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# REGIONAL GEOLOGICAL ASSESSMENT OF THE DEVONIAN-MISSISSIPPIAN SHALE SEQUENCE OF THE APPALACHIAN, ILLINOIS, AND MICHIGAN BASINS RELATIVE TO POTENTIAL STORAGE/DISPOSAL OF RADIOACTIVE WASTES

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## ABSTRACT

The thick and regionally extensive sequence of shales and associated clastic sedimentary rocks of Late Devonian and Early Mississippian age has been considered among the "nonsalt geologies" for deep subsurface containment of high-level radioactive wastes. This report examines some of the regional and basin-specific characteristics of the black and associated nonblack shales of this sequence within the Appalachian, Illinois, and Michigan basins of the north-central and eastern United States.

Principal areas where the thickness and depth of this shale sequence are sufficient to warrant futher evaluation are identified, but no attempt is made to identify specific storage/disposal sites. Also identified are other areas with less promise for further study because of known potential conflicts such as geologic-hydrologic factors, competing subsurface priorities involving mineral resources and groundwater, or other parameters.

Data have been compiled for each basin in an effort to indicate thickness, distribution, and depth relationships for the entire shale sequence as well as individual shale units in the sequence. Included as parts of this geologic assessment are isopach, depth information, structure contour, tectonic elements, and energy-resource maps covering the three basins.

Summary evaluations are given for each basin as well as an overall general evaluation of the waste storage/disposal potential of the Devonian-Mississippian shale sequence, including recommendations for future studies to more fully characterize the shale sequence for that purpose. Based on data compiled in this cursory investigation, certain rock units have reasonable promise for radioactive waste storage/disposal and do warrant additional study.

# 1. INTRODUCTION

## 1.1 Purpose and Scope

Geologic containment of high-level radioactive wastes in deep subsurface rocks has repeatedly been judged to be the most viable disposal alternative in the United States (National Academy of Sciences 1957, 1970; U.S. Energy Research and Development Administration 1976; Interagency Review Group 1979). Although salt remains as the most favored potential host rock, increased interest in so-called "nonsalt geologies" has developed within this country as the result of various developments in foreign nations as well as revised federal government policy (Interagency Review Group 1979). Two other rock types that exhibit definite disposal potential are granites and argillaceous strata (shales, mudstones, clays, and argillites).

Within the Appalachian, Illinois, and Michigan basins of north-central and eastern United States (Fig. 1), a thick and regionally extensive sequence of shales and associated clastic sedimentary rocks (mainly siltstones and some sandstones) of Upper Devonian and Lower Mississippian age are present. This report examines some of the regional and basin-specific characteristics of the black and associated nonblack shales within this sequence in an effort to determine the preliminary suitability of these argillaceous strata for possible radioactive waste disposal.

Because the degree of integrity required by any disposal site is great, an extensive program of geologic and hydrologic studies must be conducted to both assess and eventually qualify any sites. These studies must examine geologic structure, seismicity, stratigraphy, rock properties, mineral-resource development, ground- and surface-water relationships, and competing subsurface uses. In any such investigation, an essential need is an understanding of the regional geologic setting of any potential host rock prior to the initiation of more detailed studies in smaller areas. This report therefore describes the Upper Devonian-Lower Mississippian shale sequence from this regional perspective.

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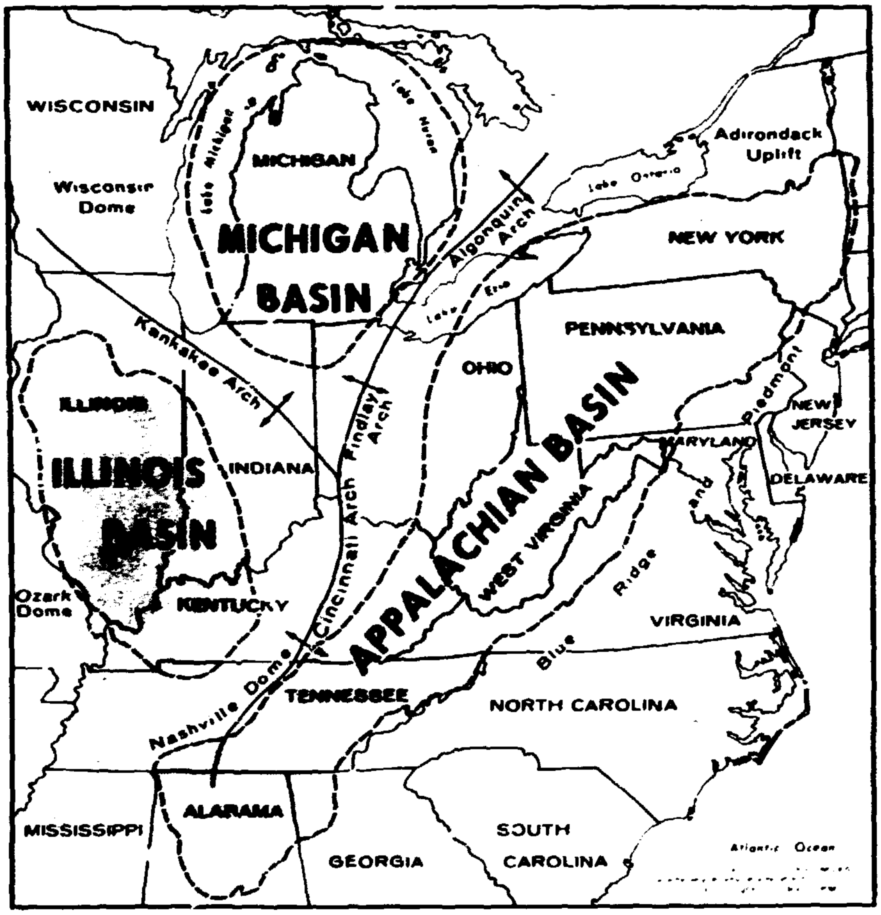


Fig. 1. Location of the Appalachian, Illinois, and Michigan basins relative to some principal tectonic-structural elements.

The scope of this report has been to identify the principal areas where the Upper Devonian-Lower Mississippian shale sequence is of sufficient thickness and at acceptable depths to warrant further evaluation in subsequent studies for its potential to contain nuclear wastes. Because the treatment has emphasized a regional approach, there has been no effort or intent to identify specific disposal sites. Possible, however, is the ultimate selection of one or more study areas from those portions in each geologic basin where the regional characteristics appear more promising. In some cases, other regions that appear to have conflicts can similarly be identified, and as a result, their promise with regard to future study areas definitely lessened. These conflicts may either be related to geologic-hydrologic factors, competing subsurface priorities involving mineral resources and groundwater, or other parameters.

## 1.2 Approach Used in This Study

This report describes the geologic characteristics of the Upper Devonian-Lower Mississippian shale sequence from a regional perspective and discusses individual aspects by means of a basin-by-basin treatment. The report is based on the following information sources: (1) the general geologic literature on the Appalachian, Illinois, and Michigan basins and adjoining areas, and (2) specific investigations on the shales as conducted by the U.S. Geological Survey, several state geological surveys (New York, Pennsylvania, Ohio, West Virginia, Kentucky, Tennessee, Indiana, Illinois, and Michigan), and the Eastern Gas Shales Project (hereafter designated as EGSP) of the U.S. Department of Energy. Data available from the latter source have been presented in professional journals, reports issued by various cooperating state geological surveys, and documents published by the Morgantown, West Virginia, Energy Technology Center of the U.S. Department of Energy. Particularly useful in the last category are the proceedings volumes from symposia held in 1977, 1978, and 1979, and devoted solely to research and applied investigations conducted on the eastern gas shales.

The data from the EGSP and other sources have been integrated so that the discussion on the shale sequence is organized according to basin (Appalachian, Illinois, and Michigan). A brief introduction to the regional tectonics-seismicity and the regional stratigraphy of the shale sequence of the three-basin region sets the stage for the more detailed basin-by-basin discussion. The basins are discussed according to their alphabetical sequence; thus, the order followed is Appalachian, Illinois, and Michigan.

In each basin, an effort has been made to indicate the thickness, distribution, and depth relationships of the entire shale sequence, as well as of individual shale formations within the sequence. Complementing the isopach and depth information previously published on individual shale units (e.g., Cohee and others 1951; Schwietering 1979) and used in the discussion of specific basins, we also present structure-contour mapping, which uses the top or base of the shale sequence as the mapped datum, and isopach and depth mapping for the entire three-basin region (Plates 3 and 4). Although generalized and certainly subject to more detailed refinement by means of localized mapping, these data provide a good first-level estimation about the physical dimensions of the shale sequence. These regional maps, together with an index map, tectonic-elements map, and energy-resource map, all covering the three basins, are included as large plates within the pocket at the end of this report.

In addition to the summary-evaluation which concludes the sections on each basin, there is a general evaluation on the waste-disposal potential of these shales and a set of recommendations regarding proposed studies which can more fully characterize the shale sequence to that end. These recommendations treat both specific studies which would rely on analysis of the voluminous EGSP data (both currently available and that to be acquired) and preliminary assessment of some more promising areas within each basin.

## 1.3 Eastern Gas Shales Project Studies

The Eastern Gas Shales Project (EGSP) was formally initiated in 1976 and has been coordinated since its inception by the Morgantown, West Virginia, Energy Technology Center. Because black and brown shales of Devonian and Mississippian age may represent a significant natural-gas resource (unconventional when compared with typical petroleum reservoirs) and their distribution within the Appalachian, Illinois, and Michigan basins lies close to major natural-gas markets (Fig. 2), the U.S. Department of Energy (formerly the Energy Research and Development Administration) began an 8-year program to evaluate these shales with an eye toward increasing production of natural gas from them.

These shales, or rather the kerogen-rich black and dark brown units within the entire stratigraphic sequence, and especially those of Devonian age, already produce natural gas from some 9600 wells in the Appalachian Basin alone (U.S. Department of Energy 1979). Productive fields are

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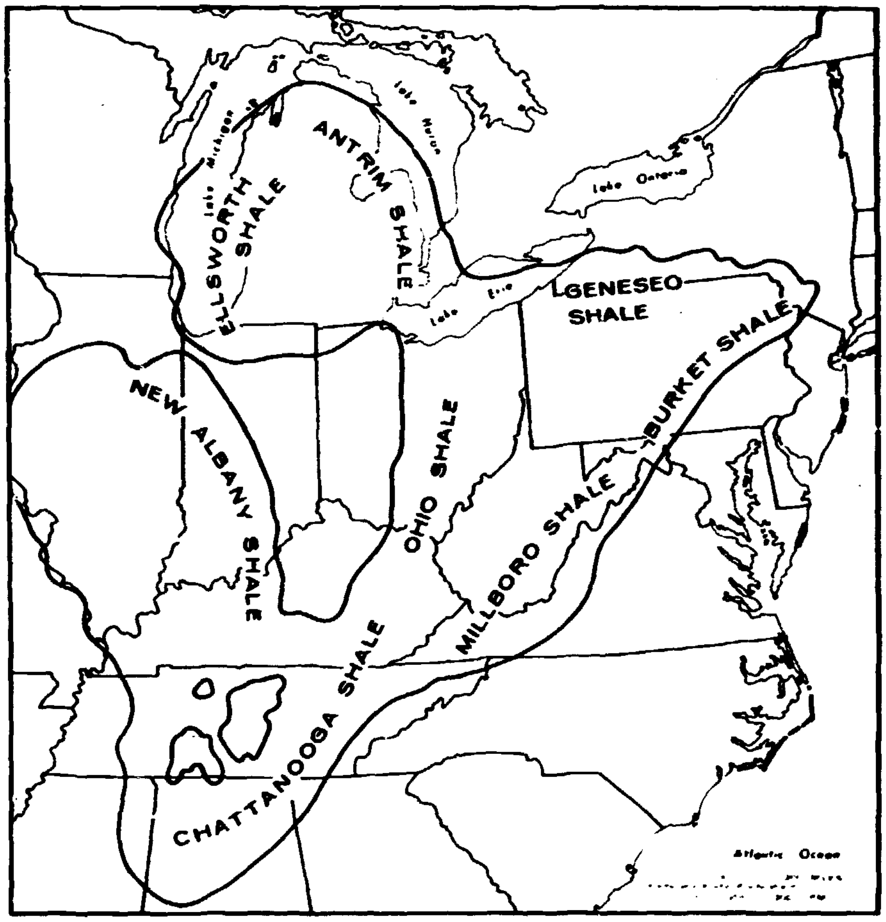


Fig. 2. Areal extent of the Middle-Upper Devonian to Lower Mississippian shale sequence; note regional use of principal Devonian formational names.

located mainly in Ohio, eastern Kentucky, and southwest West Virginia, and their cumulative production has exceeded 56 billion cubic meters of gas from the natural fracture systems in these shales. Major program elements of the EGSP are to more fully characterize these shales geologically, assess the magnitude of the resource in terms of in-place and recoverable natural gas, develop and test improved extraction technology (especially stimulation techniques), and provide a transfer of information to private industry so that future commercial production of gas might become possible (Science Applications, Inc. 1980).

To these ends, the EGSP has developed several cooperative research and applied technology agreements with other federal government laboratories, research organizations, universities, state geological surveys, the U.S. Geological Survey, and private petroleum-industry firms. From the four years of effort expended to date, considerable new geologic, geochemical, gas-volume, rock-property, and well-logging data have become available. Wise (1979) has summarized the status of these studies, which also include various applied schemes for improved well stimulation and completion techniques.

A major source of data from the EGSP has been the analyses conducted on cores recovered from coreholes drilled within the Appalachian and Illinois basins (Fig. 3). Additional information has been obtained from the Michigan Basin where the Dow Chemical Company has recovered three cores in the eastern part of the basin (Sanilac County). Several future

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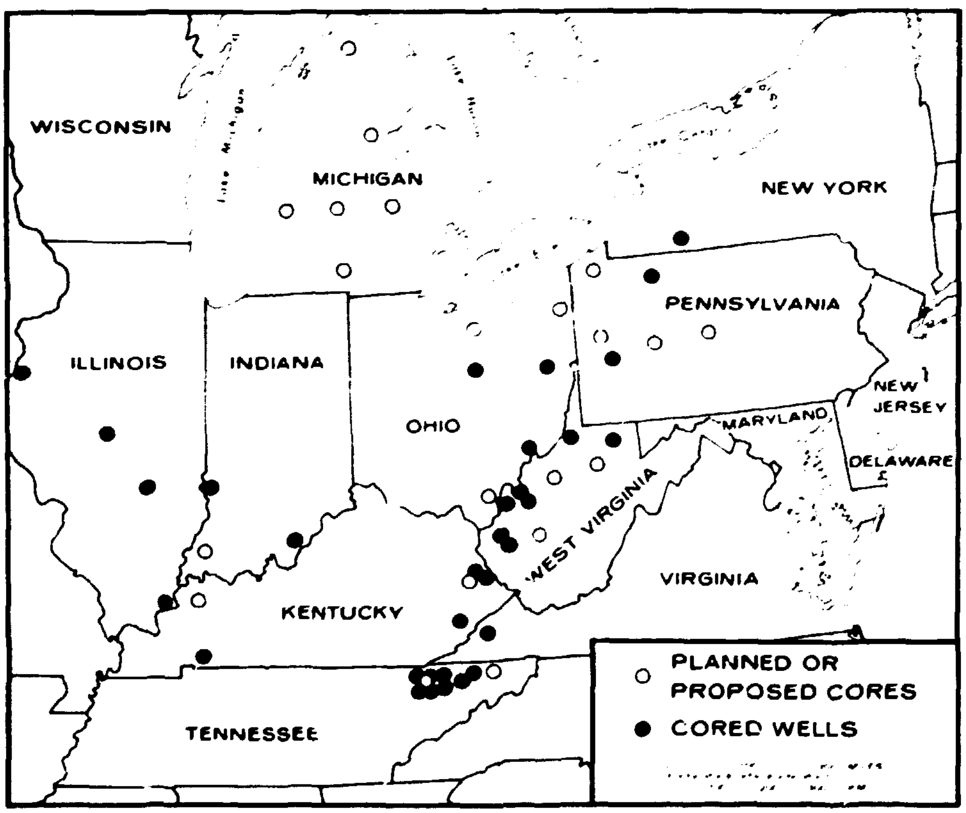


Fig. 3. Locations of completed and proposed coreholes of the Eastern Gas Shales Project within the Appalachian, Illinois, and Michigan basins. Adapted from Wise 1979.

EGSP coreholes are also planned for the Michigan Basin. Cores recovered in the program have been analyzed for a range of geologic, geochemical, and physical-property data (Tables 1, 2, and 3).

Although the impressive volume of data collected from the EGSP has evolved in response to energy-resource considerations, additional value can be extracted from these data because of their applicability to the scope of this report. The abundant core and borehole logging information available will furthermore be very useful in future, more detailed studies, including those related to smaller study areas.

## 1.4 General Characteristics of the Shale-Bearing Region

### 1.4.1 Regional tectonics and seismicity

As already noted, the Upper Devonian-Lower Mississippian shale sequence occupies a portion of the stratigraphic succession within three major geologic basins (i.e., the Appalachian, Illinois, and Michigan basins) in the eastern United States (Figs. 1 and 2). In fact, the shale sequence extends laterally beyond the actual boundaries of these basins (Fig. 2); however, in such transitional areas, the shales are generally too thin, too discontinuous, or largely exposed in outcrops. Inasmuch as a principal requirement is for the shale sequence to be sufficiently thick and deep, interest is focused on the basins.

The Appalachian, Illinois, and Michigan basins are structural and depositional basins, all of which developed by early Paleozoic time. Each contains a thick sequence of primarily Paleozoic strata. Non-Paleozoic rocks are limited to thin Jurassic strata in the central Michigan Basin and thick Precambrian-age sedimentary units in the southeastern Appalachian Basin.

Large expanses in each basin are devoid of any significant structural deformation such as major faults or large-scale folds. Natural fracture and joint systems and smaller scale faults are more common, although there are large areas that lack appreciable development of even these structural elements. The eastern margin of the Appalachian Basin and the southern third of the Illinois Basin are the most structurally

Table 1. Categories of data available from Eastern Gas Shales Project wells in the Appalachian Basin

| | Site selection criteria | Lithologic description | Fracture density | Index properties | Directional properties | Outgassing | Elemental analysis | Mineralogy | Organic analysis | Thermal maturity | Completion operations | Stimulation operations | Fracture design | Prefracture buildup and flow tests | Postfracture buildup and flow tests | Production | Logs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Johnson County, Ky. | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ |
| Martin County, Ky. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ |
| Perry County, Ky. | | | | | | | | | | | ✓ | | | | | | |
| Allegany County, N.Y. | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ |
| Knox County, Ohio | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ |
| Washington County, Ohio | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ |
| Allegheny County, Pa. | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ |
| McKean County, Pa. | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | |
| Wise County, Va. | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ | | | ✓ | | | ✓ | ✓ |
| Lincoln County, W. Va.[a] | ✓ | ✓ | | ✓ | | ✓ | ✓ | | | | ✓ | | ✓ | | | | ✓ |
| Lincoln County, W. Va.[b] | ✓ | ✓ | | ✓ | | | ✓ | ✓ | | | ✓ | ✓ | | ✓ | ✓ | | ✓ |
| Mason County, W. Va. | ✓ | ✓ | | ✓ | | | | ✓ | ✓ | ✓ | | | | | | | ✓ |
| Monongalia County, W. Va. | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ |
| Wetzel County, W. Va. | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ |

[a] I.D. number 20402.
[b] I.D. number 204[illegible]3.

Table 2. Eastern Gas Shales Project data available from supplemental wells in the Appalachian Basin

| Location of well | I.D. number | Site selection criteria | Lithology | Elemental analysis | Mineralogy | Organic analysis | Completion operations | Stimulation operations | Fracture design | Production | Logs |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Martin County, Ky. | 20337 | ✓ | ✓ | | | | | | | | |
| Perry County, Ky. | 685-1 | ✓ | | | | | | | | ✓ | |
| Perry County, Ky. | KY-WV 1627 | | ✓ | | | | | ✓ | | ✓ | |
| Perry County, Ky. | KY-WV 7264 | | | | | | | ✓ | | ✓ | ✓ |
| Pike County, Ky. | 685-2 | ✓ | | | | | | | | | |
| Pike County, Ky. | 685-3 | ✓ | | | | | | | | | |
| Chautauqua County, N.Y. | 20489 | ✓ | | | | | | | | | |
| Carroll County, Ohio | 11354 | | ✓ | | | | | | | | |
| Coshocton County, Ohio | 11354 | | | | | | | | ✓ | | |
| Mahoning County, Ohio | 20237 | | ✓ | | | | | | | | |
| Trumbull County, Ohio | 11236 | | | | | | | | ✓ | ✓ | |
| Trumbull County, Ohio | 20245 | | | | | | | | ✓ | | |
| Buchanan County, Va. | 20342 | ✓ | ✓ | | | | | | | | |
| Buchanan County, Va. | 20546 | | | | | | | ✓ | | | |
| Dickerson County, W. Va. | 20211 | | ✓ | | | | | | ✓ | ✓ | |
| Jackson County, W. Va. | 1369 | | ✓ | | | | | | | | ✓ |
| Jackson County, W. Va. | 1371 | | ✓ | | | | | | | | ✓ |
| Lincoln County, W. Va. | 686-1 | ✓ | | | | | ✓ | ✓ | | | |
| Lincoln County, W. Va. | 686-2 | ✓ | | | | | | | | | |
| Lincoln County, W. Va. | 686-3 | ✓ | | | | | | | | | |
| Lincoln County, W. Va. | 20401 | ✓ | ✓ | | | | ✓ | ✓ | | | |
| Lincoln County, W. Va. | 20538 | | | | | | | ✓ | | | |
| Raleigh County, W. Va. | 83 | | | ✓ | ✓ | ✓ | | | | | |

Table 3. Categories of data available from Eastern Gas Shales Project wells in the Illinois Basin

| Location of well | Site selection criteria | Lithologic description | Fracture density | Index properties | Directional properties | Outgassing | Elemental analysis | Mineralogy | Organic analysis | Thermal maturity | Cost | Production |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Effingham County, Ill. | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | |
| Hardin County, Ill. | | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ | | |
| Henderson County, Ill. | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | |
| Tazewell County, Ill. | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | |
| Clark County, Ind. | | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ | | |
| Sullivan County, Ind. | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | |
| Christian County, Ky. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

deformed. Numerous folds, thrust faults, and joint sets occur in the former area, whereas appreciable faulting and attendant rock fracturing are developed in the latter area.

The bordering, structurally high features such as the Cincinnati Arch system, the Wisconsin Arch-Dome system, and the Kankakee Arch (Fig. 1 and Plate 2) represent mildly uplifted tectonic elements. Only the Shawneetown-Rough Creek zone of faulting, which extends along the southern margin of the Illinois Basin and merges with the structurally complex New Madrid seismic zone further to the west, and the fold and thrust-fault belts along the eastern margin of the Appalachian Basin can be considered strongly deformed tectonic trends.

Another regional tectonic feature of more recently recognized significance is the Rome Trough (Plate 2). In eastern Kentucky, the Kentucky River fault zone has been recognized for some time on the basis of its surface expression within Ordovician rocks there. As the result of recent geophysical investigations and some exploratory drilling, this fault zone is currently believed to be only a relatively small portion of a much more extensive fault system called the Rome Trough (Harris 1978; Ammerman and Keller 1979). This feature extends at least as far northeast as Pennsylvania; however, the faults associated with it appear to be historically inactive. Harris (1978) has interpreted this feature to be primarily a graben structure that initially formed within the Precambrian basement rocks prior to the deposition of Cambrian sediments in that area of the Appalachian Basin. Recurrent movement along both the zones of weakness in the basement and the faults developed within the overlying sedimentary strata exerted a profound influence upon the deposition of sedimentary material within that part of the basin until at least Pennsylvanian time.

The importance of geologic structures, or the lack of them, to the integrity of confinement for nuclear wastes is clear, and thus any region, small study area, or specific sequence of rock units must be examined carefully by various means of investigation to ensure that any significant structural deformation is absent. Because geologic structures can also play a role in the thermal maturation of sedimentary organic matter into hydrocarbons (in addition to the primary roles exerted by depth of burial and geothermal gradient), attention must be especially paid to such structures when examining this Upper Devonian-Lower Mississippian shale sequence whose potential as a natural-gas resource may be significantly influenced by structures.

Exclusive of the tectonically deformed areas noted to this point, the three basins can be characterized on a regional basis as tectonically stable. Although they each experienced uplift, erosion, glaciation, and postglacial rebound, only the easternmost Appalachian Basin has been subjected to major tectonic deformation on a regional scale; each basin furthermore contains extensive areas, underlain by the shale sequence, where the geologic structures are too small to be detected by regional-level investigation.

Figure 4 shows the nationwide distribution through 1973 of earthquakes whose intensities on the Modified Mercalli Scale equaled or exceeded a value of V. General observation of this information shows that most of the Michigan Basin, most of the northern half of the Illinois Basin, and large portions throughout the Appalachian Basin lack any historically occurring seismic events. Those events that have occurred within or near the basins furthermore are either small in their intensity (most in the V-VII range), isolated single occurrences, or both. The only marked exception to this trend is the large concentration of events, several of which displayed high intensities, within the area where the states of Illinois, Missouri, Kentucky, Arkansas, and Tennessee merge. This area is known as the New Madrid seismic zone and was the site of several highly destructive earthquakes in 1811 and 1812. The central area of this belt has consequently been assigned on the basis of these historical events to seismic risk zone 3, or where major destructive damage can be expected. There clearly has been repetitive seismicity here, even though events since the early 1800s have never been as large in magnitude.

Another method by which to gage seismic risk or hazard has been devised by Algermissen and Perkins (1976). Their approach entails the contouring of statistically expected ground shaking. Maximum expected horizontal accelerations in bedrock, expressed as percentages of the

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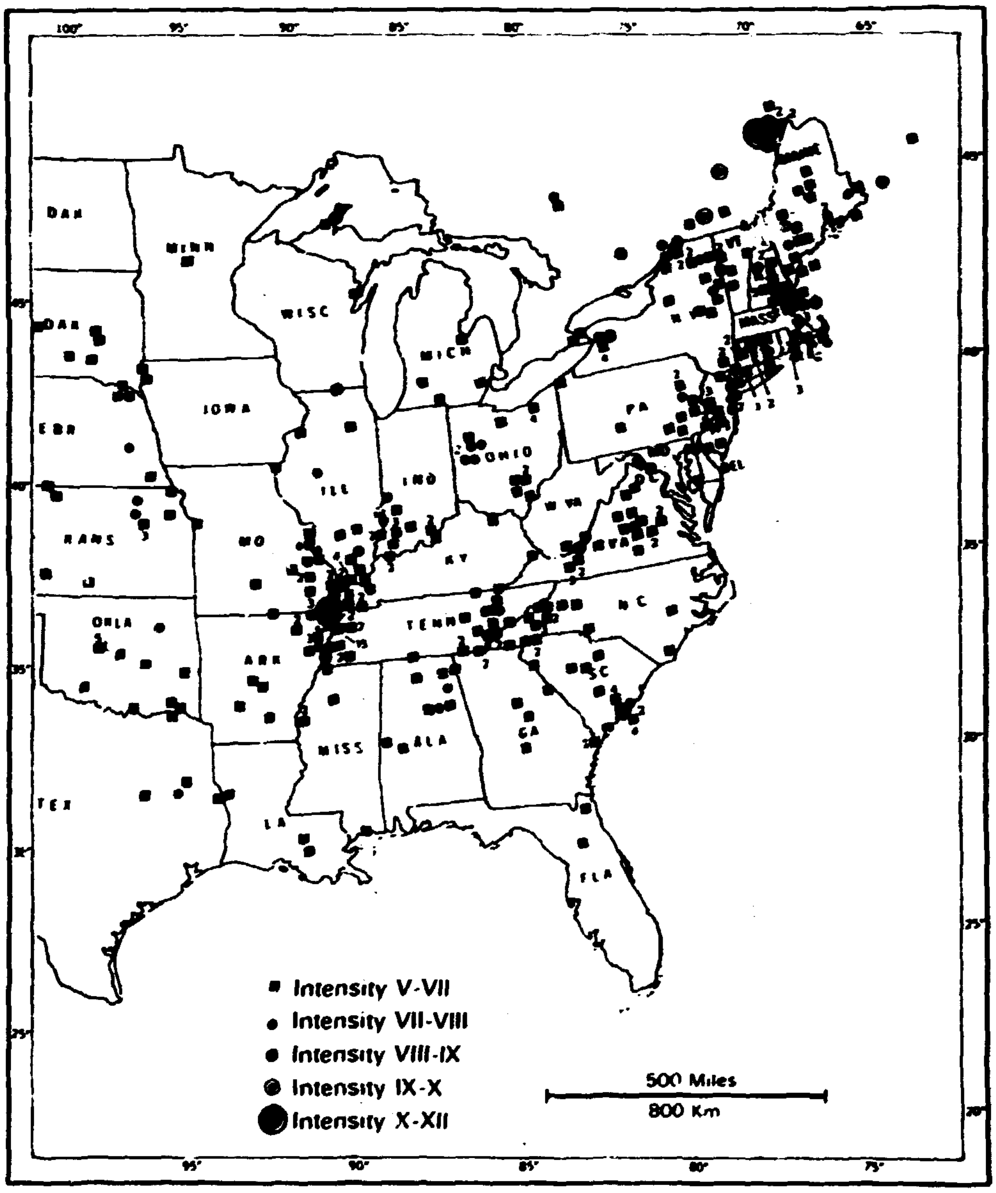


Fig. 4. Distribution of earthquakes in the eastern United States of intensity V or greater on the Modified Mercalli Scale. Adapted from Coffman and von Hake 1973.

earth's gravitational acceleration, have been contoured at a 90% probability that the accelerations will not be exceeded over a 50-year period (Fig. 5). A large area within the New Madrid zone could be expected to exhibit ground shaking equal to 10% of the normal gravity value, and some portions could experience shaking up to 19%. That 10% line includes the southern part of the Illinois Basin.

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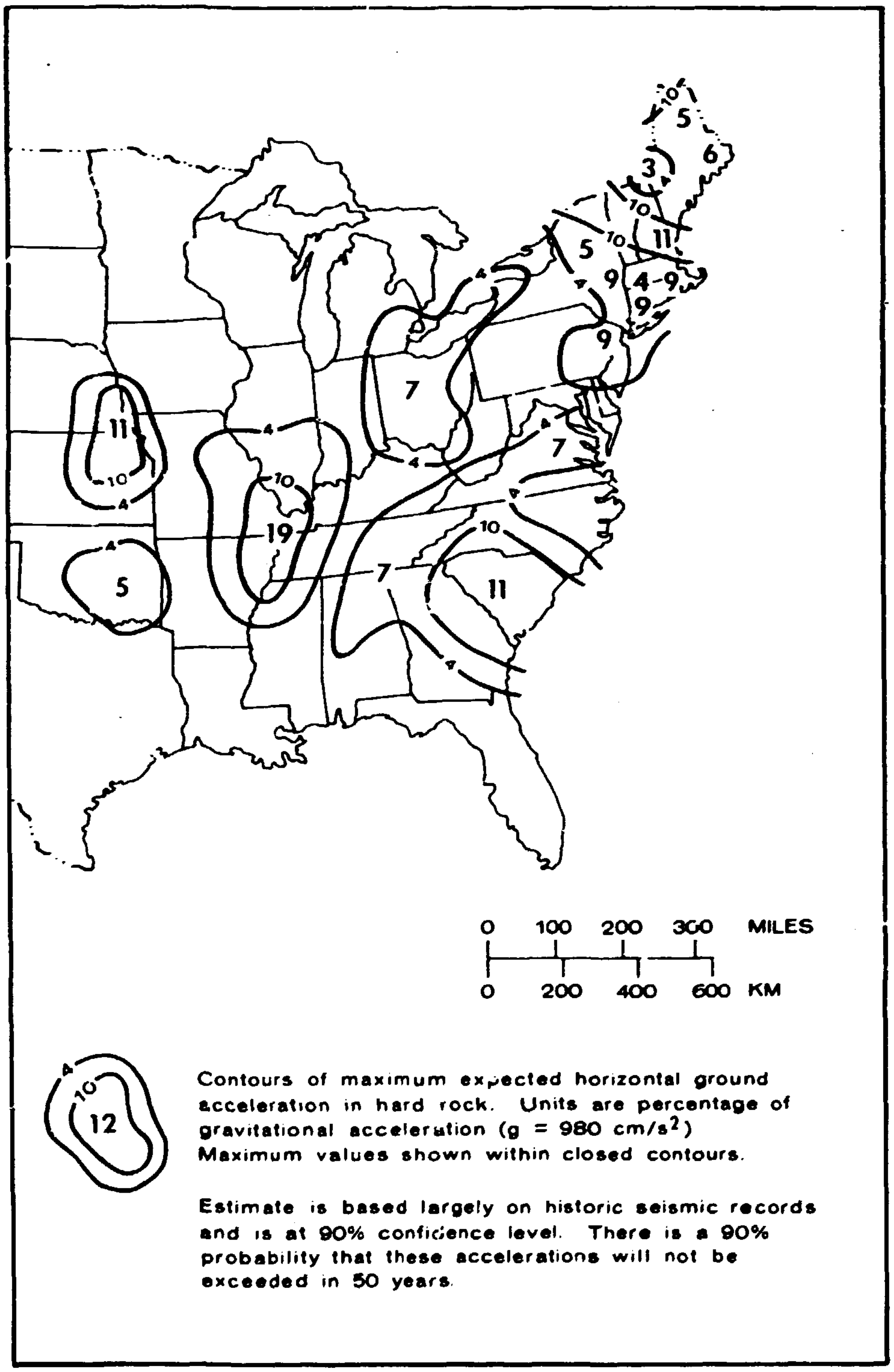


Fig. 5. Anticipated seismic hazard within the eastern United States as expressed by horizontal ground shaking. Adapted from Algermissen and Perkins 1976.

Based on the values given in Fig. 5, most of the Michigan Basin lies within a region having values less than 4%; much of the Appalachian Basin has similar low values except for portions of Ohio, Kentucky, West Virginia, and New York where up to 7% shaking might be expected; and the remainder of the Illinois Basin is within the 4 to 10% range. Although the New Madrid zone represents a seismically active and potentially dangerous area, there is still a large portion of the Illinois Basin where ground-shaking effects from a seismic event in that zone would be expected to be minimal.

Thus for the most part, large tracts within all three basins exhibit a low level of past seismic activity and reveal relatively low expectations of seismic hazard due to ground shaking from anticipated future events.

### 1.4.2 Regional shale stratigraphy

A thorough and fully accepted understanding of the Middle-Upper Devonian and Lower Mississippian stratigraphy found throughout the three-basin region has been hindered even to the present because of (1) complex facies changes resulting from sediment deposition in laterally changing deltaic, delta-front, nearshore-marine, and open-marine environments, and (2) a long history of differing stratigraphic terminology and numerous revisions to the nomenclature by both individual investigators and organizations such as state geological surveys. Adding to the problem has been the development of stratigraphic terminology which is largely based on outcrop information, but which becomes confusing and/or unusable when applied to subsurface conditions. Another contributing problem is the wide variation in the regional thickness of individual rock units within the sequence.

As a result, and as shown in Fig. 2, the stratigraphic nomenclature applied to even correlative black-shale units varies from one area to another, and in some cases from one state to an adjacent state. The complexity of the entire stratigraphic terminology can be readily observed in a correlation chart that covers the sequences found in all three basins (Fig. 6).

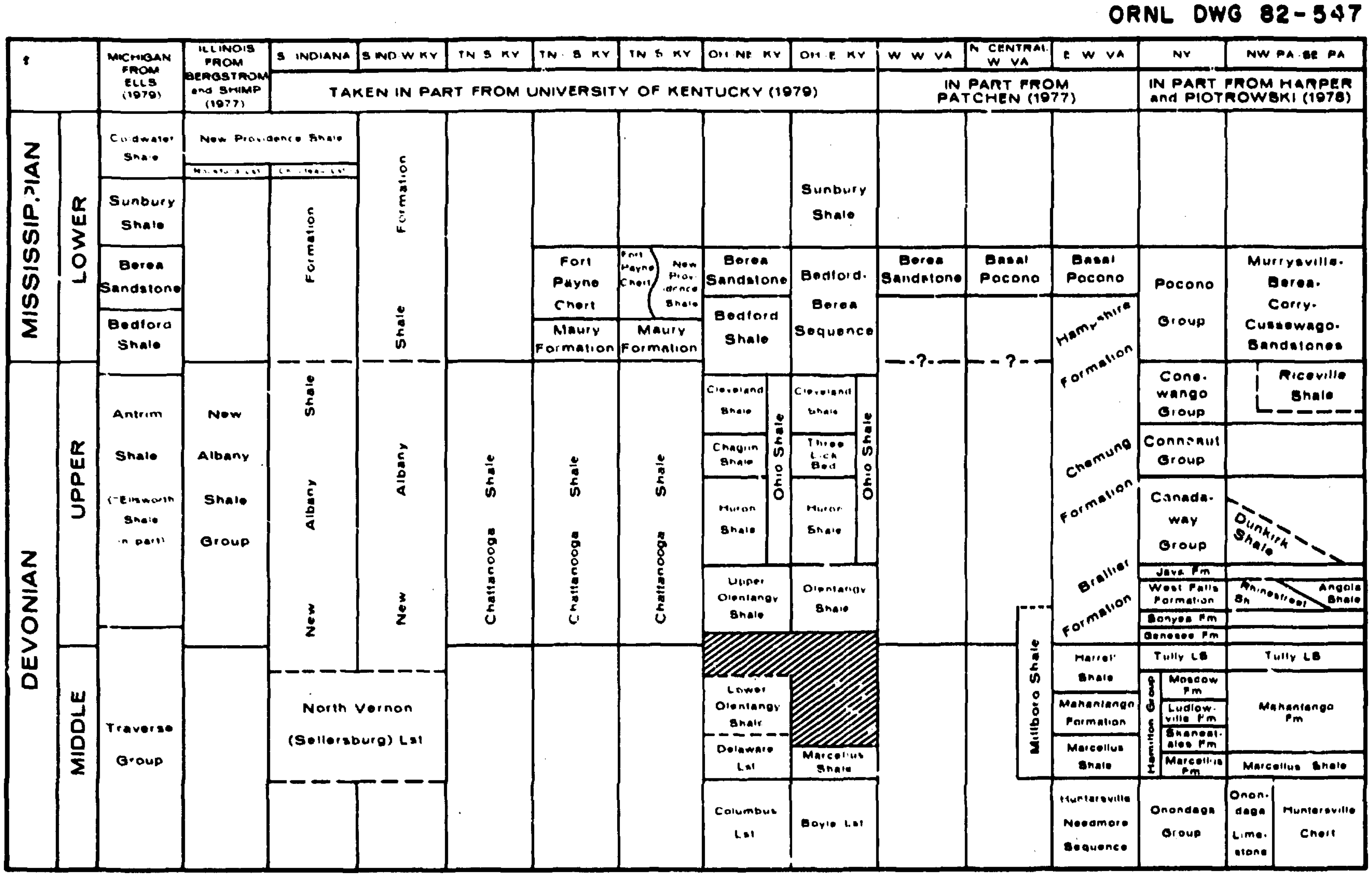


Fig. 6. Generalized correlation chart of Middle-Upper Devonian to Lower Mississippian stratigraphic sequences between the Appalachian, Illinois, and Michigan basins.

The stratigraphic sequence within the Appalachian Basin is possibly the most difficult to comprehend because the lateral thickness variations are more pronounced, there is a greater total sequence of strata which contains more discrete shale (and black shale) intervals, and deltaic and coarse clastic units exert more of an influence. By contrast, even though the nomenclature is different among the basins involved, the Antrim-Sunbury sequence of the Michigan Basin is essentially equivalent to the New Albany Shale Group (or Formation, depending on reference source) found in the Illinois Basin.

The black and dark brown shales that are of interest to the EGSP clearly began forming in the Appalachian Basin at an earlier geologic time than those found in the more westerly basins. For example, the Needmore, Marcellus, and Millboro shales, which all contain black shales rich in organic matter, were formed during Middle Devonian time, whereas the Antrim and New Albany shales (Blocher, Sweetland Creek, and Grassy Creek units) were not formed until Late Devonian time in the Michigan and Illinois basins respectively.

Even though problems in stratigraphic terminology and correlation persist within and between basins, the information shown in Fig. 6 represents a significant improvement as compared to that known in the early 1960s. Increased surface mapping and subsurface studies such as those by Tillman (1970), Lewis and Schwietering (1971), Rickard (1975), Bassett and Hasenmueller (1977), Bergstrom and Shimp (1977, 1979), Patchen (1977), Wallace and others (1977, 1978), Harper and Piotrowski (1978), Hasson and Dennison (1978), Kepferle and others (1978), Provo and others (1978), Reinbold (1978), Roen and others (1978a, 1978b), West (1978), Ells (1979), and Schwietering (1979) have substantially expanded the level of understanding about the stratigraphic relationships of the Middle/Upper Devonian-Lower Mississippian shale sequence discussed in this report.

# 2. APPALACHIAN BASIN

## 2.1 General Setting

The Appalachian Basin is an elongate, northwest-southeast-trending structural and sedimentary basin in the eastern United States, and is bordered at its northern end by the Canadian provinces of Quebec and Ontario, while extending as far south as the states of Alabama and Mississippi. The axial trace of the Cincinnati Arch system (i.e., Findlay and Algonquin arches, and Jessamine and Nashville domes) defines the basin's western boundary, whereas the eastern margin roughly follows the western extent of the Blue Ridge and Piedmont physiographic provinces (see Fig. 1). In the latter case, this boundary is basically formed by regional thrust faults which have displaced Precambrian or Lower Paleozoic rocks westward upon Middle and Upper Paleozoic strata (Plate 2).

The basin embraces all of West Virginia, most of New York, Pennsylvania, and Ohio, as well as large portions of Kentucky, Tennessee, Virginia, and Alabama. Several hundred kilometers wide at its center, the basin is almost 1600 km long and embraces a land area of nearly 540,000 $km^2$.

The outline of the basin as described above does not entirely conform to established physiographic divisions. Geomorphic processes that created landforms characteristic of physiographic provinces were of course governed by geologic structural elements, as well as climate and the sedimentary rock types present. Hence, several provinces are recognizable within the basin, and include the Valley and Ridge, Appalachian and Interior Low plateaus, and Central Lowlands (Fenneman 1946; Harris 1978).

Lying along the eastern edge of the basin, the Valley and Ridge consists of alternating, northeast-southwest-trending ridges and valleys which were produced by differential erosion of folded and faulted rocks. Because of the faulted, fractured nature of the strata here, this deformed belt is of decidedly less interest for the purpose of this report.

The Appalachian Plateaus occupy most of the basin and reveal a rolling to maturely dissected upland lying between elevations of 300 and 915 m. Paleozoic strata which have been only slightly deformed and gently dip east and southeastward underlie much of this province. Portions of the province have been glaciated, a process that has had a strong influence on the groundwater hydrology of many areas.

The Interior Low Plateaus lie mainly along the axis of the Cincinnati Arch system and south of the glacial boundary. A gently rolling topography with elevations averaging less than 150 m is characteristic. To the north are the Central Lowlands, which describe a glaciated plain that generally slopes from an average elevation of 300 m along its eastern edge where it joins the Appalachian Plateaus to about 150 m near the Mississippi River. Bedrock in both of these provinces is only mildly warped, except for some localized zones of faulting.

## 2.2 Geologic and Tectonic Framework

The Appalachian Mountains belt is the dominant regional tectonic feature in the eastern United States; it is traceable from north-central Alabama through the New England states into the Canadian Maritime Provinces. Along the most eastward part is a large volume of metamorphic and igneous rocks as found in the Blue Ridge, Piedmont, and New England provinces. Present in the western part, namely the Appalachian Basin, is a great thickness of sedimentary rocks which range in age from the Precambrian to the Permian. Comprehensive treatments of the Appalachian Basin have been given by Woodward (1958), Colton (1961, 1970), and Roth (1968).

Aside from the tectonic and/or plate-tectonic events that gave rise to the general configuration of the Appalachian Basin, both the underlying basement complex and the sedimentary sequence within the basin have been subjected to several episodes of compressive stress directed from the east and southeast. The complexity of deformation is most pronounced along the eastern margin of the basin and lessens in a westward direction (Plates 2 and 3). Although this decreasing level of structural complexity is progressive, the basin nevertheless can be divided into an intensely deformed eastern part and a mildly deformed western part. The expression "Appalachian Structural Front," as originally invoked by Price (1931), pertains to the line of demarcation between these two areas of contrasting deformation. That line closely agrees with such topographic-geomorphic features as the Allegheny Front and the Catskill and Cumberland escarpments.

The basin contains a prism-shaped mass of Paleozoic-age sandstones, shales, carbonates, and evaporites which thickens to the east and southeast and attains an aggregate thickness ranging from 2000 to more than 12,000 m. Sedimentation within the basin, however, extended from Late Precambrian until the end of the Paleozoic, at which time a major tectonic event generally described as the Appalachian Orogeny terminated deposition. Much of the present tectonic style and most individual geologic structures were formed then. Although Triassic-age continental sedimentation persisted within graben structures in the Piedmont to the east, these deposits are not considered further here.

Upper Precambrian and Lower Cambrian sequences are dominated by marine clastics, whose provenance together with that of some younger Lower Paleozoic units is thought to have been the continental interior to the west. Precambrian clastic strata are estimated to attain more than 10,000 m of thickness in eastern Tennessee, while the Lower Cambrian sequence, which is more fully developed within the southern half of the basin, locally exceeds 3000 m in thickness. These older clastics are succeeded by a carbonate-dominated sequence of Upper Cambrian to Middle Ordovician strata which includes such well-known stratigraphic divisions as the Knox, Beekmantown, and Black River groups. In north-central to northwest New York, a minimum thickness of less than 200 m is attained; maximum development reaches more than 2500 m in both east-central Pennsylvania and eastern Tennessee. Dolostone is the principal rock type throughout much of this marine sequence, which in turn is overlain by Upper Ordovician and Lower Silurian clastic units that resulted from renewed tectonic activity along the eastern margin of the depositional basin. Maximum thickness approximates 2000 m in eastern

Pennsylvania. Some of these sandstone-siltstone-shale units represent deltaic deposits whose rate of accumulation exceeded basin subsidence; thus, intervals of oxidized sediment formed under subaerial conditions are preserved.

Middle Silurian to Middle Devonian strata are represented principally by marine limestones and secondarily by evaporites (mainly salt). Well-known stratigraphic units within this interval include the Salina and Helderberg groups and the Onondaga Limestone and its lateral equivalents. The maximum thickness of these marine units occurs in central Pennsylvania and New York where nearly 1000 m are present. The southern half of the basin essentially lacks any development of this interval. Although the succeeding Upper Devonian-Lower Mississippian clastic sequence also contains eastwardly derived deltaic sediments, of which portions are continental in nature, the dark gray to brown and black shales were exclusively formed in the marine environment. These shales are of course the object of this report. Equivalent strata to the east represent deposits formed under deltaic-terrestrial conditions. Of these intervals, the Pocono Group is perhaps the best known. Aggregate thickness of the Upper Devonian-Lower Mississippian sequence exceeds 3100 m in eastern Pennsylvania and portions of western Maryland and Virginia and eastern West Virginia. Some of the black shales also extend westward from the basin proper and represent deposits formed on stable shelf or platform areas in shallower marine waters. The remaining Mississippian strata are principally marine limestones, with lesser amounts of nonblack shales and evaporites. This largely carbonate sequence is the result of the last major, extensive subsidence (i.e., marine inundation) for the basin. Several units, such as the Salem, St. Louis, and Ste. Genevieve limestones, are also developed well to the west within the Illinois Basin region. Maximum thickness within the Appalachian Basin occurs in eastern Kentucky, where some 1800 m of strata is present.

Most of the remaining Pennsylvanian and Permian sedimentary rocks are clastic units, many of which are deltaic to continental in origin. Sandstones, siltstones, shales, and widespread coal seams comprise the main post-Mississippian lithologies. From 2500 to 3000 m of Pennsylvanian strata are present in the southern half of the basin, especially in Alabama, whereas some 1200 m represents the maximum development farther to the north in West Virginia and Pennsylvania. Permian strata, collectively referred to as the Dunkard Group are found in a localized area where the states of Ohio, Pennsylvania, and West Virginia merge. Here, only about 100 m of nonmarine post-Pennsylvanian strata is present.

Selected references that discuss the correlation, lithologies, and depositional conditions of these stratigraphic sequences within the Appalachian Basin are well inventoried by Colton (1970). Articles that discuss the regional, basin-wide stratigraphy of the Devonian-Mississippian sequence include Pepper and others (1954), Oliver and others (1969), Wallace and others (1977), Kepferle and others (1978), Roen and others (1978a, 1978b), West (1978), and Klepser and Hyder (1980). Numerous other references that treat individual stratigraphic units or more localized extent of the sequence are contained in the three Eastern Gas Shales Symposia Proceedings volumes.

The regional distribution of principal rock types and certain specific lithologies for the entire Appalachian Basin have been summarized by Colton (1970). Of interest are the several areas that contain the highest percentage of argillaceous strata within the entire stratigraphic succession for they are typically coincident with areas where the Upper Devonian-Lower Mississippian shale sequence is also thickest (Fig. 7).

East of Price's "structural front" in the Central Appalachians, the structural style is characterized by numerous parallel folds, but in the southern portion thrust faults associated with strongly asymmetric folds are the dominant structures (Plates 2 and 3). In this thrust belt, upward ramping is a common feature and has been aided by incompetent beds acting as glide zones. Strata, which include the Upper Devonian-Lower Mississippian shales, within these glide zones are extensively deformed and have been called major detachment horizons (Shumaker 1976). The incompetency of the shales so involved is typically shown by intense folding, fractures, expanded joints, and splay faulting. Evidence of such deformation is well preserved along zones involved in the Pine Mountain thrust in eastern Kentucky (Dames and Moore 1978).

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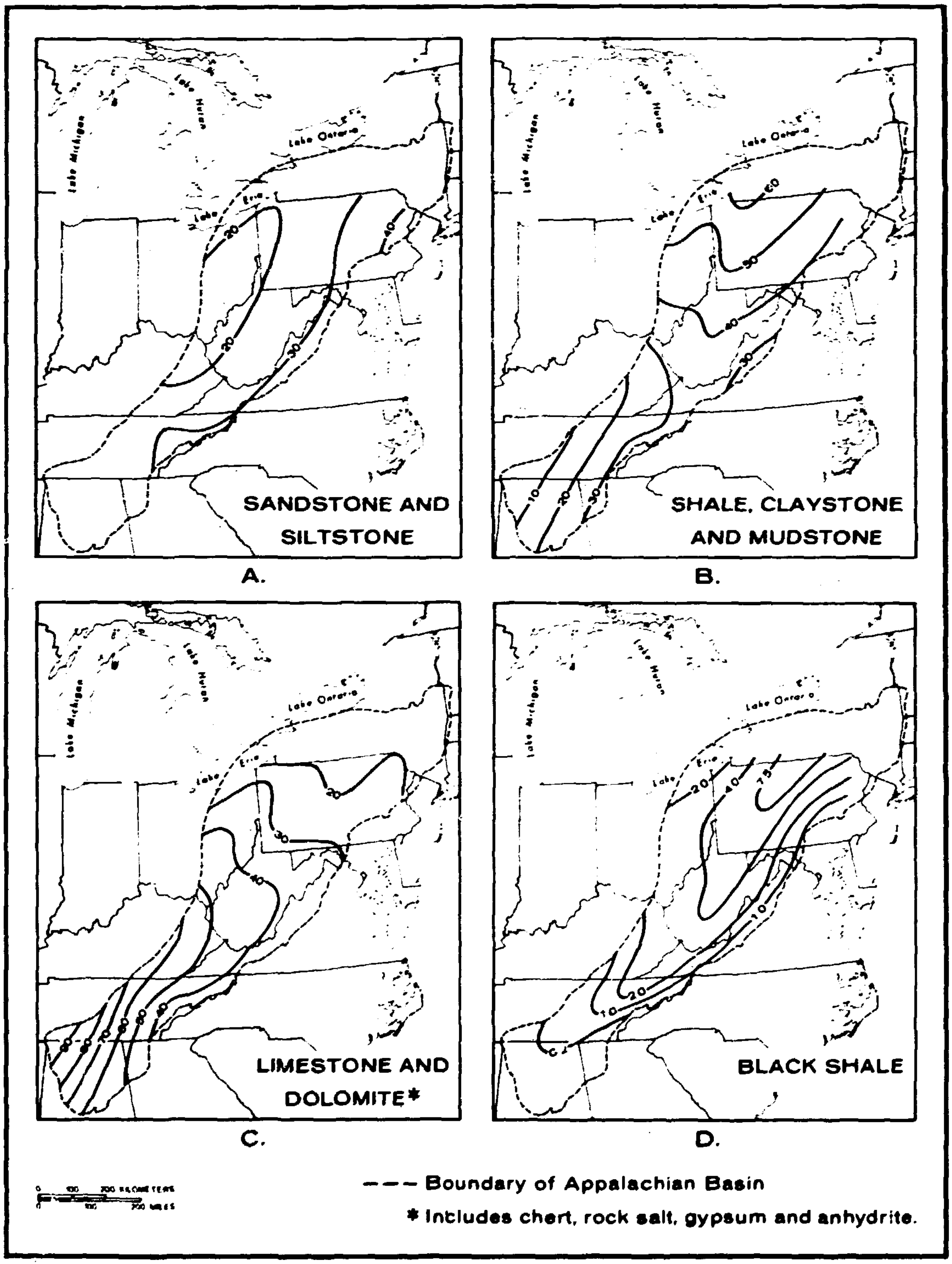


Fig. 7. Distribution of the principal lithotypes that comprise the Paleozoic rock sequence in the Appalachian Basin. Contour lines are iscpleths of equal percentage. Adapted from Colton 1970.

To the west, geologic structures developed in the sedimentary bedrock are much more gentle; regional dips are generally measured at less than a degree. Some folds near the eastern margin of the Appalachian Plateaus are, however, tightly developed; some have also been faulted. This pattern of very mild deformation is also reflected in the broad uplifts along the Cincinnati Arch system.

The Kentucky River fault zone in eastern Kentucky represents one prominent structural feature whose regional expression can be determined from surface exposures. As noted in a preceding section, this fault zone is now thought to be part of a more regionally extensive fault system called the Rome Trough (Harris 1978). Regarding this major basement, cross-basin structural trend, Shumaker (1976) made the following noteworthy observations:

1. The most prolific gas production from Devonian shales in this basin occurs from fields (Big Sandy Field) in juxtaposition to the border faults of this feature.

2. A prominent cross-basin lineament known as the "38th parallel lineament" lies very close to the subsurface position of this feature.

3. This general location is where the fold belt of the Central Appalachians essentially stops and is replaced by the thrust-fault style of the Southern Appalachians.

Whether this significant change in structural style along the Appalachian trend of deformed sedimentary rocks is genetically related to the basement-controlled Rome Trough is speculative; the tectonic history of the Rome Trough is complex, contains several episodes of rifting, and cannot be fully deciphered on the basis of available data (Ammerman and Keller 1979).

Within the northern portion (New York and Pennsylvania) of the basin, some of the folds that affect post-Silurian strata are interpreted from seismic and drilling evidence to have resulted from décollements that extend into but not through the salts of the Salina Group (Frey 1973).

Other data indicate that anticlinal folds, especially toward the deeper part of the basin in Pennsylvania, contain thickened salt cores, whereas the adjacent synclines display thinned salt. Décollements associated with low-angle thrusting in the Central Appalachians (Virginia and West Virginia) have also been viewed as involving Salina Group salt; the Burning Springs anticline in western West Virginia has been interpreted as forming from two levels of décollement, one of which involves Silurian salt, and small-scale thrust faults (Gwinn 1964, 1967). Salt and thrust faulting are also intimately related in the Saltville, Virginia, salt district (Cooper 1966).

Fractures or joints are features that can markedly influence the porosity and permeability, and hence response to fluids, of fine-grained rocks like shales. With regard to the gas-productive Devonian shales, natural fracture systems are clearly related to improved production (Hunter and Young 1953; Nuckols 1978; Shumaker 1978). Several mechanisms which could have caused the joints that developed in the Appalachian Basin include (1) the regional deformation which created the fold and thrust-fault structures, (2) reactivation along basement structures such as the Rome Trough, (3) topographic unloading or overburden removal, and (4) postdepositional processes. Studies conducted under the EGSP have indicated that cleats, or joints in coal, show the most consistent regional orientation of the lithologies analyzed, and that areas where changes in orientation occur may be influenced by rotation from nearby thrust faults (Long 1979). Surface joints in Devonian shales showed first- and second-formed sets striking northeast and northwest respectively, or opposed to the major coal-cleat orientation. One possible explanation is that joints in coal are caused in part by the coalification process, or at least are influenced by the stage of coalification at the time of tectonic-stress application.

Disagreement on surface orientation between lithologies is, however, not the major obstacle revealed to date. Rather, no conclusive evidence has been presented to show any region-wide correlation between surface-joint orientations and those subsurface joints which are clearly essential to high gas production from the Devonian shales. Subsurface fractures in the highly organic Devonian shales are abundant, uniquely oriented, and commonly mineralized. In eastern Kentucky and West Virginia evidence from cores taken in commercially productive fields suggests that fractures are more concentrated within a stratigraphic interval in the lower part of the shale sequence; this so-called "fracture facies" has been interpreted as being the result of tectonic stress combined with a high-pressured (gas) zone in the shales (Shumaker 1978). If fracturing for whatever genetic reason were stratigraphically influenced, the likelihood of finding surface to subsurface relationships would diminish. Lineaments from remote sensing typically show a relationship to stress fields and surface fractures; interestingly, Werner (1978) found that better-yield gas wells were plotted between photolineaments rather than adjacent to or superimposed upon them within the Appalachian Plateau area of West Virginia.

Clearly, more investigation on the origin of subsurface joints in the Upper Devonian-Lower Mississippian shale sequence is mandated. Continued effort to find relationships between surface-joint systems and subsurface joints is currently in progress. Inasmuch as the evidence collected to data diminishes the role of major surface-expressed faulting as a cause for subsurface joints, the role of deeper or basement structures as a cause of such fracturing assumes greater significance. Assessment of the gas production-fracture relationships in the Midway-Extra and Cottageville fields in West Virginia tends to support the concept that basement growth structures are more effective in creating porosity in Devonian shales (Shumaker and others 1979). Work remains to extend this concept to other areas.

### 2.3 Stratigraphy of the Devonian-Mississippian Shale Sequence

Within the main portion of the Appalachian Basin, the Upper Devonian part of the sequence is much more important than the younger Mississippian, which is dominated by coarse clastic units. Shale units, including black shales, are also well developed along the eastern side of the basin within the Middle Devonian. Farther to the west in Ohio, the Bedford Shale of Early Mississippian age is better developed, but even so, Mississippian shales comprise a smaller component of the total sequence in this basin than in either the Michigan or Illinois basins.

Strata within the Devonian-Mississippian interval are, on the average, moderately thick and consist dominantly of shale, mudstone, siltstone, and sandstone. Portions of the section are calcareous, and limestone beds and concretionary carbonate masses occur in certain horizons. Rocks of this interval, although widely distributed regionally, are absent in parts of the southern end of the basin in Tennessee and Alabama. Over most of the basin, Devonian shales in the lower portion of the interval conformably overlie carbonate rocks of Silurian-Devonian age with a sharp contact, but in the southern part of the basin, the contact of the Devonian shales with subjacent rocks is disconformable. Strata as old as Middle Ordovician are truncated at this surface, while coarse clastic units of Mississippian age comprise most of the overlying sequence.

The Devonian-Mississippian shale sequence is wedge-shaped, ranging in thickness from slightly more than 3350 m in northeastern Pennsylvania to a feather edge in Alabama and Tennessee. The entire wedge does not consist of argillaceous rocks but rather contains coarse-grained quartzose rocks, including red beds, as the dominant lithology in the northeastern portion of the basin where the sequence is the thickest. Medium-grained, gray-colored rocks predominate where the sequence is of intermediate thickness, whereas fine-grained carbonaceous shale (Chattanooga Shale) is dominant in the southwestern portion of the basin where the sequence is thinnest.

Inasmuch as the most important aspect of the rock sequence is its lithology, classical biostratigraphic criteria are not used here to delineate individual rock units. The base of the sequence, except where disconformable in the southern end of the basin, is placed at the top of the Onondaga Limestone or the equivalent uppermost unit within the Silurian-Devonian carbonate sequence. The top of the sequence is assigned to the base of the lowest relatively coarse-grained clastic rock of Mississippian age. This is the Pocono Formation or Group in the northeastern part of the basin; the Berea Sandstone, Cussewago Sandstone, or Corry Sandstone in the northwestern part; and the Price Sandstone or its equivalents elsewhere in the basin.

In northeastern Ohio the contiguous shale sequence below the Berea Sandstone includes the Bedford Shale, a section of strata interpreted as being Early Mississippian in age. Here the Devonian-Mississippian section consists mainly of gray shale, calcareous gray mudstone, and carbonaceous shale.

The Middle and Upper Devonian portion of the shale sequence, and to a lesser degree the Lower Mississippian portion, is characterized by a significant degree of facies changes, by a sizeable number of stratigraphic terms (see Fig. 6), and by a greater level of difference in the applicable stratigraphic nomenclature (Fig. 8). Therefore, the many individual shale or shale-dominated units are not described here separately as is possible with the fewer, more readily differentiated units in the Illinois and Michigan basins. Rather, the detailed study of the strata in the Appalachian Basin by Klepser and Hyder (1980) provides a summarized identification of the more promising units. The basic element pursued in that study was to locate stratigraphic intervals where the shale units had a lower hydrocarbon potential, yet were thickest in the subsurface. Four parameters used to identify such units were (1) an absence or low development of interbedded lithologies such as sandstones, siltstones, and carbonates which might provide undesired permeability zones and/or included fluids; (2) lower amounts of black shales having higher hydrocarbon potential; (3) sufficient thickness; and (4) adequate depth.

From a simplistic viewpoint, a thick shale section of gray to dark gray color, containing no porous lithologies, and lacking any hydrocarbon-rich black shales would thus be a very promising candidate interval for waste disposal. Because of the nature of the Devonian-Mississippian strata in the Appalachian Basin, no such sequence with all those qualities was found. It is nevertheless possible to identify nine stratigraphic units which, on the basis of their regional expression according to the parameters cited above, appear more favorable for further study relative to a potential for the dipsosal of radiaoctive waste (Table 4).

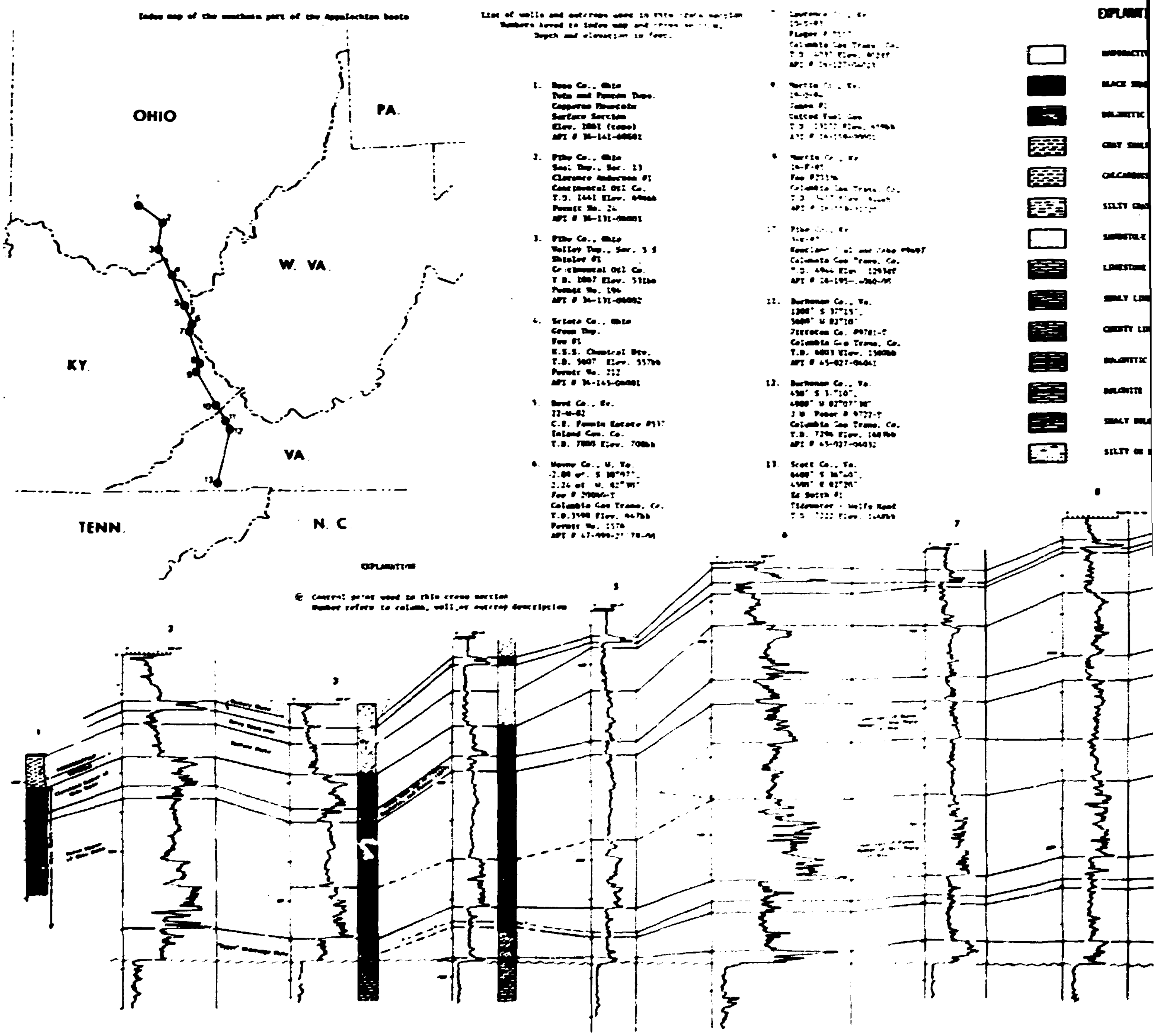


Fig. 8. Northwest-southeast cross section of the Devonian black Appalachian Basin showing zones of higher natural radioactivity and di nomenclature. Adapted from Kepferle and others 1978.

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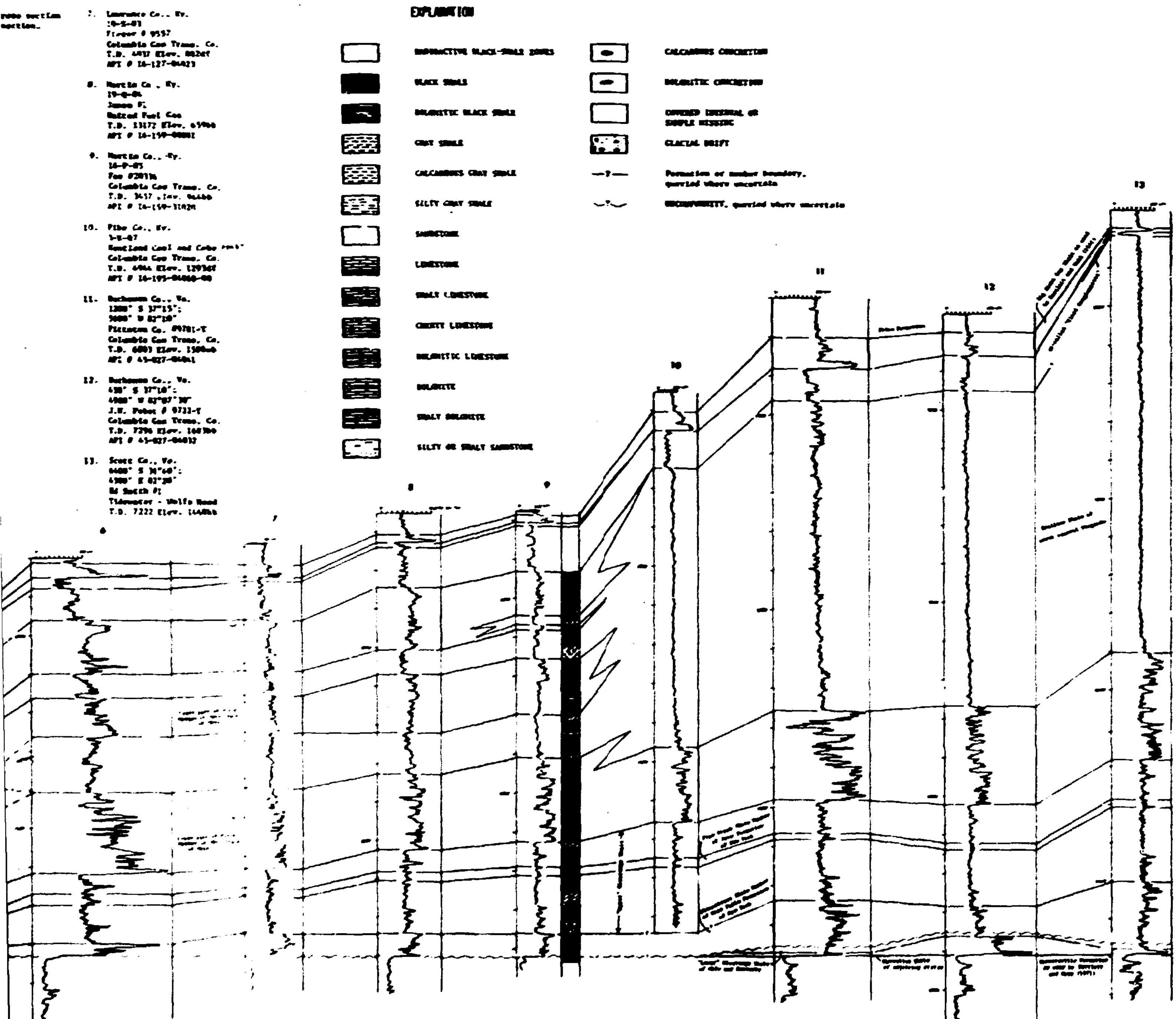


east cross section of the Devonian black shale sequence in the southern
es of higher natural radioactivity and differing regional stratigraphic
pferle and others 1978.

Table 4. Regional characteristics of those stratigraphic units in the Appalachian Basin considered promising for radioactive waste disposal

| Unit | Lithology | | | Organic carbon content | Adjacent units | |
|---|---|---|---|---|---|---|
| | Shale type | Silt content | Limestone content | | Below | Above |
| Hamilton Group | Gray and black | Minor in western New York, increases eastward | Minor to moderate | High in basal unit | Limestone | Shale, limestone |
| Millboro Shale | Grayish black | Minor | Minor to moderate | Low to high | Bentonite | Shale, siltstone |
| Lower Olentangy | Gray and black | Absent | Minor | High in basal unit | Limestone | Shale, limestone |
| Genesee Group | Gray and black | Minor in western New York, increases eastward | Minor to moderate | High to west | Shale, limestone | Black shale |
| Sonyea Group | Gray and black | Minor in western New York, increases eastward | Minor | Moderate | Gray shale | Black shale |
| West Falls Group | Gray and black | Low, increases eastward | Minor | High to west | Shale, siltstone | Black |
| Upper Olentangy Shale | Gray and black | Absent | Minor | High in basal unit | Gray shale | Black shale |
| Huron Shale | Gray and black | Minor | Minor | High in upper and lower units | Gray shale | Gray shale |
| Chagrin Shale | Bluish gray | Minor | Absent | Low | Black shale | Black shale |

Source: Adapted from Klepser and Hyder 1980.

It should also be noted that these, and possibly other, intervals within the basin are not to be inferred as having favorable characteristics throughout their extent. They merely meet some generalized stratigraphic criteria which may or may not reflect more localized conditions that more detailed studies would be needed to detect. Certainly, such detailed studies would further discriminate among either the units, or different areas underlain by the units. There furthermore has been no effort to evaluate these units based on other considerations, such as borehole density, oil and gas development in associated strata, or active coal mining.

## 2.4 Distribution, Thickness, and Depth

The nine stratigraphic intervals identified in the preceding section as having more promising regional attributes show appreciable thickness and depth variations throughout the Appalachian Basin. All are exposed at the surface either along the narrow eastern or western belts or in the more extensive New York-Pennsylvanian trend that characterizes the outcrop pattern for Devonian strata in the northern three-quarters of the basin (Plate 4). The units range in depth within the subsurface from 150 to more than 1600 m. Thus, all are present within a depth range of 300 to 900 m. A point of clarification is that the depth and isopach (thickness) data presented in Plate 4 are for the entire shale-clastic sequence, and not solely for the nine designated stratigraphic intervals or any individual unit within them.

The thinnest unit, as expressed in terms of a maximum thickness, is the Lower Olentangy Shale, which does not exceed 50 m throughout its extent. By contrast, the Upper Olentangy Shale reaches 240 m in maximum thickness. The thickness relationships of the Olentangy Shale are shown in Fig. 9, where its maximum thickness along the Ohio-Pennsylvania border is evident.

The Hamilton Group ranges in thickness from some 80 m in western New York to more than 300 m in central New York. A possibly limiting factor is that over this trend, the depth increases to more than 900 m.

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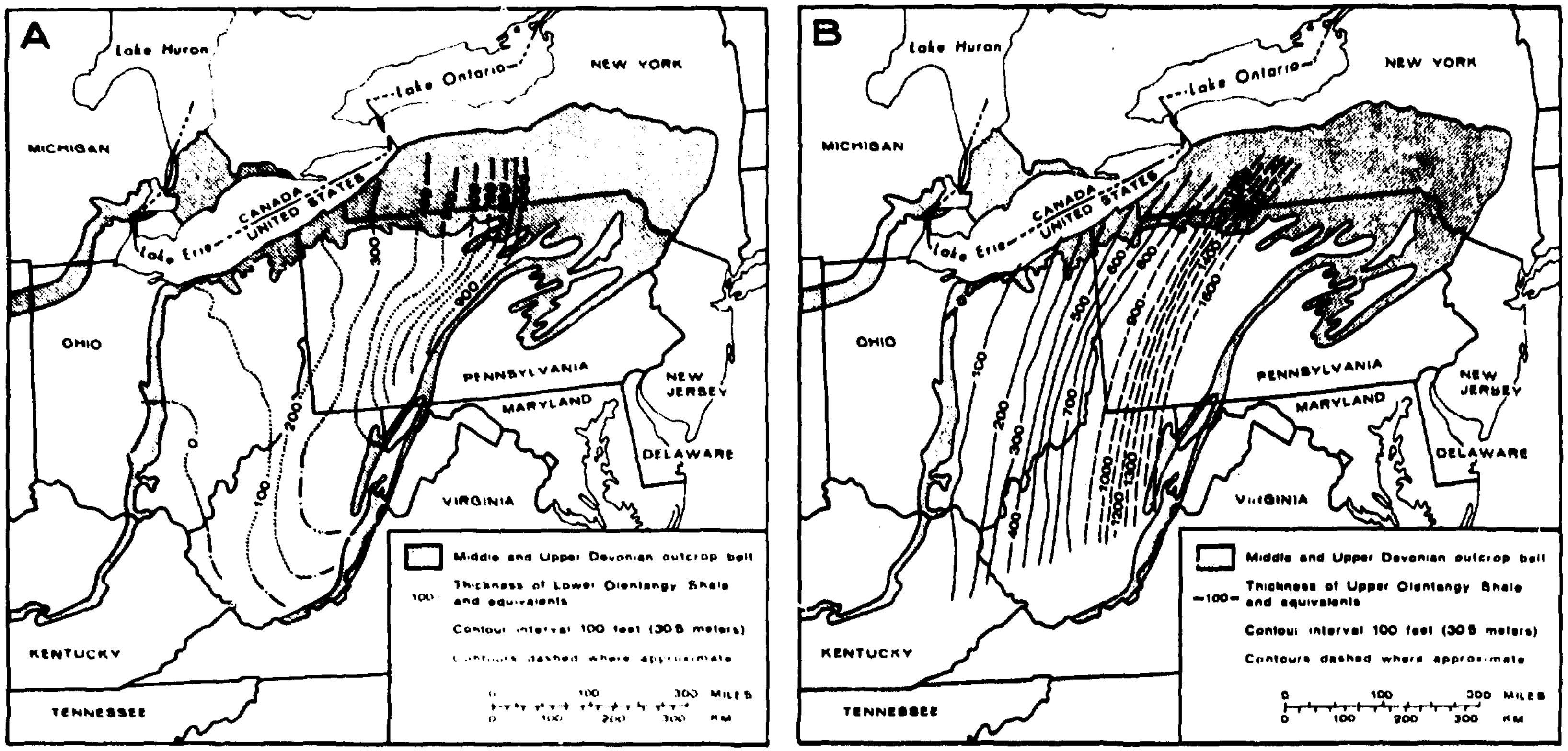


Fig. 9. Isopach maps of the (*a*) lower and (*b*) upper Olentangy shales and their stratigraphic equivalents in the Appalachian Basin. Adapted from Schwietering 1979.

The Millboro Shale attains a maximum thickness of 450 m along its easternmost extent. Westward into West Virginia, it thins to some 60 m but is too deeply buried both here and in adjacent Pennsylvania.

Although the thickness aspects of the Olentangy Shale appear favorable (Fig. 9), the unit is more than 900 m deep in several areas, including Harrison County, Ohio, and eastward; and along the Ohio-West Virginia state line and to the southeast.

The Genessee Group, while only a few meters thick in western New York, increases to 300 m in the central part of the state. The unit, in its thicker expression, is generally 600 to 900 m in depth. The Sonyea Group displays comparable thickness and depth relationships to those of the Genessee Group.

As the most regionally shallow unit, the West Falls Group is some 150 m thick at its maximum depth in western New York. Although the unit thickens eastward, it also becomes exposed at the surface in the central part of the state.

An average thickness value for the Huron Shale in Ohio is 125 m. Eastward from central Ohio, the unit thins slightly but becomes more deeply buried in that direction. The unit lies below 900 m in southeast Ohio and is more than 1500 m deep in the western part of Virginia. The gray shales of the Middle Huron interval may be particularly noteworthy throughout this thickness/depth trend.

Of all the units, possibly the Chagrin Shale illustrates the most pronounced changes over the shortest lateral distances. Only a few meters thick in north-central Ohio and a few tens of meters thick in southern Ohio, the unit increases to more than 350 m in northeastern Ohio. Although exposed at the surface in much of north and central Ohio, the Chagrin Shale does, however, lie 200 to 300 m below the surface in east-central Ohio.

## 2.5 Physical, Mineral, and Chemical Properties

Physical properties reported by the EGSP for Devonian shales cored in the Appalachian Basin include the density and porosity in quantitative terms and the permeability in qualitative terms (Table 5; Fig. 10). As shown there, the bulk density remains fairly constant; an average value for the four samples is 2.65 g/cm$^3$ with a maximum variance of only 0.04 from the mean. Data reported by the several references used to compile Table 5 reveal a range in bulk density of 2.35 to 2.70 g/cm$^3$ for all measured samples, and slight fluctuation between samples from greater depths. The samples from the Appalachian Basin show a higher average value than those determined from the Illinois Basin.

Table 5. Physical properties of Devonian shales from four coreholes in the Appalachian Basin

| Well location | Well No. | Average bulk density (g/cm$^3$) | Average porosity (vol %) | Average permeability |
|---|---|---|---|---|
| Martin County, Ky. | C-336 | 2.66 | 2.86 | Very low |
| Allegany County, N.Y. | Y-1 | 2.61 | *a* | Very low |
| Wise County, Va. | C-338 | 2.66 | 3.14 | Low |
| Lincoln County, W. Va. | C-2 | 2.62 | 3.87 | Very low |

[a] Not determined.

Source: From Kalyoncu 1979; Kalyoncu and Snyder 1978, 1979; Kalyoncu and others 1979a, 1979b, 1979c, and 1979d.

There was, however, a greater regional variation in porosity. Samples from eastern Kentucky were a full percent point lower than certain other samples. Nevertheless, values of less than 4% porosity indicate the small amount of pore space left in these fine-grained rocks following compaction. The permeability is generally so low as to prevent quantitative determination; regardless, the permeability of unfractured Devonian shales is such that they can be reasonably classified as impermeable until specific hydraulic testing can be performed to more fully qualify that designation.

Mineralogical studies based on petrographic, x-ray diffraction, and scanning microscopy methods reveal that the clay mineral illite is the dominant species within the likewise dominant clay fraction (Table 6).

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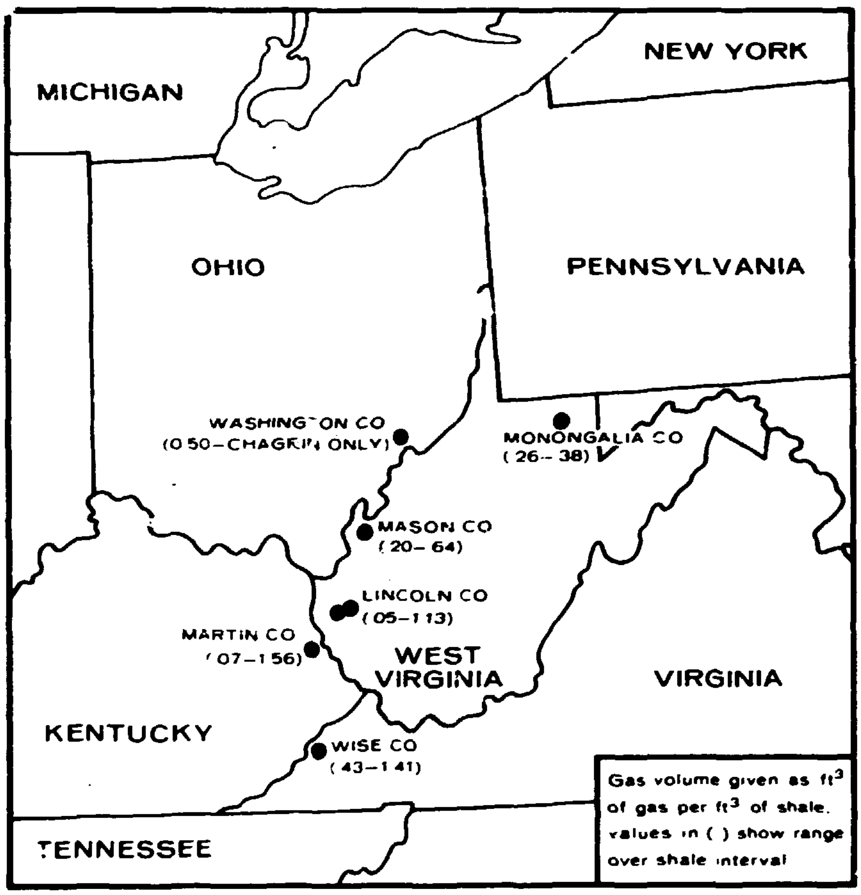


Fig. 10. Locations of Eastern Gas Shales Project test coreholes drilled in the Appalachian Basin for which gas-volume data are available. Adapted from Streib 1979.

One exception is the C-2 well in Lincoln County, West Virginia, where kaolinite is the dominant clay mineral (Kalyoncu and Snyder 1979). Illite in the other samples ranged as high as 80% of the clay-mineral fraction. Other clay minerals present include chlorite and mixed-layer types; kaolinite is a minor constituent in all cores except that from well C-2.

Quartz and pyrite are essentially ubiquitous in all samples; the former may range up to 20% in some samples. The distribution of carbonate minerals and other species determined in the several studies on gross mineralogy essentially shows variability to be the rule, and reveals no systematic pattern to the variation.

Table 6. Mineralogy of Devonian shales from five coreholes in the Appalachian Basin as determined by petrographic and x-ray diffraction studies

| Mineral | Well location and identification number | | | | |
|---|---|---|---|---|---|
| | Martin County, Ky., C-336 | Allegany County, N.Y., Y-1 | Wise County, Va., C-338 | Lincoln County, W. Va., C-1 | Lincoln County, W. Va., C-2 |
| | PETROGRAPHIC DETERMINATION | | | | |
| Illite | D[a] | ND | D | ND | ND |
| Quartz | P | ND | V | ND | ND |
| Pyrite | V | ND | P | ND | ND |
| Carbonates | P | ND | ND | ND | ND |
| | X-RAY DIFFRACTION DETERMINATION | | | | |
| Illite | ND | V | D | D | ND |
| Quartz | ND | V | P | P | P |
| Pyrite | ND | P | P | P | P |
| Calcite | ND | ND | ND | ND | ND |
| Nahcolite | ND | P | P | V | P |
| Shortite | ND | P | P | V | P |
| Siderite | ND | P | P | ND | P |
| Kaolinite | ND | ND | A | P | D |
| Feldspar | ND | ND | ND | ND | A |
| Gypsum | ND | ND | ND | ND | ND |

[a]Key to abbreviations: D, dominant mineral species; P, present in samples; V, variable amounts; A, absent from samples; ND, not determined.

Sources: From Kalyoncu 1979; Kalyoncu and Synder 1978, 1979; Kalyoncu and others 1979a, 1979b, 1979c, 1979d, Leventhal (1978) determined the abundance and distribution of major, minor, and trace elements in nine cored intervals from the Appalachian Basin. Two samples from each of Kentucky, Ohio, and West Virginia, plus single samples from New York, Tennessee, and Virginia were analyzed. This study found little variation with depth for $SiO_2$, $Al_2O_3$, $TiO_2$, $K_2O$, and $Fe_2O_3$ in all nine cores. Varying amounts of carbonates, however, produced larger fluctuations in CaO; the greatest range was in the New York core. Organic carbon and sulfide richness also produced wide variations up to a maximum/minimum value ratio of 50. This wide variation may be attributed to the amount of organic carbon and sulfide richness that is present in the black-shale portions of the cores. The Tennessee core was consistently lower than the other eight cores in all the major elements except calcium. The mean calcium value (expressed as CaO) from this core was equal to the CaO mean value for the New York core. No similar trend was found for the other major elements. The Tennessee core was also higher than the other cores in organic carbon and total sulfur, which might indicate slightly different depositional conditions toward the southern part of the basin. One possibility is a greater influx of coaly, humic material as found in the Chattanooga Shale (Breger 1979).

Large variations in concentrations occur in the following minor and trace elements: Mn, Sb, As, Cd, Mo, Zn, Se, Hg, U, Cu, and V (Leventhal 1978). Variability within the minor and trace elements is clearly greater. A similarity exists between the minor and trace element variations and those of organic carbon and sulfide. This is possibly due to "fixing" of these soluble trace elements into the shales with organic carbon and sulfides acting as concentrators and/or chemical reductants.

Smaller variations are exhibited by Ni, Th, Zr, Sr, Ba, Be, and La. Nonsoluble trace amounts of these elements are probably present in silicate phases in the clay-mineral fraction. If the trace elements are soluble or slightly soluble, the reducing conditions associated with the origin of these shales do not appear to represent a major factor in their concentration.

## 2.6 Mineral Resources in Shale Units

### 2.6.1 Natural gas and oil

As noted in Sect. 1, Devonian-age shales have produced appreciable natural gas in the Appalachian Basin. Principal production has come from fields in eastern Kentucky, southwestern West Virginia, and eastern Ohio; less substantial volumes of gas have been recovered from wells in northeastern Pennsylvania, southwestern New York, and southwestern Virginia. Production in some areas dates back to the early 1800s, and while many of these older fields are not currently producing gas, other long-established fields have been producing at fairly sustained levels for several decades. Estimates indicate that approximately 14% of all the gas-producing wells developed within the Appalachian Basin are completed in the Devonian shales (Ray 1977).

Lockett (1968) described the following four characteristics as typical of much of this Devonian shale gas production:

1. Very few wells will yield commercial volumes of gas without artificial stimulation.

2. Explosive fracturing (the stimulation technique largely in use at that time) is generally successful provided the well is properly located within the shale sequence.

3. Shale gas has a relatively high thermal value.

4. Average ultimate delivery from shale wells is exceptionally high.

Possibly the most noteworthy Devonian shale gas field is the Eastern Kentucky Field (also called Big Sandy Field), so named because it occupies a large area in easternmost Kentucky. Approximately 60% of the field's cumulative production of $84 \times 10^9$ $m^3$ (as of January 1, 1975) has come from the Devonian shale interval (Ray 1977); the remainder of production is from shallower Mississippian units (Maxon Sand, Newman Limestone). This field commenced production in 1920 and has historically accounted for between 85 and 95% of the annual gas production in Kentucky. The average open flow for a recently completed shale-gas well in this field is 16,000 $m^3$/day.

Conventional practice used in this and other shale-gas fields to stimulate production was explosive fracturing with nitroglycerin over the entire prospective section. Some of the earliest success at hydraulically fracturing shale wells was achieved in this field. One advantage to the newer hydraulic stimulation practice, as shown by this field's statistics, is that the average well delivery improves each year over that realized by explosive fracturing (Ray 1977).

The most important producing horizon in the Eastern Kentucky Field is the Upper Devonian Ohio Shale, which is locally called Devonian Brown Shale. Of particular production significance is the lowermost black shale (designated zone D), which also exhibits a characteristically higher response on gamma-ray logs. In this area, the Devonian Brown Shale is equivalent, from oldest to youngest, to the Huron Shale, Three Lick Bed (i.e., Chagrin Shale), and Cleveland Shale (Negus-deWys 1979). Producing zone D correlates with the Huron interval.

A significant characteristic of wells in this field is that while they are individually small producers, they exhibit extremely long, productive lives. Many wells have sustained production at very slowly declining rates for more than 50 years (Ray 1977).

There are numerous other smaller gas fields in eastern and southeastern Kentucky which produce from the Devonian shales. One of the more recently discovered fields, named the Canada Mountain Field, is of particular interest because it extends Devonian-shale production into the Cumberland thrust-fault block in extreme southeastern Kentucky (Weaver and others 1978). Fracturing of a thicker-than-normal shale section is directly related to the thrust faulting associated with the Pine Mountain fault system; this has both produced effective porosity within the shale and served to liberate additional gas that has accumulated in shallower Mississippian carbonate units. The faulting is also responsible for the thicker shale interval due to repetition of section.

In adjacent southwestern Virginia, more than 90% of that state's natural-gas production comes from Buchanan and Dickenson counties; in fact, all of the gas produced in Virginia is from five counties in this part of the state. More than 200 wells account for this production, which comes primarily from several Mississippian-age sandstones such as the Maxon, Ravencliffe, Weir, and Berea (Patchen and others 1979). Other production is from the Mississippian Greenbriar Limestone and Devonian shales. Fields such as Nora, Haysi, Keen Mountain, and Stonega are the major gas-producing deposits in this five-county area. The gas-productive shale intervals here are comparable to those in adjacent Kentucky.

Most of the Devonian shale gas produced in West Virginia comes from fields located in some 18 counties in the southwest and northwest parts of the state. Some selected examples from the nearly 30 named fields include Midway-Extra, Scott Depot, Ground Hog Creek, Sissonville-Elk Poca-Oriskany, and Cottageville (also called Mt. Alto). The belt of productive fields extends from the Kentucky-West Virginia line on the southwest across two-thirds of the state, essentially parallels the Ohio River, and embraces an area approximately three counties wide throughout its extent. Production in Cabell County extends westward into eastern Ohio while that in Wayne and Mingo counties merges in a southwest direction with the Eastern Kentucky (Big Sandy) Field in adjacent Kentucky. The gas-productive interval here in West Virginia has generally been described as Devonian Brown Shale and has sustained production in some areas for more than five decades (Negus-deWys and Shumaker 1978). Many of these productive fields are aligned along the trend of the subsurface Rome Trough which is felt to be a cause of the natural-fracture porosity (Nuckols 1978).

Wells here produce at small daily volumes, generally from 1500 to 3000 $m^3$/day; however, success ratios in drilling exceed 90% (Patchen 1977). Bagnall and Ryan (1976) showed very stable production-decline curves for several categories of flow volumes in this area; at the time of their study, some 950 wells were active producers. From a stratigraphic viewpoint, the principal gas-producing interval occurs in the lower part of the Lower Huron Shale although other productive zones within the 350-m prospective section include the Upper Huron and Rhinestreet (or its equivalent here) shales (Nuhfer and Vinopal 1979). Fields farther to the northeast are said to also obtain production from the Middle Devonian Marcellus Shale, although problems in applying the correct stratigraphic nomenclature may be involved in some of these designations.

One of the more widely studied fields is the Cottageville Field, which lies in Mason and Jackson counties near the Ohio state line (Martin and Nuckols 1976; Nuckols 1978; Hennington 1979). Under an informal designation scheme (Martin and Nuckols 1976), the production intervals are termed (from oldest to youngest) zone I (i.e., Rhinestreet Shale), and zones II and III (i.e., Lower Huron Shale); these are recognizable on the basis of their characteristic response on gamma-ray logs. Zone II is the principal producing interval, although Hennington (1979) showed that zone III contributed production to one-third of the wells drilled into the prospective interval. The average cumulative production per well from this field, which was discovered in 1929, is $4 \times 10^6$ $m^3$, while total field production has amounted to $470 \times 10^6$ $m^3$ (Hennington 1979).

The orientations of surface joints and joints measured in cores from the Cottageville Field appear very similar; Nuckols (1978) is of the belief that there is a direct correlation. If so, this would be one of the few fields where such a relationship either exists or has been detected.

According to Janssens and deWitt (1976), natural gas has been produced since 1860 from Devonian black shales in eastern Ohio, where four separate surges of drilling activity have cumulatively accounted for more than 1500 productive wells. In the nearly 20 counties that have established production, the prospective shale interval extends from the top of the Middle Devonian Onondaga Limestone to the base of the Lower Mississippian Berea Sandstone. The latter rock unit is itself a widely productive, shallow horizon throughout most of eastern Ohio. The overlying Sunbury Shale, where present, typically registers gas shows in boreholes. Some Devonian shale gas is actually produced from minor siltstone and sandstone units within the shale-dominated interval.

Data tabulated by the Ohio Geological Survey reveal that more than 140 wells are currently producing gas from Devonian shales at initial production rates which range from 1500 to 15,000 $m^3$/day (Majchszak 1978).

The most current annual petroleum statistics assembled by the American Association of Petroleum Geologists show that in 1978 fifteen gas wells and one gas-oil well were completed in Devonian shales within eastern Ohio (Patchen and others 1979).

An empirical relationship matching those shale zones of higher gas production with those of a more pronounced natural radioactivity level as measured on gamma-ray logs has clearly been established for eastern Ohio by Majchszak (1978). This same correlation has been demonstrated in West Virginia by Martin and Nuckols (1976), and subsequent discussion reveals a similar relationship in adjacent Pennsylvania and nearby New York.

As shown in Fig. 11, the Cleveland, Upper Huron, Lower Huron, and Rhinestreet (or its equivalent) shales appear as those traceable units exhibiting both higher natural radioactivity and higher gas production. The characteristic gamma-ray signature not only facilitates lateral correlation of these black shales but also permits their separation from the nonblack-shale intervals, such as Chagrin and Bedford shales, within the subsurface.

Natural gas was produced from Devonian shales by means of low-pressure wells along Lake Erie in northwestern Pennsylvania and adjacent southwestern New York during the span 1821 and 1880 (Piotrowski and others 1978). Although these early wells are no longer productive, the Welch Foods, Inc., No. 3 well, which lies within one of the old producing areas known as the North East Field, was the first of several recently completed gas producers. Five other producing wells have been completed in this general area since 1976 (Harper and Piotrowski 1978). Two other wells, of which only the Metropolitan Brick Company No. 1 well is able to maintain adequate gas pressure for sustained production, are located in Beaver County far to the south.

The productive zone in the old fields adjacent to Lake Erie and in the six newly developed wells in Erie County is primarily the Dunkirk Shale, which is the lowermost unit within the Canadaway Group according to New York State stratigraphic nomenclature. This black shale is approximately equivalent to the Huron Shale farther west in Ohio. After

ORNL DWG 82-552

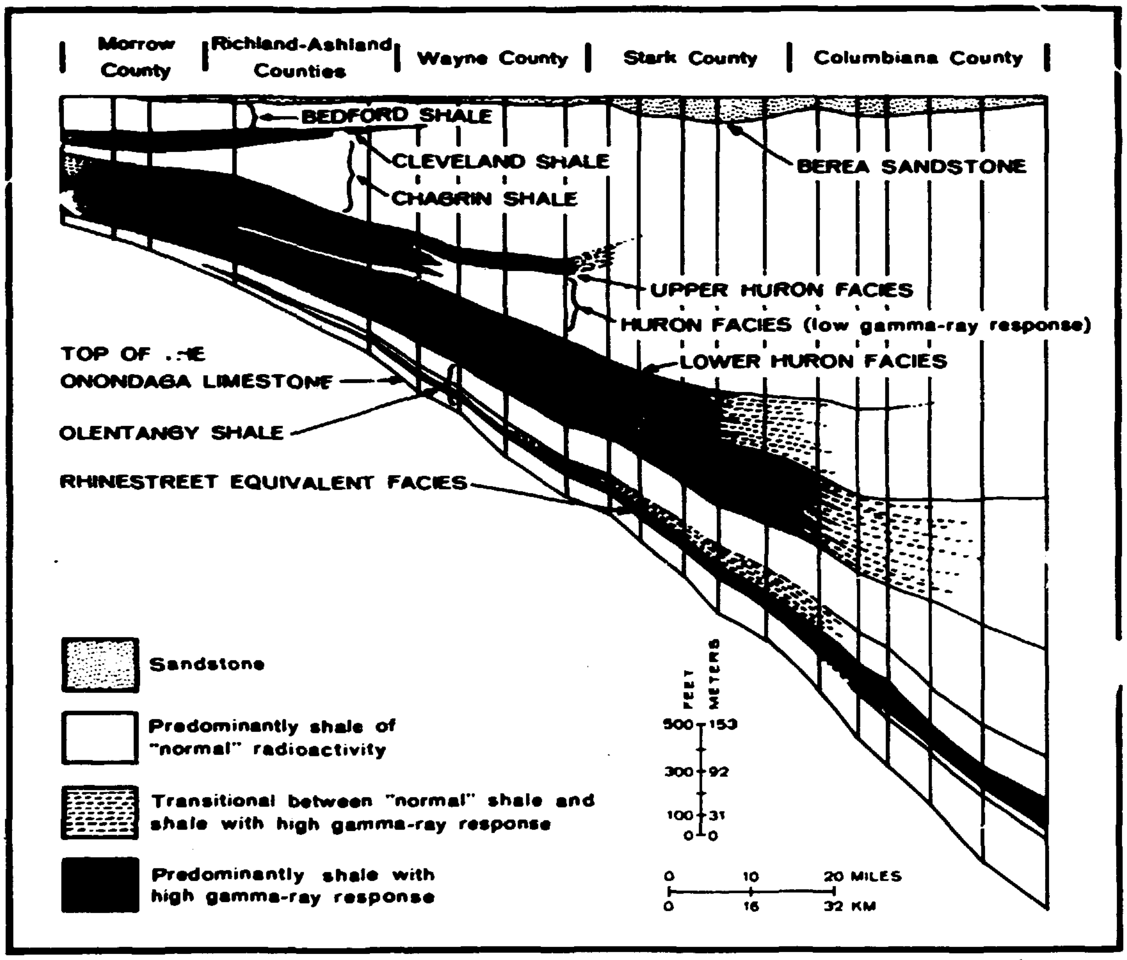


Fig. 11. Generalized cross section of the Devonian shale sequence in eastern Ohio showing stratigraphic relationships and radioactive facies. Adapted from Majchszak 1978.

artificial fracturing, the Welch well established a gas flow of 4500 $m^3$/day; several of the other wells tested higher initial flow rates, but declining pressure mandated reductions in their daily production (Harper and Piotrowski 1978).

Two productive zones, the most important of which is the Rhinestreet Shale, or the basal shale within the West Falls Group of New York, account for the gas recovered in the two wells in Beaver County (Piotrowski and others 1978). Flow rates (after fracturing) comparable to the Welch well have been experienced by the more reliable producer of the two.

Both of these major, productive black shales exhibit pronounced "kicks" on gamma-ray well logs but have low density readings as measured by neutron logs. The correlation between higher natural radioactivity and better gas production in Devonian shales is a relationship that other investigators (Martin and Nuckols 1976) observed from examining the records of 37 wells from the well-known Cottageville Field in West Virginia.

Inasmuch as the Rhinestreet Shale is more regionally extensive, thicker, and maintains its characteristic gamma-ray response over that extent, Piotrowski and others (1978) have evaluated it to be the most prospective interval in western Pennsylvania. The shallow depth and established productive attributes of the Dunkirk Shale, even though it is thinner and less extensive, also make it an attractive drilling target for shale gas. No fields are known to produce oil from the Devonian shales in Pennsylvania.

Van Tyne and Peterson (1978) have identified five productive gas fields (Bristol, Dansville, Naples, Rathbone, and Rushville) in southwestern New York where either Middle or Upper Devonian black shales are the pay horizons. These fields are in addition to the old productive trend along Lake Erie described above. Although there are several continuous Devonian black shales in the stratigraphic succession in western New York, only the Middle Devonian Marcellus (Hamilton Group) and Upper Devonian Middlesex, Rhinestreet, and Dunkirk shales appear highly gas prospective. These units also demonstrate characteristically higher readings on gamma-ray logs, and thus exhibit the same correlation between natural radioactivity and hydrocarbon potential as other black shales that are productive in adjacent states. Of the five known fields in New York, three produce from the Hamilton (mainly the Marcellus Shale), while the other two recover gas from the Rhinestreet Shale.

Although all three basins discussed in this report contain gas-prospective Devonian-Mississippian shales, the Appalachian Basin clearly has been the most productive, and very likely contains the most sizeable resource of natural gas destined for future production. As the preceding discussion reveals, this gas resource is unevenly distributed both geographically and vertically within the stratigraphic column. Stratigraphic zones with high gas contents, as reflected by either established production from them or the generation of gas shows when penetrated, are characteristically dark-brown to black shales that have a high carbon content and a relatively high response on gamma-ray logs. In the latter case, the natural radioactivity causing this response generally exhibits gamma-ray intensities in excess of 200 American Petroleum Institute units. The natural radioactivity is related to the concentration of uranium, which is believed more readily precipitated from seawater where organic matter is present (Swanson 1960). Of the shales in the Appalachian Basin, the Lower Huron, Dunkirk, Rhinestreet, and Marcellus shales (or their equivalents in certain areas) are representative of zones with high natural radioactivity and higher gas contents.

The EGSP has recovered and analyzed several cores from boreholes in Kentucky, Ohio, Virginia, and West Virginia (see Fig. 10). Data on gas volume and carbon content for five of the seven coreholes are presented in Table 7. By comparing the values obtained for the Cleveland Shale, for example, the lack of a direct correlation between gas volume and carbon content over the geographic area from southwest Virginia (Wise County) to southwest West Virginia (Lincoln County) becomes evident. There is, however, a much better agreement between carbon content and gas volume in any given well; even in those cases, there is not perfect agreement for any of the wells listed.

Data on gas content and carbon content for the Lower Huron Shale in the Martin, Mason, and Wise county wells when compared with vitrinite-reflectance information show that higher thermal maturation (as indicated by reflectance values) may partially account for gas volumes not in agreement with the percent carbon. These relationships are given in Table 8. Another way of explaining this relationship may be seen by comparing the Martin and Wise county wells. The former has a lower gas value but a higher carbon value than the latter, which however has a much higher reflectance reading, indicative of greater thermal maturation. In other words, more of the carbon originally in the Wise County well appears to have been converted to gas. By this same reasoning, the

Table 7. Gas volume and carbon content of shale units in the Appalachian Basin

| Devonian shale unit | Corehole location and depth interval cored | | | | |
|---|---|---|---|---|---|
| | Martin County, Ky. 2432-3409 ft | Wise County, Va. 4868-5678 ft | Lincoln County, W. Va. 2792-4045 ft | Mason County, W. Va. 2678-3407 ft | Monongalia County, W. Va. 7163-7509 ft |
| Chagrin | 0.07[a]<br>1.36 | 0.43<br>2.03 | 0.07<br>0.95 | | |
| Cleveland | 0.56<br>5.66 | 1.41<br>4.55 | 0.09<br>1.98 | | |
| Upper Huron | 0.09<br>3.16 | | 0.15<br>1.03 | | |
| Lower Huron | 0.55<br>3.90 | 1.20<br>3.24 | 0.36<br>3.73 | 0.20<br>3.08 | |
| Huron (undifferentiated) | 1.56/1.54[b]<br>6.37/5.86 | | | | |
| Upper Olentangy | 0.12<br>1.32 | | 0.11<br>[c] | | |
| Rhinestreet | 0.43<br>3.79 | | 0.87<br>2.80 | 0.64<br>[c] | |
| Marcellus | | | | | 0.38<br>6.79 |

[a]Upper number is gas volume in cubic feet of gas per cubic feet of rock; lower number is carbon content in percent.

[b]Different values obtained from material cored at different depths.

[c]Value not determined.

Source: Streib 1979.

Table 8. Hydrocarbon (gas) maturation data for the Lower Huron Shale in the Appalachian Basin

| Corehole location | Gas volume ($ft^3$ gas/$ft^3$ shale) | Carbon content (average %) | Mean average reflectance (Ro) |
|---|---|---|---|
| Martin County, Ky. | 0.55 | 3.90 | 0.52 |
| Wise County, Va. | 1.20 | 3.24 | 1.02 |
| Mason County, W. Va. | 0.20 | 3.08 | 0.63 |

Source: Streib 1979.

intermediate reflectance and carbon values for the Mason County well may explain its comparatively low gas content.

Claypool and others (1978) are of the opinion that the variations in the chemical (hydrocarbon) and isotopic composition of Devonian shale gas revealed in their research are systematic, and reflect the same regional gradients in organic metamorphism (catagenesis in the case of hydrocarbons) as seen in the systematic variations of coal rank in younger Pennsylvanian strata. A similar, orderly variation on a regional basis can be observed in the belts of conventional oil and gas occurrence.

According to Nance and others (1979), the factors that determine the natural-gas potential in Devonian shales are organic carbon content, thermal maturation, and type of organic matter. With regard to the latter, evidence appears to indicate that an organic facies which is predominantly algal-amorphous in nature with a significant component of herbaceous material may be closely related to higher gas potential. There also appears to be a relationship between the nature of the organic-matter type and the general sedimentologic framework. In this case, the algal-amorphous content increases and the more woody material (important in coal types) decreases with increasing distance westward within the basin, or farther from the area dominated by terrestrially derived clastics.

Summarized evidence from the EGSP (Nance and others 1979) also indicates that (1) the Devonian shales in the Appalachian Basin are more thermally mature (when compared to those in the Illinois Basin);

(2) thermal maturation increases with depth, but is also significantly influenced by proximity to regional or major local structures, especially within the eastern part of the basin; and (3) the stage of thermal alteration has clearly reached the level of catagenesis in many areas and has even reached metagenesis in areas close to the eastern margin of the basin.

### 2.6.2 Other mineral resources

Although no specific inventory of mineral-industry uses of shales recovered from surface pits and quarries was made during this study, such a review would undoubtedly reveal sites where Devonian shales are so mined. Industries such as the brick, cement, lightweight aggregate, and possibly ceramics are all likely candidates to either utilize shale from surface sites or contemplate such use. Where shale units are near surface, low in organic matter, and associated with carbonate zones, the likelihood of utilization by the construction-materials industry increases. This form of mineral-resource application, being confined to outcrop and near-surface occurrences, would however pose no conflict to the use of the more deeply buried zones for waste disposal.

In most places and at most depths, the shales are uraniferous, although those zones richer in organic matter are similarly richer in their content of uranium. The average concentration of uranium in these Devonian shales is only 0.0012% (Swanson 1961), which is a grade much too low to consider these rocks as viable commercial sources of that energy resource. More recent work by Leventhal and Goldhaber (1978) shows that the uranium content of selected Devonian shales from New York, Kentucky, and West Virginia varies from 0.0002 to 0.0038% and is positively correlated to organic carbon and sulfur contents. The Gassaway Member of the Chattanooga Shale throughout parts of southern Kentucky and central Tennessee, however, contains from 0.0050 to 0.0070% uranium (Conant and Swanson 1961) and has been viewed by some as a long-range, low-grade uranium resource. The Chattanooga Shale is both too thin and too close to the surface throughout most of its extent, and hence is not viewed as favorable for the purposes of this report.

Of the several mined-storage caverns developed within shales of the Appalachian-Illinois Basin region (see Sect. 3.7), only one, in northern Kentucky (site G), is developed within the Devonian-Mississippian shale sequence. This facility has functioned satisfactorily since its construction.

## 2.7 Mineral Resources in Other Rock Units

A broad range of mineral resources is recovered from rock units above and below the Devonian-Mississippian shales in the Appalachian Basin. Principal among these resources are oil and gas, coal, stone (for cement and crushed-stone applications), sand and gravel, salt, gypsum, zinc, barite, brines (for salt), and phosphate (U.S. Bureau of Mines 1978). The areal distribution of oil, gas, and coal resources within the Appalachian Basin is shown on Plate 5.

Oil and gas are produced from sandstone and carbonate reservoirs of every geologic age from the Cambrian through the Pennsylvanian. The entire central area of the Appalachian Basin from south-central New York to northeast Tennessee, including the Black Warrior Basin in northern Alabama and northeastern Mississippi as well as parts of the western extent of the basin into Ohio and Kentucky, contains producing oil and gas fields. Several Devonian or Mississippian reservoirs which are widely developed and the targets of increased exploration include the Oriskany Sandstone, Onondaga Limestone (reef-phase), Maxon Sandstone, "Big Lime," and Berea Sandstone. There are also various sandstones and siltstones within the shale (clastic) sequence from which localized production (generally gas) has been established. Because of the considerable past and ongoing efforts to drill exploratory tests for prospects older and deeper than the Devonian, especially in the Silurian and Ordovician, numerous boreholes have penetrated the shale sequence. One future area of investigation would be a more detailed assessment of the petroleum production above, within, and below the shale sequence, and the regional density of deeper boreholes.

Several depleted gas reservoirs and fields have also been converted for gas storage because their reservoir characteristics are quite amenable to this application provided all abandoned wells can be properly plugged to prevent gas loss. An inventory of these facilities constitutes an essential part of any detailed petroleum-development evaluation as suggested above. Such a study would extend the work of Netherland, Sewell and Associates, Inc. (1975), who did a generalized inventory of the age of production in south-central to western New York, western Pennsylvania, and eastern Ohio.

The Appalachian Basin contains the largest and most extensive resources of bituminous coal in the United States (Averitt 1975). This coal is Pennsylvanian in age, is present in multiple seams, and is recovered by both surface (strip and auger methods) and underground mining. Extensive production of these bituminous coals has been established in eastern Ohio, Pennsylvania, West Virginia, western Maryland, eastern Kentucky, east-central Tennessee, and northern Alabama. Production of Pennsylvanian-age anthracite from the structurally deformed eastern part of the basin has also been developed in eastern Pennsylvania. The states of Kentucky, Pennsylvania, and West Virginia remain among the leading producing areas of coal today (Wilkinson 1980).

The distribution and production of salt by conventional underground mines and solution brining operations from the thick and extensive Silurian Salina Group have been described by Johnson and Gonzales (1978). Salt from these deposits is produced extensively from several counties in northern Ohio and south-central New York. Mississippian salt was produced in the past by solution mining within the Saltville district of far southwestern Virginia. Salt and other minerals are also extracted from natural brines recovered by wells from Mississippian aquifers in the eastern Ohio River Valley in the general vicinity of Charleston, West Virginia.

Gypsum within the Silurian Salina Group is mined underground at three sites in western New York and two in northwestern Ohio. Mississippian-age strata at Saltville, Virginia, are also mined for gypsum at two underground sites.

Although the majority of crushed stone is recovered from surface pits and quarries, there are some exceptions of interest. Several subsurface mines in Ohio recover limestone, the most noteworthy of which is the Barberton Mine where Devonian-age limestone overlain by black shales is mined (Byerly 1975). Most of the sand and gravel are derived from glacially formed deposits at the surface; however, the Sharon Conglomerate in Ohio and several sandstone units elsewhere in the basin are mined in surface quarries as sources of glass and foundry sand.

The zinc produced comes from the east and central Tennessee districts, where the sphalerite mineralization occurs in Cambrian-Ordovician carbonates, and is recovered in several underground mines. Ordovician-age carbonates in central Tennessee are also the source of residual deposits of phosphate, where recovery is by surface mining. The relatively small production of barite is also from residual deposits formed on top of Cambro-Ordovician carbonates found in the fold belt of northwestern Georgia (Cartersville district).

Those several mineral resources other than coal which are surface mined present no real conflict for the possible subsurface utilization of the Devonian-Mississippian shale sequence. Furthermore, those resources recovered via subsurface means from deeper strata are fairly localized in extent when compared to the area underlain by a sufficiently deep and thick shale sequence. Only the widespread nature of coal seams, both those under production and those under lease, pose a conflict as an extensive and valuable mineral resource found in shallower units. Oil and gas, because of their occurrence in strata both shallower and deeper than the shale sequence (and locally within it), can also be expected to represent conflict in some areas.

## 2.8 Hydrology

### 2.8.1 Surface water

Depending on location within the basin and whether streams are flowing through terrain composed of bedrock versus those of unconsolidated materials (commonly glacial), the drainage is derived from differing contributions of direct runoff from precipitation and groundwater discharge (base flow) into streams. Groundwater discharge may range as high as 90% in certain bedrock terrains within the basin, but an average value is closer to 40% (Sinnott and Cushing 1978). Average annual precipitation, which of course accounts for the recharge of aquifers that discharge into streams, varies from about 90 cm in the northern part of the basin to nearly 140 cm in the southern part.

Drainage in a relative small portion of the northern part, namely northeastern Ohio, western Pennsylvania, and western New York, is generally northward into the Great Lakes. South of there, the drainage is either through several river systems that flow eastward into the Atlantic Ocean, or through river systems that connect to the Ohio and Mississippi rivers and eventually flow into the Gulf of Mexico. Eastward-flowing systems include those of the Hudson, Susquehanna, Delaware, Potomac, and James rivers. River networks flowing into the Ohio-Mississippi drainage network include the Allegheny, Monongahela, Muskingum, Kanawha-Little Kanawha, Big and Little Sandy-Guyandotte, Cumberland, and Licking-Kentucky (Bloyd 1974).

Appreciable use of surface water from rivers and lakes (especially Lakes Erie and Ontario adjacent to the basin) is made for municipal, industrial, and recreational applications. Numerous small and several sizeable stream basins in West Virginia, Pennsylvania, Kentucky, and western Maryland are, however, severely contaminated as the result of acid-mine drainage from years of improperly designed surface and underground coal mines. In some areas, these mine waters, which are very high in iron content and have pH values as low as 3, have also contaminated some groundwater aquifers (Sinnott and Cushing 1978).

### 2.8.2 Groundwater

The groundwater regime in the highly deformed area east of the Appalachian Front is not discussed in this report because of the complexity of the geohydrology in that terrain, and also because rock units in this structurally complex area are unlikely candidates for further consideration.

Occurrence of groundwater within other sections of the basin can be categorized into three types: (1) that found in either bedrock or unconsolidated glacial materials in areas covered by glacial drift; (2) that which is in bedrock beneath unglaciated terrain; and (3) that which occurs in alluvial aquifers along stream valleys. Although there is a profound stratigraphic break between consolidated rock and unconsolidated sediment in the areas blanketed by glacial drift, there exists a hydraulic continuity between the drift and the uppermost bedrock. Piper (1972) has described a transition zone between characteristically fresh water of glacial drift and saline water that occurs in the deeper bedrock. Piezometric levels in drift and in the uppermost bedrock fluctuate correlatively in accordance with groundwater recharge and withdrawal so that the chemical composition of the water of the lowest drift layers commonly resembles that of the bedrock water and vice versa. At the present state of the art, neither the tops nor the bottoms of these transition zones can be readily defined. Any natural relationship of equilibrium that may have existed within these zones has probably been drastically affected in areas where there has been extensive commercial withdrawal of brines from deep bedrock sources, where there has been heavy withdrawal of fresh water from drift, or where penetrating wells have been inadequately cased or improperly plugged when abandoned.

In the drift-covered areas, the bulk of fresh water is primarily derived from the coarser-grained units in the drift. Where the drift is several hundred meters thick, it is easily recharged, can store large volumes of water, and can sustain moderate withdrawals over long periods of time. Single-well yields from drift can range from several hundred to a few thousand liters per minute. Because drift is commonly inhomogeneous and can contain predominantly clay layers, there are areas where the glacial sediments are not good groundwater sources. Alluvial aquifers, especially where they are in association with glacial outwash that fills buried valleys, are also excellent sources of groundwater. The hydraulic conductivities of nonclay drift and alluvial aquifers are several orders of magnitude greater than those of the region's bedrock aquifers (Bloyd 1974).

In the unglaciated portions of the basin, most fresh water derived from bedrock comes from rather shallow depths. Near the edges of the basin where Silurian-Devonian carbonate rocks are near the surface, these rocks are major aquifers that are capable of yielding from 400 to 1200 L/min of mostly hard water that is often high in sulfate and chloride (Piper 1972). Away from the basin margins, principal aquifers are sandstones in the Pennsylvanian (Allegheny and Pottsville formations) and Mississippian (upper part of Berea Sandstone and Cuyahoga Formation). Where these sandstone aquifers are involved, the water is soft and low in dissolved solids unless they are close to areas of coal mining where iron contents are typically high. Well yields up to 800 L/min are possible.

Below the Berea Sandstone, little or no water is available until strata below the Devonian-Mississippian shale sequence are reached, and there the waters are typically highly saline brines. These brines have been pumped commercially from stratigraphic units both above and below the Devonian-Mississippian shales. Large sections of the Devonian-Mississippian shale sequence are almost totally impermeable; however, the integrity of the shales can be weakened hydrologically in areas where brines have been developed, where boreholes have been drilled and not properly cased, or where fractures are abundant. Sinnott and Cushing (1978) report that some shale zones in eastern West Virginia have yielded small amounts of hard groundwater high in iron.

Outside of the areas within the basin where glacial-drift and/or alluvial aquifers constitute reliable groundwater sources, there is relatively small use of bedrock-contained groundwater. Aquifers beneath the shale sequence contain only brines, and the sites for commercial extraction of these brines are well known and localized. The shale (clastic) sequence itself, with the exception of portions of the Berea Sandstone in local areas, does not contain utilized aquifers although certainly sandstone and siltstone zones, where present, contain water. Thus the only bedrock aquifers from which fresh groundwater is obtained lie stratigraphically above the shale sequence.

There has been some utilization of deeper salaquifers throughout the Appalachian Basin for injection-disposal of various industrial effluents. Here again, the magnitude of this practice is rather small for the purposes of this report, and the sites do not interfere with most areas underlain by the shale sequence. The number and location of such industrial-disposal wells have been inventoried by Warner and Orcutt (1973).

### 2.9 Seismic Activity

Figures 4 and 5 show that large areas within the extent of the Appalachian Basin either have never experienced a seismic event of Modified Mercalli Intensity V or greater, or lack any appreciable seismic hazard as measured by the probability of ground shaking according to the method of Algermissen and Perkins (1976).

There has, however, been a slightly greater incidence of moderate-sized seismic events in the Cleveland and northeast Ohio area, and within a small trend near Attica, New York, farther to the northeast. These two zones account for the assignment of a seismic-shaking hazard value of 7 to part of the northern half of the basin, whereas most of the basin is characterized by values of 4 or less.

Although the zone of influence from the New Madrid seismic zone in the general Missouri-Illinois-Kentucky area does not effectively extend far enough east to affect the Appalachian Basin, the corresponding zone related to the Charleston, South Carolina, seismic center does influence the southeastern and south-central parts of the basin. The small concentration of moderate-sized events in western North Carolina and eastern Tennessee is probably genetically unrelated to the events that have frequented the immediate Charleston area, although a clear understanding of earthquakes in the eastern United States is not well established because there is a lack of a cause-and-effect relationship between seismic events and faults detectable at the surface. Bollinger (1973), in studying the distribution of seismic events from Virginia to Georgia, most of whose epicentral locations lie outside the limits of the Appalachian Basin, has however interpreted that several linear zones of seismicity are aligned essentially perpendicular to the general

Appalachian structural trend in addition to those events aligned parallel to the regional trend itself. The most significant of these extends northwestward from coastal South Carolina into western North Carolina. There are indications that deep-seated, possibly basement, faults are involved in some of the seismic activity along this zone.

Despite the northeast Ohio-western New York trend within the basin and the potential influence of the Charleston, South Carolina, trend from outside the basin, the general level of seismicity inside the Appalachian Basin is quite low, and the overall seismic hazard to most of the northern and north-central parts is similarly low. Even though the southern portion of the basin might experience some "felt-zone" shaking if a future seismic event were to occur along the Charleston trend, the seismic hazard in this region appears to be well within acceptable limits.

## 2.10 Summary and Regional Evaluation

On the basis of this preliminary assessment, much of the Appalachian Basin appears to exhibit a suitable geologic framework, while the Middle to Upper Devonian and Mississippian shale (clastic) sequence within that region also appears to display favorable characteristics that might lend one or more shale units for the subsurface disposal of radioactive wastes. The basin has been tectonically stable since the end of the Paleozoic when its eastern margin was involved in various deformational events which produced the Appalachian Mountains. With the exception of numerous folds and thrust faults, also along its eastern margin, the strata within the basin proper show evidence of only gentle warping, and regional dips are for the most part less than a degree throughout. There is one principal cross-basin zone of faulting, but it is primarily narrow and is localized when compared to the large regional expanse of the entire basin. There are large sections of the basin which lack on the basis of readily discernible geologic data any major folds, faults, or extensive zones of fractures. Joints are developed in many of the strata at the surface, but in most such areas it remains to be demonstrated that these smaller-scale structures affect rock units in the deeper subsurface.

Seismic activity within the basin has likewise been minimal; many large areas have never experienced a historic event of an intensity greater than V on the Modified Mercalli Scale, and many areas have never experienced any historic events. Seismic-hazard rating for most of the basin is similarly low; only a small area in northeastern Ohio and western New York shows values above the generally low figures for the basin as a whole, and even here the difference is slight. Some external effect to the southeastern and south-central parts of the basin might be anticipated from the historically significant Charleston, South Carolina, seismic center and the possibly related northwest-trending belt that reaches western North Carolina. Slightly higher seismic hazard values in this part of the basin reflect the proximity of these seismic areas which lie well to the east of the basin.

The shale or clastic sequence reaches several thousand meters in thickness, and individual, more promising intervals within the sequence generally range from 80 to >300 m in thickness. These same intervals, where they attain acceptable thicknesses, occur within depth ranges generally of 600 to 900 m, although some are shallower or deeper depending on exact location within the basin.

There are numerous black and dark brown shales which are rich in organic matter, exhibit higher natural radioactivity, and commonly yield gaseous hydrocarbons. Such zones have already proven to be gas productive for many years in portions of Ohio, Pennsylvania, West Virginia, Kentucky, Virginia, and New York. The most sizeable gas fields are located in southwest West Virginia and easternmost Kentucky. There are conversely several shale zones that are either interspersed with the black to dark brown intervals or laterally equivalent with them where lesser amounts of organic matter are present, and where the hydrocarbon potential, especially if the thermal maturation has not been appreciably greater, is decidedly lowered. Porosity and permeability in all the shale intervals is low unless natural fractures have been effective. There is agreement that fractures in some areas are related to more deeply buried structures, are related to thrust faults in other areas, and may be stratigraphically controlled in others. There seems to be little evidence which ties surface joints to deeper fracture porosity;

similarly, there is no agreement on how to detect subsurface fractures outside those areas where established gas production has already proven their existence.

Several other mineral resources are produced within the basin, and those with the greatest potential for conflict with the shale sequence are (1) conventional oil and gas and (2) coal because the extent of development in each is large and embraces areas where sufficiently thick shales occur at moderate depth. Where reservoirs deeper than the shales have been actively sought, penetrating boreholes also become a factor. Although coal lies shallower than the shales, it poses conflicts in the tieing up of surface acreage.

Groundwater does not appear to present the same potential conflicts as petroleum and coal. Relatively little groundwater is used within the basin, and that which is used comes mainly from very shallow, non-bedrock aquifers. Groundwater deeper than the shale sequence is all saline and is not developed. Admittedly, more geohydrologic information specifically about the shale sequence that is not pursued as an aquifer is needed for a full characterization; the same holds in even a larger sense for any smaller study areas.

Within the Appalachian Basin, there exist sizeable areas in which thick deposits of undeformed shales occur at reasonable depths. There are furthermore within these areas shales that are lower in their hydrocarbon potential, have not been extensively affected by boreholes, and lie outside areas with competing resource applications. Although much more detailed study is needed, there clearly is a regional potential to the shale sequence within certain areas of the Appalachian Basin.

# 3. ILLINOIS BASIN

## 3.1 General Setting

The Illinois Basin is a spoon-shaped sedimentary and structural basin in the eastern interior region of the United States. Trending north-south, the basin is about 500 km long and about 350 km wide. Within the basin lies most of Illinois as well as all of southwestern Indiana and parts of western Kentucky and eastern Missouri (see Fig. 1). Bordering the basin are the Cincinnati Arch system on the east, the Wisconsin and Kankakee arches to the north, the Mississippi Arch and Ozark Dome on the west, and the Pascola Arch on the south (Bond and others 1971; Bristol and Buschbach 1971).

Most of the Illinois Basin lies in the Till Plains section of the Central Lowland province, according to Fenneman (1946). This glaciated region consists chiefly of young till plains which lack typical morainic topography and lakes. The southeast one-third of the basin (southern Indiana and western Kentucky) is in the western section of the Interior Low Plateaus province; this part of the basin was not glaciated and is characterized by low, maturely dissected plateaus with silt-filled valleys (Fenneman 1946). The elevation of the land surface ranges from about 100 m in the south to more than 200 m in some of the upland areas.

## 3.2 Geologic and Tectonic Framework

The Illinois Basin is a large region of the craton characterized by regional warping and differential sinking since Precambrian time. A thick sequence of Paleozoic strata was deposited in the basin, and these sedimentary units now dip gently at a rate of some 10 m/km (i.e., 0.5 degree) toward the deep part of the basin (Plate 3). Total thickness of the sedimentary sequence ranges from about 1000 to 3000 m around the perimeter of the basin to as much as 4300 m in the deepest part (Buschbach 1971). Carbonates, shales, and sandstones representing each geologic period from Cambrian through Pennsylvanian are present in the basin. Bedrock in most areas north of the Ohio River is mantled by Pleistocene glacial deposits that are 10 to more than 100 m thick (Fig. 12). At the south end of the basin, Cretaceous and Tertiary sand and clay of the Mississippi Embayment overlie Paleozoic strata. Most of the data presented in this part of the report are based on publications by Atherton (1971), Bond and others (1971), Bristol and Buschbach (1971), Buschbach (1971), and McGinnis and others (1976).

Precambrian basement rocks, consisting mainly of granites and rhyolites, were first inundated over most of the region in Late Cambrian time. A thick section of pre-Knox sandstone, siltstone, shale, and carbonates attained a maximum thickness of 1000 m in the northern part of the basin. The depocenter of the basin shifted to the south end of the basin after that, and up to 2500 m of sediments were deposited from Late Cambrian through Middle Ordovician time (Buschbach 1971). Principal rock units formed during this period include the Knox Megagroup (mostly dolomite), St. Peter Sandstone, Glenwood Shale, and Ottawa Megagroup (carbonates).

In Late Ordovician time the Maquoketa sequence of silty and dolomitic to calcitic, argillaceous sediments was deposited across the basin. The Maquoketa interval is generally 50 to 100 m thick over most of the basin, but it thickens eastward across Indiana and is more than 200 m thick on the west flank of the Cincinnati Arch. Overlying this shale unit is a southward-thickening wedge of limestones and dolomites of the Hunton Megagroup (Silurian through Middle Devonian in age). These carbonates are locally as much as 550 m thick in southern Illinois and adjacent parts of Kentucky.

During Late Devonian and earliest Mississippian time, an extensive deposit of dark argillaceous sediments was laid down across the Cincinnati Arch and Illinois Basin. The rock unit, called the New Albany Shale in the Illinois Basin and the Chattanooga Shale around the Cincinnati Arch, was a westward-thinning wedge of fine clastics eroded from the mountains rising on the east side of the Appalachian trough (Atherton 1971). Thickness of the unit in the Illinois Basin generally ranges from about 30 to 125 m. The Illinois Basin was sinking slowly during this time, and the resulting systemic boundary between the Devonian and Mississippian is transitional.

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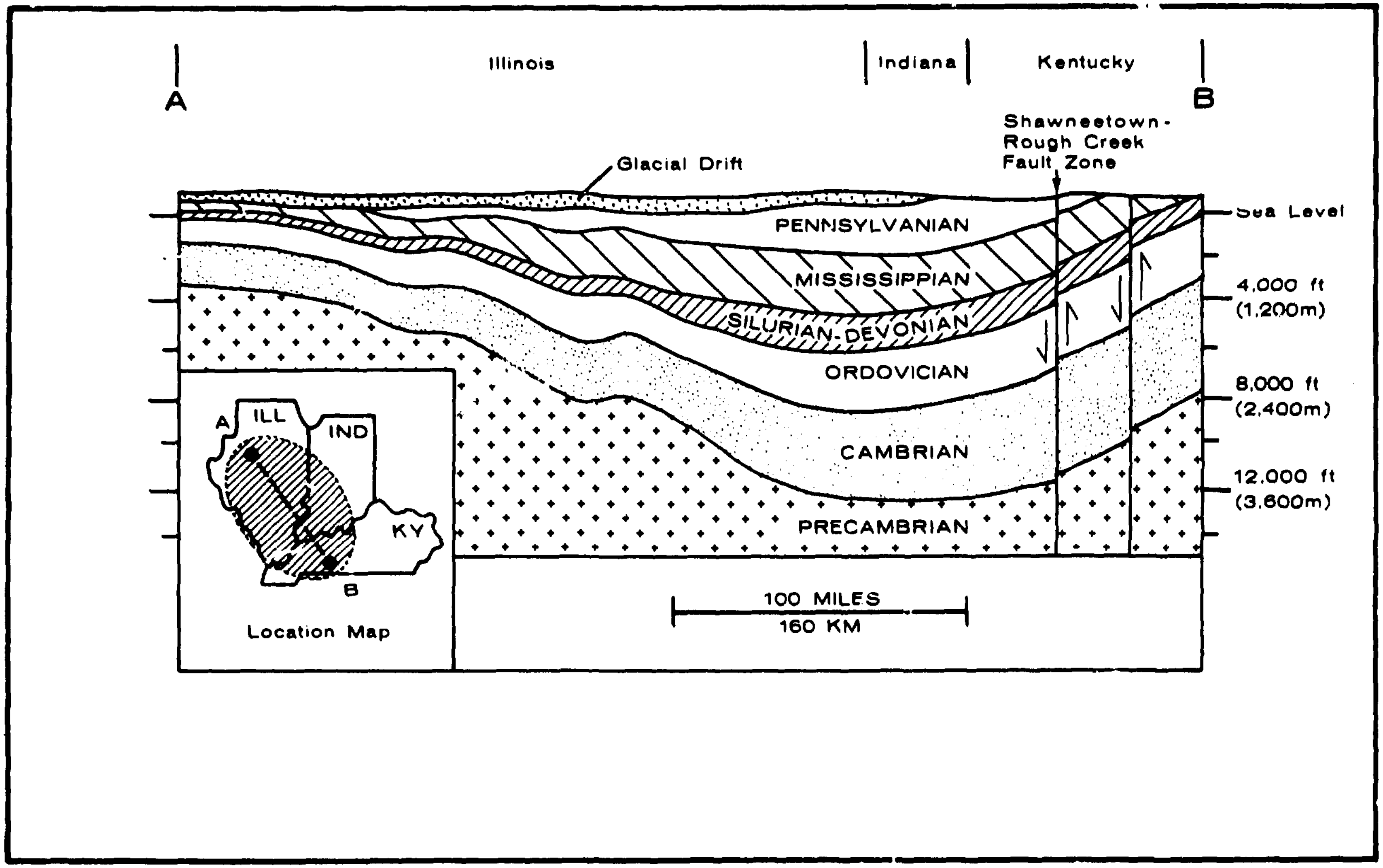


Fig. 12. Schematic northwest-southeast cross section through the Illinois Basin. Adapted from Bergstrom 1968.

Overlying the New Albany Shale are shales and siltstones of the Borden Formation in the east part of the basin and carbonates and shales of the Burlington, Keokuk, and Warsaw formations in the west. These units in turn are overlain by the Salem, St. Louis, and Ste. Genevieve limestones, which extend over most parts of the basin. Lower and Middle Mississippian units above the New Albany Shale have an aggregate thickness of about 300 to 600 m and reach their maximum thickness in southern Illinois. The basin continued to sink slowly through Late Mississippian (Chesterian) time, and from 100 to 300 m of cyclic alternations of limestone-dominated and clastic-dominated units were formed.

Following Late Mississippian deposition, the seas withdrew and the Illinois Basin region was tilted down to the south and leveled by erosion (Atherton 1971). During this erosional period the La Salle Anticline began its development. Pennsylvanian sediments were laid down on the erosional surface in a series of cyclic units consisting mainly of shale and sandstone with thin, but extensive, beds of limestone, coal, and underclay. The area underlain by Pennsylvanian strata has subsequently been reduced by erosion, but the remaining strata are generally 200 to 600 m thick in the basin and are as much as 1000 m thick locally in western Kentucky.

Pennsylvanian sedimentation was followed by a long period of erosion which removed a great thickness of strata, probably at least 1500 m in southern Illinois. Although only gentle warping was occurring in most parts of the basin, several events that took place in and near the region included uplift of the Cincinnati Arch, faulting along the Shawneetown-Rough Creek fault zone and in the fluorspar district of southern Illinois and western Kentucky, and continued activity along the La Salle Anticline and the Du Quoin Monocline (Atherton 1971).

Whereas the Illinois Basin was a region of erosion throughout most (or all) of the Mesozoic Era and Tertiary Period, the nearby Mississippi Embayment south of the basin subsided during much of the Tertiary and received a thick sequence of sands and clays. Pleistocene glaciers spread southward across most of the basin, extending at times as far south as the Ohio River. The region covered by glaciers was depressed by the great load of ice, and the northern part of the region is now rebounding in response to the final retreat of glacial ice.

Several major structural features within the Illinois Basin affect the Upper Devonian-Lower Mississippian shales and younger strata (Plates 2 and 3). The La Salle anticlinal belt, which was first activated after Late Mississippian deposition, is a complex of minor structures that are aligned in a north-northwest-trending belt across the north-central part of the basin. The structure is asymmetrical, with steep dips to the west and gentle dips to the east (Bristol and Buschbach 1971).

The Shawneetown-Rough Creek fault zone extends east-west across southern Illinois and northwestern Kentucky. The zone is bounded by a high-angle reverse fault that is uplifted on its south side (Bristol and Buschbach 1971). The fault zone is crossed by a northeast-trending system of faults known as the Wabash Valley faults in southeast Illinois and by a complex system of faults making up the southern Illinois-western Kentucky mineralized region.

Despite these several intersecting zones of faulting, the remainder of the Illinois Basin has been tectonically stable since Precambrian time. As noted, rather localized faulting has cut the Devonian-Mississippian shale sequence in the southern part of the basin, and a sharp anticlinal uplift extends across the central and northern part of the basin, but the region has not been subjected to major orogenic processes. Owing to the known structural complexities in the south and the proximity of this area to the New Madrid seismic activity, the southern part of the basin is less appealing. A study of the effect of these localized tectonics upon fracturing within the shale sequence, however, might be informative.

### 3.3 Stratigraphy of the New Albany Shale

Upper Devonian-Lower Mississippian shales of the Illinois Basin are referred to as the New Albany Shale (see Figs. 2 and 6). This unit is characterized as a sequence of interbedded brown, black, and gray shales that are typically 30 to 120 m thick. New Albany strata are mainly equivalent to the Antrim and Ellsworth shales of the Michigan Basin and to the Chattanooga, Ohio, and correlative shales of the Appalachian Basin. Equivalent strata also extend west and northwest of the Illinois Basin across much of Missouri and Iowa (Collinson and others 1968).

Until recently, the New Albany Shale was subdivided into different units in the three states of the Illinois Basin, but recent coordinated studies sponsored by the U.S. Department of Energy's Eastern Gas Shale Project have enabled standardization of subsurface stratigraphic nomenclature throughout most of the basin (Fig. 13).

Inasmuch as the major emphasis of this report is on the subsurface aspects of these shales, this newly accepted subsurface nomenclature will be followed. The New Albany Shale is therefore subdivided, in ascending order, into the (1) Blocher Shale, (2) Sylamore Sandstone, (3) Sweetland Creek Shale, (4) Grassy Creek Shale, (5) Saverton Shale, (6) Louisiana Limestone, (7) "Glen Park" Formation, and (8) Hannibal Shale. In the Illinois part of the basin, the New Albany Shale has been assigned group status, and thus these subdivisions represent formations. The Indiana Geological Survey contrastingly regards the New Albany Shale as a formation, thus making the subdivisions members.

Although the vertical sequence of rock units is well established in various parts of the basin (Fig. 14), there are some problems with regard to correlation because of facies changes and interfingering relationships within the New Albany Shale (Fig. 15).

### 3.3.1 Blocher Shale

The Blocher Shale is brownish black, calcareous, dolomitic, carbon rich, and pyritic, and is present in southeast Illinois as well as farther east and south across the Indiana and Kentucky parts of the basin. The high carbonate content of the unit is reflected by high resistivity readings on electric logs; a relatively low radioactivity is reflected by a low gamma-ray count (Fig. 14). In parts of southwest Indiana, the Blocher contains a brown, argillaceous limestone at its base. The thickness of the Blocher typically ranges from 10 to 20 m throughout much of the basin, but it locally reaches about 25 m in the vicinity of the Ohio River.

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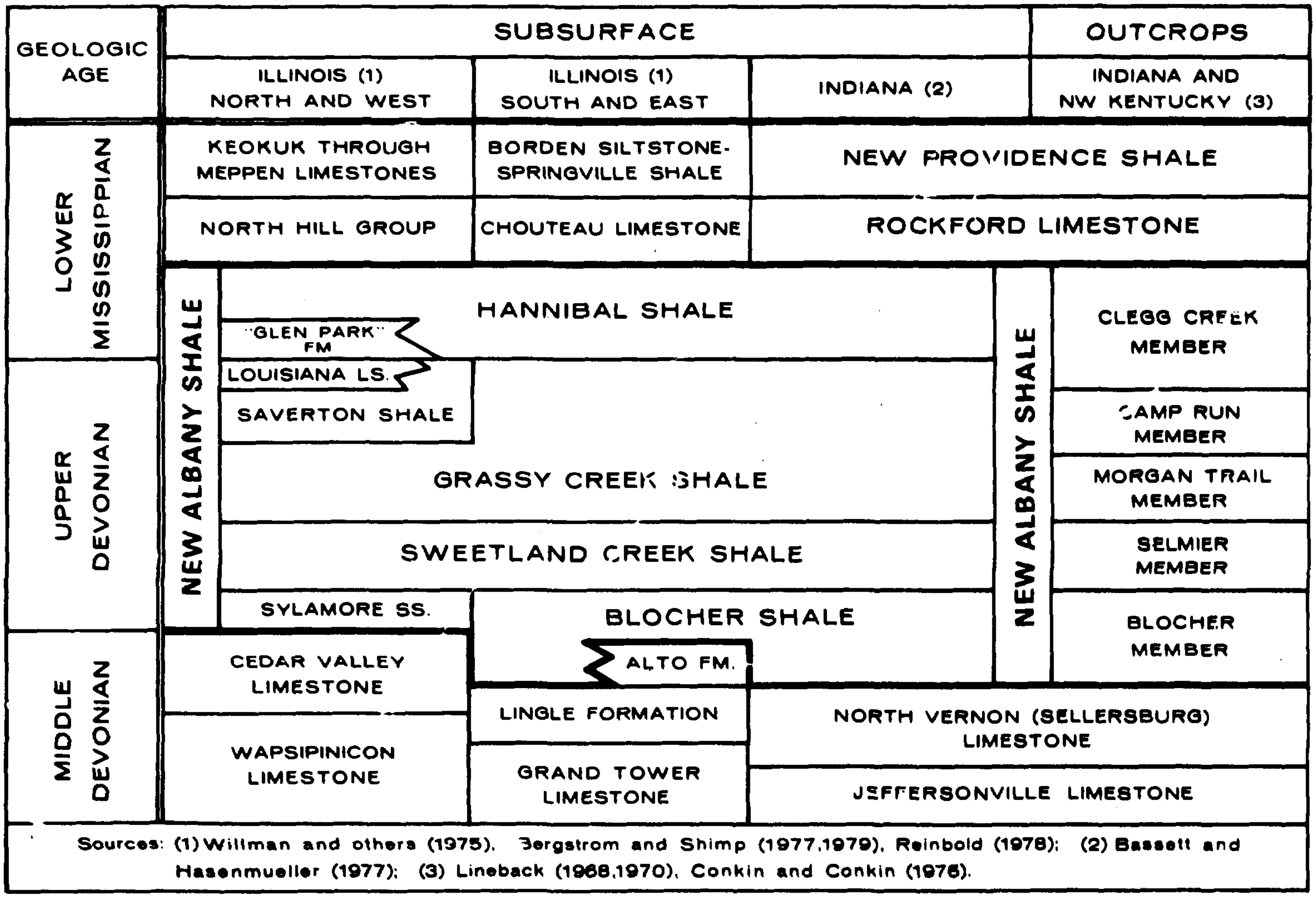


Fig. 13. Correlation chart of the New Albany Shale and adjacent stratigraphic units within the Illinois Basin.

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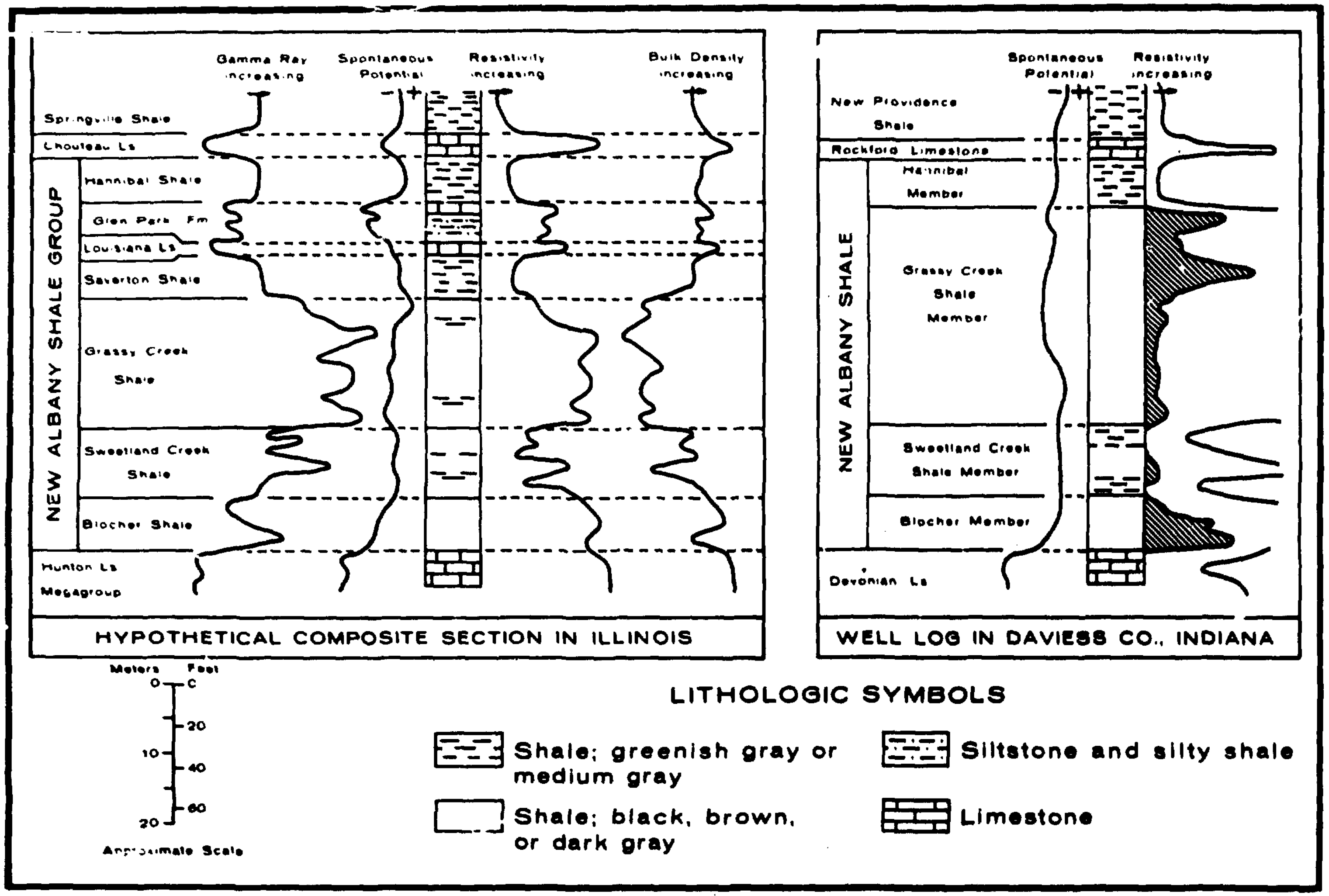


Fig. 14. Borehole logs showing the stratigraphy of the New Albany Shale in the Illinois Basin. Illinois data adapted from Reinbold 1978; Indiana data adapted from Bassett and Hasenmueller 1977.

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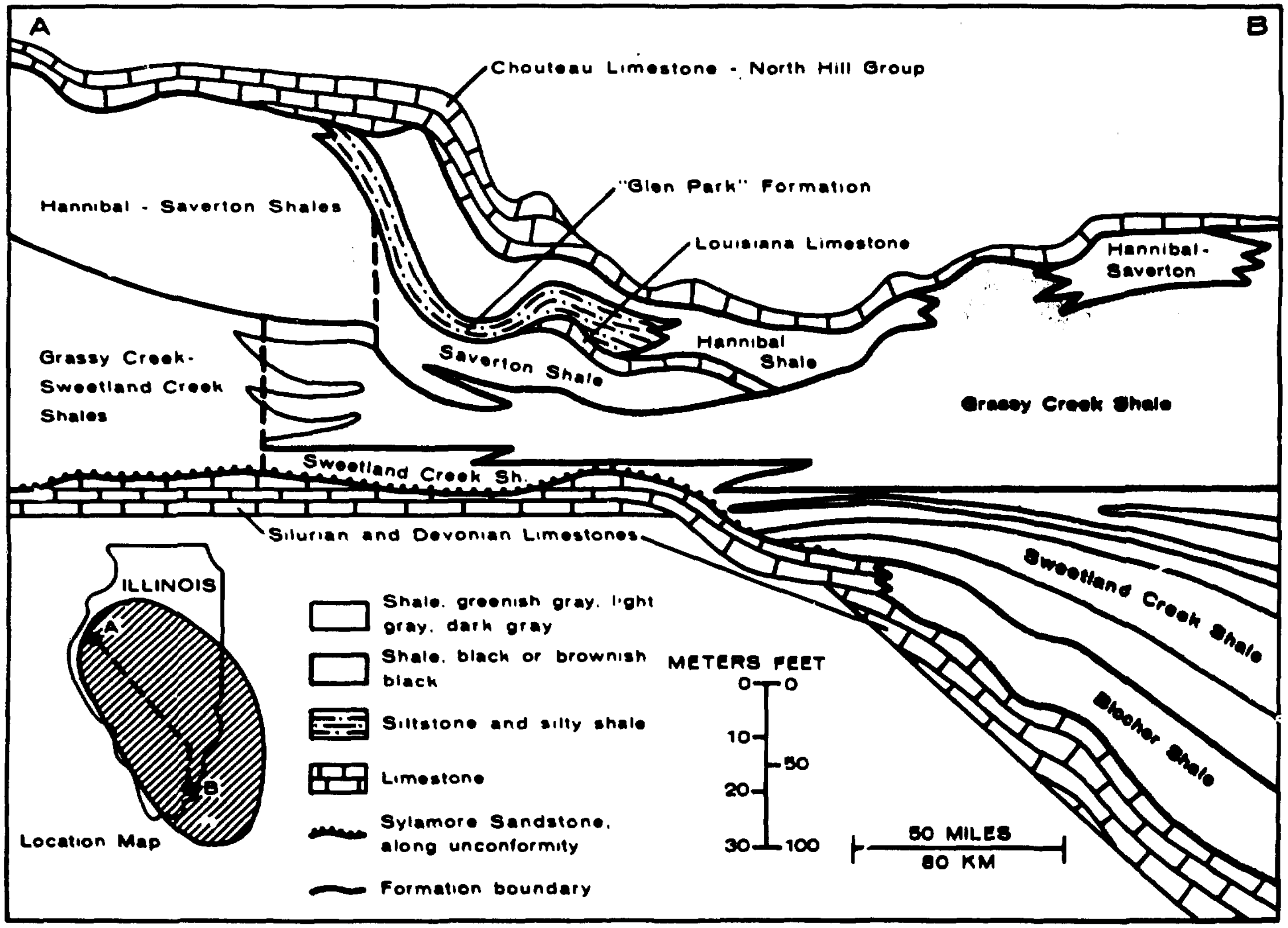


Fig. 15. Generalized northwest-southeast cross section of the New Albany Shale in the Illinois part of the Illinois Basin. Adapted from Reinbold 1978.

### 3.3.2 Sylamore Sandstone

The Sylamore Sandstone is the basal unit of the New Albany Shale in much of central and western Illinois and consists of well-rounded, fine to medium quartz grains. Rarely more than 2 m thick and typically only a few centimeters, the unit commonly is but a thin layer of sand embedded in the base of the overlying shale. The Sylamore Sandstone grades eastward into thin sandy beds within the upper part of the Blocher Shale and the lower part of the Sweetland Creek Shale in southeastern Illinois. Even where present, this unit is difficult or impossible to identify, except in cores, and thus is generally not mapped as a separate stratigraphic division.

### 3.3.3 Sweetland Creek Shale

The Sweetland Creek Shale is mainly gray and greenish gray in the Illinois Basin, although some beds are dark gray to black. In southeast Illinois and locally in parts of Indiana, the unit is largely dark gray or black. Samples are not easily separated from those of the underlying and overlying shales in the southeast part of the basin, but the unit can be readily identified from well logs because it displays lower resistivity and gamma radiation than the overlying Grassy Creek Shale. The Sweetland Creek Shale is only a few centimeters thick in southwest Illinois, but reaches about 15 m thick in northwest Illinois and parts of Indiana and is as much as 60 m thick in southeast Illinois. The Sweetland Creek Shale is equivalent ot the Selmier Shale in outcrops on the east side of the basin in Indiana and Kentucky (Fig. 13).

### 3.3.4 Grassy Creek Shale

The Grassy Creek Shale is a brownish black to black, pyritic, and noncalcareous shale that is rich in organic matter and widespread throughout the Illinois Basin. Typically the unit is 15 to 30 m thick in much of the basin, yet it reaches a thickness in excess of 45 m locally in southeast Illinois. The shale can generally be recognized on well logs because of its high resistivity and gamma-ray values. In some areas, particularly toward the northwest, the unit contains much interbedded greenish gray shale (Fig. 15) and exhibits somewhat lower resistivity and gamma-ray readings. The Grassy Creek Shale is equivalent to the Morgan Trail, Camp Run, and lower Clegg Creek members in outcrops along the east side of the basin (Fig. 13).

### 3.3.5 Saverton Shale

The Saverton Shale consists of bluish to greenish gray, silty shale that is recognized mainly in western Illinois. It contains thin arenaceous and calcareous beds, and ultimately grades upward into calcareous siltstone. The formation is as much as 30 m thick in western Illinois. In eastern and southern Illinois, the unit commonly is not distinguishable from the overlying Hannibal Shale, and this has resulted in a sequence named the Hannibal-Saverton Shales undifferentiated. This condition is especially true where the Saverton Shale is not overlain by either the Louisiana Limestone or the "Glen Park" Formation.

### 3.3.6 Louisiana Limestone

The Louisiana Limestone is a light-gray to buff, lithographic limestone with thin shale partings and interbeds of dolomite. Restricted to a narrow east-west belt only 15 to 30 km wide in west-central Illinois, this lenticular deposit is only 3 to 6 m thick on the average and 12 m in maximum thickness. Elsewhere in Illinois the underlying Saverton Shale, or the Grassy Creek Shale, is in contact with the overlying Hannibal Shale.

### 3.3.7 "Glen Park" Formation

In west-central Illinois, the lower part of the Hannibal Shale grades laterally into beds of silty shale, siltstone, sandstone, and limestone which are referred to as the "Glen Park" Formation. The "Glen Park" typically ranges from 5 to 10 m in thickness.

### 3.3.8 Hannibal Shale

The Hannibal Shale is mainly greenish gray to gray in color and consists in part of argillaceous siltstone and silty shale. In parts of Illinois it also contains some black shale, particularly near the top. The unit attains a maximum thickness of about 30 m in the west (Calhoun County, Illinois) but thins eastward and is difficult to differentiate from the underlying Saverton or Grassy Creek shales in the deeper parts of the basin and in Indiana. The Hannibal Shale is characterized by low to moderate resistivity and gamma-ray values, and correlates with the upper part of the Clegg Creek Member in eastern outcrops (Fig. 13). Overlying the Hannibal is a light brownish or greenish gray, lithographic to fine-grained limestone that typically is 3 to 5 m thick. This unit is called the Chouteau Limestone in much of Illinois, but toward the northwest, correlative strata are called the N[illegible] Hill Group. The term Rockford Limestone is used for equivalent rocks [illegible] much of Indiana and Kentucky.

## 3.4 Distribution, Thickness, and Depth

The New Albany Shal[illegible] is a widespread unit that underlies almost all parts of the Illinois Basin. The updip edge of the unit has been eroded around the perimeter of the basin, but the unit thickens toward the axis of the basin (Plate 4). Total thickness of the New Albany Shale typically ranges from 30 to 120 m while its depth [illegible]elow the surface ranges from 150 to 1200 m. The unit is thickest in the deep part of the basin and toward the southeast, but is also quite thick in a second area to the northwest, where a separate depocenter within the Illinois Basin has been referred to as the Petersburg Basin (Bergstrom and Shimp 1977).

The greatest thickness (about 120 m) of New Albany Shale occurs near the Ohio River in parts of Hardin and Gallatin counties, Illinois, and Union, Webster, and Crittenden counties, Kentucky (Plate 4). In this area the top of the shale sequence is at considerable depth, or about 1200 m below the surface. In much of the remaining deep part of the basin, where the shale is more than 900 m below the surface, thickness ranges from 30 to 100 m.

In the Petersburg Basin area, the New Albany Shale ranges from 30 to 90 m thick and consists mainly of the light gray, greenish gray, and dark gray shale facies that are not particularly rich in organic matter (Fig. 15). In a substantial part of this area the top of the shale is 300 to 900 m below the surface. Where the shale is slightly more than 60 m thick, it is 300 to 450 m deep and extends across parts of Greene, Macoupin, Morgan, Sangamon, Christian, Menard, Logan, DeWitt, and McLean counties, Illinois, in a northeast-trending belt.

On the east side of the basin, the New Albany Shale varies from 30 to 50 m thick over a large area. In much of this eastern shelf the top of the shale is from 300 to 900 m below the surface. As much as 50 to 60 m of shale is present between depths of 750 and 900 m in parts of Knox, Daviess, Pike, Dubois, Warrick, and Spencer counties, Indiana. This south-southeast-trending belt also extends into adjacent portions of Kentucky.

### 3.5 Physical, Mineral, and Chemical Properties

Physical properties reported include the density, porosity and permeability, and hardness of various units of the New Albany Shale from several cores recovered in the three-state region. The density of the shale ranges from about 2.2 to 2.7 g/cm$^3$. The average density in five wells ranged from 2.36 to 2.53 g/cm$^3$ with a median value of 2.47 g/cm$^3$ (Table 9). Harvey and others (1977) reported that in cores from Sangamon County, Illinois, and Christian County, Kentucky, the density averaged 2.41 and 2.48 g/cm$^3$ respectively.

Porosity of the shale in the Illinois Basin is low; an average value in four wells ranged from 0.95 to 4.64 vol %, and the median was 2.67 vol % (Table 9). Permeability of the shales is also very low inasmuch as it was not detectable in samples from the one well that was tested.

The relative hardness of various shale samples was determined with a Shore scleroscope hardness tester, which is a dynamic-rebound type of test commonly used to determine the hardness of metals, plastics, and other uniform materials (Harvey and others 1977). Shore hardness

Table 9. Physical properties of the New Albany Shale from five coreholes in the Illinois Basin

| Location of well | Well No. | Average bulk density ($g/cm^3$) | Average porosity (vol %) | Average permeability |
|---|---|---|---|---|
| Clark County, Ind. | I-2 | 2.36 | 0.95 | |
| Clark County, Ind. | M-1 | 2.53 | | |
| Sullivan County, Ind. | P-1 | 2.48 | 3.32 | Not detectable |
| Effingham County, Ill. | T-1 | 2.49 | 4.64 | |
| Christian County, Ky. | O-1 | 2.48 | 1.75 | |
| Median | | 2.47 | 2.67 | |

Sources: From Kalyoncu 1979; Kalyoncu and Snyder 1978; Kalyoncu and others 1979b, 1979e, 1979f, 1979g.

values reported by these investigators range from 20.2 to 22.7 for core samples from the Sangamon County, Illinois, well to values of 21.4 to 34.6 for the Christian County, Kentucky, core samples. Shaffer and others (1978) determined that shale units characterized by high gamma-ray readings and an abundance of kerogen, unless spores are numerous, are harder than greenish gray shales with low gamma-ray values.

Mineralogical studies show that black shales of the New Albany Shale contain quartz as the dominant mineral and also contain illite (2M polymorph) and chlorite in a weight ratio of approximately 2:1 (Patton 1977). Other minerals include pyrite, marcasite, mixed-layer clays, kaolinite, and dolomite, along with minor amounts of calcite and feldspar. Pyrite and marcasite are the dominant accessory minerals. They comprise a high percentage of some thin beds or laminae, and they occur as tiny disseminated crystals, irregular blebs, nodules, and as cement in some coarse-grained beds (Patton 1977). Greenish gray units in the New Albany Shale have a similar mineralogy, but they contain more mixed-layer clay minerals.

Harvey and others (1977) report that in cores from Sangamon County, Illinois, and Christian County, Kentucky, samples are rich in illite-type clay and quartz, and also contain lesser amounts of calcite, dolomite, pyrite, chlorite, and feldspar. Kaolinite was not detected in any of these samples. Studies of the New Albany Shale from four coreholes (Table 10) show that the dominant mineral is illite, and that other minerals include quartz, pyrite, and carbonates.

Chemical analyses of organic-matter-rich New Albany Shale near Indianapolis, Indiana, provided the following data (Patton 1977):

| Component | Weight percent | Component | Weight percent |
|---|---|---|---|
| $SiO_2$ | 50.34 | $K_2O$ | 4.56 |
| $TiO_2$ | 0.88 | $P_2O_5$ | 0.102 |
| $Al_2O_3$ | 14.38 | $CO_2$ | 3.77 |
| $Fe_2O_3$ | 3.83 | $H_2O$ | 1.27 |
| MnO | 0.034 | S | 1.56 |
| MgO | 2.59 | C | 9.0 |
| CaO | 3.06 | H | 1.34 |
| $Na_2O$ | 0.55 | | |

Analyses of black, olive black, and greenish gray shale samples from two cores produced similar results (Harvey and others 1977):

| Component | Weight percent |
|---|---|
| $SiO_2$ | 48.0 to 65.0 |
| $Al_2O_3$ | 9.0 to 15.0 |
| $Fe_2O_3$ | 2.5 to 6.0 |
| MgO | 1.0 to 4.0 |
| CaO | 0.4 to 7.0 |
| S | 0.2 to 2.0 |
| C | 1.0 to 11.0 |

## 3.6 Mineral Resources in Shale Units

### 3.6.1 Natural gas and oil

A great many wells have been drilled in the Illinois Basin in the search for oil and gas. Gas shows have been reported from the Upper Devonian-Lower Mississippian shale sequence in each of the three states, and natural gas has been produced commercially from fracture-type reservoirs in ten fields in Indiana. Gas shows were reported for about 6% of the 1400 wells penetrating the New Albany Shale in Indiana (Bassett

Table 10. Mineralogy of New Albany Shale from four coreholes in the Illinois Basin as determined by petrographic and x-ray diffraction studies

| Mineral | Well location and identification number | | | |
|---|---|---|---|---|
| | Clark County, Ind., M-1 | Sullivan County, Ind., P-1 | Effingham County, Ill., T-1 | Christian County, Ill., O-1 |
| PETROGRAPHIC DETERMINATION | | | | |
| Illite | D[a] | D | D | D |
| Quartz | P | P | P | P |
| Pyrite | V | P | P | P |
| Carbonates | V | P | P | P |
| X-RAY DIFFRACTION DETERMINATION | | | | |
| Illite | D | D | D | D |
| Quartz | ND | P | P | P |
| Pyrite | ND | P | A | P |
| Calcite | ND | ND | ND | P |
| Nahcolite | ND | ND | ND | P |
| Shortite | ND | ND | P | P |
| Siderite | ND | ND | ND | P |
| Kaolinite | P(?) | ND | P | ND |
| Feldspar | ND | ND | ND | P |
| Gypsum | ND | ND | ND | P |

[a]Key to abbreviations: D, dominant mineral species; P, present in samples; V, variable amounts; A, absent from samples; ND, not determined.

Sources: From Kalyoncu 1979; Kalyoncu and Snyder 1978; Kalyoncu and others 1979b, 1979e, 1979f, 1979g.

and Hasenmueller 1977), and preliminary studies by the Illinois Geological Survey indicate that a dozen gas shows were reported in a 19-county area in the southeastern part of the state.

Nearly all of the producing gas fields were discovered many years ago and are now largely depleted and abandoned. Indiana has had commercial production from the New Albany Shale in seven fields in Harrison County, two fields in Daviess County, and one field in Martin County (Bassett and others 1978). Although most of the fields are small, the largest ones (five of them in Harrison County) contain 13 or more wells each. In general, the wells are not noted for high daily gas production, but some of them have been producing for more than 50 years.

Studies by Bassett and others (1978) focused on three fields in Harrison County, Indiana. The largest field, the Laconia Field, contains 106 gas wells, whereas the Corydon and New Middletown fields were developed with 15 and 26 gas wells respectively. Because the discovery wells for these fields were drilled between 1863 and 1923, not much information is available on early gas production. A 1926 report on seven wells, however, describes pressures of 634 to 869 kPa and daily open flows of up to 6000 $m^3$ of gas. In the three fields, the top of the New Albany Shale ranges from 100 to 250 m below the surface. Production from other fields in Indiana came from depths between 100 and 650 m, and the average initial daily production of individual wells ranged from 3000 to 22,000 $m^3$ (Bassett and Hansenmueller 1977).

Gas has been produced mainly from two horizons in the New Albany Shale in Harrison County (Bassett and others 1978). In all wells, salt water was also present and was produced along with the gas. Although the average life of a commercial gas well was about 20 years, some of the wells remained productive for a much longer time. Fields in this area are now largely abandoned, except for the Laconia Field, which has been converted into a gas-storage facility.

As part of the EGSP, five coreholes have been drilled to study the geologic and geochemical character of the New Albany Shale and to evaluate the unit as a source of hydrocarbons (Fig. 16). These wells have not yielded significant amounts of gas, with the exception of the Sullivan County, Indiana, well which tested more than 1.5 $ft^3$ of gas per cubic

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Fig. 16. Locations of the test coreholes drilled in the Illinois Basin for which gas-volume data are available. Adapted from Streib 1979.

foot of rock (i.e., 0.04 $m^3$ per 0.028 $m^3$). Data on the content of natural gas and percent carbon for three of the five cores are presented in Table 11.

In general, the New Albany Shale is less thermally mature than equivalent shales in the Appalachian Basin (Streib 1979). Thermal maturity, however, increases with depth in most of these Illinois Basin wells. Although the shale generally contains only small amounts of gas, several zones near the base do exhibit a high gas content. The Sullivan County, Indiana, well has a substantial gas content, and this is reflected by a slightly higher level of thermal maturity than the other EGSP wells in this basin.

Table 11. Gas volume and carbon content of stratigraphic units within New Albany Shale from three coreholes in the Illinois Basin

| Location of well | Stratigraphic unit | Depth (ft) | Gas volume ($ft^3$ gas/$ft^3$ rock) | Carbon content % | Organic carbon content (%) |
|---|---|---|---|---|---|
| Henderson County, Ill. | Hannibal-Saverton | 316-442 | | 2.34 | 0.39 |
| | Grassy Creek | 442-583 | 0.007 | 2.58 | 1.85 |
| | Sweetland Creek | 583-604 | 0.001 | 6.20 | 0.14 |
| Tazewell County, Ill. | Hannibal-Saverton | 925-1055 | 0.006 | 1.78 | 0.73 |
| | Grassy Creek | 1055-1126 | 0.020 | 5.03 | 3.44 |
| | Sweetland Creek | 1126-1146 | 0.003 | 2.00 | 1.58 |
| Christian County, Ky. | Grassy Creek | 2177-2253 | 0.512 | 7.43 | |
| | Sweetland Creek | 2253-2304 | 0.373 | 9.92 | |
| | Blocher | 2304-2423 | 0.230 | 16.75 | |

Source: Streib 1979.

3.6.2 Other mineral resources

Potential is limited for use of the New Albany Shale as a mineral resource. At most places the shale in uraniferous, but its grade is well below that for rock from which uranium is now being recovered commercially. Analyses for uranium content were performed on 37 samples from two cores drilled in the Illinois Basin (Bergstrom and Shimp 1977). Eighteen of the samples came from a corehole in Christian County, Kentucky, and the average uranium concentration was only 0.0019%. The highest analyzed value was 0.0061%. The remaining samples, from a corehole in Sangamon County, Illinois, revealed even lower uranium concentrations that ranged from 0.0003 to 0.0031% with an average value of 0.0011%.

Shale from this stratigraphic sequence has a potential for use as raw material in the manufacture of ceramics, brick, cement, or possibly expanded-shale lightweight aggregate. With regard to any of these uses, the shale would undoubtedly be mined from open pits at the surface, far from any area where the New Albany Shale occurs at depths possibly suitable for waste disposal.

## 3.7 Mineral Resources in Other Rock Units

A variety of mineral resources are present in the Illinois Basin in rock units above or below the New Albany Shale. Principal resources include oil and gas, coal, rock for cement, stone, clay, sand and gravel, gypsum, and fluorspar (U.S. Bureau Mines 1978). Twelve mined storage caverns have also been formed in Mississippian and Pennsylvanian shales and limestones at nine separate sites scattered throughout the basin.

Petroleum is produced in the Illinois Basin from rocks of Ordovician, Silurian, Devonian, Mississippian, and Pennsylvanian age, with most of the production coming from Chester-age rocks of the Late Mississippian (Bond and others 1971). The main producing area is the southeastern half of the basin (Plate 5). About three-fourths of the oil has been found in sandstones, and the remainder occurs in carbonates. Structural and stratigraphic traps have contributed nearly equal quantities of oil. Natural gas has been present with the oil as solution gas in most fields, and locally as gas caps. Few fields produce gas in marketable quantities, and the chief gas-producing rock units are Ordovician in age.

About 80% of the recoverable oil discovered in the basin has been found in the Mississippian and Pennsylvanian rocks overlying the New Albany Shale. The producing areas for this oil are almost entirely in the southeastern half of the basin. Although this is the deeper part of the basin, the production from these units is typically from depths of only 300 to 1200 m below the surface. Principal petroleum-producing rock units underlying the New Albany Shale are the Hunton Megagroup (Silurian and Devonian) and the Ottawa Megagroup (Ordovician); these producing areas are mainly in the central part of the basin with a few fields in the northwest (Bond and others 1971).

Many exploratory boreholes have been drilled in the basin in search of petroleum; most of these test wells are located in the southeastern half of the basin, and typically they have been drilled only into the rocks overlying the New Albany Shale. Thus, there are large parts of the basin, particularly in the northwest, where few boreholes penetrate the shale unit.

Coal mining has been a major industry in the Illinois Basin for a long time, and the basin ranks as one of the major coal-producing regions of the United States. The coal is bituminous in rank, Pennsylvanian in age, and is distributed throughout almost all parts of the basin (Plate 5). Individual coal beds typically are 0.5 to 2 m thick, although locally several of the coals are up to 4 m thick. Strip mining is the principal means of coal recovery at present, but underground mining was the dominant method years ago and is still being practiced in each of the three states comprising the basin. A shaft mine, for example, was opened recently to a depth of 280 m in Hamilton County, in southern Illinois (U.S. Bureau Mines 1978). Detailed information about the distribution, reserves, and market potential of Illinois Basin coals is presented by Malhotra (1977).

Major minerals for the construction industry are widely distributed throughout the basin and are being mined in each of the three states. Stone, clays, sand and gravel, and cement-making materials are produced from open pits in almost every county in the region (U.S. Bureau Mines 1978). Continued development of these resources should not be adversely affected by underground use of shales for storage of waste materials. Gypsum is being mined from Mississippian rocks that overlie the New Albany Shale in the Shoals district of Martin County, Indiana (Jorgensen and Carr 1972). One inclined-shaft mine and another vertical-shaft mine have been opened to depths of 100 to 150 m below the surface to recover this resource.

Fluorspar production from Hardin County, southeast Illinois, and adjacent Crittenden County, Kentucky, continues to make this area the leading domestic source of fluorspar (U.S. Bureau Mines 1978). Relatively shallow underground mines in both these counties also are producing barite, lead, and zinc as by-products along with the fluorspar.

Storage caverns have been developed by underground mining of shales and limestones at several sites scattered in the Illinois Basin and adjacent areas to the northeast. Twelve separate caverns have been created at nine different sites [H, I, P, Q, R, S (3 sites), and T (Fig. 17)], with six sites located in Illinois and one each in Indiana, Kentucky, and Missouri (Cobbs Engineering 1975). All caverns actually within the confines of the basin are in rock units younger (shallower) than the New Albany Shale. Three caverns are in Pennsylvanian shales, while two occur in similar-age limestones and four caverns are in Mississippian limestones (Table 12).

The mined caverns in the Illinois Basin range in depth from 70 to 140 m below the surface and have fluid storage capacities from 50,000 to 864,000 bbl (26,000 and 450,000 $m^3$). All but one of the caverns in the basin was developed by conventional room-and-pillar mining methods. The one exception, a cavern in Pennsylvanian limestone in Douglas County, Illinois, consists of five drifts or tunnels about 100 m long with a continuous pillar between drifts.

All caverns in shale and most of the limestone caverns have operated since construction without evidence of water inflow or of structural failure (Cobbs Engineering 1975). Two caverns in limestone (O and T) displayed slight inflows of groundwater, but this has not presented any problems in operation. Although some of the caverns are in areas that

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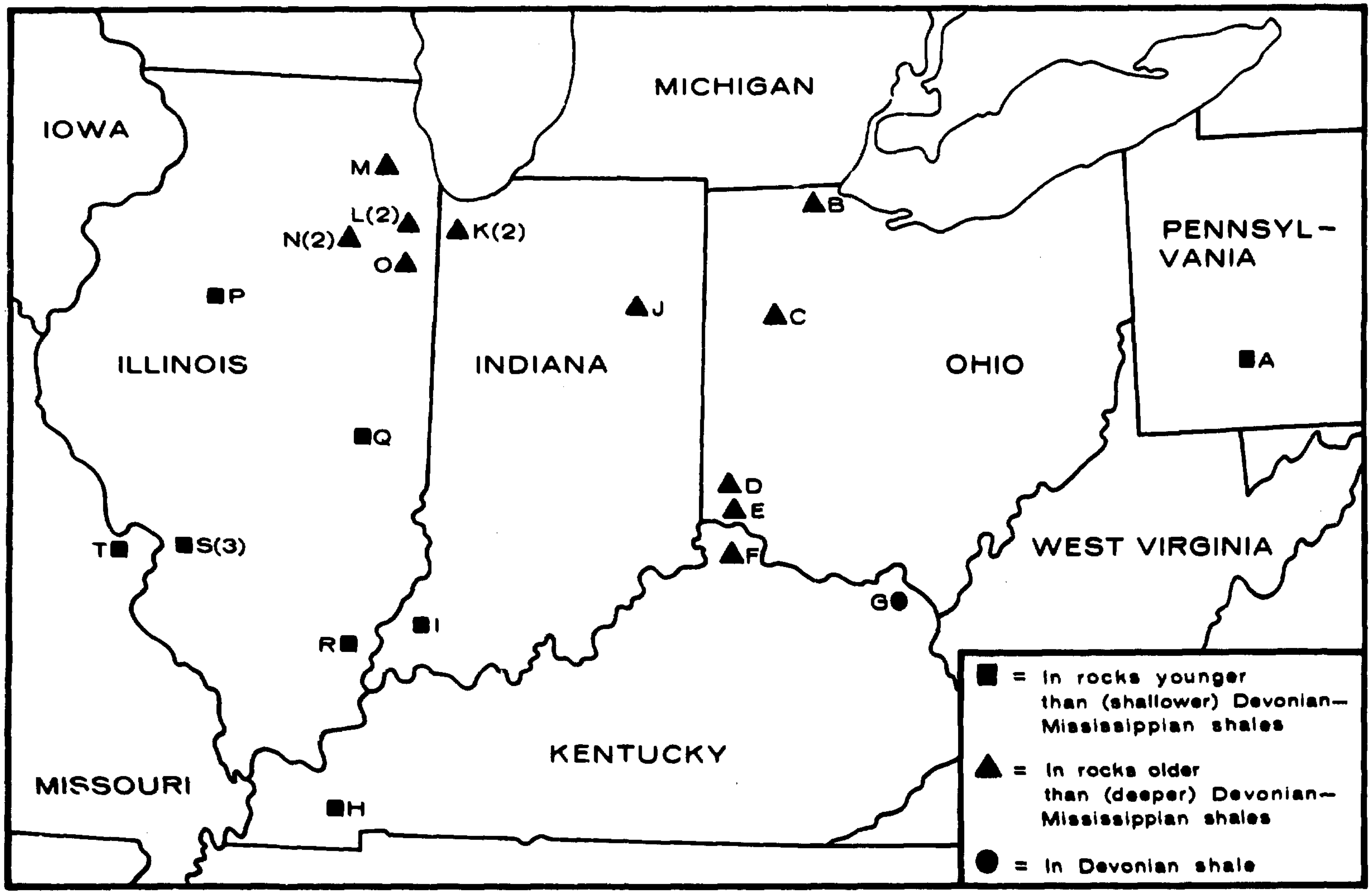


Fig. 17. Locations of mined-storage caverns and the relative geologic age of the host rock in the Illinois and Appalachian basins and adjacent areas. Adapted from Cobbs Engineering 1975.

Table 12. Mined-storage caverns in the Illinois Basin and adjacent areas

| Map letter[a] | Site location | Cavern host rock | | | Depth to cavern top (m) |
|---|---|---|---|---|---|
| | | Geologic age | Lithology | Stratigraphic unit | |
| A | Westmoreland County, Pa. | Pennsylvanian | Shale | Conemaugh Formation | 104 |
| B | Lucas County, Ohio | Ordovician | Shale | White River Shale | 171 |
| C | Allen County, Ohio | Ordovician | Shale | Cincinnatian Series | 151 |
| D | Butler County, Ohio | Ordovician | Shale | Eden Shale | 120 |
| E | Hamilton County, Ohio | Ordovician | Limestone | Black River Formation | 115 |
| F | Kenton County, Ky. | Ordovician | Limestone | Black River Formation | 116 |
| G | Greenup County, Ky. | Devonian | Shale | Ohio Shale | 116 |
| H | Marshall County, Ky. | Mississippian | Limestone | Fort Payne Formation | 118 |
| I | Gibson County, Ind. | Pennsylvanian | Shale | Des Moines Series | 137 |
| J | Huntington County, Ind. | Ordovician | Shale | Maquoketa Formation | 139 |
| K | Lake County, Ind. | Silurian | Dolostone | Salamonie Dolomite | 104 |
| | (2 sites) | Silurian | Shale | Edgewood Formation | 183 |
| L | Will County, Ill. | Ordovician | Dolostone | Maquoketa Formation | 150 |
| | (2 sites) | Ordovician | Shale | Maquoketa Formation | 150 |
| M | Du Page County, Ill. | Ordovician | Shale | Maquoketa Formation | 64 |
| N | Grundy County, Ill. | Cambrian | Shale | Elmhurst Formation | 55 |
| O | Kankakee County, Ill. | Ordovician | Shale | Maquoketa Formation | 63 |
| P | Peoria County, Ill. | Pennsylvanian | Shale | Carbondale Group | 90 |
| Q | Douglas County, Ill. | Pennsylvanian | Limestone | Millersville Limestone | 112 |
| R | White County, Ill. | Pennsylvanian | Shale | Undifferentiated | 70 |
| S | Madison County, Ill. (3 sites) | Mississippian | Limestone | St. Louis Limestone | 95–138 |
| T | St. Charles County, Mo. | Mississippian | Limestone | Keokuk-Burlington Formations | 117 |

[a]Corresponds to Fig. 17.

Source: Cobbs Engineering 1975.

had been subjected to earthquakes which caused some damage at the surface, the caverns themselves have suffered no damage from any seismic event (Cobbs Engineering 1975).

## 3.8 Hydrology

### 3.8.1 Surface water

The Mississippi River and some of its major tributaries constitute the surface-drainage system for the Illinois Basin region. Principal rivers crossing parts of the basin include, from northwest to southeast: the Mississippi, Illinois, Kaskaskia, Wabash, White, Ohio, Green, Cumberland, and Tennessee rivers. Most of these rivers have their headwaters outside of the basin, but they flow across part of the region and then join the Mississippi River, which eventually empties into the Gulf of Mexico.

Average annual precipitation is about 85 cm in the northwestern part of the basin, and this increases to about 120 cm in parts of Kentucky toward the southeast. Precipitation and direct runoff provide nearly all the water to streams, rivers, and lakes, although a small portion of the surface flow is derived from springs in glacial drift and bedrock. Surface water is the main source of water for municipal and industrial use.

### 3.8.2 Groundwater

Groundwater supplies in the Illinois Basin constitute a large and important resource that is not being utilized to its fullest extent (Bloyd 1974, 1975). Much of the highest quality water is present at shallow depths in glacial outwash and alluvial aquifers, but the largest quantity of groundwater is in bedrock aquifers that generally underlie the glacial drift.

Glacial outwash and alluvial deposits were formed beyond or south of the glacial ice front as well as across some of the previously deposited drift areas to the north as the glaciers advanced and retreated across the region. Beyond the ice front, meltwaters flowed down the valleys and partially filled them wit. deposits of outwash consisting of sorted sands and gravels. Some of the outwash and alluvial aquifers are as much as 60 m thick, but most of them range from 5 to 20 m in thickness. Water-well yields from these unconsolidated aquifers in many parts of the region range from 100 to 400 L/min, and yields and alluvial and terrace deposits along and near the present major rivers are typically as high as 2000 L/min (Bloyd 1974, 1975).

Bedrock aquifers in the Illinois Basin region consist of limestone, dolomite, and sandstone units that underlie glacial drift in the north and crop out in much of the south. Yields of 100 to 400 L/min are common in some parts of the region, but in many areas the yield is considerably less.

Pennsylvanian sandstones are highly variable in their capacity to yield groundwater. The Mississippian System contains limestones and sandstones that generally are widespread and represent dependable aquifers. The aquifers are mainly a water supply for farm and domestic use, although they are also used locally for municipal and industrial purposes. Lower Mississippian strata close to the thick black-shale sequence are generally tight and are not noted as sources of groundwater. Pre-Mississippian strata underlying the basin do yield water at scattered localities in the basin, mainly where they are at relatively shallow depth around the perimeter of the basin or along the La Salle Anticline. The St. Peter Sandstone of Ordovician age is one of the principal groundwater aquifers in the extreme northern part of the basin.

Some of the permeable formations in the Illinois Basin are currently being used for the deep-well disposal of liquid industrial wastes (Warner and Orcutt 1973). The principal disposal reservoirs are in the deep part of the basin and include the St. Peter Sandstone and the Cambrian-age Ironton-Galesville and Mt. Simon sandstones. These strata are, however, important freshwater aquifers in the far northern part of the basin. Other rock units below the New Albany Shale that might locally be suitable for industrial-waste disposal are limestones and dolomites of the Hunton Megagroup and dolomites of Ordovician and Cambrian age. Rock units above the New Albany that may locally be amenable for this use are sandstones of Pennsylvanian age and Chesterian sandstones and Valmeyeran limestones of Mississippian age (Bergstrom 1968).

### 3.9 Seismic Activity

Recorded seismic activity in the Illinois Basin is low in the north and is moderate to high in the south (see Fig. 4). Earthquakes with a Modified Mercalli Intensity of V or greater are common in the south, and more than 50 of these events have been recorded in the basin since the late 1700s (Docekal 1970; Coffman and von Hake 1973). Most of this activity in the south has occurred near the New Madrid seismic zone, the site of a series of catastrophic earthquakes in southeast Missouri in 1811 and 1812. Many tremors accompanied this episode of seismic activity, with the most intense being three events of Modified Mercalli Intensity XII (Coffman and von Hake 1973). Owing to the importance of earthquakes in this area, a comprehensive assessment of the seismotectonics in the New Madrid region has been initiated by the Nuclear Regulatory Commission (Buschbach and others 1980). An earlier study of the seismotectonics of this area and the entire eastern United States was conducted by Hadley and Devine (1974).

The southern half of the Illinois Basin has been placed in seismic-risk zones 2 and 3, but the latter designation applies to the southern end of the basin closest to the New Madrid belt (Algermissen 1969). An area of greater seismic hazard based on ground shaking encompasses the southern part of the basin as well (see Fig. 5), according to the calculations of Algermissen and Perkins (1976).

Because of the intensity and frequency of earthquakes in the southern part of the Illinois Basin, the seismotectonics of that area tend to greatly diminish the potential for nuclear waste disposal there. Considering the lesser amount of recorded seismic activity in the northern part of the basin, that area appears more promising for future, more detailed studies of the Devonian-Mississippian shale sequence.

## 3.10 Summary and Regional Evaluation

Based on this review, portions of the Illinois Basin appear to have a favorable geologic framework and appear to be underlain by fairly thick shales that could be suitable host rocks for the subsurface disposal of radioactive wastes. Most of the region has been tectonically stable since Precambrian time, and the sedimentary strata in the basin have not been subjected to mountain-building processes. Although few faults are present in the northern half of the basin, the southern area contains the regionally extensive Shawneetown-Rough Creek and Wabash Valley fault zones, as well as a number of smaller faults throughout the mineralized zone of southern Illinois and western Kentucky. Recorded seismic activity follows this trend — namely, that the northern and eastern parts of the basin have had few earthquakes of Modified Mercalli Intensity V or greater and lie within seismic-risk zone 1, whereas the southern area is adjacent to the New Madrid seismic zone, the site of major earthquake activity nearly 170 years ago, and falls within risk zones 2 and 3. Because of the pronounced seismic activity and known structural complexities in the southern part of the basin, this area is considered to have a very low regional potential.

Thickness of the New Albany Shale ranges from 30 to 120 m in most parts of the basin, while depths typically range from 150 to 1200 m. The shale is thickest in the southern part of the basin, where it also is deepest. In most of this southern area the shale is up to 120 m thick and up to 1200 m deep. On the eastern side of the basin, as much as 60 m of shale is present locally at moderate depths as shallow as 750 m, but over much of this eastern area the unit is thinner and shallower than that. A well-developed sequence of shales low in organic matter is present to the northwest in the so-called Petersburg Basin area. Much of this area is underlain by more than 60 m of shale at depths between 300 and 450 m.

In much of the basin the shale is predominantly brownish black to black and is rich in organic matter. There are, however, some large areas where one or several of the units is light gray to greenish gray and contains little organic matter. Porosity of the shale is low and permeability is extremely low, except in areas where the rock has been fractured; there, porosity and permeability values are highly variable. Data on fractures within the shales are now being collected under the EGSP and will prove valuable in any future assessment of potential fluid flow into or through the shales.

Eastern Gas Shales Project studies have shown that modest to moderate amounts of natural gas are present in the shale from some parts of the Illinois Basin and that there are a few areas, such as southern Indiana, where commercial amounts of gas occur in fractured shale. Because special mining and safety techniques are needed when excavating rock that may contain natural gas, considerable attention needs to be paid to the distribution, character, and quantity of such gases that might be present in any prospective waste-disposal area.

Oil and some natural gas are produced from many fields, chiefly in the southeastern half of the basin. Most of the production comes from rock units above the New Albany Shale, although some petroleum is produced from older or deeper formations. There are large parts of the basin, particularly in the northwest, where few boreholes penetrate the shale unit. Groundwater resources are found in the glacial drift that mantles much of the basin, as well as in both sandstone and carbonate aquifers. Additional study will be needed to more fully identify freshwater resources and to evaluate deeper brackish-water formations that may lie close to the New Albany Shale.

The operational success of the several underground-storage caverns which have been mined in shale and limestone formations in the basin is also noteworthy. Almost all of these caverns have operated for many years without evidence of water inflow or structural fracture, and the slight water inflow observed in two caverns has not presented any problems.

In summary, there are areas in the Illinois Basin where reasonably thick deposits of undeformed New Albany Shale are present at moderate depths; conditions favorable for the disposal of radioactive wastes may exist in one or more of these areas.

# 4. MICHIGAN BASIN

## 4.1 General Setting

The Michigan Basin is one of the major sedimentary and structural basins in the stable interior of continental North America. Roughly circular in plan view with a slight north-south elongation, the basin covers approximately 300,000 $km^2$ and embraces all of Michigan's Southern Peninsula, as well as parts of Wisconsin, Illinois, Indiana, Ohio, and the Province of Ontario (see Fig. 1). The basin is bounded on the north and northeast by the Canadian Shield; on the east and southeast by the Algonquin Arch in Ontario, by the Findlay Arch in northern Ohio, and by the Kankakee Arch in northern Indiana and northeastern Illinois; and on the west and northwest by the Wisconsin Arch and Wisconsin Dome (Ells 1967, 1969).

As a physiographic division, the Michigan Basin represents a glacial plain which is referred to as part of the Eastern Lake section of the Central Lowland Province (Fenneman 1946). The terrain consists mainly of maturely dissected and glaciated cuestas interspersed with lowlands containing glacial moraine or lacustrine deposits. Elevations generally range from nearly 200 m near the Great Lakes to 300 to 400 m toward the basin interior.

## 4.2 Geologic and Tectonic Framework

The Michigan Basin lies in a tectonically stable region which is characterized by essentially flat-lying sedimentary rocks that are neither folded nor faulted appreciably (Plates 2 and 3). Strata are inclined gently into the center of the basin from the adjacent positive structural areas at rates from 5 to 10 m/km (<0.5 degree).

Approximately 5000 m of sedimentary rock is believed to overlie the Precambrian in the deepest part of the basin in Clare and Gladwin counties (Ells 1967). Included in the sedimentary sequence are strata of Cambrian, Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, and Jurassic age (Fig. 18). Lithologies are principally carbonates, shales, sandstones, salt, and anhydrite. They are overlain at most places by Pleistocene glacial drift that ranges from 60 to 275 m in thickness.

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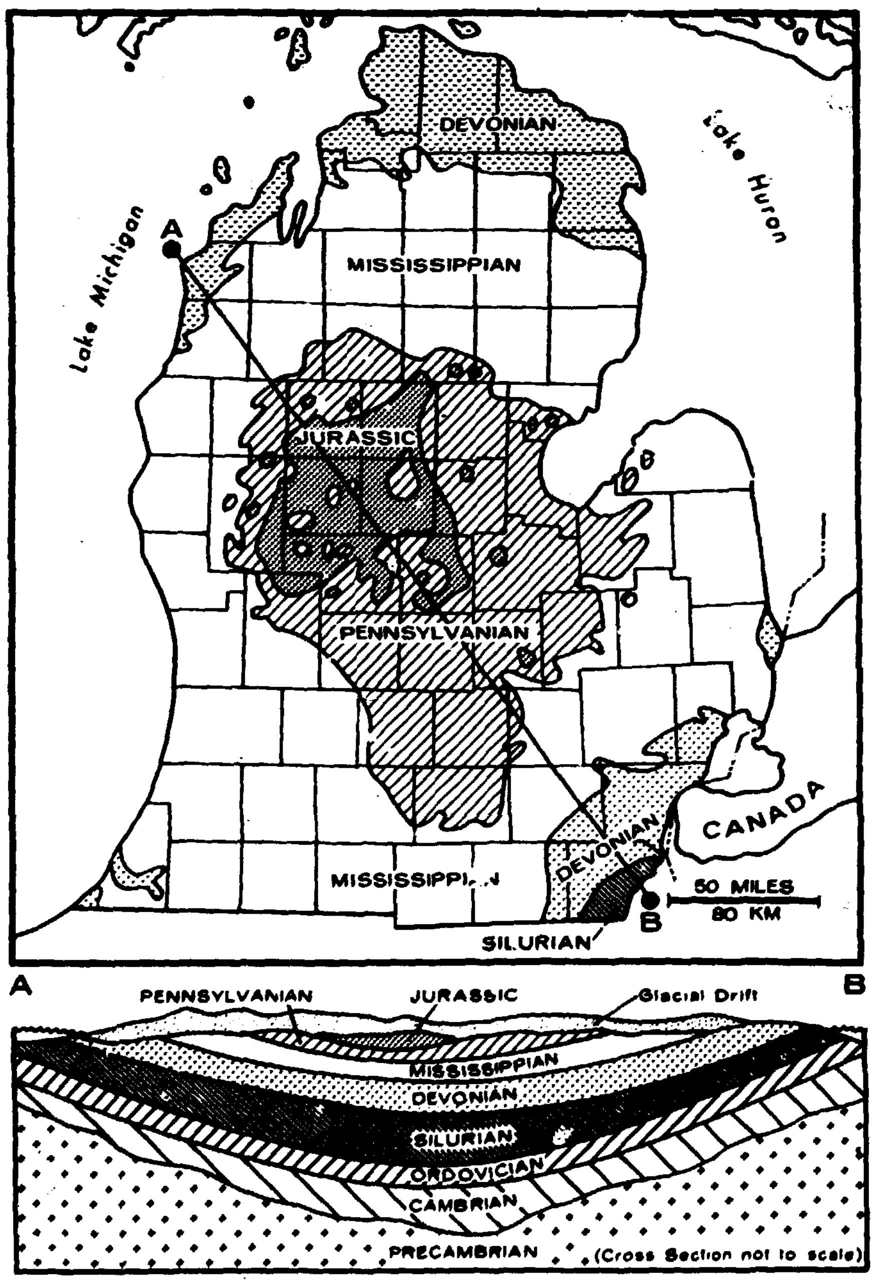


Fig. 18. Generalized bedrock geologic map and northwest-southeast cross section of the Michigan Basin. Adapted from Kelley 1968.

The basin appears to have developed initially as an embayment of an Early Cambrian shallow marine sea (Fisher 1969). Throughout the Paleozoic Era, the basin subsided more than adjacent regions, and thus received a great thickness of sediments in its central part. Major subsidence occurred during Silurian and Devonian times, when more than 2000 m of strata were formed. Silurian strata include the thick and widespread salt deposits of the Salina Group, which were previously reviewed by Johnson and Gonzales (1978) as potential host rocks for storage of radioactive wastes. After deposition of these evaporites, the Bass Islands Dolomite was formed, and this was followed by a subsequent erosional period. Silurian strata reach a thickness of 1200 m in the center of the basin and thin to 200 m along the southern margin (Fisher 1969).

Lower Devonian dolomites were deposited unconformably upon the low-relief surface on eroded Bass Islands strata (Gardner 1974). During subsequent deposition of the Middle Devonian Detroit River Group, the northern part of the basin became more restricted until a series of salts and anhydrites was deposited with the carbonates. The Devonian sequence is capped by several limestones, designated the Dundee Limestone and the Traverse Group.

Above these Devonian carbonates are clastic rocks which extend upward to the top of the rock column. The lower part of this clastic sequence includes the thick Upper Devonian-Lower Mississippian shales that are the subject of this report. The Antrim, Ellsworth, Bedford, Sunbury, and Coldwater shales comprise a sequence of fine-grained clastic sediments laid down across the Michigan Basin with east-west intertonguing relationships. The aggregate thickness of these argillaceous units is as much as 500 m. These shales have been the subject of some earlier studies by deWitt (1960) and Merewether and others (1973) relative to their general potential for the disposal of radioactive wastes.

Following deposition of the Upper Devonian-Lower Mississippian shale sequence, a series of alternating shales, sandstones, and limestones was formed throughout the end of Jurassic time. Of special interest is the Marshall Sandstone, which directly overlies the Coldwater Shale and is one of the main freshwater bedrock aquifers in the Michigan Basin.

Aggregate thickness of these Mississippian to Jurassic rock units overlying the Coldwater Shale generally ranges from 200 to 400 m within the basin.

Thick glaciers covered all of Michigan and surrounding states during the Pleistocene Epoch. Four major ice sheets advanced southward across the region with subsequent retreats, leaving behind thick glacial deposits that mantle the bedrock. Thickness of this drift is from 60 to 80 m throughout most of the state; locally, it exceeds 275 m in the north-central part of the Southern Peninsula (Akers 1938). Areas of thin or locally absent drift are typical in the northeastern, northwestern, south-central, and east-central parts of the basin.

The most significant geologic structure that affects Paleozoic and younger rocks in the basin is the Howell Anticline. This northwest-trending fold is located in the southeastern part of the basin and has been regarded as the largest of several northwest-plunging, subparallel folds developed upon a broad, uplifted block called the Washtenaw Anticlinorium (Ells 1969).

Major faults appear to be of minor significance within the Michigan Basin. Of the known faults, the most noteworthy is located on the west flank of the Howell Anticline, where a basement fault appears to grade upward into a sharp flexure within Ordovician and younger strata (Ells 1969). The presence of faults with small displacements is indicated by local anomalous changes in dips and outcrop patterns. These relationships are, however, far from conclusive in proving the existence of such faults. Certain surface lineaments that have been detected on aerial photographs and by satellite imagery have also been interpreted as being controlled by subsurface faults (Prouty 1976). More detailed studies on possible faulting in any particular area would be needed before it could be considered free of such structures.

The Michigan Basin thus has been characterized by tectonic stability since the beginning of the Paleozoic Era. No major deformation or structural disruption has affected the region, and the Devonian-Mississippian shales and younger strata appear virtually free of significant folding and faulting except near the Howell Anticline. Since the final retreat of Pleistocene ice sheets, portions of the basin, relieved of great overburden pressures, have experienced some measure of glacial (isostatic) rebound. This in itself does not represent a deformational hazard to the shales under consideration here.

## 4.3 Stratigraphy of the Devonian-Mississippian Shale Sequence

Upper Devonian-Lower Mississippian shales in the Michigan Basin are divided, in ascending order, into the following units: (1) Antrim Shale, (2) Ellsworth Shale (which is stratigraphically equivalent to part of the Antrim Shale as well as to the Bedford, Berea, and Sunbury formations), (3) Bedford Shale, (4) Berea Sandstone, (5) Sunbury Shale, and (6) Coldwater Shale. The first five units named above are in large part equivalent to the Upper Devonian-Lower Mississippian shales described elsewhere from the Appalachian and Illinois basins (see Fig. 3), whereas the Coldwater Shale is younger than the shales in either of the other basins. Because the Coldwater is also a thick shale and is directly superjacent to the main sequence of black shales, it is included here. Total thickness for this group of shales ranges from about 150 to 500 m depending on location within the basin.

The Antrim-Ellsworth unit and equivalent strata appear to have had a complicated depositional origin. The upper part of the Antrim Shale on the eastern side of the basin interfingers with, or exhibits a facies relationship with, the Ellsworth Shale in the west. This same basic relationship also exists higher in the stratigraphic section, for the Bedford, Berea, and Sunbury units change facies into the Ellsworth Shale in the western part of the basin (Fig. 19). Although placement of the Devonian-Mississippian boundary within this argillaceous sequence is difficult, the common practice places the contact at the top of the Antrim Shale in eastern Michigan and at the top of the Ellsworth Shale in western Michigan (Lilienthal 1978).

### 4.3.1 Antrim Shale

The Antrim Shale is mainly a dark gray to black and brown, hard, thin-bedded, brittle, carbonaceous shale that is interbedded with some gray shale in the lower part (Lilienthal 1978; Ells 1979). Dark brown,

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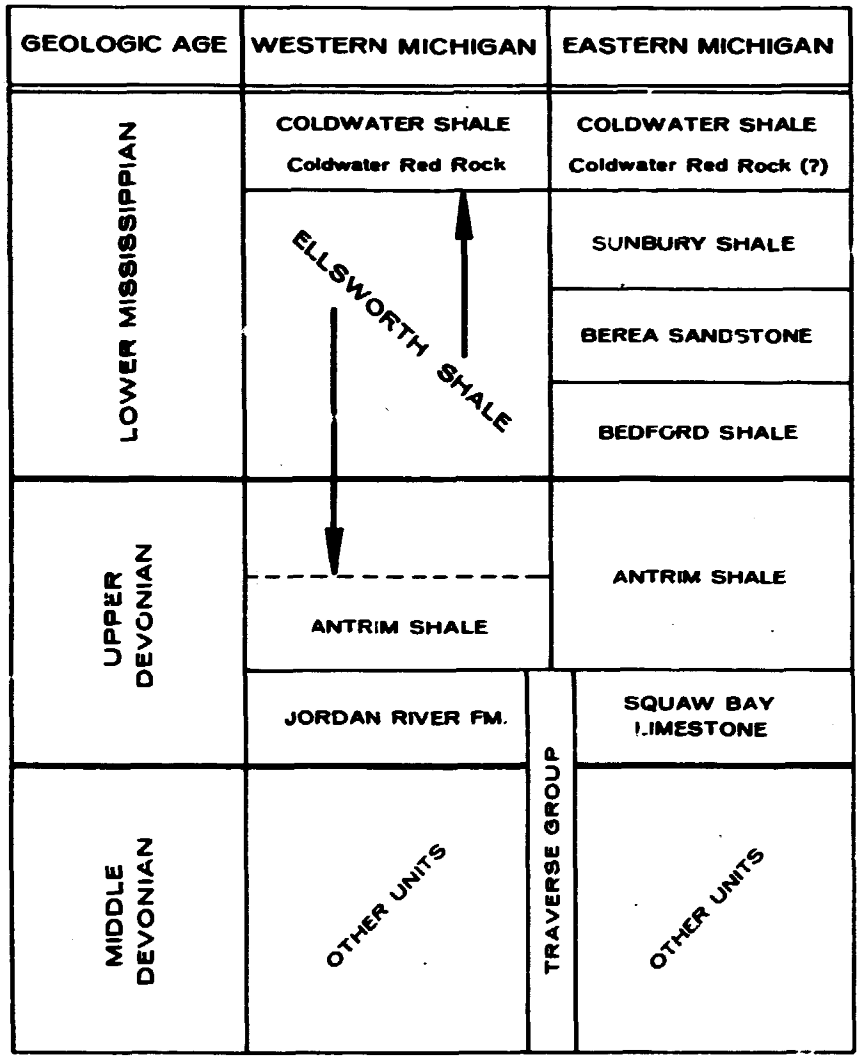


Fig. 19. Generalized relationships between Upper Devonian-Lower Mississippian shale units in the eastern and western parts of the Michigan Basin. Adapted from Ells 1979.

bituminous limestone concretions up to 1.5 m in diameter occur near the base and are associated with pyrite and marcasite grains. The presence of sizeable amounts of organic matter and iron sulfides in this unit indicates that a euxinic depositional environment was widespread throughout much of the Michigan Basin at that time (Asseez 1969). The thickness of the formation ranges from 35 m in some areas to as much as 175 m in the northern part of the Southern Peninsula.

Recent subsurface study of the Antrim has relied heavily on the use of gamma-ray logs in picking contacts with underlying and overlying rock units (Lilienthal 1978; Ells 1979). The degree of natural radioactivity normally associated with rocks classified as Antrim Shale has enabled confident separation of this unit from the less-radioactive strata in the underlying Traverse Group or the overlying Bedford and Ellsworth shales (Figs. 20 and 21).

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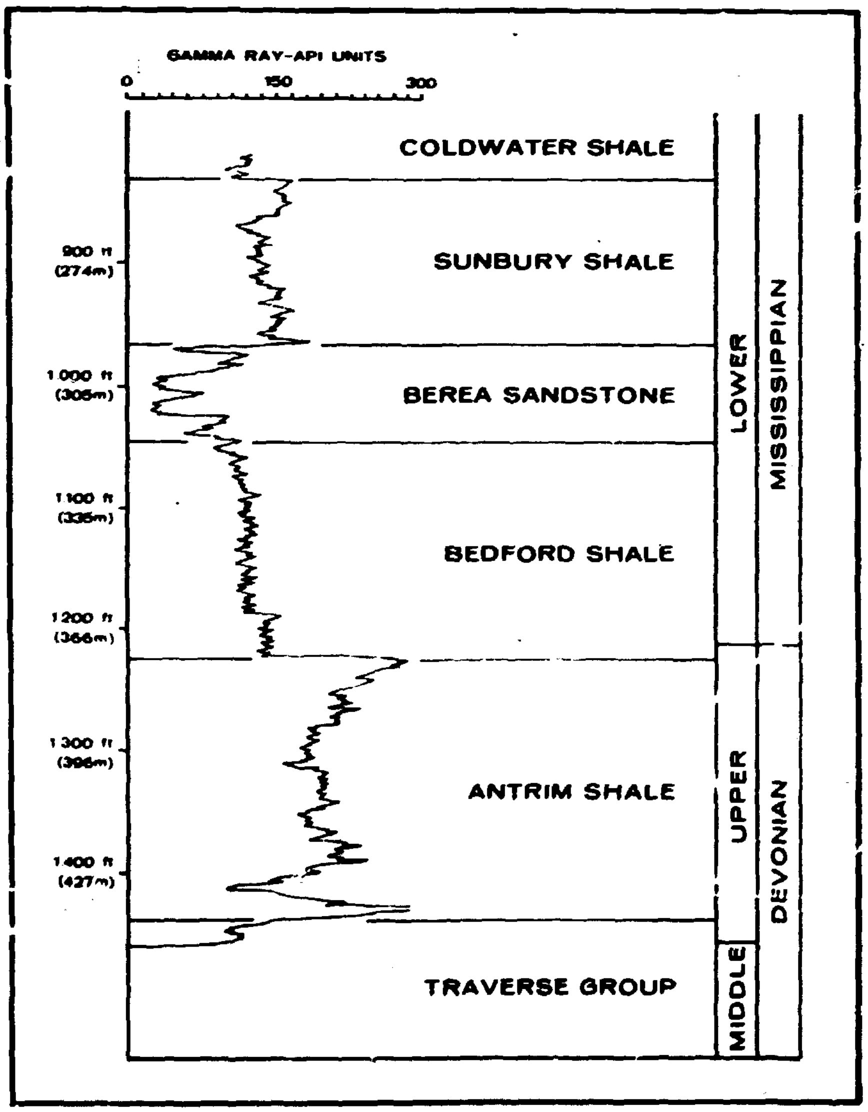


Fig. 20. Gamma-ray log of the Upper Devonian-Lower Mississippian shale sequence on the eastern side of the Michigan Basin. Log is from the Dow Chemical Company No. 1 Rhoburn well, sect. 8, T.9N., R.15E., in Sanilac County. Adapted from Ells 1979.

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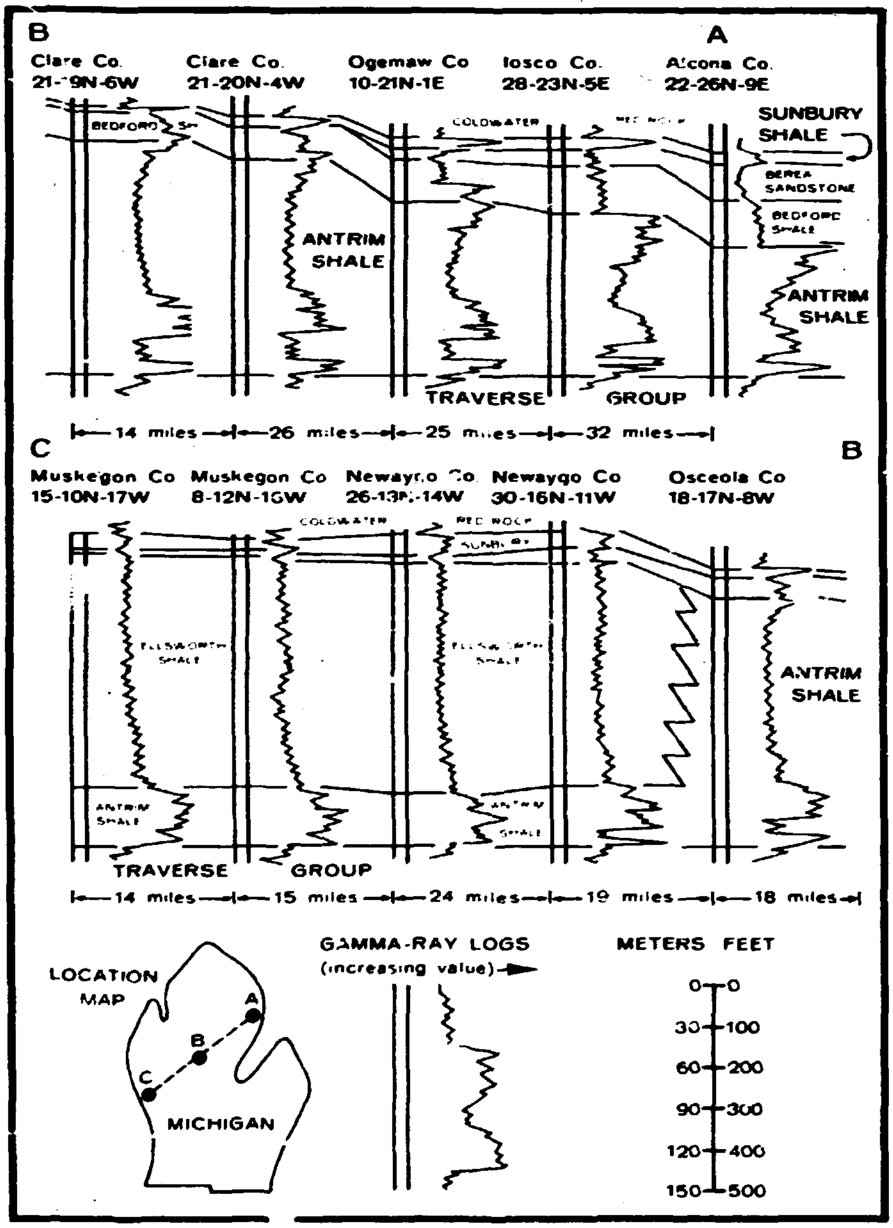


Fig. 21. Northeast-southwest stratigraphic cross section of the Michigan Basin showing relationships between Upper Devonian-Lower Mississippian shales and associated strata. Adapted from Ells 1979.

### 4.3.2 Ellsworth Shale

The Ellsworth Shale consists predominantly of green shale with some gray and greenish gray shale near the contact with the underlying Antrim Shale (Lilienthal 1978; Ells 1979). The shales are quite silty in western Michigan, particularly in the southwestern part of the basin where much siltstone is interbedded with greenish gray shale. The Ellsworth Shale also contains beds of limestone and dolomite, some of which are sandy and oolitic, in several counties in the western and southwestern part of the basin. Ellsworth sediments accumulated in an open-sea environment on the western side of the Michigan Basin, while euxinic conditions existed farther east where Antrim sediments were being deposited (Asseez 1969). The thickness of the Ellsworth Shale ranges from 75 to 200 m.

The top of the Ellsworth Shale is placed at the base of the overlying Coldwater Shale, which generally has a basal red limestone that is traceable over a large area of western Michigan. The base of the formation is drawn at the contact with the more radioactive brown or black shales in the underlying Antrim Shale (Figs. 20 and 21).

Several studies through the years have concluded that the general relationship between the green Ellsworth Shale to the west and the upper part of the black Antrim Shale to the east is either an intertonguing, interfingering, lateral transition, or facies relationship (Tarbell 1941; Cohee and others 1951; Lilienthal 1978; Ells 1979). In general, the transition occurs along a north-south line running approximately through the center of the state (Cohee and others 1951). Parts of the Ellsworth Shale also correlate with the Bedford, Berea, and Sunbury formations, which overlie the Antrim Shale in eastern Michigan (Figs. 19 and 21).

### 4.3.3 Bedford Shale

The Bedford Shale is commonly described as a gray shale that is silty and sandy, especially near the top where it grades into the overlying Berea Sandstone (Lilienthal 1978; Ells 1979). The formation also contains dark gray to black shales that resemble those of the Antrim, and thin beds of Berea-like sandstone. The Bedford Shale is locally as much as 60 m thick and is confined to the eastern part of the state.

This formation can be recognized on gamma-ray logs because it shows greater radioactivity than does the Berea Sandstone but shows much less radioactivity than the underlying Antrim Shale (Figs. 20 and 21).

As noted by Cohee and others (1951), the Bedford Shale thins toward the western part of the basin and grades into the upper part of the Ellsworth Shale.

### 4.3.4 Berea Sandstone

The Berea Sandstone is a light gray, fine-grained sandstone that locally contains layers of gray shale similar to those of the underlying Bedford Shale (Lilienthal 1978; Ells 1979). The formation appears to be a deltaic deposit that is confined to the eastern part of the State, and overlies the Bedford Shale everywhere on the eastern side of the Michigan Basin even though the contact appears to be gradational. The contact with the overlying Sunbury Shale is, however, sharp and easily recognized (Fig. 20). Total thickness of this arenaceous interval generally ranges from 5 to 35 m.

Toward the western part of the basin, the Berea Sandstone becomes dolomitic and grades into the Ellsworth Shale (Figs. 19 and 21). A sandy dolomite that is locally present on the west side of the basin at the Berea horizon has even been called the "Berea."

Petroleum has been produced from the Berea Sandstone in several areas in eastern Michigan. The most important fields are in Saginaw, Genesee, Shiawassee, Arenac, and Ogemaw counties (Lilienthal 1978) although other counties in the east have also had production from this unit, and shows of oil and gas have been reported at other localities. The "Berea" dolomite has also yielded hydrocarbons in Muskegon and Oceana counties in the western part of the State.

### 4.3.5 Sunbury Shale

The Sunbury Shale is black and bituminous and is similar lithologically to the Antrim Shale (Lilienthal 1978; Ells 1979). As a widespread, easily recognized marker bed, the Sunbury Shale underlies the Coldwater Shale in all parts of the state except for the far west, where it pinches out or grades into the green Ellsworth Shale. The formation is generally 5 to 15 m thick but reaches 30 or more meters in the eastern part of the state, particularly in the vicinity of Saginaw Bay.

## 4.3.6 Coldwater Shale

The youngest of the Upper Devonian-Lower Mississippian shales in the Michigan Basin is the Coldwater Shale. This formation consists mainly of gray and bluish gray shale with some thin limestone, dolomite, and sandstone interbeds (Cohee and others 1951; Lilienthal 1978). The thickness of the Coldwater Shale ranges from 150 m in the west to 300 m in the central part of the basin. A thickness between 150 and 180 m is common in the east (Fig. 22).

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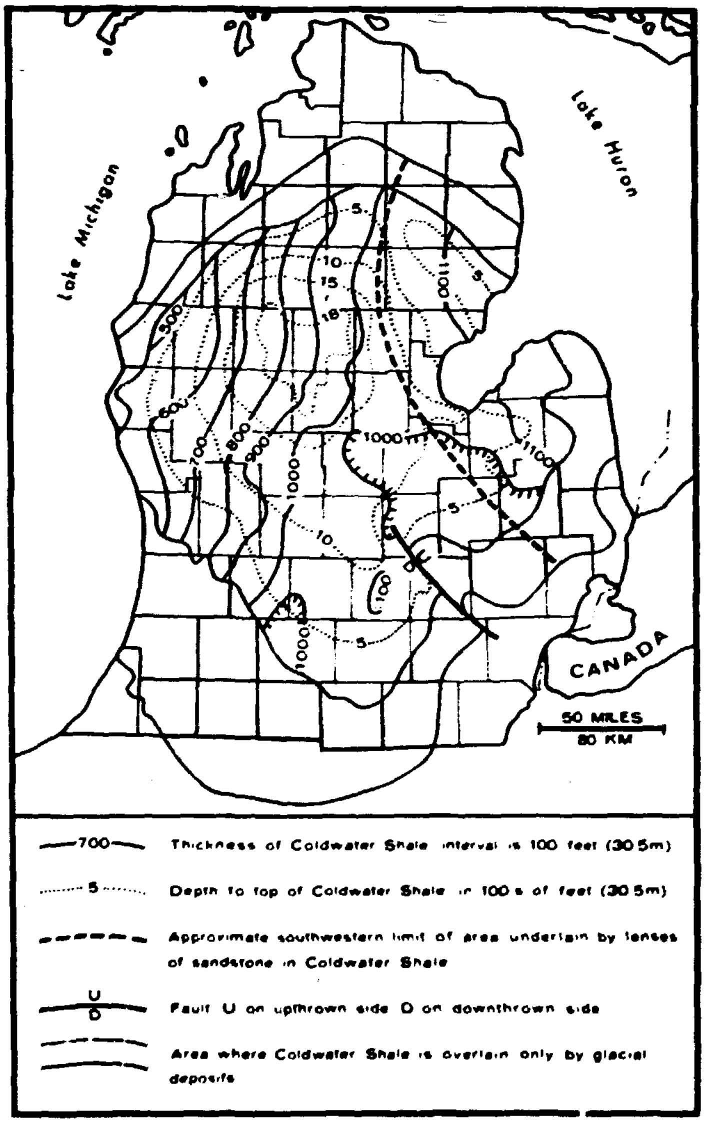


Fig. 22. Thickness and depth of the Mississippian Coldwater Shale in the Michigan Basin. Adapted from Cohee and others 1951; Merewether and others 1973.

The Coldwater Shale contains lenticular sandstones and siltstones in eastern Michigan (Fig. 23), and these lithologies make up much of the formation in the northeastern one-third of the state (Cohee and others 1951). Properly defining the formation contact with the overlying Marshall Sandstone is made difficult by the presence of these sandstones.

The base of the Coldwater Shale is easily recognized by means of a red argillaceous limestone or dolomite, known as the Coldwater "red rock." This persistent marker bed is present in most parts of the basin, varies from 3 to 6 m in thickness, and directly overlies the black Sunbury Shale or the Ellsworth Shale.

## 4.4 Distribution, Thickness, and Depth

The Antrim-Ellsworth sequence of shales underlies almost all parts of Michigan's Southern Peninsula, and it subcrops beneath glacial drift at the perimeter. The thickness of this shale interval ranges from about 100 m in the southern part of the Michigan Basin to nearly 300 m in the northwest. Almost everywhere in the western half of the basin, where the sequence consists mainly of the greenish gray Ellsworth Shale and some of the black Antrim Shale in the lower part, the thickness is more than 150 m. In the eastern half of the basin, the upper part of the underlying shales decreases to typically less than 150 m. Depth to the top of the Antrim-Ellsworth sequence ranges from 0 to 300 m around the perimeter of the basin but is in excess of 300 m in most parts of the Southern Peninsula (Plate 4). The maximum depth to the top of the shales is 850 m in Clare County and adjacent counties in the north-central part of the basin.

The Coldwater Shale, which is separated from the underlying Antrim-Ellsworth sequence by up to 6 m of limestone (i.e., Coldwater "red rock"), consists of shale in the western and central parts of the basin and contains lenticular sandstone and siltstone interbeds in the east. Thickness of the formation ranges from 150 m in the west to 300 m in the central part of the basin, but may reach 330 m in the east (Fig. 22). The top of the Coldwater Shale lies from 300 to 550 m below the surface in much of the west and central parts of the basin. Because

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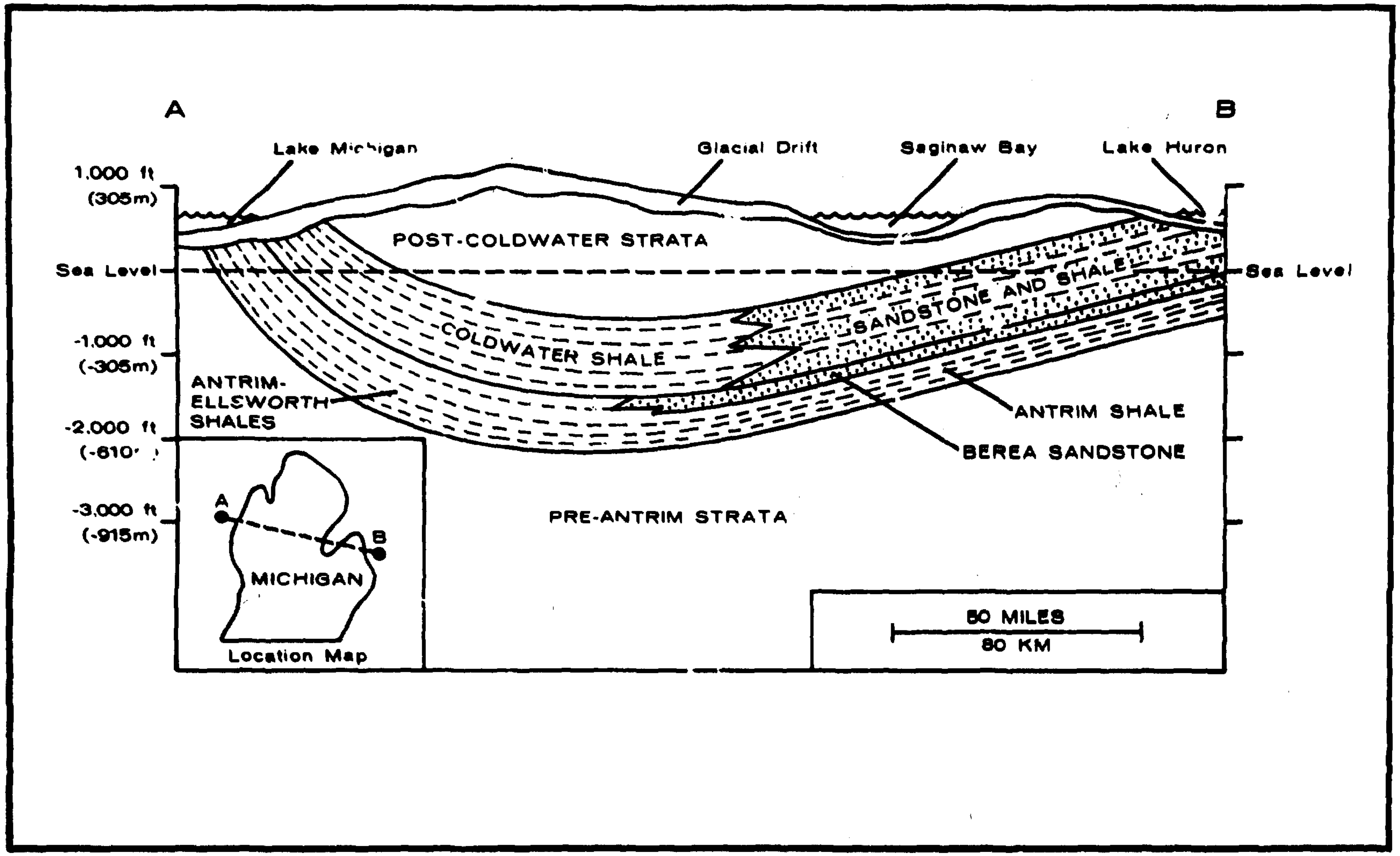


Fig. 23. Generalized east-west cross section of the Michigan Basin showing shale-sandstone relationships and depth of Coldwater and Antrim-Ellsworth shales.

of its appreciable thickness, the lower part of the formation is at least 300 m deep in a still larger area that extends westward almost to where the Coldwater subcrops.

In the western half of the basin, the combined thickness of the Antrim-Ellsworth shales and the overlying Coldwater Shale is typically between 400 and 500 m (Fig. 23); thus, a substantial thickness of largely impermeable strata is present.

Detailed subsurface mapping of the Bedford-Antrim interval within an area of seven counties (Arenac, Bay, Huron, Iosco, Lapeer, Sanilac, and Tuscola) in eastern Michigan reveals a range of shale thickness from 105 to 145 m within depths between 305 and 670 m (Fig. 24). Also, large areas within these favorable thickness and depth ranges lack any appreciable borehole penetrations of the shale sequence. Figure 25 indicates the stratigraphic, thickness, and depth relationships of these units in a three-dimensional sense within this seven-county area. More detailed examination of well-log information in small areas such as this is but one approach by which to more fully evaluate the potential of these shales throughout the basin.

## 4.5 Physical, Mineral, and Chemical Properties

Principal sources of data on properties of the Devonian-Mississippian shales in the Michigan Basin include reports by Young (1978) and by Hockings and others (1979). These reports are based on detailed study of three cores of the Antrim Shale taken from depths of 350 to 450 m beneath property in Sanilac County owned by the Dow Chemical Company. The reports also include data on samples that were roasted to 500°C to simulate in situ retorting of the shale. Physical properties measured include density, porosity, permeability, and specific surface area.

Bulk density of the shale samples ranges from about 2.2 to 2.8 g/cm$^3$ and averages 2.51, 2.57, and 2.75 g/cm$^3$, respectively, for each of the three separate cores. Densities of samples increase with depth in each core. When the shales are roasted, the bulk density increases to between 2.6 and 3.0 g/cm$^3$.

Porosity of the shale samples ranges from about 3 to 10% and averages about 6%. Roasting the samples approximately doubles those values.

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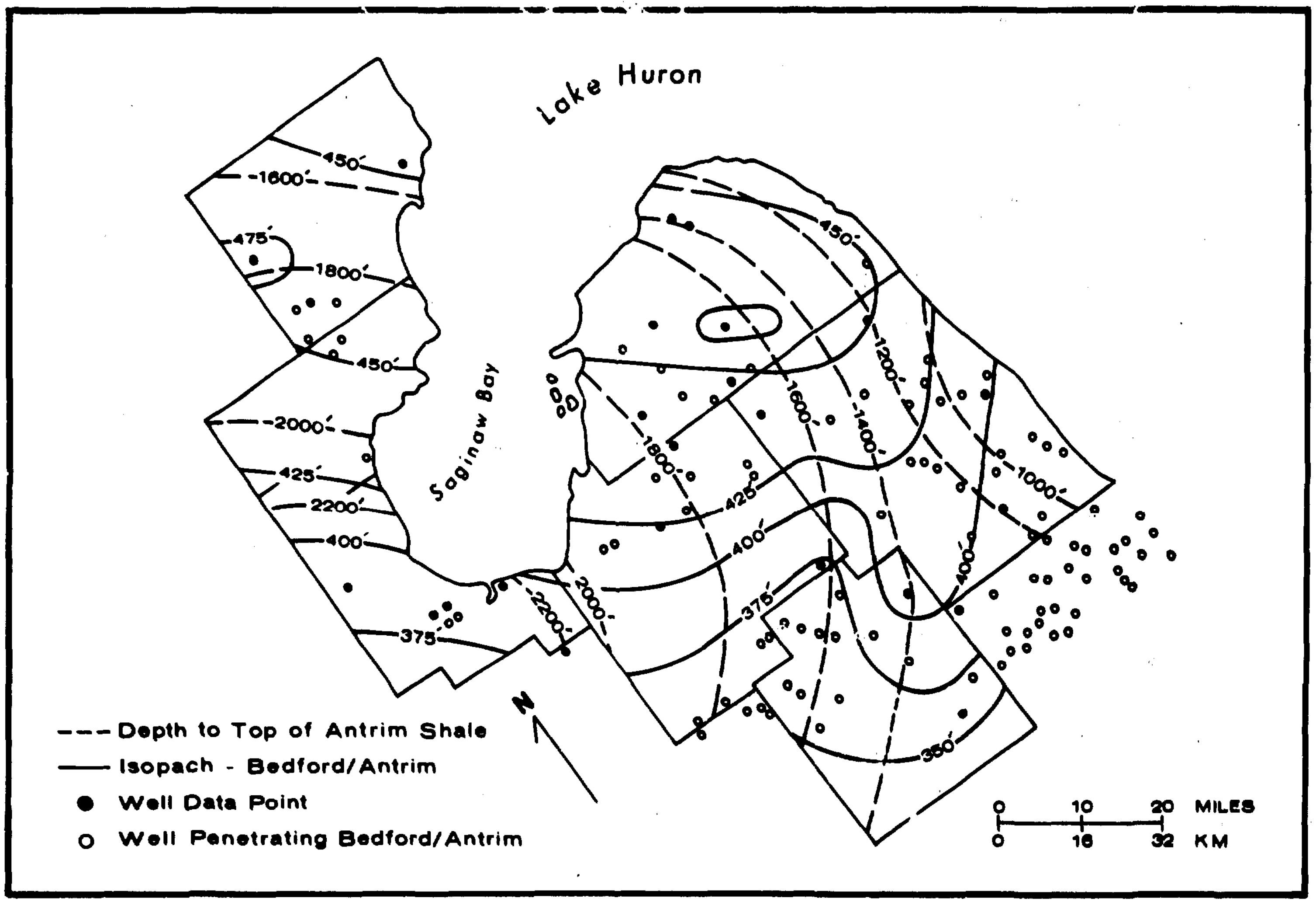


**Fig. 24. Thickness of the Bedford-Antrim interval and depth to the top of the Antrim Shale within a seven-county area adjacent to Saginaw Bay, eastern Michigan.**

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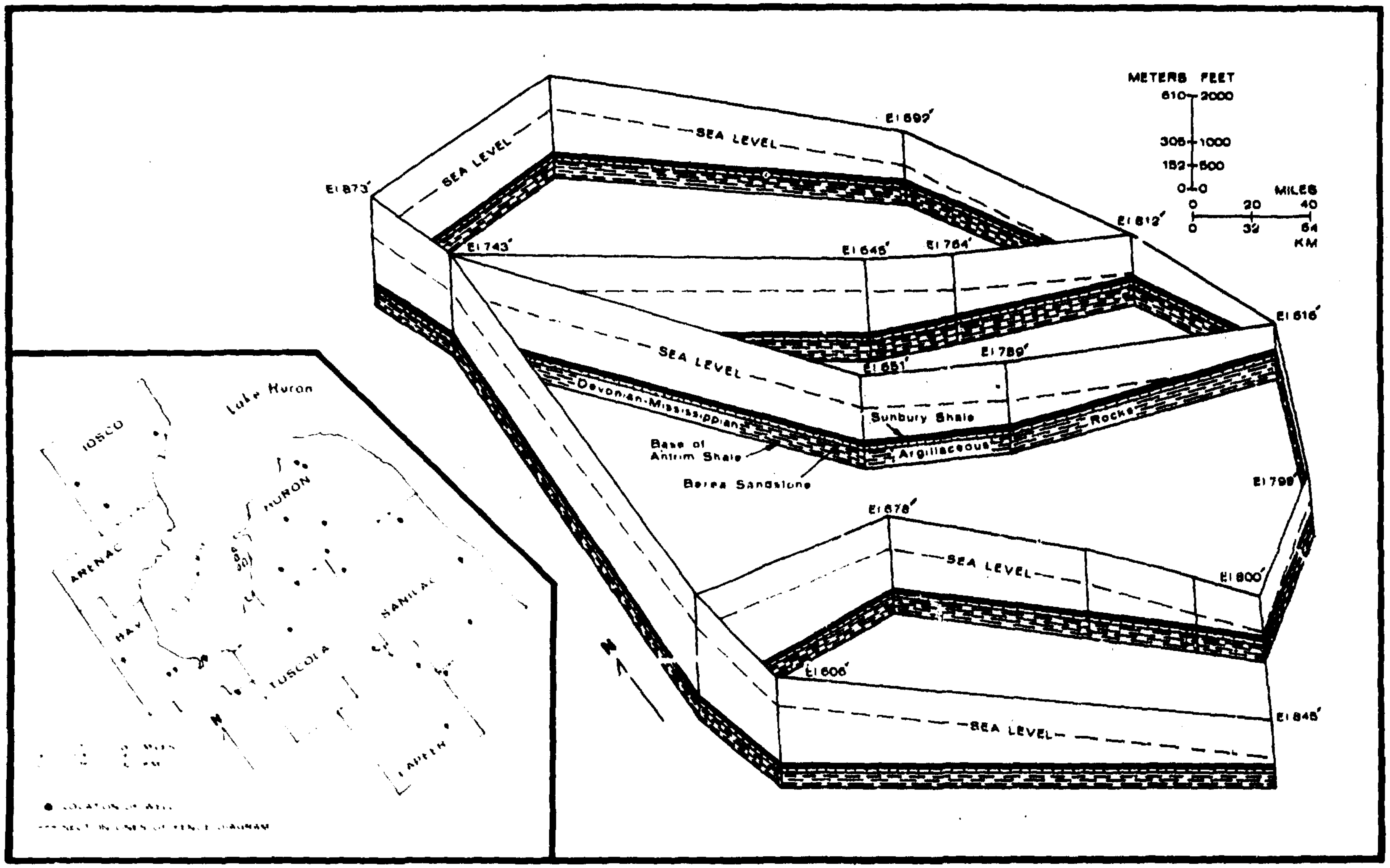


Fig. 25. Fence diagram showing stratigraphic, thickness, and depth relationships of the Bedford-Antrim interval within a seven-county area in eastern Michigan.

Permeability values are low, with most of the samples measuring between 0.001 and 0.03 millidarcy and none exceeding 2.0 millidarcies. Geometric averages of the permeability are 0.0045, 0.0063, and 0.0328 millidarcy for samples from each of the three core holes. Horizontal permeability (parallel to bedding planes) is significantly higher than vertical permeability. After roasting, the permeabilities of all samples increase, and almost none of the samples yield values less than 0.010 millidarcy.

The specific surface area of unroasted shale samples is generally low; values generally range from 0.05 to 1.0 $m^2/g$. A few samples gave readings as high as 1.2 $m^2g$. These values, however, probably do not accurately represent the true surface area because internal portions of the core samples possess additional porosity that was not measured adequately. Roasting the shale samples increases the specific surface area by nearly a factor of ten.

Other studies of the mechanical properties of the Antrim Shale were carried out by Kim (1978). He found that Young's modulus and compressive strength decrease with organic-matter content, whereas Poisson's ratio remains at a fairly constant level. In addition, density decreases in a linear fashion with increasing organic matter. Kim (1978) also observed that the Antrim Shale exhibits an extreme weakness along the bedding planes.

Mineralogical studies by x-ray analyses of the three Sanilac County cores were also conducted by Hockings and others (1979). In most samples, the Antrim Shale consists of 50 to 60% quartz, 20 to 35% illite, and 5 to 15% kaolinite. Some samples contain large amounts (15 to 80%) of calcite and/or dolomite that occur mainly as interbeds in the lower half of the formation. Pyrite is commonly present in trace amounts throughout the formation. The Antrim Shale from Sanilac County differs from other black shales largely in its high kaolinite content and its lack of chlorite. The Bedford Shale is distinguishable from the underlying Antrim Shale because the former generally contains less quartz and about twice as much kaolinite.

Geochemical analyses of the Antrim Shale are underway at the present time, but data from those studies are currently unavailable.

## 4.6 Mineral Resources in Shale Units

### 4.6.1 Natural gas and oil

The bituminous and combustible characteristics of the black shales in the Antrim Shale have been known for more than 100 years. Commercial production of oil and natural gas from rock units within the Antrim-Ellsworth sequence was first proven in 1925 (Ells 1978). The Antrim Shale has yielded gas from fracture-type reservoirs in several parts of the basin, whereas the Berea Sandstone in the east and the Ellsworth Shale in the west have both yielded oil and gas at a number of localities. A total of 39 oil and gas fields have been found in these rock units (Fig. 26).

The Antrim Shale is a gas producer in six fields in the northern and southern parts of the Michigan Basin. Production comes mainly from the lower part of the formation in the fields that appear to be associated with structural closures (Ells 1978). The gas reservoirs may be related to naturally occurring fracture systems that are many orders of magnitude greater than those normally induced by artificial fracturing schemes. Wells in these gas fields have also been subjected to "fracing" techniques to further stimulate production. Although the Antrim Shale can technically be classed as an oil shale, oil reservoirs capable of yielding fluids in the conventional manner have not been discovered.

The Ellsworth Shale, which grades laterally into the Antrim Shale but is lithologically distinctive from it, produces oil or gas from 17 fields in the western part of the basin (Fig. 26). Reservoir rocks in this predominantly shale formation are mainly brown crystalline dolomites, sandy dolomites, or sandy limestones, some parts of which are oolitic (Ells 1978). Individual reservoir rocks occur chiefly in the upper 30 m of the formation but apparently are not continuous from pool to pool. The reservoir units in this western area commonly are referred to as "Berea" because they occur at about the same stratigraphic position as the Berea Sandstone; however, this is a questionable correlation inasmuch as the Berea Sandstone does not extend into western Michigan. Reservoirs in the Ellsworth Shale are thin, averaging only 2 m in thickness; their oil and gas may be localized either by structural entrapment or varying permeability.

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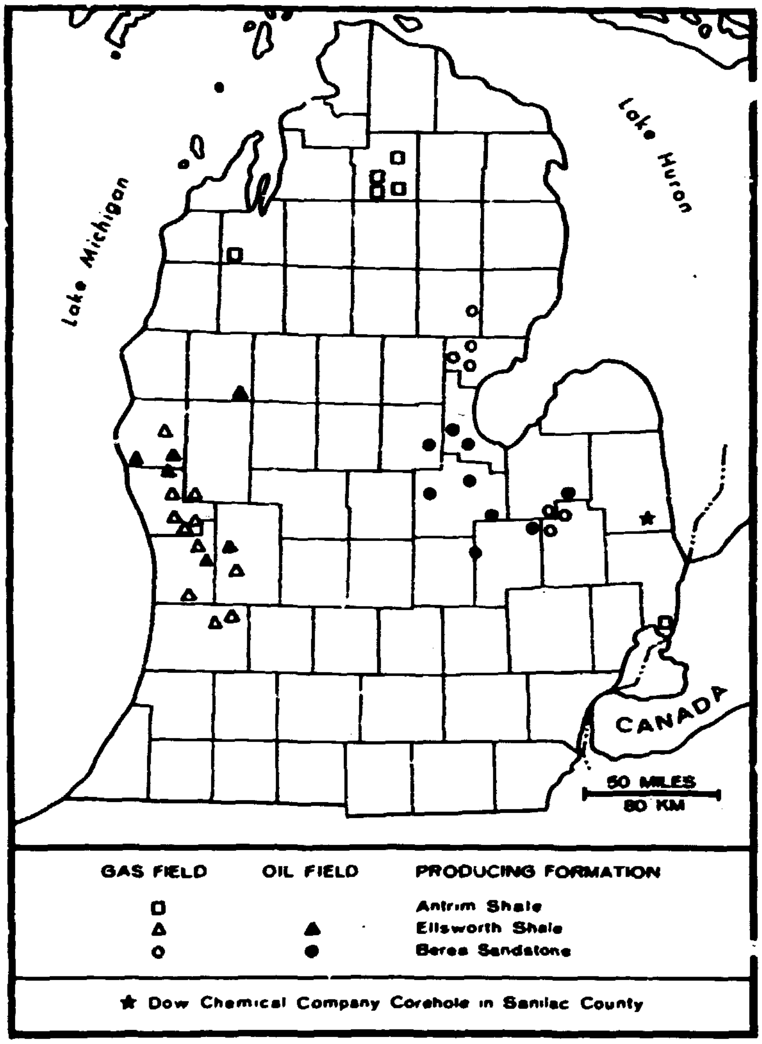


Fig. 26. Distribution of oil and gas fields producing from reservoirs within the Upper Devonian-Lower Mississippian sequence in the Michigan Basin. Adapted from Ells 1978.

Most of the petroleum production from the Antrim-Ellsworth sequence comes from the Berea Sandstone in the eastern part of the basin (Fig. 26). This sandstone is productive in 16 separate fields, and cumulative production from these fields exceeds $318 \times 10^3$ $m^3$ of oil and $340 \times 10^6$ $m^3$ of natural gas (Ells 1978). The largest two fields are the Saginaw Field (oil) in Saginaw County and the Clayton Field (gas) in Arenac County. Producing zones in the Berea Sandstone are as much as 8 m thick in some fields, and most are associated with structural traps. Some minor stratigraphic traps may be involved as well in the smaller fields.

The Coldwater Shale has had some reported gas shows in the "Weir sand" within the lower part of the formation (Lilienthal 1978), and a few gas wells have even been completed in this unit. Oil shows have also been reported locally from certain limestones in the Coldwater Shale on the western side of the basin.

Around the perimeter of the basin, gas is frequently found in the glacial drift where it directly overlies the subcrop of either the Antrim or Ellsworth shales (Ells 1978). In all probability, other units such as the Bedford Shale and Berea Sandstone also contribute to the supply of gas migrating slowly into the glacial deposits. These shallow gas pockets commonly cause problems in completing water wells.

In addition to EGSP studies directed at characterization of the Devonian–Mississippian shales in the basin, a second study is focused on the feasibility of in situ retorting of the Antrim Shale for low-Btu natural gas (Matthews and others 1978). This study, being conducted by the Dow Chemical Company under contract to the U.S. Department of Energy, is analyzing testing procedures and is being carried out in Sanilac County, eastern Michigan (Fig. 26). Specific objectives are evaluation of in situ partial combustion of the shale's kerogen and assessment of the feasibility of creating artificial porosity and permeability by means of hydraulic fracturing and chemical or explosive underreaming.

### 4.6.2 Other mineral resources

The Antrim-Ellsworth shales have had limited use as a nonhydrocarbon mineral resource in Michigan. The Antrim Shale is uraniferous in most areas, and at several places one of the shale units has been mined by open pit for the manufacture of Portland cement or brick.

Determinations of uranium content in the Antrim Shale were made on 38 samples from two wells drilled in the Michigan Basin (Swanson 1960). The average uranium content is about 0.0021%; maximum content is 0.004%. Thus the uranium concentration of the Antrim Shale is not especially high in comparison to other black shales. Comparison of test data with oil-content assays shows that there is, however, a marked increase in uranium with increasing oil content (Swanson 1960).

Shales of the Antrim and Ellsworth formations have been or are being mined in open pits at several localities for the manufacture of cement or brick (Sorensen 1970). Quarries have been operated in Alpena, Antrim, and Charlevoix counties in the north and in Wayne County in the southeast. The Coldwater Shale was mined for cement or brick raw materials from several open pits in Branch County in the south.

## 4.7 Mineral Resources in Other Rock Units

In addition to the potential for mineral development and use of materials within the shale units, other mineral resources in rock units above or below the shales also must be considered. These resources include oil and gas, salt, natural brines, coal, and other minerals that were summarized by Johnson and Gonzales (1978) and Gere (1979). A single, mined storage cavern in Ordovician-age shale has been developed in the far southeast.

Petroleum is produced in the Michigan Basin from reservoir rocks of Ordovician, Silurian, Devonian, and Mississippian age (Ells 1971; Ells and others 1975; Netherland, Sewell and Associates, Inc. 1975). Most of the production comes from reservoirs below the Upper Devonian-Lower Mississippian shale sequence. Production in the central part of the basin is generally from structures located along salt-cored anticlines, whereas production around the perimeter of the basin comes chiefly from pinnacle reefs (Plate 5). Although many oil and gas test wells have been drilled in the state, most are concentrated in certain areas and along specific trends. Thus, there are large parts of the Michigan Basin where only a few boreholes have penetrated the shale sequence.

Salt resources are vast in Michigan and are found in the Silurian Salina Group and Devonian Detroit River Group. Salt or salt brines are produced at nine mines or brine-well plants located in Wayne and St. Clair counties in the southeast, in Midland County in the center, and in Manistee and Muskegon counties in the western part of the basin (Gere 1979). Summary discussions of these salt units are given by Ells (1967), Johnson and Gonzales (1978), and Lilienthal (1978). Potash salts have also been identified within the Salina Group in the central part of the basin, but no production from these deposits has yet been established.

Natural brines or salt water produced from deep wells in the state have been a commercial source of such important chemicals as bromine, iodine, calcium chloride, and magnesium compounds. The principal source beds for these brines are the Filer and Sylvania sandstones in the Detroit River Group, which underlies the thick shales of interest. Michigan currently ranks first in the domestic production of natural brines. Five operating plants are located across the central part of the state in Lapeer, Midland, Mason, and Manistee (2 plants) counties (Gere 1979).

Coal is present in the Pennsylvanian-age Saginaw Formation within the central part of the basin (Plate 5). Many coal beds are known, but they are typically no more than 1.5 m thick. No commercial mines are operating at the present time, although coal has been produced in Bay, Calhoun, Eaton, Genesee, Ingham, Jackson, Saginaw, Shiawassee, and Tuscola counties. Unused coal reserves within the basin are estimated to be about 200 million metric tons (Cohee and others 1950).

Other mineral resources that are currently being extracted in the Southern Peninsula come from surface mines; thus, disposal of waste in underlying shales should not conflict with such development. These other resources include cement, gypsum, stone, peat, shale and clay (in glacial drift or rock units other than the shales involved in this study), and sand and gravel (Gere 1979).

A single, mined storage cavern in the region is located on the southeast margin of the basin in Lucas County, Ohio (see Fig. 17, site B, and Table 12). The Ordovician White River Shale was mined here by conventional room-and-pillar methods in 1969 and designed to store 28,000 $m^3$ (175,000 bbl) of liquid hydrocarbon products at depths between 170 and 177 m (Cobbs Engineering 1975). This cavern has been operated since 1970 without evidence of either water inflow or structural failure.

## 4.8 Hydrology

### 4.8.1 Surface water

Streams and rivers that flow toward Lake Michigan and Lake Huron account for the surface drainage in the Southern Peninsula of Michigan. Most headwaters and drainage areas lie within the state, but some streams in the south flow through parts of Ohio and Indiana. Principal rivers in the state include the St. Joseph, Grand, Muskegon, Manistee, and Au Sable. Lakes are also quite common in the Lower Peninsula.

Precipitation and runoff provide nearly all of the water in streams, rivers, and lakes, but some is derived from springs which flow from the glacial drift and bedrock. Excess water produced from water wells adds slightly to the discharge. Average annual precipitation ranges from 66 to 92 cm although higher values are typical of most of the southwest.

Municipalities and industries located near the Great Lakes extensively utilize water from these bodies. Inland from the Great Lakes, the several surface-water occurrences serve as a major freshwater source for municipal, industrial, and rural use.

### 4.8.2 Groundwater

In much of the Southern Peninsula that is remote from Lake Huron or Lake Michigan, glacial deposits furnish appreciable fresh groundwater for urban, industrial, and rural use (Waller and Allen 1975; Weist 1978). Where thick drift is chiefly sand, it is easily recharged by precipitation. In such areas, large volumes of fresh groundwater are stored, and good yields persists for long periods of time. Areas of thin or clay-rich drift permit little water infiltration, and in turn well yields are small or nonexistent.

Water-well yields from glacial drift range from 35 to more than 1875 L/min in many parts of the Southern Peninsula (Twenter 1966a). Groundwater from glacial deposits is generally good quality but commonly is moderately hard. Total dissolved solids may range from 200 to 500 mg/L, whereas hardness, expressed as $CaCO_3$, ranges from 175 to 350 mg/L (Piper 1972).

Limestone, dolomite, and sandstone aquifers provide fresh groundwater in the south-central, east-central, and northeastern parts of the basin (Twenter 1966a). Yields range from about 375 to 1875 L/min. Higher yields are commonly from sandstones and some limestones, whereas yields of less than 35 L/min are typical from shales.

Principal bedrock aquifers that overlie the shale sequence are the Pennsylvanian Saginaw Formation and Mississippian Marshall Sandstone. These two units are important aquifers mainly in the southern and southeastern parts of the basin (Fig. 27) where they contain fresh water to depths as great as 120 m below the land surface.

At depth, all bedrock formations in the basin contain saline or mineralized water. The base of fresh water in these aquifers ranges from about 60 to 270 m in different areas (Fig. 27). Below these depths, the water is generally too saline for any practical application. Natural brines are, however, commercially obtained in certain areas as discussed in Sect. 4.7. Most of the commercial brines are produced from Devonian strata beneath the thick shales, but there is also some potential for production from the Marshall Sandstone that overlies the Coldwater Shale.

Another geohydrologic application that has been widely instituted in the basin is the installation of industrial-disposal wells (Ives and Eddy 1970; Warner and Orcutt 1973). Sufficiently permeable and thick saline aquifers which are overlain by effective seals have been selected for the injection-disposal of a wide variety of industrial effluents. The greatest concentration of such disposal systems is near Midland in east-central Michigan.

## 4.9 Seismic Activity

Compared with the rest of the United States, seismic activity in the Michigan Basin and surrounding areas is low. Earthquakes with a Modified Mercalli Intensity of V or greater are sparse in the region (Coffman and von Hake 1973; Bricker 1977) except for two areas — namely, northwest Michigan and western and northwest Ohio (see Fig. 4). In adjacent parts of Canada, earthquakes with Instrumental Magnitudes of 3.5 ($M_L$ 3.5) or greater are sparse (Smith 1966). The entire Michigan Basin lies within a region in which the seismic hazard as expressed by ground shaking is quite low (see Fig. 5).

Four earthquakes of Modified Mercalli Intensity V or VI recorded in Michigan's Lower Peninsula occurred in the south (Coffman and von Hake 1973). These seismic events were recorded in 1872, 1877, 1883, and 1947. Other earthquakes recorded in Michigan occurred in the Upper Peninsula and include events in 1905 (Menominee, V; Calumet, VI), 1906 (Keweenaw Peninsula, VIII), and 1909 (Houghton, V).

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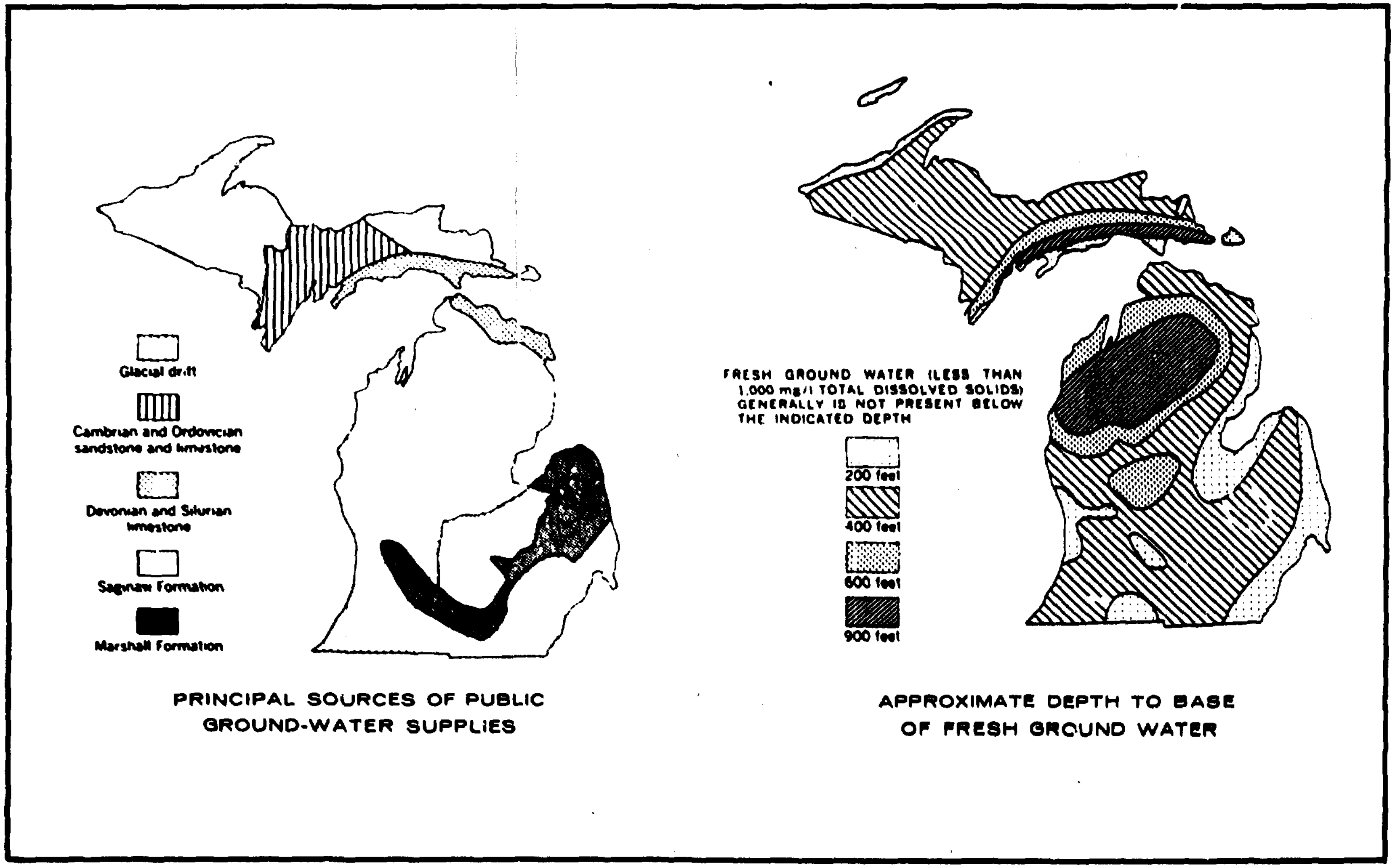



Fig. 27. Principal sources of public groundwater supplies and approximate depth to the base of fresh water in Michigan. Adapted from U.S. Geological Survey 1968.

Larger earthquakes in nearby Canada include three events during 1947 at Sudbury, Laforest, and in Georgian Bay. Another event near London occurred in 1957.

The low level of recorded seismic activity in the Michigan Basin indicates that earthquakes should not be a special problem when considering any rock type for waste disposal.

## 4.10 Summary and Regional Evaluation

The Michigan Basin appears to have a geologic framework and a series of thick shale deposits that may be locally suitable for the underground disposal of radiaoctive wastes. The basin has been tectonically stable since Precambrian time, and the sedimentary rocks contained within it are nearly flat-lying and lack significant deformation. Earthquake activity in the region has been relatively low, inasmuch as only four events of Modified Mercalli Intensity V or greater have ever been recorded in the Southern Peninsula, and all parts of the basin are assigred to seismic-risk zone 1.

The thickness of the shale sequence ranges from about 150 m in the southeastern part of the basin to as much as 500 m in much of the west. The Antrim-Ellsworth part of the sequence underlies the entire basin and is typically from 150 to 300 m thick, whereas the overlying predominantly argillaceous Coldwater Formation ranges from 150 to 300 m thick in the western half of the basin. The area of greatest shale thickness, namely the central and western parts of the basin, is also where the stratigraphic units consist almost entirely of lighter colored shales that are low in organic matter. Depth to the top of the shale sequence is less than 300 m only around the perimeter of the basin; elsewhere in the basin the depth ranges up to a maximum of about 850 m.

Black, brown, and dark gray shales with high organic content predominate in the eastern half of the basin and extent as a westward-thinning wedge across the remainder of the basin within the lower part of the shale sequence. Thus the greater proportion of the shales in the west are light gray and greenish to bluish gray, and generally lack significant amounts of organic matter. Porosity of the shales typically is low; permeability is extremely low, except where the rock is naturally fractured, whereupon both these physical properties become highly variable.

Oil and natural gas occur in various intervals of the thick shale sequence in different parts of the basin. Major production comes from the Berea Sandstone in the east, but commercial production has also been found in the Ellsworth Shale in the west and in the Antrim and Coldwater shales at widely scattered locations throughout the basin. Dark shales that are rich in organic matter contain moderate amounts of natural gas in fractured zones in various areas. Special attention therefore needs to be paid to the possible occurrence of these hydrocarbons because they would invoke special mining and safety procedures in the event a subsurface excavation in such rock were contemplated.

Petroleum production in the Michigan Basin comes mainly from rock units that underlie the Devonian-Mississippian shales; consequently, there are local areas where numerous boreholes penetrate the shale sequence. However, because most of this drilling is concentrated in specific areas or along specific trends, there are large segments of the basin where boreholes drilled into the shales are few or widely spaced. Other penetrations of the shales include the salt mines and brine wells that currently recover resources from Silurian and Devonian strata.

Major groundwater resources occur in the glacial drift that covers most of the basin and also in several Mississippian and Pennsylvanian sandstones in the southern portion. Other sources of groundwater are scattered throughout the basin. A detailed study of the geohydrology of any area to be considered for waste disposal will of course be needed.

## 5. CONCLUSIONS AND RECOMMENDATIONS

This regional investigation of the Upper Devonian-Lower Mississippian shale or clastic sequence within the Appalachian, Illinois, and Michigan basins has revealed the following:

1. Extensive portions of each basin are characterized by tectonic stability, a lack of major large-scale geologic structures, and very low levels of seismic activity and attendant seismic hazard.

2. There are large expanses within the structurally favorable parts of each basin where the shale sequence is sufficiently thick and at depths moderate enough to warrant additional consideration solely on the basis of its physical distribution.

3. Because the black to dark brown shale units are richer in organic matter, tend to be the hydrocarbon-productive intervals for established gas (and some oil) fields, and typically liberate some gas as shows in wells, they represent that portion of the shale sequence in which there exists greater energy-resource potential, and thus a higher level of possible conflict from competing uses.

4. In contrast to the preceding point, the dark gray, gray, gray-green, and related shale intervals that contain less organic matter, and hence exhibit a lower hydrocarbon potential, are possibly more promising with regard to nuclear-waste disposal.

5. Even where certain darker colored shale units are rich in organic matter, the degree of natural thermal maturation applied to them through geologic time may have been less than that needed to produce hydrocarbons (natural gas) in amounts adequate to encourage resource development.

6. The Eastern Gas Shales Project and studies related to that program have generated a significant volume of geotechnical data about the shale sequence and can be expected to continue generating appreciable new information in the future.

7. In response to the energy-resource potential of these shales, the focus of the EGSP has clearly been directed toward acquiring and analyzing data that have their greatest utility in stimulating greater future production of natural gas. Since much of this information has value to

other applications, such as the purpose of this report, there remains considerable room for greater analysis of EGSP data from the perspective of nuclear-waste disposal.

There are also certain topical areas of interest for which both the acquisition of more data and more analysis of those data are needed in regard to nuclear-waste disposal. Included here are such aspects as the ion-exchange and hydraulic properties of the shales, the nature of associated groundwater (both in terms of any free water within shale units and the detailed hydrology of adjacent aquifers), and rock-mechanical properties of the shales.

Because fractures, which create desirable porosity and permeability relative to gas production, may be stratigraphically influenced (fracture facies) or aligned with more deeply buried structures, an allied need closer to the scope of this report is to learn considerably more about the spatial distribution and magnitude of fractures (if any exist at depth) in the less hydrocarbon-prospective intervals. This need is closely related to general rock-mechanical parameters and may in part be addressable by means of data acquired from various hydraulic fracturing experiments conducted to date and planned for the future.

Another field of investigation with greater orientation toward nuclear-waste disposal centers upon a determination of the effects on these particular shales from any artificial thermal load produced by heat-generating wastes. Three subareas of interest here involve (1) the degree of possible dewatering from the clay minerals present and the chemical nature of any such released fluids, (2) the impact on various rock-mechanical properties, and (3) the effect on the contained organic matter and the general susceptibility toward liberating hydrocarbons.

Based on the reasonable promise exhibited by these shales on a regional basis, the leading recommendation from this investigation is that certain of these rock units warrant additional study. Two contrasting approaches could be pursued in this context. First, more thorough evaluations could be made of the extensive data available from the voluminous inventory of cores, well logs, and rock-property analyses. Such data is already at hand from the EGSP and from other sources, and more will be acquired in the coming year(s). An allied possibility would involve hydraulic and in situ rock-mechanical testing within certain existing boreholes. The emphasis in all such studies and research would be to evaluate these data sources principally from the nuclear-waste perspective.

A second approach would entail the selection of one or more smaller study areas based on the regional assessment represented by this study. Detailed examination of all subsurface data including EGSP information would more fully characterize certain of the more promising shale intervals from the viewpoint of more localized thickness, depth, geologic-structure, groundwater-hydrology, and rock-property relationships. Elements of the first approach could also be interrelated within any or all of the selected study areas to form either a sequential or more comprehensive evaluation.

Depending on the level of interest and the availability of future funding, either or both of these approaches appear tenable. An additional consideration is that either recommended approach could be implemented within any one of the geologic basins or within all three simultaneously.

# 6. REFERENCES


Aker, J. 1938. *Drift thickness map of Michigan's Southern Peninsula.* Mich. Geol. Surv. Map 3528, scale 1:500,000.

Algermissen, S. T. 1969. *Seismic risk map of the United States.* U.S. Dep. Commerce, ESSA/Coast and Geodetic Survey Map.

Algermissen, S. T., and Perkins, D. M. 1976. *A probabilistic estimate of maximum acceleration in rock in the contiguous United States.* U.S. Geol. Surv. Open-File Rep. 76-416.

Ammerman, M. L., and Keller, G. R. 1979. Delineation of Rome Trough in eastern Kentucky by gravity and deep drilling data. *Am. Assoc. Pet. Geol. Bull.* 63: 341-53.

Asseez, L. O. 1969. Paleogeography of the Lower Mississippian rocks of the Michigan Basin. *Am. Assoc. Pet. Geol. Bull.* 53: 127-35.

Atherton, E. 1971. Tectonic development of the eastern interior region of the United States. In *Background materials for symposium on future petroleum potential of NPC region 9 (Illinois Basin, Cincinnati Arch, and northern part of Mississippi Embayment).* Ill. State Geol. Surv., Ill. Pet. 96, pp. 29-43.

Averitt, P. 1975. *Coal resources of the United States, January 1, 1974.* U.S. Geol. Surv. Bull. 1412.

Bagnall, W. D., and Ryan, W. M. 1976. The geology, reserves, and production characteristics of the Devonian Shale in southwestern West Virginia. In *Devonian Shale production and potential,* ed. R. C. Shumaker and W. K. Overbey, Jr. U.S. Energy Res. Dev. Adm., Morgantown Energy Res. Cent. Pub. MERC/SP-76/2, pp. 41-53.

Bassett, J. L., and Hasenmueller, N. R. 1977. The New Albany Shale and correlative strata in Indiana. In *Proceedings, first eastern gas shales symposium.* U.S. Dep. Energy, Morgantown Energy Res. Cent. Pub. MERC/SP-77/5, pp. 183-94.

Bassett, J. L., and others. 78. Relationship of lineaments to gas production in the New Albany Shale in Indiana. In *Preprints, second eastern gas shales symposium*. U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-78/6, vol. 1, pp. 251-63.

Bergstrom, R. E. 1968. *Feasibility of subsurface disposal of industrial wastes in Illinois*. Ill. State Geol. Surv. Circ. 426.

Bergstrom R. E., and Shimp, N. F. 1977. Geologic and geochemical studies of the New Albany Group (Devonian black shale) in Illinois to evaluate its characteristics as a source of hydrocarbons. *Ill. State Geol. Surv. Q. Rep. Oct. 1-Dec. 31, 1977*. ORO-5203-3.

Bergstrom, R. E., and Shimp, N. F. 1979. Geologic and geochemical studies of the New Albany Group (Devonian black shale) in Illinois to evaluate its characteristics as a source of hydrocarbons. *Ill. State Geol. Surv. Q. Rep. for Q1-Q4*.

Bloyd, R. M., Jr. 1974. *Summary appraisals of the nation's groundwater resources — Ohio region*. U.S. Geol. Surv. Prof. Paper 813-A.

Bloyd, R. M., Jr. 1975. *Summary appraisals of the nation's groundwater resources — Upper Mississippi region*. U.S. Geol. Surv. Prof. Pap. 813-B.

Bollinger, G. A. 1973. Seismicity of the southeastern United States. *Seis. Soc. Am. Bull.* 63: 1785-1808.

Bond, D. C., and others. 1971. Possible future petroleum potential of region 9 (Illinois Basin, Cincinnati Arch, and northern Mississippi Embayment). In *Future petroleum provinces of the United States — their geology and potential*, ed. I. H. Cram. Am. Assoc. Pet. Geol. Memo. 15, part 2, pp. 1165-218.

Breger, I. A. 1979. A suggested origin for the gas in eastern Devonian shales. In *Proceedings, third eastern gas shales symposium*. U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-79/6, p. 26.

Bricker, D. M. 1977. *Seismic disturbances in Michigan*. Mich. Geol. Surv. Circ. 14.

Bristol, H. M., and Buschbach, T. C. 1971. Structural features of the eastern interior region of the United States. In *Background materials for symposium on future petroleum potential of NPC region 9 (Illinois Basin, Cincinnati Arch, and northern part of Mississippi Embayment)*. Ill. State Geol. Surv., Ill. Pet. 96, pp. 21-28.

Buschbach, T. C. 1971. Stratigraphic setting of the eastern interior region of the United States. In *Background materials for symposium on future petroleum potential of NPC region 9 (Illinois Basin, Cincinnati Arch, and northern part of Mississippi Embayment)*. Ill. State Geol. Surv., Ill. Pet. 96, pp. 3-20.

Buschbach, T. C., and others. 1980. *New Madrid seismotectonic study; activities during fiscal year 1979*. U.S. Nucl. Regul. Comm. Pub. NUREG/CR/0977.

Byerly, D. W. 1975. *The stability and tightness of the Columbus Limestone and surrounding rocks in the vicinity of Barberton, Ohio*. Office of Waste Isolation, Union Carbide Corp., Consultant's Rep. Y/OWI/SUB-4251/1.

Claypool, G. E.; Threlkeld, C. N.; and Bostick, N. H. 1978. Natural gas occurrence related to regional thermal rank of organic matter (maturity) in Devonian rocks of the Appalachian Basin. In *Preprints, second eastern gas shales symposium*. U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-78/6, vol. 1, pp. 54-65.

Cobbs Engineering. 1975. *Study of mined storage caverns*. Oak Ridge National Laboratory, Union Carbide Corp., Consultant's Rep. ORNL/SUB-75/64509.

Coffman, J. L., and von Hake, C. A., Eds. 1973. *Earthquake history of the United States*. Nat. Oceanic Atmos. Adm. Pub. 41-1, rev. ed.

Cohee, G. V., and others. 1950. *Coal resources of Michigan*. U.S. Geol. Surv. Circ. 77.

Cohee, G. V., and others. 1951. *Thickness and lithology of Upper Devonian and carboniferous rocks in Michigan*. U.S. Geol. Surv. Oil Gas Investigations Chart OC-41.

Collinson, C., and others. 1968. Devonian of the north-central region, United States. In *International Symposium on the Devonian System*, ed. D. H. Oswald. Alberta Soc. Pet. Geol., vol. 1, pp. 933-71.

Colton, G. W. 1961. *Geologic summary of the Appalachian Basin*. U.S. Geol. Surv. Open-File Rep. TEI-791.

Colton, G. W. 1970. The Appalachian Basin — its depositional sequences and their geologic relationships. In *Studies of Appalachian geology: central and southern*, ed. G. W. Fisher and E. Cloos. New York: John Wiley & Sons, pp. 5-47.

Conant, L. C., and Swanson, V. E. 1961. *Chattanooga Shale and related rocks of central Tennessee and nearby areas*. U.S. Geol. Surv. Prof. Pap. 357.

Conkin, J. E., and Conkin, B. M. 1976. *Guide to the rocks and fossils of Jefferson County, Kentucky, southern Indiana, and adjacent areas*. 2d ed. Univ. Louisville Reprod. Serv.

Cooper, B. N. 1966. Geology of the salt gypsum deposits in the Saltville area, Symth and Washington counties, Virginia. In *Second symposium on salt*, ed. J. L. Rau. Cleveland: Northern Ohio Geol. Soc., vol. 1, pp. 11-34.

Dames and Moore. 1978. *Baseline rock properties — shale*. Office of Waste Isolation, Union Carbide Corp., Consultant's Rep. Y/OWI/TM-36/6, Technical Support for GEIS, vol. 6.

de Witt, W., Jr. 1960. *Geology of the Michigan Basin with reference to subsurface disposal of radioactive waste*. U.S. Geol. Surv. Trace Elements Investigations Rep. 771.

Docekal, J. 1970. *Earthquakes of the stable interior with emphasis on the Midcontinent*. Unpublished Ph.D. dissertation, Univ. Neb.

Ells, G. D. 1967. *Michigan's Silurian oil and gas pools*. Mich. Geol. Surv. Rep. of Investigation 2.

Ells, G. D. 1969. Architecture of the Michigan Basin. In *Studies of the Precambrian of the Michigan Basin*. Mich. Basin Geol. Soc. Annu. Field Excursion Guidebook, pp. 60–88.

Ells, G. D. 1971. Future oil and gas possibilities in Michigan Basin. In *Future petroleum provinces of the United States — their geology and potential*. Am. Assoc. Pet. Geol. Memo. 15, vol. 2, pp. 1124–64.

Ells, G. D. 1978. An appraisal of known Antrim Shale and Berea oil and gas pools in Michigan. In *Preprints, second eastern gas shales symposium*. U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-78/6, vol. 1, pp. 280–30.

Ells, G. D. 1979. *Stratigraphic cross sections extending from Devonian Antrim Shale to Mississippian Sunbury Shale in the Michigan Basin*. Mich. Geol. Surv. Rep. of Investigation 22.

Ells, G. D., and others. 1975. *Michigan's oil and gas fields, 1974*. Mich. Geol. Surv. Annu. Stat. Summ. 20.

Fenneman, N. M. 1946. *Physical divisions of the United States*. U.S. Geol. Surv. map, scale 1:7,000,000.

Fisher, J. H. 1969. Early Paleozoic history of the Michigan Basin. In *Studies of the Precambrian of the Michigan Basin*. Mich. Basin Geol. Soc. Annu. Field Excursion Guidebook, pp. 89–93.

Frey, M. G. 1973. Influence of Salina salt on structure in New York–Pennsylvania part of Appalachian Plateau. *Am. Assoc. Pet. Geol. Bull.* 57: 1027–37.

Gardner, W. C. 1974. *Middle Devonian stratigraphy and depositional environments in the Michigan Basin*. Mich. Basin Geol. Soc. Spec. Pap 1.

Gere, M. A., Jr. 1979. Michigan mineral producers, 1978. *Mich. Geol. Surv. Annu. Dir.*, vol. 12.

Gwinn, V. E. 1964. Thin-skinned tectonics in the Plateau and northwestern Valley and Ridge provinces of the central Appalachians. *Geol. Soc. Am. Bull.* 75: 863-900.

Gwinn, V. E. 1967. Lateral shortening of layered rock sequences in the foothills regions of major mountain systems. *Miner. Ind. J.* 36(5): 1-7.

Hadley, J. B., and Piotrowski, R. G. 1978. Stratigraphy, extent, gas production, and future gas potential of the Devonian organic-rich shales in PennysIvania. In *Preprints, second eastern gas shales symposium.* U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-78/6, vol. 1, pp. 310-29.

Harris, L. D. 1978. The Eastern Interior aulacogen and its relation to Devonian shale-gas production. In *Preprints, second eastern gas shales symposium.* U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-78/6, vol. 2, pp. 55-72.

Harvey, R. D., and others. 1977. Petrology of New Albany Shale Group (Upper Devonian and Kinderhookian) in the Illinois Basin, a preliminary report. In *Proceedings, first eastern gas shales symposium.* U.S. Dep. Energy, Morgantown Energy Res. Cent. Pub. MERC/SP-77/5, pp. 328-54.

Hasson, K. O., and Dennison, J. M. 1978. Devonian Harrell and Millboro shales in parts of Pennsylvania, Maryland, West Virginia, and Virginia. In *Proceedings, first eastern gas shales symposium.* U.S. Dep. Energy, Morgantown Energy Res. Cent. Pub. MERC/SP-77/5, pp. 634-41.

Hennington, W. M. 1979. Unconventional evaluation of the Cottageville Devonian Shale field, Jackson and Mason counties, West Virginia. In *Proceedings, third eastern gas shales symposium.* U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-79/6, pp. 371-84.

Hockings, W. A.; Ruotsala, A. P.; and Bennett, G. W. 1979. *X-ray mineralogy and physical properties of Antrim Shale samples from Sanilac County, Michigan.* Dow Chemical Co. and U.S. Dep. Energy Rep. FE-2346-32.

Hunter, C. D., and Young, D. M. 1953. Relationship of natural gas occurrence and production in eastern Kentucky (Big Sandy gas field) to joints and fractures in Devonian bituminous shale. *Am. Assoc. Pet. Geol. Bull.* 37: 282-99.

Interagency Review Group. 1979. *Report to the President by the Interagency Review Group on nuclear waste management.* U.S. Gov. Rep. TID-29442.

Ives, R. E., and Eddy, G. E. 1970. *Subsurface disposal of industrial wastes, 1st supplement.* Oklahoma City, Okla.: Interstate Oil Compact Commission.

Janssens, A., and de Witt, Jr. 1976. *Potential natural gas resources in the Devonian shales in Ohio.* Ohio Geol. Surv. Geol. Note 3.

Johnson, K. S., and Gonzales, S. 1978. *Salt deposits in the United States and regional geologic characteristics important for storage of radioactive waste.* Office of Waste Isolation, Union Carbide Corp., Consultant's Rep. Y/OWI/SUB-7414/1.

Jorgensen, D. B., and Carr, D. D. 1972. Influence of cyclic deposition, structural features, and hydrologic controls on evaporite deposits in the St. Louis Limestone in southwestern Indiana. In *Proceedings, eighth forum on geology of industrial minerals.* Iowa Geol. Surv. Inf. Circ. 5, pp. 43-65.

Kalyoncu, R. S., and Snyder, M. J. 1978. *Characterization and analysis of Devonian shales as related to release of gaseous hydrocarbons.* Q. Tech. Prog. Rep. for Q1-Q4. Battelle Columbus Laboratories.

Kalyoncu, R. S., and Snyder, M. J. 1979. *Characterization and analysis of Devonian shales as related to release of gaseous hydrocarbons, well C-2, Lincoln County, W. Va.* Tech. Rep., Mar. 30. Battelle Columbus Laboratories.

Kalyoncu, R. S., and others. 1979a. *Characterization and analysis of Devonian shales as related to release of gaseous hydrocarbons, well C-1, Lincoln Co., W. Va.* Tech. Rep., Mar. 10. Battelle Columbus Laboratories.

Kalyoncu, R. S., and others. 1979b. *Characterization and analysis of Devonian shales as related to release of gaseous hydrocarbons.* Q. Tech. Prog. Rep. for Q1-Q4. Battelle Columbus Laboratories.

Kalyoncu, R. S., and others. 1979c. *Characterization and analysis of Devonian shales as related to release of gaseous hydrocarbons, well C-338, Wise Co., Va.* Tech. Rep., May 15. Battelle Columbus Laboratories.

Kalyoncu, R. S., and others. 1979d. *Characterization and analysis of Devonian shales as related to release of gaseous hydrocarbons, well C-336, Martin Co., Ky.* Tech. Rep., May 16. Battelle Columbus Laboratories.

Kalyoncu, R. S., and others. 1979e. *Characterization and analysis of Devonian shales as related to release of gaseous hydrocarbons, well P-1, Sullivan Co., Ind.* Tech. Rep., May 18. Battelle Columbus Laboratories.

Kalyoncu, R. S., and others. 1979f. *Characterization and analysis of Devonian shales as related to release of gaseous hydrocarbons, well 0-1, Christian Co., Ky.* Tech. Rep., May 25. Battelle Columbus Laboratories.

Kalyoncu, R. S., and others. 1979g. *Characterization and analysis of Devonian shales as related to release of gaseous hydrocarbons, well T-1, Effingham Co., Ill.* Tech. Rep., July 24. Battelle Columbus Laboratories.

Kelley, R. W. 1968. *Bedrock of Michigan.* Mich. Geol. Surv. small-scale map 2, scale 1:2,535,000.

Kepferle, R. C.; Wilson, E. N.; and Ettensohn, F. R. 1978. *Preliminary stratigraphic cross section showing radioactive zones in the Devonian black shales in the southern part of the Appalachian Basin.* U.S. Geol. Surv. Oil Gas Investigations Chart OC-85.

Kim, K. 1978. *Mechanical characteristics of Antrim Shale; interim report for period April 1977-January 1978.* Dow Chemical Co. and U.S. Dep. Energy Rep. FE-2346-24.

Klepser, H., and Hyder, J. L. 1980. *Preliminary stratigraphic engineering analysis and design for a radioactive waste repository in Devonian black shales*. Oak Ridge National Laboratory, Union Carbide Corp., Consultant's Rep.

Leventhal, J. S. 1978. Summary of chemical analyses and some geochemical controls related to Devonian black shales from Tennessee, West Virginia, Kentucky, Ohio, and New York. In *Preprints, second eastern gas shales symposium*. U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-78/6, vol. 1, pp. 339-46.

Leventhal, J. S., and Goldhaber, M. B. 1978. New data for uranium, thorium, carbon, and sulfur in Devonian black shale from West Virginia, Kentucky, and New York. In *Proceedings, first eastern gas shales symposium*. U.S. Dep. Energy, Morgantown Energy Res. Cent. Pub. MERC/SP-77/5, pp. 259-96.

Lewis, T. L., and Schwietering, J. F. 1971. Distribution of the Cleveland black shale in Ohio. *Geol. Soc. Am. Bull.* 82: 3477-82.

Lilienthal, R. T. 1978. *Stratigraphic cross sections of the Michigan Basin*. Mich. Geol. Surv. Report of Investigation 19.

Linebach, J. A. 1968. Subdivisions and depositional environments of New Albany Shale (Devonian-Mississippian) in Indiana. *Am. Assoc. Pet. Geol. Bull.* 52: 1291-303.

Linebach, J. A. 1970. *Stratigraphy of New Albany Shale in Indiana*. Ind. Geol. Surv. Bull. 44.

Lockett, R. 1968. Production of gas in northern Cincinnati Arch province. In *Natural gases of North America*, ed. B. W. Beebe and B. F. Curtis. Am. Assoc. Pet. Geol. Memo. 9, vol. 2, pp. 1716-45.

Long, B. R. 1979. Regional survey of surface joints in eastern Kentucky. In *Proceedings, third eastern gas shales symposium*. U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-79/6, pp. 445-50.

Majchszak, F. L. 1978. Progress report on characterization of the Devonian black shales in Ohio. In *Proceedings, first eastern gas shales symposium*. U.S. Dep. Energy, Morgantown Energy Res. Cent. Pub. MERC/SP-77/5, pp. 668-77.

Malhotra, R. 1977. *Market potential for coals of the Illinois Basin*. Ill. State Geol. Surv. Ill. Miner. Note 67.

Martin, P., and Nucklos, E. B., III. 1976. Geology and oil and gas occurrence in the Devonian shales: northern West Virginia. In *Devonian shale production and potential*, ed. R. C. Shumaker and W. K. Overbey, Jr. U.S. Energy Res. Dev. Adm., Morgantown Energy Res. Cent. Pub. MERC/SP-76/2, pp. 20-40.

Matthews, R. D., and others. 1978. In situ processing of Michigan Antrim-field tests. In *Preprints, second eastern gas shales symposium*. U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-78/6, vol. 1, pp. 230-39.

McGinnis, L. D., and others. 1976. *The gravity field and tectonics of Illinois*. Ill. State Geol. Surv. Circ. 494.

Merewether, E. A., and others. 1973. *Shale, mudstone, and claystone as potential host rocks for underground emplacement of waste*. U.S. Geol. Surv. Open-File Rep. USGS-4339-5.

Nance, S. W.; Seabaugh, P. W.; and Zielinski, R. E. 1979. A current assessment of the physiochemical characterization data for the eastern gas shales. In *Proceedings, third eastern gas shales symposium*. U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-79/6, pp. 83-84.

National Academy of Sciences. 1957. *The disposal of radioactive waste on land*. Div. Earth Sci. Comm. Rep., Natl. Res. Counc. Pub. 519.

National Academy of Sciences. 1970. *Disposal of solid radioactive waste in bedded salt deposits*. Comm. Radioact. Waste Manage. Rep.

Negus-deWys, J. 1979. Lithology studies of Upper Devonian well cuttings in the Western Kentucky gas field. In *Proceedings, third eastern gas shales symposium*. U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-79/6, pp. 331-69.

Negus-deWys, J., and Shumaker, R. C. 1978. Trend analysis of gas production in the Cottageville Field. In *Preprints, second eastern gas shales symposium*. U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-78/6, vol. 1, pp. 186-91.

Netherland, Sewell and Associates, Inc. 1975. *Preliminary regional study of the present and possible future oil and gas development in the areas of thick rock salt and shale deposits of Michigan, Ohio, Pennsylvania, and western New York as of December 1975*. Oak Ridge National Laboratory, Union Carbide Corp., Consultant's Rep. ORNL/SUB-75/87989.

Nuckols, E. B., III. 1978. Exploration parameters derived from historical Devonian shale production in western West Virginia. In *Preprints, second eastern gas shales symposium*. U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-78/6, vol. 1, pp. 169-73.

Nuhfer, E. B., and Vinopal, R. J. 1979. A fabric-element based classification for low-porosity-shale gas reservoirs. In *Proceedings, third eastern gas shales symposium*. U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-79/6, pp. 485-98.

Oliver, W. A., Jr., and others. 1969. *Correlation of Devonian rock units in the Appalachian Basin*. U.S. Geol. Surv. Oil Gas Investigations Chart OC-64.

Patchen, D. G. 1977. *Subsurface stratigraphy and gas production of the Devonian shales in West Virginia*. U.S. Dep. Energy, Morgantown Energy Res. Cent. Pub. MERC/CR-77/5.

Patchen, D. G., and others. 1979. Oil and gas developments in Maryland, Ohio, Pennsylvania, Virginia, and West Virginia in 1978. *Am. Assoc. Pet. Geol. Bull.* 63: 1244-77.

Patton, J. B. 1977. Carbonaceous shales of Indiana as sources of energy, petrochemicals, and ceramic materials: first annual progress report. In *Proceedings, first eastern gas shales symposium.* U.S. Dep. Energy, Morgantown Energy Res. Cent. Pub. MERC/SP-77/5, pp. 702-708.

Pepper, J. F.; de Witt, Wallace, Jr.; and Demarest, D. F. 1954. *Geology of the Bedford Shale and Berea Sandstone in the Appalachian Basin.* U.S. Geol. Surv. Prof. Pap. 259.

Piotrowski, R. G.; Krajewski, S. A.; and Keyman, L. 1978. Stratigraphy and gas occurrence in the Devonian organic-rich shales of Pennsylvania. In *Proceedings, first eastern gas shales symposium.* U.S. Dep. Energy, Morgantown Energy Res. Cent. Pub. MERC/SP-77/5, pp. 127-44.

Piper, A. M. 1972. *Regional groundwater hydrology of the Southern Peninsula of Michigan and of certain districts in New York and Ohio.* Office of Waste Isolation, Union Carbide Corp., Consultant's Rep. Y/OWI/SUB-3745/1.

Price, P. H. 1931. The Appalachian structural front. *J. Geol.* 39(1): 24-44.

Prouty, C. E. 1976. Implications of imagery studies to time and origin of Michigan Basin linear structures (abstract). *Am. Assoc. Pet. Geol. Bull.* 60: 709.

Provo, L. J.; Kepferle, R. C.; and Potter, P. E. 1978. Division of black Ohio shale in eastern Kentucky. *Am. Assoc. Pet. Geol. Bull.* 62: 1703-13.

Ray, E. O. 1977. Devonian shale production — eastern Kentucky field. In *The future supply of nature-made petroleum and gas: proceedings, first UNITAR conference on energy and the future,* ed. R. F. Meyer. Pergamon Press, pp. 679-96.

Reinhold, M. L. 1978. Stratigraphic relationships of the New Albany Shale Group (Devonian-Mississippian) in Illinois. In *Preprints, second eastern gas shales symposium.* U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-78/6, vol. 1, pp. 443-54.

Rickard, L. V. 1975. *Correlation of the Silurian and Devonian rocks in the New York State.* New York State Mus. Sci. Serv., Map and Chart Series No. 24.

Roen, J. B.; Wallace, L. G.; and de Witt, W., Jr. 1978a. *Preliminary stratigraphic cross section showing radioactive zones of the Devonian black shales in eastern Ohio and west-central Pennsylvania.* U.S. Geol. Surv. Oil Gas Investigations Chart OC-82.

Roen, J. B.; Wallace, L. G.; and de Witt, W., Jr. 1978b. *Preliminary stratigraphic cross section showing radioactive zones in the Devonian black shales in the central part of the Appalachian Basin.* U.S. Geol. Surv. Oil Gas Investigations Chart OC-87.

Roth, E. E. 1968. Natural gas of Appalachian Basin. In *Natural gases of North America,* ed. B. W. Beebe and B. F. Curtis. Am. Assoc. Pet. Geol. Memo 9, vol. 2, pp. 1702-15.

Schwietering, J. F. 1979. *Devonian shales of Ohio and their eastern and southern equivalents.* U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/CR-79/2.

Science Applications, Inc. 1980. *Devonian shale gas.* U.S. Dep. Energy, Morgantown Energy Technol. Cent. Spec. Pub.

Shaffer, N. R., and others. 1978. Comparison of the New Albany Shale from deep and shallow parts of the Illinois Basin in Indiana. In *Preprints, second eastern gas shales symposium.* U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-78/6, vol. 1, pp. 219-29.

Shumaker, R. C. 1976. A digest of Appalachian structural geology. In *Devonian shale production and potential,* ed. R. C. Shumaker and W. W. Overbey, Jr. U.S. Energy Res. Dev. Adm., Morgantown Energy Res. Cent. Pub. MERC/SP-76/2, pp. 75-93.

Shumaker, R. C. 1978. Porous fracture facies in the Devonian shales of eastern Kentucky and West Virginia. In *Preprints, second eastern gas shales symposium.* U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-78/6, vol. 1, pp. 360-69.

Shumaker, R. C., and others. 1979. Parameters of geologic structure which affect Devonian gas shale production in West Virginia and eastern Kentucky — a progress report 1978-1979. In *Proceedings, third eastern gas shales symposium.* U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-79/6, pp. 451-72.

Sinnott, A., and Cushing, E. M. 1978. *Summary appraisals of the nation's groundwater resources — Mid-Atlantic region.* U.S. Geol. Surv. Prof. Pap. 813-I.

Smith, W. E. T. 1966. Earthquakes of eastern Canada and adjacent areas, 1928-1959. *Canada Dept. Mines Tech. Serv., Dominion Observatory Pub., Ottawa* 32(3): 85-121.

Sorenson, H. O. 1970. Michigan's clay deposits and industry. In *Proceedings, sixth forum on geology of industrial minerals.* Mich. Geol. Surv. Misc. 1, pp. 143-55.

Streib, D. L. 1979. *EGSP outgassing analysis — special report (draft).* U.S. Dep. Energy, Morgantown Energy Technol. Cent.

Swanson, V. E. 1960. *Oil yield and uranium content of black shales.* U.S. Geol. Surv. Prof. Pap. 356-A.

Swanson, V. E. 1961. *Geology and geochemistry of uranium in marine black shales, a review.* U.S. Geol. Surv. Prof. Pap. 356-C, pp. 67-110.

Tarbell, E. 1941. Antrim-Ellsworth-Coldwater shale formations in Michigan. *Am. Assoc. Pet. Geol. Bull.* 25: 724-33.

Tillman, J. R. 1970. The age, stratigraphic relations, and correlations of the lower part of the Olentangy Shale of central Ohio. *Ohio J. Sci.* 70(4): 202-17.

Twenter, F. R. 1966a. *General availability of groundwater in the glacial deposits in Michigan.* Mich. State Resour. Planning Div. and Mich. Water Resour. Comm. map.

Twenter, F. R. 1966b. *General availability and quality of groundwater in the bedrock deposits in Michigan.* Mich. State Resour. Planning Div. and Mich. Water Resour. Comm. map.

University of Kentucky. 1979. *Black shale studies in Kentucky*, ed. W. H. Blackburn. Dep. Geol. and Ky. Geol. Surv. Res. Group, Annu. Rep. 9/30/78 to 10/1/79.

U.S. Bureau of Mines. 1978. *Minerals yearbook 1975*. U.S. Bur. Mines Miner. Yearbook, vol. 2, area reports, domestic.

U.S. Department of Energy. 1979. *Semiannual report for the unconventional gas recovery program, period ending September 30, 1978 (draft)*. U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub., pp. 59-121.

U.S. Energy Research and Development Administration. 1976. *Alternatives for managing wastes from reactors and post-fission operations in the LWR fuel cycle*. ERDA-76-43.

U.S. Geological Survey. 1968. *Water resources investigations in Michigan*. U.S. Geol. Surv. Water Resour. Pam.

Van Tyne, A. M., and Peterson, J. C. 1978. Thickness, extent of and gas occurrences in Upper and Middle Devonian black shales of New York. In *Preprints, second eastern gas shales symposium*. U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-78/6, vol. 1, pp. 99-128.

Wallace, L. G.; Roen, J. B.; and de Witt, W., Jr. 1977. *Preliminary stratigraphic cross section showing radioactive zones in the Devonian black shales in the western part of the Appalachian Basin*. U.S. Geol. Surv. Oil Gas Investigations Chart OC-80.

Wallace, L. G.; Roen, J. B.; and de Witt, W., Jr. 1978. *Preliminary stratigraphic cross section showing radioactive zones in the Devonian black shales in southeastern Ohio and western West Virginia*. U.S. Geol. Surv. Oil Gas Inventory Chart OC-83.

Waller, R. M., and Allen, W. B. 1975. Geology and groundwater. In Appendix 3 of *Great Lakes Basin framework study*. Great Lakes Basin Commission.

Warner, D. L., and Orcutt, D. H. 1973. Industrial wastewater-injection wells in United States — status of use and regulations, 1973. In *Preprints, symposium on underground waste management and artificial recharge*. Am. Assoc. Pet. Geol., vol. 2, pp. 687-97.

Weaver, O. D.; McGuire, W. H.; and Smitherman, J., III. 1978. Overthrust belt in southeast Kentucky yields prolific discovery. *Oil Gas J.* 76(18): 92-95.

Weist, W. G., Jr. 1978. *Summary appraisals of the nation's groundwater resources — Great Lakes region.* U.S. Geol. Surv. Prof. Pap. 813-J.

Werner, E. 1978. Interrelationships of photolineaments, geological structures, and fracture production of natural gas in the Appalachian Plateau of West Virginia. In *Proceedings, first eastern gas shales symposium.* U.S. Dep. Energy, Morgantown Energy Res. Cent. Pub. MERC/SP-77/5, pp. 474-83.

West, M. 1978. *Preliminary stratigraphic cross section showing radioactive zones in the Devonian black shales in the eastern part of the Appalachian Basin.* U.S. Geol. Surv. Oil Gas Investigations Chart OC-86.

Wilkinson, J. F. 1980. The 1980 forecast: mixed sunshine and clouds. *Coal Age* 85(2): 58-64.

Willman, H. B., and others. 1975. *Handbook of Illinois stratigraphy.* Ill. State Geol. Surv. Bull. 95.

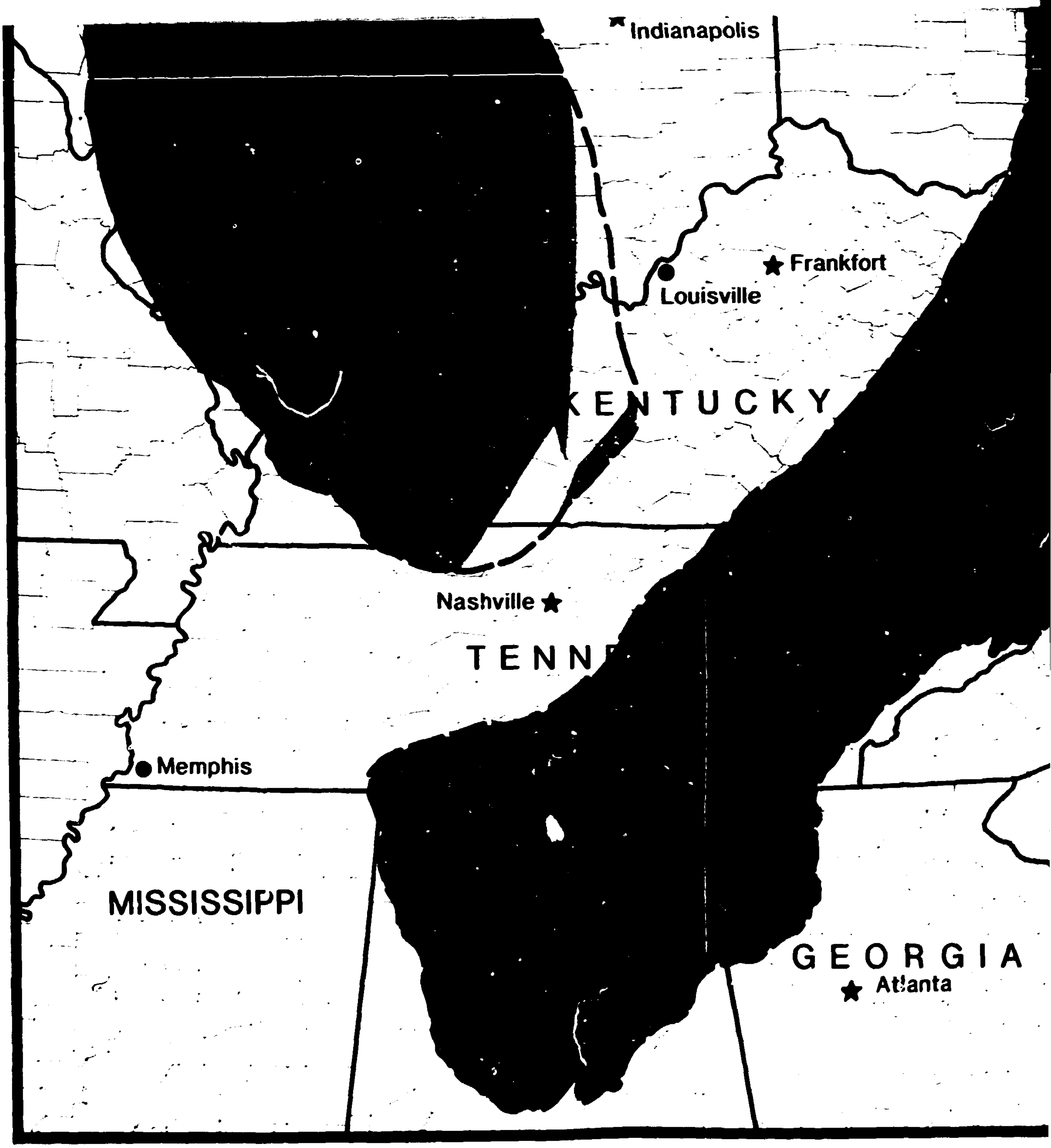
Wise, R. L. 1979. Status report of the Eastern Gas Shales Project. In *Proceedings, third eastern gas shales symposium.* U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-79/6, pp. 3-13.

Woodward, H. P. 1958. Emplacement of oil and gas in Appalachian Basin. In *Habitat of oil,* ed. L. G. Weeks. Am. Assoc. Pet. Geol. Spec. Pub., pp. 494-510.

Young, D. C. 1978. Chemical and physical properties of Michigan Antrim Shale. In *Preprints, second eastern gas shales symposium.* U.S. Dep. Energy, Morgantown Energy Technol. Cent. Pub. METC/SP-78/6, vol. 1, pp. 129-37.

WISCONSIN
Madison
Racine
Chicago
Toledo
Ft. Wayne
OHIO
INDIANA


Lake Ontario
NEW YORK
New
York
NEW
Trenton
JERSEY
Philadelphia
MARYLAND
Baltimore
Annapolis
Dover



Indianapolis
Frankfort
Louisville
KENTUCKY
Nashville
TENN
Memphis
MISSISSIPPI
GEORGIA
Atlanta

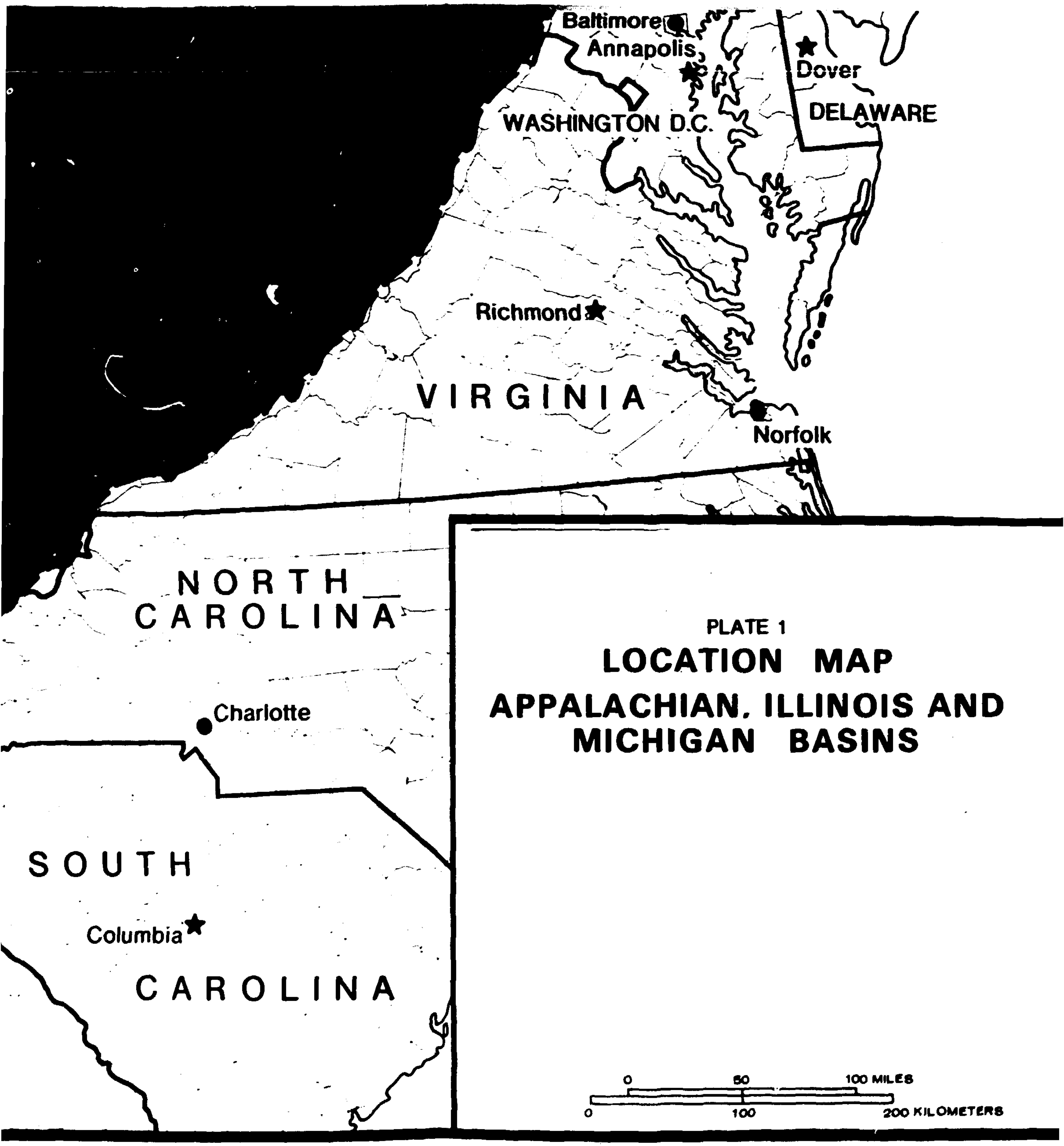
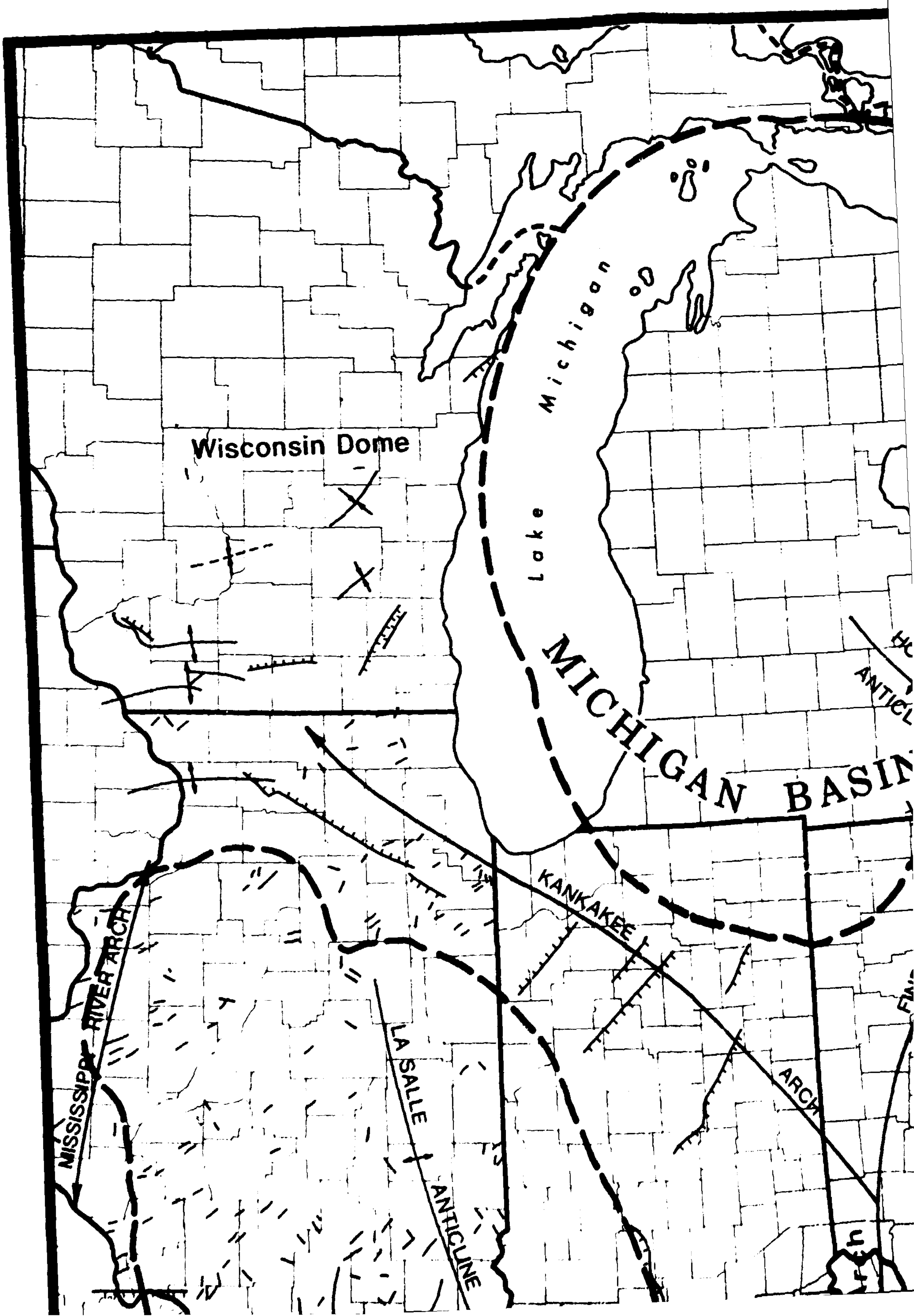
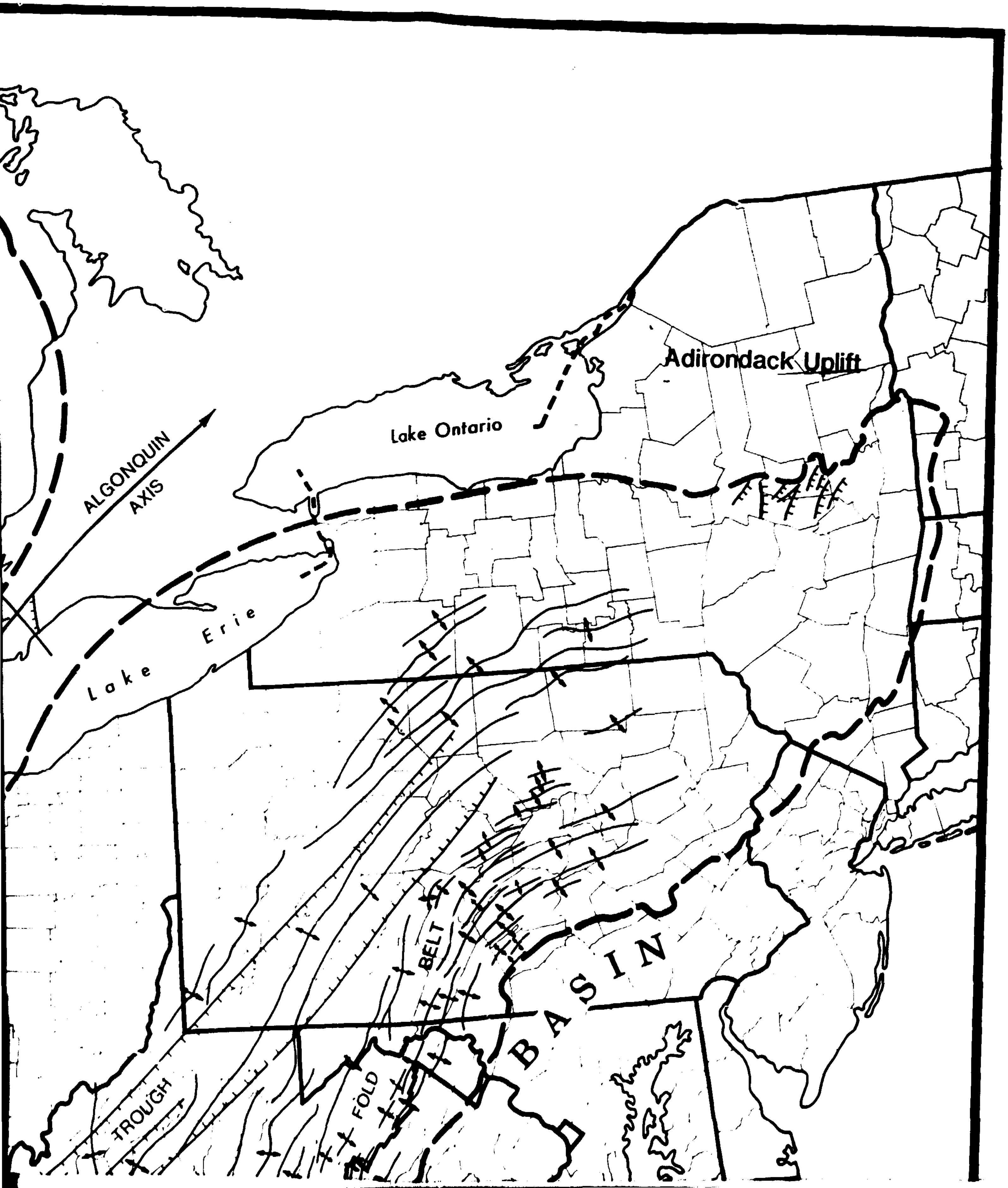
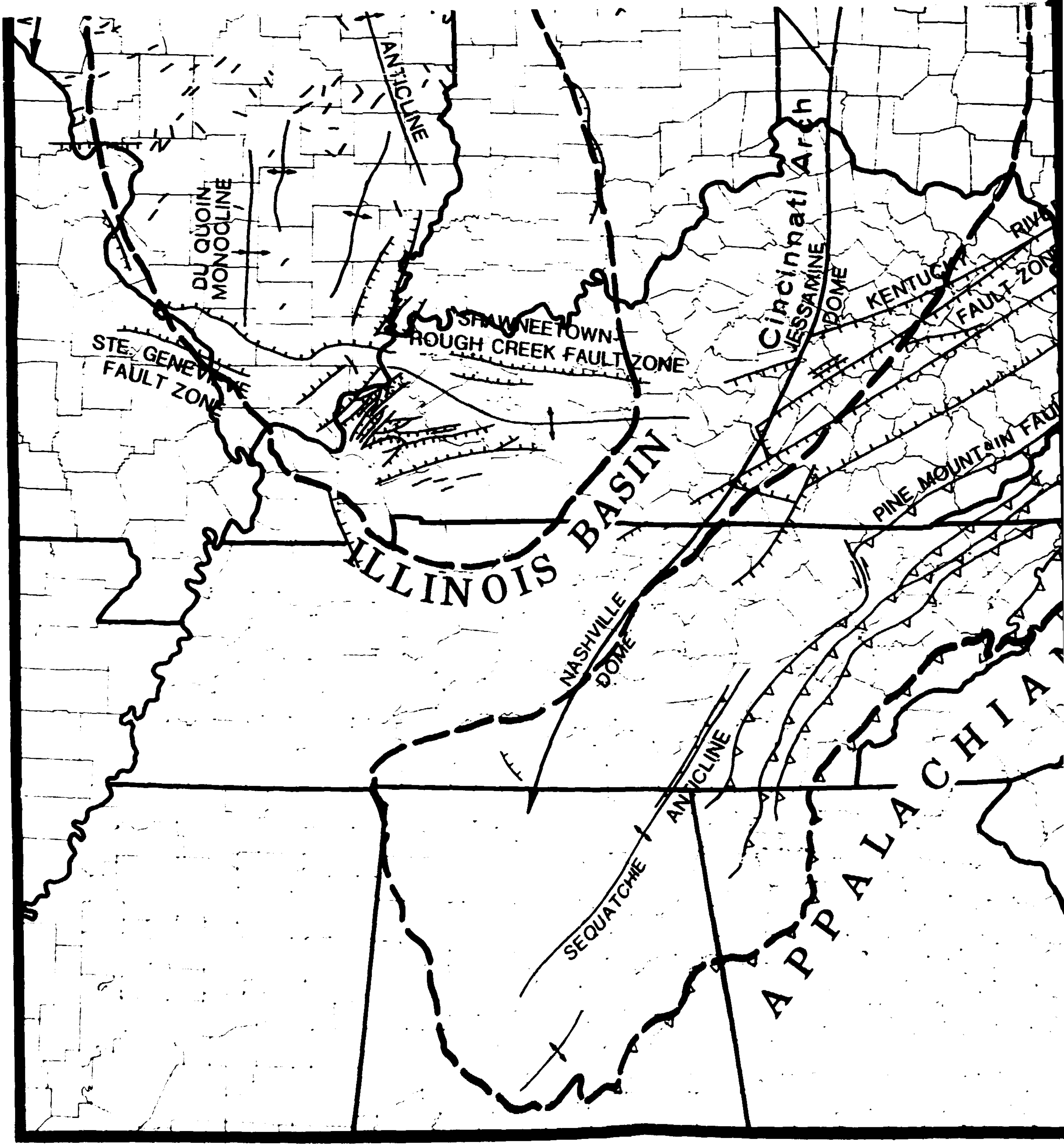



PLATE 1
**LOCATION MAP**
**APPALACHIAN, ILLINOIS AND MICHIGAN BASINS**

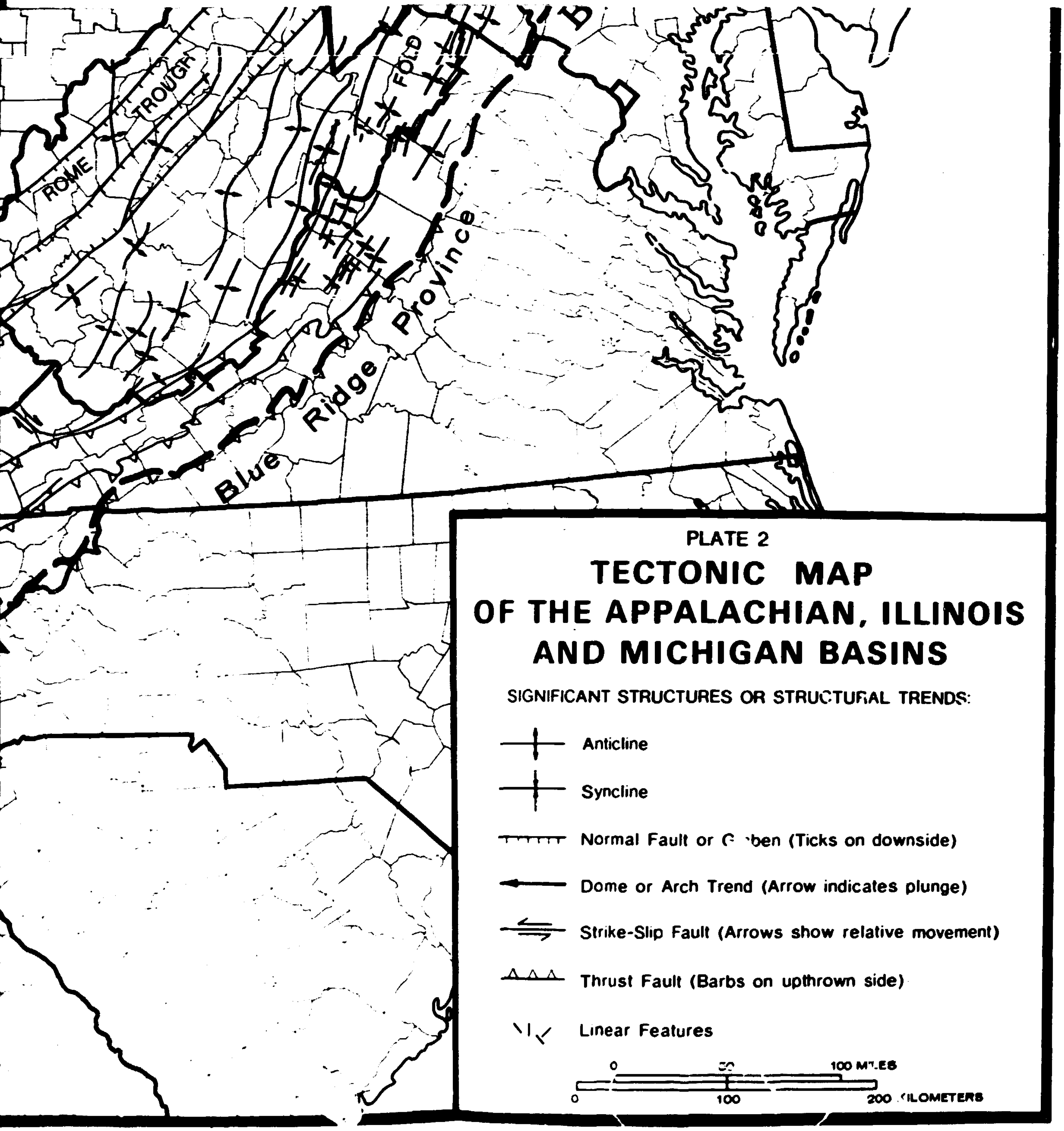

Wisconsin Dome
Lake Michigan
MICHIGAN BASIN
KANKAKEE ARCH
MISSISSIPPI RIVER ARCH
LA SALLE ANTICLINE

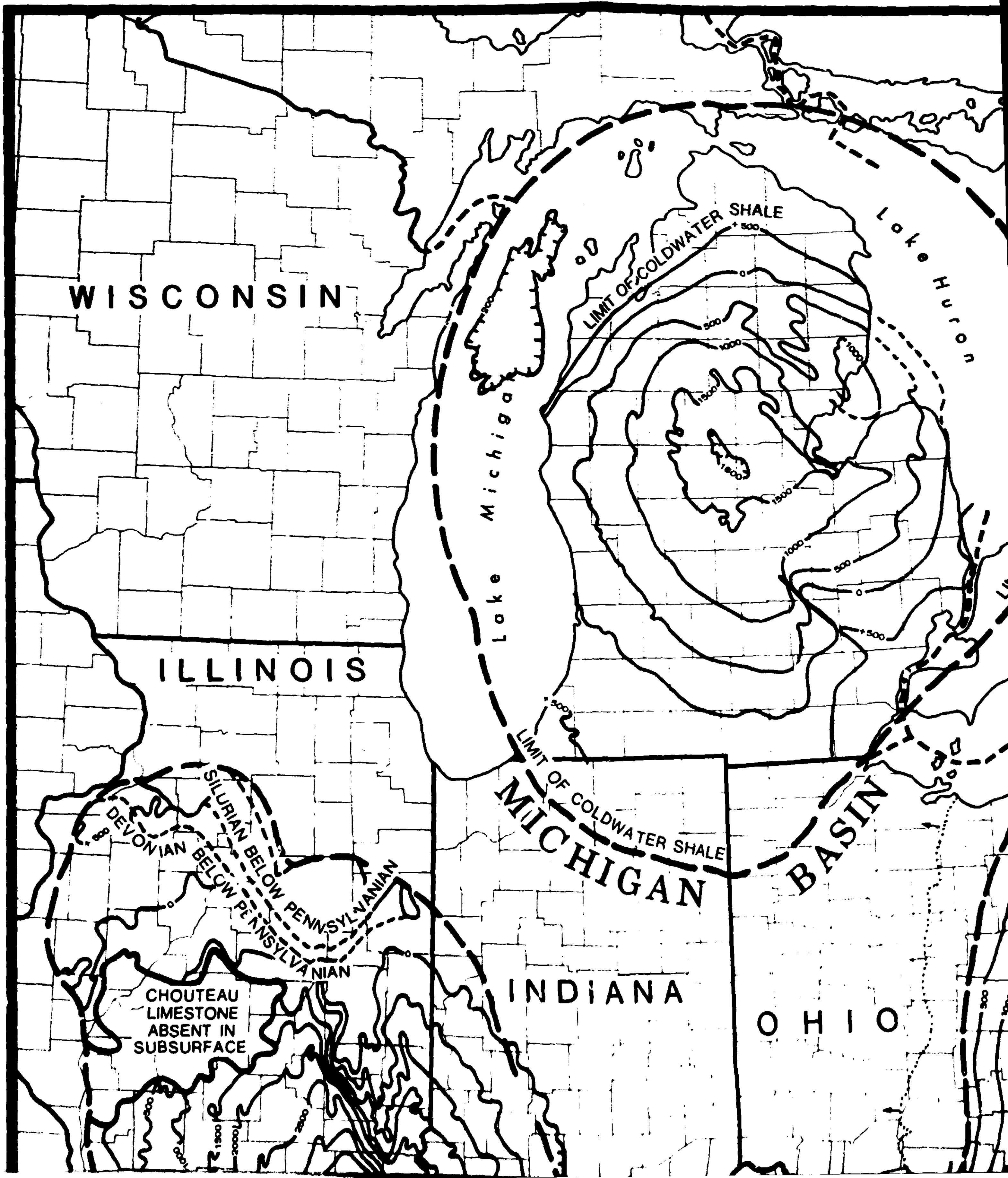


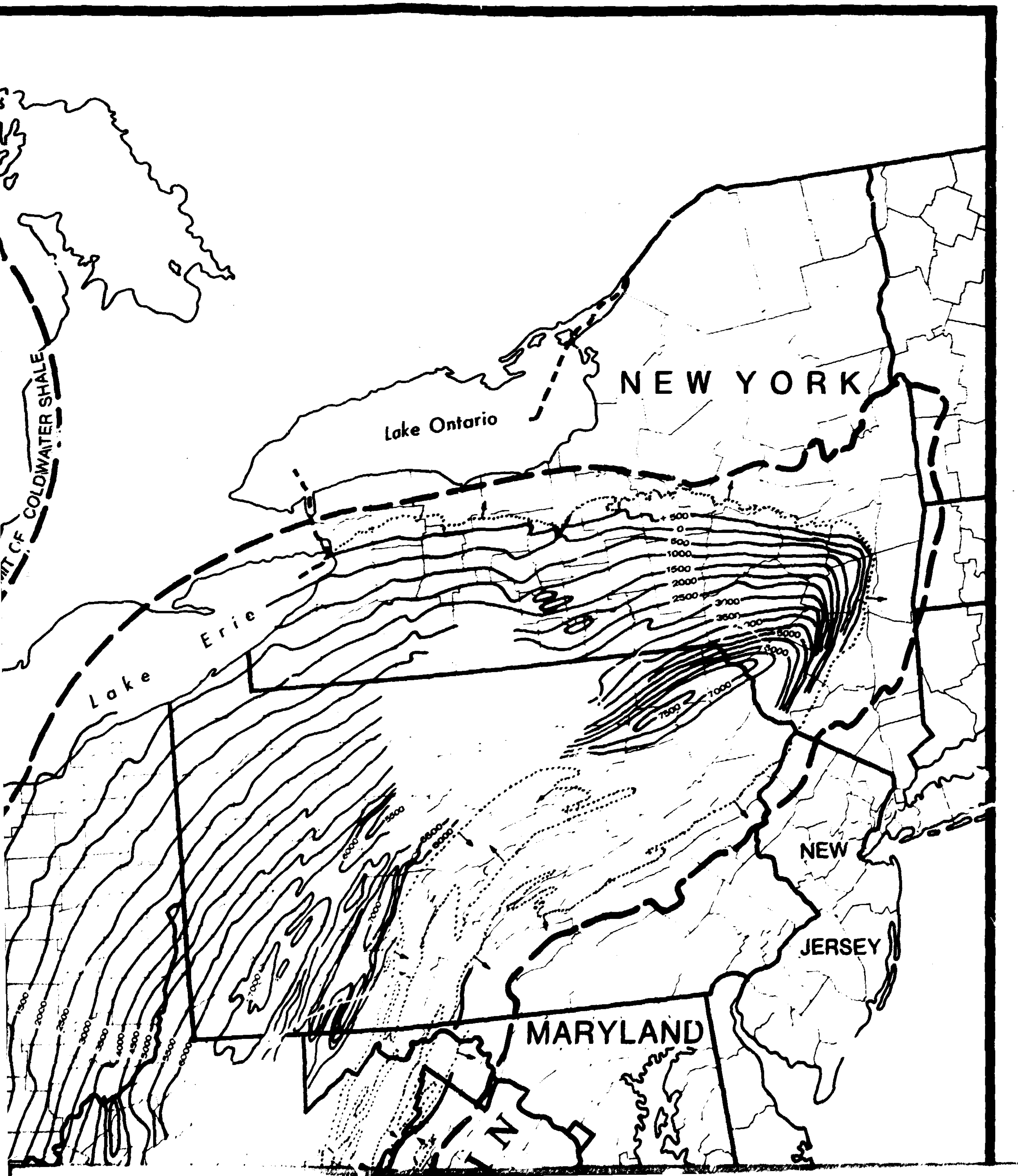
Adirondack Uplift
Lake Ontario
ALGONQUIN AXIS
Lake Erie
BASIN
BELT
FOLD
TROUGH

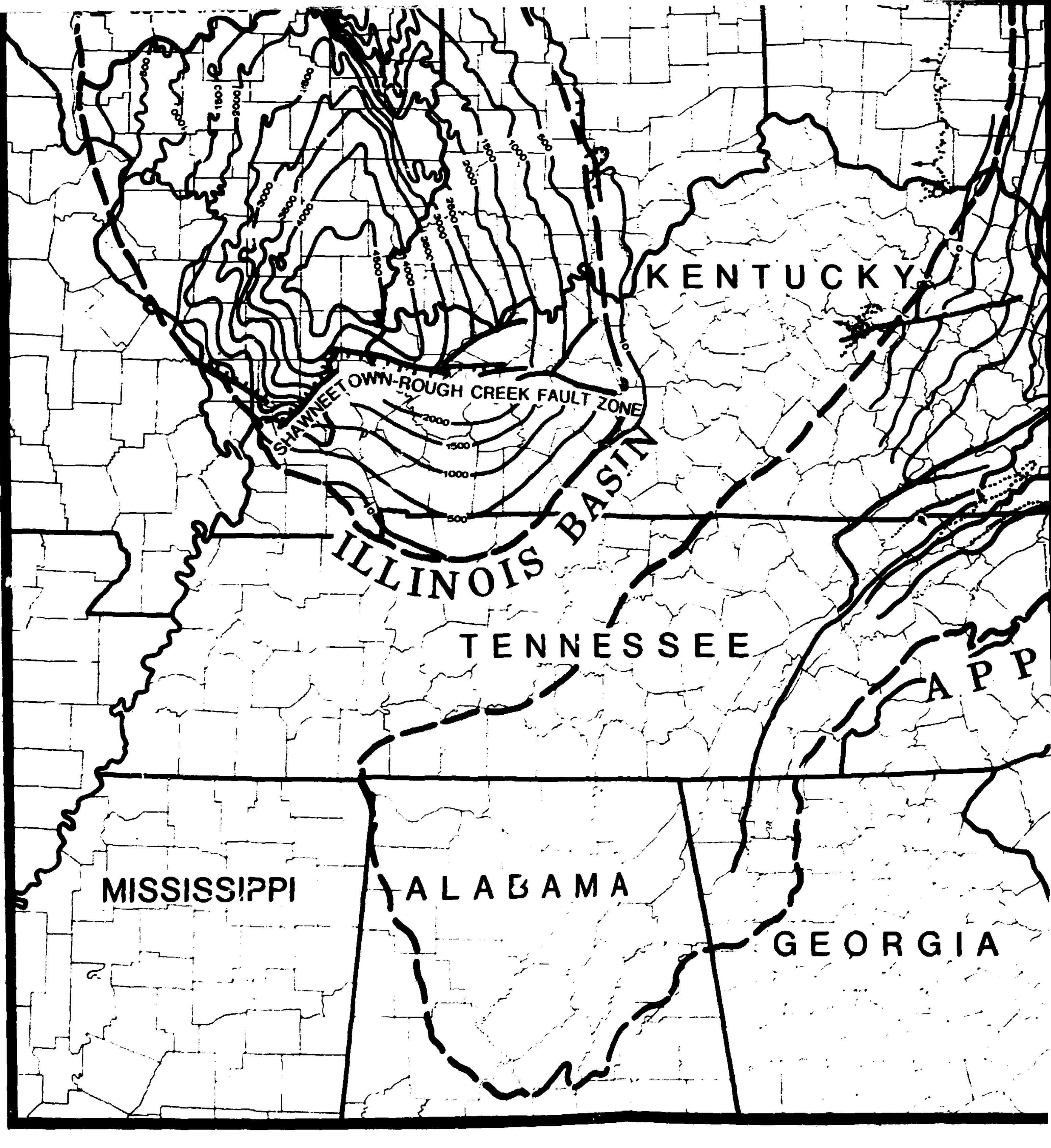


ANTICLINE
DU QUOIN MONOCLINE
SHAWNEETOWN-ROUGH CREEK FAULT ZONE
STE. GENEVIEVE FAULT ZONE
ILLINOIS BASIN
Cincinnati Arch
JESSAMINE DOME
KENTUCKY RIVER FAULT ZONE
PINE MOUNTAIN FAULT
NASHVILLE DOME
SEQUATCHIE ANTICLINE
APPALACHIAN


ROME
TROUGH
FOLD
Blue Ridge Province
PLATE 2
TECTONIC MAP
OF THE APPALACHIAN, ILLINOIS AND MICHIGAN BASINS
SIGNIFICANT STRUCTURES OR STRUCTURAL TRENDS:
Anticline
Syncline
Normal Fault or G ·ben (Ticks on downside)
Dome or Arch Trend (Arrow indicates plunge)
Strike-Slip Fault (Arrows show relative movement)
Thrust Fault (Barbs on upthrown side)
Linear Features
0
100 MILES
0
100
200 KILOMETERS


WISCONSIN
ILLINOIS
INDIANA
OHIO
Lake Michigan
Lake Huron
LIMIT OF COLDWATER SHALE
LIMIT OF COLDWATER SHALE
MICHIGAN BASIN
SILURIAN BELOW PENNSYLVANIAN
DEVONIAN BELOW PENNSYLVANIAN
CHOUTEAU LIMESTONE ABSENT IN SUBSURFACE


NEW YORK
Lake Ontario
Lake Erie
COLDWATER SHALE
NEW
JERSEY
MARYLAND



KENTUCKY
SHAWNEETOWN-ROUGH CREEK FAULT ZONE
ILLINOIS BASIN
TENNESSEE
APP
MISSISSIPPI
ALABAMA
GEORGIA

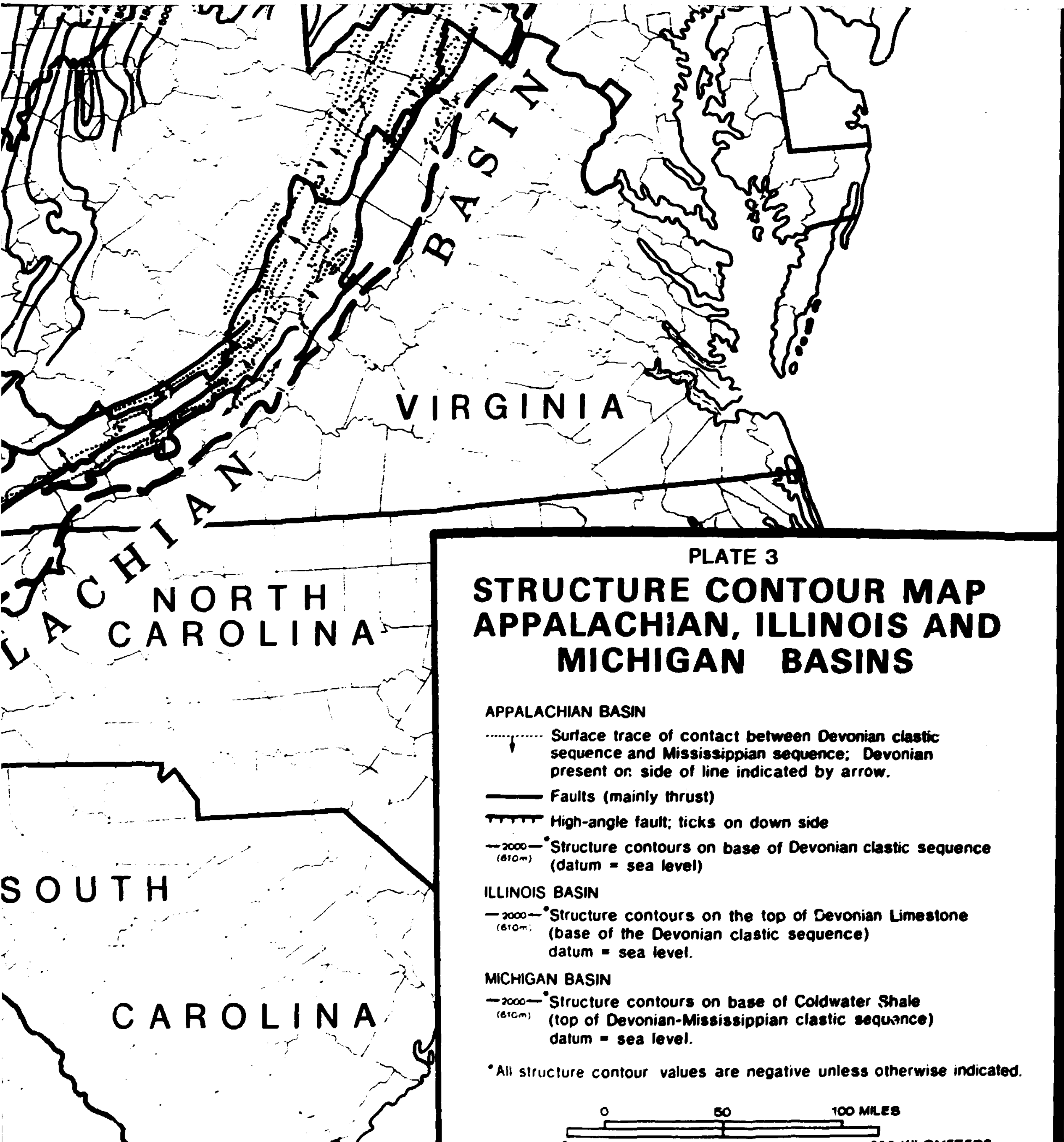



PLATE 3

# STRUCTURE CONTOUR MAP APPALACHIAN, ILLINOIS AND MICHIGAN BASINS

APPALACHIAN BASIN

Surface trace of contact between Devonian clastic sequence and Mississippian sequence; Devonian present on side of line indicated by arrow.

Faults (mainly thrust)

High-angle fault; ticks on down side

—2000—* (610m) Structure contours on base of Devonian clastic sequence (datum = sea level)

ILLINOIS BASIN

—2000—* (610m) Structure contours on the top of Devonian Limestone (base of the Devonian clastic sequence) datum = sea level.

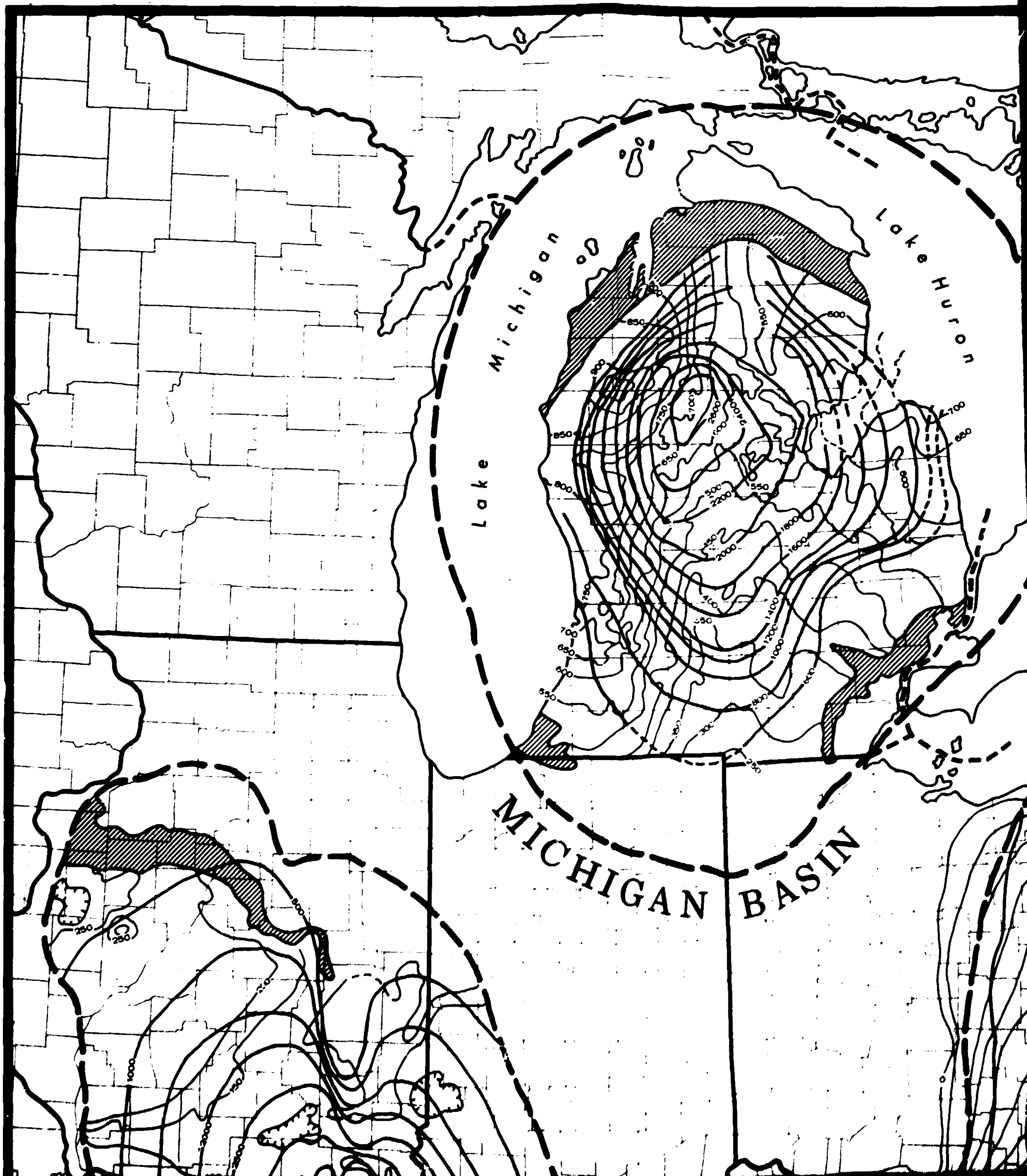
MICHIGAN BASIN

—2000—* (610m) Structure contours on base of Coldwater Shale (top of Devonian-Mississippian clastic sequence) datum = sea level.

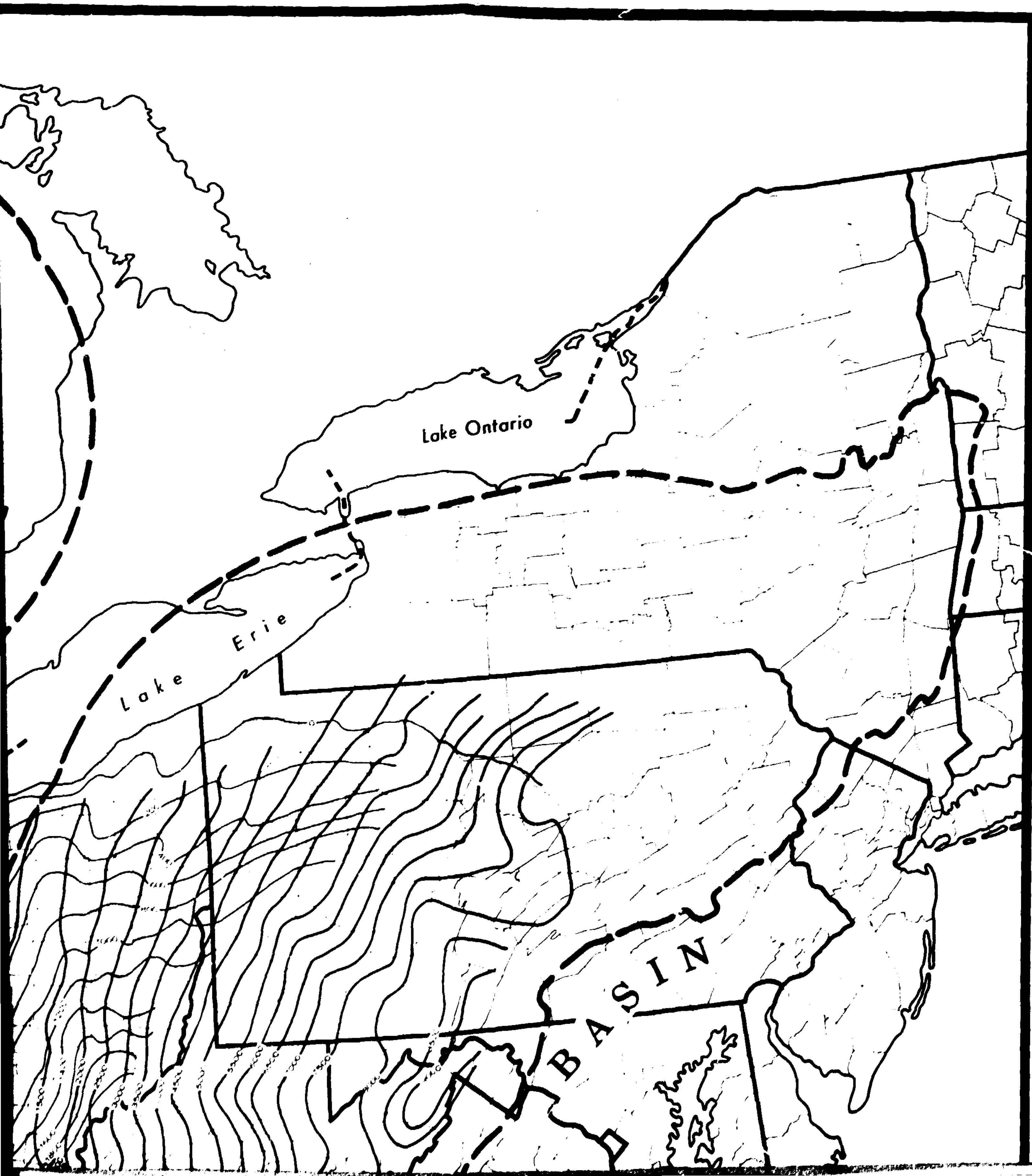
*All structure contour values are negative unless otherwise indicated.

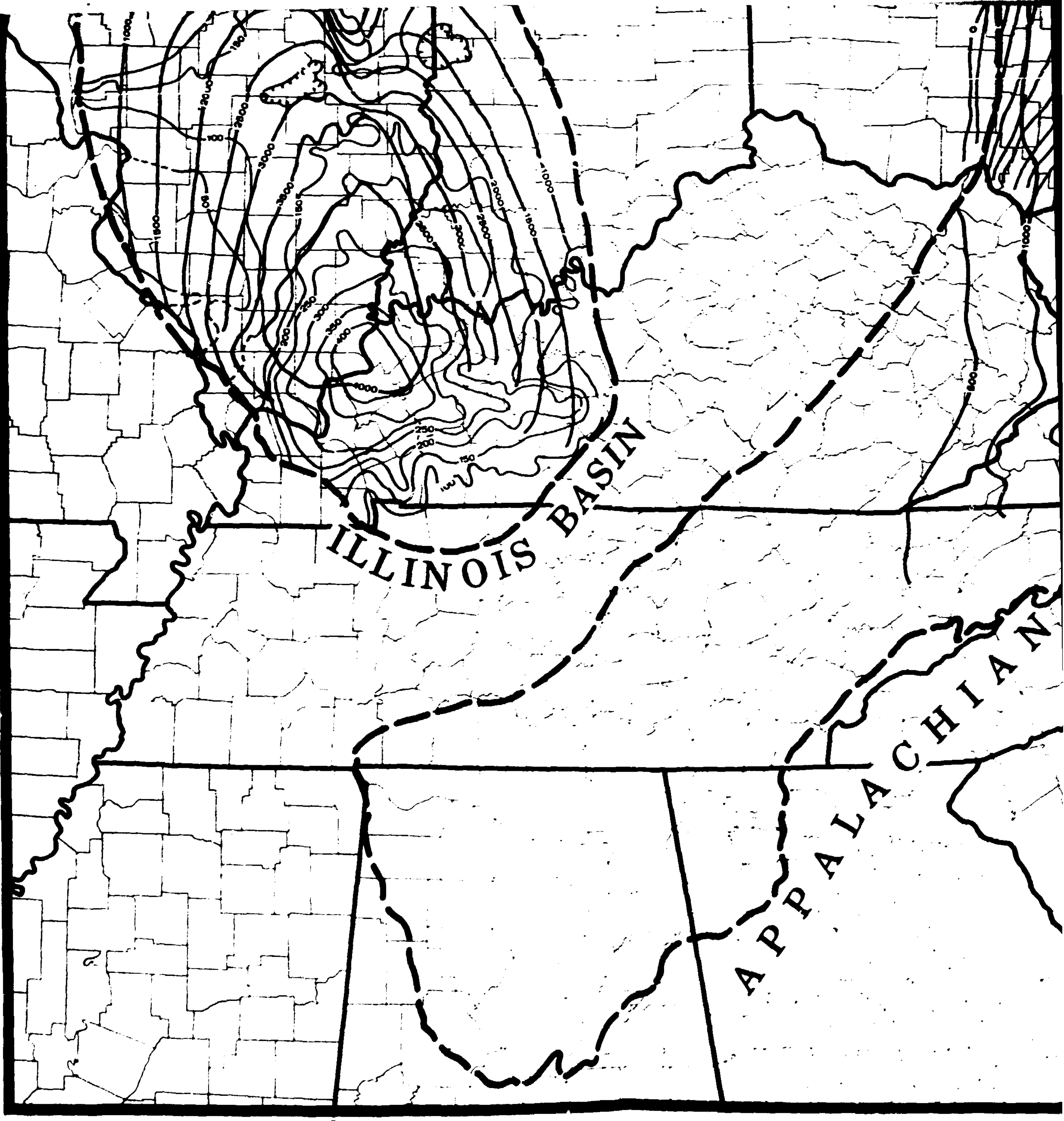
0 50 100 MILES

0 100 200 KILOMETERS



Lake Michigan
Lake Huron
MICHIGAN BASIN


Lake Ontario
Lake Erie
BASIN


ILLINOIS BASIN
APPALACHIAN

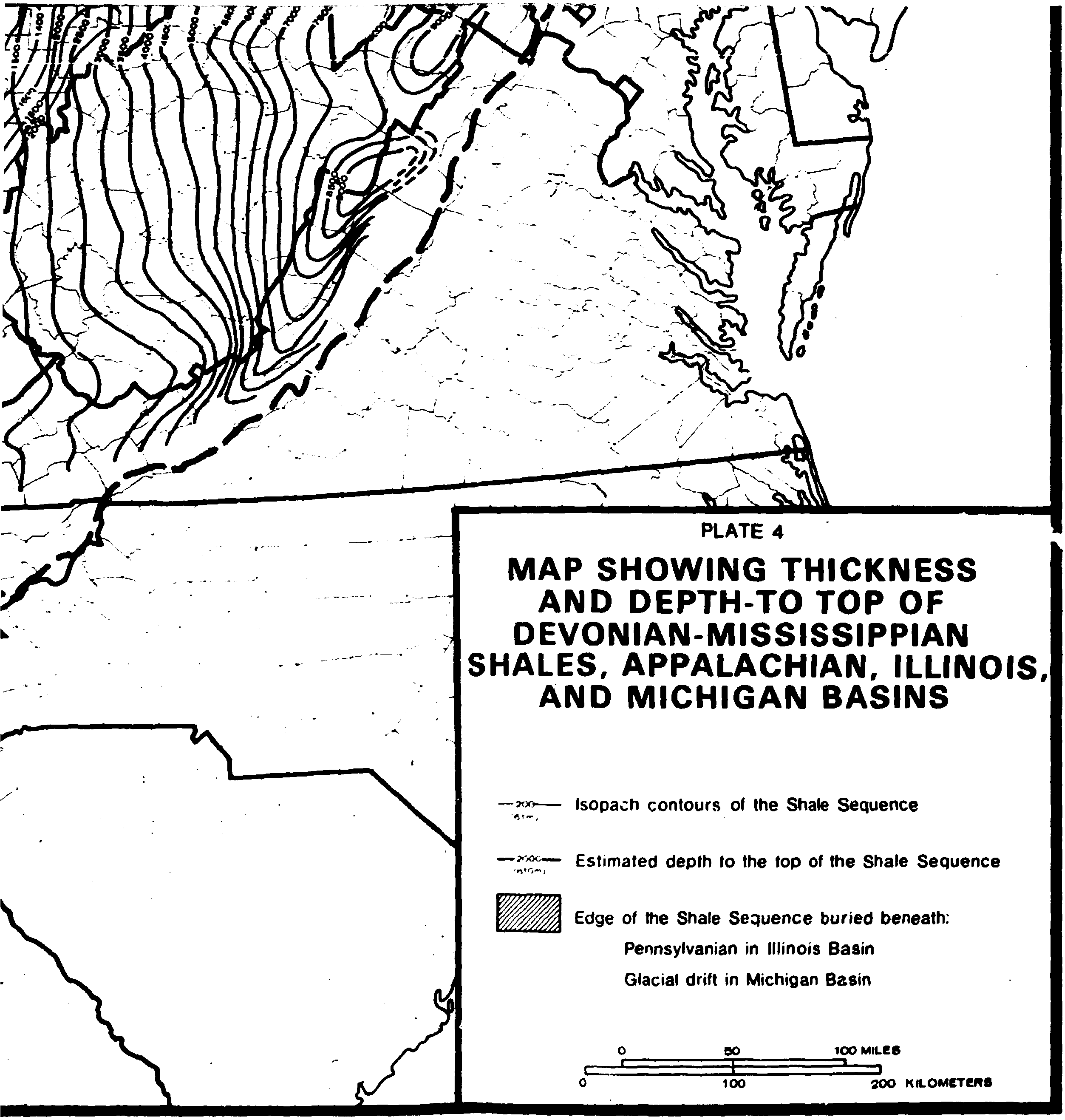
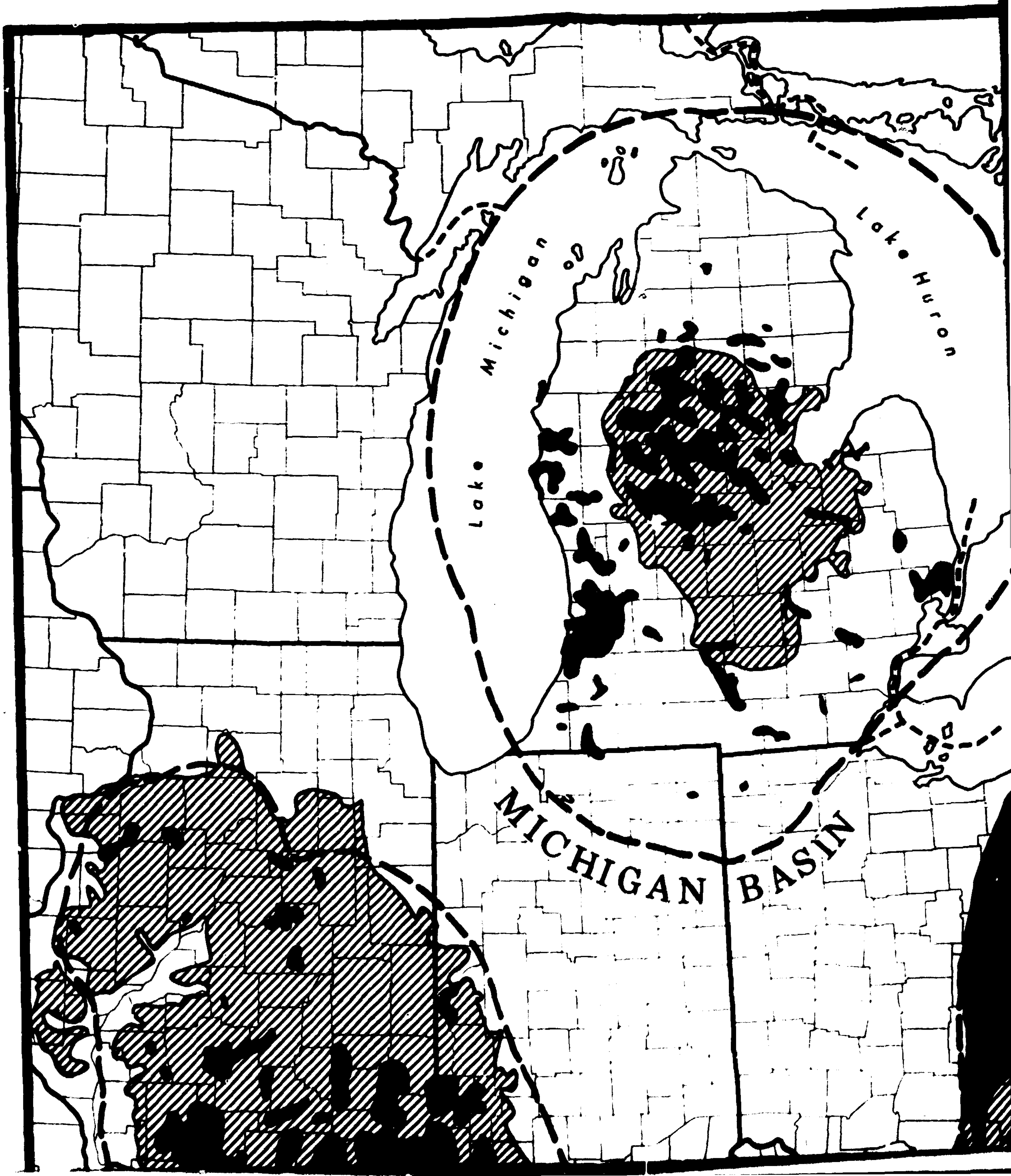
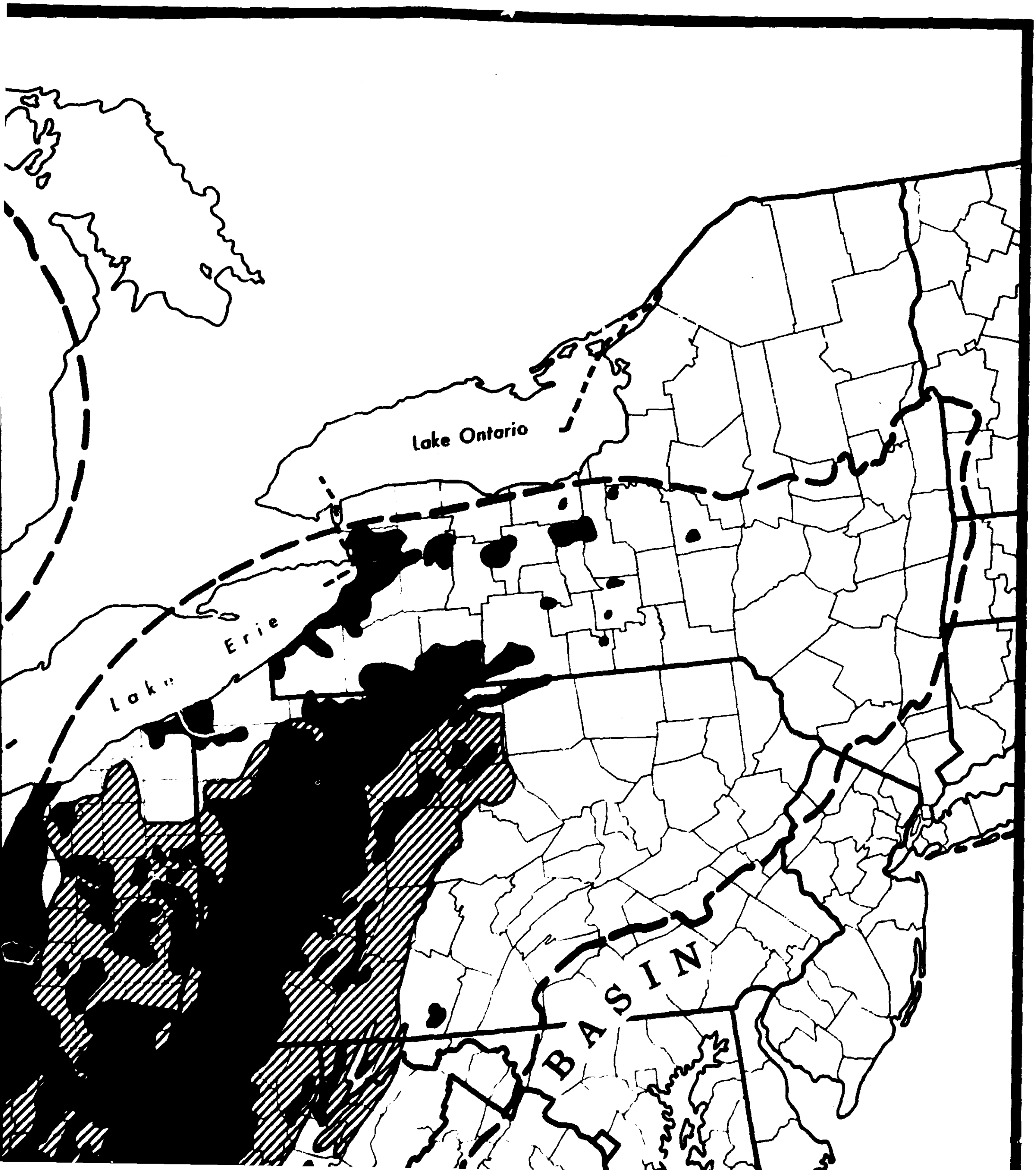


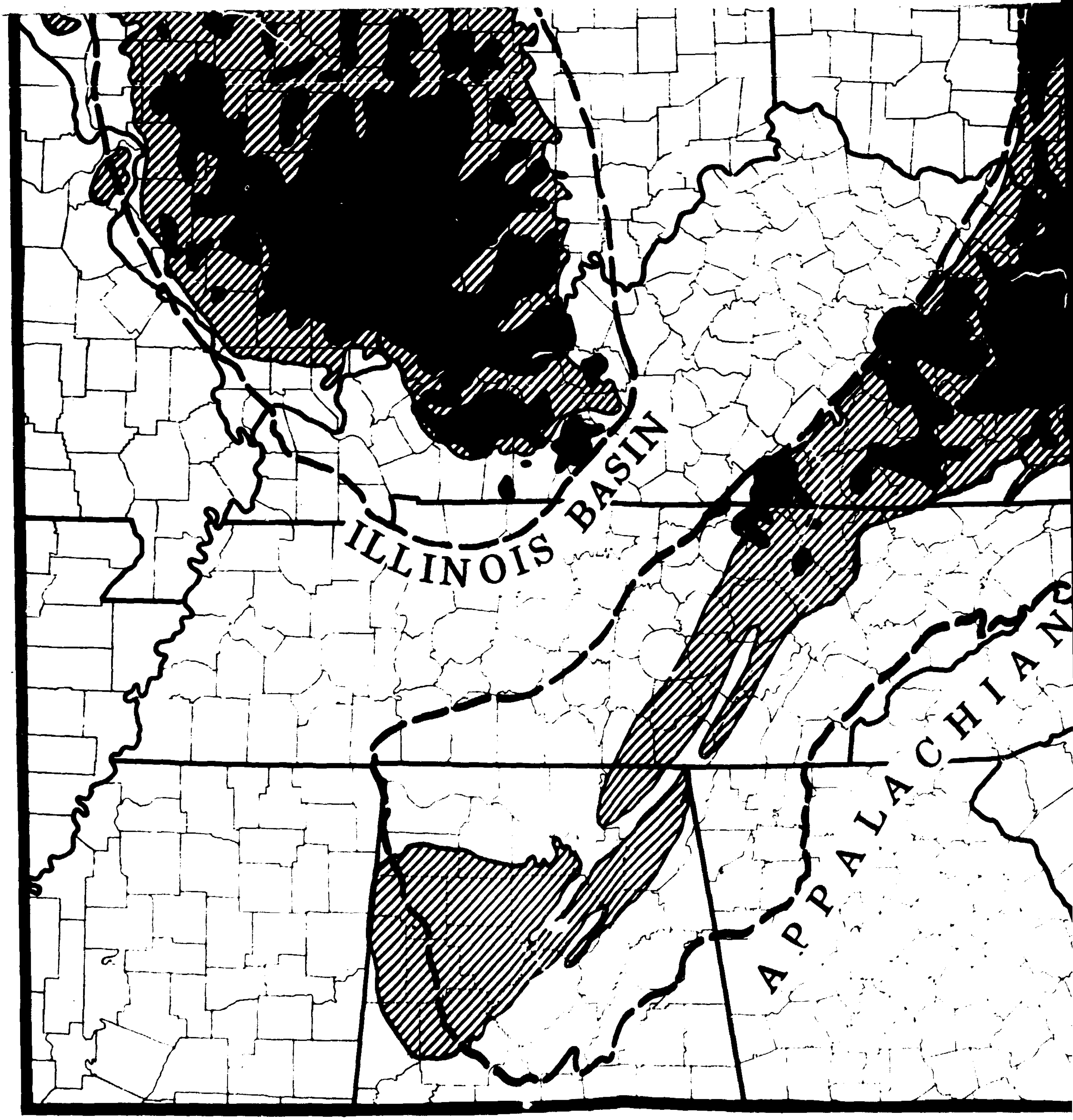

PLATE 4

# MAP SHOWING THICKNESS AND DEPTH-TO TOP OF DEVONIAN-MISSISSIPPIAN SHALES, APPALACHIAN, ILLINOIS, AND MICHIGAN BASINS


Lake Michigan
Lake Huron
MICHIGAN BASIN



Lake Ontario
Lake Erie
BASIN


ILLINOIS BASIN
APPALACHIAN

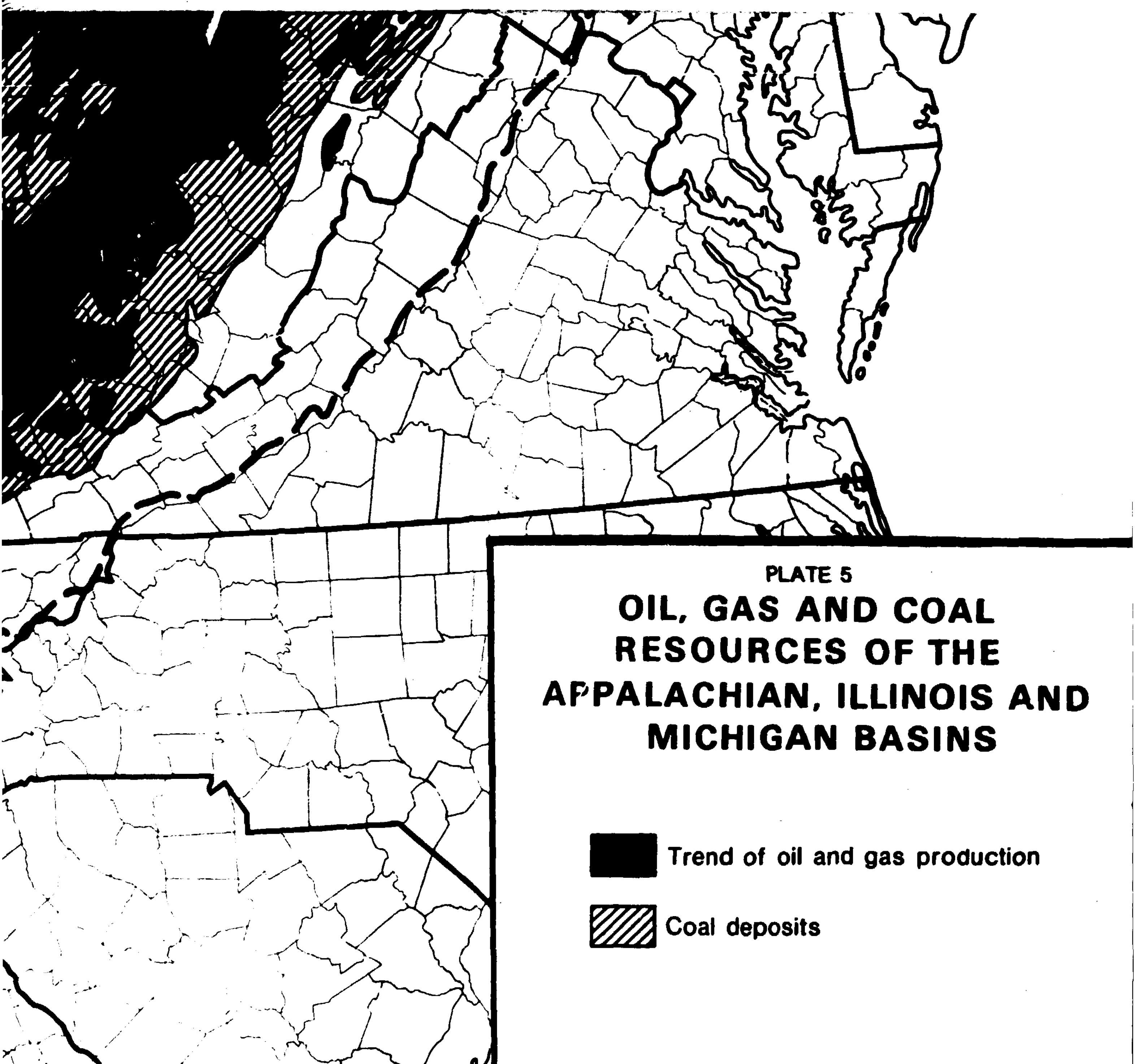



PLATE 5

# OIL, GAS AND COAL RESOURCES OF THE APPALACHIAN, ILLINOIS AND MICHIGAN BASINS