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STUDIES OF THE NEW ALBANY SHALE (DEVONIAN AND MISSISSIPPIAN) AND EQUIVALENT STRATA IN INDIANA

Edited by
N. R. Hasenmueller and G. S. Woodard

September 1981

Under Contract No. DE-AC21-76MC05204

Indiana Geological Survey
Bloomington, Indiana

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DOE Eastern Gas Shales Project

Contract No. DE-AC21-76-MC05204

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STUDIES OF THE NEW ALBANY SHALE (DEVONIAN AND MISSISSIPPIAN) AND EQUIVALENT STRATA IN INDIANA

SUMMARY OF RESULTS

A formation of black carbonaceous shale, later named the New Albany Shale, was first recognized in 1837 and reported in 1839 by David D. Owen. Since then, the New Albany has been the subject of numerous investigations by individuals affiliated with the Indiana Geological Survey and others, but the present investigation, involving petrology, mineralogy, stratigraphy, geomorphology, organic and inorganic geochemistry, and physical properties, has been the most comprehensive. The lower part of the New Albany Shale is late Middle Devonian in age, and the upper part is Early Mississippian in age.

The shale paraconformably overlies the Muscatatuck Group (Middle Devonian) and is overlain by the Rockford Limestone, a thin Mississippian limestone, throughout much of the Illinois Basin. In areas where the Rockford is absent the New Albany is directly overlain by the New Providence Shale of the Borden Group (Mississippian).

In the subsurface the New Albany was divided into four mappable units. These units are listed below in ascending order.

1. The Blocher Member is brownish-black carbonaceous slightly to moderately calcareous shale.

2. The Selmier Member is greenish-gray to dark-olive-gray shale that contains small amounts of brownish-black fissile shale, dolomite, limestone, and quartz sandstone.

3. The undifferentiated Morgan Trail, Camp Run, and Clegg Creek Members are composed of brownish-black carbonaceous fissile siliceous pyritic shale with some green-gray to olive-gray shale beds in the Camp Run Member.

4. The Ellsworth Member is interbedded brownish-black and greenish-gray shale in the lower part and greenish-gray shale in the upper part.

The New Albany thickens and dips in a southwesterly direction into the Illinois Basin. The shale is 100 to 130 feet thick in southeastern Indiana and as much as 337 feet thick in southern Posey County in southwestern Indiana.

The generally uniform dip is interrupted locally by: (1) the faults of the Wabash Valley Fault System in Posey and Gibson Counties; (2) the Mt. Carmel Fault, a normal fault, in the south-central part of the state; and (3) a series of small structures reflected upward from underlying Silurian reefs in southwestern Indiana.

The sediments of the lower part of the New Albany Shale were deposited in a transgressing sea.

The shale is interpreted as having been deposited in an anoxic basin with stratification of oxygen levels.

The Devonian-Mississippian units of the Michigan Basin area of Indiana that are equivalent to the New Albany Shale are listed below in ascending order.

1. The Antrim Shale is brownish-black carbonaceous noncalcareous fissile shale with a basal unit in some places that contains medium-gray calcareous shale or limestone.

2. The Ellsworth Shale is interbedded greenish-gray and brownish-black shale in the lower part and greenish-gray shale in the upper part.

3. The Sunbury Shale is thin brownish-black carbonaceous shale in Lagrange and Steuben Counties and limited areas of Noble and DeKalb Counties in northeastern Indiana.

In the Michigan Basin area of Indiana the Antrim Shale is underlain by the Traverse Formation (Middle Devonian). In the western part of the Michigan Basin the New Albany equivalents are overlain by thick glacial drift, and to the east they are overlain by the Coldwater Shale (Mississippian).

In the Michigan Basin the base of the Antrim-Ellsworth-Sunbury interval dips northward at 10 to 20 feet per mile. No known major faults interrupt the northward dip of the shale.

The New Albany Shale consists of two major types of beds: hard black carbonaceous shale and softer greenish-gray shale. Dark beds dominate in the southwest, and all are nearly impermeable except where fractures occur.

Major components of the shale are silt or smaller sized detrital quartz, clay minerals, carbonaceous (organic) material, and authigenic iron sulfides and carbonate minerals. Numerous minor minerals also occur, and relative amounts of minerals vary vertically and geographically.

Oil yields of the New Albany Shale are generally directly proportional to the organic content of the shale.

Gas yields of the New Albany Shale do not necessarily correlate with the organic content of the shale, but low organic shales do not yield significant gas.

Compositional differences between the gases initially released from the cores from Marion County and gas obtained from these cores after repeated evacuations indicate that some gas was transported to the area by ground water and some developed in situ.

In the New Albany Shale the composition of the major minerals is rather well defined except for illite, mixed-layer clay, and chlorite. Iron and sulfur overall must be considered to be heterogeneous because of the highly variable content of iron sulfides.

The Henryville Bed, a thin carbonaceous bed near the top of the New Albany Shale, is enriched in several trace elements, particularly zinc, cadmium, molybdenum, and vanadium and, to a lesser degree, lead, nickel, and copper.

The Falling Run Bed, a phosphate-nodule bed or bone bed at the base of the Henryville Bed, is higher in uranium (as much as 100 ppm) and yttrium and, presumably, rare earths.

The area in the deepest part of the Illinois Basin in Indiana, in the southwestern part of the state, appears to be the most likely area for gas development because of probable maturity of the shale and fractures due to faulting.

In southwestern Indiana, orientation of lineaments is northeast-southwest and northwest-southeast regardless of whether the land surface is directly underlain by bedrock or glacial materials.

No preferred orientation of lineaments was observed near three gas fields in Harrison County that produced from the New Albany Shale.

All physical tests were designed to detect planes of incipient fracture. Results did not show consistency of direction similar to the directions of pronounced lineaments. Compressional velocity measurements ranged from 3.26 to 6.27 km/sec. Radical changes in velocity were subtle but consistent. Changes with depth were much more marked. Shear velocities were difficult to obtain, and the meager results are unreliable.

Gas is known to occur in and has been produced from the New Albany Shale in Indiana from 10 now largely abandoned fields. Geologic information for these fields is minimal, but it suggests that structure is not a requisite in shale-gas accumulation and that the shale in producing wells may not be richer in organic matter than that in adjacent nonproducing wells. These two factors suggest that natural fracture systems in the shale may have been important in shale-gas production.

INTRODUCTION

John B. Patton, Principal Investigator

The New Albany Shale was reported as a distinctive unit as early as 1839 (p. 15) by David D. Owen, who described the "black bituminous aluminous slate" at New Albany, and the name New Albany Slate was used by Borden in 1874 (p. 158) to describe the shale outcrops along the Ohio River near New Albany in Floyd County, Ind. Since that time the Indiana Geological Survey and others have been involved in investigations of the shale. Reeves (1922) conducted a detailed study of the shale as a possible source of oil. Huddle (1933, 1934) studied the conodonts of the New Albany. Later Campbell (1946) and Lineback (1968, 1970) made detailed stratigraphic studies of the shale. Sorgenfrei (1952) studied the gas production associated with the New Albany in some areas of Indiana.

In 1974 the Indiana Geological Survey proposed a more comprehensive study of the shale than any that had previously been undertaken, but sources of outside funding needed for part of the work were not found. In 1976 the Energy Research and Development Administration (ERDA), now the U.S. Department of Energy (DOE), invited the Survey to participate in the Eastern Gas Shales Project, a study of the gas potential of the Devonian-Mississippian black carbonaceous shales of the eastern United States.

A contract for 3 years of intensive investigation of the petrology, mineralogy, stratigraphy, geomorphology, organic and inorganic geochemistry, and physical properties of the New Albany Shale and equivalent strata in Indiana was granted to the Indiana Geological Survey by ERDA. Besides this report of our 3-year study, the Survey has completed and submitted to DOE reports, maps, and cross sections dealing with the nature and distribution of the New Albany Shale and equivalent strata in Indiana, and other maps showing structure drawn on lower horizons and oil and gas shows above and below the New Albany Shale. (See Appendixes I and II.)

STRATIGRAPHY

N. R. Hasenmueller and J. L. Bassett

Introduction

Purpose of Study

The purpose of this part of the Eastern Gas Shales Project (EGSP) was to generate and to analyze data pertaining to the lithology, distribution, thickness, and structure of the New Albany Shale and equivalent strata in the subsurface in Indiana and to prepare stratigraphic cross sections, structure maps, and maps of oil and gas shows from information on file in the Petroleum Section of the Indiana Geological Survey. Available information on the 10 New Albany gas fields in Indiana was also compiled. Data accumulated during the study should help to determine the most favorable stratigraphic units and areas for potential hydrocarbon production from the shale in the subsurface.

Geographic Extent of the New Albany Shale and Equivalent Strata

In the Illinois Basin area of Indiana the New Albany outcrop belt extends from the Ohio River in Floyd and Clark Counties northward to central Newton County in northwestern Indiana (fig. 1). The shale is exposed at numerous sites in southeastern Indiana; northward from central Bartholomew County, however, the outcrop belt is covered by relatively thick glacial deposits, and exposures are few. West of the outcrop belt the New Albany Shale is present throughout the Illinois Basin in Indiana and is overlain by younger strata. In northern Indiana on the southern margin of the Michigan Basin the Antrim, Ellsworth, and Sunbury Shales, which are equivalent to the New Albany Shale, also are covered by thick glacial deposits. Northeast of the subcrop area these units, which were continuous with the New Albany before the erosion of the shale over the Cincinnati Arch (Lineback, 1970, p. 2), are overlain by younger strata.

Previous Work

The name New Albany Black Slate was first used by Borden (1874, p. 158) for the brownish-black shale exposed along the Ohio River at New Albany, Floyd County, Ind. Later, Blatchley and Ashley (1898, p. 16, pl. 2) introduced the name New Albany Shale. Campbell (1946, p. 835) subdivided the unit into several formations and members according to lithology, paleontology, and jointing. And Lineback (1968, p. 1291) subdivided the New Albany in the outcrop belt in southeastern Indiana by lithology into five members, which are in ascending order the Blocher,

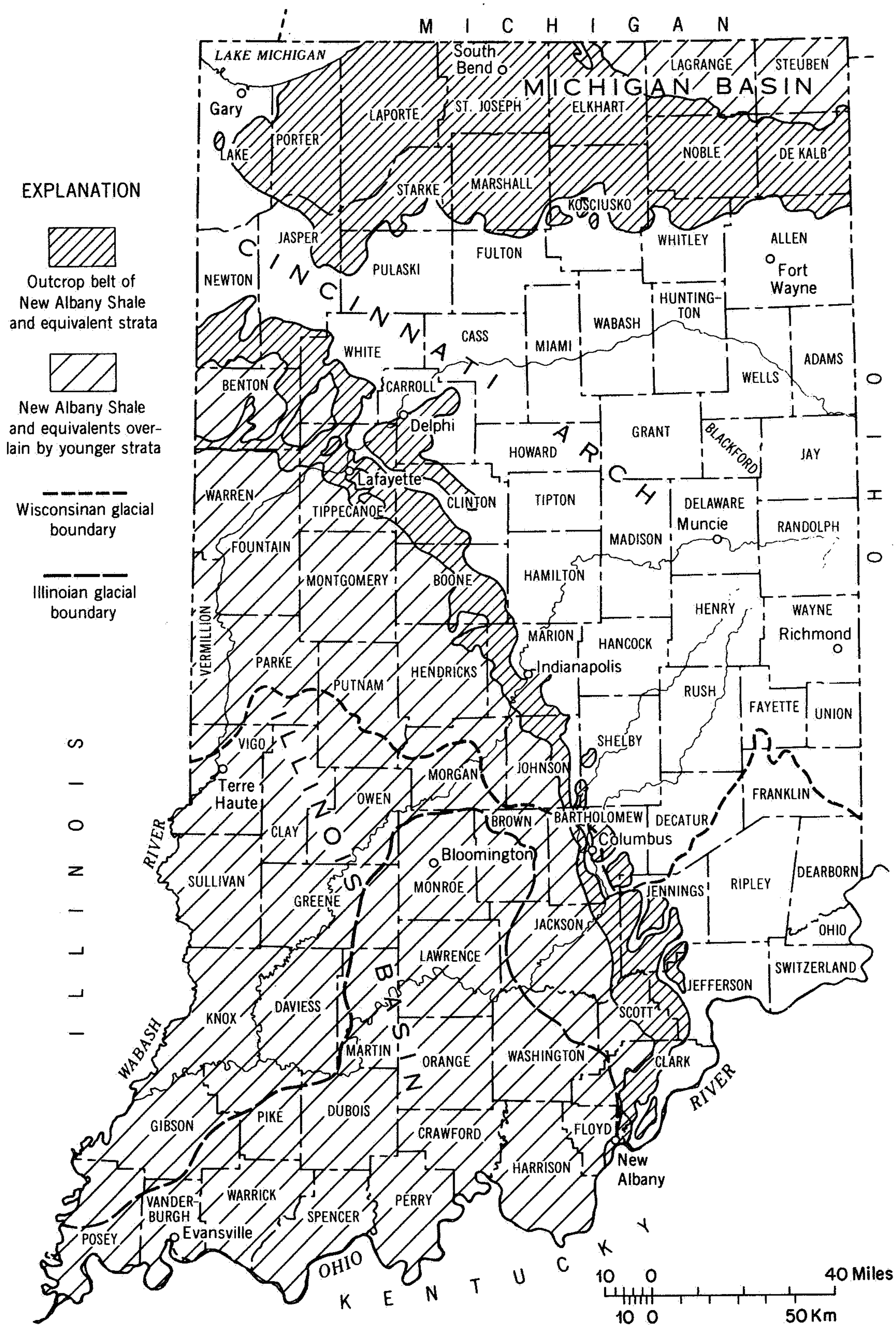

Figure 1. Map of Indiana showing distribution of the New Albany Shale and equivalent strata. Geology modified from Indiana Geological Survey 1^{o}x2^{o} Regional Geologic Map Series.

Selmier, Morgan Trail, Camp Run, and Clegg Creek Members (fig. 2). In this report the outcrop terminology proposed by Lineback is used.*

Lineback (1970) identified the Blocher and Selmier Members in the subsurface of the Illinois Basin, but he could not differentiate the upper three members. He did, however, recognize four distinct lithologic units in the New Albany above the Selmier in the subsurface. He (1968, p. 1300) applied the name Ellsworth Member of the New Albany to interbedded brownish-black and greenish-gray shale and greenish-gray shale that grade laterally into the Clegg Creek Member in the northern part of the Illinois Basin, and in 1970 (figs. 13 and 14) he mapped the distribution and thickness of interbedded shale and greenish-gray shale in that area. Collinson and others (1967, p. 959), using geophysical logs, recognized and mapped the thickness of the lowermost outcrop member, the Blocher, in the subsurface in the Illinois Basin. They (1967, fig. 13) also recognized the Selmier interval on geophysical logs but did not map the distribution and thickness of that unit.

Lane (1901, p. 9) proposed the name Antrim Shale for shale exposed in Antrim County, Mich. Lineback (1968, p. 1291) recognized the Antrim in the Michigan Basin part of northern Indiana. Newcombe (1933, p. 49-51) formally proposed the name Ellsworth Shale for greenish-gray shale exposed near Ellsworth in Antrim County, Mich. Lineback (1968, p. 1291) noted the Ellsworth Shale in the Michigan Basin area in northern Indiana and mapped (1970, figs. 13 and 14) the distribution and thickness of the unit there. Hicks (1878, p. 216, 220) originally used the name Sunbury Black Slate, now the Sunbury Shale, for rocks near Sunbury, Delaware County, Ohio. Lineback (1968, p. 1291) recognized this unit in northern Indiana.

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*When we began our subsurface mapping of the New Albany Shale in Indiana in 1977, we used Illinois stratigraphic terminology (Sweetland Creek, Grassy Creek, and Hannibal) for the subdivisions or members of the New Albany Shale in Indiana. Later in our study it became apparent that the units recognized by Lineback in the outcrop area in southeastern Indiana in 1968 could be traced westward in the Illinois Basin. Therefore, we have decided to use the stratigraphic terminology proposed by Lineback rather than introduce new stratigraphic names for the members of the New Albany Shale in Indiana.

The Selmier Member of the New Albany Shale is equivalent to the unit that was mapped as the Sweetland Creek Member from 1977 through 1978. The Morgan Trail, Camp Run, and Clegg Creek Members are equivalent to the unit that was mapped as the Grassy Creek Member from 1977 through 1978. The Ellsworth Member of the New Albany Shale is equivalent to the unit that was mapped as the Hannibal Member from 1977 through 1979.

SUBSURFACE UNITS ILLINOIS BASIN Kentucky (From Schwalb & Norris, 1980)	SUBSURFACE UNITS ILLINOIS BASIN Central Illinois (From Reinbold, 1978)	SUBSURFACE UNITS ILLINOIS BASIN Southeastern Illinois (From Reinbold, 1978)	SUBSURFACE UNITS ILLINOIS BASIN Indiana (Northwest of arbitrary cutoff) (present study)	SUBSURFACE UNITS ILLINOIS BASIN Indiana (Southeast of arbitrary cutoff) (present study)	SURFACE UNITS Southeastern Indiana (Lineback, 1968)	SUBSURFACE UNITS MICHIGAN BASIN Northern Indiana
New Providence Shale	Borden Siltstone	Springville Shale	New Providence Shale	New Providence Shale	New Providence Shale	Coldwater Shale
Rockford Limestone	Chouteau Limestone	Chouteau Limestone	Rockford Limestone	Rockford Limestone	Rockford Limestone	
New Albany Shale	New Albany Shale Group	New Albany Shale Group	New Albany Shale	New Albany Shale	New Albany Shale	
Hannibal Member Grassy Creek Member Sweetland Creek Member Blocher Member	Hannibal Shale "Glen Park" Formation Louisiana Limestone Saverton Shale Grassy Creek Shale Sweetland Creek Shale	Henryville Bed Hannibal and Saverton Shales Grassy Creek Shale Sweetland Creek Shale Blocher Shale	Jacobs Chapel* Bed Henryville Bed Ellsworth Member Clegg Creek, Camp Run, and Morgan Trail Members (undifferentiated) Selmier Member Blocher Member	Clegg Creek, Camp Run, and Morgan Trail Members (undifferentiated)* Selmier Member Blocher Member	Jacobs Chapel Bed Henryville Bed Underwood Bed Falling Run Bed Clegg Creek Member Camp Run Member Morgan Trail Member Selmier Member Blocher Member	Sunbury Shale Ellsworth Shale Antrim Shale
Middle Devonian to Upper Ordovician strata	Lingle Formation	Lingle Formation	Muscatatuck Group *Jacobs Chapel Bed present, but too thin to recognize on most geophysical logs.	Muscatatuck Group *Jacobs Chapel, Henryville, and Falling Run Beds are usually present, but cannot be recognized on geophysical logs.	North Vernon Limestone	Traverse Formation

Figure 2. Chart showing correlation and stratigraphic terminology of the New Albany Shale and equivalent rocks in Indiana and adjacent states.

Methods of Study

Our work centered on the shale in the subsurface, although some outcrops were examined. Where data were available, one well record per section was selected and examined. In all, about 1,550 well records in the Illinois Basin and 400 well records in the Michigan Basin pertaining to the New Albany were used. Geophysical logs, cores, core descriptions, driller's logs, scout tickets, and well cuttings from these wells were examined.

Geophysical logs were used to compile the stratigraphic cross sections and isopach maps of the four subsurface units recognized in the New Albany Shale. Cores and well cuttings were examined to substaniate correlations made using the geophysical logs. All available information from the selected wells was used in constructing the structure maps on the top and the base (fig. 3) of the formation and the thickness map of the formation (fig. 4). Driller's logs and scout tickets were used to compile the maps of oil and gas shows. All of these maps were compiled at a scale of 1:500,000 and have been published as part of the METC/EGSP map series. (See Appendix I.)

Structure maps on significant stratigraphic units underlying the New Albany Shale in Indiana were also prepared as part of the EGSP study. Structure maps on the top of the Silurian strata, the Maquoketa Group (Ordovician), and the Trenton Limestone (Ordovician) were compiled at a scale of 1:500,000. And structure maps on the top of the Knox Dolomite (Ordovician and Cambrian), the Mount Simon Sandstone (Cambrian), and the Precambrian basement complex were compiled at a scale of 1:1,000,000. Copies of these maps are not included in this report but have been published as part of the METC/EGSP map series. (See Appendix I for the list of all maps that were compiled.)

Data for more than 400 key wells used in this study were compiled and sent to the Illinois Geological Survey (DOE/EGSP coordinator for the Illinois Basin). In general, one well was selected for each township. Data for all wells used in constructing the stratigraphic cross sections in the Illinois Basin, data for all cores taken as part of the study, and data for wells that were geochemically analyzed were included in the data file.

Cores

Five complete cores of the New Albany Shale were taken during the EGSP study in Indiana (fig. 5); only two of these were officially part of the project (costs paid in part by contract budget) and were studied in part by other contractors. One core (EGSP IN-1) was taken in western Indiana, and the other four cores, including EGSP IN-2, were taken just west of the outcrop belt of the shale in central and southeastern Indiana. One partial core of the shale was taken in Marion County. Other complete and partial cores in the core library of the Indiana Geological Survey were also examined during our study.

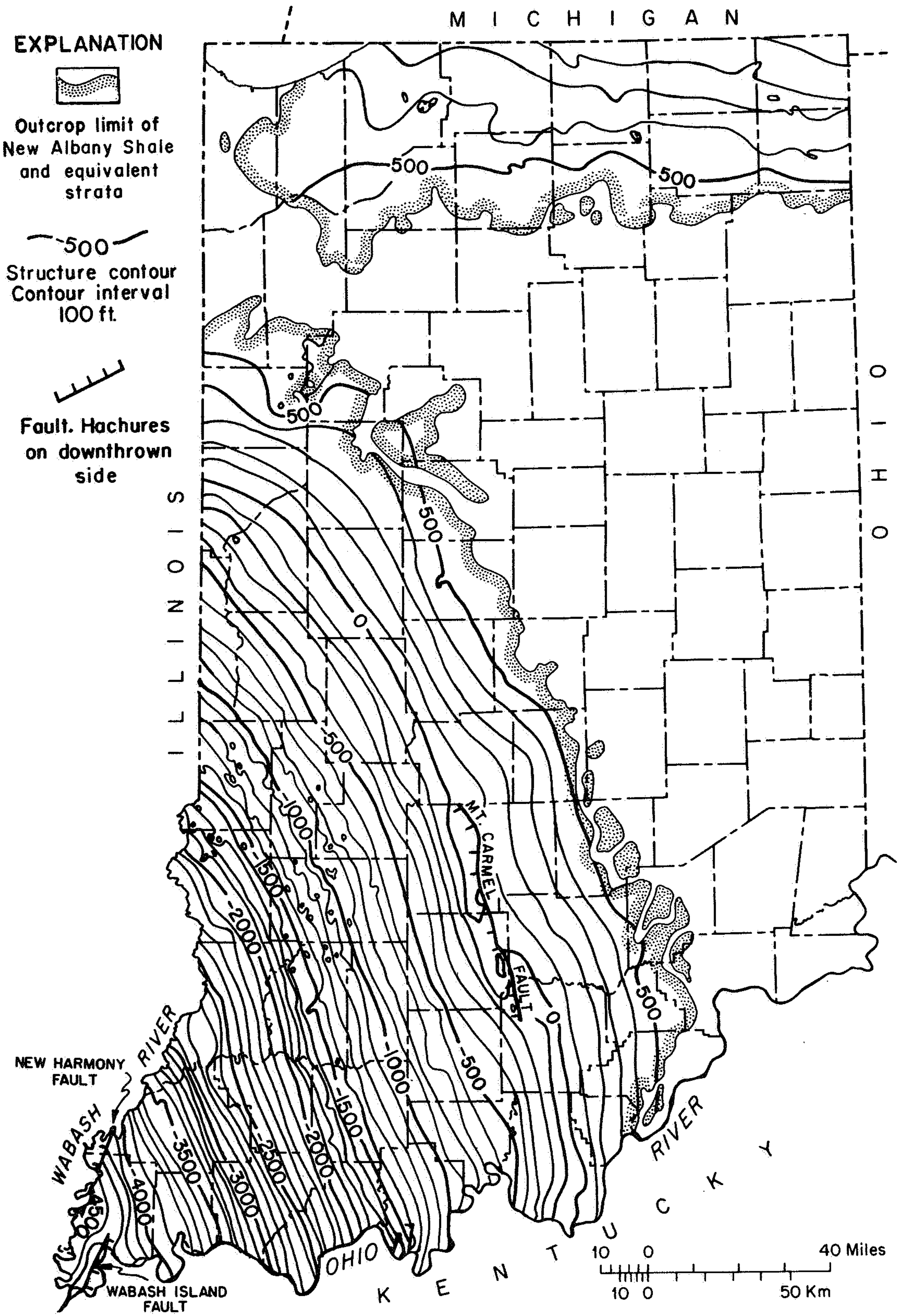

Figure 3. Map of Indiana showing structure on the base of the New Albany Shale and equivalent strata.

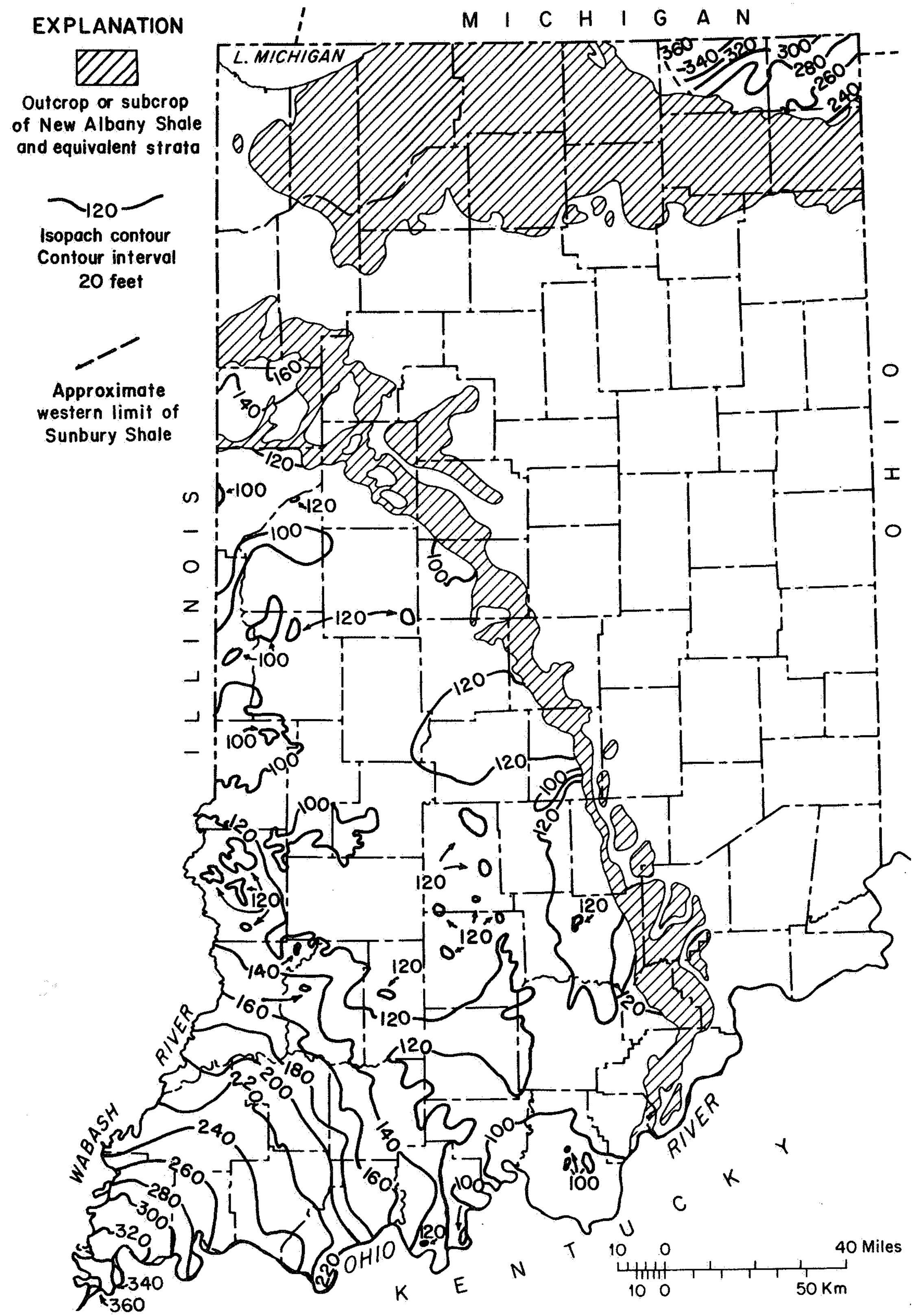

Figure 4. Map of Indiana showing thickness of the New Albany Shale and equivalent strata.

Cores taken during the DOE/EGSP study*

1. Energy Resources No. 1 (EGSP IN-1), Sullivan Co.
2. Indiana Geological Survey drill hole 273 (SDH 273), Marion Co.
3. SDH 274, Marion Co.
4. SDH 275, Marion Co.
5. SDH 291, Jackson Co.
6. SDH 290 (EGSP IN-2), Clark Co.

Other cores referenced*

7. SDH 80, Benton Co.
8. SDH 241, Brown Co.
9. Texas Eastern No. 7, Jackson Co.
10. SDH 193, Lawrence Co.
11. SDH 156, Morgan Co.
12. SDH 199, Putnam Co.
13. Gilliam No. 1, Vigo Co.

*Specific core locations are listed in Appendix III.

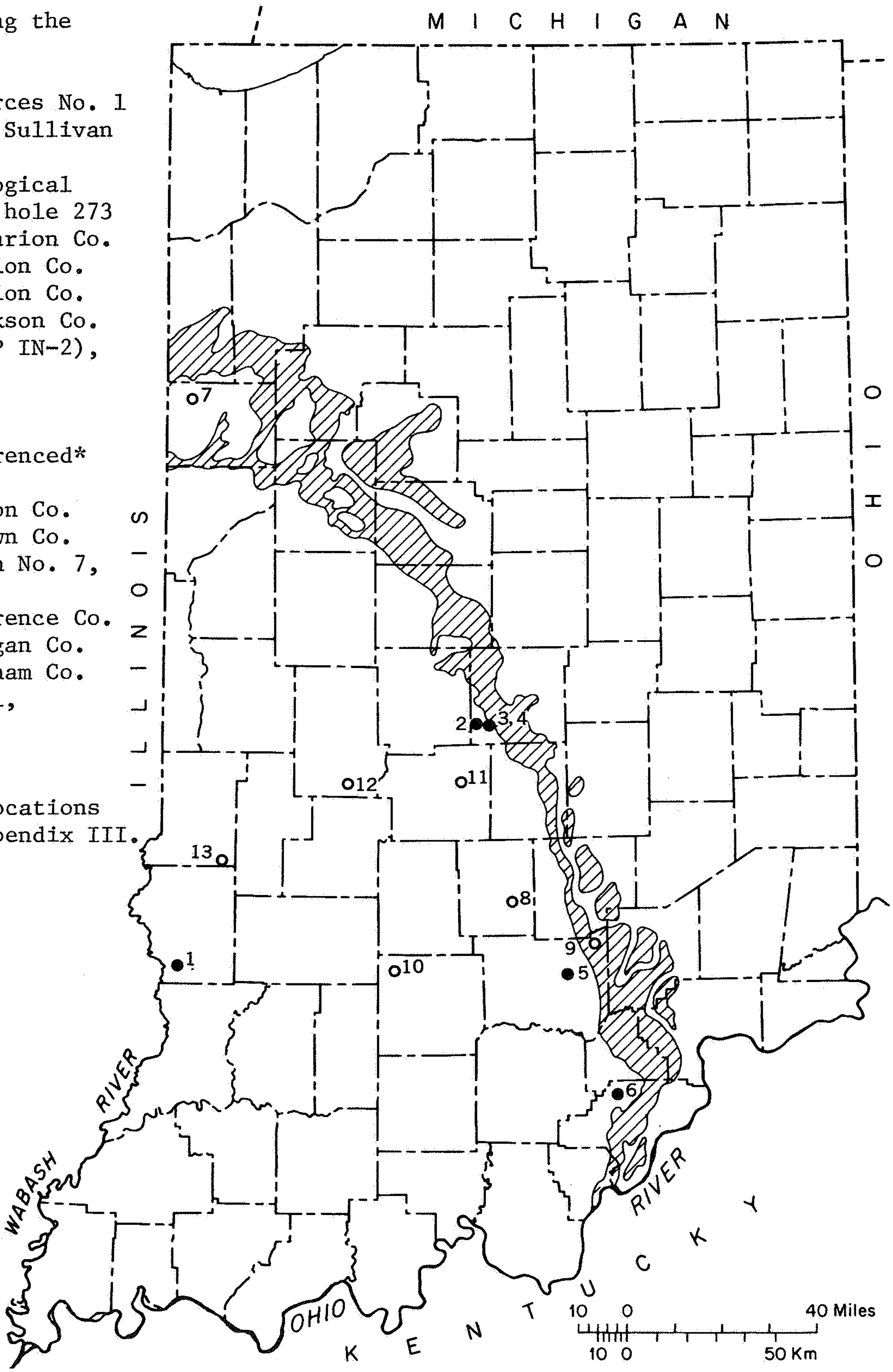

Figure 5. Map of Indiana showing the locations of cores of the New Albany Shale.

Relation to Underlying Strata

The New Albany Shale in the Illinois Basin and equivalent rocks (the Sunbury, Ellsworth, and Antrim Shales) in the Indiana part of the Michigan Basin everywhere overlie the Muscatatuck Group (Middle Devonian) except in a small area in White County where the New Albany rests on Silurian rocks (Melhorn, 1958, fig. 2). The uppermost Muscatatuck limestone in the southeastern Indiana outcrop area is the North Vernon Limestone. Equivalent rocks in the Michigan Basin are placed in the Traverse Formation.

In the outcrop area in southeastern Indiana the New Albany paraconformably overlies coarsely crystalline limestone of the Beechwood Member of the North Vernon Limestone. Commonly, the limestone is pyritized in the upper 10 inches, and the contact between limestone and black shale is sharp.

Northward in the shallow subsurface of the Illinois Basin the New Albany overlies a wedge of light-gray or light-olive-gray fine-grained to sublithographic limestone that thickens to the north in Indiana. In several cores from Boone and Marion Counties this unit is seen to be completely gradational with the calcareous laminated mudstones of the basal Blocher Member of the New Albany, and no evidence of any break in sedimentation is observed. This condition is believed to exist over much of the northern part of the Illinois Basin in Indiana, where the light-gray fine-grained limestone attains a maximum known thickness of about 18 feet (Lazor, 1971, fig. 10). This limestone is in the same stratigraphic position as a transitional carbonate-shale zone in the Michigan Basin known informally as the "Traverse Formation" by drillers (Lazor, 1971, fig. 10).

Lithostratigraphy

In our study four mappable units were recognized in the New Albany in the subsurface in the Illinois Basin in Indiana. These are in ascending order the Blocher Member, the Selmier Member, the undifferentiated Morgan Trail, Camp Run, and Clegg Creek Members, and the Ellsworth Member. In the Michigan Basin the Antrim, Ellsworth and Sunbury Shales, which together are equivalent to the New Albany (Lineback, 1968, p. 1291), were mapped.

At the type area at New Albany in Floyd County the New Albany Shale is 104 feet thick (Campbell, 1946, p. 837). The formation is minimally about 85 feet thick in some areas of Harrison County and has its maximum known thickness of 337 feet in the General Electric Co. No. WD-2 General Electric Co. well, sec. 19, T. 7 S., R. 13 W., in southern Posey County. In the southern part of the Michigan Basin in Indiana strata equivalent to the New Albany are as much as 348 feet thick.

Blocher Member

The name Blocher Formation was first used by Campbell (1946, p. 840) for the brownish-black carbonaceous slightly calcareous shale in the basal New Albany in the outcrop area in southeastern Indiana. The established type section is near Blocher in the SE¼SW¼SW¼ sec. 9, T. 3 N., R. 8 E., Jefferson County, Ind. In his original description Campbell (1946, p. 841) noted that the Blocher contained calcareous material only in the lower part and had a thin zone of calcareous lenses about 6 feet above the base.

The Blocher was redefined as a member of the New Albany Shale and the upper contact of the unit raised to the base of Campbell's Spathiocaris Zone (Lineback, 1968, p. 1295). At the type locality in Jefferson County the Blocher Member described by Lineback (1968, p. 1296; 1970, p. 62) is equivalent to the Blocher Formation described by Campbell (1946, p. 845). However, at an outcrop of the Blocher in the New Albany area in Clark County Lineback's (1970, p. 70) revised Blocher includes the lower few feet of Campbell's Blackiston Formation.

Collinson and others (1967, fig. 12), using geophysical logs, mapped the thickness and distribution of the Blocher Member in the subsurface of the Illinois Basin in Illinois, Indiana, and Kentucky. In 1969 North, also using geophysical logs, mapped the Blocher in the subsurface in the Illinois part of the Illinois Basin. Lineback (1970, fig. 7), relying primarily on well cuttings, mapped the Blocher appreciably thicker in the subsurface of Indiana than previous investigators had done. In our report recognition and thickness of the Blocher in the subsurface are based on evidence from geophysical logs supplemented by core and sample studies; the unit is comparable to the interval delineated on geophysical logs as the Blocher by Collinson and others (1967, fig. 13) and Becker (1974, p. 3). This interval in the subsurface appears to correspond to the Blocher delineated by Campbell in the outcrop area in southeastern Indiana.

The Blocher Member consists of calcareous brownish-black (5YR 2/1) shale and noncalcareous brownish-black (5YR 2/1) shale with numerous carbonate laminae. The shale contains organic material that is 2 percent to slightly more than 11 percent of the shale by weight (figs. 6 and 7). The more calcareous shale is generally in the lower part of the member. Thin beds and laminations of very dark-gray finely crystalline limestone are in the upper part of the member. Thin pyrite-rich laminations and pyritic sandy laminae also occur at places in the upper part of the Blocher in the outcrop area.

In central Indiana a calcareous carbonaceous mudstone occurs in the basal part of the Blocher Member. This unit was recognized by Lineback (1970, fig. 8), who termed it "brownish-black argillaceous limestone in the lower part of the Blocher Member." The calcareous mudstone has been recognized in cores from Marion, Boone, Montgomery, and Johnson Counties. It has a maximum known thickness of 18 feet in northwestern Marion County. The calcareous mudstone in all cores and outcrops examined grades upward through about a 2-foot interval into calcareous brownish-black shale. Because of its carbonaceous nature and apparent facies relation with the lower part of the type Blocher of southeastern Indiana, the unit is here considered to be part of the Blocher Member. The calcareous

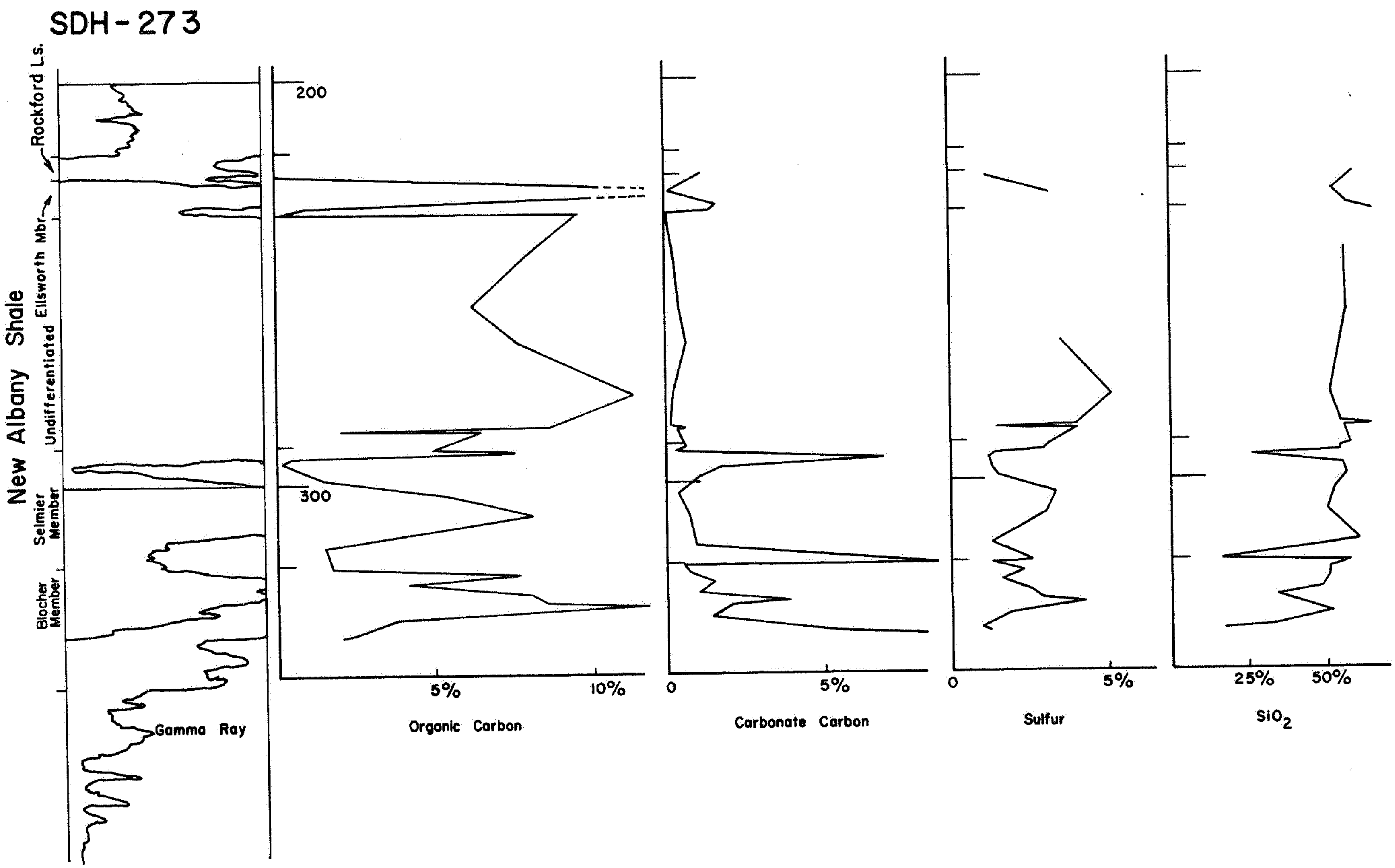

Figure 6. Diagram showing relationship of gamma-ray intensity on a geophysical log to organic carbon, carbonate carbon, sulfur, and SiO_2 content of samples from Indiana Geological Survey drill hole 273 core, Marion County. Modified from Shaffer and others, 1978.

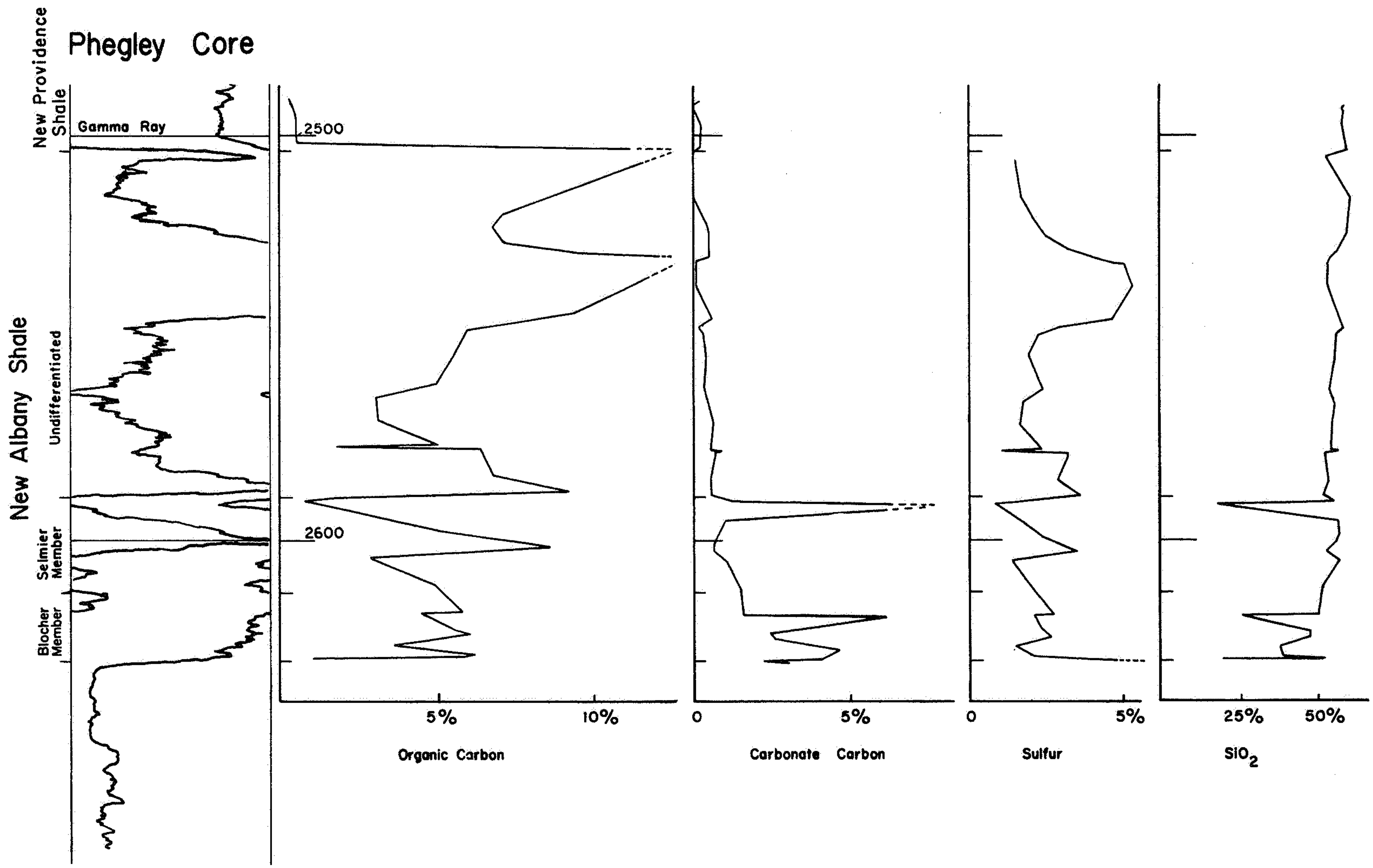

Figure 7. Diagram showing relationship of gamma-ray intensity on a geophysical log to organic carbon, carbonate carbon, sulfur, and SiO_2 content of samples from the Phegley core, Sullivan County. Modified from Shaffer and others, 1978.

mudstone appears to be completely gradational between limestone and black shale, and no stratigraphic break can be seen either above or below the unit. The mudstone is exposed at the American Aggregates Corp. quarry, NE¼NE¼ sec. 33, T. 15 N., R. 3 E., Marion County, and is present in the cores of nearby Indiana Geological Survey Drill holes (SDH) 273 and 275 in Marion County.

The Blocher Member is recognized on electric logs by high resistivity uncharacteristic of shale; this high resistivity is due to the high organic content and calcareous nature of the shale. On this type of geophysical log it is sometimes difficult to differentiate the Blocher from the underlying Middle Devonian limestone, which is also characterized by high electrical resistivity. Throughout most of Indiana the Blocher is easily differentiated from the overlying greenish-gray shale of the Selmier Member; however, southwestward into the Illinois Basin the lower part of the Selmier contains dark-gray (N3) more carbonaceous shales, and differentiation of the Blocher and Selmier on electrical logs and in well cuttings becomes more difficult. The Blocher has low to moderate gamma-ray intensity and so can be readily differentiated on gamma-ray logs from the underlying Middle Devonian limestone. In central Indiana the calcareous mudstone at the base of the Blocher is characterized by moderate electrical resistivity and low gamma-ray intensity.

Wherever the New Albany Shale is present in Indiana, the Blocher is also present except in the extreme northern part of the Illinois Basin. Along the outcrop belt the thickness of the Blocher Member ranges from less than 5 feet in western Jefferson County to about 27 feet in southwestern Marion County (fig. 8) where the basal calcareous mudstone is slightly less than half of the total Blocher. Northward from Marion County the Blocher thins to zero and is replaced as basal New Albany by the Selmier Member in Warren, Fountain, and Tippecanoe Counties. In the shallow subsurface the Blocher thins somewhat but then thickens appreciably in the southwestern part of the Illinois Basin in Indiana. The maximum known thickness of the Blocher Member in Indiana is 67 feet in Posey County.

A lower unit of black shales containing thin limestone beds capped by sandstone was recognized by Huddle (1934), who studied the conodonts of the New Albany, in the outcrop area of southeastern Indiana. The lower unit corresponds to the Blocher Formation later described by Campbell. The conodont species of Huddle's lower unit indicate that the Blocher is mostly Middle Devonian in age but includes some beds that are earliest Late Devonian (Collinson and others, 1967, p. 957).

The Blocher Member is correlative with the Blocher Shale mapped by North (1969, fig. 20) in Illinois. Evidence from geophysical logs and sample studies in Illinois indicates that the lower Blocher grades laterally into the upper part of the Lingle Limestone (Middle Devonian) in a westward direction in Illinois (North, 1969, p. 34). The Blocher as interpreted in our report is equivalent to the Blocher Member of the New Albany Shale mapped by Schwalb and Norris (1978a) in western Kentucky. The Blocher Member, as currently defined in Indiana, correlates with the Blocher Shale and the lower part of the Selmier Shale mapped by Cluff and others (1981) in Illinois.

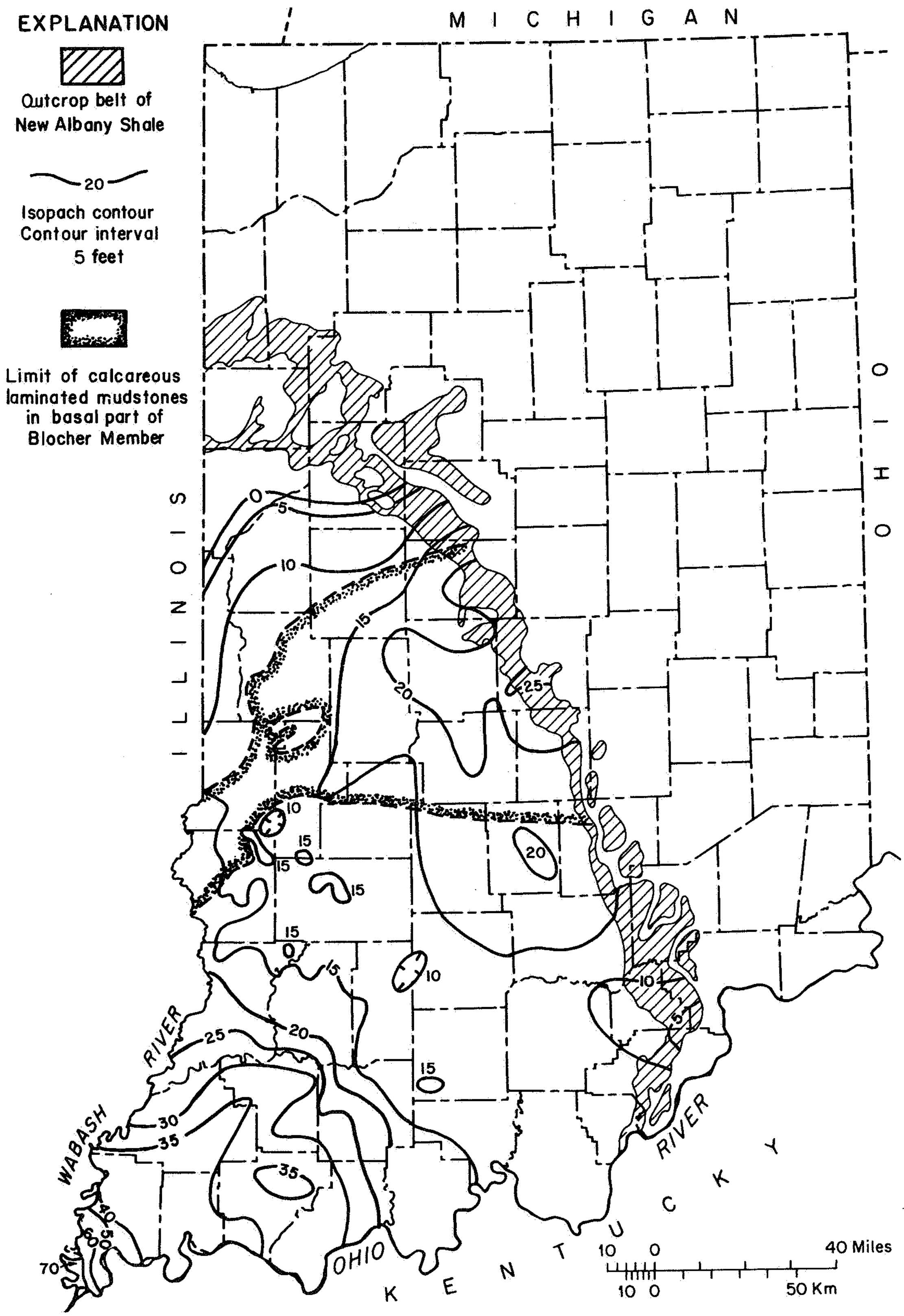

Figure 8. Map of Indiana showing thickness of the Blocher Member of the New Albany Shale.

Selmier Member

The name Selmier Member of the New Albany Shale was applied by Lineback (1968, p. 1298) to the greenish-gray shale that overlies the Blocher Member. He designated the type section as "along the south wall of the Berry Materials Company quarry" at North Vernon in Jennings County, Ind. The name is taken from the Selmier State Forest, a mile northeast of the type section. This unit corresponds to the *Spathiocaris* Zone described by Campbell (Lineback, 1970, p. 22). In our study the Selmier has been redefined by its geophysical characteristics in the subsurface to include some dark-gray shales that Lineback (1970) included in the upper part of the Blocher Member.

In the outcrop area in southeastern Indiana the Selmier in predominantly a greenish-gray (5GY 6/1) shale but also contains small amounts of brownish-black fissile shale, dolomite, limestone, and quartz sandstone. The Selmier in southwestern Indiana is generally dark-gray (N3) to dark-olive-gray (5Y 3/2). Because the differences in color between the lower part of the Selmier and the underlying Blocher are subtle in southwestern Indiana, differentiation of the two units by samples (well cuttings) alone is often difficult.

In the Phegley core, Sullivan County, organic carbon by weight ranges from as low as 1 percent in the upper part of the Selmier to as much as 9 percent in the middle part of the shale and to as little as 3 percent in the lower part of the shale (fig. 7). Organic carbon is slightly less in the Selmier interval in the SDH 273 core from Marion County in central Indiana (fig. 6), but the distribution is similar to that in the Phegley core. In both cores the upper part of the Selmier is lighter colored.

Besides numerous thin carbonate laminae in the Selmier in the SDH 273 core from Marion County, the SDH 291 core from Jackson County, and the Phegley core from Sullivan County, lenticular light-gray to light-brownish-gray dolomite and limestone beds as much as a foot thick are present. In the North Vernon area in Jennings County dolomitic septarian concretions as much as 2 feet thick and 5 feet in diameter are present (Lineback, 1970, p. 22).

At the base of the Selmier are fine- to medium-grained light-gray quartz-sandstone beds and laminae cemented with pyrite, dolomite, or calcium carbonate. These sandstone beds contain phosphatic debris, conodonts, fish fragments, and carbonized plant debris. Dark-gray shale beds interbedded with thin sandstone beds are present at the base of the Selmier in the SDH 291 core from Jackson County, where they are in a zone as much as 2.5 feet thick. The sandstone beds are present at several outcrops in Jennings County. Lineback (1970) also described a thin dolomitic quartzose rock at the base of the Selmier at outcrop localities in Scott and Jefferson Counties.

To the north, west, and south of Jennings County and eastern Jackson County the quartz-sandstone beds thin and are fewer in number. A sandy zone, 0.07 foot thick, is present in the SDH 241 core from Brown County 17.8 feet above the base of the Blocher, and in the SDH 193 core from Lawrence County a zone 0.01 foot thick is present 8.1 feet above the base. Sandstone beds are not present in either the SDH 273 core or the SDH 275 core from Marion County or in the SDH 290 core from Clark County. The sandstone beds cannot usually be recognized on geophysical logs and are difficult to distinguish in well cuttings.

In our study the Selmier interval has been recognized on geophysical logs and from well cuttings. In general, the thickness and distribution of the Selmier interval recognized on geophysical logs are greater than those recognized from well cuttings. On geophysical logs for wells in southwestern Indiana the Selmier can be divided into three subunits: (1) an upper zone with low electrical resistivity and moderate gamma-ray intensity, (2) a middle zone with high resistivity and high gamma-ray intensity, and (3) a lower zone of low to moderate resistivity and moderate gamma-ray intensity. The gamma-ray intensities of the three subunits correlate well with the amount of organic carbon in the Phegley core from Sullivan County (fig. 7).

The Selmier is 140 feet thick in southwestern Indiana but thins northward and eastward, and it is absent from some areas in southeastern Indiana (fig. 9). In southern Indiana geophysical-log correlations show that the Selmier thins and pinches out eastward. The Selmier interval was not recognized on geophysical logs or in the core from SDH 290 (EGSP IN-2), Clark County. Northward from Clark County the Selmier begins to thicken in the shallow subsurface and is 28 feet thick in the SDH 291 core from Jackson County. The northward thickening of the Selmier in the shallow subsurface appears to be partly due to a facies relationship with the overlying Morgan Trail Member. As the Selmier thickens northward the Morgan Trail Member thins from 38 feet in the SDH 290 core from Clark County to 22 feet in the SDH 291 core from Jackson County.

Conodonts from the Selmier Member, as defined by Lineback (1968), indicate Late Devonian age for the shale (Collinson and others, 1967, p. 960). As part of the underlying Blocher Member has conodont species indicative of Late Devonian age, it seems likely that the expanded Selmier of our report is entirely Late Devonian in age in the outcrop area and the shallow subsurface.

The Selmier Member is correlative with the "unnamed shale" of Meents and Swann (1965), the Sweetland Creek Shale of the New Albany Shale Group mapped by North (1969, fig. 22) in southeastern Illinois (south of his vertical cutoff), the Sweetland Creek Member of the New Albany Shale mapped by Schwalb and Norris (1978b) in northwestern Kentucky, and the lower part of the Sweetland Creek Shale mapped by North (1969) in the northeastern part of the Illinois Basin in Illinois. The Selmier is also mostly equivalent to the Selmier Shale mapped by Cluff and others (1981) in southeastern Illinois. It is not recognized in the Michigan Basin, but it is stratigraphically equivalent to part of the Antrim Shale of northern Indiana and Michigan (Lineback, 1968; 1970). It is lithologically similar to the Olentangy Shale of Ohio and is most likely equivalent to the upper part of the Olentangy, which Tillman (1970) determined was Late Devonian in age primarily by ostracode faunas.

The sandstone beds at the base of the Selmier are in the same stratigraphic position as thin sandy beds in the lower part of the Selmier Shale in eastern Illinois. These sandy beds in eastern Illinois have been tentatively equated with the Sylamore Sandstone of central and western Illinois by Collinson and others (1967, p. 960) and Willman and others (1975, p. 122).

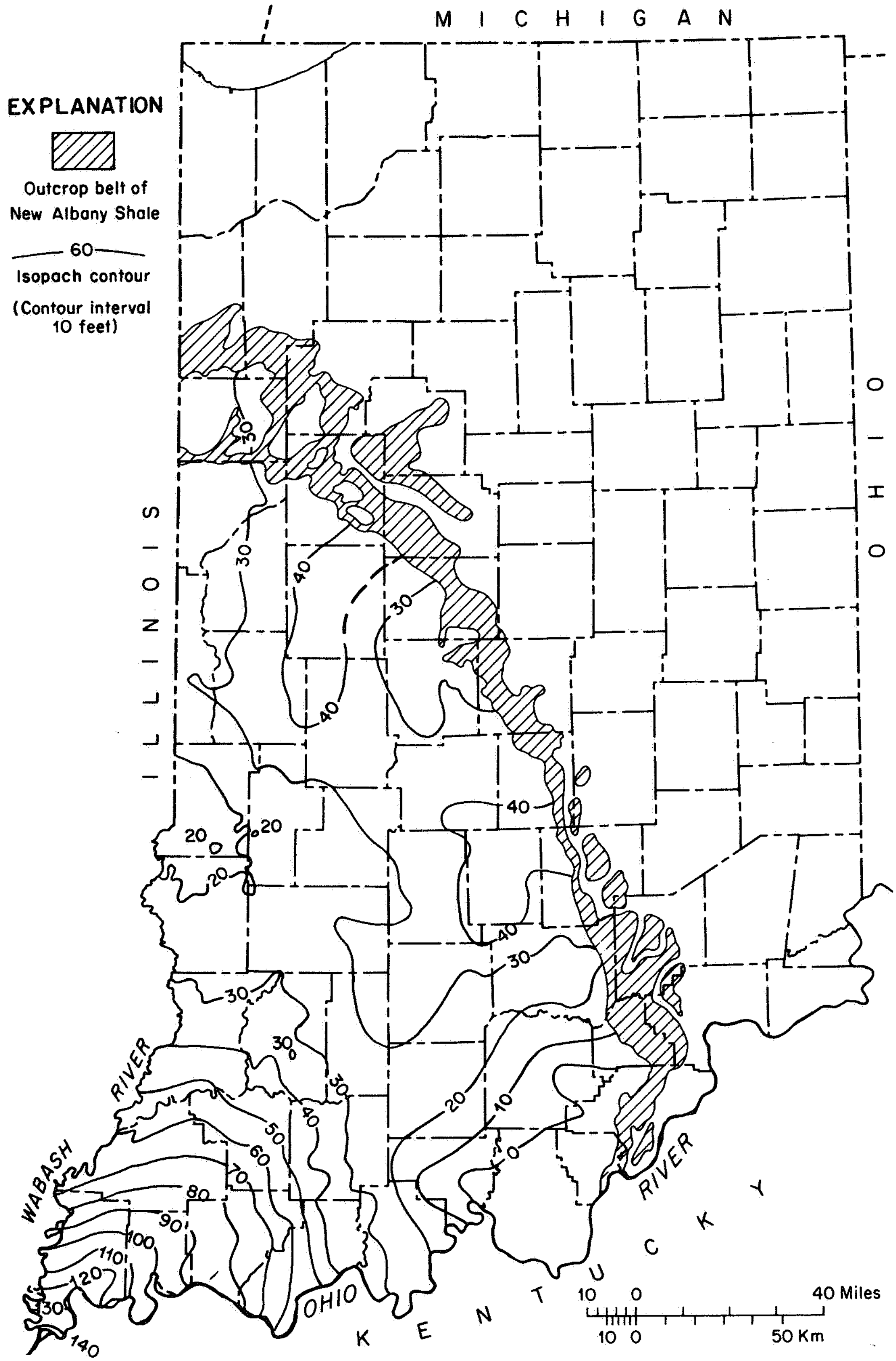

Figure 9. Map of Indiana showing thickness of the Selmier Member of the New Albany Shale.

Undifferentiated Morgan Trail, Camp Run, and Clegg Creek Members

In the outcrop area in southeastern Indiana Lineback (1968, 1970) recognized three lithologically distinct members in the upper part of the New Albany Shale. These members in ascending order are: (1) the Morgan Trail Member characterized by brownish-black fissile siliceous pyritic shale; (2) the Camp Run Member characterized by greenish- to olive-gray shale interbedded with brownish-black carbonaceous pyritic fissile shale; and (3) the Clegg Creek Member characterized by predominantly brownish-black carbonaceous fissile silty pyritic shale. A thin phosphatic nodule zone and a few thin greenish-gray shale beds at the top of the New Albany Shale were also included in the Clegg Creek Member by Lineback (1968, 1970).

These three outcrop members can be recognized in the Clark County SDH 290 core and the Jackson County SDH 291 core, which are near the New Albany outcrop belt; however, to the west and north these members cannot consistently be recognized in the subsurface because the thin greenish-gray shale beds that characterize the Camp Run Member cannot be identified in well cuttings. Also, the Camp Run usually cannot be differentiated from the Morgan Trail on geophysical logs. Therefore, in our study the Morgan Trail, Camp Run, and Clegg Creek Members were not differentiated in the subsurface.

Three thin subdivisions, the Falling Run Member, the Underwood Formation, and the Henryville Formation, near the top of the New Albany Shale were recognized by Campbell (1946) in the outcrop area. These units were later ranked as beds and included in the upper part of the Clegg Creek Member (Lineback, 1968, p. 1300). Campbell (1946) separated from the New Albany a thin greenish-gray shale overlying the Henryville and called it the Jacobs Chapel Shale. This thin shale unit was later ranked as a bed and included in the Clegg Creek (Lineback, 1968, p. 1300).

The Falling Run Bed is a zone of phosphatic nodules 0.1 to 0.2 foot thick and 0.4 to 1.4 feet below the top of the Clegg Creek Member in the outcrop area in Indiana. The Underwood Bed is a thin (0.4 foot) greenish-gray shale known at only a single outcrop locality in Clark County. This unit was not definitively recognized in the subsurface during our study. The Henryville Bed is 0.4 to 1.4 feet thick and is brownish-black to black carbonaceous fissile shale in the outcrop area. At many places this bed is more carbonaceous than the main body of brownish-black shale of the Clegg Creek. In the outcrop area the Jacobs Chapel Bed is greenish-gray calcareous glauconitic shale 0.2 to 0.6 foot thick. Because these beds are so thin they cannot be consistently recognized on geophysical logs from the subsurface in southeastern Indiana.

An arbitrary cutoff running from about northern Bartholomew County southwestward to Vanderburgh County separates the Ellsworth Member from equivalent beds in the Clegg Creek Member (figs. 10 and 11). The cutoff is based on the thickness of greenish-gray shale in the Ellsworth. Southeast of the cutoff the green shales are so thin (about 1 to 2 feet) that they cannot always be distinguished on geophysical logs or they are absent altogether. In the southeastern area the Falling Run, the Henryville, and the Jacobs Chapel are considered beds of the Clegg Creek Member. Northwest of the cutoff the Henryville and the Jacobs Chapel are considered to be beds in the Ellsworth Member. The Falling Run Bed

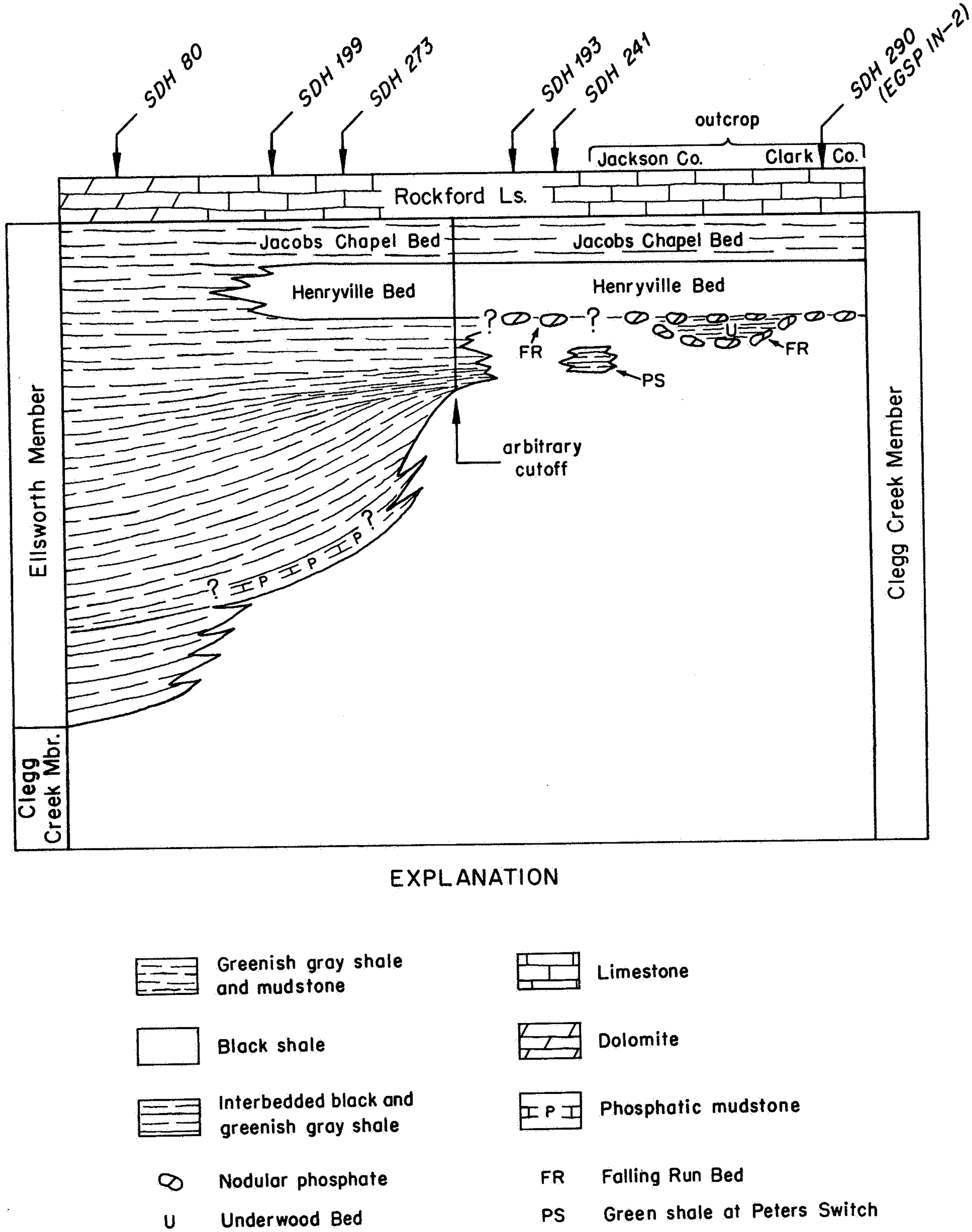

Figure 10. Diagram illustrating relationship of the Ellsworth Member to the top of the Clegg Creek Member in the southeastern Indiana outcrop area. Not to scale.

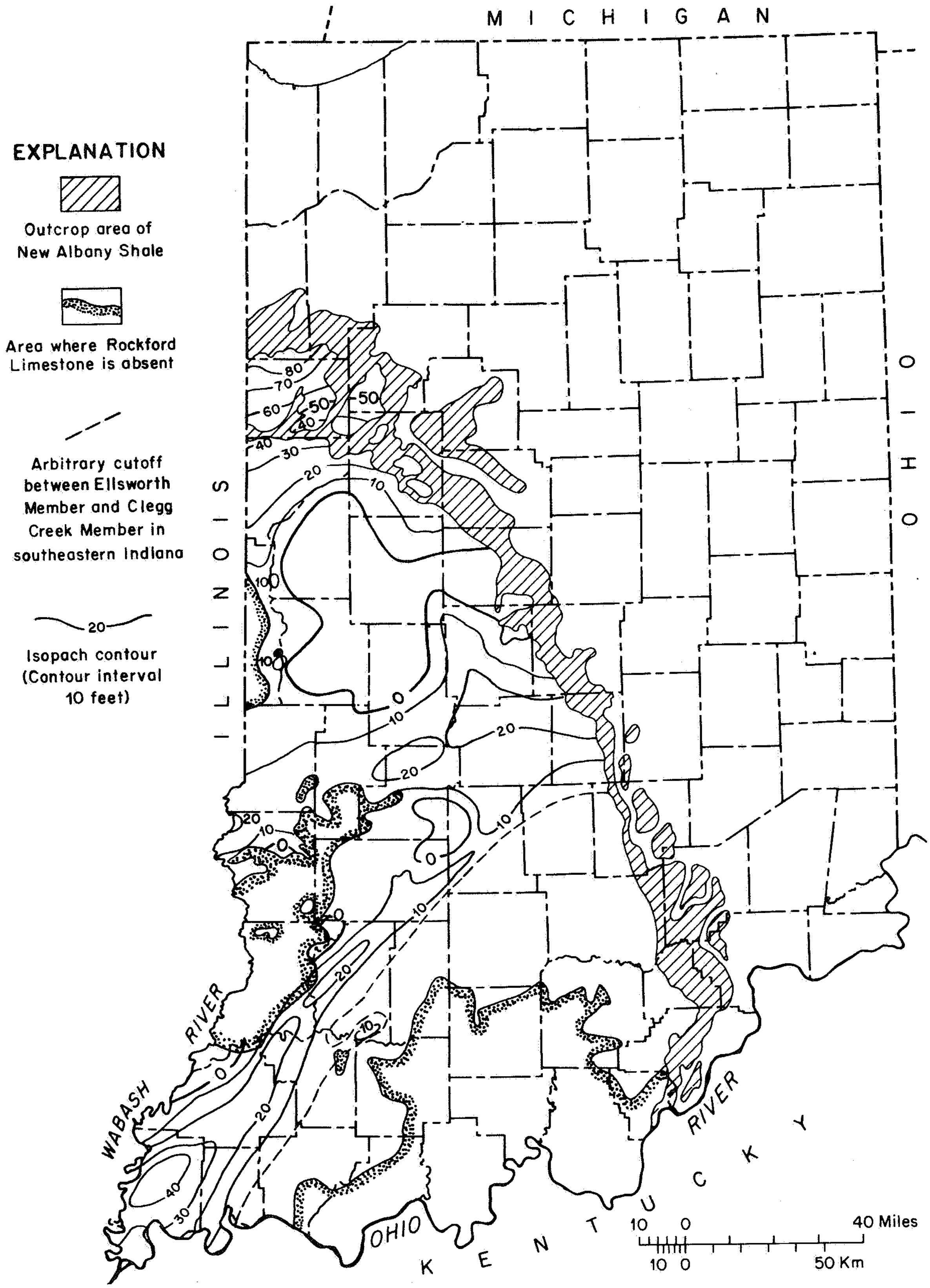

Figure 11. Map of Indiana showing thickness of the Ellsworth Member of the New Albany Shale.

has not been definitely identified northwest of the cutoff line.

In the Illinois Basin in southwestern Indiana the Morgan Trail-Camp Run-Clegg Creek interval is characterized by moderate to high electrical resistivity and high to very high gamma-ray intensity. In areas to the north and east the electrical resistivity ranges from low to high for the interval, and the gamma-ray intensity ranges from moderate to very high. The upper part of the interval is generally characterized by a higher electrical resistivity and gamma-ray intensity than the rest of the interval except in the northern part of the Illinois Basin. This upper part of the interval is probably equivalent to the Clegg Creek Member of the outcrop area.

The combined thickness of the undifferentiated three members is 140 feet in Posey County in southwestern Indiana, but the interval thins to the north and east. In Benton and Warren Counties in the northern part of the Illinois Basin in Indiana the Morgan Trail-Camp Run-Clegg Creek interval thins as the upper portion grades laterally into the Ellsworth Member. In southwestern Indiana a northeast-southwest linear trend is present where the normal basinward thickening of the Morgan Trail-Camp Run-Clegg Creek interval decreases (fig. 12). Along this same trend the Ellsworth Member, which is predominantly a greenish-gray shale, thickens to more than 40 feet (fig. 11). It appears that the thinning is in the upper part of the Morgan Trail-Camp Run-Clegg Creek interval and that the upper part of this interval grades laterally into at least part of the Ellsworth Member.

The Morgan Trail, the Camp Run, and part of the Clegg Creek are Late Devonian in age (Lineback, 1968, fig. 7). In the outcrop area the Devonian-Mississippian boundary is 2 to 6 feet below the top of the New Albany (Lineback, 1970). Therefore, the Falling Run, Underwood, Henryville, and Jacobs Chapel Beds and in some areas the upper few feet of the Clegg Creek below the Falling Run Bed are Mississippian in age.

The Underwood Bed is equivalent to the lower part of the Hannibal Shale (Kinderhookian) of Missouri and Illinois, and the Henryville Bed is equivalent to the middle part of the Hannibal (Lineback, 1970, p. 37-38). Conodont studies have shown that the Jacobs Chapel Bed correlates with the middle and upper parts of the Hannibal Shale of the Mississippi Valley (Rexroad, 1969, p. 10).

The Morgan Trail-Camp Run-Clegg Creek interval is equivalent to the Grassy Creek Shale of the New Albany Shale Group in the southeastern part of the Illinois Basin in Illinois and to the Grassy Creek Member of the New Albany Shale in northwestern Kentucky. The lower part of the interval is equivalent to the upper part of the Sweetland Creek Shale mapped by North (1969) in the northeastern part of the Illinois Basin in Illinois. These members are not recognized in the Michigan Basin, but the Morgan Trail and the Camp Run are equivalent to part of the Antrim and Ellsworth Shales of the Michigan Basin. The Clegg Creek Member is equivalent to most of the Ellsworth Shale and to the Sunbury Shale in the Michigan Basin (Lineback, 1970, p. 42).

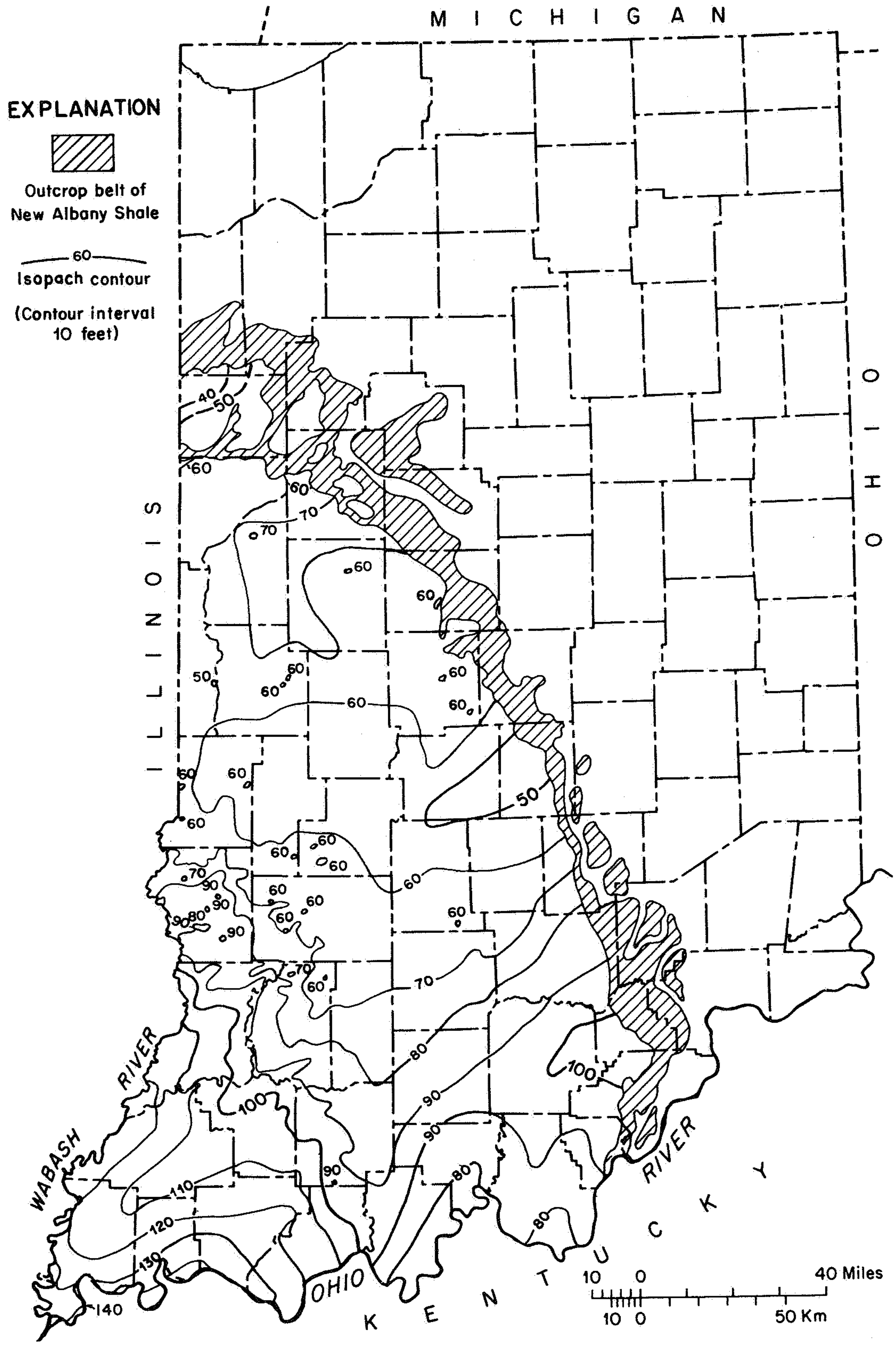

Figure 12. Map of Indiana showing thickness of the undifferentiated Clegg Creek, Camp Run, and Morgan Trail Members of the New Albany Shale.

Ellsworth Member

Greenish-gray shale occurs at the top of the New Albany throughout much of the subsurface. In the northern part of the Illinois Basin this shale was correlated with the Ellsworth Shale of the Michigan Basin by Lineback (1970, p. 32) and was called the Ellsworth Member of the New Albany Shale. The Ellsworth Member can be divided into two parts: (1) a lower part of thinly interbedded brownish-black and greenish-gray shale and (2) an upper part of greenish-gray shale.

Lineback (1970, p. 34) noted tongues of greenish-gray shale in southwestern and west-central Indiana that he believed were not connected with but did occupy the same stratigraphic position as the upper part of the Ellsworth. Later, on the basis of work by Meents and Swann (1965, fig. 4) and Collinson and others (1967, p. 947), the name Hannibal Member was applied to these tongues and to much of the shale that had been called the Ellsworth Member by Lineback (Becker, 1974, p. 47-48).

In our report the physical continuity of the Ellsworth Member of Lineback (1970) with the tongues of greenish-gray shale in west-central Indiana and central Indiana is established. The term Ellsworth Member of the New Albany Shale is applied in the same sense as the term Hannibal was applied by Becker (1974) and Lechler and others (1979), that is, to the body of dominantly greenish-gray shale lying stratigraphically beneath the Rockford Limestone and above the black shale that constitutes most of the New Albany. The Ellsworth Member of the New Albany Shale is not differentiated from the overlying New Providence Shale where the Rockford Limestone and the Henryville Bed are absent.

The Ellsworth Member contains both brownish-black and greenish-gray shales, although volumetrically greenish-gray (5G 5/1) shale is by far the dominant lithology. The Ellsworth shales are generally noncalcareous. The upper part of the Ellsworth consists predominantly of greenish-gray shale, and the lower part consists of greenish-gray shale interbedded with brownish-black shale. The interbedded lithology occurs in Benton, White, Jasper, and Newton Counties in the extreme northern part of the Illinois Basin in Indiana. In these counties the interbedded lithology is about two-thirds of the total Ellsworth interval. The northward grading of brownish-black shales of the Clegg Creek into the greenish-gray shales of the Ellsworth is the primary cause of the Ellsworth thickening in this area (fig. 11).

The Ellsworth Member is equivalent to many of the thin uppermost beds of the New Albany in the southeastern Indiana outcrop area. These units consist in ascending order of: the Falling Run, Underwood, Henryville, and Jacobs Chapel Beds of the Clegg Creek Member.

The Falling Run Bed has not been recognized in the Ellsworth Member; however, a light-greenish-gray (5Y 6/1) calcareous shale with slightly higher concentrations of P_2O_5 and yittrium is present at the base of the member in cores from Marion (SDH 273 and SDH 275), Morgan (SDH 156), and Putnam (SDH 199) Counties. This bed has a maximum known thickness of 0.4 foot.

The Underwood Bed, a greenish-gray shale, is known at a single locality in Clark County where it overlies the Falling Run Bed. The stratigraphic relationship between the Ellsworth and the greenish-gray shale of the Underwood is not entirely clear. Both shales are directly overlain by the Henryville Bed, but the exact relationship of the greenish-gray shale of the Ellsworth to the Falling Run Bed has not been determined. The Ellsworth greenish-gray shales may be equivalent either to the Underwood Bed or to a greenish-gray shale believed to lie below the Falling Run Bed near Peters Switch in Jackson County, or to both.

In our study the Henryville Bed was recognized on geophysical logs and in well cuttings in some areas of central and southwestern Indiana. In west-central Indiana the Henryville Bed is recognized as far west as Vigo and Sullivan Counties and has been recognized in Illinois by Reinbold (1978, fig. 3). The Henryville is not identified north of Hendricks, Parke, and Putnam Counties.

The Jacobs Chapel Bed is too thin to be recognized on most geophysical logs, but it is known from cores throughout the subsurface at least as far north as Morgan, Marion, and Putnam Counties. It is nowhere more than a few inches thick but is always recognized where the Rockford Limestone is present in central and southern Indiana.

The Ellsworth Member is generally characterized by low electrical resistivity and gamma-ray intensity relative to the underlying brownish-black shales of the New Albany. The Henryville Bed has high electrical resistivity and gamma-ray intensity. This bed cannot always be distinguished from the overlying Rockford Limestone on resistivity logs, but it can be distinguished from the Rockford on gamma-ray logs.

The Ellsworth Member is present throughout much of the Illinois Basin in Indiana. It cannot be recognized in areas where both the Rockford Limestone and the Henryville Bed are absent, and it is not recognized in south-central Indiana southeast of the arbitrary cutoff, which separates the member from thin equivalent beds in the Clegg Creek Member (fig. 11).

In central and southern Indiana two tongues of Ellsworth greenish-gray shale radiate from northern Johnson and Morgan Counties westward to northern Sullivan County and southwestward to Posey County. In central Indiana the Ellsworth Member, including the Henryville Bed, is about 27 feet thick in northeastern Morgan County. Westward toward Vigo and Sullivan Counties the Ellsworth is 16 to 22 feet thick along the axis of the tongue. Southwestward from Morgan County, the Ellsworth occurs in a narrow tongue and is as much as 48 feet thick in Posey County. These two tongues are separated by an area of thin greenish-gray shale and a large area where the Rockford is absent.

The Ellsworth is absent from a large area in west-central Indiana and is generally less than 10 feet thick in Vermillion County and western Parke County. In the northernmost part of the Illinois Basin in Indiana the upper part of the Clegg Creek grades into greenish-gray shales of the Ellsworth, and the Ellsworth Member thickens rapidly. It is as much as 83 feet thick in the SDH 80 core from northwestern Benton County. The Henryville Bed, where present, is generally less than 5 feet thick.

The Ellsworth Member is equivalent to the Hannibal and Saverton Shales of Illinois. The Saverton Shale is Devonian in age (Scott and Collinson, 1961).

It is correlative with the interbedded greenish-gray and brownish-black shales of the lower part of the Ellsworth and with the greenish-gray shale at Peters Switch, Jackson County, which contains Devonian brachiopods (Huddle, 1933, p. 313-314).

The Henryville Bed is at least partly equivalent to the Sunbury Shale of the Michigan Basin. Therefore, the Ellsworth Member as currently defined in the Illinois Basin is equivalent to the Ellsworth and Sunbury Shales of the Michigan Basin.

Antrim Shale

The name Antrim Shale was proposed by Lane (1901, p. 9) for shale exposed in Antrim County, Mich. The name is used in the Michigan Basin area of northern Indiana for strata that is partly coextensive with the Antrim of Michigan.

In Indiana the Antrim Shale is predominantly brownish-black noncalcareous fissile shale; however, in some places medium-gray calcareous shale or limestone is present in the lower part of the unit. In Michigan this gray calcareous shale is placed in the upper part of the Traverse Group rather than in the Antrim. In some areas in western LaPorte County there is a thin bed of fine-grained sandstone consisting of subrounded to well-rounded quartz grains at or near the base of the Antrim.

The gray calcareous shale in the lower part of the Antrim is characterized by low to moderate gamma-ray intensity and variable, but dominantly low, electrical resistivity. The overlying black shale of the Antrim has high gamma-ray intensity and electrical resistivity.

The Antrim is 60 to 80 feet thick in Porter County and thickens eastward to more than 220 feet in Lagrange and Steuben Counties. The gray calcareous shale in the lower part of the Antrim also thickens eastward from 0 feet in western LaPorte County to more than 50 feet in Elkhart County. Eastward from Elkhart County a transitional zone that lies between the gray calcareous shale and the black shale of the Antrim becomes apparent on the geophysical logs.

The gray calcareous shale in the lower part of the Antrim is equivalent to the upper part of the Traverse Group in Michigan. The total Antrim interval is equivalent to the Blocher Member, the Selmier Member, and part of the New Albany above the Selmier (Lineback, 1970, p. 31).

Ellsworth Shale

The name Ellsworth Shale was proposed by Newcombe (1933, p. 49-51) for exposures of greenish-gray shale near Ellsworth, Mich. In Indiana greenish-gray shales of the Ellsworth have formation rank in the Michigan Basin, but, as previously noted, equivalent Ellsworth shales in the Illinois Basin are regarded as a member of the New Albany Shale.

The Ellsworth of Michigan Basin terminology is greenish-gray shale or interbedded brownish-black and greenish-gray shale lying between brownish-black shales of the Antrim and the Sunbury. It is generally not distinguished from the Coldwater Shale (Lower and Middle Mississippian) beyond the limit of the Sunbury Shale in western Lagrange County (fig. 4). The Ellsworth is easily distinguished from the Antrim and Sunbury Shales on both gamma-ray and electrical resisitivity logs.

The Ellsworth Shale can be divided into an upper and a lower part, just as the equivalent Ellsworth Member of the Illinois Basin is divided. The lower part consists of interbedded brownish-black and greenish-gray shale and is laterally gradational with the upper part of the Antrim Shale in Lagrange and Noble Counties. The upper part contains no brownish-black shale and is continuous to the east beyond the area where the lower Ellsworth grades into the Antrim.

The Ellsworth Shale ranges from less than 40 feet to more than 200 feet in thickness in northern Indiana. Much of this change in thickness is attributed to the lower Ellsworth grading into the Antrim.

The Ellsworth Shale of Indiana is Late Devonian and Early Mississippian in age and is correlative with the Ellsworth Shale of Michigan and with the Bedford Shale and the Berea Sandstone of eastern Michigan and Ohio. The Ellsworth Shale and the Bedford-Berea interval intertongue in two small areas of Michigan (Asseez, 1969, p. 130).

Sunbury Shale

The type locality of the Sunbury Shale, originally named the Sunbury Black Slate by Hicks (1878), is near Sunbury, Delaware County, Ohio. In Indiana the Sunbury lies stratigraphically between the greenish-gray Ellsworth and Coldwater Shales and is the uppermost unit equivalent to the New Albany Shale of the Illinois Basin. The Sunbury is carbonaceous brownish-black shale and is easily distinguished from adjacent lithologies both in samples and on geophysical logs.

The Sunbury has a maximum known thickness of 12 feet in Steuben County, Ind., and thins southward and westward. It is absent west of Lagrange County.

It is Early Mississippian in age and probably correlates with the Henryville Bed of the Ellsworth and Clegg Creek Members of the Illinois Basin. The Sunbury is present over much of southern Michigan and in places lies directly on top of the Antrim Shale (Asseez, 1969, p. 131).

Depositional Environment

Paleogeographic Setting

The sediments of the lower part of the New Albany Shale in Indiana were deposited in a transgressing sea. This sea covered much of the eastern and central United States during Middle and Late Devonian and Early Mississippian time (Lineback, 1970, p. 42). Conant and Swanson (1961) recognized transgressive relationships in the Chattanooga Shale of Tennessee where "successively higher beds of black shale overlap the lower ones." A similar relationship exists in the northern part of the Illinois Basin in Indiana where the Selmier Member of the New Albany Shale overlaps the Blocher Member in Warren, Tippecanoe, and Fountain Counties.

Oxygen-Deficient Basin

Black shales have been interpreted as being deposited in anoxic basins with stratification of oxygen levels. Rhoads and Morse (1971) studied several modern oxygen-deficient basins and related the distribution of the benthic fauna and sedimentation fabric to changes in the amount of dissolved oxygen. They recognized three biofacies zones related to the amount of oxygen and also noted (1971, p. 414) that basins having a decrease in oxygen toward the basin floor usually have no major connection with the open ocean.

This biofacies model for oxygen-deficient basins was applied to the Middlesex Shale (Devonian) of New York, and three zones related to oxygenation were recognized (Byers, 1977). Similar zones were recognized in the New Albany Shale Group (Devonian and Mississippian) in Illinois (Cluff and Reinbold, 1978, and Cluff and others, 1981).

In the New Albany Shale of Indiana two of these three zones are recognized. The black shales of the Morgan Trail, Camp Run, and Clegg Creek Members and of the middle part of the Selmier Member were deposited in an anaerobic environment. This is indicated by the preservation of large amounts of organic material, the absence of indigenous benthonic fossils (Lineback, 1970, p. 45), and the preservation of fine laminations in the shale. The Blocher Member, which is slightly calcareous carbonaceous laminated shale, does contain some calcareous articulate brachiopods (Lineback, 1970) and thin calcareous laminae enclosing abundant *Tentaculites* and *Styliolina* (Shaffer and others, 1978). Lineback (1970) interpreted the brachiopods as being epiplanktonic in habitat, and it has been postulated that styliolinids were pelagic.

The greenish-gray shales of the Selmier, Camp Run, and Ellsworth Members were deposited in a slightly more oxygenated or dysaerobic environment. Less organic material was preserved in these shales, and there is evidence of burrowing organisms. Lineback (1970, p. 24) noted a few pelecypods and gastropods, and Campbell (1946) reported the genus *Spathiocaris* and other crustaceans from the Selmier. Articulate brachiopods in the greenish-gray shale of the Underwood Bed in Clark County and in the greenish-gray shale in the upper part of the Clegg

Creek Member exposed near Peters Switch in Jackson County indicate that more oxygenated conditions existed in localized areas in southeastern Indiana during late New Albany deposition.

Relation to Overlying Strata

Rockford Limestone

The Rockford Limestone, which overlies the New Albany Shale, is conformable and gradational with the underlying Jacobs Chapel Bed of the New Albany (Henderson, 1974, p. 9). The Rockford is greenish-gray fine-grained argillaceous dolomitic limestone or dolomite. It is sparsely fossiliferous and has a characteristic green mottling. This limestone is thin (2 to 3 feet) in the outcrop area in southeastern Indiana. Melhorn (1958, p. 196) reported a maximum thickness of about 22 feet in the outcrop area in the northern part of the Illinois Basin in Indiana. The Rockford is present in most areas in the subsurface south and west of the outcrop belt; however, it is absent from south-central Indiana, along the Indiana-Illinois state line, and in other localized areas (fig. 11). The maximum thickness in the subsurface is about 12 feet in Posey and Gibson Counties in southwestern Indiana.

The Rockford is characterized by high electrical resistivity and low gamma-ray intensity on geophysical logs. Because the Jacobs Chapel Bed, the greenish-gray glauconitic shale that underlies the Rockford, is so thin (0.2 to 0.6 foot), differentiation of the Rockford from the black shale of the Henryville Bed is difficult using resistivity logs because both units are characterized by high resistivity.

Buschbach (1953) stated that Workman and Gillette in an unpublished 1947 manuscript had shown that in the subsurface of the Illinois Basin the Rockford is physically continuous with the Chouteau Limestone of Illinois. Conodont studies indicate that the Rockford is correlative with the upper part of the Chouteau Limestone (Kinderhookian) in the Mississippi Valley and the so-called Sedalia Formation (Valmeyeran) of Illinois (Rexroad and Scott, 1964, p. 13).

New Providence Shale

The lower part of the New Providence Shale of the Borden Group (Valmeyeran) is greenish-gray shale that overlies the Rockford Limestone. In areas where the Rockford is absent the New Providence rests directly on the New Albany Shale.

STRUCTURE

N. R. Hasenmueller and J. L. Bassett

Illinois Basin

The New Albany Shale thickens and dips in a southwesterly direction into the Illinois Basin. In the outcrop belt the base of the formation is 500 to 600 feet above sea level. In southwestern Indiana the base of the shale is 4,500 feet below sea level. Within 20 miles of the outcrop belt the rocks dip 20 to 30 feet per mile toward the southwest; basinward the dip increases to about 50 to 60 feet (Bassett and Hasenmueller, 1977, p. 133). This gently westwardly increasing dip also varies locally due to (1) faults of the Wabash Valley Fault System in Posey and Gibson Counties in southwestern Indiana; (2) the Mt. Carmel Fault, a normal fault in the south-central part of the state; and (3) a series of small domal structures reflected upward from underlying Silurian reefs (fig. 3).

Displacement at the base of the New Albany along the New Harmony Fault in western Posey and Gibson Counties is more than 200 feet, and along the Wabash Island Fault in southern Posey County, displacement is about 100 feet. The faulting in this area is post-Pennsylvanian in age (Ault and others, 1980) and did not influence New Albany deposition.

The Mount Carmel Fault in south-central Indiana is a normal fault downthrown on the west (basinward) side 100 to 200 feet. Rocks on the basinward side of the fault are folded into a southward-plunging anticline in Monroe, Lawrence, and Washington Counties. The movement along the fault began during Late Mississippian time (Melhorn and Smith, 1959, p. 5).

Silurian reef structures extend in a belt, named the Terre Haute Bank (Droste and Shaver, 1975, p. 395), from Vigo and Clay Counties southeastward to the Ohio River. The reef structures are generally about a mile in diameter and are represented on the structure map on the base of the New Albany by small domes with 100 to 150 feet of closure. Such closures are at least due in part to differential compaction of the Silurian strata, the offreef rock compacting more than the reef rock (Dawson and Carpenter, 1963, p. 16). Thinning of individual members and thinning of the total New Albany over some of these reef structures have been observed in our study.

Michigan Basin

In the Michigan Basin the base of the Antrim-Ellsworth-Sunbury interval dips northward at 10 to 20 feet per mile. No major faults interrupt the northward dip of the shale. Several of the small domal structures may be partly due to the draping of the Devonian strata over Silurian reefs or carbonate banks (J. B. Droste, 1979, oral communication).

MINERALOGY AND PETROGRAPHY

N. R. Shaffer and Pei-Yuan Chen

Introduction

Cores from Marion, Jackson, Clark, and Sullivan Counties (figs. 13, 14, 15) were examined petrographically and described lithologically to characterize the New Albany Shale and interpret its origin and diagenetic history.

Regional Characteristics

Two lithotypes characterize most of the New Albany: hard brownish-black carbonaceous shale and softer greenish-gray shale containing little organic material. Proportions of these lithotypes vary in different areas of Indiana. The black to green ratio ranges from 3:1 to 10:1, and dark beds are dominant in the southwest. Intercalated with these major rock types are numerous thin lighter colored beds or laminae of quartz-feldspars-mica, carbonate minerals, pyrite, vitrain, and phosphates. Fossils are sparse throughout the shale interval, although spores make up a main part of the rock in some thin laminae.

The New Albany is structurally massive to laminated and fissile. It is fine grained and has low porosity. Fractures are generally nearly vertical and oriented northwest-southeast. Many are healed with carbonates or pyrite (fig. 16), and slickensides are seen on some fracture surfaces. Contacts between silty beds and normal shale are sharp, but some show small-scale load casts and irregularities. Contacts between greenish-gray shale and black shale are highly irregular in many places (fig. 17). Burrows are common and are filled with prominent light-green shale (fig. 18) in black shales. Burrows are also abundant though less noticeable in lighter colored shales.

Light-colored beds, lenses, or laminae 1 to 30 mm thick of coarse-grained material interpose the shale at irregular intervals. A few thick beds have graded bedding and rarely have sole marks or other scour features. Several types of coarse beds have been recognized: mainly rounded white to clear quartz sand; a combination of pyrite and quartz sand; a combination of pyrite, carbonate, and quartz sand (fig. 19); nearly pure pyrite; and crystalline carbonate (sparite), which may be dominantly dolomite (possibly ankerite), calcite, or a mixture of the two. This latter type is most common near the base of the New Albany Shale.

Fossils occur as disseminated individuals or in places as assemblages confined to thin beds. The fossils are dominated by amber discoidal resinous spores (Tasmanites) (fig. 20), but they also include plant fragments (generally vitrinized), conodonts, ostracodes, linguloid and rarely other brachiopods, cricoconarids (Styliolina and Tentaculites), Protosalvinia (Foerstia) (A. T. Cross, 1980, written communication), and gastropods. Burrows and trace fossils are common. Styliolina and Tentaculites are restricted to the Blocher Member.

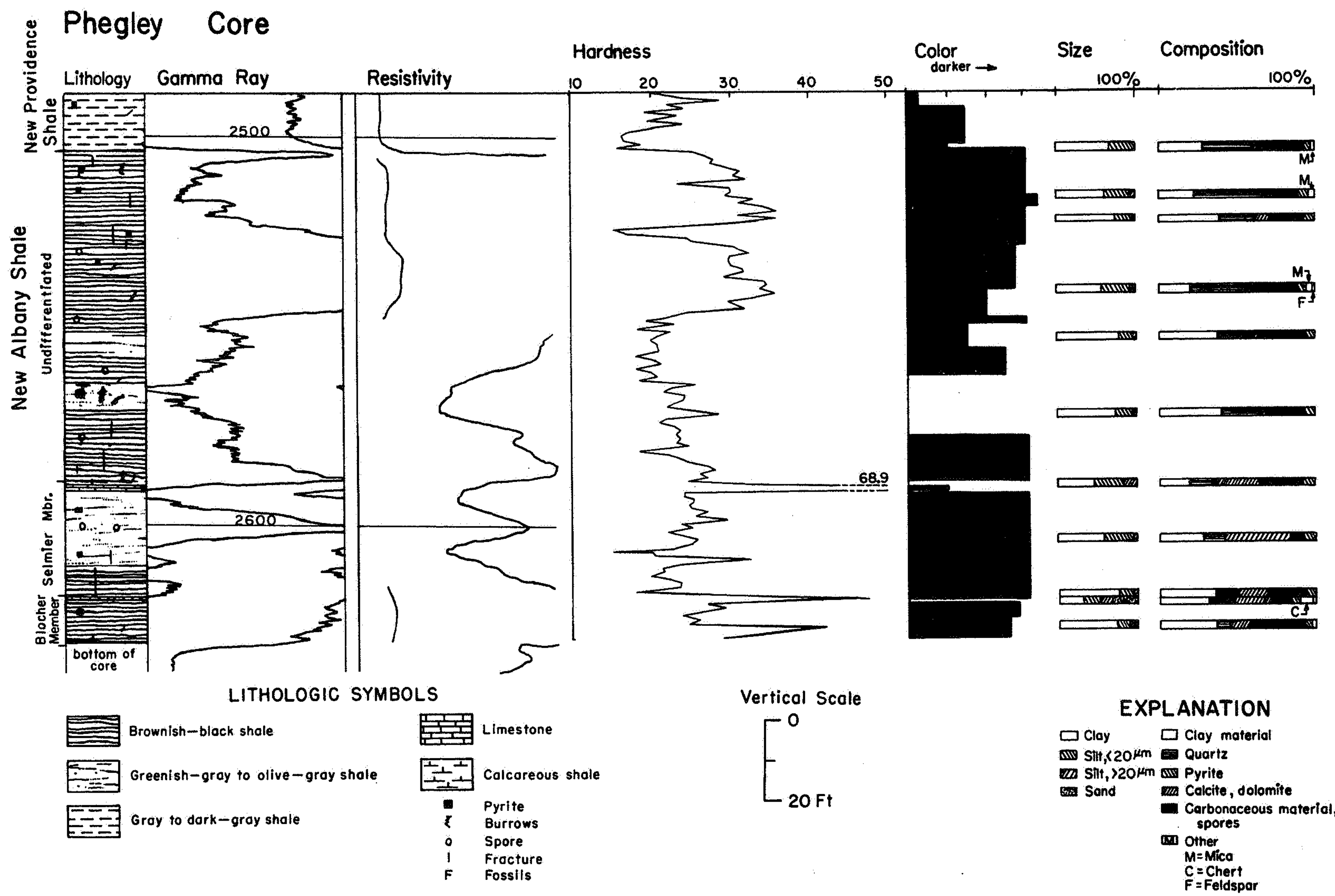

Figure 13. Diagram showing relationship of gamma-ray intensity and electrical resistivity (geophysical logs) to Shore hardness, color, particle size, and mineralogic composition of samples from the Phegley core, Sullivan County. Lithologic symbols and explanation apply to figures 13, 14, and 15.

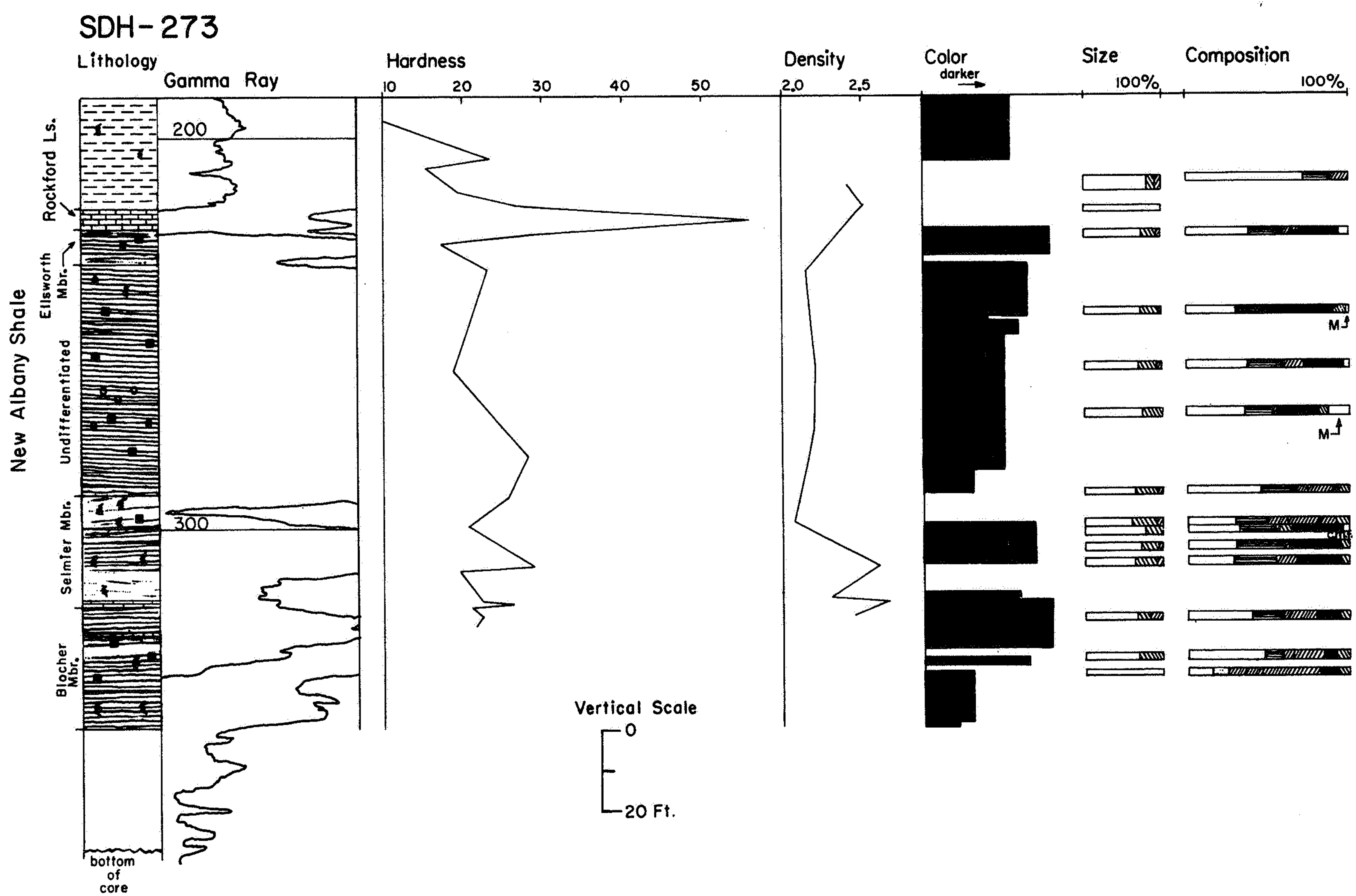

Figure 14. Diagram showing relationship of lithologies, gamma-ray intensity (geophysical log), physical properties, and mineralogic composition of samples from Indiana Geological Survey drill hole 273 core, Marion County.

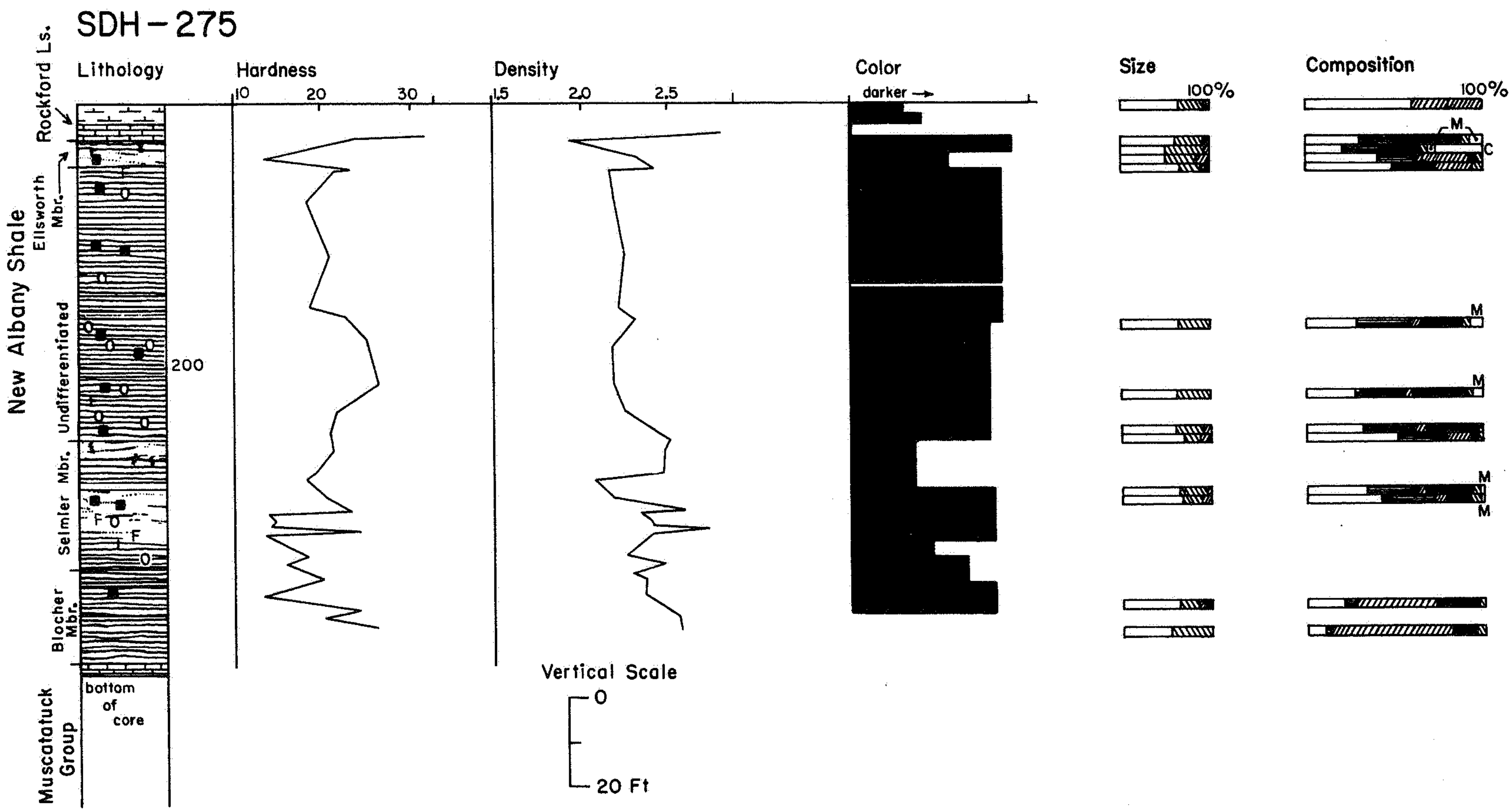

Figure 15. Diagram showing relationship of lithologies, physical properties, and mineralogic composition of samples from Indiana Geological Survey drill hole 275 core, Marion County.

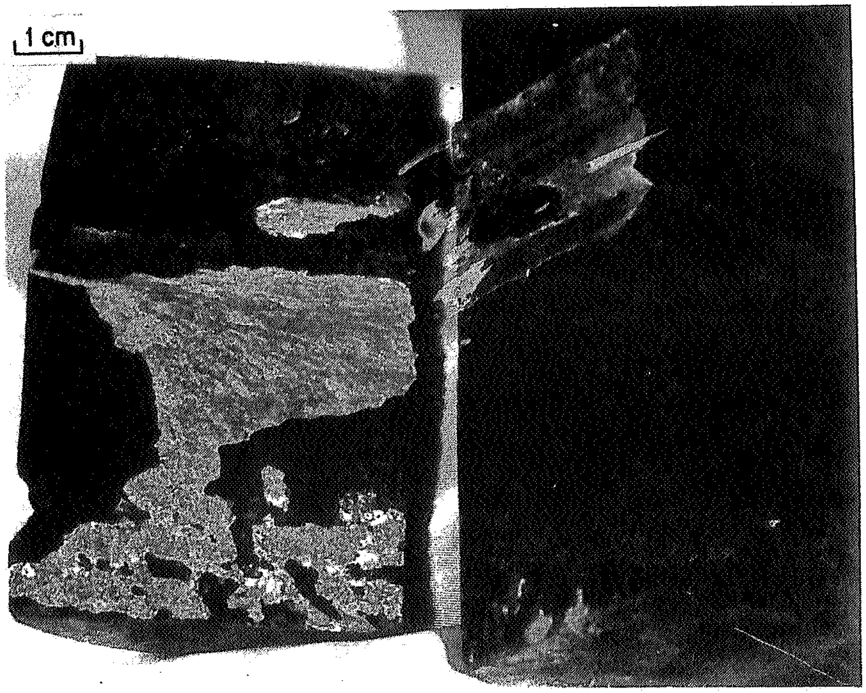

Figure 16. Vertical fracture healed with calcite and pyrite in the Phegley core, Sullivan County. Depth is 2,506 feet.

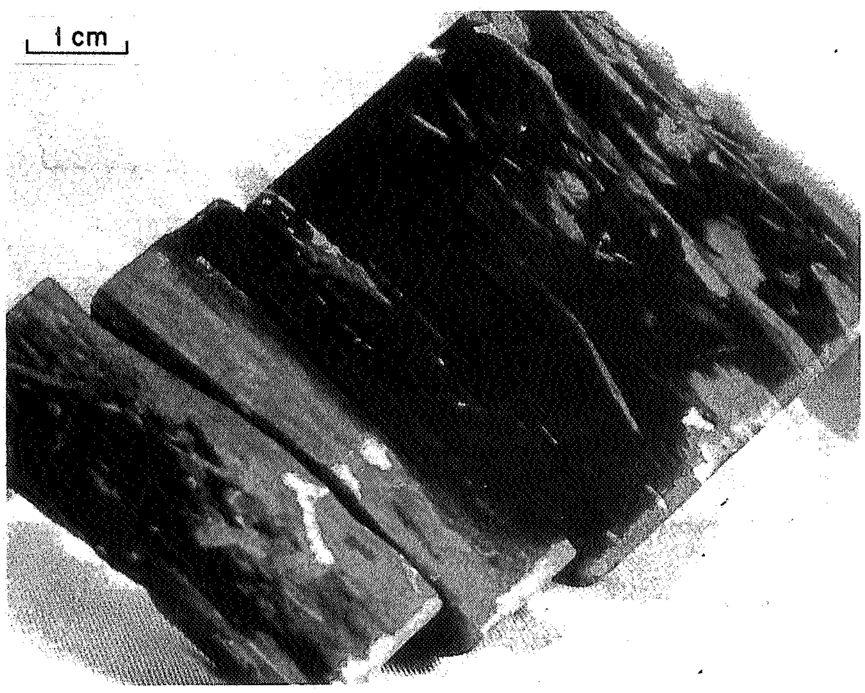

Figure 17. Contact between black shale and greenish-gray shale in Indiana Geological Survey drill hole 275 core, Marion County. Depth is 226 feet.

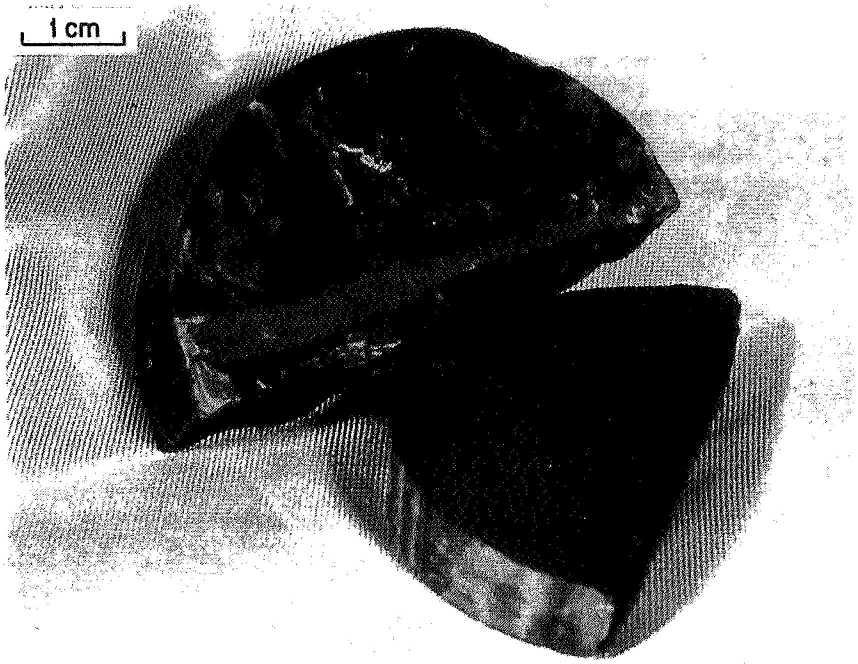

Figure 18. Horizontal burrows filled by lighter colored slightly coarser material mark the contact of black shale with greenish-gray shale in Indiana Geological Survey drill hole 273 core, Marion County. Depth is 216 feet.

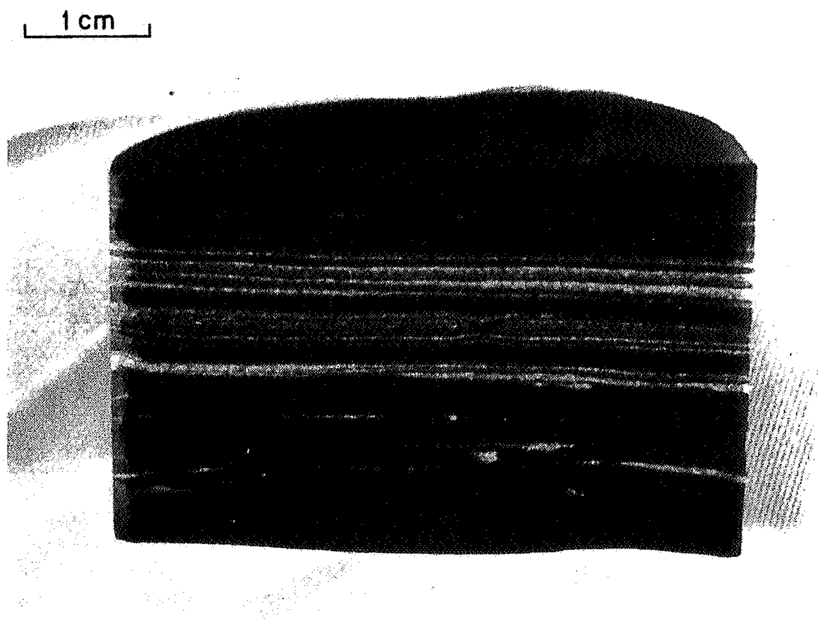

Figure 19. Coarser lighter colored laminae or thin beds of carbonate plus quartz silt and pyrite occur throughout the shale and mark changes in deposition in the Texas Eastern No. 7 core, Jackson County. Depth is 97 feet.

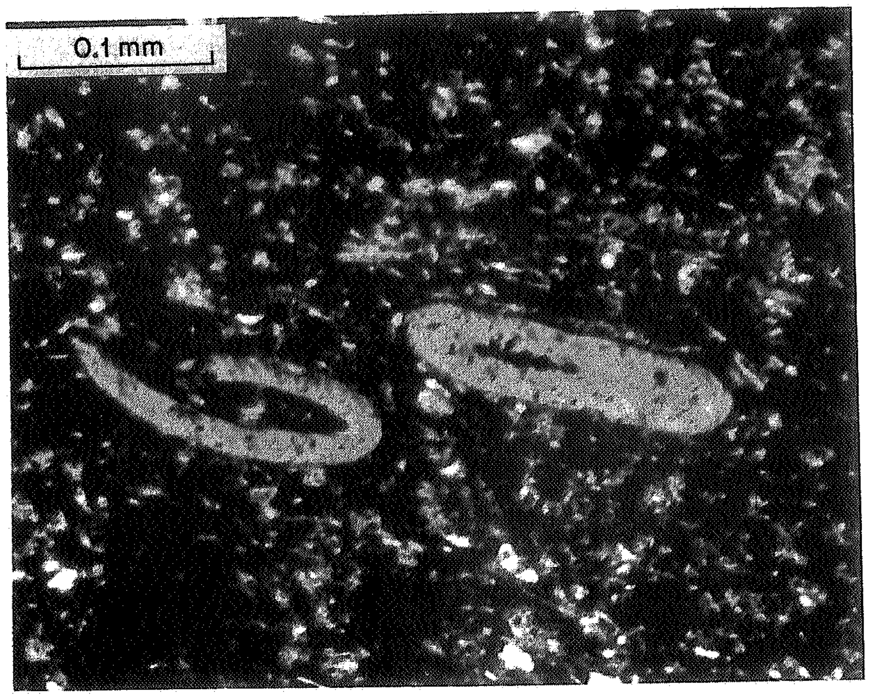

Figure 20. Thin section showing spore, silt, and organic materials in the Phegley core, Sullivan County. Depth is 2,554 feet.

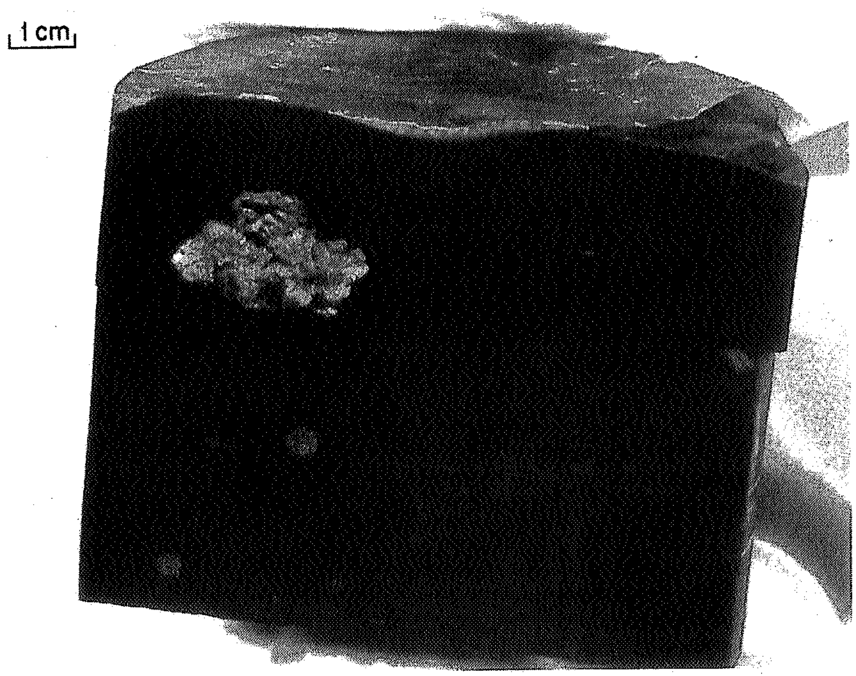

Figure 21. Pyrite nodule in black shale in the Phegley core, Sullivan County. Depth is 2,590 feet.

The New Albany is composed mainly of quartz, clay minerals, fine carbonaceous material (including resinous spores), pyrite, marcasite, and carbonates (mainly dolomite but also subordinate ferroan dolomite and calcite). Feldspars are rarely identified in thin section but commonly show as minor component on X-ray patterns. Fine flakes of sericite are present in some samples, and fluorapatite, identified in a few X-ray patterns, occurs as pellets or conodonts. Less abundant minerals include apatite, rhodochrosite, siderite, gypsum, fluorite, glauconite, barite, tourmaline, and spalerite. Diagenetic pyrite nodules, dolomite rhombs, and micropods of chert and chalcedony are abundant in several units. Except for the carbonate content, the mineral composition of the shale is rather constant throughout the entire thickness.

X-ray diffraction analyses of whole-rock (unashed) bulk samples reveal that the black shales contain illite of the 2M polymorph, minor chlorite (illite: chlorite 6.5:3.5), and accessory mixed-layer clay minerals. Nonclay minerals in decreasing order of abundance include quartz, pyrite, marcasite, feldspar, and minor calcite or rarely dolomite. Pyrite and marcasite are closely associated with each other. Greenish-gray shales are also composed of illite, minor chlorite, and mixed-layer clay minerals. Mixed-layer clay minerals are slightly more abundant in the greenish-gray shales than in the black shales. Chlorite is more common in the coarser fractions, and mixed-layer clay is more common in the finer fractions. No marked difference in clay-mineral composition was found between the black and greenish-gray shales, which suggests that they were derived from the same source material but deposited in different physical and biogenic environments.

Pyrite and marcasite are the most common accessory minerals. They occur as tiny disseminated crystrals, irregular blebs, nodules (fig. 21), and laminae and as a cementing material of coarse beds. Part of the pyrite, especially framboids (fig. 22), may have been formed in the early stage of the shale sedimentation, but part was formed by postdepositional diagenetic processes (fig. 21). The force of the crystral growth of pyrite of the latter type at places pushes the enclosing laminae outward into small-scale domelike structures. Minor amounts of barite, fluorapatite, and sphalerite have also been noted in cores.

Structure and Texture of Shale

Shales of the New Albany can be separated by two categories: black (N1) to brownish-black (5YR 2/1) and greenish-gray (5GY 6/1) shales. The black to brownish-black shales are the dominant type (65 to 80 percent), and they are generally high in carbonaceous materials. Greenish-gray shales are less abundant (6 to 18 percent), and they are only slightly carbonaceous to noncarbonaceous. They range from fissile shale to nonfissile or poorly fissile shale.

Bedding in black shales ranges from rather massive (breaking with uneven or curved surfaces) to thinly laminated. Microscopic observation indicates that beds are marked by discontinuous, somewhat curved or wavy streaks (stringers) of brownish carbonaceous material, clay, and, less commonly, minor intercalated carbonate-quartzose laminae (fig. 19).

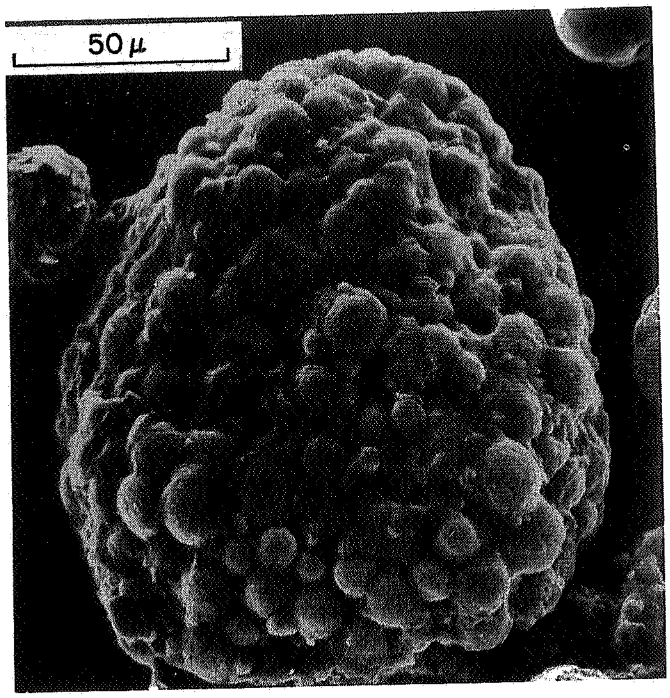

Figure 22. Early-formed pyrite framboid in the Indiana Geological Survey drill hole 290 core, Clark County. Depth is 131 feet.

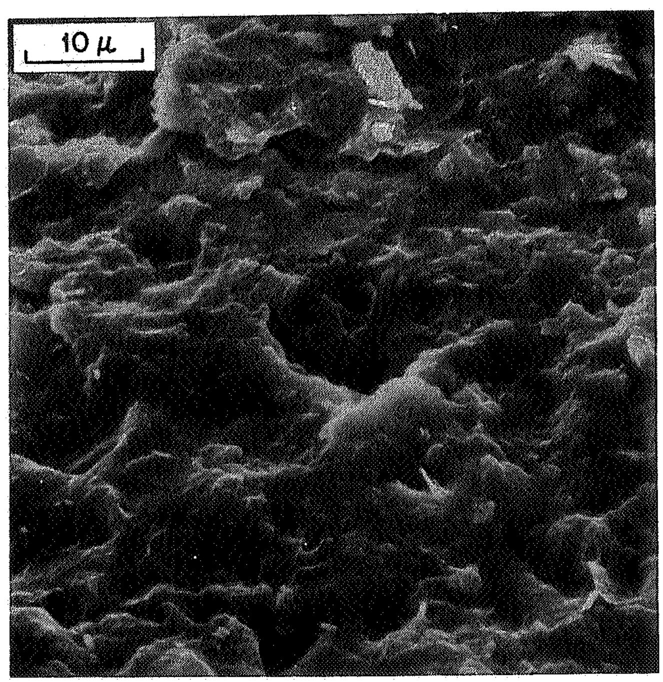

Figure 23. SEM micrograph showing flaky nature of shale and lack of pore spaces in Indiana Geological Survey drill hole 290 core, Clark County. Depth is 135 feet.

Burrows and bioturbation structures are rather rare in the black shale but are common in the greenish-gray shale (fig. 17). Those found in black shale commonly occur near the contact with overlying greenish-gray shale. Horizontal burrows are more common than vertical or oblique ones (fig. 18). The greenish-gray shales are not only commonly bioturbated but also have evidence of small-scale internal gliding or flowage.

The shales generally contain clay minerals and carbonaceous materials and fine silt-sized particles (fig. 23) that are chiefly quartz but also rarely feldspars, pyrite, dolomite, and skeletal fragments (made up largely of calcite and phosphates). Most of these particles, except skeletal grains, have particle sizes of less than 30 microns. These fine silty or coarser grains constitute no more than 40 percent of the shales. More than 80 percent of the shales can be texturally classified as silty clay-shale, and they range from carlcareous or dolomitic to noncalcareous in composition.

Particles are generally oriented more nearly parallel in black shales than in associated greenish-gray shales. The latter, due to bioturbation and possible other environmental effects, have more randomly oriented particles. Sediments inside the burrows have more silty granular particles than those in the surrounding black shale, as we observed with the scanning electron microscope. (The granular material consists of pyrite, dolomite, and organic materials singly or in combination.)

The shales of the New Albany are generally compact and low in porosity (<< 1 percent). Small pores are scarcely visible in thin sections, although a few are found in some quartzose carbonate seams or asssociated with skeletal grains. Greenish-gray shale that has burrows and randomly oriented particles has more ultra micropores between granular particles than black shales do.

Constituents of Shale

Most of the nonclay minerals are of detrital origin. Some are authigenic or diagenetic. Chert and chalcedony, alone or associated with cryptocrystalline pyrite, are observed in thin sections of black shale as micropods. These micropods are especially abundant at several thin intervals in the Clegg Creek Member where some of them obviously replace round spores. Overgrowths of quartz were occasionally observed.

Pyrite is a ubiquitous minor component in the New Albany Shale and ranges from clay-size particles to fist-size nodules. It has a variety of crystral habits, including octahedral, pyritohedral, and cubic, and a variety of aggregate forms including framboids and globules. Amounts and mineral associations vary greatly. Marcasite, known to be present by X-ray diffraction, is with pyrite, but not normally observed distinctly either in hand specimen or by microscopy.

Carbonaceous material (kerogen) in the black shale is very finely divided and is closely associated with clay minerals. It is generally seen as flaky aggregates forming discontinuous streaks, curved laminae, and patches in thin section perpendicular to bedding. In sections parallel to the bedding it looks like a nebulous cloudy network. No individual fragment with a definite outline can be recognized. Thin vitrain seams are found at some levels. Amber-yellow to brownish-yellow resinous spores are common in the black shale and much less common in the greenish-gray shales. The spores fluoresce yellow under illumination by ultraviolet light. The spore, Tasmanites, is most easily recognized on bedding planes under the binocular microscope. These spores are densely crowded on some bedding planes and give the black shale a brownish tone. Besides intact disk-shaped cells, there are numerous flattened thin-walled spores, locally abundant spherical spores, and other resinous material that enhance the fissility of the black shales.

ORGANIC GEOCHEMISTRY

W. G. Meinschein

Organic geochemical investigations of the New Albany Shale have provided information concerning: (1) the gas, water, and oil yields of shale samples from the Phegley core in Sullivan County; (2) the origins and compositions of gases in cores from Indiana Geological Survey drill holes (SDH) 273 and 274 in Marion County; (3) the composition of pyrolysis products of the pulverized shale and kerogen concentrates of the reference sample gathered from part of the Blocher Member of the New Albany Shale at the Harding Street Quarry of American Aggregates Corp. in the NE¼NE¼ sec. 33, T. 15 N., R. 3 E., Marion County; (4) the carbon isotopic ratios of the carbon dioxide and methane that were produced by the pyrolysis of the reference shale sample and its kerogen concentrates; and (5) the time of formation of natural gas and petroleum deposits.

As recorded in table 1, the oil, water, and gas yields and the organic carbon content were determined for select samples collected from the interval of 2,504 to 2,619 feet of depth in the Phegley core.

Table 1. Oil, H_2O, gas yields, and percentage of organic carbon of the Phegley core, Sullivan County

Sample	Depth (ft)	Oil (gal/tn)	H_2O (gal/tn)	Gas (ft^3/tn)	%C (organic)
8	2504.2 - 5.5	12.23	4.89	1329.0	12.72
9	2505.9 -15.3	10.65	2.66	958.0	9.13
10	2515.7 -21.2	7.99	4.0	814.0	6.97
11	2521.5 -24.2	5.45	3.63	1066.0	6.67
14	2530.7 -31.4	12.81	3.72	1559.8	13.02
16	2536.9 -45.1	8.56	3.42	1219.0	9.28
18	2547.5 -49.2	6.23	3.36	1391.6	5.86
19	2549.7 -54.3	10.55	6.23	1034.8	5.54
20	2554.8 -61.8	4.79	4.79	1055.5	4.88
23	2571.5 -78.0	4.99	4.99	1148.0	4.99
26	2579.0 -85.2	7.59	4.55	1166.0	6.70
28	2585.6 -89.3	9.12	4.39	1417.4	9.13
36	2606.3 -12.7	6.07	3.04	1119.7	4.86
37	2612.7 -18.9	5.33	5.33	1032.0	5.72

A linear relationship exists between the oil yields and the organic carbon content of the shales (fig. 24). The slope of the oil-yield plot corresponds to an oil productivity of 1 gal/ton/% organic carbon.

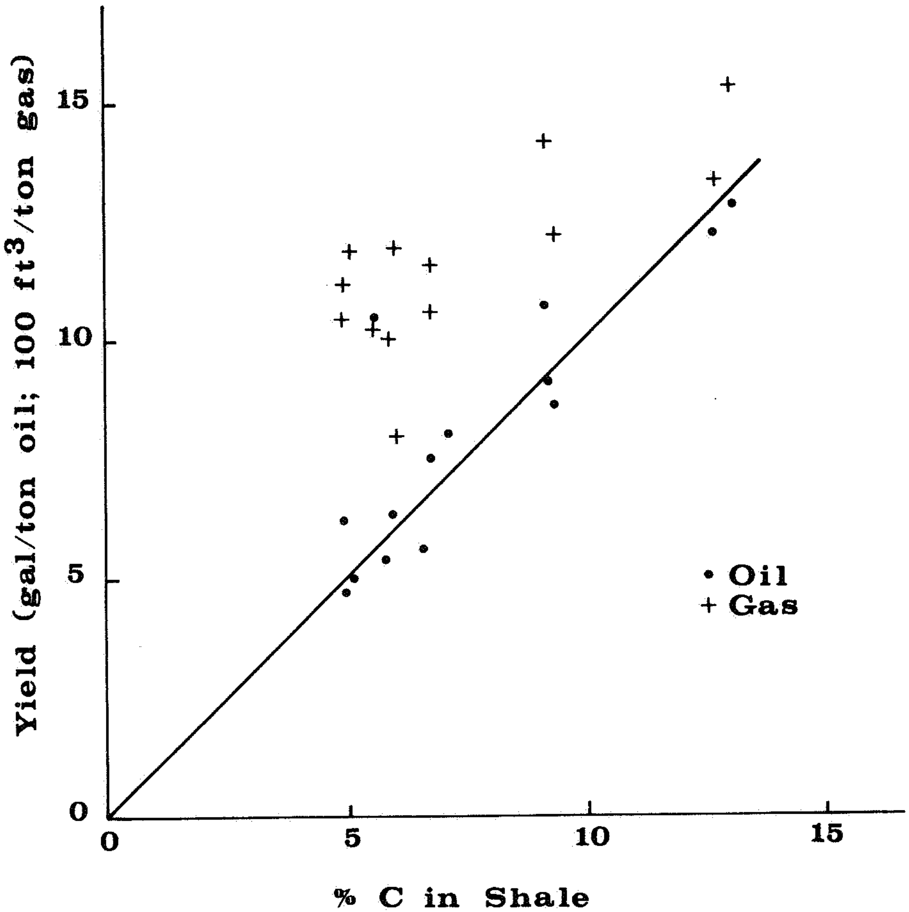

Figure 24. Plot of oil and gas yields versus organic carbon content (percentage of C) for samples of the New Albany Shale from the Phegley core, Sullivan County.

The trend for the gas yields is less clearly defined than that for the oil yields. Variations in the concentration of hydrogen sulfide in the gaseous pyrolysis products of the different shale samples are a probable cause of the poor correlation between the gas yields and organic carbon content plotted in figure 24. Because variations in the hydrogen sulfide concentration reflect variations in the sulfur content of the shale samples, the lack of a significant correlation between the gas yields and organic carbon content indicates that the sulfur content of the shale samples varies independently of their organic carbon content.

Analyses of the gases removed from the headspace of the sealed canister containing a SDH 274 core sample are reported in table 2. These samples were collected in sequence through a septum by means of a gas syringe. Between samplings the canister was evacuated to a pressure of about 1 mm Hg/cm^2, resealed, and stored for 72 hours to permit the gases released from the core to develop a positive pressure in the headspace. Similar analyses of gas samples gathered from two canisters containing SDH 273 core samples were also obtained. One of the SDH 273 core samples was analyzed by using the evacuation procedure described above for the SDH 274 core sample. The remaining SDH 273 core sample was continuously flushed with helium, and the gases flowing from the canister were monitored periodically. Equivalent results were obtained by the evacuation and flushing procedures.

Data in table 2, in conjunction with the analyses of the SDH 273 core samples, show that the concentration of methane in the headspace gases is markedly reduced by the removal of gases from the sample canisters. Particularly noteworthy is that the principal reduction in the methane concentration occurs during the initial evacuation as shown in table 2.

Table 2. Composition of gases from core sample from Indiana Geological Survey drill hole 274, Marion County

Evacuation of core canister	Methane (pct)	Ethane (pct)	Propane (pct)	*n*-Butane (pct)
Before evacuation	74	20	6	0.7
First evacuation	42	36	19	4
Standard deviation (14 samples)	42	36	19	3
Second evacuation	36	38	22	0.7
Standard deviation (2 samples)	37	38	21	0.6
Third evacuation	33	39	22	5
Standard deviation (2 samples)	33	39	23	5
Fourth evacuation	32	41	23	5
Standard deviation (3 samples)	33	41	22	4
Fifth evacuation	34	44	21	4
Standard deviation (3 samples)	30	44	22	5

Differences in the rates of diffusion of methane, ethane, propane, and *n*-butane from the core samples do not adequately explain the changes in concentration produced by evacuating and flushing the core canisters, because the changes recorded in table 2 are neither dependent on molecular weight nor systematic for all the alkanes. These data may be explained, however, if it is assumed that the gases associated with the core are composed of: (1) migrated gases with composition resembling natural gases and (2) gases formed in situ with composition controlled by the diagenesis and epigenesis of sedimentary organic materials. For reasons to be developed below, the analyses of the canister gases may also place time restrictions on the origin of natural gases and petroleum.

In accord with evidence cited by Meinschein and others (1968) crude oils are products of sequential processes that began with the isolation of natural gases by frontal analyses of ground-water solutions of the gaseous constituents of sedimentary rocks. The evidence cited includes: (1) an established interdependence between the concentrations of n-alkanes in natural gases and crude oils; (2) a direct relationship between the methane, ethane, propane, and n-butane concentrations in natural gases and the solubilities of these alkanes in water; and (3) a complete correspondence between the compositional variations in natural gases and compositional variations that could exist if these gases had been collected by a frontal analysis chromatographic process.

The concentration of methane, ethane, propane, and n-butane in gases that are transported in water should decrease logarithmically as the carbon numbers of these alkanes increase, but in plots of the logarithm of the n-alkane concentration versus carbon numbers for natural gases, the ethane and propane points fall below the line joining the methane and n-butane points (Meinschein and others, 1968). The positioning of the points in such plots indicates that the mean concentrations of ethane and propane in natural or migrated gases are 12 percent and 2 percent less than would be predicted if water solubility was the dominant factor controlling these concentrations. Meinschein and others (1968) proposed that these deficiencies in the concentration of ethane and propane are caused by "source" restrictions. Presumably these restrictions may result from the inadequate biologic production, the logarithmic decrease in water solubilities, and differences in the diagenetic production rates of ethane, propane, and n-butane.

Although anaerobes make vast quantities of methane, only trace amounts of ethane, propane, and n-butane are found in metabolic products. For this reason it is widely accepted that the ethane, propane, and n-butane in fossil fuels are formed primarily by the degradation of biologic remnants in sediments or sedimentary rocks. Such degradation is caused mainly by thermal processes that lead to the rupture of carbon to carbon bonds at high vibrational energies. Because higher mass units exert greater force than lower mass units on bonds at equivalent vibrational frequencies, n-butane is a more probable product of the thermal degradation of a common and potential organic precursor in sediments than either propane or ethane. This greater probability of formation coupled with the lower water solubility of n-butane may explain why the n-butane concentrations in natural gases are more closely tied to its water solubility than the concentrations of ethane and propane are tied to their water solubility. Probably for the same reasons the mean deficiency in the concentration of propane (-2 percent) is less than that of ethane (-12 percent), as noted above, in natural gas.

An explanation of the data in table 2 may be developed as follows: (1) the mobile gas phase, which was enriched in methane and had a composition resembling natural gas, was concentrated within the continuous pores and fractures through which this gas had moved into the cores; (2) the mobile gas phase was preferentially removed from the cores by evacuation or flushing; (3) the gases that were formed in situ were largely occluded within the shale and are difficult to remove from the cores; and (4) the gases released after repeated evacuation or extensive flushing of the core canisters have compositions resembling that of the gases formed in situ and are enriched in ethane, propane, and _n_-butane relative to the mobile gas phase.

If the proceeding explanation is valid, the high concentrations of ethane and propane relative to _n_-butane in the in situ gases indicate that the organic precursors of these alkanes contained many more C_2 and C_3 than C_4 alkyl substituents. Also, these high concentrations of ethane and propane seemingly preclude the possibility that gases compositionally equivalent to the in situ gases could have been the source of the natural gases that are apparently involved in the origin of petroleum and are concentrationally deficient in ethane and propane. Perhaps secular variations in the compositions of the alkanes formed by diagenetic and epigenetic processes may account for the compositional disparities between the C_1 and C_4 alkanes involved in the origins of natural gas and petroleum and the C_1 and C_4 alkanes formed in situ over an approximately 360 X 10^6 year time span in a Devonian shale. These compositional disparities suggest than _n_-butane may be formed preferentially during the early stages of diagenesis, but as sediments subside and lithification occurs either the precursors for _n_-butane are depleted or the degradation of _n_-butane leads to enhanced production of ethane and propane. The compositions of natural gases support the concept that the substantial quantities of hydrocarbons that were generated in situ in the New Albany Shale have been isolated from the processes forming natural gas and petroleum accumulations. Lithification may have caused this isolation, and lithification may be an essential prerequisite to the containment of gas and oil deposits. These considerations suggest that either lithification is contemporaneous with the origins of natural gas and petroleum or shales may be less important sources of the gas and oil in commercial accumulations than is widely believed.

Comparative studies of the pyrolytic products of the reference sample of the New Albany Shale and the kerogen concentrates from this sample indicate that kerogen is the major source of the carbon compounds in these products. For example, CO_2 is the only gas formed in significant quantities at 250°C. The yields of CO_2 from the shale and kerogen were 0.44 ml/g and 1.45 ml/g. The ratio of these yields corresponds closely to the weight ratio of kerogen to total shale. Likewise, the yields of CO_2 at 400°C (1.17 g/ml and 3.91 ml/g) have about the same ratio as at 250°C, and the yield of methane (CH_4) from the shale (5.2 ml/g) is 0.29 times the yield from the kerogen (18.0 ml/g), which is also comparable to the concentration of the kerogen in the shale. The carbon isotopic data for CO_2 and CH_4 obtained in these studies are shown in table 3.

Table 3. Carbon isotopic composition of carbon dioxide and methane from pyrolysis of the reference sample of the New Albany Shale and its kerogen concentrate reported as $\delta^{13}C_{PDB}$ in per mil

Temperature	Sample	CO_2	CH_4
250°C	Kerogen	-26.6	-
	Shale	-22.7	-
400°C	Kerogen	-23.9	-41.8
	Shale	-17.5	-43.3

The relatively small differences in the $\delta^{13}C$ values of the specific gases from the kerogen and shale samples in table 3 indicate, as do the yields of CO_2 and CH_4, that the kerogen fraction is the primary source of these gases. Because carbonates usually have $\delta^{13}C$ values near 0 per mil and are therefore enriched in ^{13}C relative to organic carbon, the higher $\delta^{13}C$ values of the shale CO_2 suggest that inorganic carbonates may have been a source of a minor part of CO_2 released from the shale samples. A reverse relationship exists between CH_4 and CO_2 data in table 3. CH_4 from the shale is depleted in ^{13}C relative to CH_4 in the kerogen. This depletion may indicate differences in the degree of use of the organic sources of methane in the shale and kerogen samples as may be deduced from the data in table 4.

Table 4 lists the mole percentage of the C_1 through C_8 _n_-alkanes and the ratios of nonstraight chain alkanes (NS) to total hydrocarbons (Total Hc's) in the 350°C pyrolysis products of the reference shale and kerogen concentrate that were heated for various intervals of time. Methane is concentrated in the kerogen products relative to the shale products. Conversely, propane and _n_-butane are more abundant in the shale fractions. Also, the ratio of the NS/Total Hc's is larger for the shale samples than for the kerogen samples. These compositional differences indicate that the organic materials in the kerogen concentrates have been more extensively degraded than the organics in the shale. Metal halides formed by the chemical treatments used to prepare the kerogen concentrate may have catalyzed its degradation, or possibly the mineral facies may have served as insulators to reduce the rate of methane production in the shale samples. Either of these explanations may be supported by the observation that the resemblance between the shale and kerogen pyrolyzates increases as the pyrolysis time increases. As shown in table 4, these pyrolyzates are similar in the samples that were heated for 50 hours and 100 hours.

Table 4. Light hydrocarbon products from pyrolysis of shale and kerogen at 350°C

Hydrocarbon composition in mole percentage
Pyrolysis time in hours

Product	8		20		50		100	
	K[1]	S[2]	K	S	K	S	K	S
Methane	60.7	41.3	55.8	44.4	47.1	41.7	45.3	40.0
Ethane	10.4	14.5	13.1	12.4	18.6	17.7	19.4	17.4
Propane	12.3	17.4	12.6	17.8	13.2	14.6	13.2	14.6
n-Butane	5.2	8.8	5.5	9.1	6.1	7.8	6.3	7.9
n-Pentane	2.1	3.1	2.5	3.9	3.8	5.4	4.3	5.1
n-Hexane	4.3	2.2	5.2	2.6	3.5	3.5	3.6	3.7
n-Heptane	3.0	5.1	3.7	5.6	4.0	5.2	4.2	5.2
n-Octane	1.9	3.3	1.7	4.2	3.6	4.1	3.7	6.0
$\frac{NS}{Total\ Hc's}$ X 100%	26.1	44.4	28.6	42.8	20.1	27.4	19.0	26.2

1 Kerogen
2 Shale

Regardless of why more methane was produced by pyrolysis of the kerogen than of the shale, this enhanced production would lead to an enrichment of ^{13}C in the methane produced from the kerogen relative to the methane formed from the shale for the following reasons: (1) methane produced by the partial degradation of an organic precursor is enriched in ^{12}C relative to the precursor; (2) as the degradation of a precursor to yield methane proceeds toward completion, the isotopic difference between the precursor and methane decreases; and (3) the methane formed from the kerogen should be enriched in ^{13}C relative to the methane made from the shale, as the data in tables 3 and 4 confirm, because the degradation of the kerogen in the concentrate is greater than in the shale.

Oil yields of the New Albany Shale are directly proportional to the organic carbon content of the shale samples. At 500°C under a helium atmosphere, these oil yields are about 1 gal/ton/% organic carbon.

The gas yields of the New Albany Shale do not correlate significantly with the organic content of the shale. Variations in the gas-to-oil ratios range from 90 to 230 cu ft/gal. These variations are apparently due to differences in the H_2S content of the gases, which may correlate with the sulfur content rather than with the organic carbon content of the shale.

Compositional disparities between the gases that were initially released or evacuated from the SDH 273 and 274 cores and the gases obtained from these cores after repeated evacuation or prolonged flushing indicate two essentially isolated sources of the core gases. The gases that are most readily removed by the initial evacuation are probably composed of gases that have been transported into the cores by ground water. These "transported" gases have a composition resembling that of natural gas. The strongly retained gases, removed after repeated evacuations are presumed to have formed in situ within the core. These strongly retained gases contain higher concentrations of ethane and propane than do the gases that were the sources of gases found in commercial gas and oil deposits. Therefore, these in situ gases must have been isolated from the processes forming natural gas and petroleum. Because lithification may have been the most likely cause of this isolation and a prerequisite for the containment of oil and gas deposits, the compositions of the "migrated" and "in situ" gases suggest that the origins of gas and oil may have been contemporaneous with lithification in some of the sedimentary strata in productive basins.

INORGANIC GEOCHEMISTRY

R. K. Leininger

As a stratigraphic unit, the New Albany Shale is remarkably predictable in chemical composition. The carbonaceous facies is exemplified by the reference sample SDO-1 from the Huron Member of the Ohio Shale (table 5). The formation has a matrix of fine mostly silt-size quartz with added illite and mixed-layer clay and lesser amounts of chlorite, kaolinite, and fine-grained feldspars. Except for the illite, mixed-layer clay, and chlorite, the compositions of the major minerals are rather well defined; the feldspars are generally low in sodium/calcium components. Further investigation would be necessary to ascertain the quantities and variations of the feldspars. The aluminum, potassium, and magnesium contents indicate that illite and chlorite compositions are rather consistent. Iron overall must be considered to be heterogenous because of the highly variable content of iron sulfides; both pyrite and marcasite are common, and other iron-containing minerals are likely in small amounts. Siderite is found in concretions, and ferroan dolomite is probably present. Magnesium is in excess of the requirement for carbonate and must be in the illite, chlorite, or other clay minerals. Calcium is generally low except in carbonate-rich laminae that vary from microscopic laminae and shells to substantial beds, but the thicker carbonates are commonly admixed with shale matrix and sulfides. A few quartzose sandy carbonates have been observed. Calcareous or dolomitic admixtures to the quartz/clay matrix are areally and stratigraphically significant and are amenable to mapping if sufficient data are available. Titanium follows alumina probably more faithfully than silica because of the free quartz. Manganese varies with iron but not always consistently. Phosphorus is generally low and consistent but appears as a major component in nodular beds or bone beds. Siderite nodules, however, may be mistaken for apatite nodules.

To the grossly consistent and stratigraphically and areally predictable inorganic matrix are added variable quantities, stratigraphically and areally, of organic components that are from nearly zero to nearly 25 weight percent of the rock. The specific gravity of the organic matter is near 1 and that of nonpyritic shale is near 2.5. Therefore, the volume of 25 percent organic matter by weight is nearly 40 percent of the rock. This relationship is especially evident in the thin graded intervals so high in spores that nearly half of the surface fluoresces under ultraviolet illumination. Along with the organic matter is both fine- and coarse-grained sulfide, mostly pyrite.

Trace-element content of the shale is generally predictable for those elements associated with clays, feldspars, carbonates, and phosphates and for accessory minerals, such as barite, tourmaline, and zircon. We have learned that the top carbonaceous unit of the formation, generally from 1 to 3 feet thick, is enriched in several trace elements, particularly zinc and cadmium (seen to be at least partly in fine-grained sphalerite), molybdenum, vanadium, and, to lesser degree, such others as lead, nickel, and copper. To what extent

Table 5. Chemical composition of a split of the reference sample SDO-1 from the Huron Member of the Ohio Shale, 1,200 ft FNL, 550 ft FEL, sec. 25-U-72, Rowan County, Ky., supplied by the U.S. Geological Survey.
(Sample is from the bottom 5 feet of unit 5 in the description of the type section of the Three Lick Bed by Provo and others, 1978)

Element	As-prepared (pct)	Standard deviation	Method*
SiO_2	49.9	.2	ICP
TiO_2	.69	.02	ICP
Al_2O_3	12.1	.08	ICP
FeO**	9.70	.03	ICP/AAS
MnO	.041	.001	ICP
MgO	1.47	.01	ICP
CaO	1.09	.01	ICP
Na_2O	.42	.009	ICP
K_2O	3.39	.01	ICP/AAS
P_2O_5	.11	.006	ICP
CO_2	1.38	.006	Grav.
H_2O^+	4.5	.15	Grav.
H_2O^-	.69	.03	Grav.
S	5.61	.09	Titr.
C	10.4	-	Grav.
H	1.35	.02	Grav.
N	.32	-	Titr.
$C-C_{CO_2}$	10.0	-	-
$H-H_{H_2O^{\pm}}$	.77	-	-
Subtotal	102.18		
(minus S=O)	2.81		
Total	99.37		

* ICP = Inductively coupled (argon) plasma-optical emission spectrometry; AAS = Atomic absorption spectroscopy; Grav. = Gravimetric analysis; Titr. = Titrimetric analysis.

** Total Fe calculated as FeO.

these elements (and iron and manganese) are bound in the organic matter is unknown. Separated kerogen, although still pyritic, contains high nickel and vanadium, which indicates porphyrins. No doubt other metal-organic associations exist. At the base of or included in the enriched trace element unit is usually a phosphate-nodular bed or a bone bed. This layer is high in uranium (as much as 100 ppm) and yttrium and, presumably, rare earths (tables 6 and 7). The thickness and extent of the enriched unit should be investigated.

The Clegg Creek Member is nearly 40 feet thick and contains an average of more than 10 percent organic carbon in Clark and Jackson Counties (figs. 25 and 26). Northward in Marion County and westward in Sullivan County the upper part of the formation contains less organic carbon (figs. 27 and 28). Generally in southeastern Indiana the highest organic carbon content of the shale is near the top of the formation (figs. 25 and 26). Just below, the organic carbon decreases somewhat, followed beneath by a second maximum. Then follow units with predominantly moderate to low organic carbon contents and, finally, in the Blocher Member the organic carbon content increases, but does not reach the maxima of either of the other high intervals.

In some areas the enriched trace-element unit is separated from the underlying high-carbon beds by greenish-gray low-carbon shale (Ellsworth Member) that increases in thickness toward the northwest. Westward we have little control, but generally the organic matter is lower in percentage in the thicker shale basinward. Along the outcrop the carbonaceous Blocher Member is also calcareous, so that although total carbon content is similar to that of the upper black units, the organic carbon is less.

Our speculations concerning the environment of deposition of the New Albany Shale are inconclusive. The major unanswered questions involve explanation for the enormous areal extent of similar matrix, which is remarkably coarse grained for the area. Transgression must be involved. Evolution of landforms due to contemporaneous evolution of land plants must also be included in reconstructing the processes that led to development of such an enormous deposit of fine-grained material so highly variable in organic matter and trace-element content, even though most of the organic matter is probably of marine origin.

As to the stated purpose of the overall investigation, we have not satisfied ourselves with the explanations and findings of others concerning gas reserves and potentialities. We found similar gas content volume for volume from the relatively deep (2,500 feet) Sullivan County core and shallow (155 to 220 feet) Marion County cores. Reflectance values measured by others indicate little potential for gas for these areas. No attempt has been made to produce gas in either area, but off-gas measurements show that gas is present in the shale. The relatively favorable area in the deepest part of the Illinois Basin in Indiana, in the southwest corner of the state, appears to be the most likely area for gas development because of maturity of the shale and fractures due to faulting.

Table 6. Chemical composition of samples from the Rockford Limestone and the top of the New Albany Shale from Grant 286 and sec. 21, T. 2 N., R. 7 E., Clark County (Modified from Lechler and others, 1979)

Rock Unit	Al_2O_3 (pct)	FeO (pct)	MgO (pct)	CaO (pct)	Na_2O (pct)	K_2O (pct)	TiO_2 (pct)	P_2O_5 (pct)	C (pct)	H (pct)	N (pct)
Rockford Limestone	3.22	4.88	.66	37.1	.16	.76	.14	.05			
Clegg Creek Member											
Jacobs Chapel Bed	11.2	3.88	1.05	18.4	.22	2.66	.54	.07	4.02	.35	.11
Henryville Bed	10.9	4.64	1.00	1.10	.31	3.08	.65	.17	19.5	1.88	.56
Underwood Bed	14.5	4.38	1.16	1.17	.50	3.71	.98	.45	.65	.35	.12
Falling Run Bed	1.28	1.17	.12	47.0	.49	.32	.062	21.3	.86	.12	.09
Black shale below Falling Run Bed	13.1	4.14	1.02	.96	.38	3.66	.83	.30	15.2	1.58	.37

Rock Unit	Ag (ppm)	Cd (ppm)	Cr (ppm)	Cu (ppm)	Mo (ppm)	Mn (ppm)	Ni (ppm)	Pb (ppm)	V (ppm)	Y (ppm)	Zn (ppm)
Rockford Limestone	1.6	19	30	22	3	2,800	40	17	42	54	2,990
Clegg Creek Member											
Jacobs Chapel Bed	.7	9	102	27	<1	930	105	66	237	61	788
Henryville Bed	6.6	73	202	246	495	110	772	316	5,240	60	2,960
Underwood Bed	1.4	10	128	39	50	140	53	59	643	109	1,140
Falling Run Bed	3.4	13	20	36	23	85	21	49	128	1,290	954
Black shale below Falling Run Bed	2.2	41	124	207	92	77	336	95	1,170	110	1,550

Table 7. Chemical composition of samples from the Ellsworth Member and Clegg Creek Member from the Indiana Geological Survey drill hole 273 core, Marion County (Modified from Lechler and others, 1979)

Rock Unit	Al_2O_3 (pct)	FeO (pct)	MgO (pct)	CaO (pct)	Na_2O (pct)	K_2O (pct)	TiO_2 (pct)	P_2O_5 (pct)	C (pct)	H (pct)	N (pct)
Ellsworth											
Jacobs Chapel Bed	14.0	3.95	2.75	3.94	.74	3.57	.71	.12	1.40	.37	.06
Henryville Bed	10.5	5.00	1.32	.30	.59	2.85	.62	.17	15.5	1.81	.49
Greenish-gray shale	12.5	4.12	3.52	4.61	.67	3.48	.74	.12	2.52	.39	.17
Phosphatic mudstone	10.8	3.55	2.63	4.07	.64	3.26	.78	.39	1.44	.30	.14
Clegg Creek Member (top)	13.5	6.95	1.78	.16	.60	2.96	.67	.07	9.57	1.36	.32

Rock Unit	Ag (ppm)	Cd (ppm)	Cr (ppm)	Cu (ppm)	Mo (ppm)	Mn (ppm)	Ni (ppm)	Pb (ppm)	V (ppm)	Y (ppm)	Zn (ppm)
Ellsworth Member											
Jacobs Chapel Bed	14	3	103	32	<1	760	118	51	403	54	54
Henryville Bed	14	33	126	148	494	150	327	309	2,000	49	2,980
Greenish-gray shale	9	1	82	34	1	1,400	39	25	155	46	72
Phosphatic mudstone	9	2	58	21	<1	1,200	29	22	93	123	39
Clegg Creek Member (top)	9	1	82	70	136	190	80	25	163	35	63

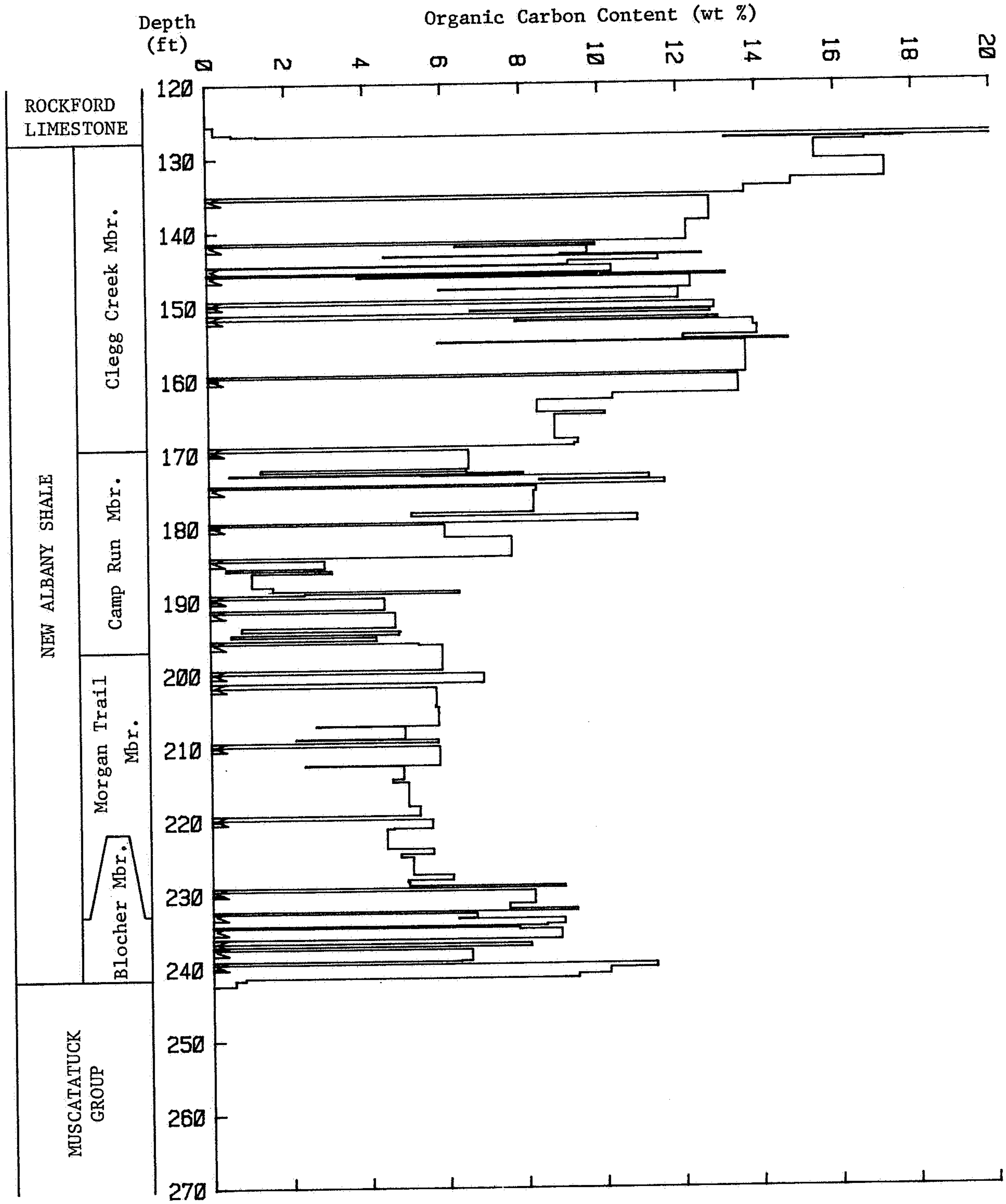

Figure 25. Graph showing percentage of organic carbon by weight in the New Albany Shale in the Indiana Geological Survey drill hole 290 core, Clark County. M indicates that a core sample has been removed.

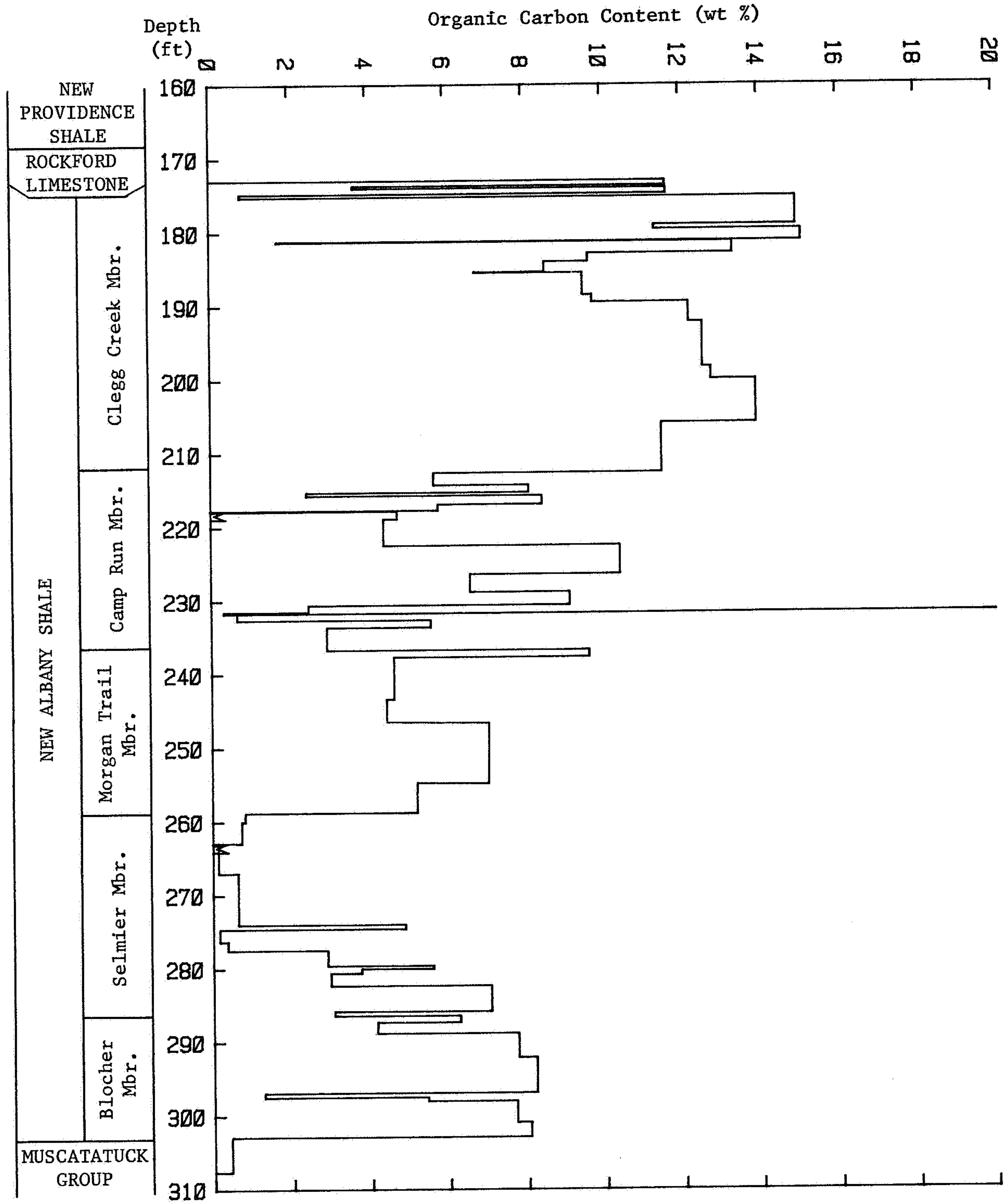

Figure 26. Graph showing percentage of organic carbon by weight in the New Albany Shale in the Indiana Geological Survey drill hole 291 core, Jackson County. M indicates that a core sample has been removed.

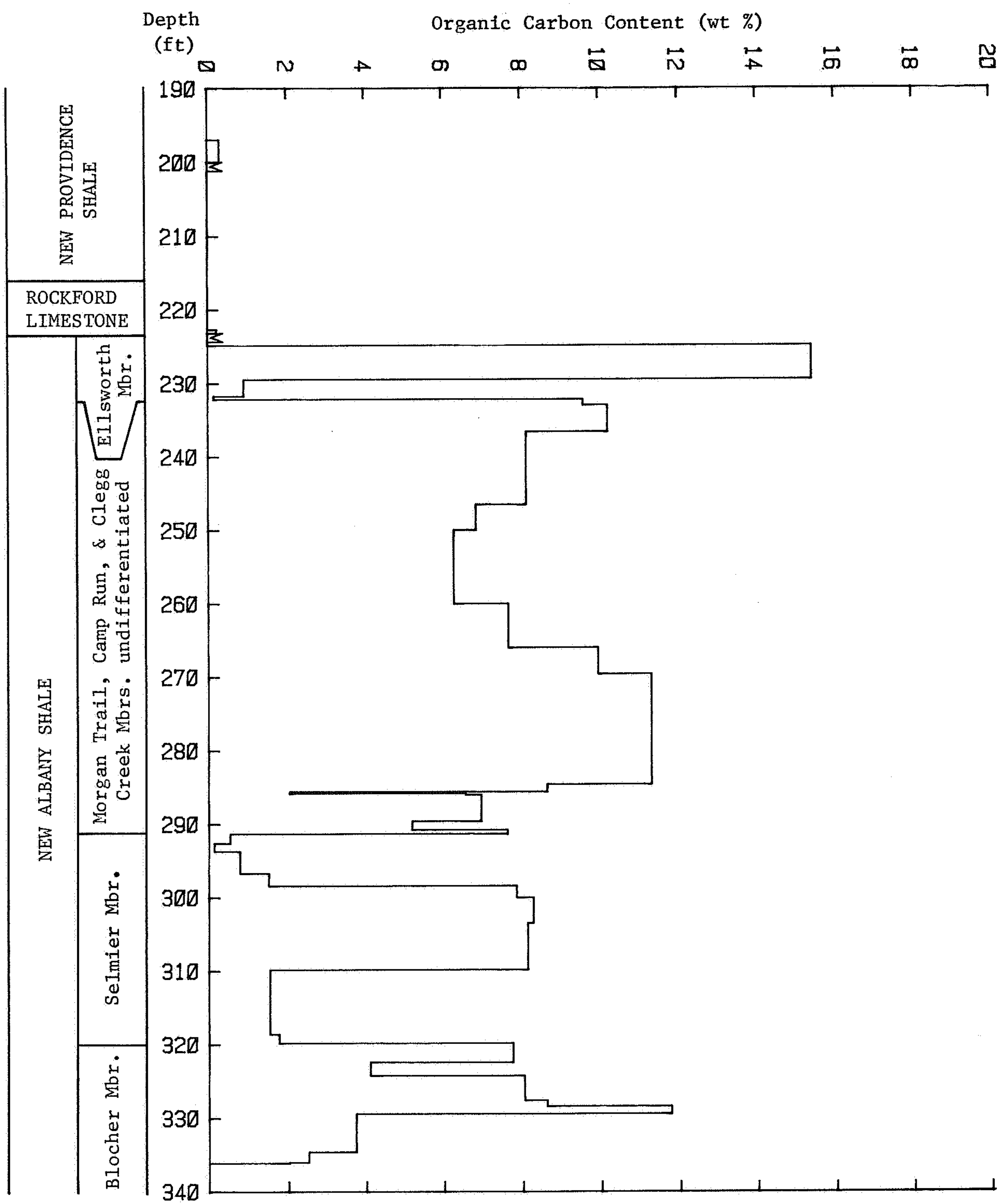

Figure 27. Graph showing percentage of organic carbon by weight in the New Albany Shale in the Indiana Geological Survey drill hole 273 core, Marion County. M indicates that a core sample has been removed.

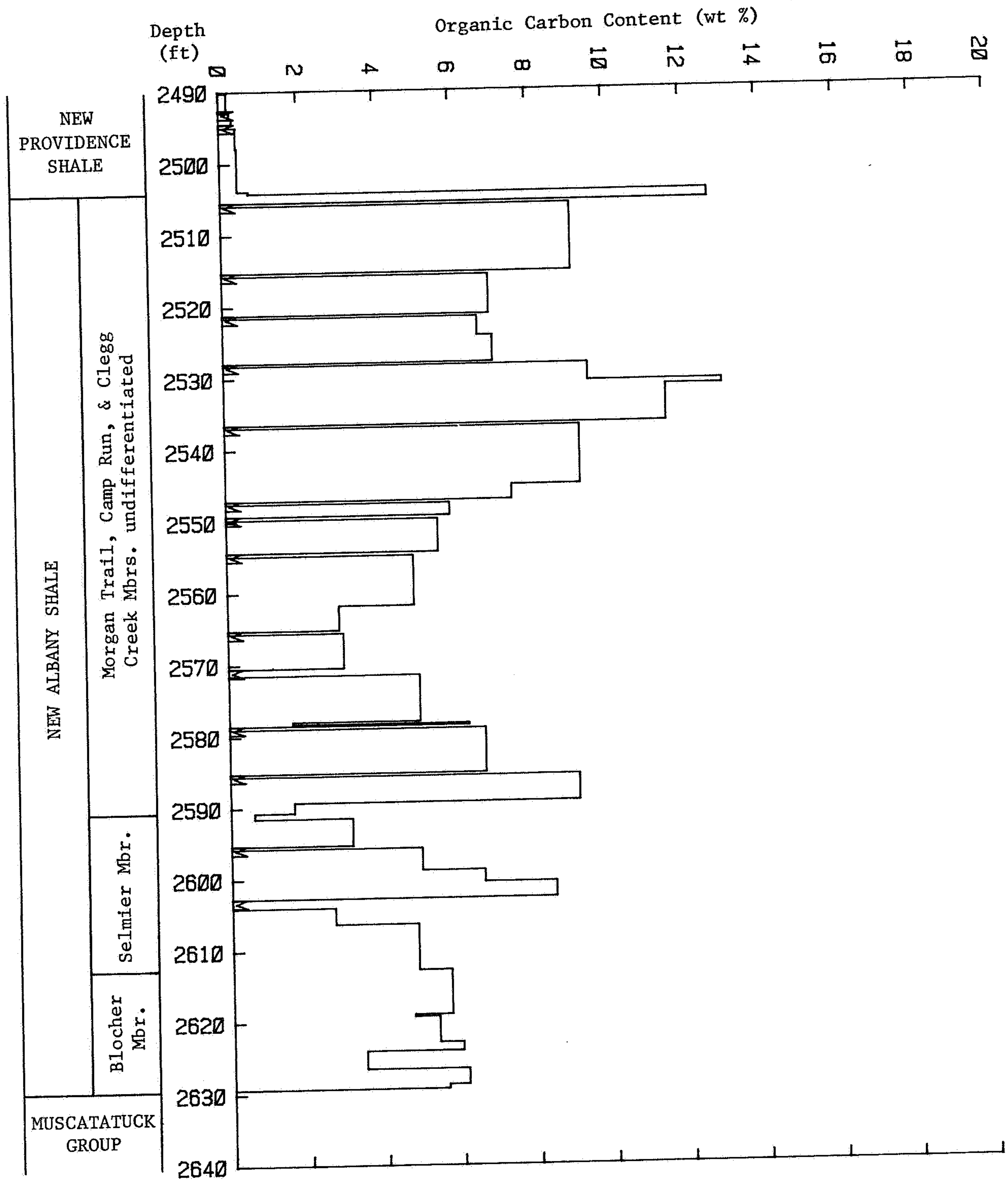

Figure 28. Graph showing percentage of organic carbon by weight in the New Albany Shale in the Phegley core, Sullivan County. M indicates that a core sample has been removed.

LINEAMENT ANALYSIS

Donald D. Carr

Introduction

Surface linear features in Indiana observed on ERTS and LANDSAT imagery and on aerial photographs were mapped, their end points were digitized, and resulting numbers, lengths, and orientations studied to determine if any relationship exists between these features and gas production from the New Albany Shale. The results of this investigation, which are detailed below, were published in a series of three lineament maps at a scale of 1:500,000 (Wier and others, 1978a, 1978b, and 1978c) that contain a supplemental description on procedures and interpretation (Powell, 1978); in articles for the general public (Carr and others, 1977; Patton and others, 1978a, b); and in technical papers (Patton, 1977; Bassett and others, 1978; and Powell and others, 1978).

Lineaments are linear features that can be observed on the earth's surface, either visually from the air or by aerial photography or imagery, and that represent an alignment of topographic features, vegetal characteristics, soil tonal differences, or some combination of each. Although their origin is obscure, lineaments presumable reflect subsurface phenomena. In this study only lineaments greater than one-quarter mile in length were mapped, because these are thought to hold greater significance as indicators of regional structure.

Besides mapping the lineaments in southwestern Indiana, another purpose of the project was answering the following questions:

(1) What relationship do lineaments in Indiana have to each other and where do they occur? (2) Do lineaments have any relationship to structural features, such as faults, fractures, and joints? (3) Is there any relationship between lineaments and production of gas from the New Albany Shale in Indiana?

Results

Regional Aspects

Information from more than 12,000 datum points in southwestern Indiana indicates that lineaments show a remarkable consistency of orientation within the area mapped. The orientation is bimodal; principal modes are oriented 90° apart at 45°-225° and 135°-315° (fig. 29). Glacial cover apparently has no appreciable effect on the orientation of lineaments, since the orientation of lineaments in the area of the Danville 1°x 2° Quadrangle, an area mainly covered by glacial deposits, is similar to that in the area of the Vincennes 1°x 2° Quadrangle, an area with little glacial cover. The lengths of lineaments show a log-normal distribution (fig. 30).

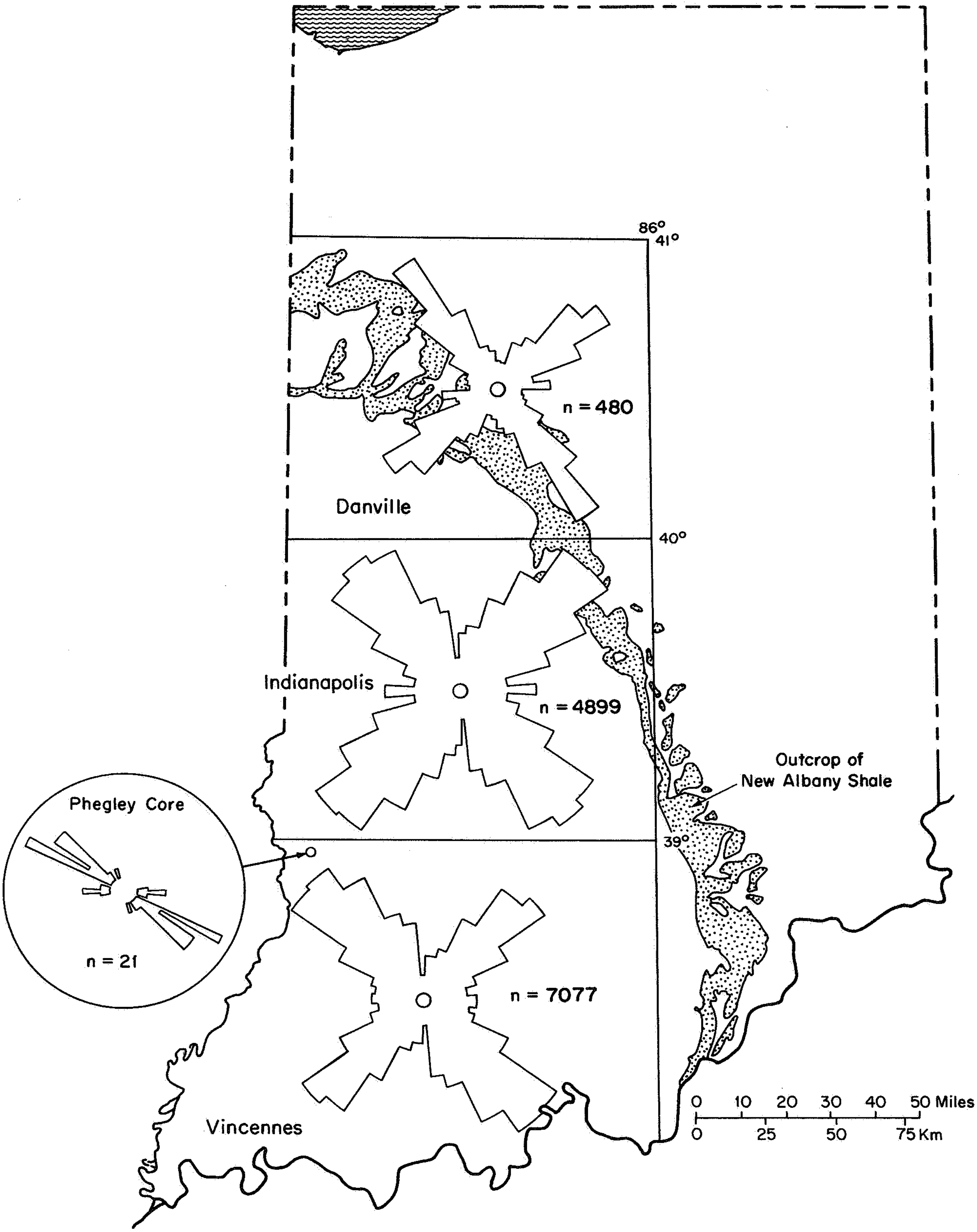

Figure 29. Rose diagrams showing the orientation of lineaments that have been mapped on the Danville, Indianapolis, and Vincennes 1° x 2° Quadrangles and the orientation of fractures in the New Albany Shale recovered in the Energy Resources of Indiana, Inc., Phegley Farms No. 1 core in Sullivan County.

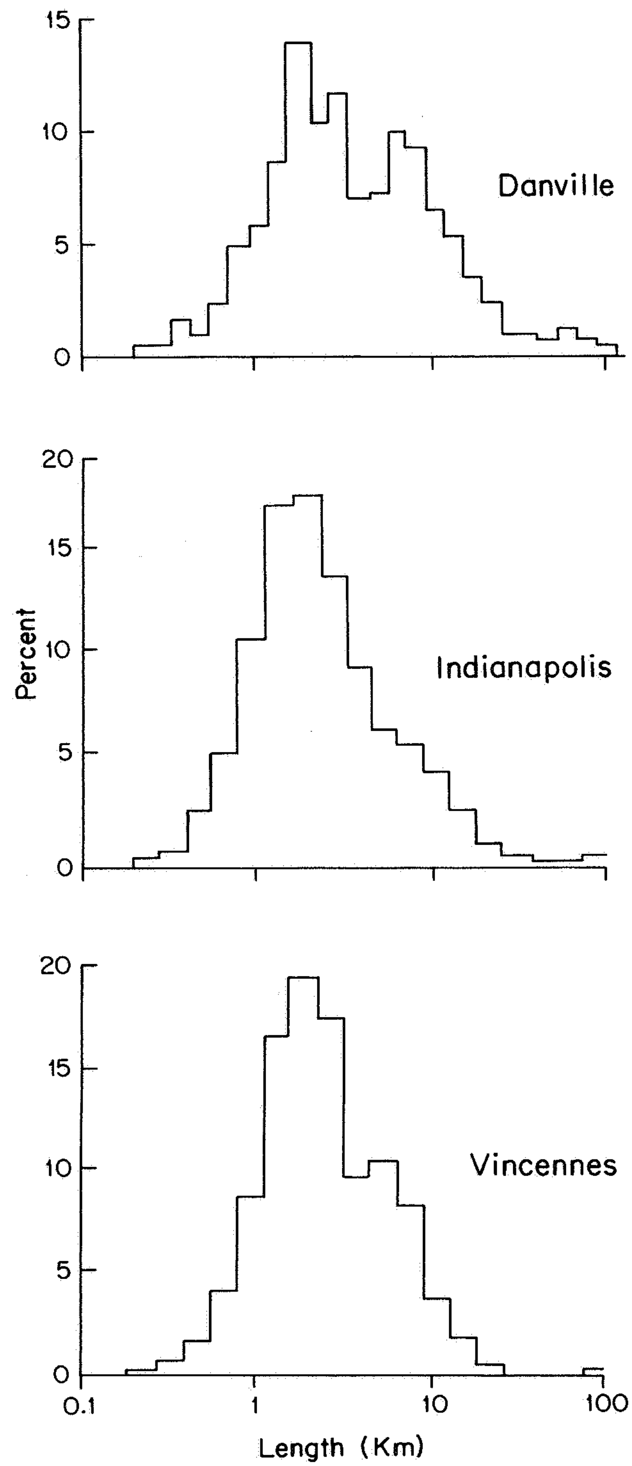

Figure 30. Histograms showing logarithm of lineament length versus percentage of occurrence for the area of the Danville, Indianapolis, and Vincennes $1^{\circ} \times 2^{\circ}$ Quadrangles.

Relationship to Structure

No hint of the smiliarity of the orientation of lineaments to faults or joints could be found, but the orientation of fractures in one oriented core drilled in Sullivan County is similar to the regional lineament orientation (fig. 29). Joints mapped near the outcrop of the New Albany Shale have a pronounced east-west and north-south orientation (fig. 31), about 45° to the orientation of lineaments. The orientation of lineaments can be explained as resulting from weathering and erosion along closely fractured bedrock zones characterized by joints oriented east-west and north-south (fig. 32).

Few faults have been mapped at the surface in southwestern Indiana, but the orientation of the most prominent one, the Mt. Carmel Fault, has little relationship to the orientation of mapped lineaments. The number of lineaments does not appear to increase near the fault.

Relationship to Gas Production

Three gas fields in Harrison County that produced from the New Albany Shale were examined to determine if any relationship exists between the alignment of lineaments and gas production (fig. 33). Although few lineaments could be mapped near the Corydon and New Middletown Fields, the orientation there and at the Laconia Field is similar to the orientation for all lineaments in Harrison County (fig. 34) and in southwestern Indiana (fig. 29). Structural maps prepared for these three fields show structural highs that probably resulted from minor folding. Lineaments show neither a marked increase in number nor variance in orientation in vicinity to these minor structural features.

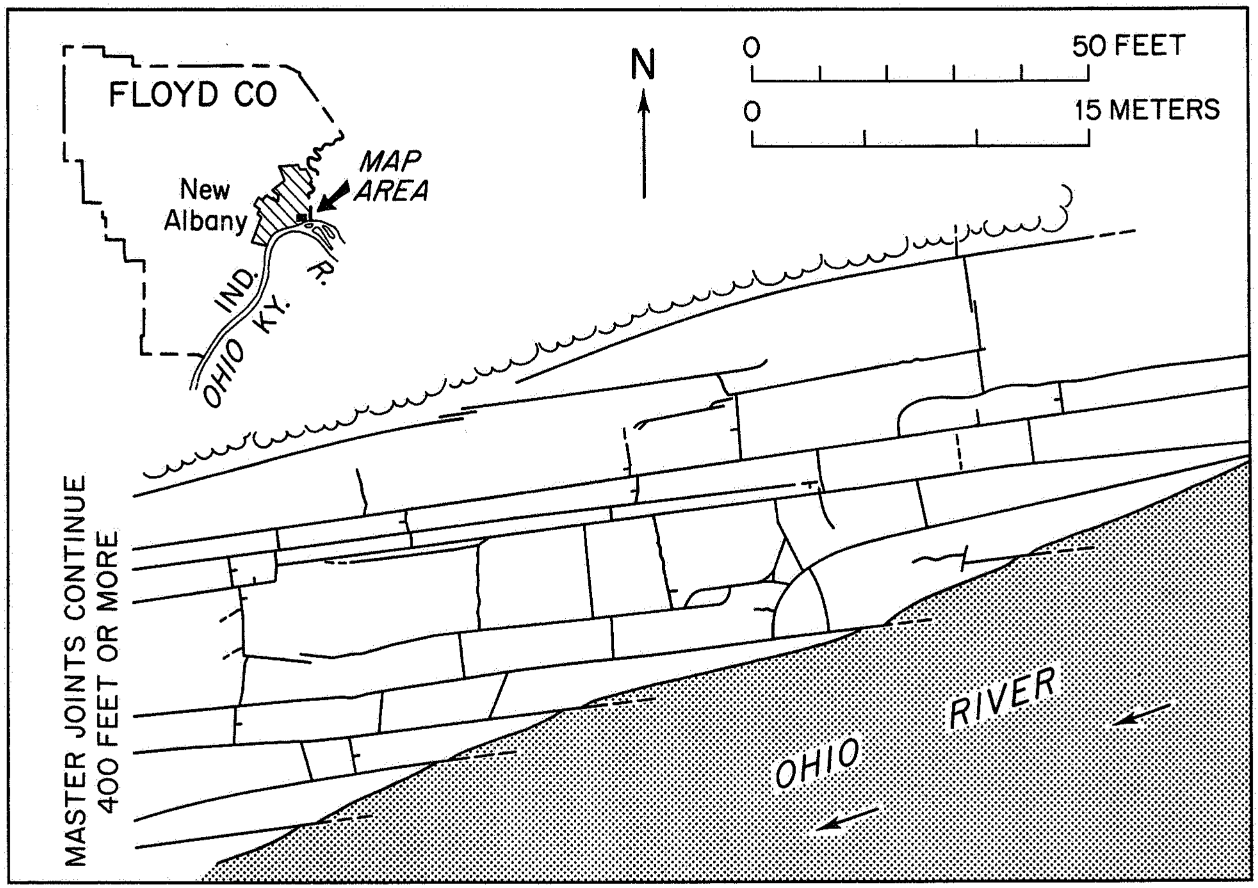

Figure 31. Map showing jointing in the New Albany Shale in an exposure along the Ohio River near New Albany. Joint orientation at other outcrops of the New Albany in Indiana is similar to the orientation at this exposure. From Powell, 1978.

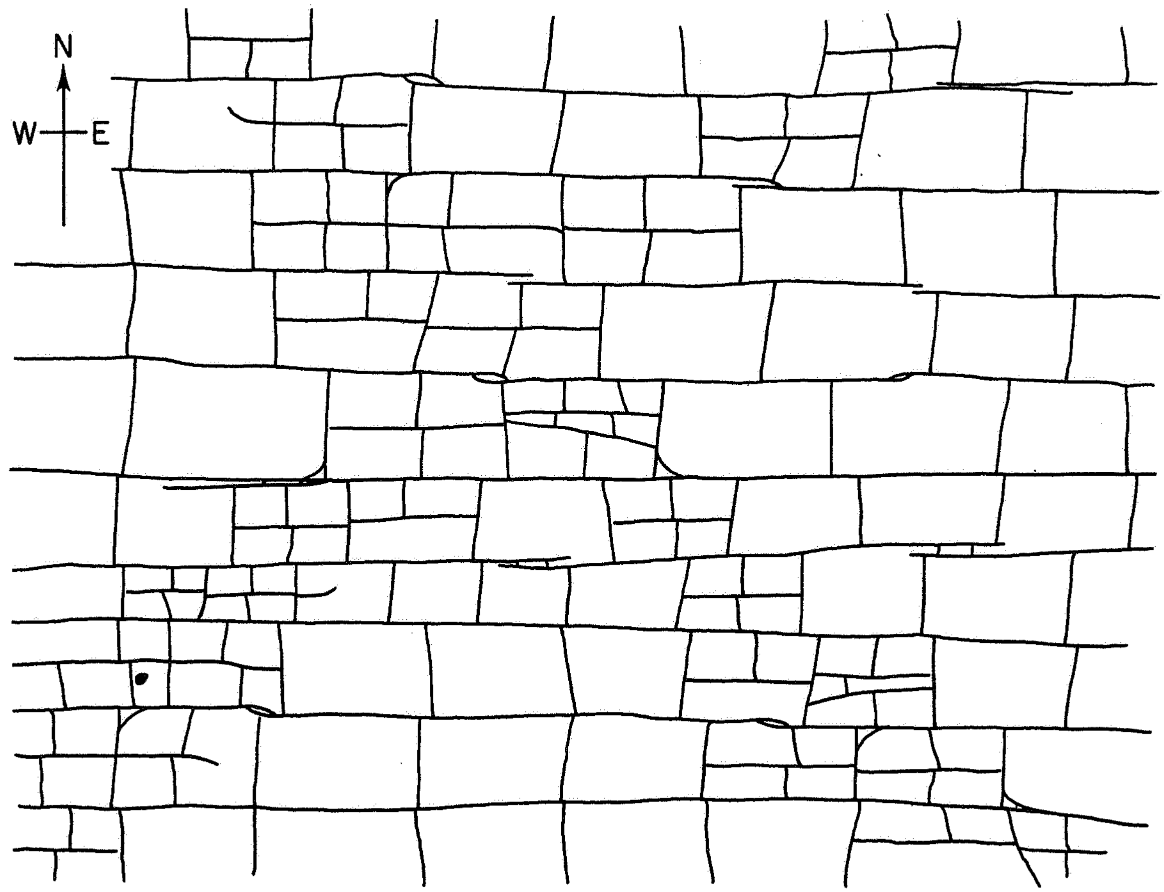

Figure 32. An idealized drawing showing a possible explanation for the origin of lineaments. Zones of greater joint frequency within a set of master joints oriented east-west and cross joints oriented north-south could result in valley development with preferred orientations of northwest-southeast and northeast-southwest. From Powell, 1978.

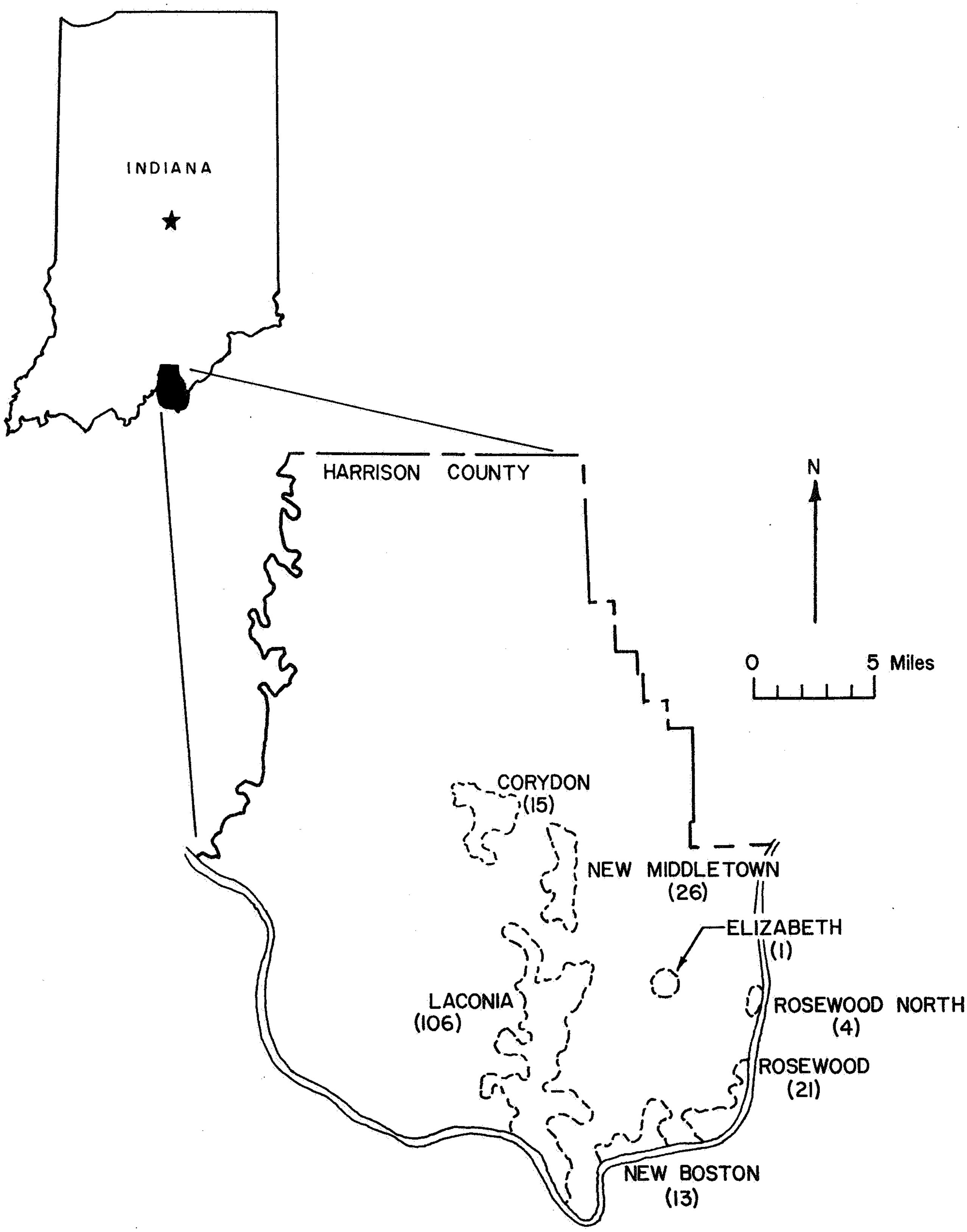

Figure 33. Map showing locations of gas fields producing from the New Albany Shale in Harrison County. Number of wells are shown in parentheses. Lineaments were studied in the area of the Corydon, New Middletown, and Laconia Fields. From Bassett and others, 1978.

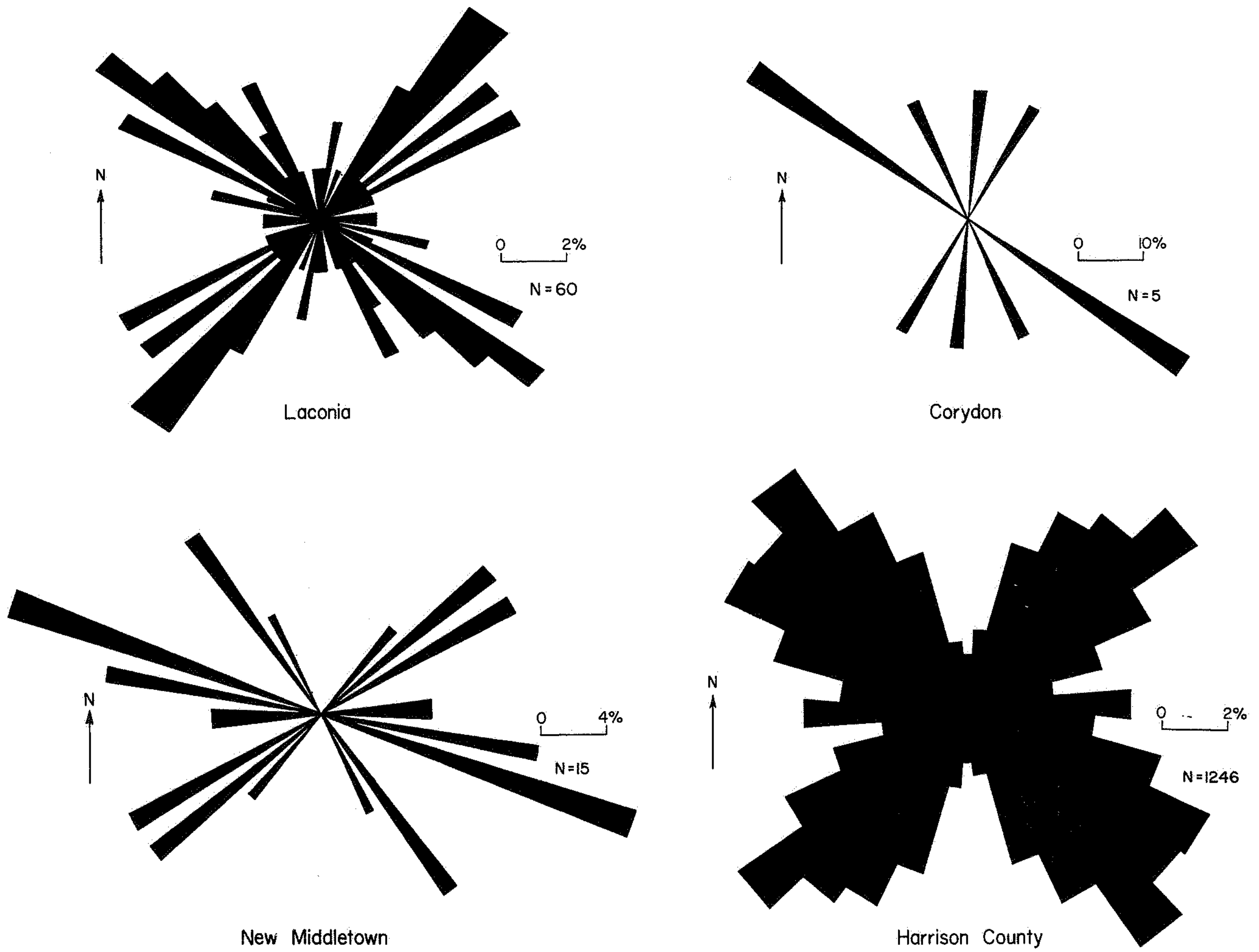

Figure 34. Rose histograms showing orientation by percentage of lineament angles associated with the Corydon, New Middletown, and Laconia Fields and combined results for Harrison County.

PHYSICAL TESTS

R. F. Blakely

Introduction

All physical tests were designed to determine planes of incipient fracture. They were made according to the procedures outlined by Lewis and Tandanand (1974).

The tests were: (1) directional seismic velocity, (2) directional tensile strength, and (3) point loading (to determine fracture direction). All tests required oriented cores. Before testing, the segments of cores were marked according to footage, upper and lower face, and the direction of north.

Two oriented cores were tested. One was from SDH 290 (EGSP IN-2) in Grant 283, T. 2 N., R. 7 E., Clark County, Ind., hereafter referred to as SDH 290, and the other was from the Phegley Farms, Inc. No. 1 well (EGSP IN-1), NW¼NW¼NE¼ sec. 14, T. 6 N., R. 10 W., Sullivan County, hereafter referred to as Phegley.

Velocity Measurements

Method

(1) All velocity measurements were made on the velocity bench at the U.S. Bureau of Mines Twin Cities Mining Research Center in Minneapolis with the cooperation of Mr. Richard E. Thill.

(2) Velocities were measured in six directions with respect to north at 30° intervals. Axial velocity was also measured. Shear velocities were measured on the Phegley core but were not determined for the SDH 290 core.

(3) Sharply peaked sonic pulses were sent through the samples. From the times and distance of transit the velocities were computed. Results are in km/sec.

Results

(1) Phegley compressional-velocity results from 18 samples are shown in table 8. The low axial velocity appears to be due to horizontal shale partings.

Table 8. Compressional velocities (km/sec) for the Phegley core, Sullivan County

Depth (ft)	N 60 W	N 30 W	N	N 30 E	N 60 E	E	Axial
2,492	4.81	4.81	4.83	4.80	4.83	4.84	1.92
2,496	4.67	4.62	4.64	4.64	4.70	4.67	1.78
2,510	4.28	4.30	4.21	4.24	4.27	4.27	2.83
2,520	4.67	4.66	4.68	4.68	4.64	4.69	3.30
2,531	4.19	4.19	4.16	4.18	4.20	4.19	2.93
2,540	4.35	4.39	4.38	4.36	4.39	4.36	3.32
2,550	4.67	4.61	4.66	4.69	4.65	4.64	1.70
2,560	4.97	4.95	4.93	4.91	4.94	4.97	1.73
2,563	4.85	4.93	4.81	4.83	4.82	4.75	2.31
2,570	5.09	5.15	5.07	5.05	5.06	5.06	2.28
2,580	4.56	4.52	4.50	4.50	4.48	4.56	1.79
2,588	4.49	4.47	4.40	4.43	4.39	4.49	2.76
2,590	4.86	4.80	4.76	4.76	4.77	4.82	3.43
2,591	6.19	6.19	6.27	6.19	6.15	6.19	6.10
2,606	4.89	4.85	4.86	4.90	4.93	4.89	2.30
2,610	5.35	5.19	5.54	5.44	5.48	5.39	2.16
2,624	4.71	4.69	4.73	4.73	4.74	4.71	3.13
2,628	5.02	5.13	5.05	4.99	4.99	5.04	1.70

Table 9. Shear velocities (km/sec) for the Phegley core, Sullivan County

Depth (ft)	N 60 W	N 30 W	N	N 30 E	N 60 E	E	Axial
2,492	3.08	3.06	3.05	3.05	3.06	3.06	1.20
2,496	3.01	3.00	2.99	2.98	2.99	2.99	1.18
2,510	2.63	2.64	2.65	2.64	2.59	2.69	1.66
2,520	2.88	2.88	2.91	2.90	2.90	2.91	2.16
2,531	2.61	2.91	2.62	2.59	2.66	2.61	1.80
2,540	2.73	2.72	2.71	2.74	2.72	2.73	2.09
2,550	2.91	2.90	2.89	2.89	2.90	2.91	1.08
2,560	3.14	3.15	3.15	3.15	3.15	3.13	1.13
2,563	3.00	3.00	3.00	2.99	3.01	2.99	1.39
2,570	3.14	3.14	3.14	3.15	3.14	3.14	1.49
2,580	2.80	2.86	2.78	2.79	2.80	2.81	1.34
2,588	2.74	2.75	2.79	2.80	2.78	2.76	1.05
2,590	2.93	2.93	3.03	2.97	2.98	3.00	2.11
2,591	3.46	3.17	3.46	3.39	3.38	3.41	3.47
2,606	3.00	2.98	2.99	3.00	2.99	3.01	1.47
2,610	3.04	3.02	3.01	3.01	3.05	3.02	1.25
2,624	2.94	2.93	2.95	2.95	2.94	2.95	1.74
2,628	2.85	2.82	2.81	2.79	2.63	2.66	1.06

(2) Table 9 lists the 18 shear velocities obtained from the Phegley core. Because of difficulties in determining these values, they are not reliable, and no conclusions can be drawn from them.

(3) The 56 compressional velocities from the SDH 290 core are listed in table 10. The experience with the Phegley core kept us from measuring shear velocities in the SDH 290 samples.

Tensile Testing

Method

(1) A jig to apply compression along the diameter of a disk was fabricated in our shop (fig. 35). The load is translated into tensile stress across the plane of the diameter. In this way planes of weakness reveal themselves.

(2) Samples were smoothed so that the loading might be uniform. Loading was applied at a uniform rate of 1,000 lb/min.

Results

(1) Loads were applied along a diameter made parallel to north and at 30° intervals for five other directions.

(2) The 58 results for the Phegley core are listed in table 11, and the 76 results for the SDH 290 core are listed in table 12. The results are in lb/mm^2.

Point-Load Tests

Method

(1) Load is applied to the center of a disk at two points along the axis of the disk. Lines of weakness should cause rupture along their planes.

(2) A jig to apply this load (fig. 36) was constructed in our shop. The opposing force of the restoring springs was subtracted from the applied load.

(3) The load was applied at a rate no greater than 1,000 lb/min. Results show the direction of most prominent failure in the left column. Progressively weaker failures are shown to the right.

Table 10. Compressional velocities (km/sec) for the Indiana Geological Survey drill hole 290 core, Clark County

Depth (ft)	N 60 W	N 30 W	N	N 30 E	N 60 E	E	Axial
131	3.85	3.85	3.85	3.87	3.87	3.86	2.39
131	3.26	3.27	3.27	3.27	3.26	3.26	2.94
131	3.92	3.93	3.79	3.93	3.86	3.93	3.70
132	3.94	3.93	3.95	3.79	3.77	3.77	2.33
132	3.26	3.29	3.31	3.30	3.30	3.29	2.16
133	3.37	3.37	3.36	3.32	3.32	3.34	2.91
133	3.86	3.81	3.80	3.80	3.88	3.91	3.43
136	3.85	3.90	3.82	3.81	3.81	3.78	2.60
136	3.32	3.33	3.38	3.41	3.40	3.37	2.22
137	3.79	3.76	3.76	3.78	3.77	3.87	2.58
137	3.29	3.29	3.32	3.36	3.35	3.33	2.82
138	3.96	3.96	3.88	3.99	3.95	3.96	2.50
139	3.32	3.35	3.37	3.40	3.39	3.38	2.02
139	3.92	3.87	3.88	3.90	3.89	3.88	2.55
144	4.11	4.09	4.11	4.12	4.11	4.13	2.89
147	4.07	4.06	4.05	4.07	3.93	4.04	2.87
149	3.35	3.36	3.39	3.41	3.41	3.36	2.19
149	3.96	3.95	3.94	3.94	3.98	3.95	2.87
150	4.02	3.95	3.92	3.96	3.95	3.93	4.43
150	3.30	3.32	3.35	3.39	3.38	3.34	2.94
153	3.95	3.96	3.97	3.97	3.84	3.84	2.81
154	4.01	4.04	4.02	4.05	4.03	4.03	2.94
154	3.95	4.00	3.99	3.95	3.94	3.97	2.87
154	3.39	3.39	3.36	3.33	3.33	3.36	2.61
154	3.38	3.37	3.35	3.35	3.37	3.37	3.36
155	3.94	3.95	3.95	3.97	3.96	3.95	2.86
156	3.97	3.96	3.96	3.98	3.96	3.99	2.90
156	3.96	3.93	3.94	3.95	3.89	3.88	2.81
156	3.30	3.32	3.35	3.35	3.34	3.33	2.15
156	3.35	3.36	3.37	3.40	3.40	3.38	2.27
157	3.86	3.84	3.87	3.86	3.85	3.91	4.17
157	3.34	3.36	3.36	3.40	3.40	3.40	2.96
157	4.03	3.97	4.02	4.08	4.02	4.03	2.85
166	4.05	4.08	4.06	4.00	4.02	4.07	2.82
169	4.04	4.08	4.07	4.06	4.04	4.02	2.93
170	4.32	4.15	4.15	4.18	4.15	4.27	2.75
171	4.37	4.32	4.28	4.27	4.31	4.39	3.07
176	4.31	4.28	4.22	4.23	4.23	4.19	2.86
176	4.26	4.24	4.20	4.20	4.24	4.19	2.86
177	4.42	4.42	4.44	4.41	4.42	4.39	2.81
183	4.39	4.34	4.34	4.36	4.34	4.36	
187	4.44	4.51	4.48	4.55	4.41	4.45	2.29
187	4.43	4.41	4.44	4.40	4.27	4.27	
192	4.37	4.38	4.37	4.37	4.36	4.31	2.85
193	4.54	4.53	4.57	4.54	4.48	4.49	2.94
198	4.46	4.43	4.42	4.38	4.40	4.40	2.79

Table 10. Compressional velocities (km/sec) for the Indiana Geological Survey drill hole 290 core, Clark County--Continued

Depth (ft)	N 60 W	N 30 W	N	N 30 E	N 60 E	E	Axial
202	4.31	4.34	4.27	4.30	4.29	4.31	2.81
206	4.22	4.20	4.22	4.22	4.22	4.22	2.85
206	4.18	4.18	4.20	4.19	4.16	4.26	2.88
210	4.13	4.11	4.18	4.16	4.15	4.16	2.92
214	4.33	4.31	4.33	4.35	4.30	4.29	3.21
221	4.34	4.36	4.37	4.34	4.30	4.34	3.16
222	4.31	4.33	4.31	4.25	4.27	4.30	3.09
224	4.33	4.36	4.31	4.30	4.32	4.34	3.04
234	4.29	4.30	4.28	4.30	4.20	4.23	2.93
235	4.23	4.24	4.26	4.24	4.23	4.27	2.95

Table 11. Brazil split tests for Phegley Core, Sullivan County

Depth (ft)	Direction of load	Tensile Strength (lb/mm^2)*	Depth (ft)	Direction of load	Tensile strength (lb/mm^2)*
2,509.6	30 W	1.94	2,552.0	60 E	2.10
2,509.9	60 W	1.87	2,559.8	00	2.14
2,510.2	90 E	0.72	2,560.7	30 E	2.50
2,510.7	60 E	1.98	2,561.0	90 E	2.32
2,511.0	30 E	1.41	2,561.1	30 W	1.40
2,511.7	60 W	2.04	2,561.9	60 E	2.20
2,519.5	00	1.93	2,562.0	60 W	2.20
2,519.8	30 E	1.60	2,568.0	00	1.64
2,520.1	60 E	1.83	2,568.4	30 E	1.32
2,520.3	60 W	1.38	2,568.5	60 E	1.42
2,520.6	90 E	1.13	2,569.0	60 W	1.45
2,521.8	30 W	2.27	2,570.0	30 W	2.06
2,530.3	90 E	2.32	2,570.3	90 E	1.75
2,530.5	30 W	1.61	2,579.1	00	2.35
2,530.8	60 W	2.63	2,579.3	60 W	1.78
2,531.1	60 E	1.71	2,579.6	30 E	2.06
2,532.0	30 E	2.35	2,580.0	00	1.69
2,532.1	00	1.90	2,589.8	30 W	0.81
2,539.0	00	1.90	2,592.0	00	1.46
2,539.1	30 E	1.55	2,592.6	60 W	0.24
2,539.5	90 E	2.26	2,593.0	90 E	0.89
2,540.0	60 W	1.75	2,593.2	60 E	1.31
2,540.2	60 E	2.61	2,593.4	30 E	1.46
2,540.3	30 W	2.25	2,604.6	90 E	1.51
2,547.9	90 E	2.36	2,604.7	30 W	1.15
2,548.2	60 W	2.69	2,605.2	60 W	1.00
2,548.7	30 W	2.50	2,605.4	60 E	1.66
2,551.6	00	1.31	2,605.8	00	1.84
2,551.8	30 E	2.45	2,606.0	30 E	1.27

* 1 lb/mm^2 = 645 lb/in^2 = 4.45 MPa (mega pascals)

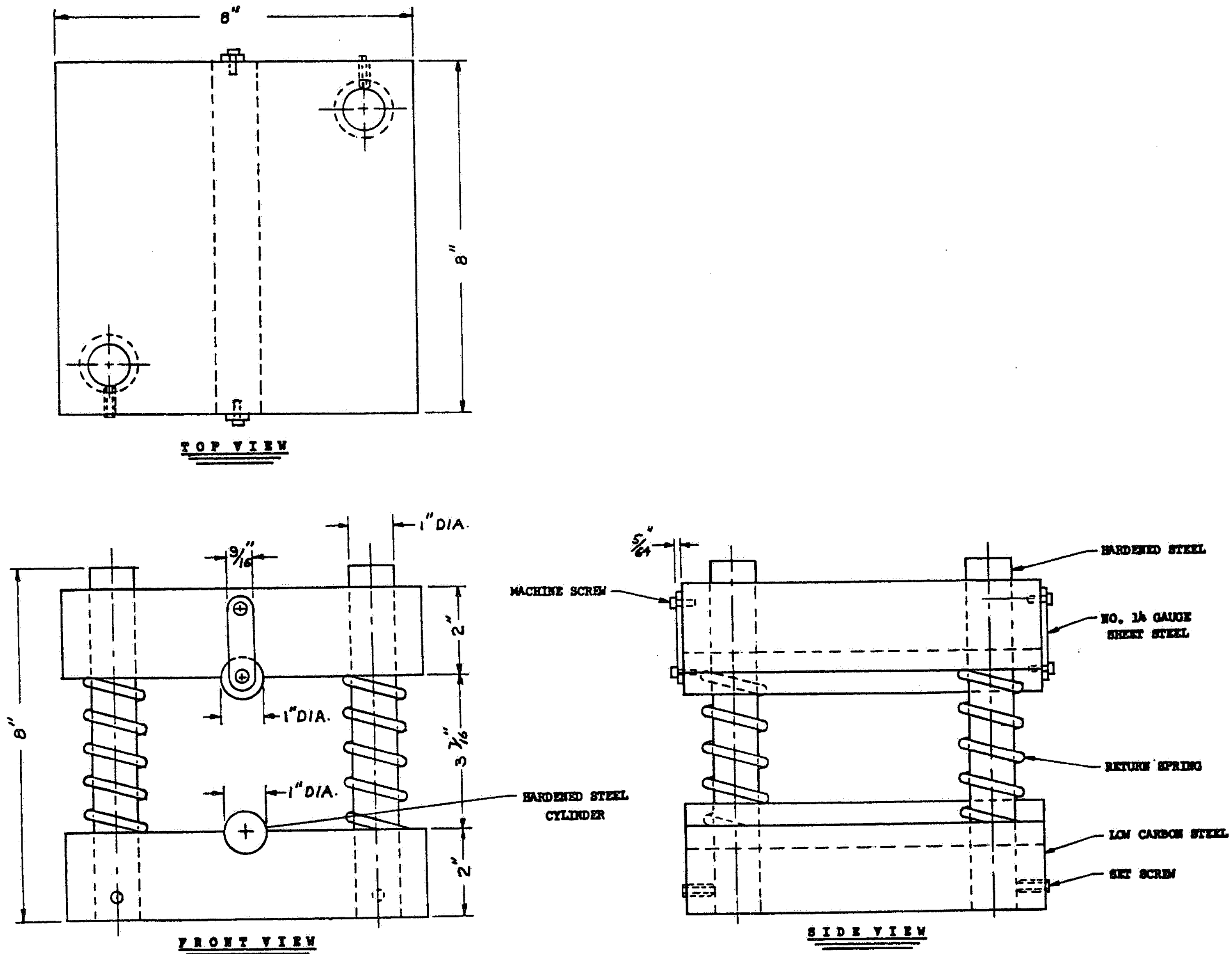

Figure 35. Drawing showing details of construction of a device used to make Brazil split tests.

Table 12. Brazil split tests for the Indiana Geological Survey drill hole 290 core, Clark County

Depth (ft)	Direction of load	Tensile strength (lb/mm²)*
134.5	30 W	2.27
134.7	60 W	3.24
135.6	30 E	1.20
135.8	30 E	0.27
136.7	60 E	2.57
136.8	90 E	2.39
136.9	00	3.99
140.5	60 W	1.91
140.7	30 W	2.97
140.8	90 E	3.01
141.0	30 E	
141.2	00	2.64
141.7	60 E	2.68
152.6	30 E	2.97
153.1	00	3.41
153.3	30 W	2.79
153.5	60 W	2.62
153.8	60 E	2.96
154.0	90 E	
155.0	90 E	2.78
165.1	60 W	2.93
165.3	30 E	2.33
165.4	90 E	2.28
165.7	00	2.46
166.3	60 E	0.33
166.5	30 W	2.07
167.6	30 E	2.74
169.0	90 E	2.39
170.1	60 W	1.91
170.3	30 W	2.74
170.6	60 E	1.64
171.2	30 E	2.34
171.3	00	2.75
175.3	90 E	2.21
175.6	60 W	2.16
176.0	60 E	2.01
176.2	30 W	2.34
176.4	30 E	2.39
176.8	00	2.10
185.7	60 W	1.17
185.8	90 E	1.74
186.7	30 W	1.42
187.0	00	2.02
187.1	60 E	1.81
187.3	30 E	1.57
191.1	00	1.73
192.3	30 E	2.19
192.5	60 E	2.11
192.6	60 W	3.08
192.8	30 W	1.97
193.4	90 E	1.60
205.1	30 E	2.14
205.3	60 E	2.11
205.5	90 E	2.19
206.1	00	2.36
206.4	30 W	2.16
206.5	60 W	2.09
216.5	60 W	1.85
216.7	00	1.92
216.8	30 E	2.51
217.4	90 E	2.41
217.6	60 E	2.58
217.8	30 W	2.46
221.2	90 E	1.34
221.3	60 E	1.96
221.6	30 W	2.60
221.8	00	2.45
222.2	60 W	2.08
222.3	30 E	2.27
232.8	90 E	2.41
233.2	60 W	2.30
233.7	90 E	
233.9	30 W	2.13
234.9	60 E	2.05
235.1	00	2.21
235.2	30 E	2.14

*1 lb/mm^2 = 645 lb/in^2 = 4.45 MPa (mega pascals)

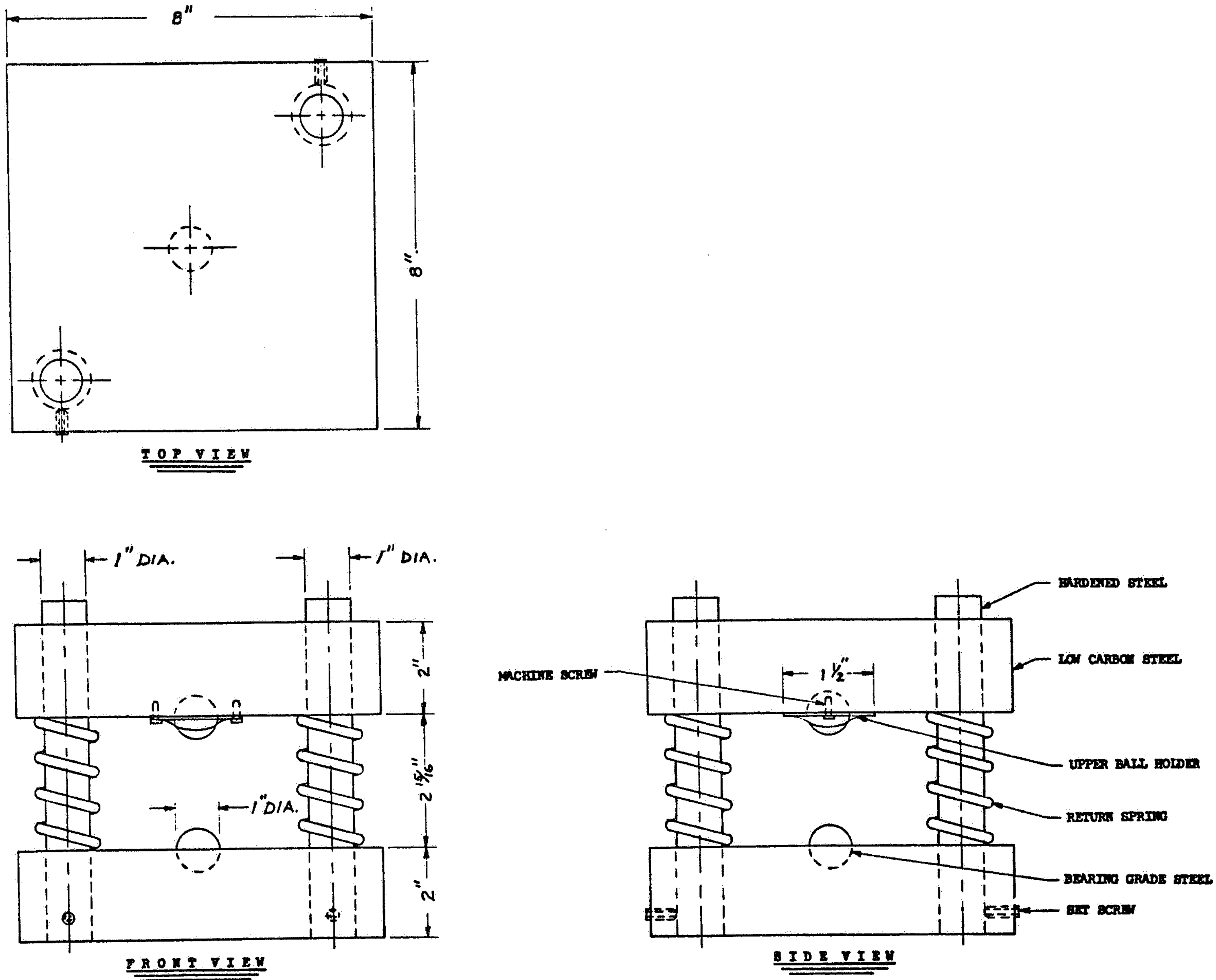

Figure 36. Drawing showing details of construction of a device used to make point-load tests.

Results

(1) Results of the testing on the 130 Phegley samples are listed in table 13.

(2) Results of the testing on the 115 SDH 290 samples are listed in table 14.

(3) Sketches of the mode of the failures were made for each sample. The sketches are on file at the Indiana Geological Survey.

Table 13. Point-load results for the Phegley core, Sullivan County

Depth (ft)	Direction of prominent failure				Direction of insignificant failure	
2,509.0	N 80 W	S 80 E				
2,509.1	N 75 W	S 80 E				
2,509.3	N 30 E	S 60 E	N 15 W			
2,510.5	N 90 E		N 90 W			
2,511.1	N 35 W	S 35 E				
2,511.3	N 55 E	S 50 W		S 65 W		S 35 E
2,511.5	N 40 E	S 40 W				
2,519.1	N 35 W	S 30 E				
2,520.9	N 50 E	S 10 W				
2,521.6	N 10 W	S 80 W				
2,522.0	N 60 W	S 50 E				
2,522.4	N 10 W	S 10 E				
2,522.5	N 65 E	S 65 W		S 30 E		
2,528.3	N 60 W	S 60 E	N 20 E	S 10 W	N 55 W	S 90 E
2,528.5	N 60 W	S 60 E				
2,529.1	N 85 E	S 30 W				
2,529.2	N 50 W	S 50 E				
2,529.8	N 15 W	S 50 W		S 05 W		
2,530.0	N 70 W	S 70 E				
2,531.1	N 55 W	S 40 E	N 50 E			
2,531.3	N 10 W		N 85 E			
2,531.5	N 45 W	S 25 E		S 75 E		
2,531.6	N 60 W	S 80 E	N 40 W	S 10 E	N 90 W	S 50 E
2,532.5	N 30 W	S 30 E		S 65 E		
2,532.6	N 40 E	S 55 E		S 10 E		
2,533.5	N 10 E	S 10 E		S 55 E		
2,533.7	N 50 E	S 60 W	N 10 W			
2,534.5	N 80 W	S 80 E				
2,534.7	N 00 W	S 50 W				
2,534.8	N 20 W	S 10 E	N 90 W			
2,535.0	N 05 E	S 40 E				
2,535.9	N 00 W	S 90 W				
2,536.0	N 05 E	S 35 W	N 85 W			
2,537.2	N 15 W	S 20 E		S 60 W		
2,537.4	N 65 W		N 50 E		N 30 E	
2,537.9	N 40 W	S 60 E	N 50 E			
2,538.0	N 10 W	S 65 W	N 65 W			
2,538.3	N 05 E	S 05 W	N 90 E			
2,539.7	N 10 W	S 80 W				
2,540.7	N 90 W		N 90 E			
2,541.0	N 50 W	S 70 W	N 50 E			
2,542.3	N 05 E	S 05 W				
2,542.5	N 70 E	S 80 W	N 10 W			
2,542.7	N 10 E	S 50 W	N 50 W			
2,544.0	N 10 W	S 40 E		S 70 W		
2,544.2	N 10 W	S 40 E		S 60 W		

Table 13. Point-load results for the Phegley core, Sullivan County--Continued

Depth (ft)	Direction of prominent failure				Direction of insignificant failure	
2,544.4	N 40 W	S 50 E		S 40 W		
2,544.8	N 05 W	S 05 E		S 50 W		
2,545.0	N 00		N 90 W		N 90 E	
2,545.1	N 40 W		N 30 E			
2,546.0		S 80 W		S 05 E		S 65 E
2,546.2	N 60 W	S 70 E		S 35 W		
2,546.6	N 50 W	S 50 E	N 80 E			
2,546.8	N 50 W	S 40 E	N 40 E			
2,548.4	N 65 W	S 75 E		S 10 W		
2,549.1	N 05 W	S 65 W	N 85 E			
2,552.2	N 35 E	S 15 E				
2,552.3	N 65 E	S 25 W	N 50 W	S 40 E		
2,552.5	N 05 E	S 45 W				
2,552.7	N 10 E	S 60 E	N 70 E		N 80 W	
2,553.6	N 50 W	S 50 E		S 40 W		
2,553.8	N 55 E	S 55 W	N 20 W			
2,554.0	N 05 E		N 90 W			
2,555.3	N 70 E	S 65 W	N 15 W	S 50 E		
2,555.4	N 90 E	S 90 W	N 30 E	S 00		
2,555.8	N 10 W	S 05 E				
2,556.3	N 30 E	S 40 W	N 35 W	S 40 E		
2,556.5	N 80 W	S 50 E	N 10 E			
2,556.8	N 30 E	S 30 W		S 60 E		
2,557.3	N 50 W	S 65 E	N 30 E	S 10 E		
2,557.5	N 60 E	S 05 E				
2,557.6	N 60 W	S 30 E	N 80 E	S 50 W		
2,557.8	N 85 W		N 70 E		N 05 W	
2,558.5	N 55 E	S 55 W		S 10 W		S 30 E
2,558.8	N 25 E	S 30 W		S 60 E		
2,559.0	N 50 W	S 50 E	N 15 E			
2,560.3	N 05 E	S 05 E		S 80 E		
2,560.4	N 35 W	S 05 W	N 80 E			
2,561.4	N 65 E	S 70 W		S 10 E		
2,561.6	N 10 W	S 25 E		S 85 W		
2,563.2	N 20 W	S 20 E	N 80 E			
2,564.5		S 85 E		S 70 W		
2,564.7	N 20 E	S 15 W	N 55 E	S 50 W		
2,564.9	N 10 W	S 60 E				
2,565.7	N 30 E	S 40 W	N 65 W	S 85 E		
2,565.8	N 30 W	S 20 W	N 80 E			
2,566.2	N 60 E	S 75 W	N 50 W		N 10 E	
2,566.3	N 25 E	S 50 W	N 30 W	S 65 E	N 40 W	
2,566.5	N 10 W	S 50 W		S 80 E		S 20 E
2,566.7	N 70 E	S 60 W				
2,566.8	N 35 E	S 45 W	N 35 W			
2,567.4	N 40 E	S 50 W		S 55 E		

Table 13. Point-load results for the Phegley core, Sullivan County--Continued

Depth (ft)	Direction of prominent failure			Direction of insignificant failure
2,567.7	N 30 W	S 25 W		
2,567.9	N 10 E	S 10 W	N 90 E	
2,569.3	N 80 W	S 60 E		
2,569.7		S 80 E		S 45 W
2,571.6	N 40 E	S 20 E		
2,571.9	N 45 W	S 00	N 85 W	
2,572.0	N 20 E	S 40 W	N 90 E	S 45 E
2,572.3	N 10 E	S 10 E	N 90 W	
2,572.6	N 55 W	S 35 E	N 60 E	
2,572.8	N 10 W		N 60 E	N 80 W
2,573.5	N 20 W	S 35 E		S 45 W
2,573.7	N 85 W	S 10 E	N 65 E	
2,574.1	N 60 E	S 35 E		
2,574.3	N 10 W	S 60 E		
2,574.5	N 00	S 15 W		
2,574.7	N 65 E	S 60 W	N 40 W	
2,575.2	N 70 E	S 70 W	N 30 W	
2,579.7	N 90 W	S 90 E		
2,586.3	N 20 W	S 25 E		
2,586.5	N 80 W	S 80 E		
2,586.7	N 40 W	S 55 E		S 85 E
2,586.9	N 85 W	S 45 E		
2,587.0	N 10 W	S 45 E	N 50 E	
2,587.8	N 00	S 45 E	N 70 E	
2,589.0	N 35 W	S 45 W		
2,592.3	N 20 W	S 50 W		
2,592.4	N 75 W	S 40 W		S 20 W
2,592.7	N 80 E	S 45 W		S 30 E
2,593.9	N 30 E	S 25 W		S 55 E
2,594.0	N 50 W	S 50 E		
2,594.7	N 80 W	S 80 E		
2,594.9		S 85 E		S 85 W
2,595.0	N 20 W	S 85 W		S 70 E
2,595.8	N 90 W	S 35 E	N 30 W	
2,596.0	N 10 W	S 30 E	N 85 E	
2,596.8	N 85 W	S 85 E	N 30 W	
2,597.0		S 10 E		
2,597.2	N 10 W	S 10 E		

Table 14. Point-load results for the Indiana Geological Survey drill hole 290 core, Clark County

Depth (ft)	Direction of prominent failure				Direction of insignificant failure	
127.8	N 65 W	S 30 E				
128.8	N 60 E	S 65 W				
129.4	N 80 E	S 80 W				
129.9		S 85 E	N 10 E	S 70 W		
131.0	N 75 E	S 70 W		S 30 E		
131.1	N 50 E	S 10 E	S 90 W			
131.3	N 20 E	S 15 E		S 80 W		
132.0	N 20 W	S 45 E	N 75 E	S 75 W		
132.6	N 75 W	S 80 E		S 65 W		
132.7		S 85 W		S 70 E	N 25 E	
137.1	N 40 W	S 20 W				
137.7	N 60 W	S 90 E		S 60 W		
138.0	N 55 E	S 90 W		S 15 E		
138.5		S 50 E		S 90 W		
142.2		S 85 W		S 20 E		
142.4	N 70 E	S 70 W	N 65 W	S 05 E		
143.0	N 85 E	S 85 W		S 15 E		
143.5	N 00	S 00	N 55 E			
143.7	N 10 W	S 70 E				
145.5	N 40 E	S 30 W		S 85 W		S 40 E
146.5	N 45 W	S 65 E	N 30 E	S 90 W		
146.6	N 60 W	S 50 E				
146.8	N 30 W	S 10 E	N 80 E		N 75 W	
147.0	N 55 E	S 45 W		S 50 E		
148.1	N 05 W	S 05 W		S 80 E		
149.1	N 55 W	S 30 E	N 65 E			
149.8	N 30 E	S 15 W	N 70 W			
150.4	N 50 W	S 20 E				
152.2	N 55 W	S 50 E				
153.7	N 80 W	S 90 E				
155.2	N 65 E	S 55 W				
155.4	N 85 E	S 75 W				
155.6	N 15 W	S 25 E				
156.3	N 20 E	S 40 E				
156.5	N 45 W	S 45 E	N 40 E	S 45 W		
156.9	N 15 W	S 30 E	N 80 E			
157.2	N 50 W	S 50 E	N 45 E	S 40 W		
157.5	N 15 E	S 00	N 90 W			
158.4	N 65 W	S 75 E		S 25 W		
159.2	N 10 W	S 45 E				
160.2	N 55 W	S 05 E				
160.6	N 15 W	S 55 E				
161.3	N 60 E	S 30 W	N 60 W	S 50 E		
162.0	N 65 E	S 65 W				
163.3	N 75 W	S 20 E				

Table 14. Point-load results for the Indiana Geological Survey drill hole 290 core, Clark County--Continued

Depth (ft)	Direction of prominent failure				Direction of insignificant failure
164.1	N 80 E	S 85 W			
167.9	N 20 E	S 30 W	N 90 W		
168.8	N 40 W	S 65 E		S 65 W	
170.8	N 15 W	S 40 E	N 85 E		
171.0	N 90 E	S 80 W		S 05 E	
172.2	N 80 W	S 80 E			
172.5	N 20 W	S 00	N 90 W		
173.1	N 05 W	S 25 W		S 65 E	
173.5	N 50 W	S 80 E		S 40 W	
174.2	N 10 E	S 25 W	N 85 E		N 75 W
174.8	N 90 W	S 35 E			
175.8	N 55 W	S 60 E		S 25 W	
177.2	N 70 W	S 55 E	N 25 E		
177.4	N 70 W	S 70 E			
180.6	N 60 W	S 55 E			
181.5	N 10 E	S 50 E		S 80 W	
182.7	N 70 E	S 55 W	N 30 W	S 25 E	
182.9	N 55 E	S 25 W	N 50 W		
183.9	N 40 W	S 30 E			
184.6	N 00	S 25 W	N 90 W	S 80 E	
185.1	N 05 E	S 40 W		S 65 W	
186.4	N 75 E	S 80 W		S 40 E	
186.6	N 30 E	S 60 W	N 25 W	S 20 E	
188.3	N 50 W	S 55 E			
189.0	N 75 E	S 60 W	N 30 W		
190.6	N 35 E	S 60 W			
193.1	N 10 W	S 10 E			
193.7	N 20 E	S 35 E	N 80 W	S 85 W	
195.3	N 40 E	S 05 E			
197.7	N 65 W	S 65 E			
198.7	N 40 W	S 10 W	N 55 E	S 85 E	
199.2	N 70 W	S 25 E	N 65 E		
200.5	N 70 W	S 60 E	N 80 E		
202.3	N 55 W	S 60 E			
202.5	N 05 W	S 10 W			
203.6	N 40 E	S 00		S 90 W	
205.7	N 70 E	S 75 W		S 05 E	
205.9	N 75 W	S 80 E		S 60 W	
207.4	N 40 E	S 50 W		S 40 E	
208.3	N 25 W	S 40 E	N 50 E		
210.2	N 65 W	S 65 E			
210.4	N 60 E		N 60 W		
211.0	N 40 W	S 30 E			
211.6	N 05 W	S 10 E	N 90 W	S 70 E	
212.2	N 75 W	S 25 E	N 40 E		

Table 14. Point-load results for the Indiana Geological Survey drill hole 290 core, Clark County--Continued

Depth (ft)	Direction of prominent failure				Direction of insignificant failure
212.7	N 30 E	S 35 W			
213.3	N 10 W	S 10 W	N 60 W		
213.5	N 20 W	S 40 E		S 40 W	
213.7	N 45 E	S 45 W		S 45 E	
213.9	N 35 W	S 60 E		S 50 W	
215.9	N 45 E	S 30 W	N 35 W		
219.2	N 35 E	S 45 W		S 40 E	
220.1	N 90 W	S 70 E	N 15 E		
220.2	N 60 W	S 55 E			
220.7	N 85 E	S 80 W			
222.7		S 85 W		S 60 E	
223.5	N 35 W	S 40 E		S 90 W	
223.7	N 55 E	S 60 W			
224.4	N 90 W	S 90 E		S 20 E	
228.2	N 85 E	S 85 W		S 05 W	
229.0	N 15 W	S 50 E			
229.9	N 50 W	S 30 E		S 45 W	
230.0	N 55 W	S 10 W	N 90 E		
230.2	N 60 W	S 25 E	N 75 E		
231.2	N 60 W	S 05 W			
231.7	N 15 W	S 70 E		S 45 W	
235.8	N 15 E	S 30 W			
237.8	N 40 W	S 55 E			
238.9	N 60 E	S 90 W		S 60 E	
239.8	N 05 E	S 20 W	N 80 E		N 85 W

GAS PRODUCTION

J. L. Bassett and N. R. Hasenmueller

Gas occurs in and has been produced from the New Albany Shale in Indiana. Numerous shows of gas in the New Albany Shale have also been reported in southwestern Indiana from tests of the underlying Muscatatuck Group, a few scattered shows have been reported from the Antrim Shale in the Indiana part of the Michigan Basin (fig. 37).

In all, about 6 percent of the well records examined reported shows of gas from the shale. This figure is probably extremely conservative, as gas occurrence is common in the shale and therefore is not always documented in well records. The shows are scattered throughout southwestern Indiana, and their distribution probably reflects, more than anything else, drilling density and accuracy in reporting shows.

Gas has been commercially produced from the shale in 10 now largely abandoned fields in the Illinois Basin part of Indiana (table 15). Seven fields were developed in Harrison County, one field in Martin County, and two one-well fields in Daviess County. By far, most of the production was from Harrison County, where 186 wells produced shale gas (fig. 33). Total shale-gas production from Harrison County has been estimated at 5 billion cubic feet (Sorgenfrei, 1952, p. 7), but this figure may include some gas from the Muscatatuck Group.

Harrison County Fields

Gas was first reported in Harrison County by Collett (1879, p. 382) in the 10th Annual Report of the Geological Survey of Indiana. It was reported bubbling up from the bottom of the Ohio River in two places. Wells drilled at Tobacco Landing near the gas springs yielded both gas from the shale and salt brine from the underlying Devonian limestone. The gas was used for evaporating the brine for salt and in the booming hydraulic lime industry in the area.

The first drilling specifically for gas occurred in 1885, and between 1885 and 1925 seven fields were producing New Albany gas in Harrison County. The wells were 300 to 800 feet deep and were drilled by the Kentucky Heating Co. (which later became the Louisville Gas and Electric Co.) and the Railroaders Gas Co. (now the Indiana Utility Corp.). The gas was piped across the Ohio River to Louisville, Ky.

The Railroaders Co. explored and developed the Laconia Field and by 1924 was producing 7,500 MCF/day. This was the peak period of shale-gas production in the county. Soon afterward, the greatly increased production from West Virginia and eastern Kentucky made the low-volume Harrison County production unprofitable, and by 1931 the Louisville Gas and Electric Co. had shut in all of its shale-gas production.

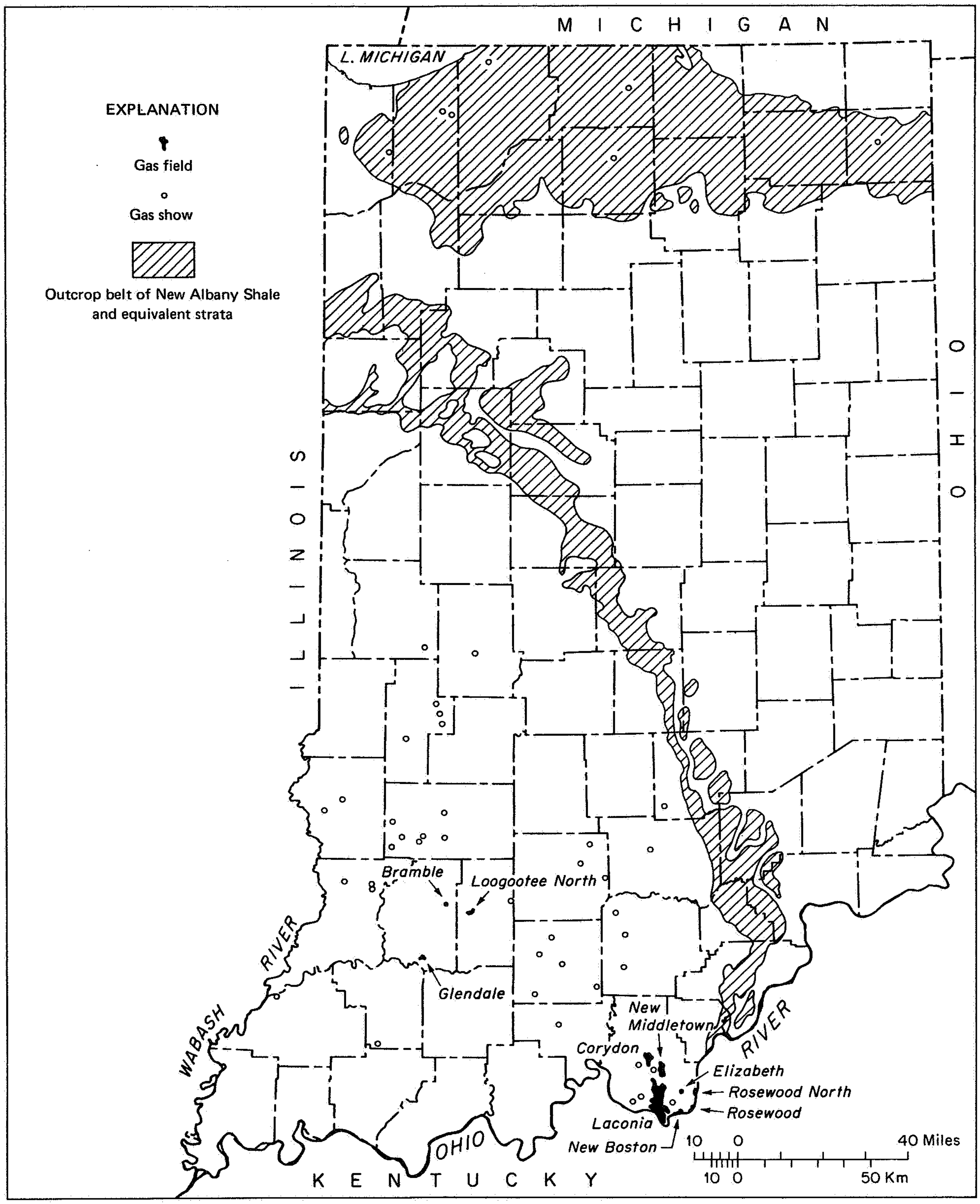

Figure 37. Map of Indiana showing locations of gas shows and gas fields producing from the New Albany Shale. From Bassett and Hasenmueller 1977.

Table 15. Gas fields in the New Albany Shale in Indiana
(Modified from Becker and Keller, 1976)

County	Field name	Discovery year	Number of wells	Average initial production	Average depth (ft.)	Status (1977)
Daviess	Bramble	1974	1	250MCF/24	1,700	Active
Daviess	Glendale	1940	1	750MCF/24	2,100	Abandoned
Harrison	Corydon	1923	15	110MCF/24	800	93% abandoned
Harrison	Elizabeth	1925	1	Gas	750	Abandoned
Harrison	Laconia	1915	106	220MCF/24	700	99% abandoned
Harrison	New Boston	1885	13	245MCF/24	450	85% abandoned
Harrison	New Middletown	1923	26	120MCF/24	750	96% abandoned
Harrison	Rosewood	1895	21	225MCF/24	300	90% abandoned
Harrison	Rosewood North	----	4	Gas	300	Abandoned
Martin	Loogootee North	1902	12	780MCF/24	1,500	92% abandoned

Little geologic and production information is available concerning the Harrison County shale gas. The information summarized below was gathered by Sorgenfrei (1952) during a study of New Albany gas production in Indiana.

A 1926 report on 26 wells in three fields generally indicated low rock pressure (48 to 169 psi) and open-flow rates ranging from 27 to 1,361 MCF. Gas was produced from two zones in the shale. The best production was from a zone 15 to 30 feet into the shale corresponding to the carbonaceous part of the shale in the Clegg Creek Member. A zone 20 to 30 feet above the base of the shale also yielded gas in some wells. This interval probably corresponds to a zone in the Morgan Trail Member, as the Selmier greenish-gray shale is absent from the gas-producing area of Harrison County (fig. 9).

All shale wells produced salt water along with gas, sometimes in amounts sufficient to cause the flow of gas to cease. Many of the wells were exceedingly long lived and yielded gas for 20 years or more. The fields are now almost totally abandoned. Part of the largest field, Laconia, is now being used by Louisville Gas and Electric for underground gas storage in Devonian and Silurian carbonate rocks.

Structure maps drawn from existing well data indicate some structural doming or flattening imposed on the general westward dip over the three fields for which there is sufficient well control (figs. 38, 39, and 40). Organic content of the shale as estimated by natural gamma-ray intensity does not seem to be significantly different from that of adjacent nonproducing areas, although the paucity of log data in the gas-field area prohibits a detailed analysis.

Loogootee North Field

The Loogootee North Field in Martin County (fig. 37) yielded shale gas from 12 wells, but it now contains only one producing home-use well. Gas was produced from one well in 1902, but the other 11 wells were drilled between 1948 and 1953. Gas was encountered in the upper 50 feet of the shale at a depth of about 1,500 feet, and the maximum gas flow was from about 30 feet into the shale. Deeper than 50 feet into the shale, salt water was encountered, and it interfered with production. As in Harrison County, production appears to be in the carbonaceous Clegg Creek Member.

According to the standard practice of the Appalachian shale-gas fields, the wells were all shot with nitroglycerine, which reportedly increased open-flow rates threefold to fourfold. Initial production ranged from 200 to 2,000 MCFD from an average depth of 1,500 feet. Average initial production of the wells was 780 MCFD. A structure map of the Loogootee North Field compiled by Sorgenfrei (1952) on the top of the New Albany Shale showed a small structural low. But the Loogootee North Field does not appear to be associated with any pronounced structural configuration or change in shale thickness.

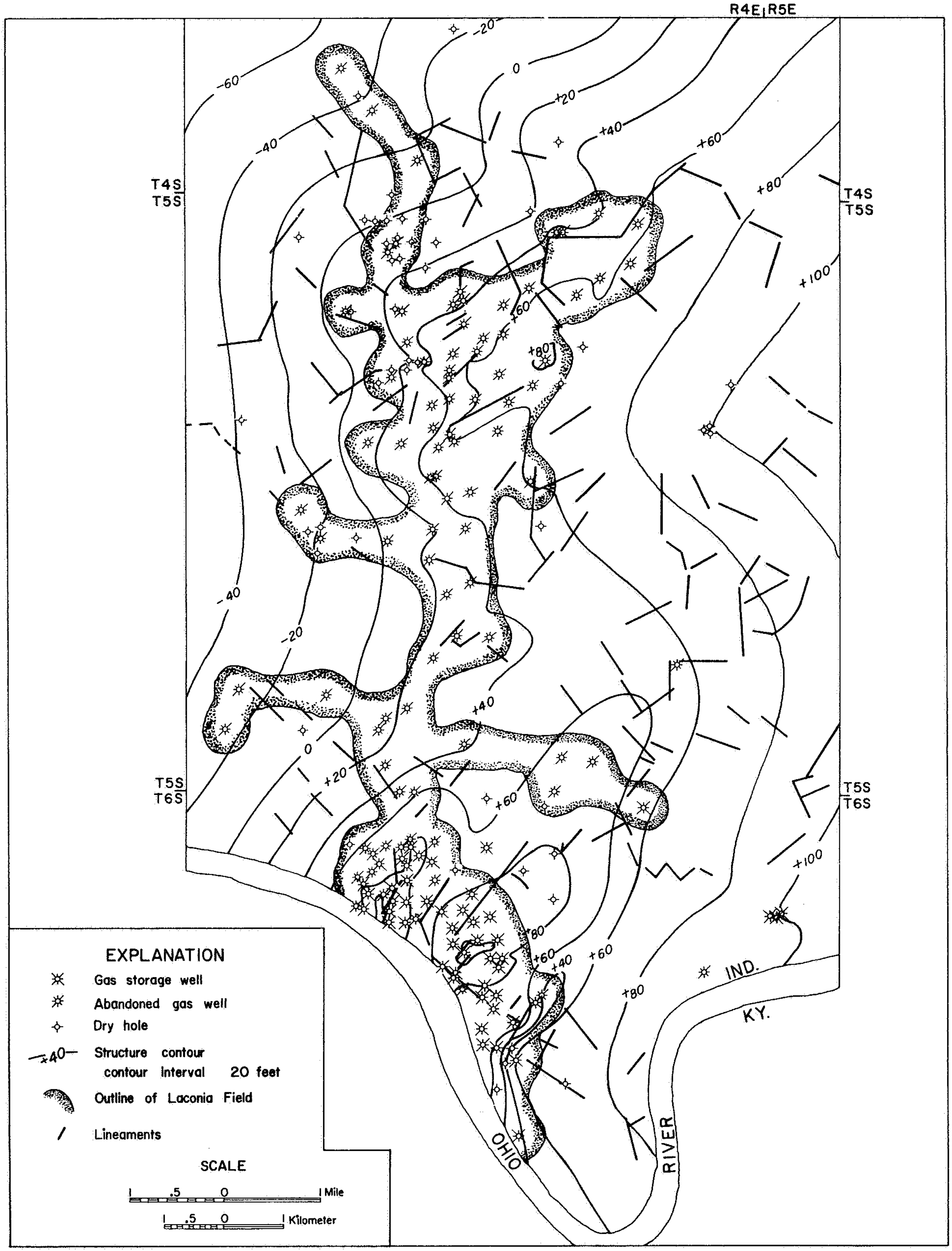

Figure 38. Map showing structure on the top of the New Albany Shale and lineaments near the Laconia Field, Harrison County. From Bassett and others, 1978.

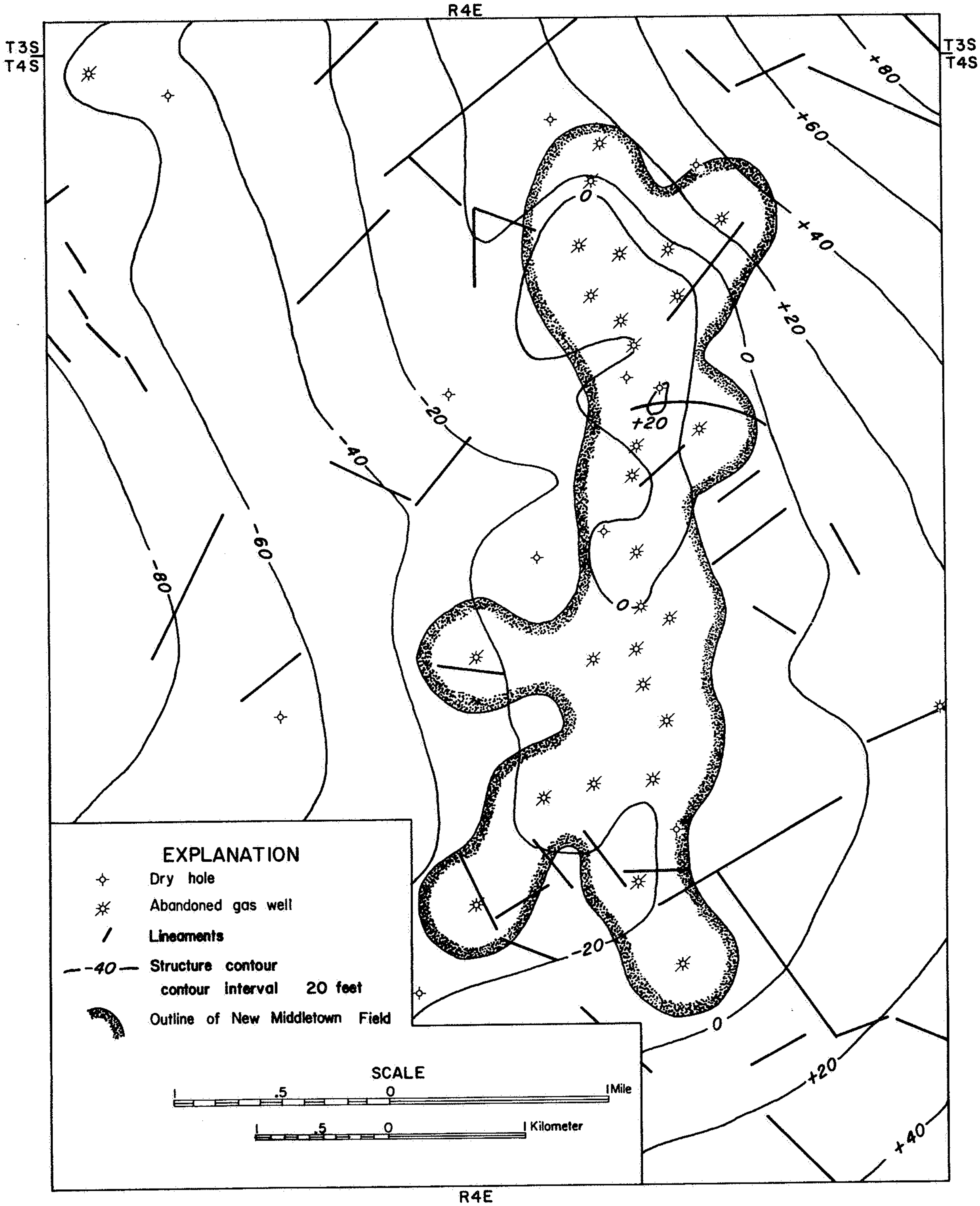

Figure 39. Map showing structure on the top of the New Albany Shale and lineaments near the New Middletown Field, Harrison County. From Bassett and others, 1978.

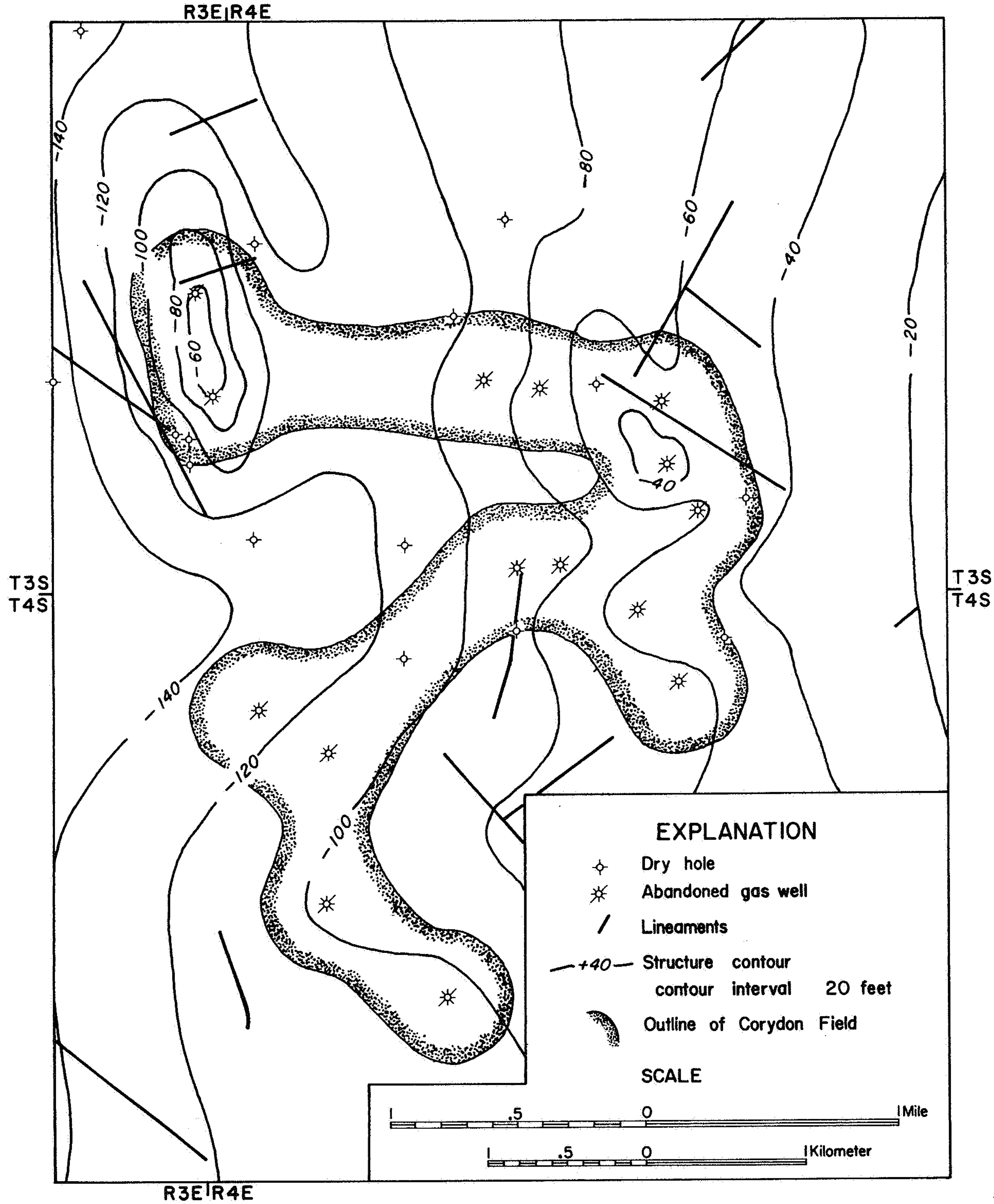

Figure 40. Map showing structure on the top of the New Albany Shale and lineaments near the Corydon Field, Harrison County. From Bassett and others, 1978.

Daviess County Fields

Two one-well New Albany fields (Glendale and Bramble) are known in Daviess County (fig. 37). The Glendale well (Norris No. 1 Connelly) was drilled in 1940 and had an initial production of 750 MCFD from both the Muscatatuck Group and the New Albany Shale. The shale production was from a 7-foot-thick zone probably near the base of the Morgan Trail-Camp Run-Clegg Creek interval. This well is now abandoned.

The Bramble well (Finch No. 1 Knepp) was drilled in 1974 and is the most recent productive shale-gas well to be drilled in Indiana. The well was an open-hole completion and tested 250 MCFD natural flow from the entire shale thickness. Two other wells in the same section drilled by the same operator reported no gas shows in the shale. The Bramble well did not seem to be structurally higher than either of the other two wells. Gas from the Bramble well was analyzed and had a BTU rating (wet basis) of 1,002 BTU/CF. The well has been shut in since completion.

Summary

Ten gas fields that have or could have produced gas from the New Albany Shale are known in Indiana. Geologic information is minimal but suggests that structure is not a requisite in shale-gas accumulation and that the shale penetrated by producing wells may not be richer in organic matter than shale penetrated by adjacent nonproducing wells. These two factors suggest that natural fracture systems in the shale may be the primary control of shale-gas productivity.

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APPENDIX I. DOE/EGSP MAPS AND STRATIGRAPHIC CROSS SECTIONS

METC/EGSP Series No.

800 Map showing structure on base of New Albany Shale (Devonian and Mississippian) and equivalent strata in Indiana

801 Map showing structure on top of New Albany Shale (Devonian and Mississippian) and equivalent strata in Indiana

802 Map of Indiana showing reported oil and gas shows from 100 feet of strata overlying New Albany Shale

803 Map of Indiana showing reported oil and gas shows from the New Albany Shale

804 Map of Indiana showing reported oil and gas shows from Middle Devonian carbonate rocks

805 Map of Indiana showing thickness of New Albany Shale (Devonian and Mississippian) and equivalent strata

806 Maps of northern Indiana showing thicknesses of the Sunbury, Ellsworth, and Antrim Shales (New Albany Shale equivalents)

807 Map of Indiana showing thickness of the Blocher Member of the New Albany Shale (Devonian and Mississippian)

808 Map of Indiana showing thickness of the Selmier Member of the New Albany Shale (Devonian and Mississippian)

809 Map of Indiana showing thickness of the Clegg Creek - Camp Run - Morgan Trail Members (undifferentiated) of the New Albany Shale (Devonian and Mississippian)

810 Map of Indiana showing thickness of the Ellsworth Member of the New Albany Shale (Devonian and Mississippian)

811 Map of Indiana showing structure on top of Silurian rocks

812 Map of Indiana showing structure on top of the Maquoketa Group (Ordovician)

813 Map of Indiana showing structure on top of the Trenton Limestone (Ordovician)

814 Map of Indiana showing structure on top of the Knox Dolomite (Cambro-Ordovician), Mt. Simon Sandstone (Cambrian), and Precambrian basement complex

815 Map of Indiana showing locations of selected wells that penetrate New Albany Shale (Devonian and Mississippian) and equivalent strata

METC/EGSP Series No.

816 Stratigraphic cross sections showing members of the New Albany Shale (Devonian and Mississippian) in Indiana

817 Stratigraphic cross sections showing the Sunbury, Ellsworth, and Antrim Shales (Devonian and Mississippian) in northern Indiana

M10 Geological Lineament Map: $1^{\circ}x2^{\circ}$ Danville Quadrangle, Indiana and Illinois

M11 Geological Lineament Map: $1^{\circ}x2^{\circ}$ Indianapolis Quadrangle, Indiana and Illinois, and part of the $1^{\circ}x2^{\circ}$ Cincinnati Quadrangle, Indiana

M03 Geological Lineament Map: $1^{\circ}x2^{\circ}$ Vincennes Quadrangle Indiana and Illinois, and part of the $1^{\circ}x2^{\circ}$, Louisville Quadrangle, Indiana

APPENDIX II. EASTERN GAS SHALES SYMPOSIUM PAPERS

1. Bassett, J. L., and Hasenmueller, N. R., 1977, The New Albany Shale and correlative strata in Indiana: Proceedings (for) First Eastern Gas Shales Symposium, Morgantown, W. Va., p. 130-141, 6 figs., 1 table.

2. Bassett, J. L., and others, 1978, Relationship of lineaments to gas production in the New Albany Shale in Indiana: Preprints for Second Eastern Gas Shales Symposium, Morgantown, W. Va., v. 1, p. 251-263, 9 figs.

3. Lechler, P. J., and Leininger, R. K., 1978, Analysis of black shale by inductively coupled plasma: Preprints for Second Eastern Gas Shales Symposium, Morgantown, W. Va., v. 1, p. 273-279, 1 fig., 4 tables.

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7. Shaffer, N. R., and others, 1978, Comparison of the New Albany Shale from deep and shallow parts of the Illinois Basin in Indiana: Preprints for Second Eastern Gas Shales Symposium, Morgantown, W. Va., v. 1, p. 219-229, 6 figs.

APPENDIX III. LOCATIONS OF CORES FROM THE NEW ALBANY SHALE REFERRED TO IN TEXT

1. Sullivan County
   Energy Resources Indiana
   No. 1 Phegley Farms (EGSP IN-1)
   14-6N-10W
   (Core File No. 554)

2. Marion County
   Indiana Geological Survey
   SDH 273 Indianapolis Airport
   27-15N-2E
   (Core File No. 557)

3. Marion County
   Indiana Geological Survey
   SDH 274 Indianapolis Airport
   25-15N-2E
   (Core File No. 558)

4. Marion County
   Indiana Geological Survey
   SDH 275 Indianapolis Airport
   25-15N-2E
   (Core File No. 559)

5. Jackson County
   Indiana Geological Survey
   SDH 291 Schepman
   27-6N-5E
   (Core File No. 578)

6. Clark County
   Indiana Geological Survey
   SDH 290 Clark State Forest (EGSP IN-2)
   Grant 283-2N-7W
   (Core File No. 577)

7. Benton County
   Indiana Geological Survey
   SDH 80 Louis Strassberger
   14-26N-9W
   (Core File No. 226)

8. Brown County
   Indiana Geological Survey
   SDH 241 Moneto Church Camp
   24-9N-3E
   (Core File No. 515)

9. Jackson County
   Fenix and Scisson
   No. 7 Texas Eastern Transmission Corp.
   27-7N-6E
   (Core File No. 539)

10. Lawrence County
    Indiana Geological Survey
    SDH 193 George Armstrong
    28-6N-2W
    (Core File No. 463)

11. Morgan County
    Indiana Geological Survey
    SDH 156 Hydraulic Press Brick Co.
    36-13N-1E
    (Core File No. 336)

12. Putnam County
    Indiana Geological Survey
    SDH 199 Ohio and Indiana Stone Co.
    1-12N-4W
    (Core File No. 474)

13. Vigo County
    Gilliam Drilling Co.
    No. 1 Ina B. Swadener
    35-10N-8W
    (Core File No. 6)

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