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EVALUATION OF DEVONIAN SHALE POTENTIAL IN WEST VIRGINIA

Morgantown
United States Department of Energy
Technology
Center

EVALUATION OF DEVONIAN SHALE POTENTIAL IN WEST VIRGINIA

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NOTICE

PREFACE

This report is a geologic screening effort to evaluate areas within West Virginia that contain sufficient geologic and geochemical characteristics to warrant industry exploration activity. The results are an integration of contractor report data, maps, and logs generated in the Eastern Gas Shales Project. The areas outlined as favorable in this report are those in which the likelihood of encountering gas is greater than elsewhere. Within these areas, local geologic and geochemical factors must be considered as they can dictate success or failure. It is hoped that this information will guide industry activity to the areas of high shale gas potential.

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Project Manager
Eastern Gas Shales

ACKNOWLEDGEMENTS

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Science Applications, Inc.
Tetra Tech, Inc.

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INTRODUCTION

Dark, organic-rich Devonian shales--distributed across more than 10 states from Illinois to Pennsylvania and Michigan to Mississippi, in the contiguous Appalachian, Illinois, and Michigan basins--represent an important natural gas resource. A recent authoritative estimate indicates in-place reserves of gas, entrapped in the matrix and fracture systems of the shale, at 277 to 900 trillion cubic feet (Tcf). Of this, about 20 Tcf of gas are expected to be recoverable using presently available methods (Pulle and Seskus, 1980).

Although geologic and engineering evidence indicates that the volume of natural gas in the eastern Devonian shales is enormous, little of the gas can be recovered by conventional methods. Production to date has been limited to areas where fracturing is present and geochemical parameters are favorable. As a result, although production of gas from Devonian black shales began in 1821 with the drilling of a well near Fredonia, New York, only about 2.5 Tcf of gas have been produced; most (2 Tcf) came from the Big Sandy gas field in eastern Kentucky (Hunter and Young, 1953). Additional production of gas from these eastern gas shales depends on identifying favorable areas for exploration and developing new stimulation techniques that will enhance the rate of gas recovery.

To evaluate the potential of the Devonian shale as a source of natural gas, the U.S. Department of Energy (DOE) has undertaken the Eastern Gas Shales Project (EGSP). The EGSP is designed not only to quantify the resource, but also to test improved methods of inducing porosity and permeability to facilitate gas drainage, collection, and production. The ultimate goal of this project is to increase the production of gas from the eastern shales through advanced exploration and exploitation techniques.

The purpose of this report is to inform interested oil and gas operators about EGSP results as they pertain to the Devonian gas shales of the Appalachian basin in West Virginia. Geologic data and interpretations are summarized, and areas where the accumulation of gas may be large enough to justify commercial production are outlined.

Information on the Devonian shales in West Virginia was compiled from a variety of recent studies. A comprehensive study of the subsurface stratigraphy and gas production of the Devonian shales in West Virginia was conducted by Patchen (1977). West Virginia Devonian shale stratigraphy was studied by Schwietering (1979), who made a thorough surface and subsurface stratigraphic investigation of Upper and Middle Devonian shales throughout the Appalachian basin. He produced a set of stratigraphic cross sections and a series of isopach and structure contour maps of the radioactive Devonian shales in West Virginia from this work. Roen, et al. (1978) also constructed a regional cross section for West Virginia as part of a study of the Devonian black shales in the central portion of the Appalachian basin.

Neal (1979) and Dowse (1980) concentrated on the subsurface stratigraphy of the Devonian sequence and its relationship to gas production in southern and northwestern West Virginia, respectively. Bagnall and Ryan (1976) also reported on Devonian shale geology, reserves, and production characteristics in the southwestern portion of the state. A report by Marten and Nuckols (1976) characterized the geology as well as oil and gas occurrences in Devonian shales in northern West Virginia. A revised map showing producing oil and gas fields in West Virginia was compiled by Cardwell (1976) along with a report on the same topic (1977).

The relationship for the determination of stress ratios in the Devonian shales of the Appalachian basin was developed by Komar and Bolyard (1981). The geochemical data were compiled by Streib (1980).

Because the data presented in this report are generalized and not suitable for evaluation of specific sites for exploration, the reader should consult the various reports cited for more detail and discussion of the data, concepts, and interpretations presented.

SUMMARY AND CONCLUSIONS

In West Virginia, all significant areas of current Devonian shale gas production are situated where the radioactive shale units are thicker than 200 feet. Most areas of current gas production exhibit a close correlation with the trend of the Rome trough structure, and nearly all lie within the optimum stress-ratio zone. In addition, most of the current gas-producing areas are located within the zone of optimum shale thermal maturity, and optimum shale thermal maturity nearly coincides with the optimum shale stress-ratio value (0.43) in western and southwestern West Virginia.

Areas adjacent to existing gas fields, within northeastern Cabell County, northern Lincoln County, and central Wayne County, are excellent prospects for future production. Additional deeper drilling in existing gas fields within the main trend may tap potential new reservoirs in the Rhinestreet and Marcellus Shales. The area east of the Warfield anticline in central Boone, Logan, and eastern Mingo Counties also may be favorable for gas exploitation of the radioactive Huron Shale. Fractures associated with the flank of the anticline and possible reactivation of basement faults in this area should be sufficient to provide the means for production. Further drilling should also be conducted along extensions of the border fault zone of the Rome trough in the western portion of the state. However, the subsurface trend of the trough must be carefully delineated to successfully develop gas production from potential fractured reservoir systems.

GEOLOGIC SETTING AND STRUCTURE

The Devonian shales in West Virginia occupy the stratigraphic section between the lower Middle Devonian Onondaga Limestone and the Lower Mississippian Berea Sandstone. The Devonian shales outcrop in the eastern portion of the state along the Deer Park anticline, around Browns Mountain anticline, and east of the Allegheny Front in the Valley and Ridge province (fig. 1). The shales extend westward in the subsurface from this outcrop area throughout the remainder of the state. Within this area, the shale thickness ranges from less than 1,000 feet in southwestern West Virginia to more than 7,000 feet in the east-central portion of the state (fig. 2).

The major geologic structures existing in West Virginia are shown in figure 3. Of special interest is the regional basement feature (graben) known as the Rome trough. Subsurface stratigraphic data indicate that, although the trough formed during Lower Cambrian time, it influenced sedimentation during deposition of the Devonian, Mississippian, and Pennsylvanian systems. Although some authors Woodward (1961), Silberman (1972), and Horn and others (1976) show normal fault movement for the graben, studies by Heyl (1972) and Murany (personal communication 1980) suggests that right lateral strike-slip fault movement may be the dominant displacement on the Rome trough, and probably has been very influential in causing fractures to be developed in the Devonian shales. The location of the Big Sandy gas field in Kentucky and West Virginia proximal to the Rome trough suggests that accumulation and production is controlled by the fracture system generated by Rome trough movements (Fig. 4). The phenomenon is especially noticeable where recent extensions of the gas field in West Virginia are close to the border fault zones of the trough.

Two additional geologic features shown in figure 3 are the Parsons and Petersburg cross-strike structural discontinuities. Recent studies (Sites, 1978; Wheeler, 1980) have shown that these structural lineaments represent zones of increased fracture intensity within the Middle Devonian shales that the lineaments intersect. The documented presence of more intense jointing in these shales may increase their porosity and permeability, thereby producing a fracture gas reservoir.

A basement depth map of West Virginia is shown in figure 5. Depth to the basement ranges from less than 8,000 feet in the extreme western portion of the state to more than 28,000 feet in the east.

The depth to the base of the Devonian shale (top of the Onondaga Limestone) in West Virginia is presented in figure 6. Depths range from 2,000 feet below sea level in the extreme western portion of the state to more than 6,500 feet below sea level in north-central West Virginia. Actual drilling depths from the surface to the base of the Devonian shales vary from 3,000 feet in western West Virginia to 8,000 feet in the north-central portion of the state (fig. 7).

STRATIGRAPHY

As shown in figure 2, the thickness of the entire Devonian shale sequence ranges from less than 1,000 feet in southwestern West Virginia to more than 7,000 feet in the east-central region of the state. Only about 10 to 60 percent of this interval is black or dark gray, so-called "brown shale", ranging from less than 300 feet to more than 1,000 feet thick (fig. 8). In northern Wayne County, where the total shale section is about 1,000 feet thick, the black shale facies are 600 feet thick (60 percent). These dark shales thin

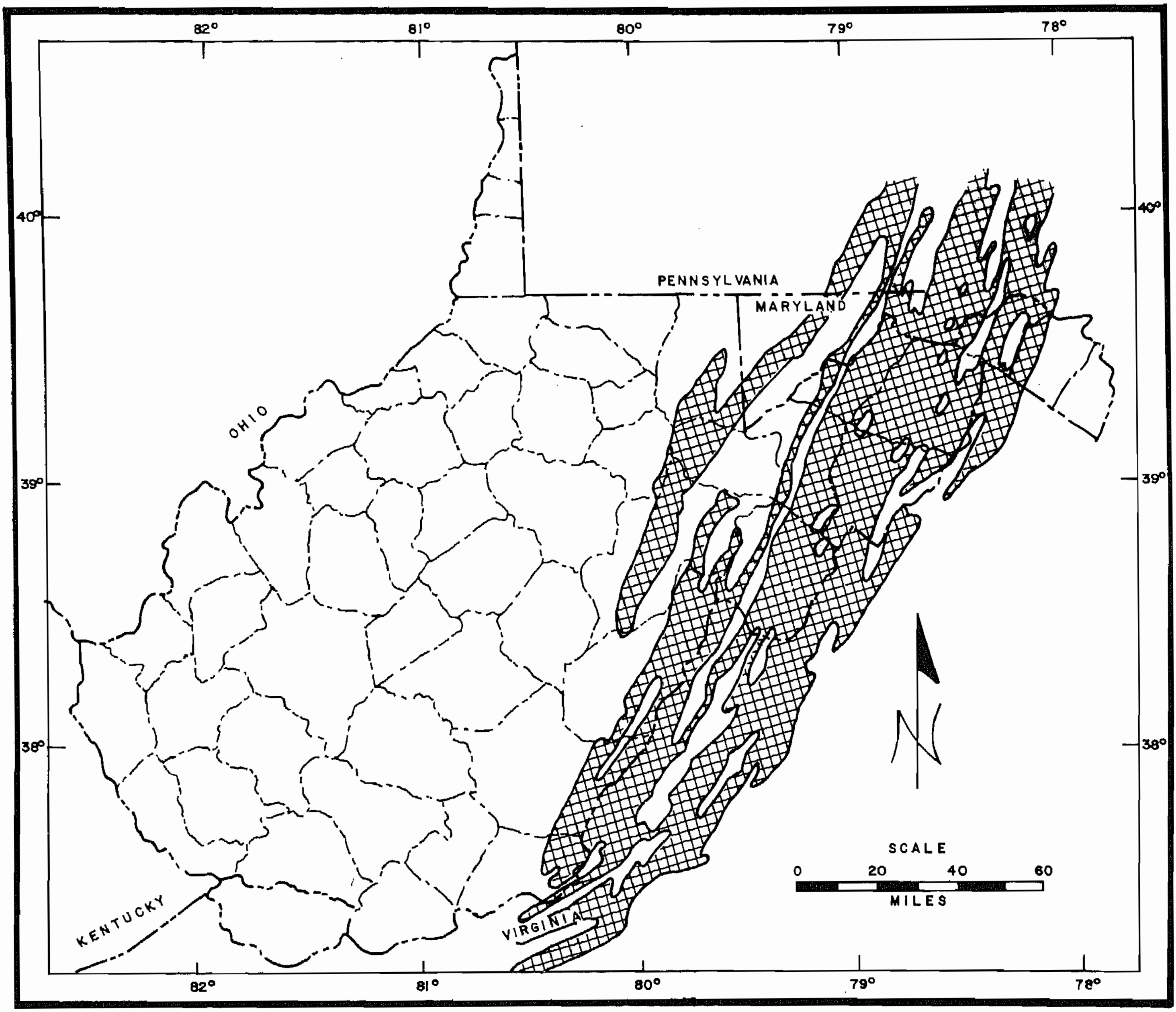

Figure 1. Outcrop areas of the Devonian shales in West Virginia. From SAI (1980), after Patchen (1977).

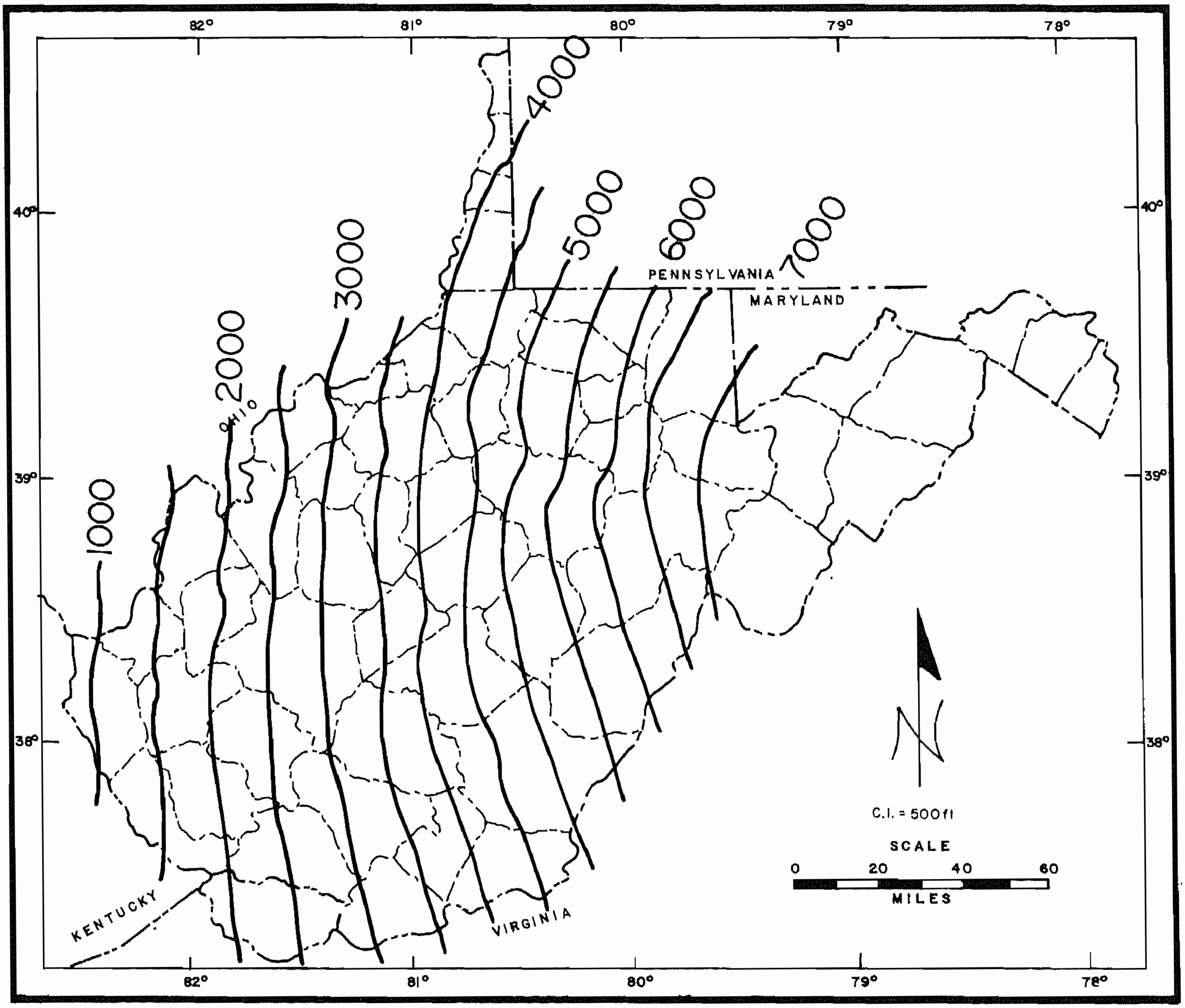

Figure 2. Isopach map of the Devonian shales in West Virginia. From SAI (1980), after Patchen (1977).

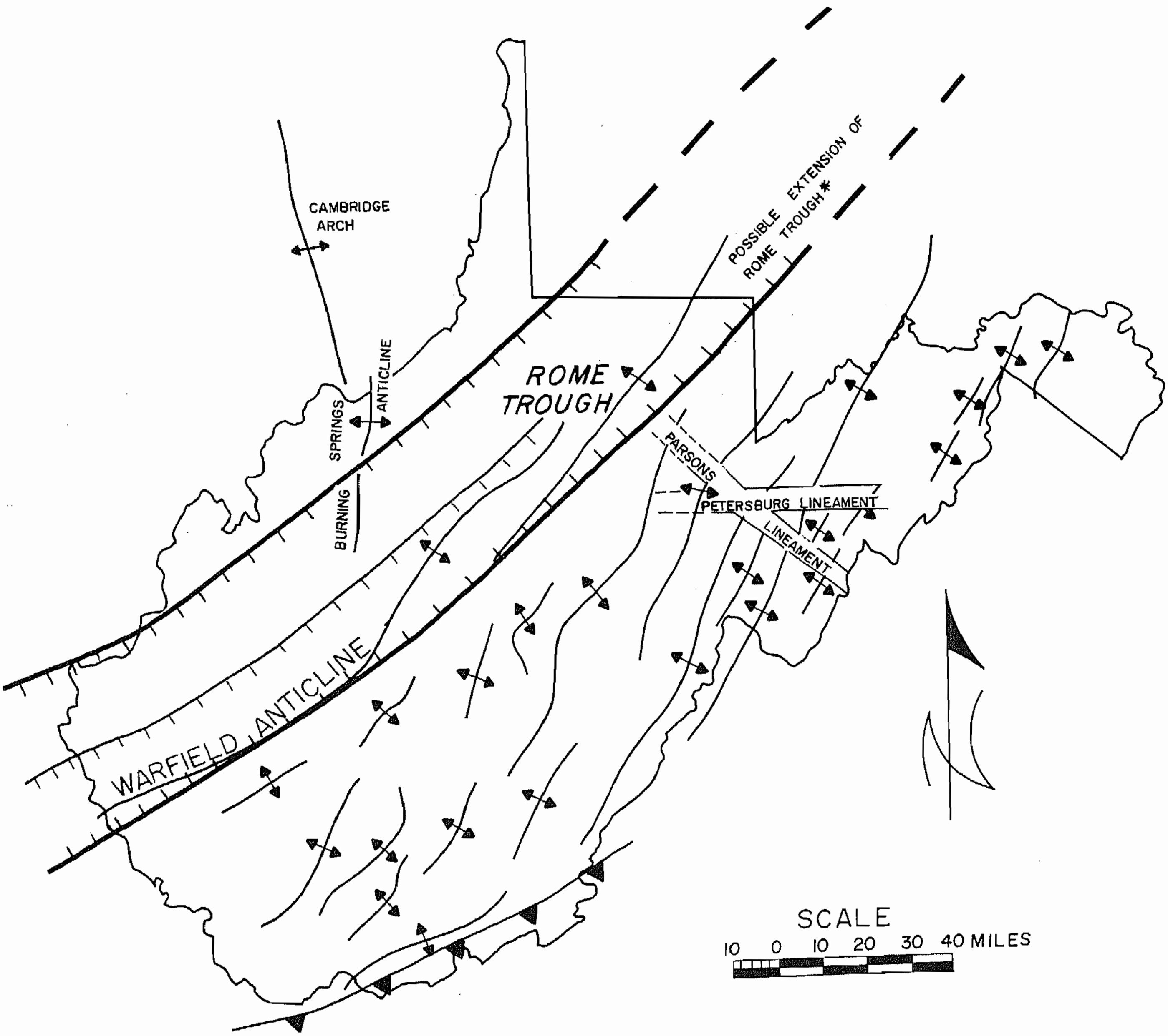

Figure 3. Major geologic structures in West Virginia. From SAI (1980).
*Rome trough extension after Harris (1978).

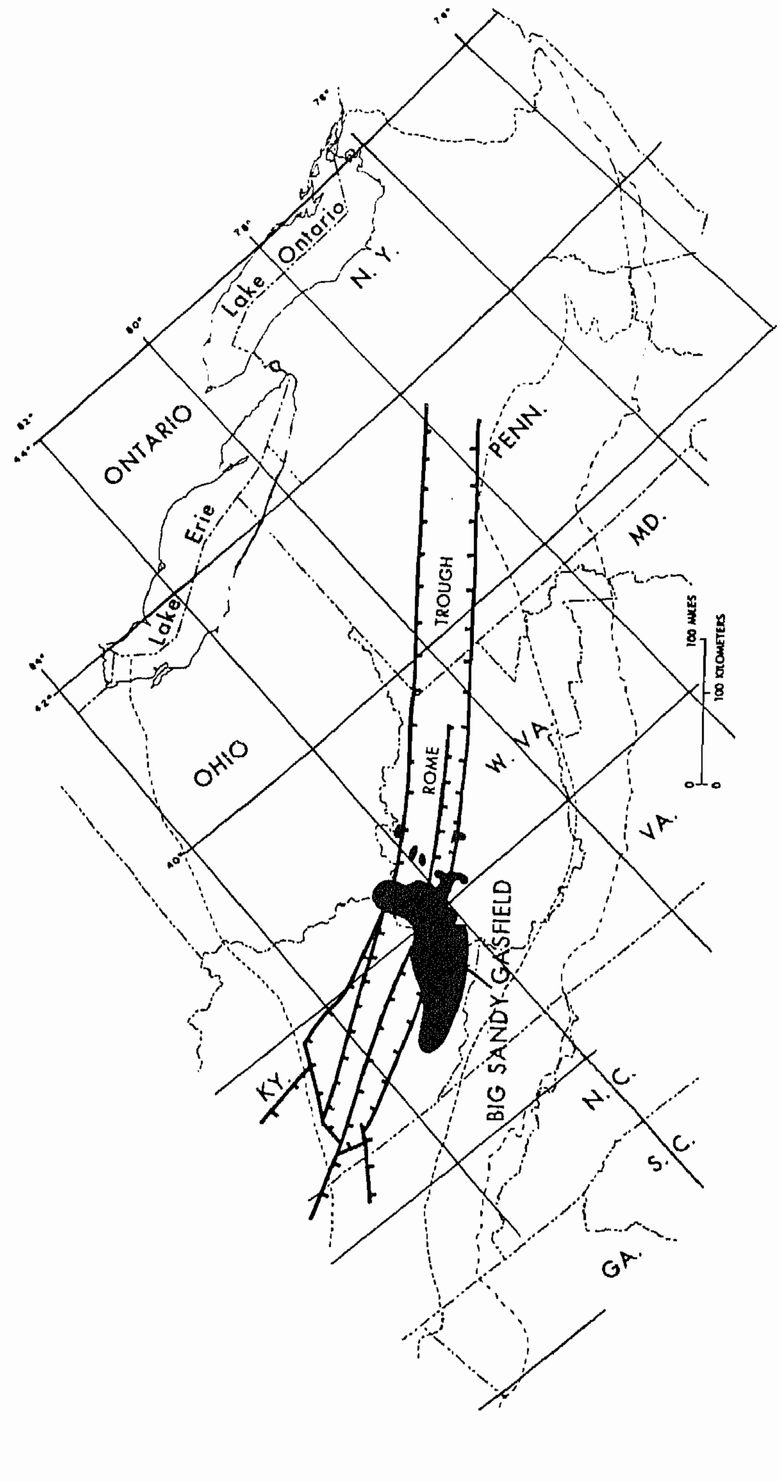

Figure 4. Comparison of the location of the faults of the Rome trough to the Big Sandy gas field in Kentucky and West Virginia. From SAI (1980), after Harris (1978).

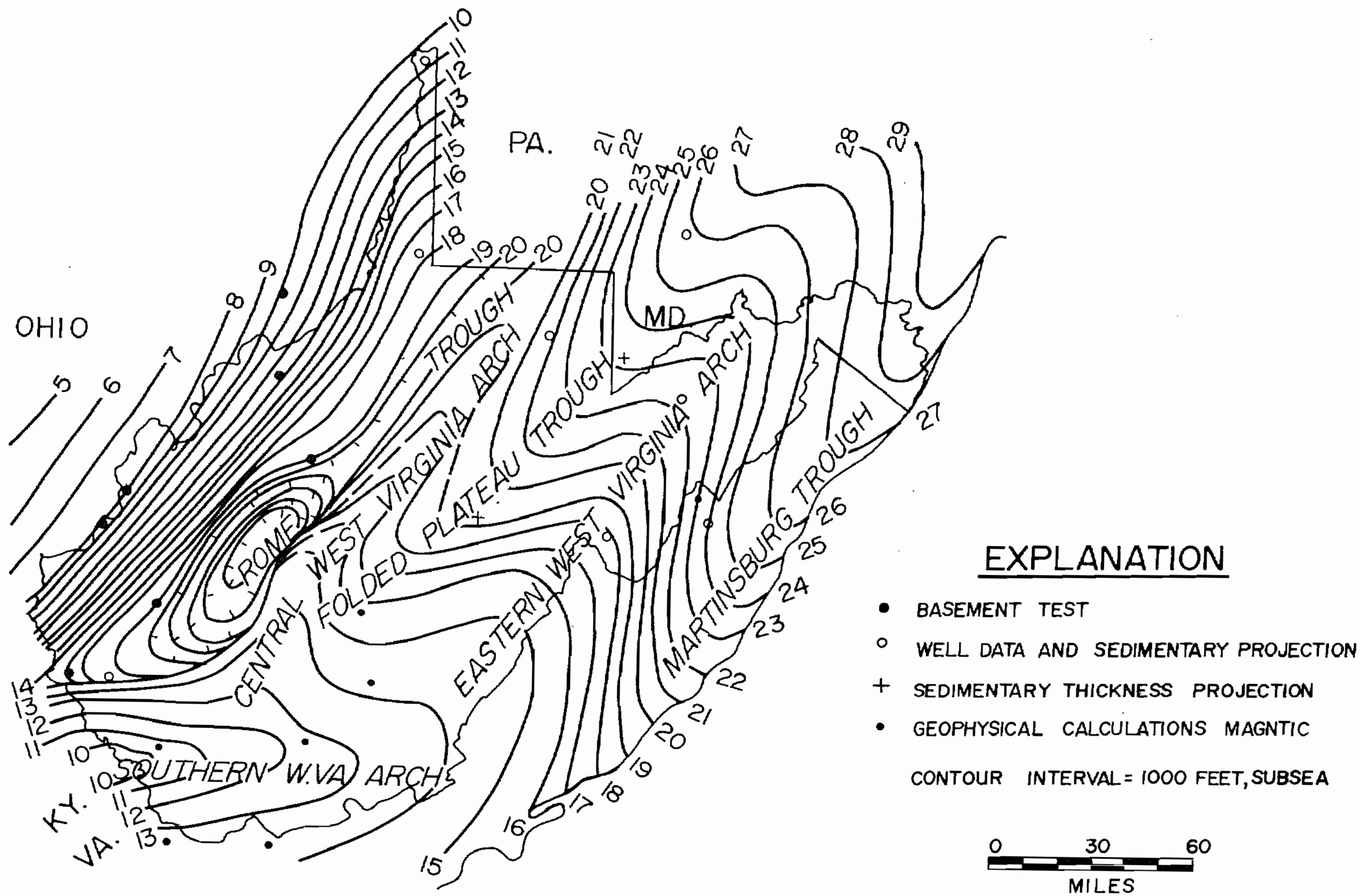

Figure 5. Basement depth map of West Virginia. From SAI (1980), after Kulander, et al. (1977).

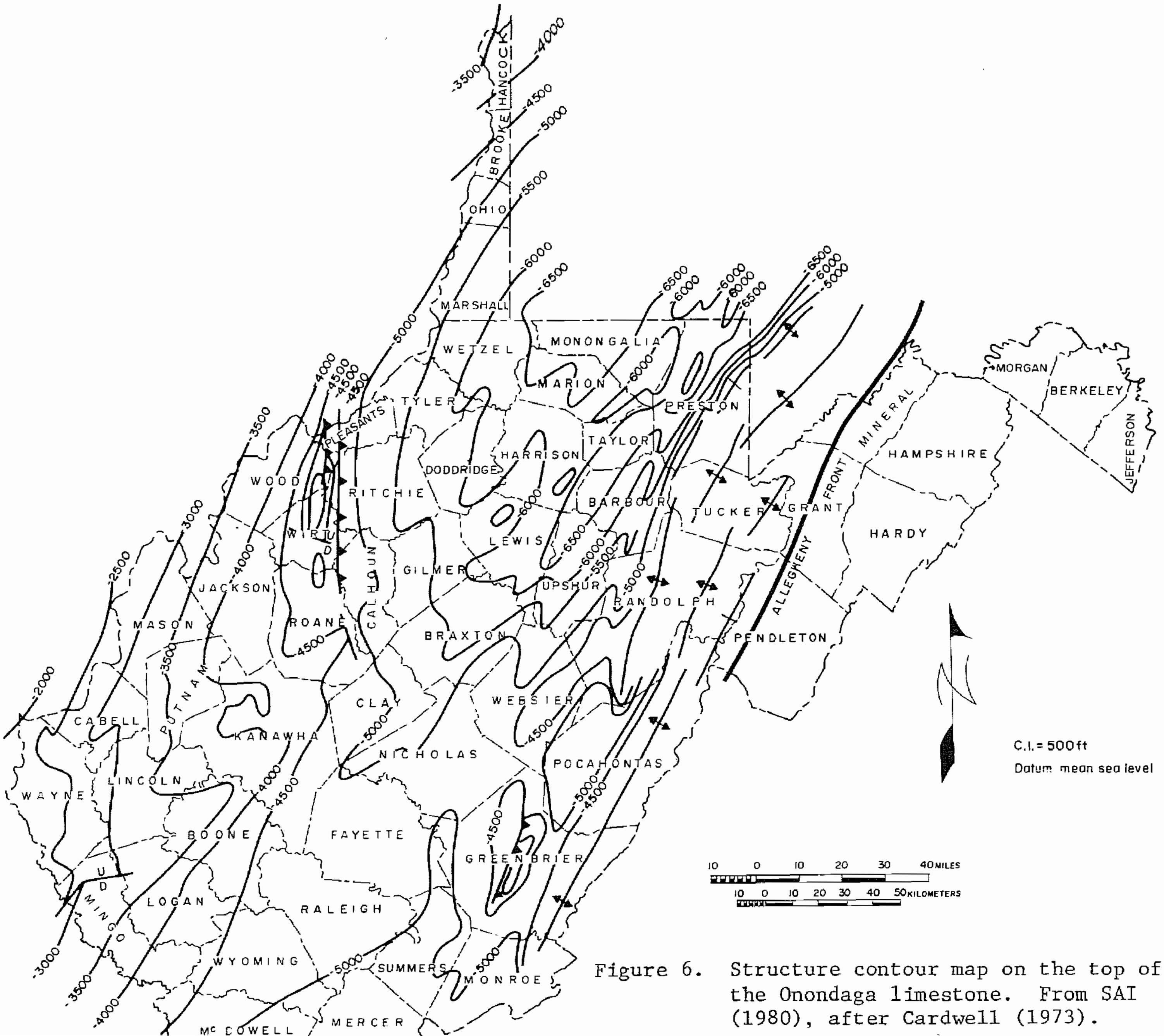

Figure 6. Structure contour map on the top of the Onondaga limestone. From SAI (1980), after Cardwell (1973).

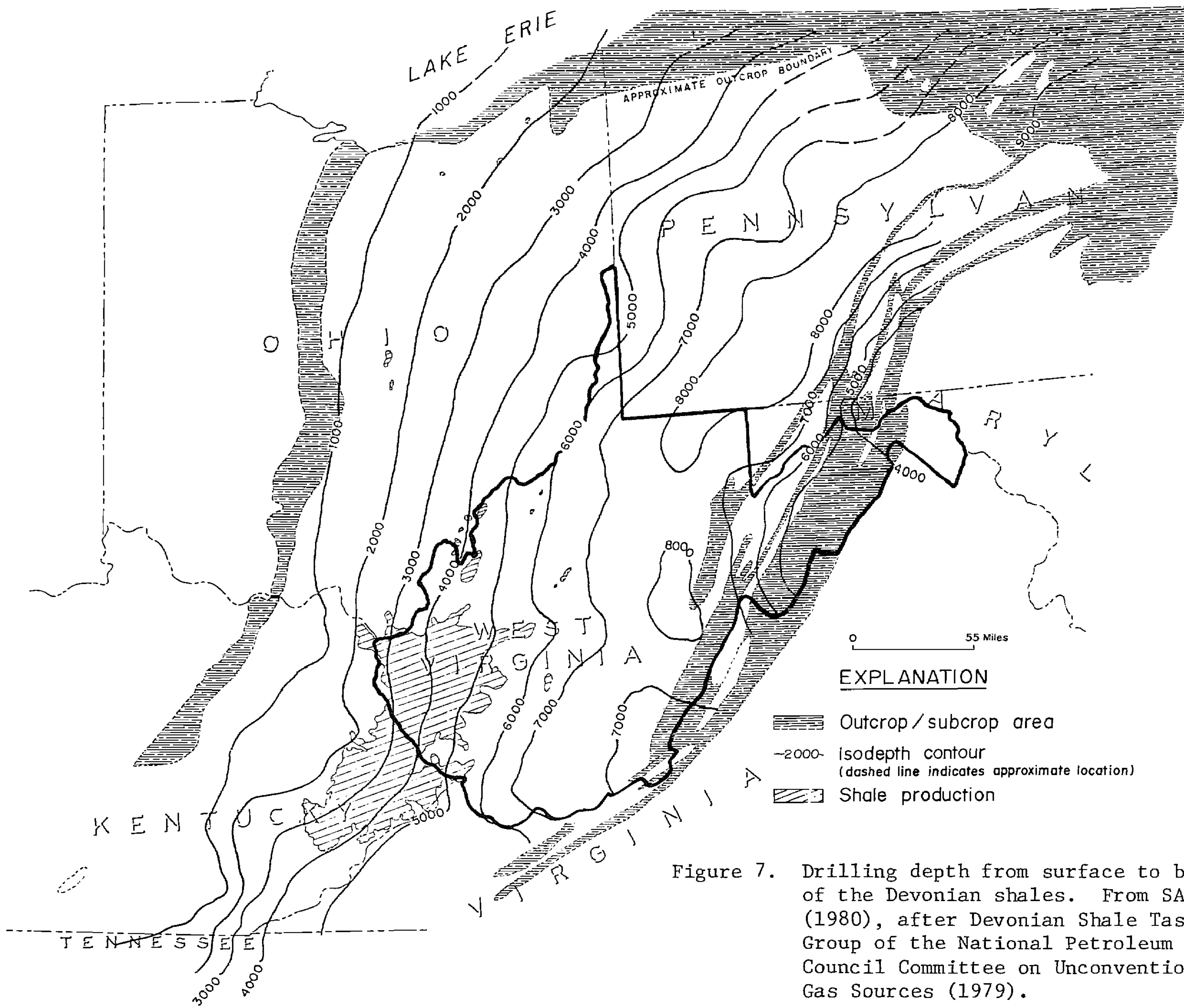

Figure 7. Drilling depth from surface to base of the Devonian shales. From SAI (1980), after Devonian Shale Task Group of the National Petroleum Council Committee on Unconventional Gas Sources (1979).

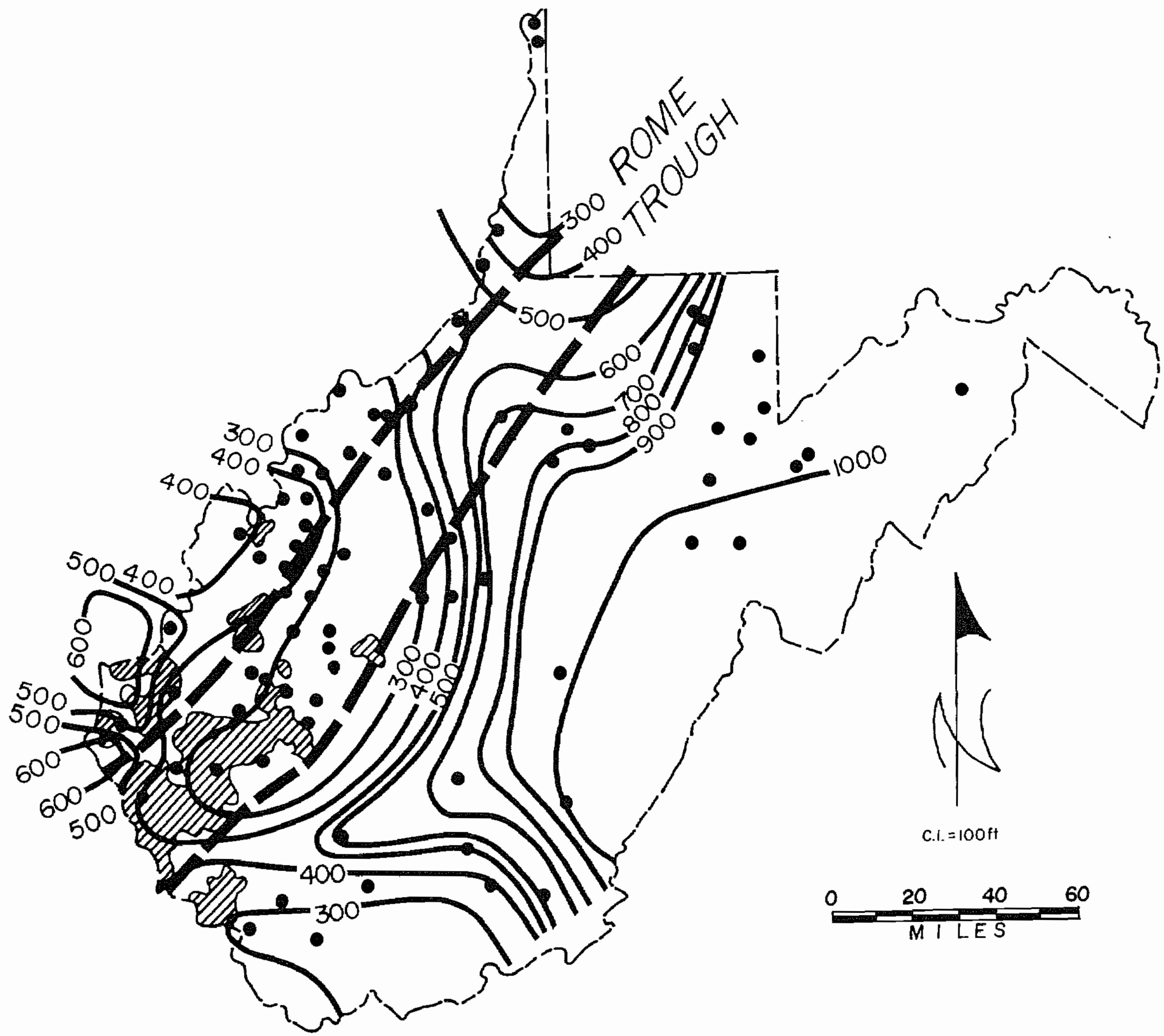

Figure 8. Thickness of the Devonian black shales in West Virginia. From SAI (1980), after Patchen (1977).

eastwardly to about 300 feet thick in northeastern Kanawha County, where the entire section is 3,000 feet thick (10 percent). East of Kanawha County, the black shales thicken to a maximum of 1,000 feet, and the entire shale sequence ranges from 5,000 to 7,000 feet thick (20 to 15 percent). Therefore, even as the black shales thicken to the east, they comprise a smaller percentage of the total Devonian shale section and occur at greater depths.

The total thickness of radioactive shale within the Devonian black shale units is presented in figure 9. Thickness values range from 500 feet in the extreme western area to less than 50 feet in the northern, eastern, and southeastern portions of the state. Aggregate radioactive shale thicknesses average only about 75 feet in the eastern half of West Virginia.

The stratigraphic framework developed for use in the subsurface of West Virginia is based on a combination of Ohio and New York nomenclature (fig.10). Radioactive black shales within the Devonian shale sequence include the Marcellus Shale (Hamilton Group), Geneseo Shale (Genesee Formation), Middlesex Shale (Sonyea Formation), Rhinestreet Shale (West Falls Formation), Pipe Creek Shale (Java Formation), Huron and Cleveland Shales (Ohio Shale Group). The Middle and basal Upper Devonian nomenclature is that used in New York; the Upper Devonian sequence correlates with Ohio terminology.

Generalized stratigraphic cross sections of the Devonian shale sequence in the western two-thirds of West Virginia are presented in plates 1 through 6. These cross sections show the interval thickening to the east and northeast, with facies becoming more coarsely clastic. In the north-central portion of the state, numerous siltstones and sandstones have replaced much of the Devonian shale section, particularly the radioactive black shales. Relatively good lateral continuity of the units is indicated for the western region of the state.

Plates 4 through 6 show the lateral and vertical relationships of the Middle and Upper Devonian sequence in southwestern West Virginia. The cyclic nature of the formations, with a basal high radioactive black shale overlain by less radioactive gray shale and siltstone, is most apparent in the interval between the base of the Ohio Shale and the Middle-Upper Devonian unconformity. The boundaries between formations are not as prominent in the east as in the west, primarily because of the eastward decrease in the volume of radioactive black shale and the corresponding increase in the volume of gray shale and siltstone. These cross sections illustrate the eastward loss of radioactive black shale units above the lower part of the Huron Shale Member of the West Falls Formation.

Marcellus Shale

The Marcellus Shale is the only recognizable formation of the Hamilton Group in West Virginia and is more widespread in its geographical distribution than any of the other radioactive Devonian shales. The Marcellus attains its maximum thickness of nearly 125 feet in the north-central portion of the state (fig. 11). The elevation of the base of the Marcellus approximately corresponds to the elevation of the base of the Devonian shales in West Virginia (fig. 6), ranging from 2,000 feet below sea level in the southwest to more than 6,500 feet below sea level in the north-central area of the state.

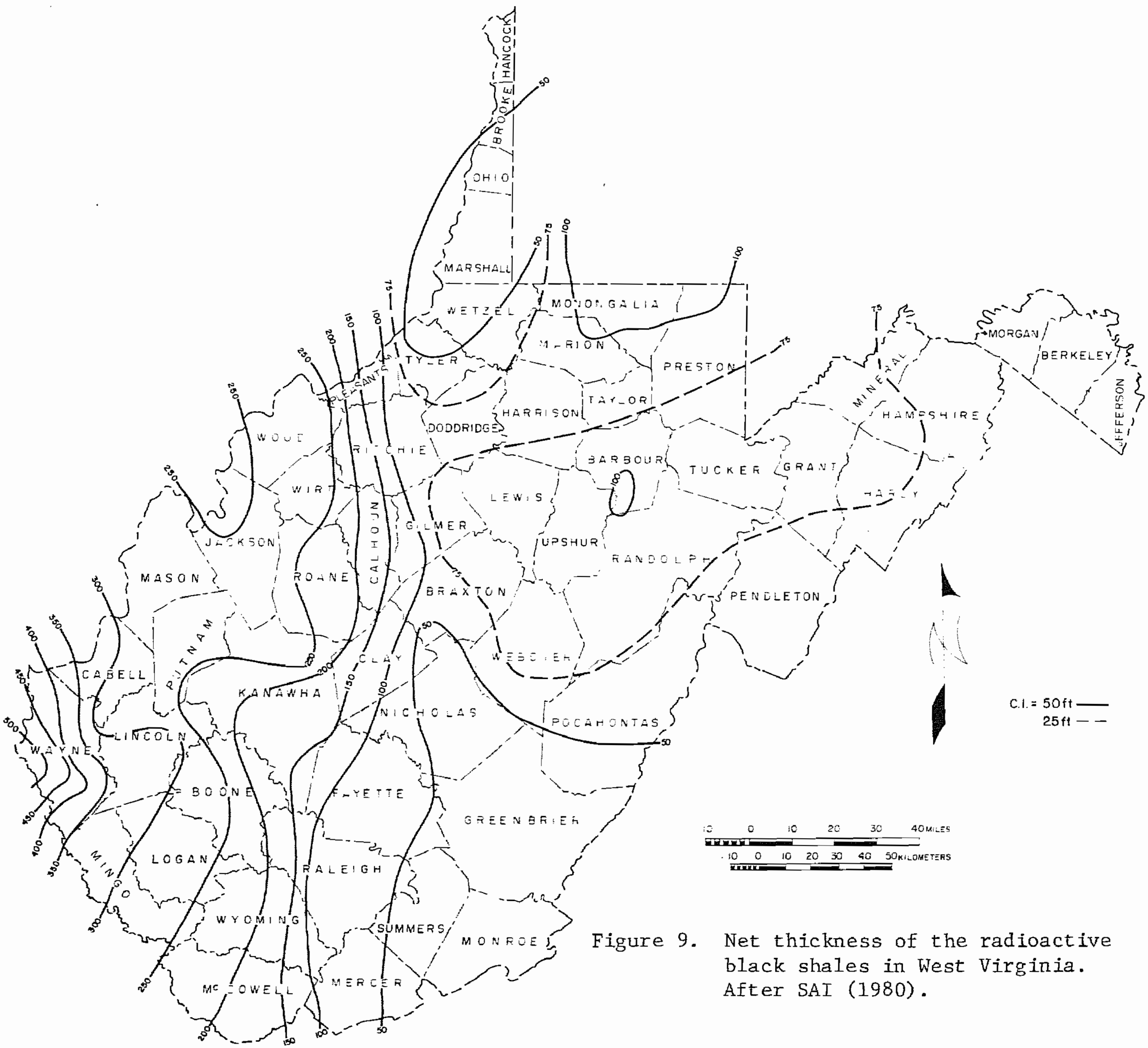

Figure 9. Net thickness of the radioactive black shales in West Virginia. After SAI (1980).

	OHIO	VIRGINIA	PENNSYLVANIA / WEST VIRGINIA	NEW YORK		
	BEREA SANDSTONE	POCONO FORMATION	POCONO FORMATION		MISSISSIPPIAN	
	BEDFORD SHALE					
OHIO SHALE	CLEVELAND MEMBER	HAMPSHIRE FORMATION	HAMPSHIRE FORMATION	CONEWANGO GROUP	DEVONIAN	UPPER
	CHAGRIN SHALE	CHEMUNG FORMATION	CHEMUNG FORMATION	CONNEAUT GROUP		
	HURON MEMBER			CANADAWAY GROUP		
	UPPER OLENTANGY SHALE	BRALLIER FORMATION	BRALLIER FORMATION	JAVA FORMATION		
				WEST FALLS FORMATION		
			HARRELL SHALE	SONYEA FORMATION		
		MILLBORO SHALE	BURKET SHALE	GENESEE FORMATION		
	LOWER OLENTANGY SHALE		TULLY LIMESTONE	TULLY LIMESTONE		MIDDLE
			MAHANTANGO FORMATION	MOSCOW FORMATION		
				LUDLOWVILLE FORMATION		
				SKANEATELES FORMATION		
			MARCELLUS SHALE	MARCELLUS SHALE		
	DELAWARE LIMESTONE COLUMBUS LIMESTONE	ONONDAGA LIMESTONE/ HUNTERSVILLE CHERT NEEDMORE SHALE/	ONONDAGA FORMATION	ONONDAGA LIMESTONE		

Figure 10. Stratigraphic nomenclature of Middle and Upper Devonian strata in the Appalachian basin. After Neal (1979), with modifications.

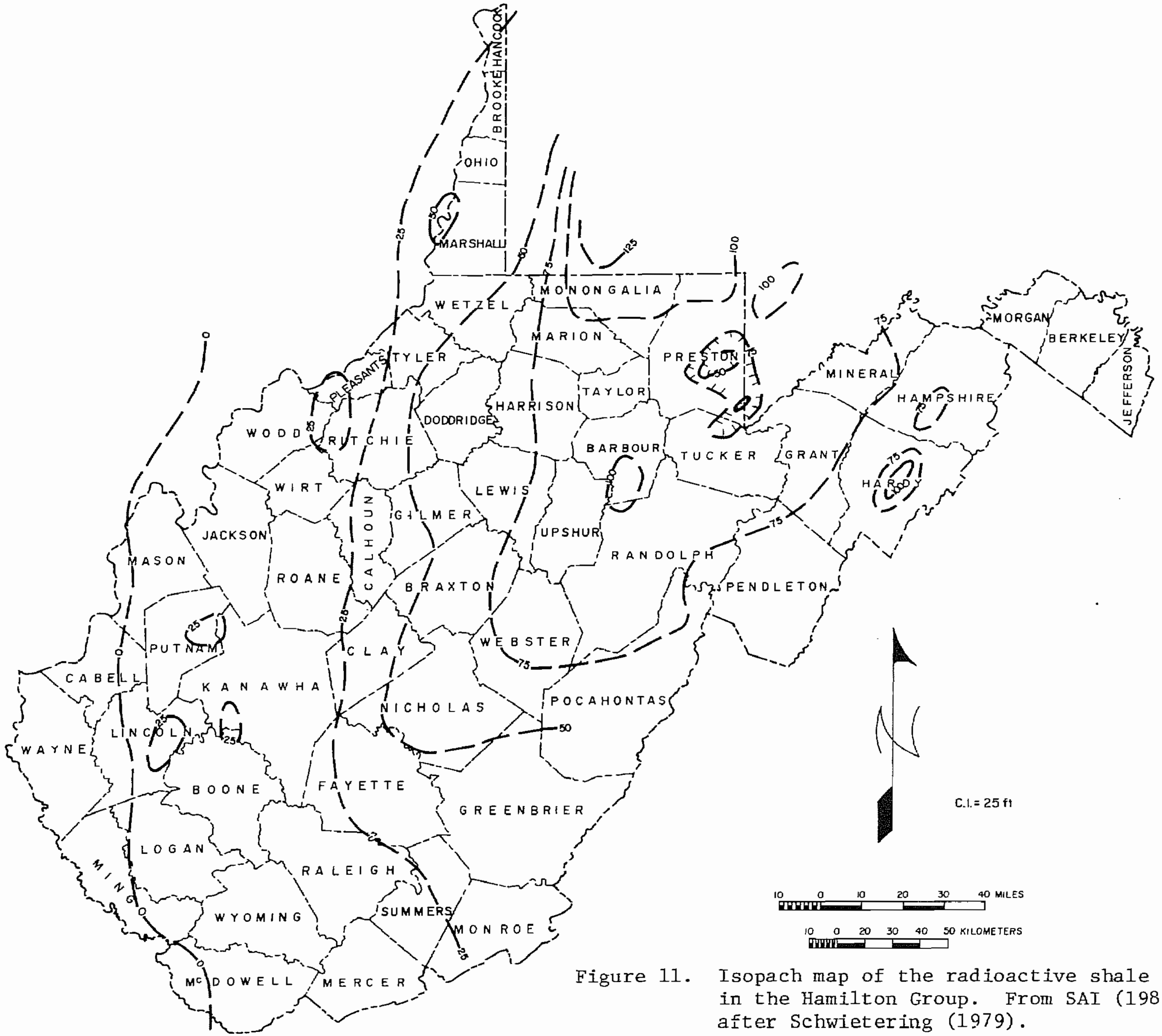

Figure 11. Isopach map of the radioactive shale in the Hamilton Group. From SAI (1980), after Schwietering (1979).

Genesee Formation

The Genesee Formation exists within the central portions of West Virginia, where its maximum thickness of about 25 feet occurs at several scattered locations (fig. 12). The elevation of the base of the Genesee ranges from 3,000 feet below sea level in the southwest to 6,300 feet below sea level in the north-central portion of the state (fig. 13). In southwestern West Virginia, the Genesee Formation has been separated into the Geneseo Shale and West River Shale Members (plates 4 and 5). The Geneseo Shale, the basal member of the formation, is a black pyritic shale with some minor olive-gray to black siltstone. The Geneseo varies from zero to 30 feet thick in West Virginia. The radioactivity of the Geneseo is higher than the overlying West River Shale, but is significantly lower than the underlying Marcellus Shale. The West River Shale Member represents the upper unit of the Genesee cycle and occurs in West Virginia as a dark gray shale containing olive-gray siltstone. The thickness of this unit varies from zero to slightly more than 100 feet.

Sonyea Formation

The Sonyea Formation exists in the western two-thirds of the state and reaches a maximum thickness of slightly more than 50 feet (fig. 14). The elevation of the base of the Sonyea occurs at 2,500 feet below sea level in the western portion of the state and deepens to more than 6,000 feet below sea level in the north-central region (fig. 15). In West Virginia, the Sonyea Formation is comprised of the Middlesex and Cashaqua Shale Members. The Middlesex is the basal black shale of the depositional cycle and is zero to 30 feet thick. The Cashaqua Shale Member overlies the Middlesex and is further divided into two intervals in southwestern West Virginia--beds α and β (plates 4 through 6). Bed α consists of medium-dark to dark gray shale with interbedded olive-gray to olive-black siltstone and varies from zero to 200 feet thick. The boundary between beds α and β is evidenced by a considerable shift from lower (bed α) to higher (bed β) radioactivity. Bed β is comprised of interbedded black shale and dark gray siltstone and ranges in thickness from zero to more than 600 feet.

West Falls Formation

The radioactive shale facies of the West Falls Formation is present throughout the western half of the state and reaches its greatest thickness of 125 feet in the northwest area (fig. 16). In West Virginia, the West Falls Formation is comprised of two units--the Angola Shale Member, a gray silty shale with scattered siltstone, and the Rhinestreet Shale Member, a basal black shale. The Angola has been further subdivided in the southwestern portion of the state into two subunits, α and β (plates 4 through 6). Unit α contains interbedded gray siltstone and shale and ranges in thickness from less than 50 feet to more than 250 feet. Unit β is composed primarily of slightly calcareous, gray siltstone and varies in thickness from 40 to 120 feet. The Rhinestreet Shale Member is a massive black, pyritic shale with minor amounts of siltstone, and has a high radioactivity. The elevation of the base of the West Falls ranges from 2,000 feet below sea level in the extreme western part of the state to more than 5,500 feet below sea level in the north-central region (fig. 17).

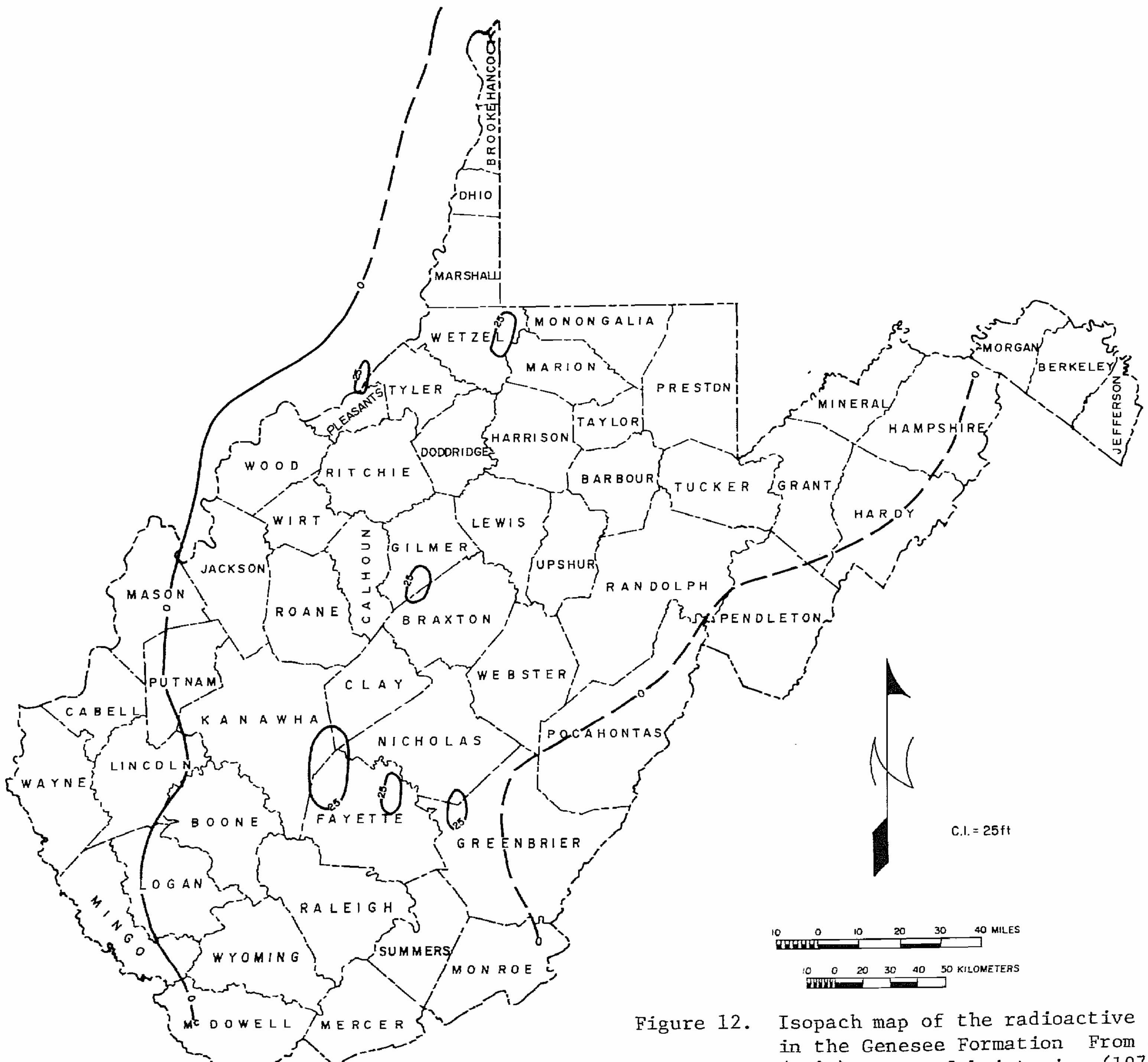

Figure 12. Isopach map of the radioactive shale in the Genesee Formation From SAI

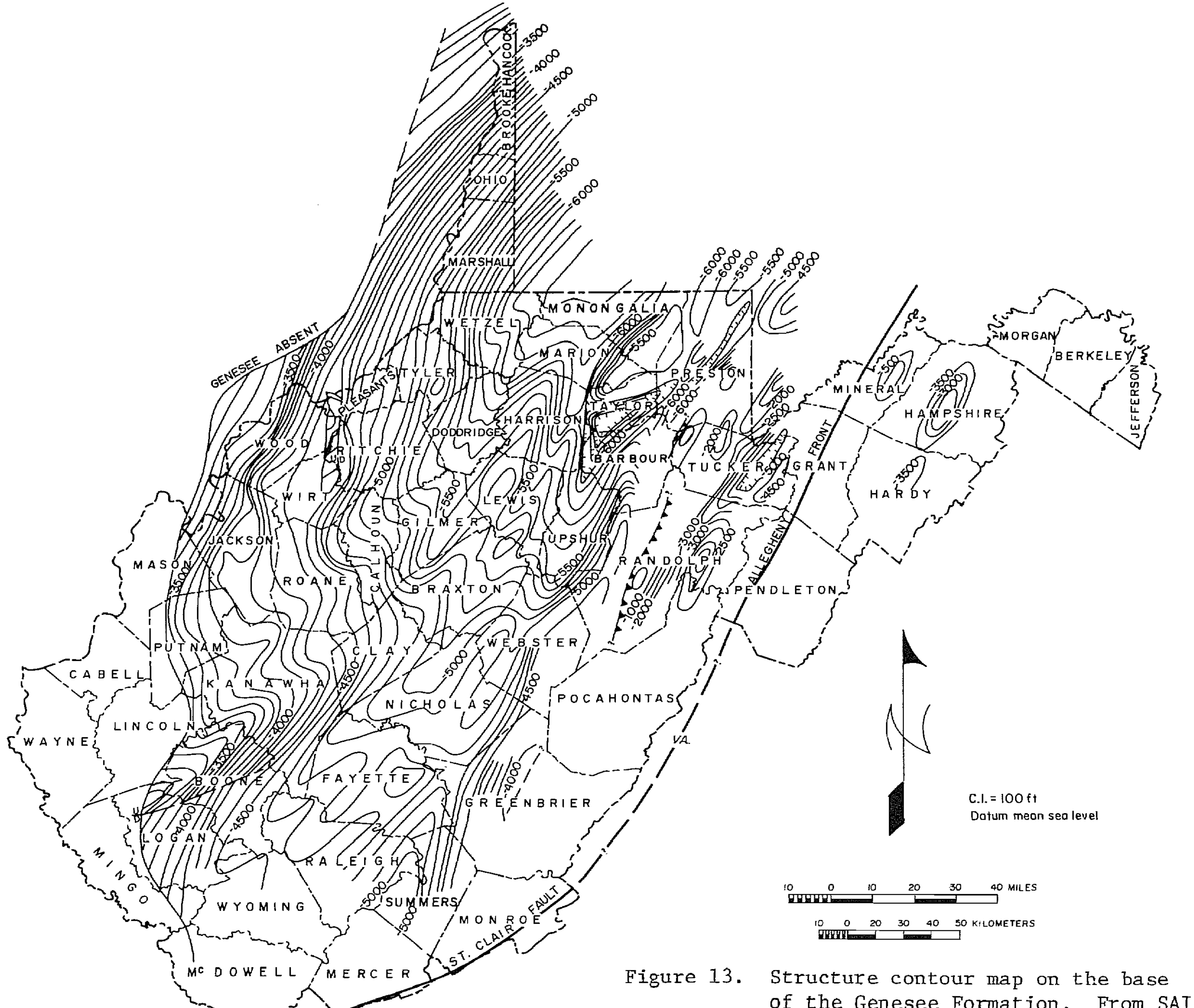

Figure 13. Structure contour map on the base of the Genesee Formation. From SAI (1980), after Schwietering (1979).

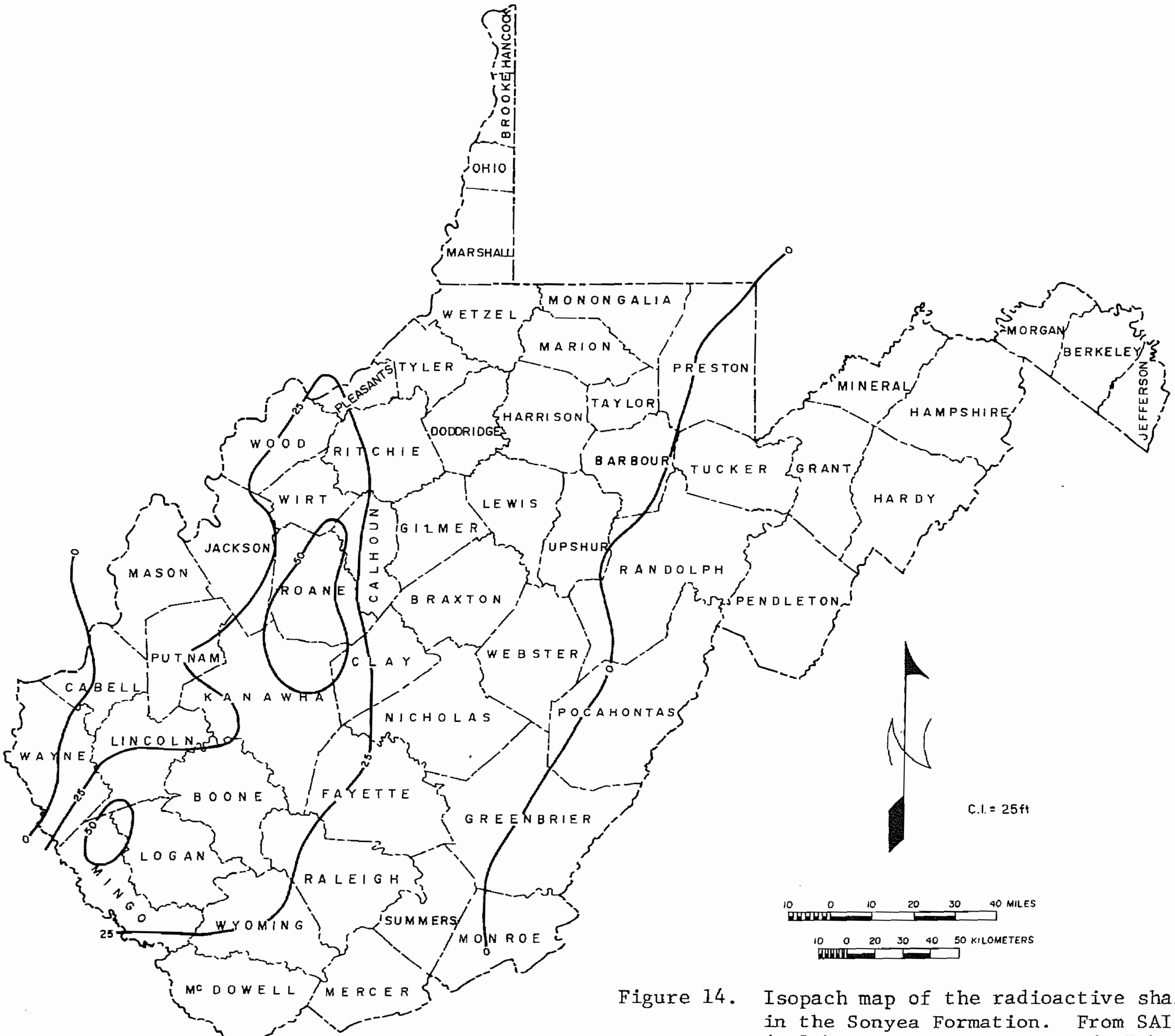

Figure 14. Isopach map of the radioactive shale in the Sonyea Formation. From SAI (1980), after Schwietering (1979).

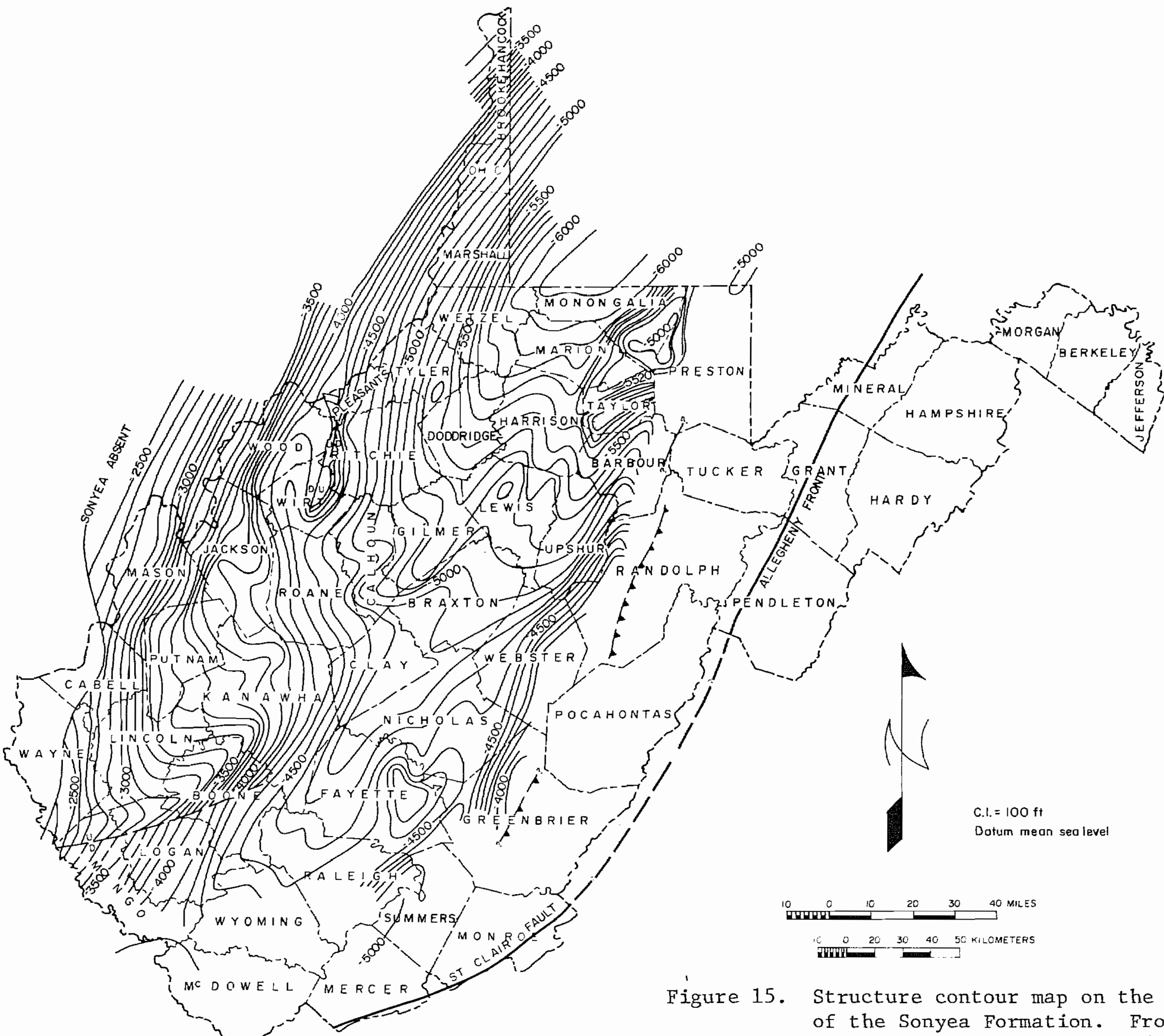

Figure 15. Structure contour map on the base of the Sonyea Formation. From SAI (1980), after Schwietering (1979).

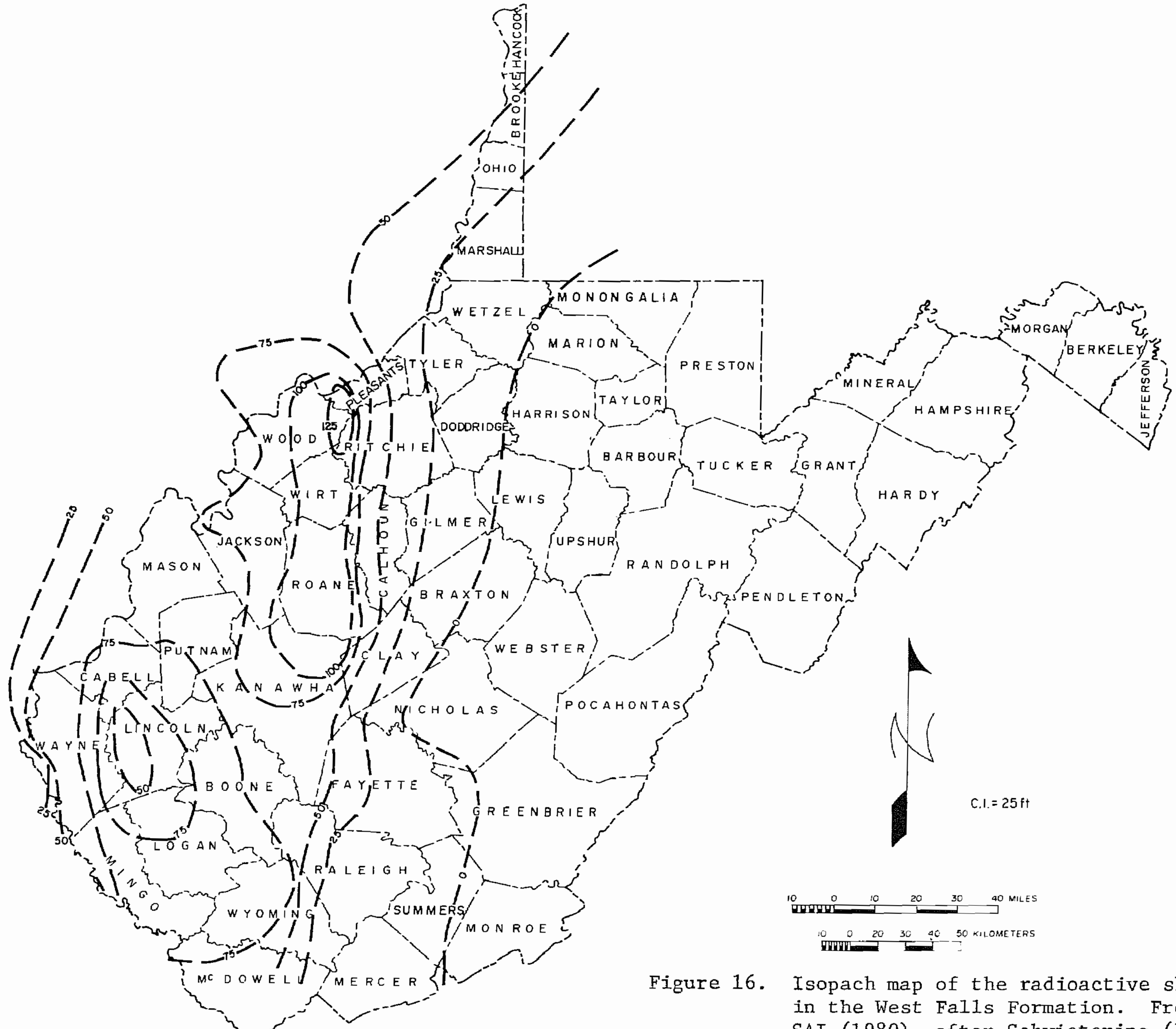

Figure 16. Isopach map of the radioactive shale in the West Falls Formation. From SAI (1980), after Schwietering (1979).

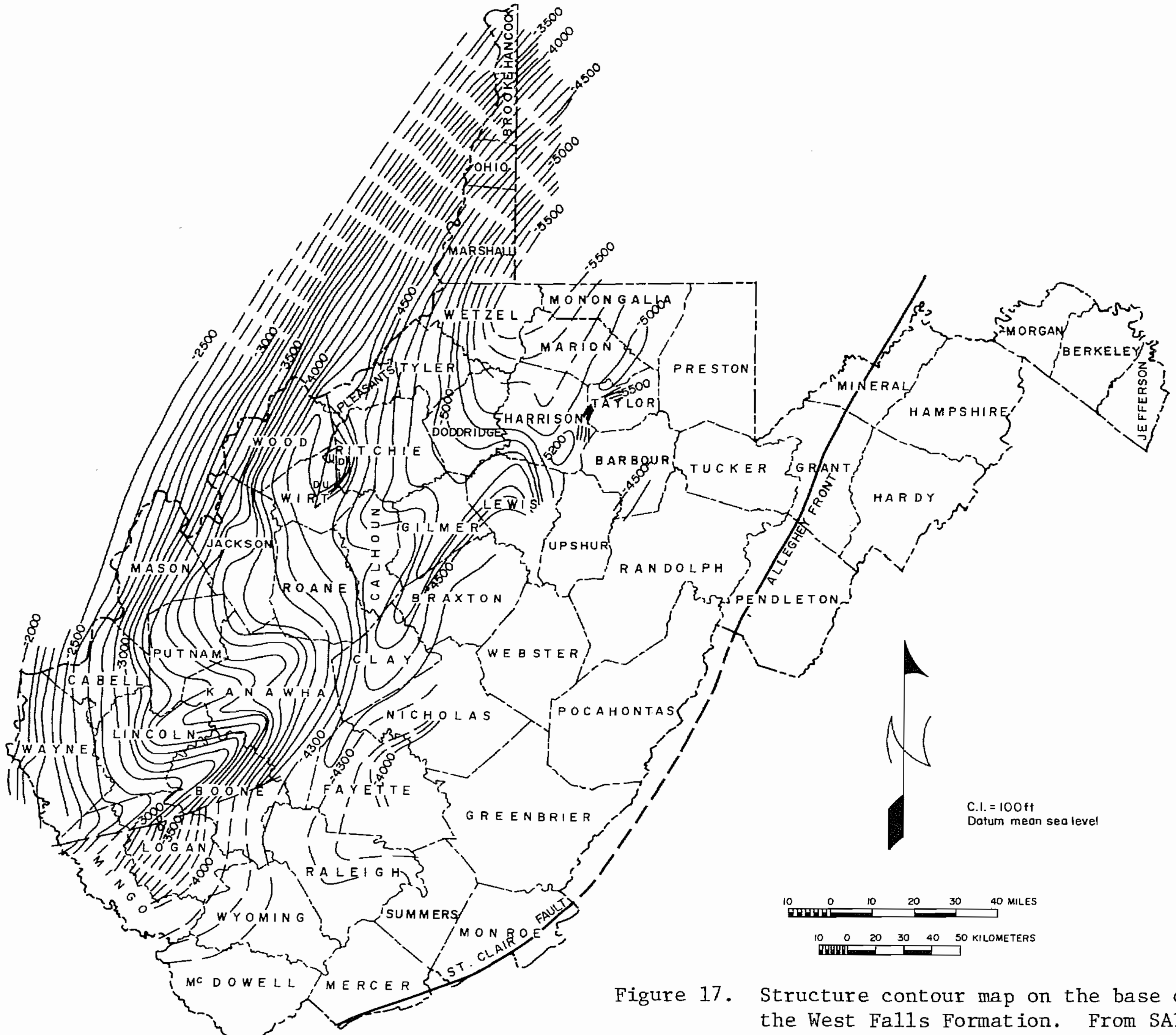

Figure 17. Structure contour map on the base of the West Falls Formation. From SAI (1980), after Schwietering (1979).

Java Formation

The Java Formation occurs only in the western third of the state where it attains a maximum thickness of slightly more than 25 feet (fig. 18). The elevation of the base of the Java varies from 2,000 feet below sea level in western Wayne County to 4,500 feet below sea level in north-central West Virginia (fig. 19). In southeastern West Virginia, two informal subdivisions of the Java are identified, which do not correspond to members recognized in the New York stratigraphic section (plates 4 through 6). The lower section, bed α , is an interval of interbedded shale and siltstone that ranges in thickness from 60 to 200 feet. The upper unit, bed β , is a 30 to 55 foot thick calcareous siltstone which exhibits a lower radioactivity than the overlying Huron Member of the Ohio Shale in southwestern West Virginia.

Huron Shale Member

The radioactive shale facies of the Huron Shale Member of the Ohio Shale occurs throughout the western half of the state and attains a maximum thickness of about 400 feet (fig. 20). The Huron accounts for most of the radioactive shale thickness in the western half of West Virginia, as shown in figure 8. The basal portion of the Huron Shale correlates with the Dunkirk Shale of New York. The elevation of the base of the Huron ranges from 2,000 feet below sea level in the westernmost region of the state to 4,000 feet below sea level in north-central West Virginia (fig. 21). The lower part of the Huron is a massive interval of highly radioactive black shale, with increasing interbeds of less radioactive gray shale near the top of the unit. Due to its geographical distribution and thickness, the lower section of the Huron should prove to be the single most important radioactive shale unit in terms of gas exploration. The upper zone of the Huron is a tongue of black shale that originates in the main black shale body to the west and thins to the east. This tongue is separated from the lower portion of the Huron by a section of Chagrin Shale, which thins to the west and eventually pinches out in the black shale of the Huron. The lower portion of the Huron intertongues with and feathers out in gray silty shale to the east (plates 1, 2, and 4).

Chagrin Shale

The Chagrin Shale occupies the interval between the Cleveland and Huron Members of the Ohio Shale. The Chagrin is composed of gray silty shale and siltstone. In West Virginia, the Chagrin is easily recognized where both the Cleveland and Huron Members of the Ohio Shale exist, but is not readily discernible from coarser eastern equivalents. Boundaries are indistinct as a result of intensive intertonguing between the Huron and Chagrin Shales (plates 4 through 6).

Cleveland Shale Member

The Cleveland Shale Member of Ohio Shale is the eastward extension of the youngest major unit of the Ohio Shale. The Cleveland occurs only in southwestern West Virginia where its maximum thickness is only about 25 feet

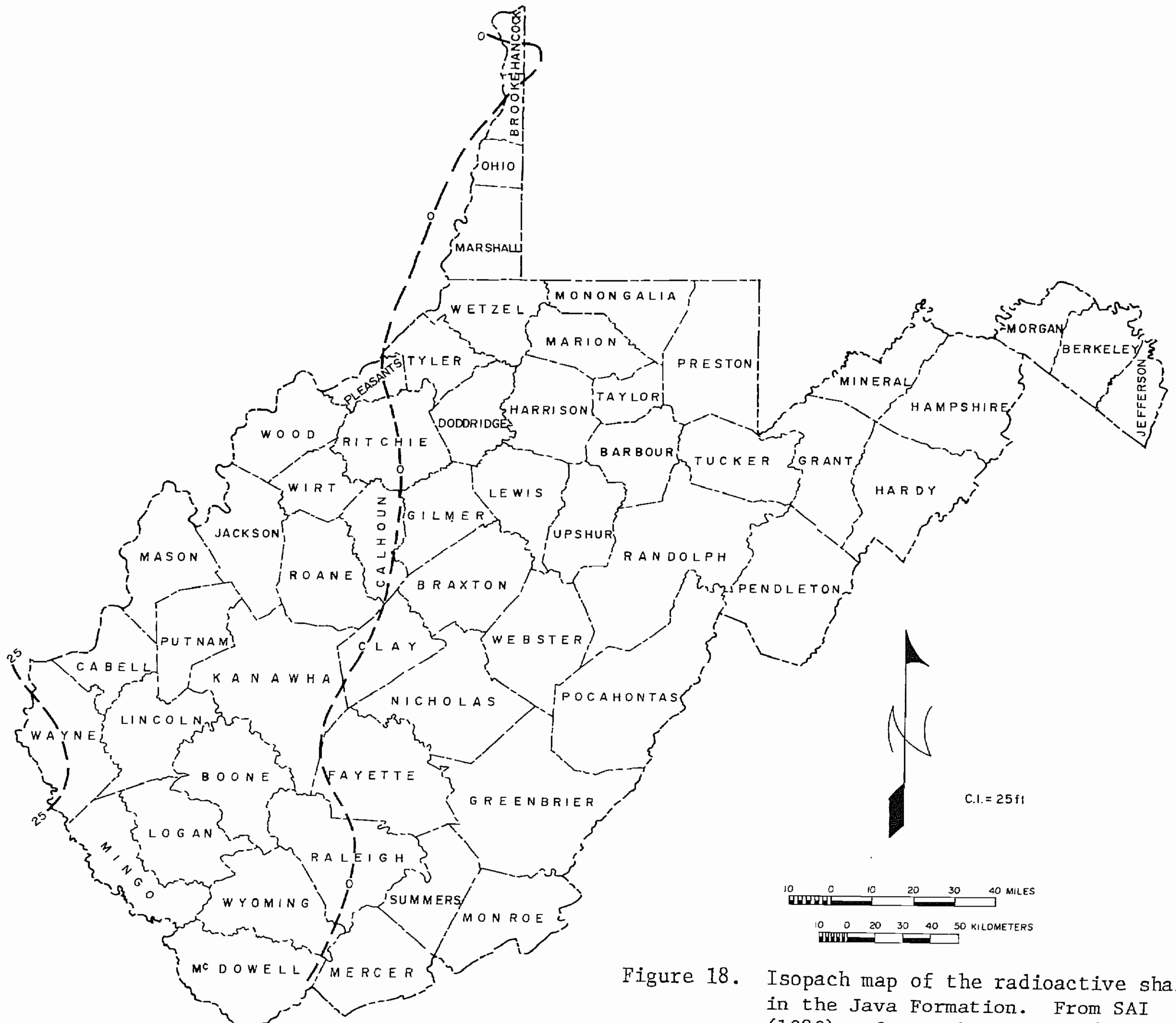

Figure 18. Isopach map of the radioactive shale in the Java Formation. From SAI (1980), after Schwietering (1979).

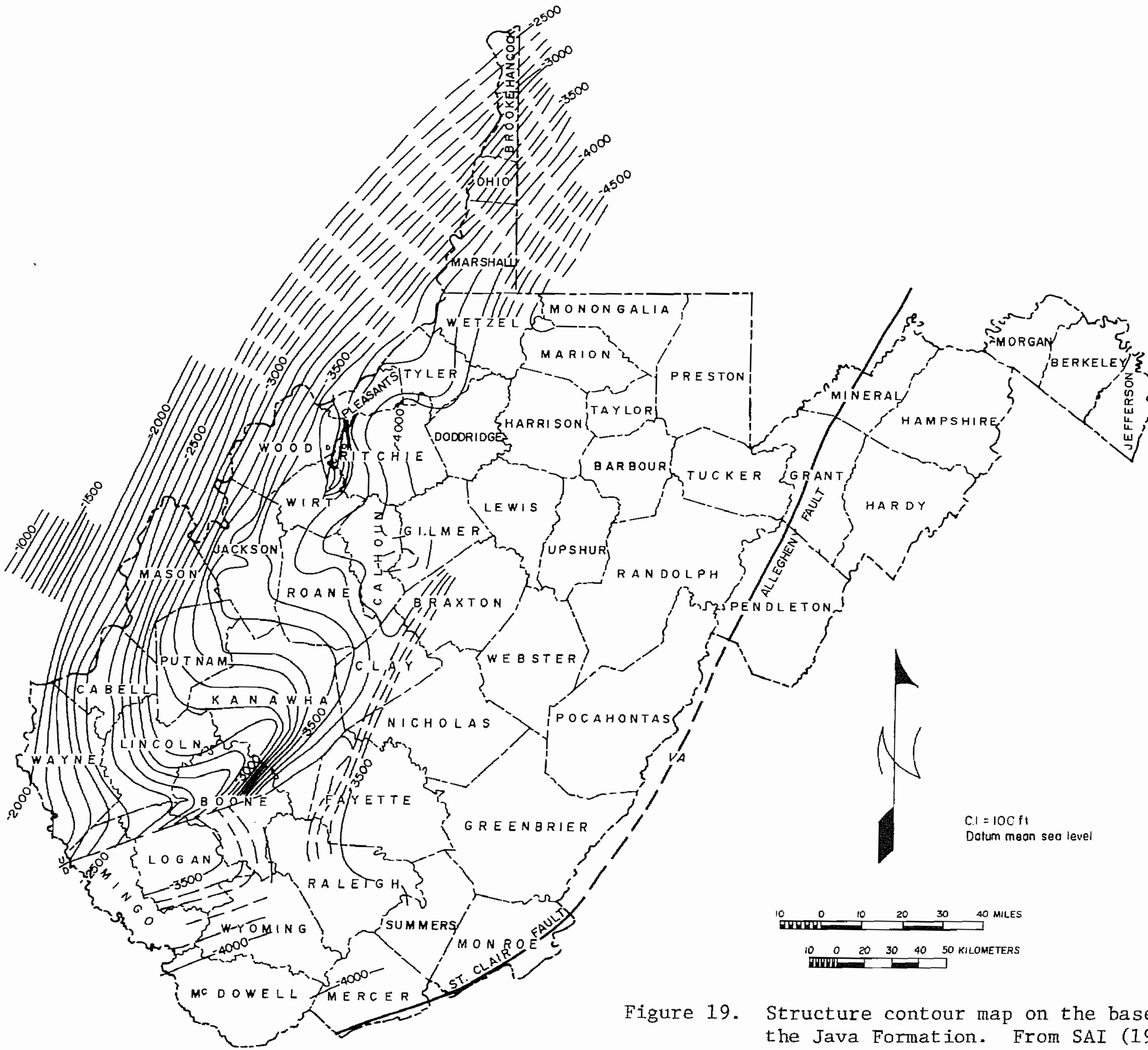

Figure 19. Structure contour map on the base of the Java Formation. From SAI (1980), after Schwietering (1979).

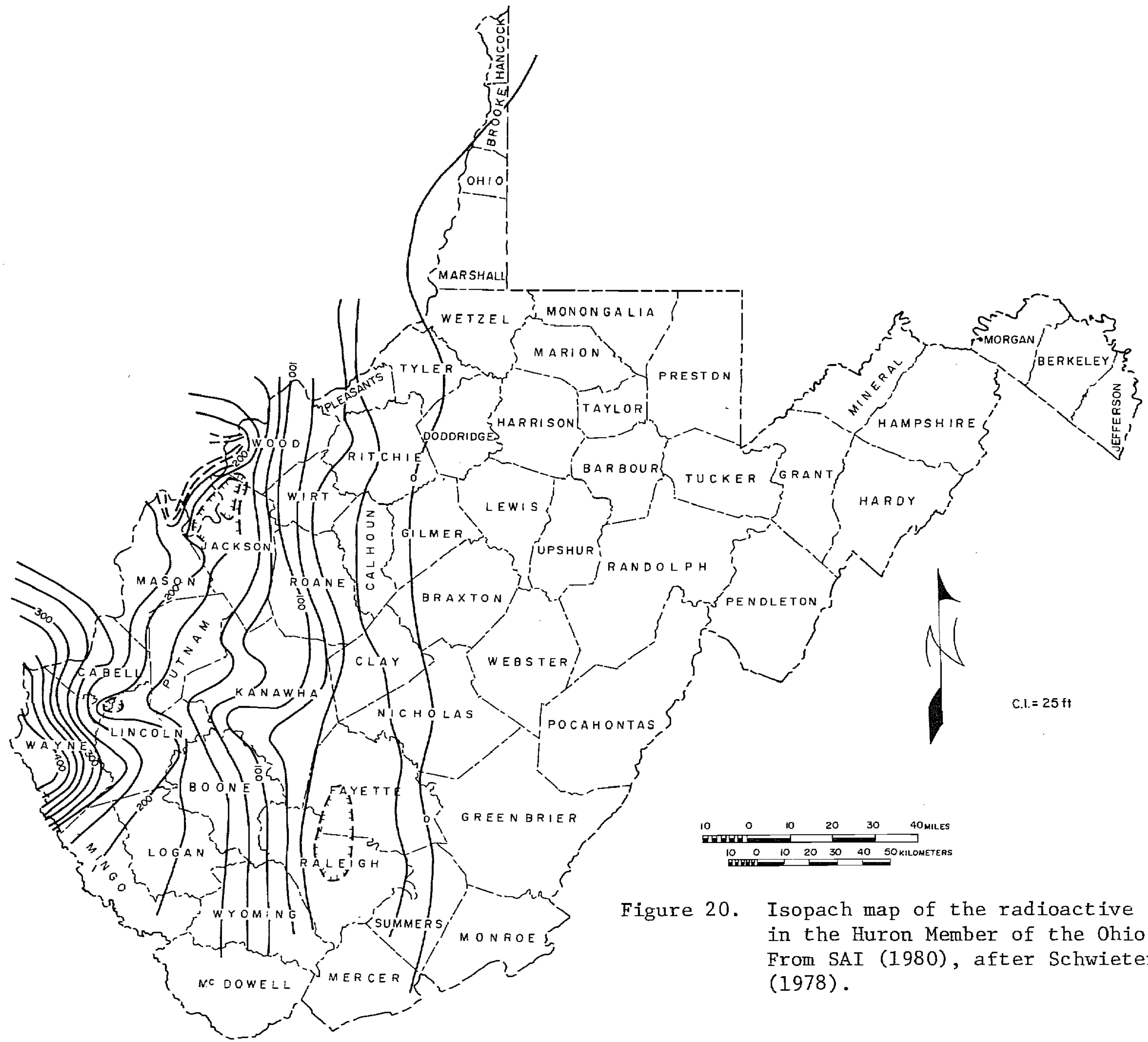

Figure 20. Isopach map of the radioactive shale in the Huron Member of the Ohio Shale. From SAI (1980), after Schwietering (1978).

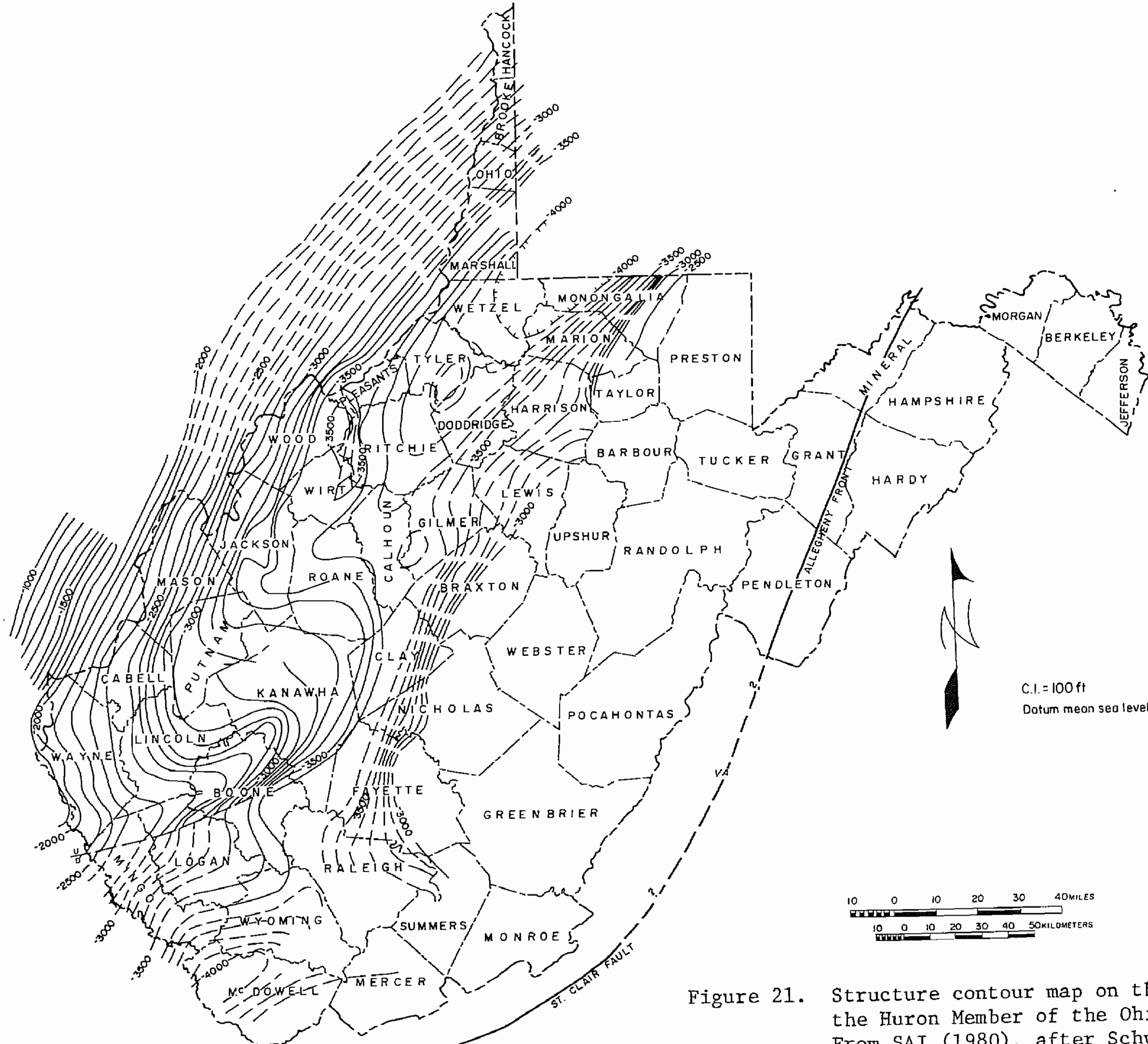

Figure 21. Structure contour map on the base of the Huron Member of the Ohio Shale. From SAI (1980), after Schwietering (1978).

(fig. 22 and plate 4). It thins rapidly to the east, where it pinches out between the Bedford Shale and the Chagrin Shale (plates 4 through 6). The elevation of the base of the Cleveland varies from about 1,200 to 1,500 feet below sea level (fig. 23).

GEOCHEMISTRY

Chemical data available on the Devonian shale in West Virginia and neighboring states include vitrinite reflectance, outgas volume, organic carbon, and carbon isotopes. Data were obtained from the following wells:

Well Designation	Well Name	County
NY-1	National Fuel Gas Supply Corp. No. 6213 (Jo) EGSP NY No. 1	Allegany
PA-1	Minard Run Oil Co. No. 1 Minard Run Exploration	McKean
PA-2	C. E. Power Systems No. 1 C. E. Power Systems	Allegheny
WV-5	Reel Drilling Co. No. 3 D/K Farm	Mason
WV-6	U.S. Department of Energy No. 1 MERC	Monongalia
WV-7	Mobay Chemical Corp. No. 1 H. Enich & A. Pyles Unit	Wetzel
R-109 (OH)	River Gas Co. No. R-109 Florence L. House	Washington
OH-3	Thurlow Weed & Associates No. 1 Louise Beckholt	Knox
20402 (WV)	Columbia Gas System No. 20402	Lincoln
20403 (WV)	Columbia Gas System No. 20403	Lincoln
KY-2	Columbia Gas Transmission Corp. No. 20336 Columbia Gas	Martin
KY-4	Ashland Oil Co. No. 3-RS Skaggs/Kelley Unit	Johnson
VA-1	Columbia Gas Transmission Corp. No. 20338 Penn. Va. Corp.	Wise

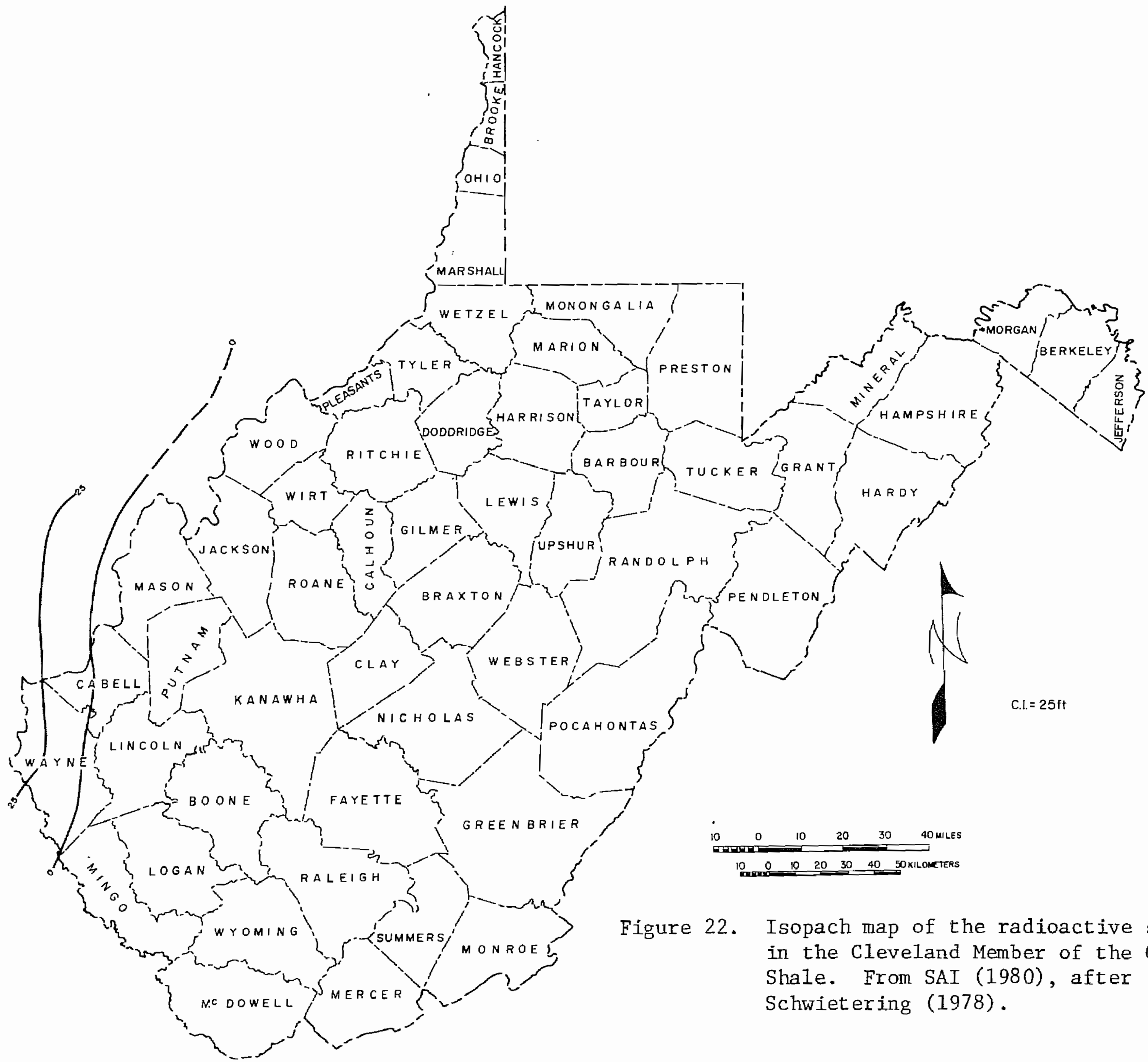

Figure 22. Isopach map of the radioactive shale in the Cleveland Member of the Ohio Shale. From SAI (1980), after Schwietering (1978).

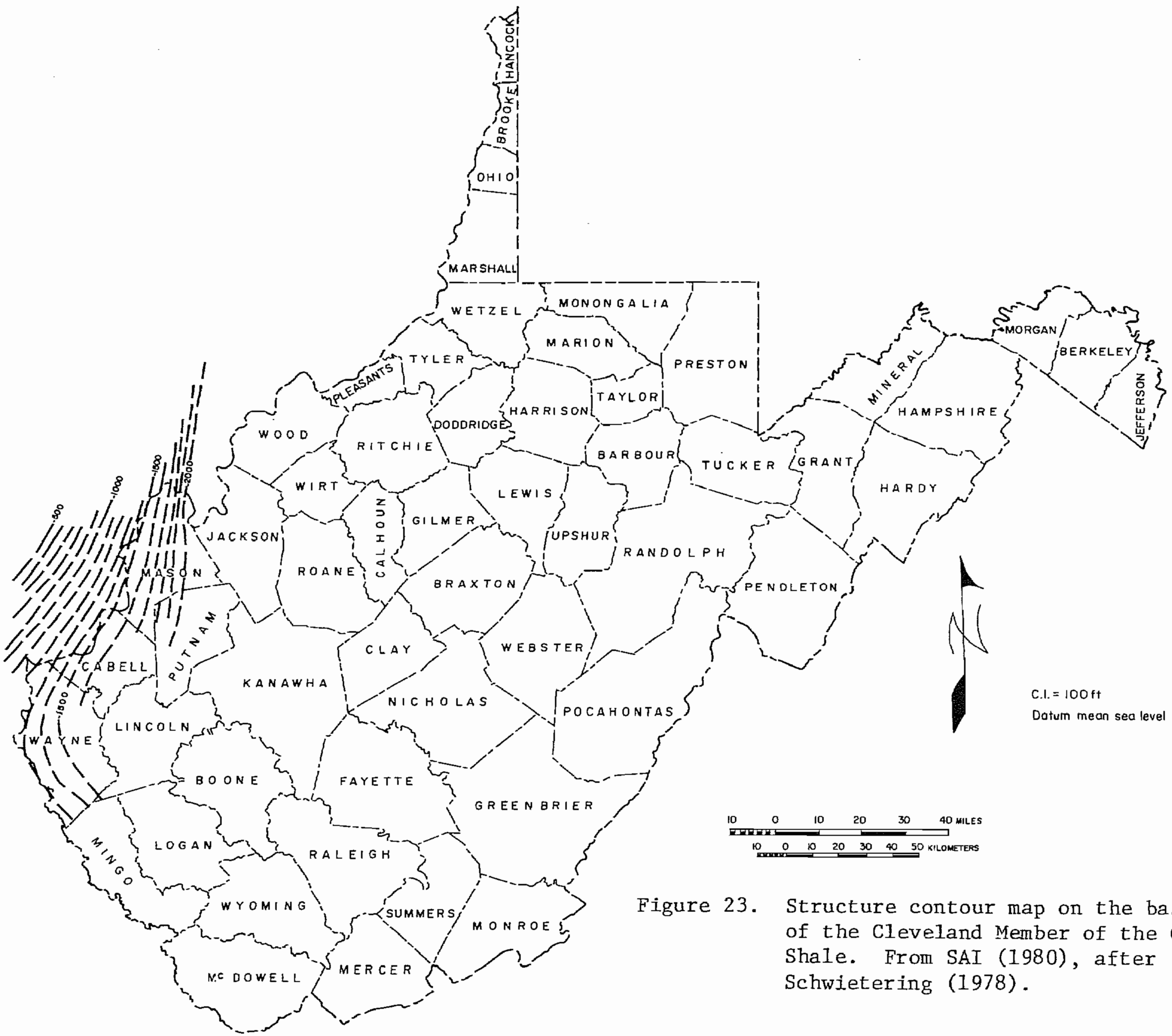

Figure 23. Structure contour map on the base of the Cleveland Member of the Ohio Shale. From SAI (1980), after Schwietering (1978).

Vitrinite Reflectance

A parameter that significantly effects the shale hydrocarbon generation is thermal maturation. Thermal maturation is the cumulative effect of the temperature and duration of heating of the shale during burial. In general, with increasing temperature, organic matter will initially yield dry gas, then wet gas and petroleum, and finally upon severe thermal alteration these products will be degraded to primarily a dry gas. Hydrocarbon generation will also proceed with increasing time at a given temperature. The minimum temperature for significant hydrocarbon generation is approximately 50°C.

The optical reflectance of vitrinite particles in the Kerogen concentrate isolated from shale, expressed at % R_o, is a measure of the maturity of the kerogen. As the value of R_o increases, the thermal maturity of the kerogen increases. Similarly significant hydrocarbon generation does not occur below a mean R_o of approximately 0.5 and commercial reserves are not known in rocks with maturities greater than 3.2 R_o.

Vitrinite reflectance values increase from less than 1.0 in southwestern West Virginia to greater than 2.0 in the northeastern section of the state (figure 24).

Outgas Volume

Outgas volume, expressed in MCF of gas per Acre-Foot of shale (MCF/A.F), is a measure of the free hydrocarbon gas that evolved from an encapsulated shale sample. This measurement is used to differentiate between stratigraphic zones of high and low gas content. Outgas volume data are available from sites in Monongalia, Wetzel, Mason and Lincoln Counties in West Virginia, and Martin County, Kentucky. Tables 1 through 5 show the stratigraphic unit, thickness and gas volume of these five sites. Outgas volume should not be construed as the free hydrocarbon content of the shale but more a conservative estimate of that content. Mound in studies using the Pressure Core Barrel and controlled off-gassing techniques has demonstrated that outgas volumes can be extremely conservative.

Organic Carbon Distribution

The weight percentage of the shale composed of organic carbon indicates the richness of the rock as a potential gas source. The higher the percentage of organic carbon, the more likely that the shale will contain gas, because stratigraphic units with high-gas content have high organic-carbon content. The percentage of organic carbon generally increases westward in the Appalachian basin. Figure 25 shows an increased organic carbon percentage eastward in the Middle Devonian Rhinestreet Shale. The Upper Devonian Huron and Cleveland Members of the Ohio Shale illustrate the westward trend of increasing organic carbon percentage (figs. 26 and 27, respectively).

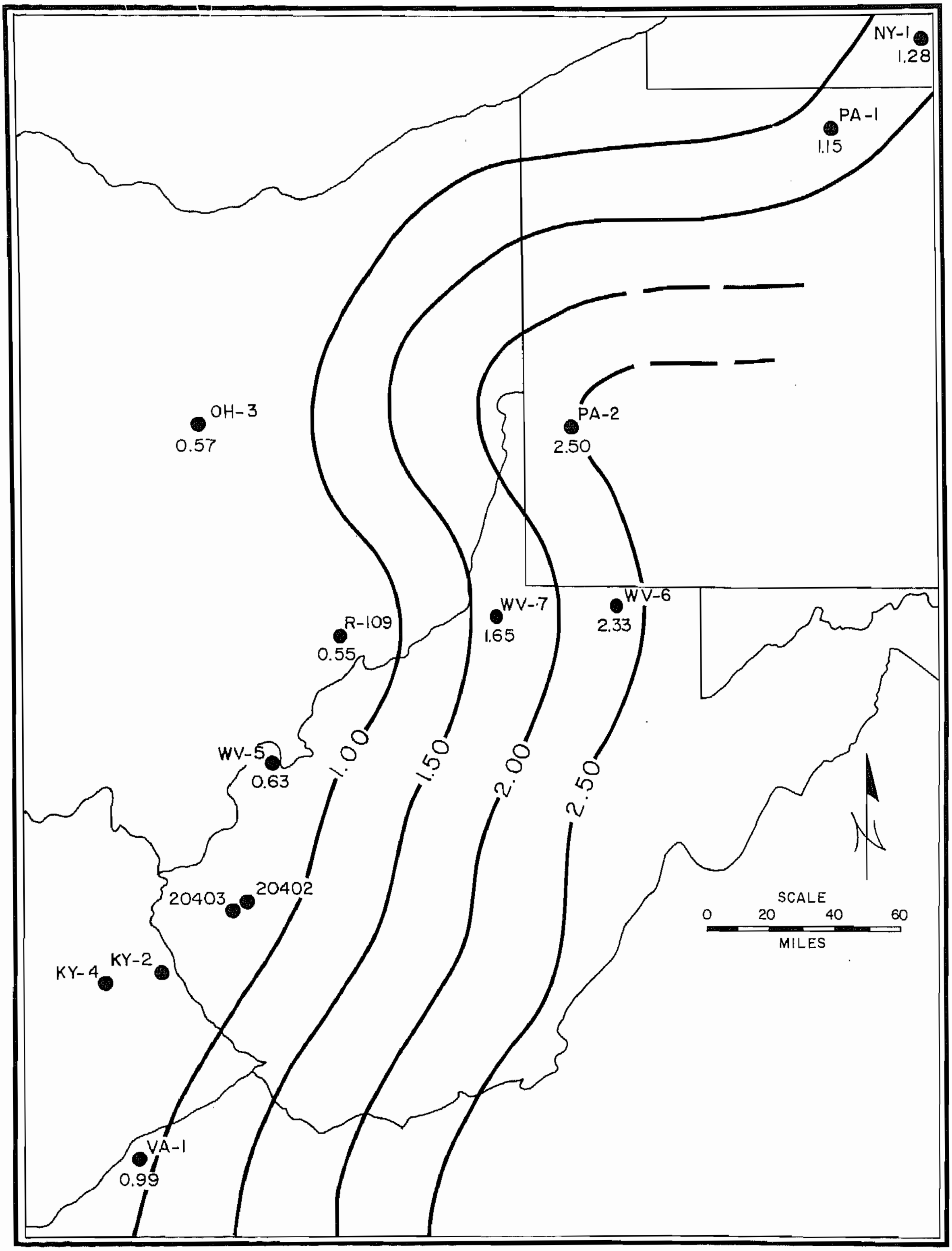

Figure 24. Distribution of vitrinite reflectance (R_o) for the Devonian shales in Ohio, Pennsylvania, and West Virginia. From SAI (1980), after Mound (1980).

Table 1. Monongalia County, West Virginia, gas volume (WV-6) From SAI (1980), modified by Mound Facility (1981).

Stratigraphic unit	Thickness (feet)	Free Hydrocarbon Gas (MCF/A.F)
Mahantango Shale	205	13.33
Marcellus Shale	110	14.71

Table 2. Wetzel County, West Virginia, gas volume (WV-7) From SAI (1980), modified by Mound Facility (1981).

Stratigraphic unit	Thickness (feet)	Free Hydrocarbon Gas (MCF/A.F)
Rhinestreet Shale	72	19.4
Cashaqua Shale	222	11.1
Middlesex Shale	28	21.2
Genesee Shale	83	17.0
Mahantango Shale	57	28.3
Marcellus Shale	55	12.8

Table 3. Mason County, West Virginia, gas volume (WV-5) From SAI (1980), modified by Mound Facility (1981).

Stratigraphic unit	Thickness (feet)	Free Hydrocarbon Gas (MCF/A.F)
Huron Shale	372	11.1
Hanover Shale	46	6.0
Pipe Creek Shale	63	11.2
Angola Shale	170	20.4
Rhinestreet Shale	78	44.2

Table 4. Lincoln County, West Virginia, gas volume (20402) From SAI (1980), modified by Mound Facility (1981).

Stratigraphic unit	Thickness (feet)	Free Hydrocarbon Gas (MCF/A.F)
Cleveland Shale	63	3.9
Chagrin Shale	219	3.1
upper Huron Shale	122	6.5
Chagrin-Chemung Shale	208	5.7
lower Huron Shale	258	15.7
upper Olentangy Shale	162	9.2
Pipe Creek Shale	18	20.0
Rhinestreet Shale	70	37.9
lower Olentangy Shale	10	33.1
Marcellus Shale	23	49.2

Table 5. Martin County, Kentucky, gas volume (KY-2) From SAI (1980), modified by Mound Facility (1981).

Stratigraphic	Thickness (feet)	Free Hydrocarbon Gas (MCF/A.F)
Cleveland Shale	80	21.6
Chagrin Shale	142	1.6
upper Huron Shale	141	5.7
Chagrin-Chemung Shale	115	5.9
lower Huron Shale	218	14.9
upper Olentangy Shale	81	10.3
Pipe Creek Shale	23	9.3
upper Olentangy Shale	148	8.8
Rhinestreet Shale	49	20.4

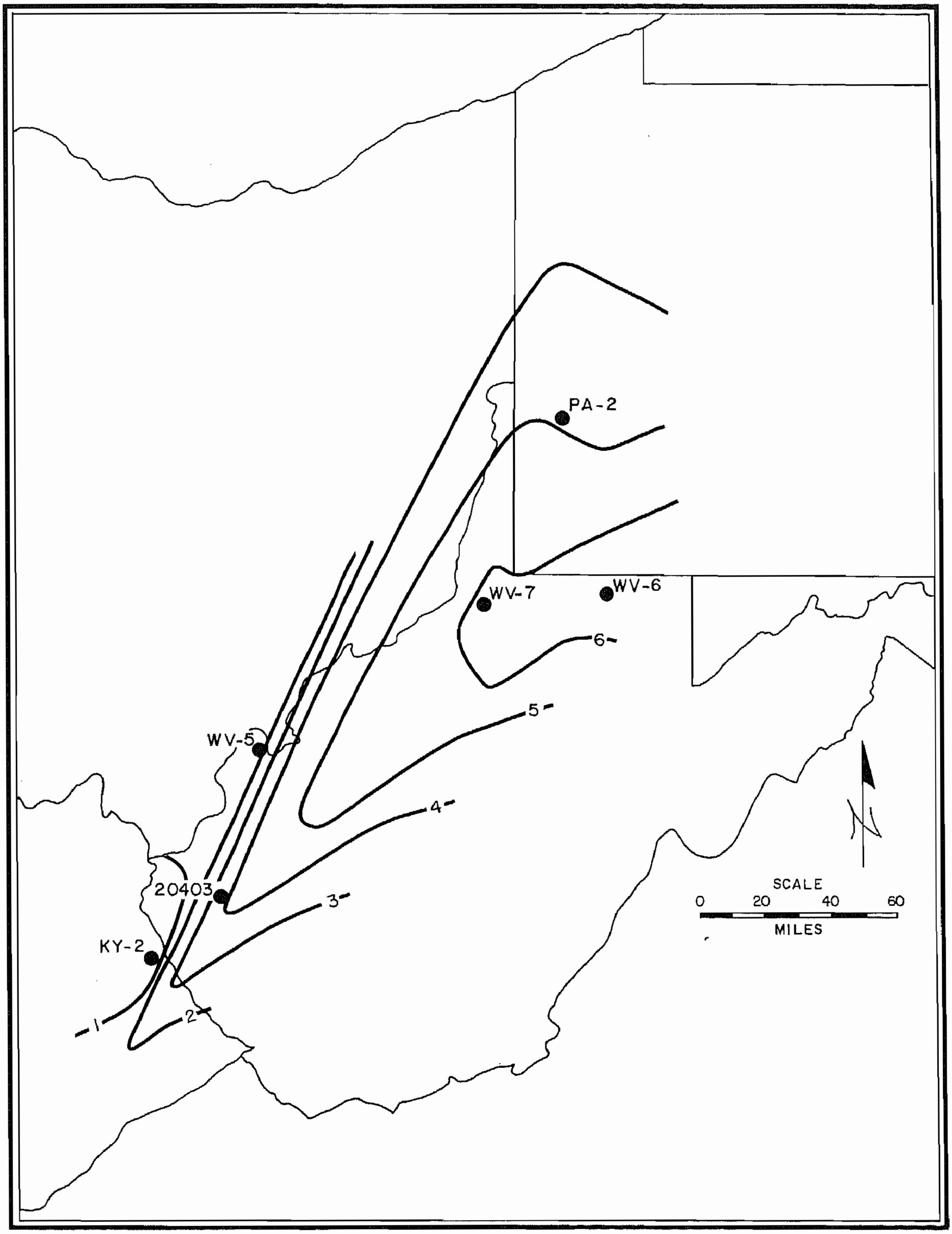

Figure 25. Distribution of organic carbon (percent) within the Rhinestreet Shale Member of the West Falls Formation. After SAI (1980).

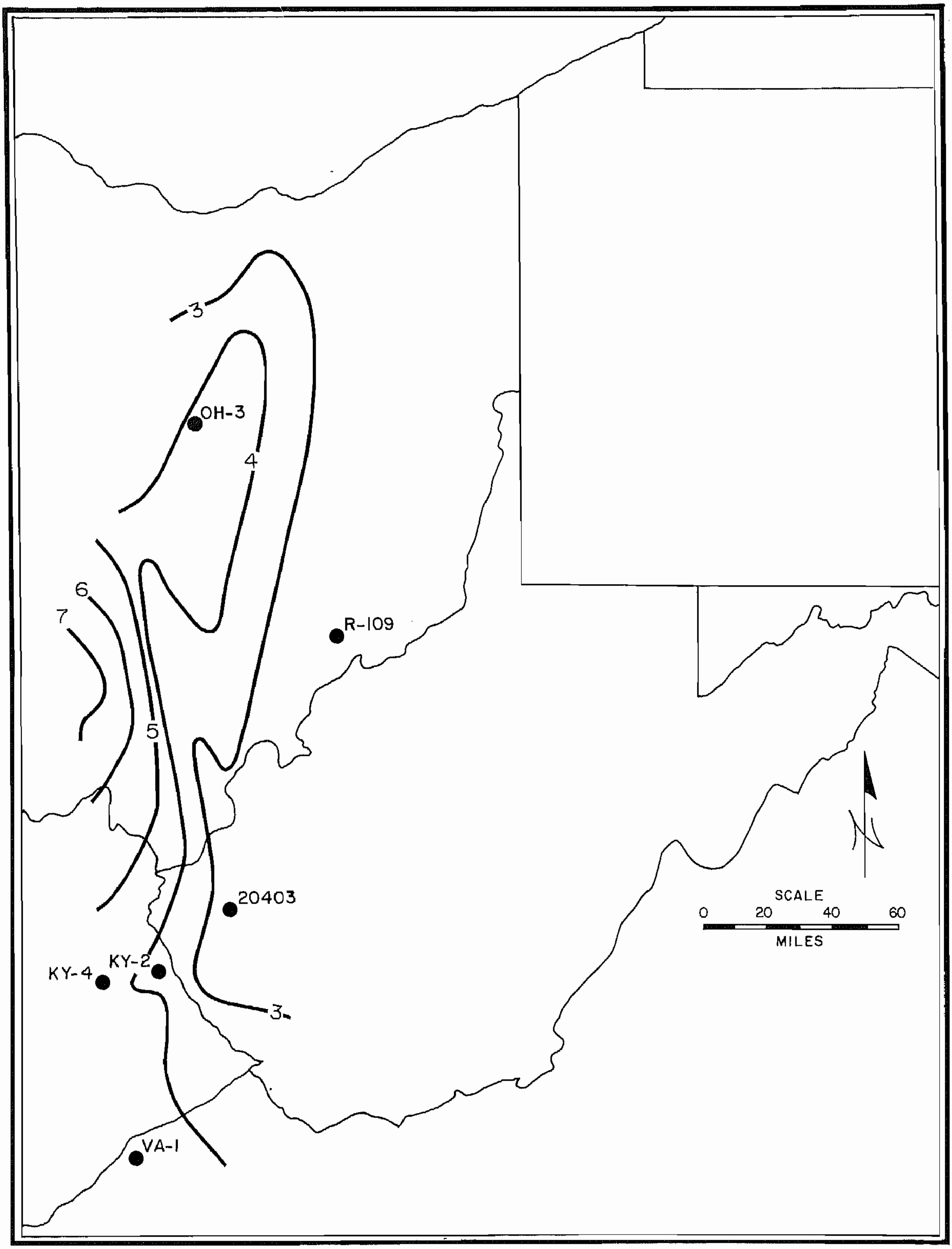

Figure 26. Distribution of organic carbon (percent) within the Huron Member of the Ohio Shale. After SAI (1980).

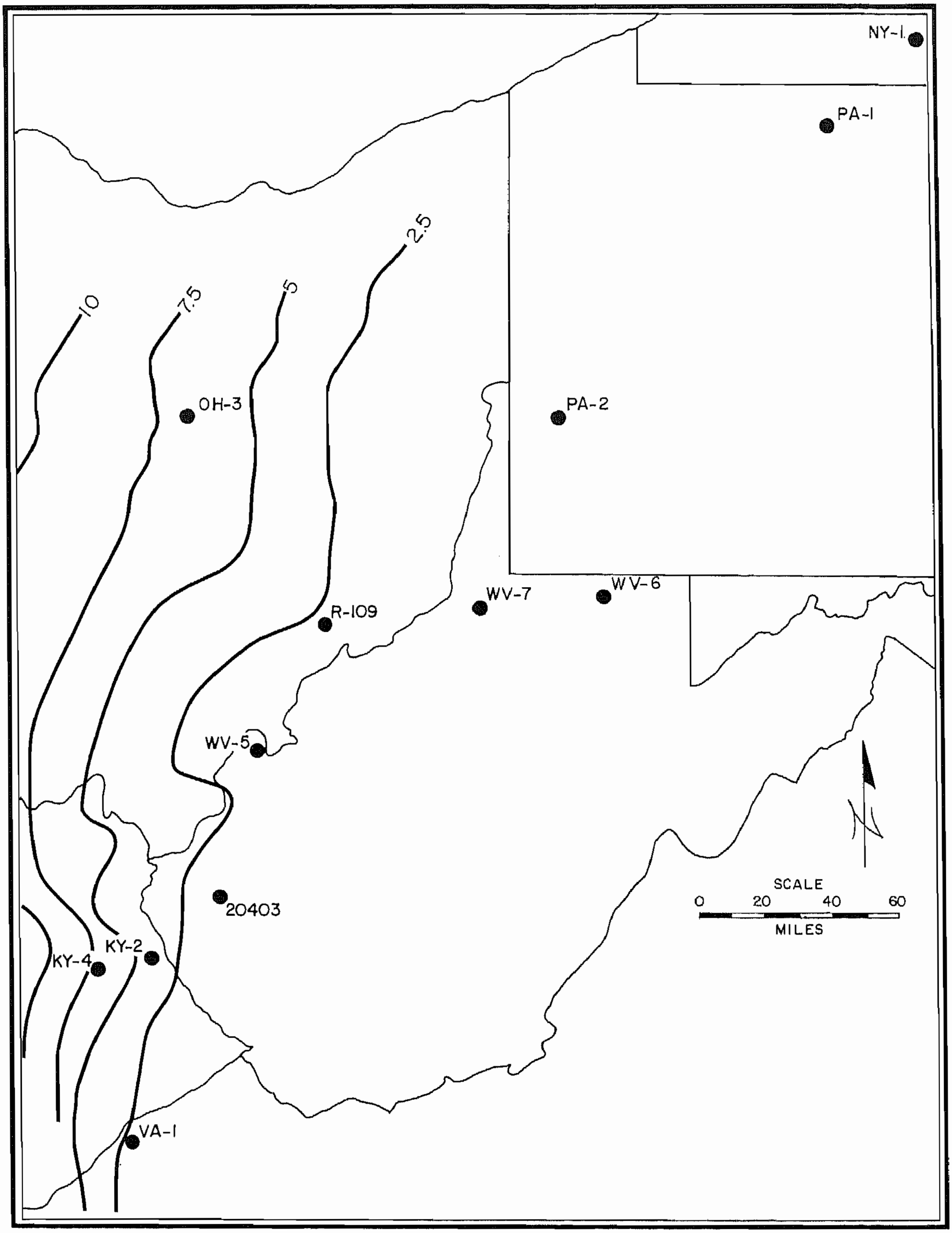

Figure 27. Distribution of organic carbon (percent) within the Cleveland Member of the Ohio Shale. From SAI (1980), after Mound (1980).

FRACTURE AND PRODUCIBILITY INDICATORS

Recent studies have been conducted to determine regional stress-ratio relationships (or fracturing gradients) for the Appalachian basin. Correlation of historical production with the stress ratio (the ratio of minimum horizontal stress to overburden stress) indicates that a regional mapping of this factor could delineate prospective areas for commercial development of shale gas production. Maximum natural fracturing density should occur in the areas of maximum horizontal stress (tensional relief), indicated by a low stress ratio. Typical stress-ratio values range from slightly less than 0.43 to greater than 1.0. A stress-ratio map based on theoretical values determined for each county containing Devonian shales within the Appalachian basin is presented in figure 28. Portions of western, southwestern, and eastern West Virginia lie within the area where stress-ratio values range from 0.43 to 0.7. Theoretically, gas production from the Devonian shale sequence should be optimized within these areas, especially within the counties intersected by the 0.43 minimum line.

The importance of fractures with respect to gas production was demonstrated by Bagnall and Ryan (1976) for Devonian shale wells in three southwestern West Virginia counties. Wells that displayed the highest average initial production--greater than 300 thousand cubic feet (Mcf) per day--showed a steep production decline curve, but leveled off at approximately 45 Mcf and continued at that rate for years. Wells ranging from 200 to 300 Mcf per day leveled off more quickly but at lower production rates, as did wells averaging between 100 and 200 Mcf. Wells with average initial flows of less than 100 Mcf per day were nearly horizontal lines from the first year to year 25.

These findings substantiate the conclusion that gas production is controlled by the presence or absence of fractures within the Devonian shale reservoirs. The wells that produced better initially intersected more fractures, and produced free gas and adsorbed fracture gas at higher rates than wells that intersected fewer fractures. Once the "flush production" (i.e., production from free and adsorbed fracture gas) is over, the larger blocks of shale between fractures yield their adsorbed gas very slowly to the fractures and then to the wellbore. When this occurs, the production decline curves are nearly horizontal and remain so for many years as this type of gas continues to bleed off very slowly. Thus, wells intersecting more fractures level off at higher flow rates than wells intersecting fewer fractures.

GAS PRODUCTION

Areas of concentrated gas well drilling in West Virginia are shown in figure 29. Few wells have been drilled entirely through the Upper and Middle Devonian sequence in the north-central portion of the state where gas is produced from 17 named Upper Devonian Hampshire (Catskill) and Chemung Sandstones. In the southwestern counties, however, gas is produced from several

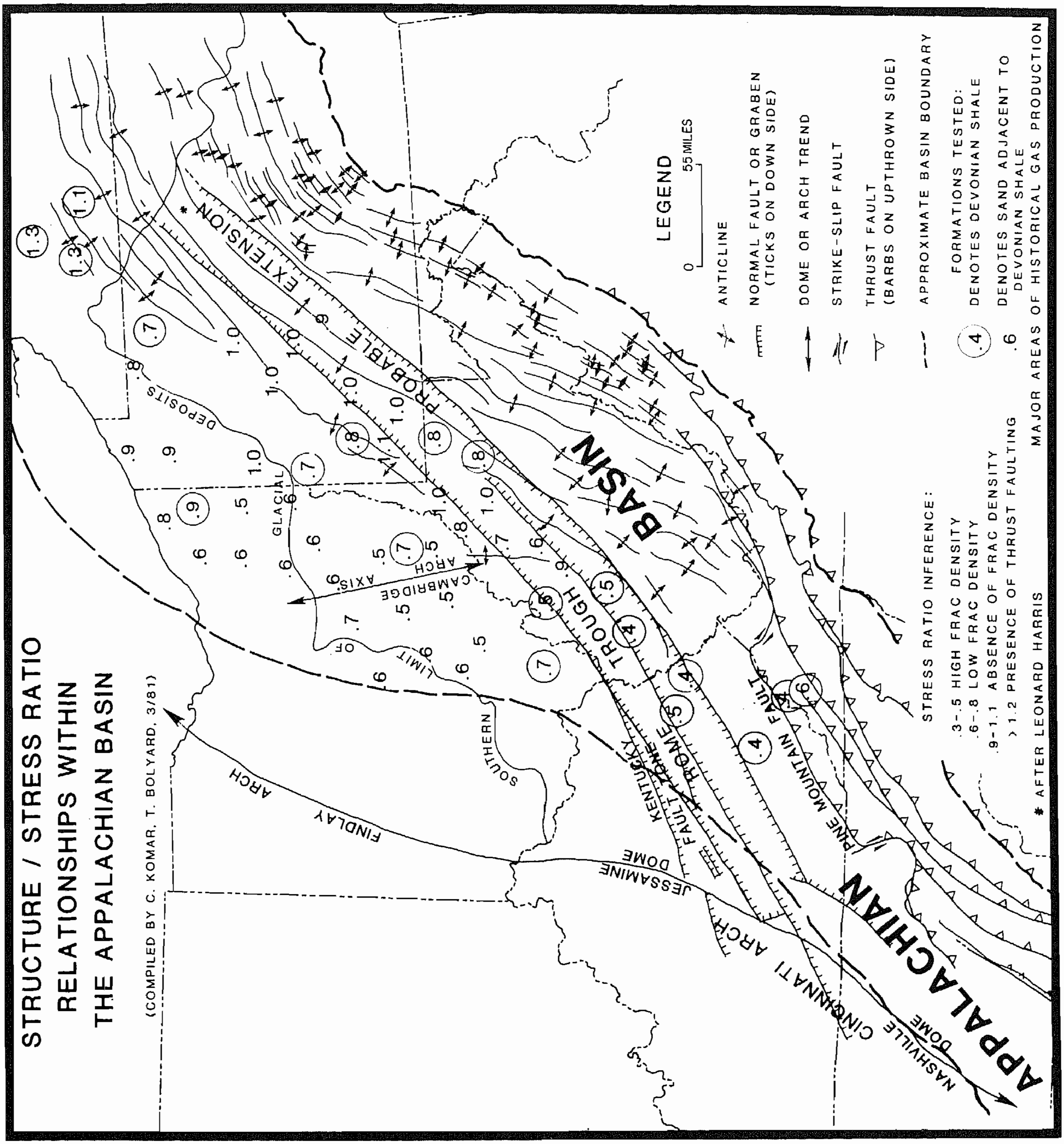

Figure 28. Structure/stress ratio relationships within the Appalachian basin. Compiled by Komar and Bolyard (1981).

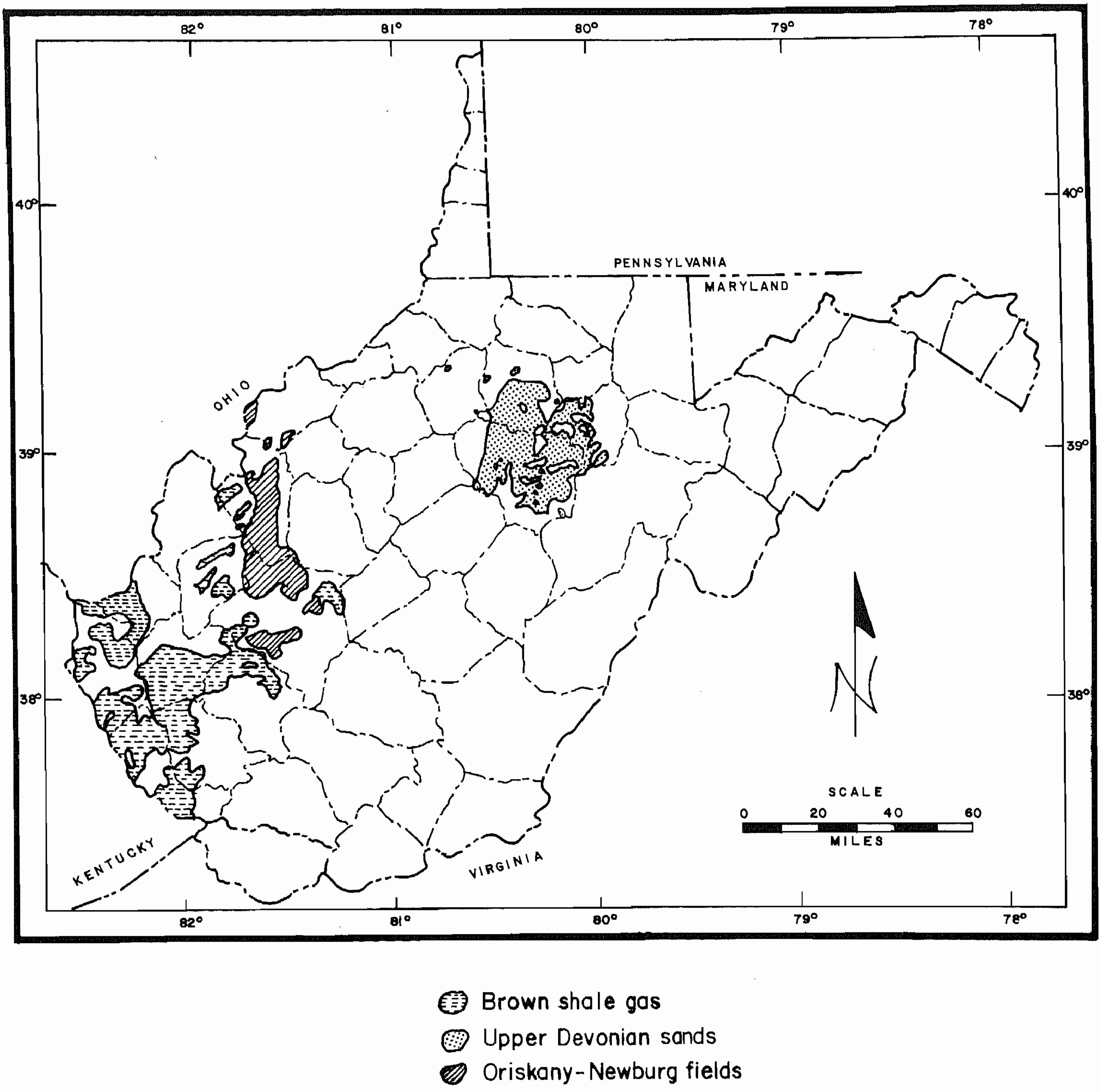

Figure 29. Areas of concentrated gas well drilling in West Virginia. From SAI (1980), after Patchen (1977).

Devonian shale zones. Between these two areas, underlying an area of Mississippian gas production, occurs the key facies change from productive sandstone to organic-rich black shales.

Gas has been produced from the Devonian shale sequence for over 50 years from wells in southwestern West Virginia. Approximately 3,000 wells have been drilled in this area, although many of these did not penetrate the entire shale section to the Onondaga. Gas production from this area has been primarily from the Huron Member of the Ohio Shale, with the lower portion of the unit constituting the primary source of the gas. Thin intervals of gray shale, are intercalated with the black radioactive shale. Gas shows have often been observed immediately below these gray shales, suggesting that these shales may form a barrier to the vertical migration of gas within the interval.

Most Devonian shale gas wells have been drilled just through the Huron Shale interval. In wells drilled through the entire Devonian shale sequence to test the Oriskany or Huntersville, a second gas-producing black shale section often is encountered. This interval consists of the Rhinestreet Shale Member of the West Falls Formation and older units. Gas shows have been recorded most often from two parts of this interval: the lower part, which corresponds to the older units (Sonyea Formation, Genesee Formation, and/or Marcellus Shale), and at the upper boundary, which is probably due to the interbedding of black Rhinestreet Shale and the overlying gray Angola Shale.

The third area of concentrated gas well drilling presented in figure 29 is the so-called "Benson trend" in north-central West Virginia. Although more than 4,000 wells have been drilled within this trend to produce from various Upper Devonian sands, 99 percent have penetrated only the upper 2,500 feet of Upper Devonian strata, down to the Benson sand. The lower 3,500 to 4,500 feet of Upper and Middle Devonian shales are relatively untested in this area.

The black radioactive Devonian shale is the main reservoir in 27 named gas fields in southwestern West Virginia (fig. 30), which extend over 500,000 acres (nearly 781 square miles). Reserve estimates calculated from the 3,000 plus wells producing in these fields approach 1 Tcf. However, in 21 of these fields, Devonian shale gas production is comingled with production from other shallow pays, especially Mississippian sandstones from the Maxton to the Berea or from the Greenbrier Limestone. Additionally, gas is produced from the deeper Onondaga Limestone and Oriskany Sandstone in three other fields. The net result is that accurate data for calculating Devonian shale gas production and reserves are not available. Brown (1976) has estimated that 10 to 25 percent of the gas now considered to be from the Devonian shales is actually being produced from Mississippian sandstones and limestones.

The success ratio for Devonian shale gas wells in these southwestern West Virginia fields has been quite high, exceeding 90 percent. Furthermore, wells are reasonably shallow with an average depth of about 3,500 feet. Initial open flows are low, averaging only 350 Mcf per day. Per well reserves have been estimated at 350 million cubic feet by Brown (1976), assuming a 150-acre well spacing.

Figures 31 through 34 are a series of maps showing areas of current gas production and radio active shale thickness, major geologic structures, stress ratios, and vitrinite reflectance. These maps were used to construct a final map (fig. 35) delineating favorable zones for development of Devonian shale gas production in West Virginia.

The areas of favorable or potentially favorable trends, shown in Figure 35, include parts of or all of twenty-three counties in southwestern and west-central West Virginia. Wells penetrating the Devonian sequence in this area should be evaluated for shale gas potential, either as a primary target or as a dual completion possibility. Reserve estimates generated by the National Petroleum Council (1980) provide a state-of-the-art calculation of in-place reserves (Table 6). Recoverable reserves will be the result of optimal geologic and geochemical conditions and technological advances.

Table 6. Devonian Shale resource assessment for West Virginia (after National Petroleum Council, 1980).

	LOG DATA			SAMPLE DATA		
	Average Thickness (Feet)	Land Area* (Sq Mi)	Total (TCF)	Average Thickness (Feet)	Land Area* (Sq Mi)	Total (TCF)
Black Shale	128	22,984	49	640	22,984	246
Gray Shale	3,252	22,984	209	2,741	22,984	176

	LOG DATA			SAMPLE DATA		
	Average Depth (Feet)	Total (TCF)	Average (BCF/Sq Mi)	Average Depth (Feet)	Total (TCF)	Average (BCF/Sq Mi)
Total Shale Resource	6,275	258	11	6,275	422	18

*Land area encompasses that portion considered as having Devonian Shale potential, and does not necessarily represent the total area of the state.

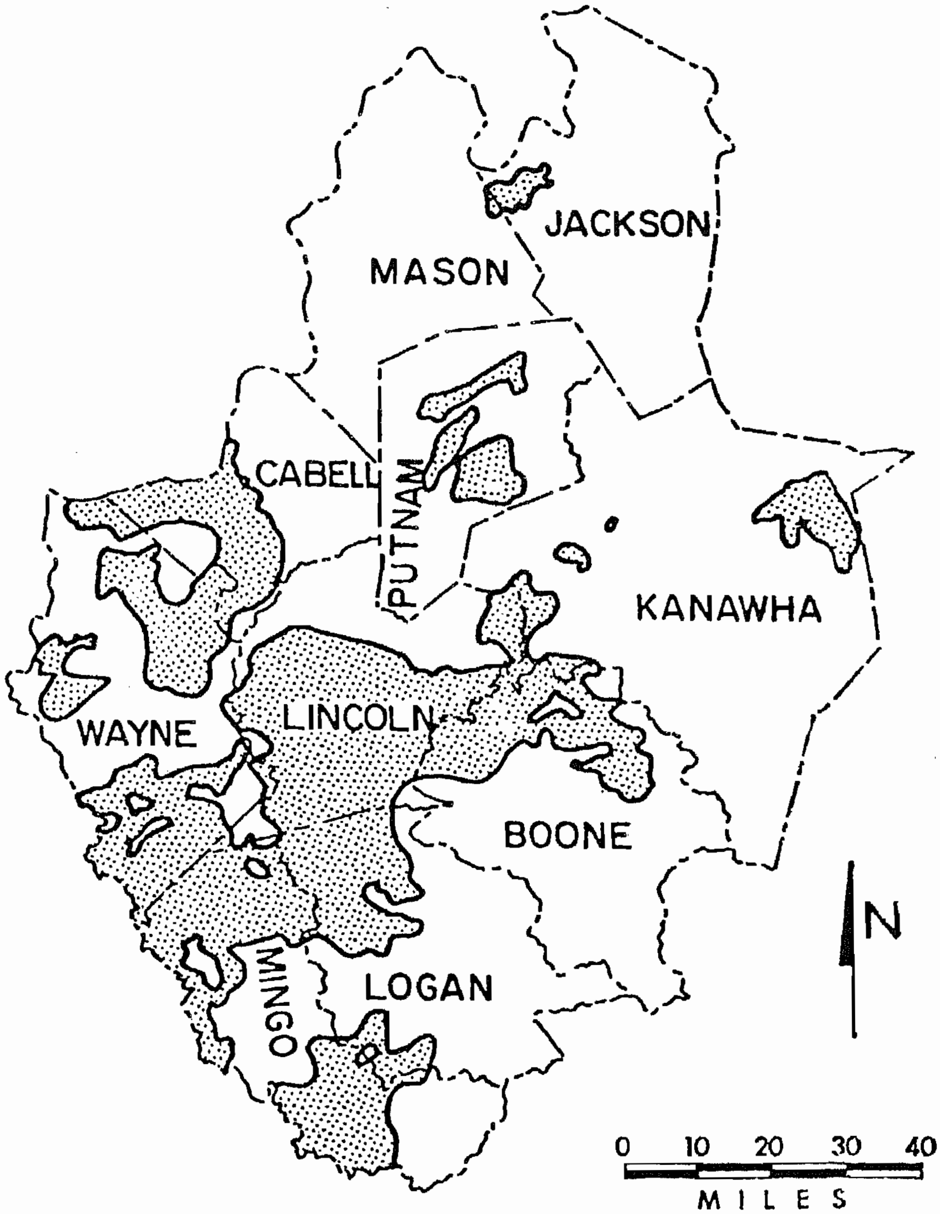

Figure 30. Areas of gas production from Devonian black shales in West Virginia. From SAI (1980), after Patchen (1977).

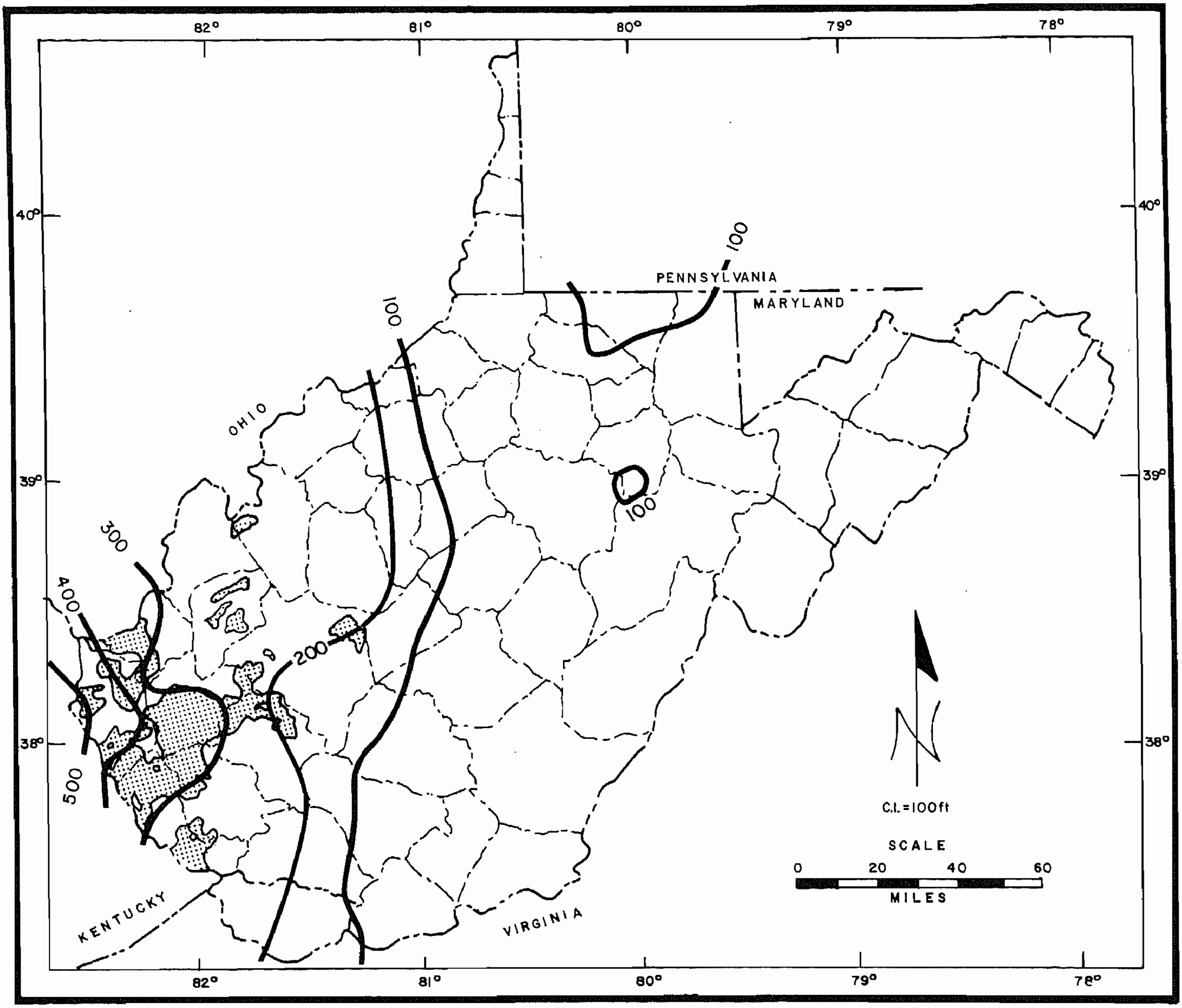

Figure 31. Areas of gas production from Devonian black shales and radioactive shale thickness greater than 200 feet in West Virginia. From SAI, (1980) and figures 9 and 30.

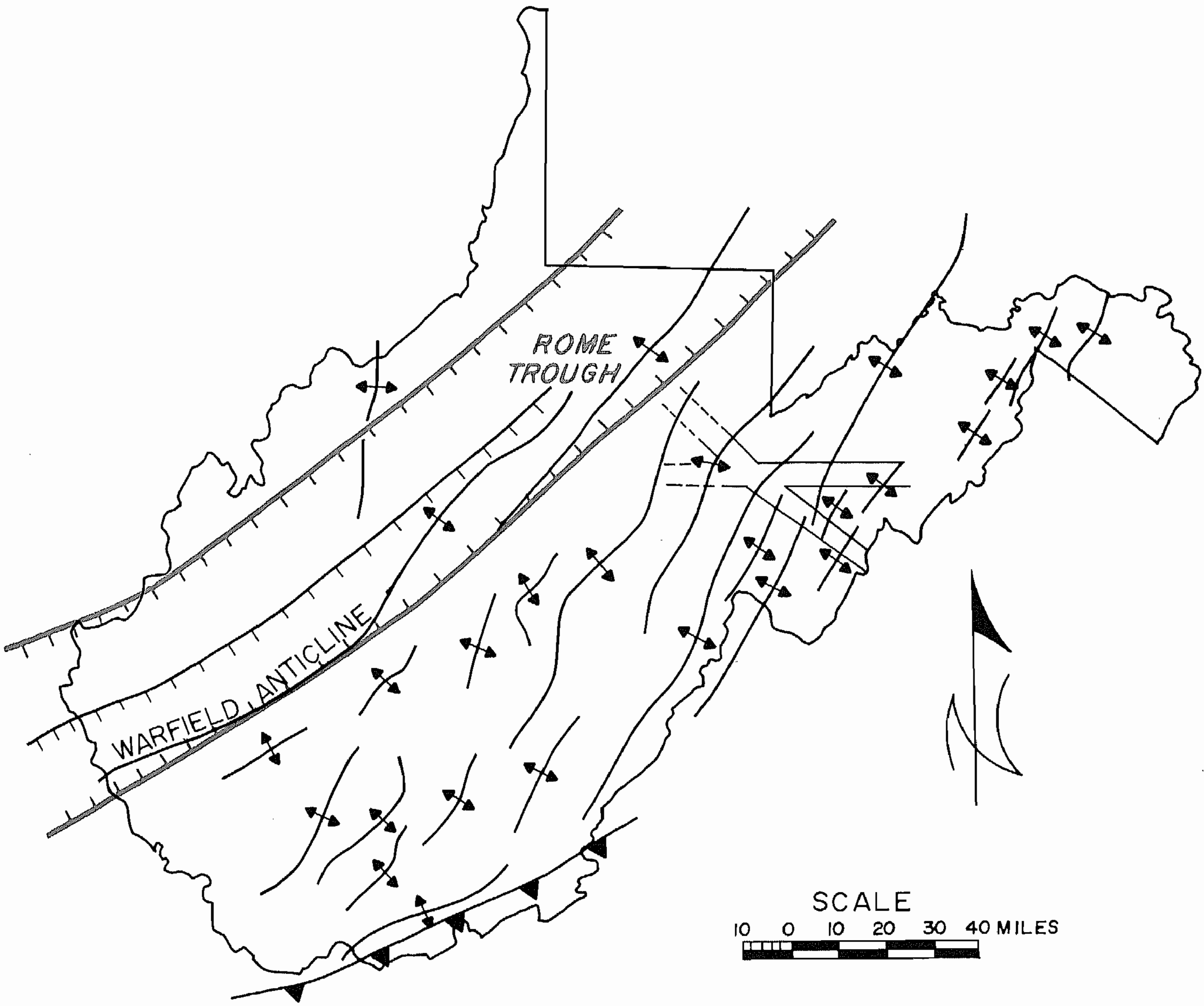

Figure 32. Major geologic structures in West Virginia.
From SAI (1980).

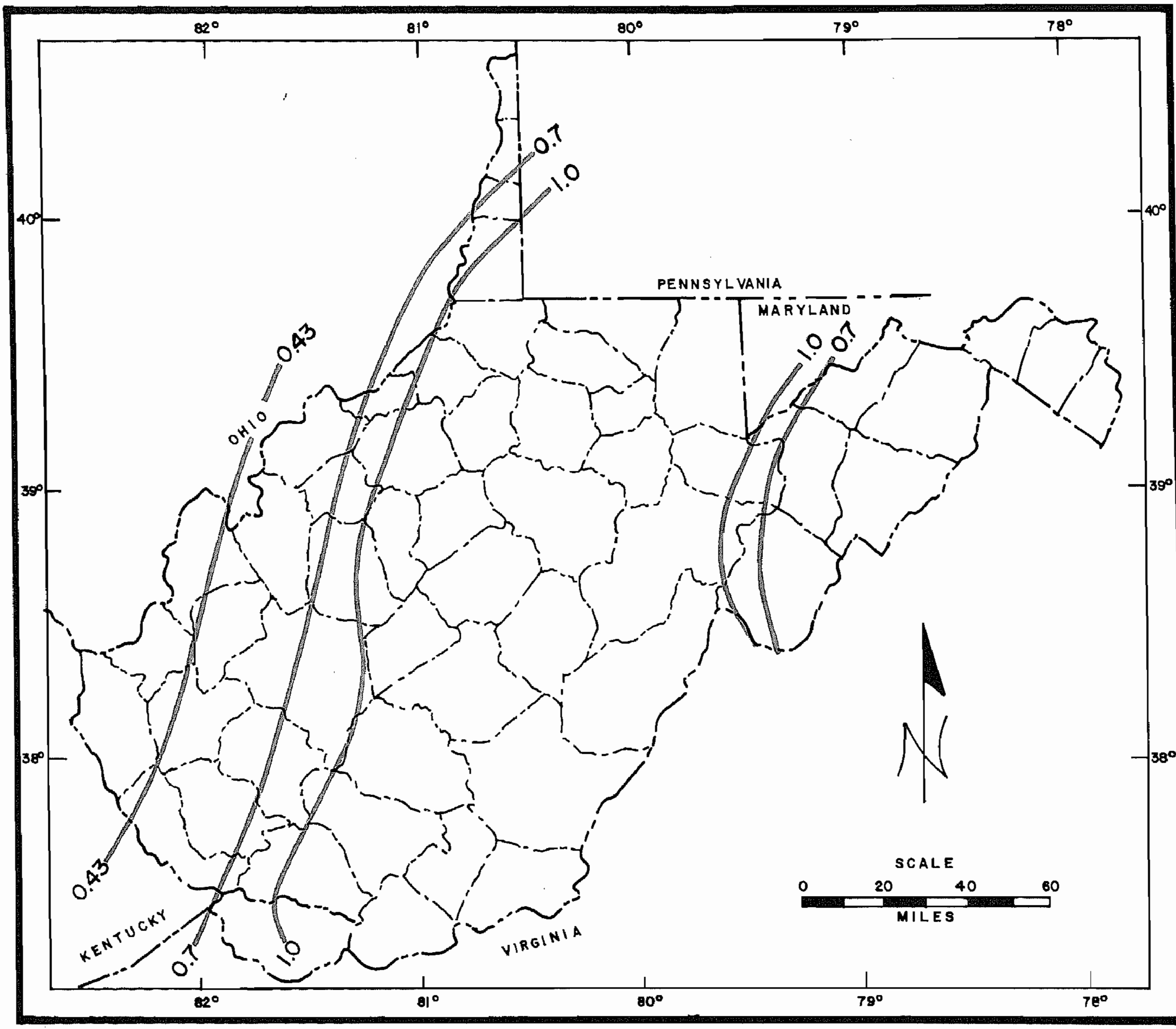

Figure 33. Stress - ratio map for West Virginia. From SAI (1980).

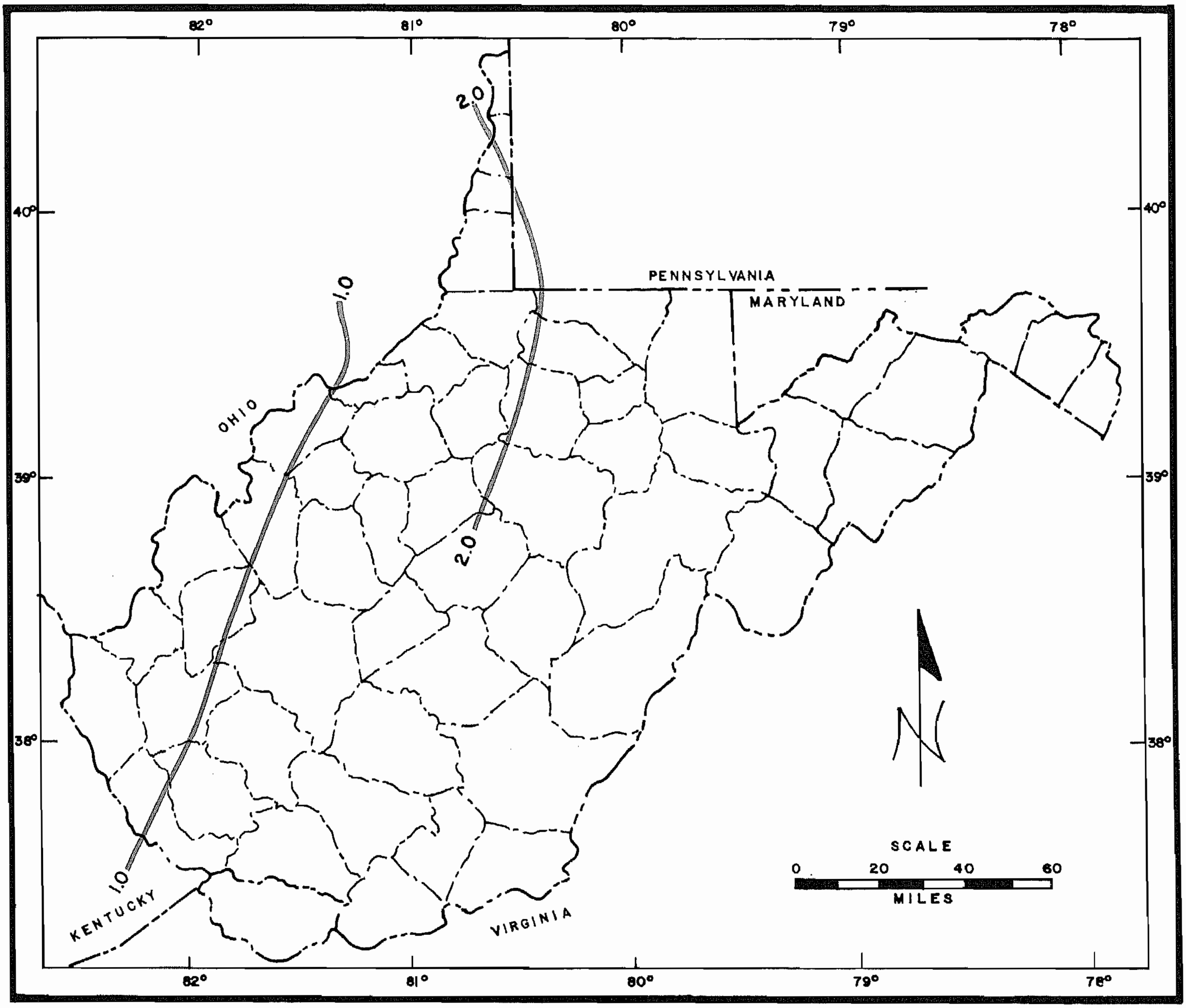

Figure 34. Distribution of vitrinite reflectance (R_o) in West Virginia. From SAI (1980).

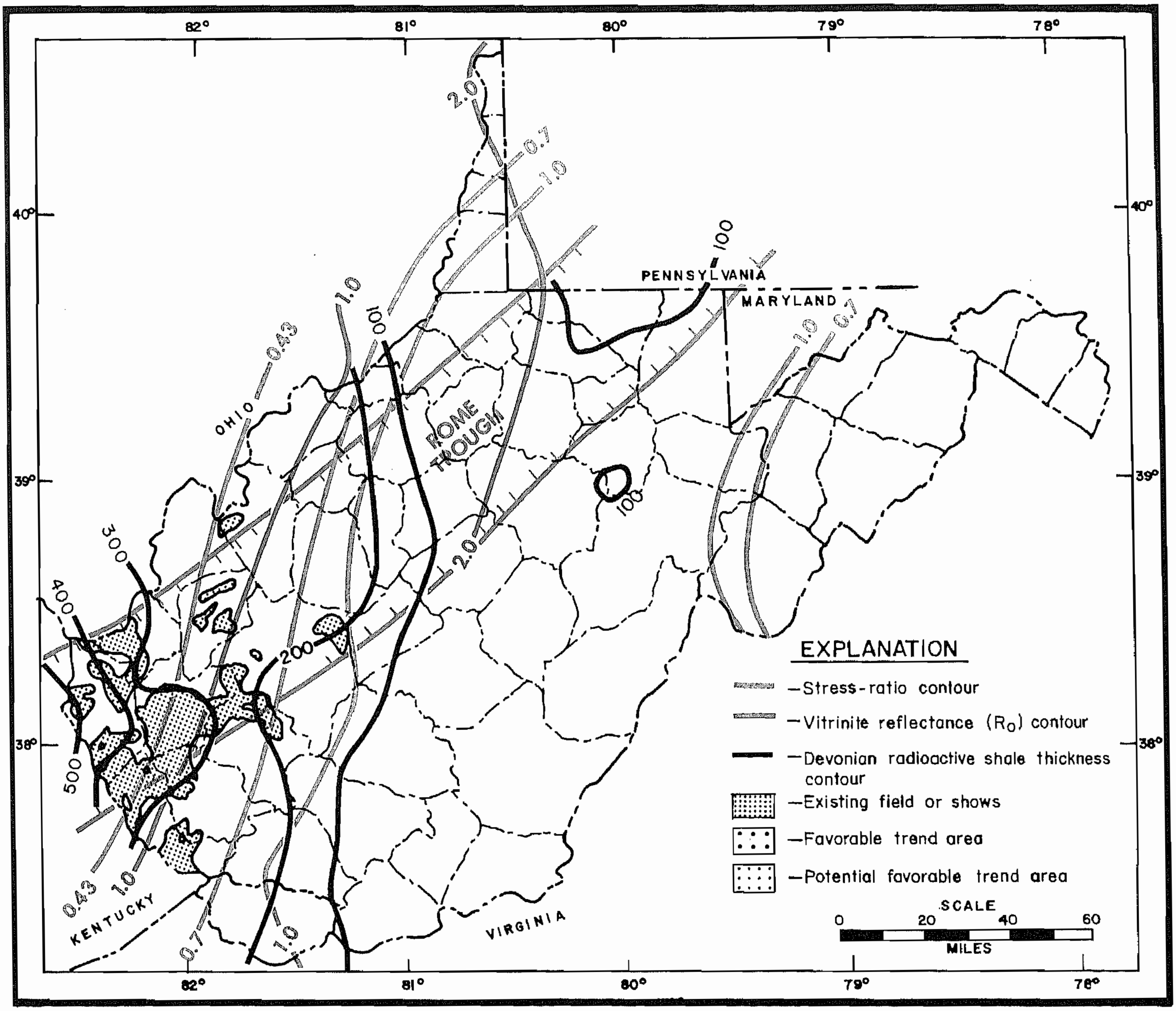

Figure 35. Exploration potential of the Devonian shales in West Virginia. From SAI (1980). Addition of contours and favorable trends by Tetra Tech (1981).

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APPENDIX
EVALUATION OF
DEVONIAN SHALE POTENTIAL
IN
WEST VIRGINIA

(Includes Documents, Logs, and Maps in the UGR Information File Concerning West Virginia)

This Appendix is cross-referenced by subtopic. UGR File Accession List Numbers are indicated for each entry. The first time a particular entry appears, the complete reference is given. Subsequent references to that entry are only indicated by the UGR File Accession List Number.

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APPENDIX
EVALUATION OF DEVONIAN SHALE POTENTIAL IN THE APPALACHIAN BASIN

(Includes Documents, Logs, and Maps in the UGR Information File concerning the Appalachian Basin)

This Appendix is cross-referenced by subtopic. UGR File Accession List Numbers are indicated for each entry. The first time a particular entry appears, the complete reference is given. Subsequent references to that entry are only indicated by the UGR File Accession List Number.

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UGR #060

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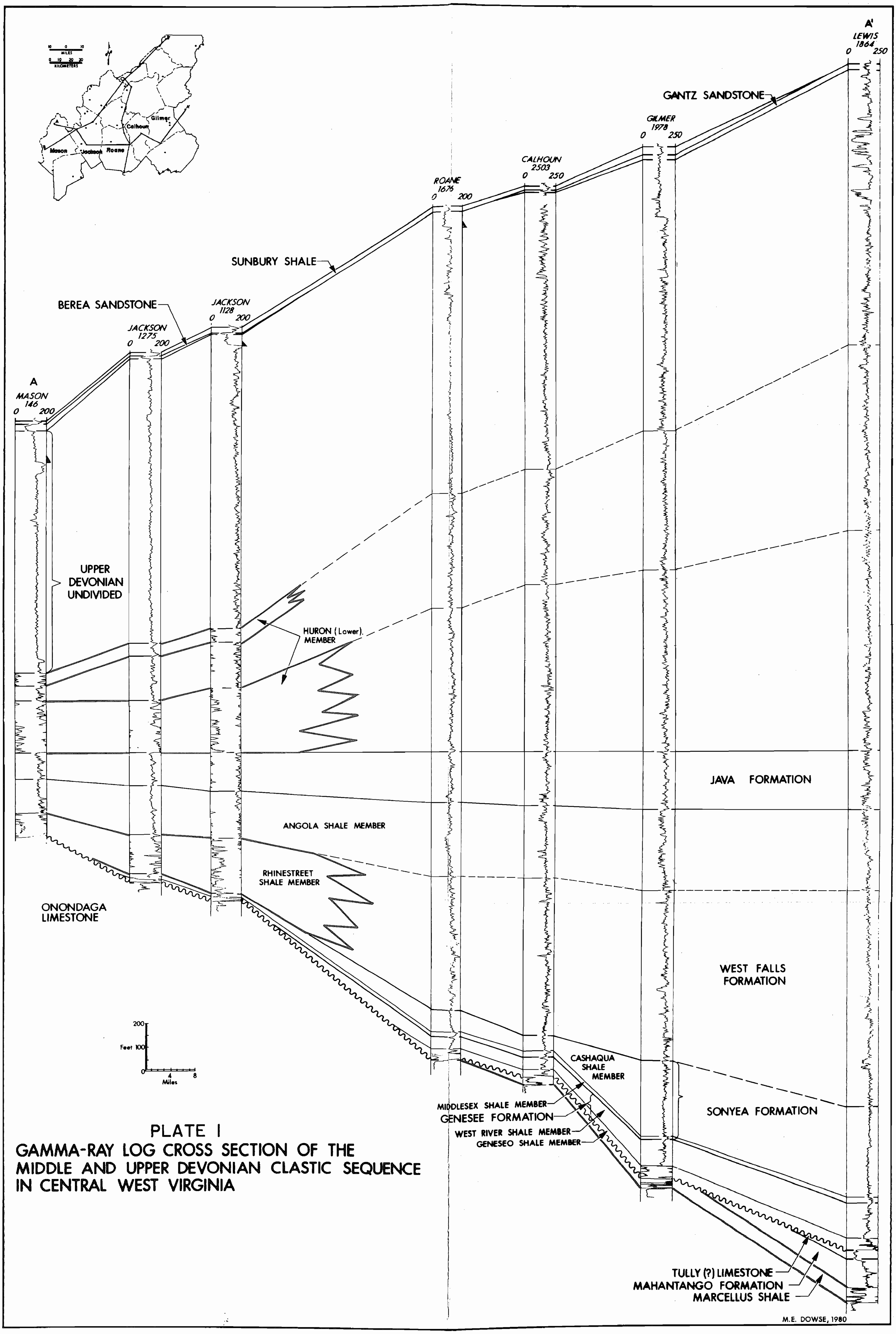


PLATE I
GAMMA-RAY LOG CROSS SECTION OF THE MIDDLE AND UPPER DEVONIAN CLASTIC SEQUENCE IN CENTRAL WEST VIRGINIA

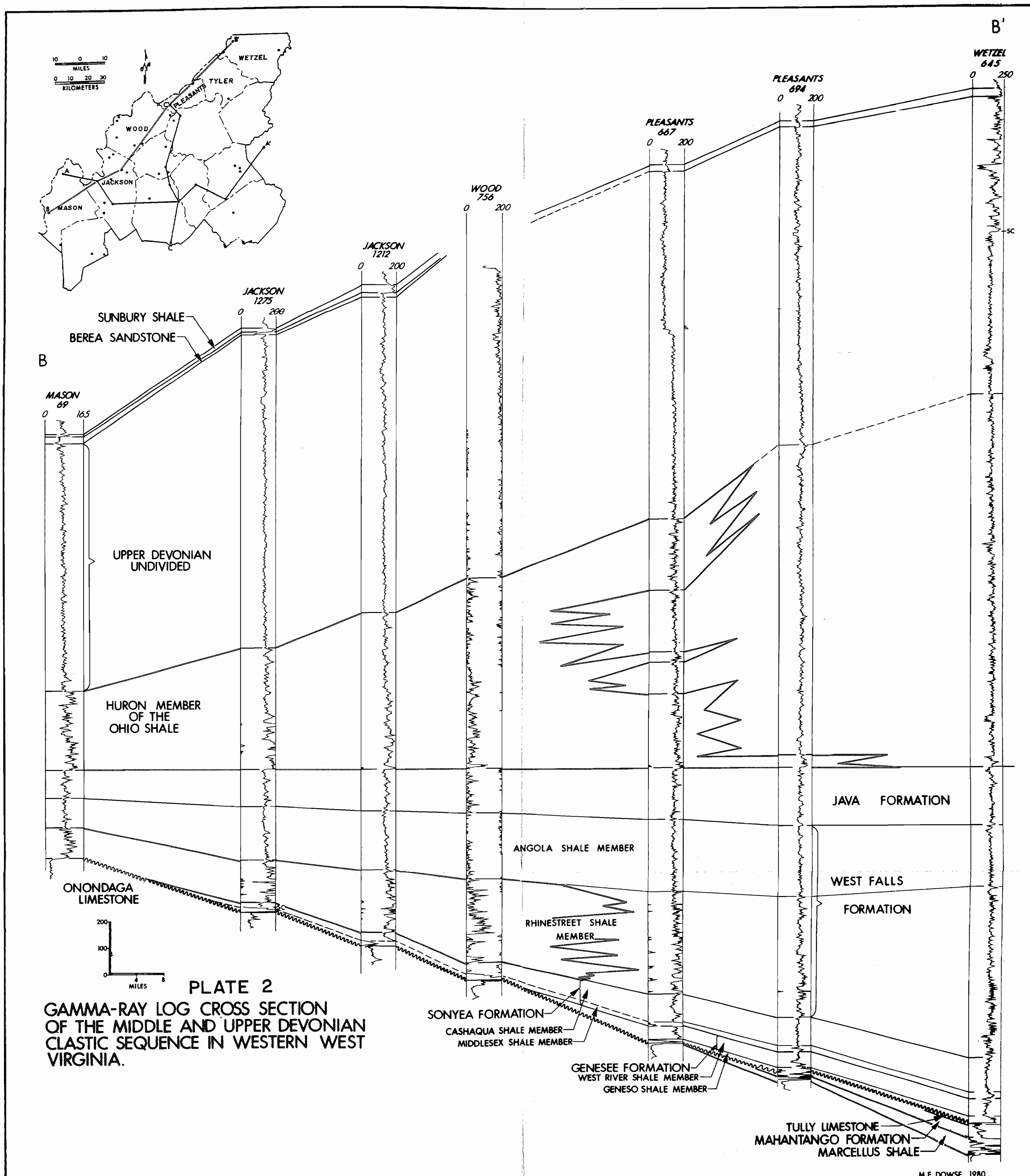


PLATE 2

GAMMA-RAY LOG CROSS SECTION OF THE MIDDLE AND UPPER DEVONIAN CLASTIC SEQUENCE IN WESTERN WEST VIRGINIA.

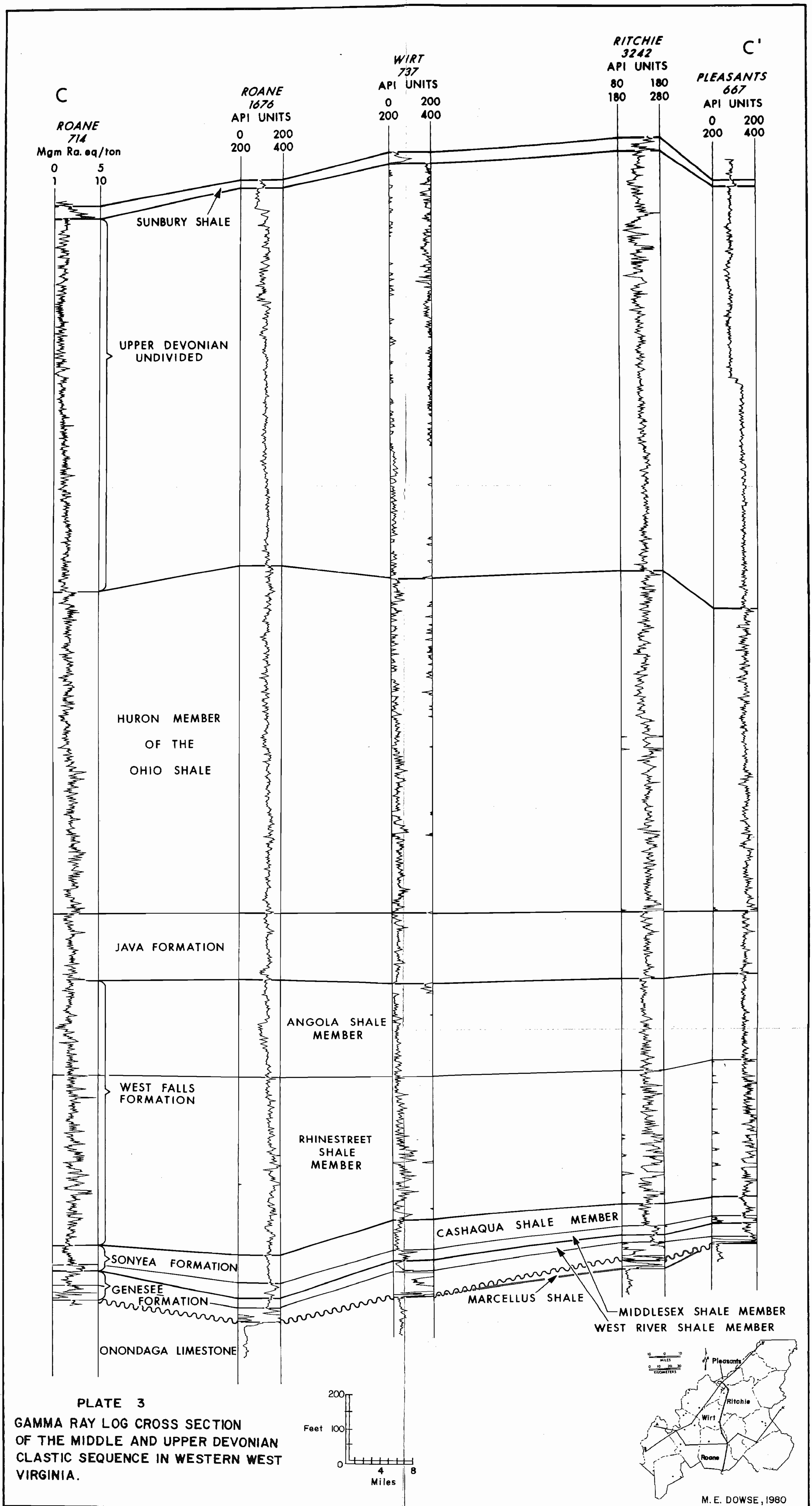


PLATE 3

GAMMA RAY LOG CROSS SECTION OF THE MIDDLE AND UPPER DEVONIAN CLASTIC SEQUENCE IN WESTERN WEST VIRGINIA.

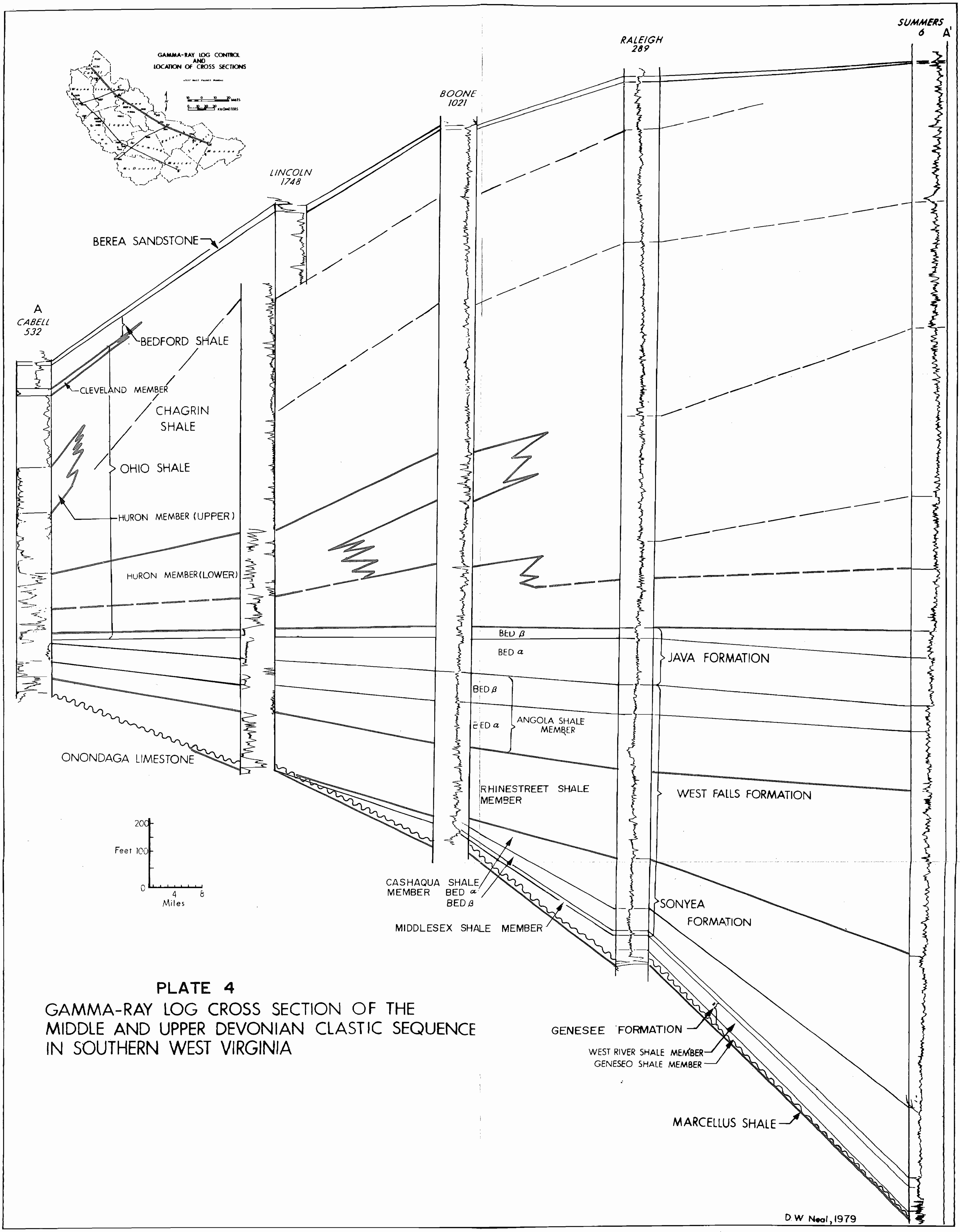


PLATE 4

GAMMA-RAY LOG CROSS SECTION OF THE MIDDLE AND UPPER DEVONIAN CLASTIC SEQUENCE IN SOUTHERN WEST VIRGINIA

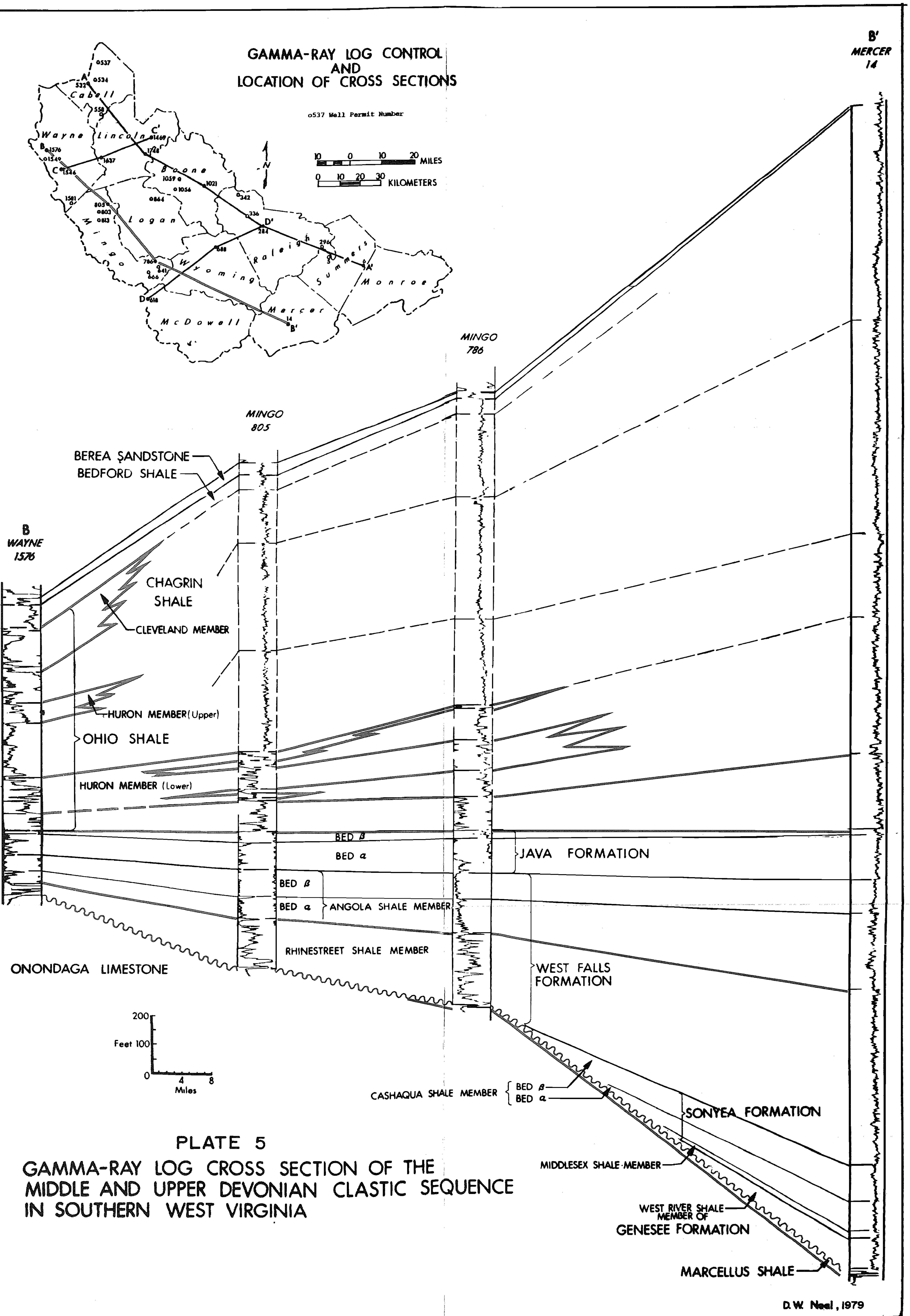


PLATE 5

GAMMA-RAY LOG CROSS SECTION OF THE MIDDLE AND UPPER DEVONIAN CLASTIC SEQUENCE IN SOUTHERN WEST VIRGINIA

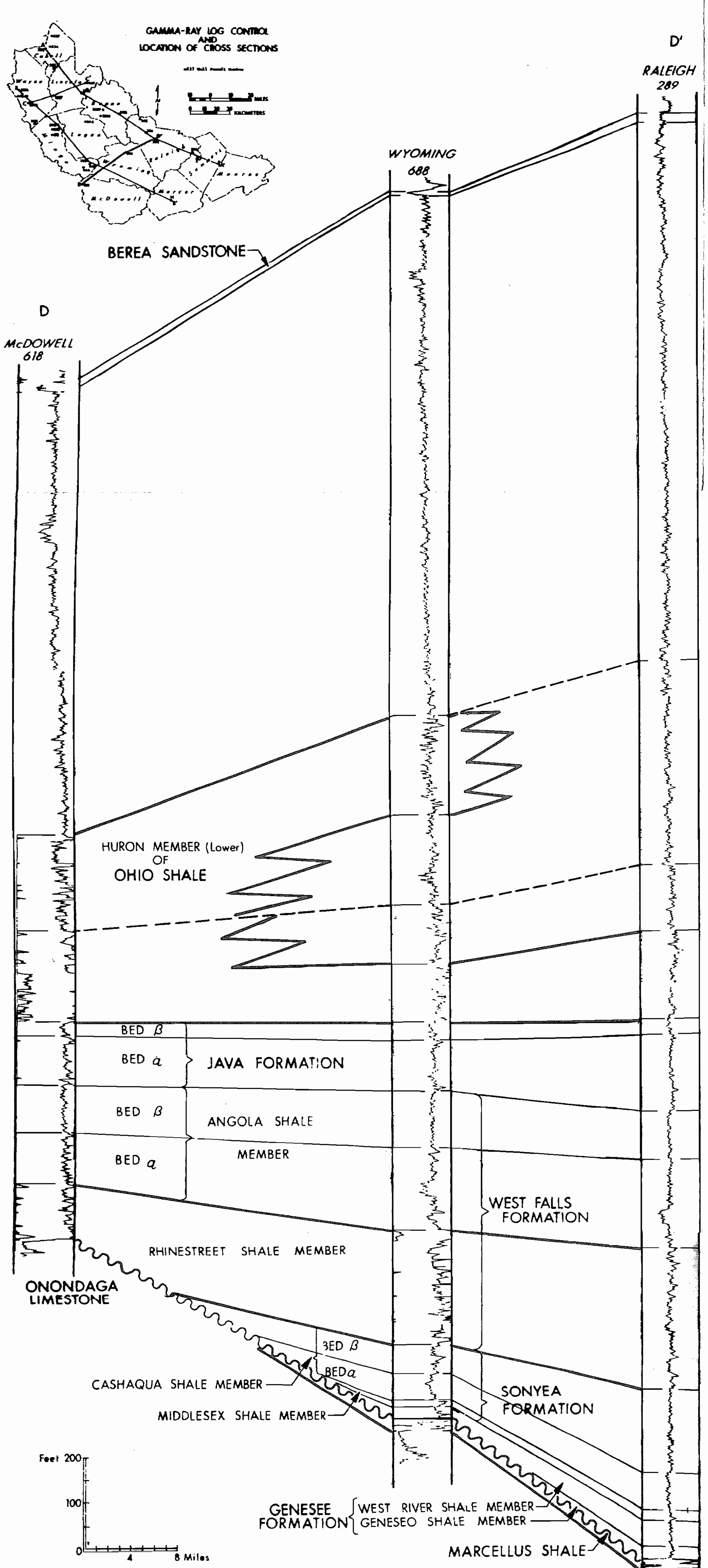
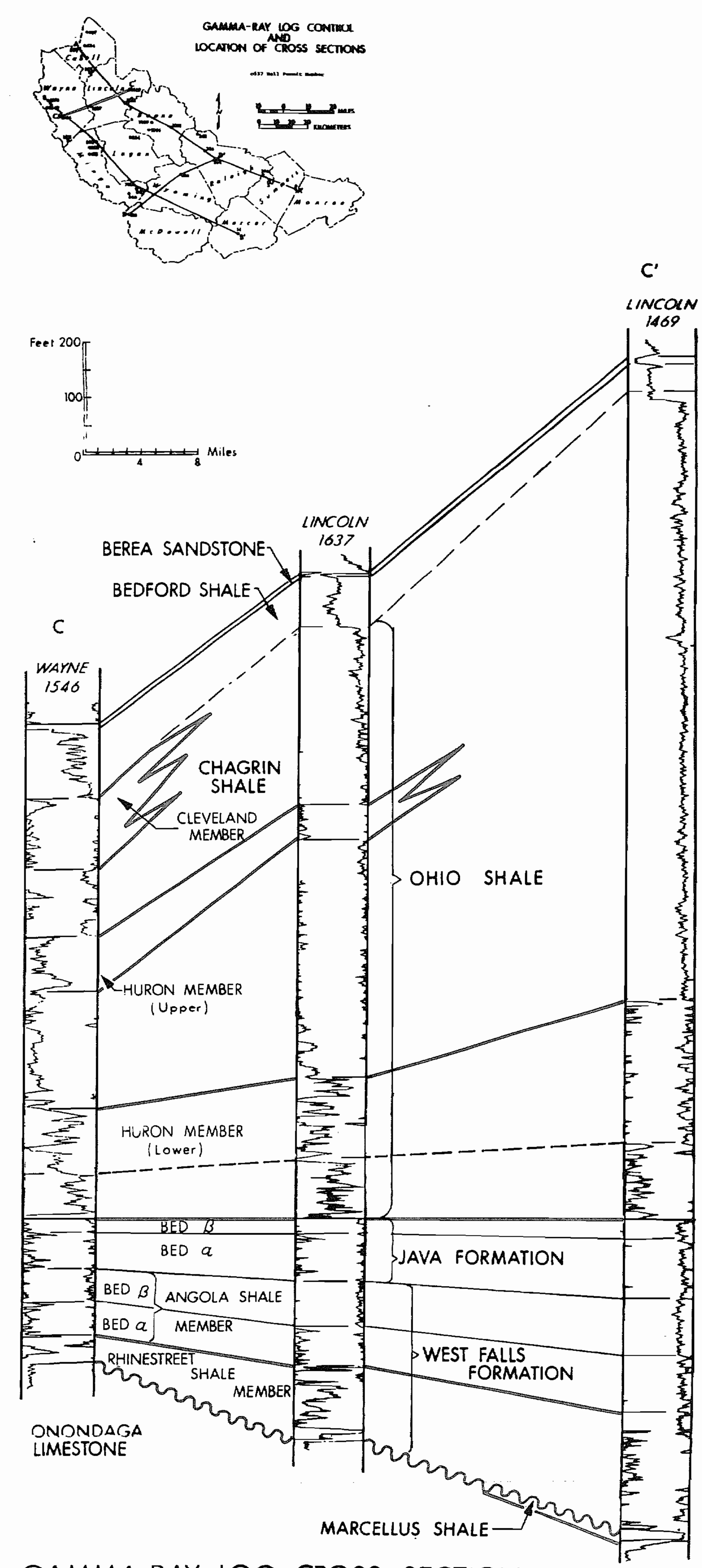


PLATE 6

GAMMA-RAY LOG CROSS SECTION OF MIDDLE AND UPPER DEVONIAN CLASTIC SEQUENCE IN SOUTHERN WEST VIRGINIA



GAMMA-RAY LOG CROSS SECTION OF MIDDLE AND UPPER DEVONIAN CLASTIC SEQUENCE IN SOUTHERN WEST VIRGINIA

D. W. Neal, 1979