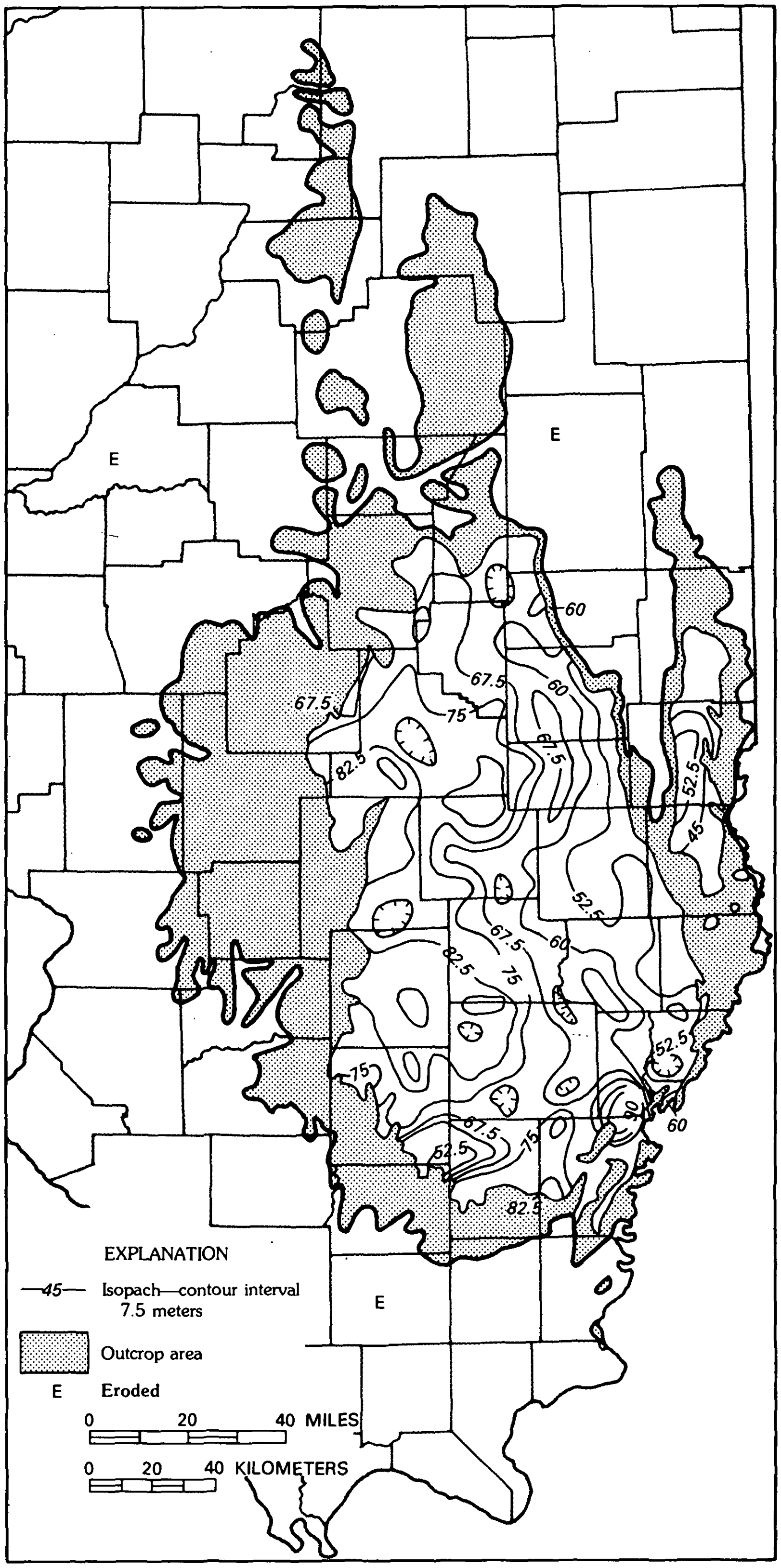

FIGURE 20.—Thickness of the Bond Formation (Willman and others, 1975).

the coal that is just below the Shumway Limestone Member. It includes the youngest Pennsylvanian-age rocks in Illinois.

Mattoon Formation.—The Mattoon Formation of the McLeansboro Group is named for the city of Mattoon, Coles County, Ill., which is located in the general outcrop area of the formation. The base of the formation is the top of the Millersville or Livingston Limestone Member; its upper boundary is an erosion surface largely covered by Pleistocene glacial deposits. No type section has been designated for the formation. A reference section for the lower 90 m of the formation has been defined in Illinois State Geological Survey Control Well 191, an oil test boring from Clay County on file at the Survey (Kosanke and others, 1960, p. 40, 83, and 84). The greatest thickness of strata of the Mattoon Formation in Illinois, slightly more than 180 m, is in Jasper County in the central part of the Illinois basin (fig. 21).

The Mattoon Formation consists largely of thick gray shales, several well-developed sandstones, black fissile shales, limestones, coals, and underclays. Most geologic data on the formation are derived from drill holes, since outcrops are widely scattered and exposed sections are relatively thin. The limestone units and coals of the Mattoon Formation are believed to be at least as persistent as others of the McLeansboro Group, but their extent cannot be determined from the limited information available. Several tan argillaceous limestones less than 1½ m thick contain only ostracodes and spirorbis. Others, including the Omega and Greenup Limestone Members, contain abundant marine fossils and are moderately thick.

The Mattoon Formation is equivalent to the upper part of the Sturgis Formation in Kentucky, but more than 200 m of strata younger than the youngest Mattoon rocks are present in the Sturgis Formation. The lowermost 45 m of Mattoon strata extend into Indiana. The named members of the formation include 10 limestones, 7 coals, and 1 sandstone (fig. 15).

CYCLOTHEMS IN ILLINOIS STRATIGRAPHY

The first clear description of cycles of strata that are now termed "cyclothems" was presented by Udden (1912) for an area in western Illinois near Peoria. He recognized a succession of strata, including coal, which was repeated almost perfectly four times. Subsequent studies indicated that repeated sequences of sedimentary strata characterize large parts of the Pennsylvanian System from at least western Pennsylvania to northern Texas. These sequences were first referred to simply as "cycles of sedimentation" by Udden (1912) and Weller (1930, 1931). Wanless and Weller believed a special term was needed for these cycles and in 1932 (p. 1003, footnote) proposed the term "cyclothem" to designate "a series of beds deposited during a single sedimentary cycle of the type that prevailed during the Pennsylvanian Period." The term won immediate acceptance and was soon in widespread use.

Although the idealized cyclothem sequence (fig. 22) is rarely complete, the units that are present retain the same relative position in sequence. Cyclothems have their greatest use in Illinois stratigraphy in aiding determination of the genetic significance of units and in detailed correlation and field mapping of Pennsylvanian strata.

The cyclothem was removed from the rock-stratigraphic classification of the Illinois State Geological Survey in 1960 (Kosanke and others, 1960) and is now included as a separate cyclical classification.

PALEONTOLOGY

Most information concerning paleontology of the Pennsylvanian System has been obtained from limestone, coal, black carbonaceous shale, and underclay limestone. Sandstone and siltstone locally may contain plant impressions and fragments, but are commonly nonfossiliferous.

The most common invertebrate macrofossils are brachiopods, crinoids, gastropods, and pelecypods. Corals, cephalopods, trilobites, foraminifers, bryozoans, and worms are also present. Biostratigraphic zones in the Pennsylvanian in Illinois are based on fusulinids, ostracodes, and spores. Floral zones for Illinois and other parts of the United States were described by Read and Mamay (1964).

Coal-bearing Pennsylvanian strata of Illinois have been fairly precisely correlated from spores and pollen in the coals. Palynological studies of other lithologic units have not been extensive, however. Major time-stratigraphic intervals are delineated by their most abundant spore taxa and by the occurrrence of certain genera and species that have relatively short stratigraphic ranges. Coals in the Illinois basin can generally be closely correlated by the study of spores.

MORROWAN SERIES

Marine fossils are rare in the Morrowan Series of Illinois, but a Morrowan fauna has been recog-

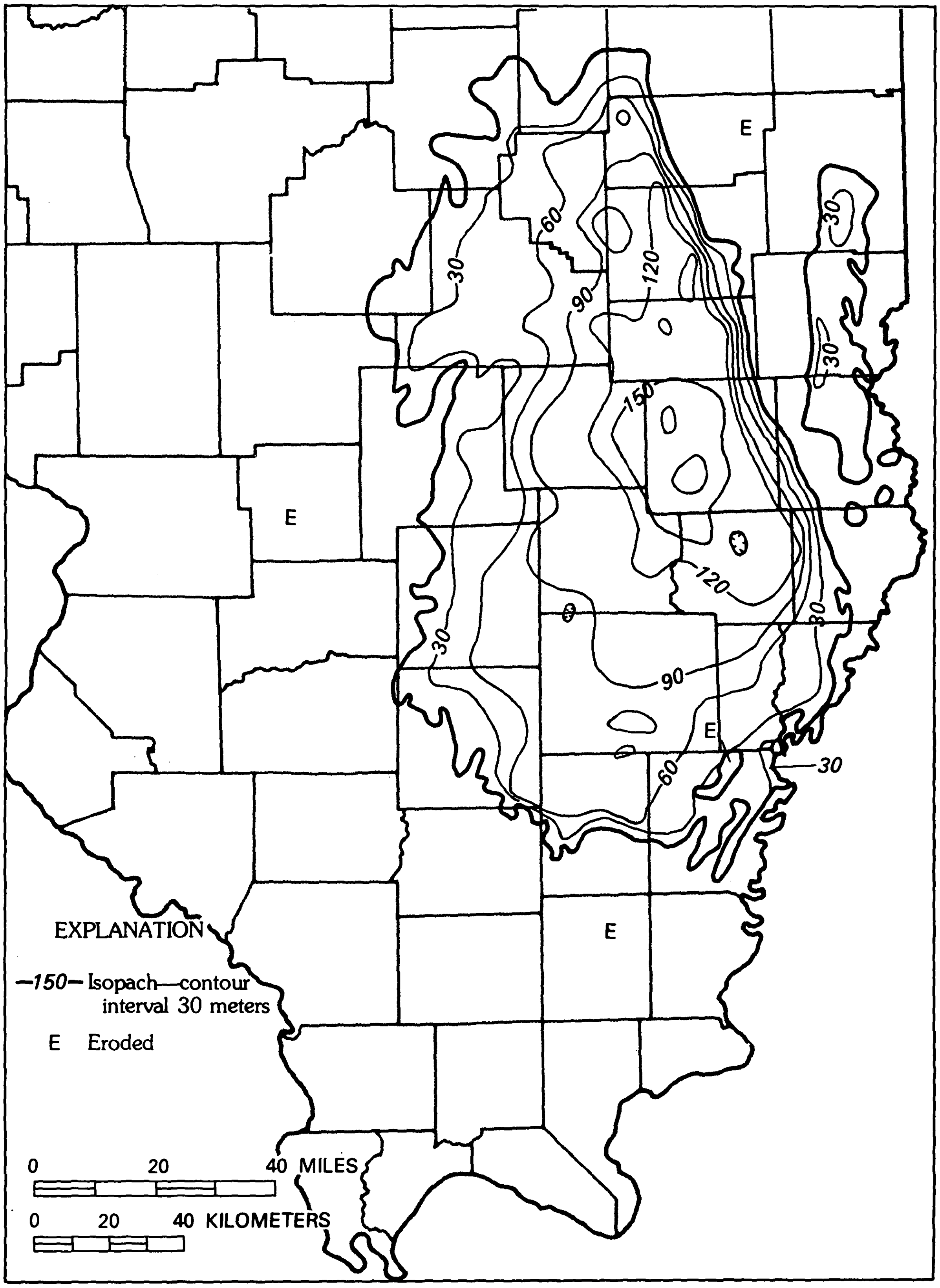

FIGURE 21.—Thickness of the Mattoon Formation (Willman and others, 1975).

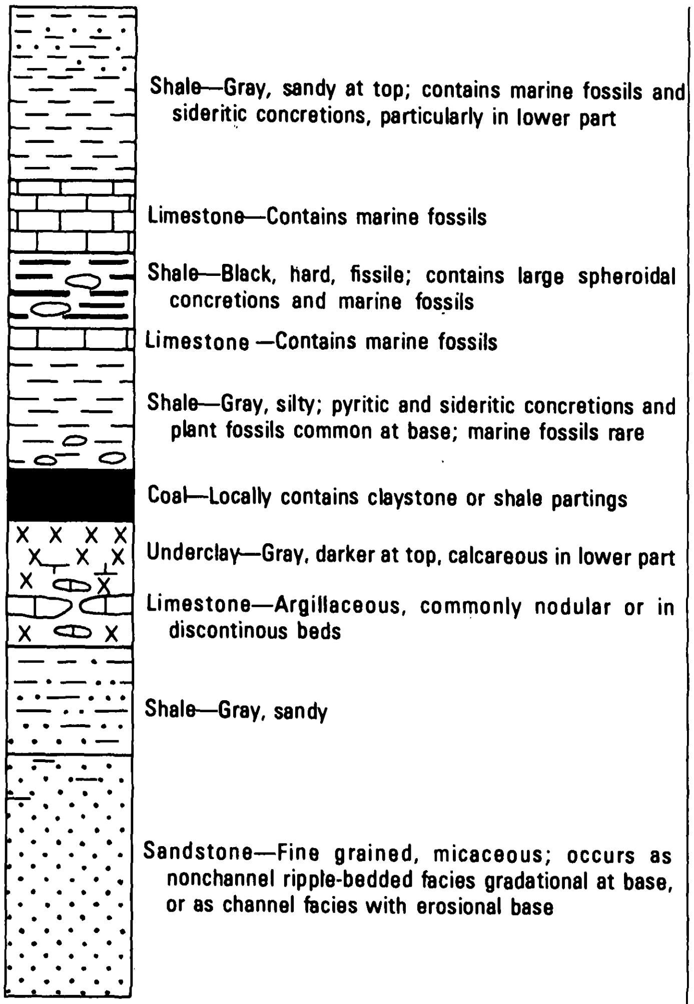

FIGURE 22.—Arrangement of lithologic units in a cyclothem (from Willman and Payne, 1942).

nized in an exposure of the Sellers Limestone Member in southeastern Illinois.

The compression plant fossils, *Neuropteris tennesseeana* and *Mariopteris pygmaea* of the Morrowan Series are in Zone 6 of Read and Mamay (1964). The roof shale of the Baldwin coal, which occurs in the Morrowan type section of Arkansas, contains a plant-impression flora similar to that above the Gentry Coal Member in southeastern Illinois. The relative ages of strata within the Morrowan Series in Illinois can best be determined from spores, which are abundant in Morrowan Series rocks of Illinois, especially in the coals. The Morrowan Series is dominated by the genus *Lycospora,* which in some coals constitutes as much as 80 percent of the spore population. Spores of herbaceous lycopods—*Densosporites, Cristatisporites,* and *Radiizonates*—are also abundant.

ATOKAN SERIES

Where marine rocks are abundant, the Atokan Series is commonly characterized as the two subzones of the earliest fusiform fusulinids, *Profusulinella* and *Fusulinella,* and the top is defined as the strata below the first appearance of *Fusulina* and *Wedekindellina*; some confusion has developed because *Fusulina* has been reported in the Atokan of the type area in Arkansas.

Plant fossils for the Atokan Series are in Zone 7, *Megalopteris* spp. and in Zone 8, *Neuropteris tenufolia* of Read and Mamay (1964). Spore assemblages are the best means for correlating the Atokan strata in Illinois with Atokan strata of other areas. They are of greater diversity and their genera are more abundant and more evenly distributed than in the Morrowan Series. *Laevigatosporites, Calamites, Florinites,* and *Punctatisporites* increase in the upper part at the expense of *Lycospora,* which with *Densosporites*—especially *D. annulatus* and *Cristatisporites indignibundus*—is common in the lower part of the Atokan. Certain species of *Radiizonates* and *Torispora* are useful in defining the upper part.

DESMOINESIAN SERIES

Fusulinids are abundant in many of the limestones in Illinois, and the Desmoinesian Series is defined as the *Fusulina* Zone. *Fusulina* is confined to the Desmoinesian Series except for one reported occurrence in Atokan rocks of Arkansas. Several other invertebrates, such as *Mesolobus, Chaetetes,* and *Prismopora,* are seldom found above the top of the Desmoinesian, and certain of their species are confined to this series. The upper boundary is difficult to determine in much of Illinois, because an interval at the top of the Desmoinesian and the base of the Missourian is barren of fusulinids.

Neuropteris rarinervis in Floral Zone 9 and *Neuropteris flexuosa* and *Pecopteris* spp. in Zone 10 of Read and Mamay (1964) are included in the Desmoinesian Series. In Illinois, this series contains the thickest and most widespread coals, and *Lycospora* is the dominant spore. This genus abruptly disappears at the top of the Desmoinesian. *Thymospora pseudothiessenii,* which appears in the bottom third, also disappears at the top of the Desmoinesian. *Densosporites* occurs only in the lower half of the Desmoinesian, and *Schopfites* is diagnostic of approximately the middle third. A marked change in the spore flora is found at the Desmoinesian-Missourian boundary.

MISSOURIAN SERIES

The Missourian Series is characterized by earlier forms of the genus *Triticites,* which is the subgenus *Kansanella* of Thompson. Floral zones are not as well defined in Illinois, where the Missourian and the overlying Virgilian together constitute Zones 11 and 12 (zone of *Odontopteris* sp.) (Read and Mamay, 1964). Delineation of the ranges of spore taxa in the Missourian and Virgilian Series has not been determined with the same degree of accuracy as in the remainder of the Pennsylvanian because the stratigraphic relation of many of the coals has not been worked out in detail. Small spores of ferns and seed ferns, many less than 30 μm in diameter, are prolific in most of the Missourian and Virgilian coals. The taxa are classified as *Punctatisporites minutus, Laevigatosporites minutus,* and species of *Cyclogranisporites* and *Apiculatisporis. Endosporites* is abundant in many of the coals.

VIRGILIAN SERIES

The Virgilian Series includes strata containing fusulinids of the genus *Triticites* that are more advanced than the subgenus *Kansanella* found in lower strata. The upper limit is placed just below the first appearance of the Permian genera *Pseudoschwagerina* and (or) *Schwagerina,* but neither have been found in the Illinois basin. The spores and plant-compression fossils in Virgilian rocks of Illinois are not well known.

ENVIRONMENTS OF DEPOSITION

Pennsylvanian-age strata of the Illinois basin were deposited in a slowly subsiding trough that remained open to the south until post-Pennsylvanian time. The trough was bounded on the east by the Cincinnati arch and on the southwest by the Ozark uplift. The present closed basin was formed through uplift of the Pascola arch after close of the Pennsylvanian Period and sometime prior to late in Cretaceous time, as indicated by the presence of late Cretaceous strata of the Gulfian Series in southern Illinois, which unconformably overlie uplifted Pennsylvanian strata.

At the beginning of Morrowan time, the area that is now the Illinois basin was crossed by a series of southwestward flowing streams whose valleys were cut to depths as much as 140 m below adjacent uplands (fig. 13). These streams deposited large quantities of clastic sediments of the Caseyville Formation in the southern part of the Illinois basin, which was then open to the south. Medium- to coarse-grained sandstone containing scattered white quartz pebbles was deposited in the stream channels, which apparently underwent substantial lateral shifting of position during sedimentation. Mudstone, siltstone, and shale were deposited on floodplains adjacent to channels and also in lakes, marshes, and deltas.

Sandstone of the Caseyville Formation is highly quartzose and was evidently derived from reworked older Paleozoic strata. Distinctive characteristics of the Caseyville Formation are extreme local variability of strata and the predominance of medium- and coarse-grained clastic deposits.

Both channel-fill and sheetlike sandstones were deposited in Illinois during the Atokan Epoch. The channel sandstone apparently filled numerous fluvial and distributary channels of deltas. Crossbedding orientations suggest that most coarse clastic deposits were derived from an easterly source. Sheetlike sandstone may have been deposited largely as interdistributary sands of deltas, or as upper delta plain deposits. The Bernadotte Sandstone Member of western Illinois is a typical sheetlike sandstone that contains abundant root (Stigmaria) impressions; this indicates that it served as a soil for vegetation that produced the Rock Island (No. 1) Coal. Dark-gray mudstones of both northwestern and southern Illinois contain clay ironstone concretions and appear to have formed in interdistributary bays and lagoons. Atokan-age sediments show a progressive increase in clay and mica content; this indicates that source areas may have been stripped of sedimentary cover and that micaceous metamorphic rocks were supplying detritus.

Minor marine transgressions occurred only in the eastern part of the Illinois basin during Atokan time. The Fulda and Ferdinand Limestone Members of the Mansfield Formation in Indiana and at least two unnamed limestone beds in western Kentucky were deposited in these seas. No equivalent strata are known in Illinois.

Depositional environments of the Desmoinesian Epoch reflect a marked transition from relatively irregular fluviatile-deltaic processes to remarkably uniform regional cycles in which nearly identical depositional environments extended without interruption for hundreds of kilometers, virtually the full extent of the Illinois basin at times. During Desmoinesian time, more marine transgressions occurred in the Illinois basin than in the Appalachians, and more nonmarine strata were deposited than in areas to the west (Wanless, 1975, p. 85). Accordingly, the nature and variability of Pennsylvanian System cyclic sedimentation is better developed in the Illinois basin than elsewhere in the United States.

Because the transgressions and regressions were relatively uniform, a single generalized depositional sequence that characterizes depositional environments of much of the Desmoinesian Epoch in the Illinois besin was described by Wanless (1975, p. 85).

Beginning with a time of maximum transgression, marine lime mud was deposited eastward from northern Missouri and Iowa into the Illinois basin, where it graded laterally into clay muds of a broad gently sloping shoreline that may have extended nearly parallel to the Cincinnati arch. At numerous points landward from the shoreline, streams fed clastic deposits into shallow seas and buried the recently deposited lime mud; construction began of a broad platform of interassociated prodelta and deltaic deposits on which a large coal swamp would later be established. Basal deposits of this unit were commonly phosphatic nodules and some fossil detritus, which graded upward into dark shale and fine, evenly laminated siltstone.

In some areas, mud of the advancing shelf-deltaic complex was eroded by river distributaries, and streams later filled some of the eroded channels with sand. As the constructional period ended, the broad shelf probably stood at or near sea level. Vegetation developed on exposed clay or sand and in shallow-water areas. In extensive areas where the water table was sufficiently high, peat accumulated.

Closely following peat accumulation in some parts of the Illinois basin was the deposition of irregular bodies of gray mudstone or shale. This deposition preceded the reestablishment of a complex marine environment. The gray shale occurs in lenses and pods, which in some areas apparently are randomly distributed but elsewhere are adjacent to large fluvial distributary channels. The gray shale bodies show evidence of erosion prior to burial by overlying marine strata. The lowermost 1 or 2 m of the gray shale locally contain impressions and casts of tree trunks, apparently in position of original growth, and woody fragments and inclusions, which suggests rapid burial of a peat swamp.

The gray shale seems to be predominantly of nonmarine origin; the shale evidently formed in association with fluvial processes (such as crevasse splays and natural levees) and as lacustrine deposits of ponded areas that existed relatively briefly before complete submergence of the peat swamps.

Following local deposition of the gray shale and limited erosion, possibly by the transgressing seas, the first sediment deposited was a black organic-rich mud that became a highly fissile, nonplastic carbonaceous shale. The shale commonly contains fish remains, inarticulate brachiopods, conodonts, and pectinoid pelecypods. The black shale is generally not present where the underlying gray shale exceeds 8 m in thickness. This fact suggests a maximum water depth of about 8 m during deposition.

After deposition of the black mud, a deeper marine environment developed. Deposits from that environment were generally lighter colored, more calcareous sediments that gradually changed to marine lime muds as water depth increased, thus completing the cycle. Advancement of prodelta mud initiated a new but similar cycle of deposition. Although many basic similarities can be recognized in the different cycles of deposition, no two are identical. The recognition of specific differences between individual cycles allows reliable correlation of individual beds over distances of several hundred kilometers.

At the beginning of the Missourian Epoch, the east-central part of the United States appears to have been more emergent than at any other time during the Middle Pennsylvanian (Wanless, 1975, p. 88). The Illinois region was subjected to erosion by many meandering rivers, whose channels were later filled with sand. As many as eight successive deltas, which consisted predominantly of mudstone and sandstone apparently derived from the northeast or north, were formed during the early part of the Missourian Epoch. No data are available concerning deltaic sedimentation late in Missouri time, but as many as six or seven deltas appear to have formed.

Numerous widespread marine transgressions, which resulted in the deposition of the thickest Pennsylvanian-age marine limestone of Illinois, are distinctive of the Missourian Epoch. Wanless (1975, p. 89) correlated these limestones with thicker limestone of the Forest City basin in the northern midcontinent region and limestones of the northern Appalachian basin, and he believed them to represent eastward transgressions of the sea for at least 1,600 km.

Mudstone and sandstone deposits of the Virgilian Epoch resemble those of the Missourian Epoch and probably represent continued deposition of fluviatile or deltaic channel deposits overlying prodelta mudstone (Wanless, 1975, p. 91). At least seven marine transgressions, probably from the west, occurred during Virgilian time, but the limestones are commonly thin and are not as extensive as those deposited during the Missourian Epoch.

No record is available of rock strata in Illinois that may have been deposited in latest Pennsylvanian or later time, prior to deposition of Upper Cretaceous strata in southern Illinois. A strongly downfaulted graben in western Kentucky opposite Shawneetown, Ill., contains 640 m of rock strata that lie above the Shoal Creek Limestone Member (Palmer, 1976). The uppermost 460 m of these strata are not present in Illinois, and data from current studies suggest that the strata, in part, may be of Permian age (T. M. Kehn, oral commun., 1977). Damberger (1971) estimated that the depth of burial of the Herrin (No. 6) Coal Member in southeastern Illinois may have been 1,370 m or more. Because the present maximum thickness of strata overlying the No. 6 Coal in Illinois is about 400 m, more than 970 m of rock strata may have been removed by erosion.

TECTONIC DEVELOPMENT

Most major structural features of Illinois originated or had important growth and development during the Pennsylvanian Period. The systematic thinning or thickening of strata in the vicinity of active structures provides most evidence of growth. The buried erosion surface developed upon Mississippian-age strata in the Illinois basin, which was mapped by Bristol and Howard (1971), also gives evidence of tectonic activity.

The La Salle anticlinal belt consists of about 25 anticlines, synclines, and domes extending from La Salle County in northern Illinois to Lawrence County in southeastern Illinois, a distance of more than 320 km.

Old Pennsylvanian-age rocks deposited directly upon strongly uplifted and beveled late Mississippian strata indicate substantial tectonic movement along the La Salle anticlinal belt during the hiatus preceding deposition of the Pennsylvanian System. Clegg (1965) reported progressive movement throughout Pennsylvanian time and an interval of intensive uplift of all Pennsylvanian strata, that took place in either very late Pennsylvanian or post-Pennsylvanian time.

Much of the area of the La Salle anticlinal belt must have been a peninsula or archipelago during early Pennsylvanian time because no Caseyville-age strata were deposited, and the Abbott and Spoon Formations are much thinner there than elsewhere (fig. 17). The Carbondale Formation also shows moderate thinning (fig. 18). Relatively thick marine limestone of the Modesto and Bond Formations, which pass entirely across the anticlinal belt, indicate complete submergence of the area late in Pennsylvanian time. The crests of higher anticlinal and domed structures were truncated by stream erosion and are now covered by Pleistocene glacial deposits.

The Du Quoin monocline and associated Salem and Louden anticlines extend along the western margin of the Fairfield basin for nearly 160 km. The monocline forms a hinge line seperating gently dipping strata to the west from more deeply dipping rocks at the western margin of the Fairfield Basin. The monocline has local structural relief of about 150 m at the horizon of the Herrin (No. 6) Coal, and more than 300 m in rocks of late Mississippian age.

The Du Quoin monocline did not develop until after deposition of youngest Chesterian Series strata; maximum growth appears to have occurred during early and middle Pennsylvanian time. The monocline was active during deposition of both the No. 5 and No. 6 Coals and influenced coal thicknesses. The western limit of thick No. 5 Coal generally occurs at the margin of the monocline. The eastern boundary of thick No. 6 Coal in south-central Illinois is along the axes of the Salem and Loudon anticlines, which are located on the northern extension of the Du Quoin monocline in south-central Illinois. However, in southern Illinois the monocline appears not to have influenced thickness of the No. 6 Coal, possibly because no differential movement occurred during deposition of the coal.

Some large structures, such as the Centralia and Assumption anticlines, underwent major growth and uplift before deposition of Pennsylvanian strata, and some continued to grow during the Pennsylvanian Period. Others, including the Salem and Louden anticlines and deeper structures within the Fairfield basin, appear to have completed all growth and development after deposition of Pennsylvanian strata. The Illinois basin remained open to the south until after deposition of the youngest of the Pennsylvanian strata.

The southern part of the Illinois basin was strongly uplifted sometime after deposition of youngest Pennsylvanian strata and prior to deposition of oldest Upper Cretaceous rocks. This uplift was more than 3,000 m at the crest of the Pascola arch, located about 160 km south of the southern boundary of Illinois, and diminished northward. The southern margin of Illinois was uplifted about 760 m.

The precise age and duration of this uplift is unknown, but may have continued over a long period because stratigraphic studies indicate that the Pascola arch was nearly continuously eroded to base level during uplift.

Major compressional thrusting of strata from the south or southeast and some concurrent uplift produced the Rough Creek-Shawneetown-Cottage Grove fault system and Hicks dome. This deformation occurred during the interval of uplift of the southern part of the Illinois basin and may have been associated with the uplift.

ECONOMIC PRODUCTS

Coal.—At least 75 coals have been identified in the Pennsylvanian System of Illinois. Coals underlie about 65 percent of the land area of the State. Resource estimates have been completed for about 25 coals that are considered to be of minable thickness (more than 70 cm thick), and approximately 20 of the coals have been mined commercially.

A total of nearly 147 billion metric tons of coal in the category of identified resources has been determined from mine, drill-hole, and outcrop data. These resources constitute the largest deposit of identified bituminous coal in any State in the United States.

Approximately 53 million metric tons of coal were produced by Illinois mines in 1976, and total production from 1833 to the end of 1976 was about 4.2 billion metric tons. As of 1977, 60 mines were in operation in Illinois, the largest number of which are in the southern part of the State.

Illinois coal extends through the complete range of the high volatile bituminous coals. The central and northern part of the State is underlain by high volatile C bituminous coal. Rank increases progressively southeastward; a small area in southeastern Illinois contains high volatile A bituminous coal. Illinois coal generally has a high sulfur content (3 to 5 percent), although several areas have been identified where coal has a sulfur content of 0.5 to 1.5 percent.

Oil.—The first major oil fields in Illinois, discovered at shallow depths in Pennsylvanian rocks along the La Salle anticline, were developed between 1903 and 1913 and resulted in annual production of 33.1 million barrels (4,500,000 metric tons) in 1910. Since these early discoveries, approximately 600 oil fields have been discovered in Illinois, and 85, or about 14 percent, produce oil from Pennsylvanian rocks. Oil has been obtained from 14 productive zones in the Modesto, Carbondale, Spoon, Abbott, and Caseyville Formations.

Original oil-in-place in Pennsylvanian rocks is estimated to be about 1.6 billion barrels (218,000,000 metric tons). Total oil production through 1975 was about 390 million barrels (53 million metric tons). Ultimate recovery of oil from Pennsylvanian rocks is estimated to total 431 million barrels (59 million metric tons).

Gas.—Of 82 relatively small gas fields that have been discovered in Illinois, 38 have produced gas from Pennsylvanian rocks. Two hundred forty-one million cubic meters of gas, or about 34 percent of estimated total commercial gas production for Illinois, has been produced from rocks of the Pennsylvanian System.

Limestone.—More than 20 limestone beds of the Pennsylvanian System, some of which are more than 8 m thick, underlie much of the State. Thirty-four active quarries produced about 8.2 million metric tons of limestone from Pennsylvanian rocks in 1975. Although production of limestone from Pennsylvanian rocks is relatively small, many quarries are of considerable economic importance locally, because they are in areas where no other sources of limestone are readily available.

Clay.—Clay from Pennsylvanian rocks of Illinois has been used for brick manufacture since about 1818 and for tile, building block, sewer pipe, terra cotta, flue liners, stoneware, refractories, bonding clays for foundry sands, and lightweight aggregate.

In 1975, slightly more than 907,000 metric tons of clay were produced from the Pennsylvanian System for brick and tile manufacture and for use as lightweight aggregate. Buff-burning deposits, which are restricted to the Spoon and Abbott Formations, yield clay at the northern and western margins of the Illinois basin. In the central part, extensive deposits of red-burning clay and shale are essentially unlimited sources of common clay.

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