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Geologic Factors Influencing the Gas Content of Coalbeds in Southwestern Pennsylvania

By James P. Ulery

BUREAU OF MINES

UNITED STATES DEPARTMENT OF THE INTERIOR

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CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Btu/lb	British thermal unit per pound	min	minute
°C	degree Celsius	m.y.	million years
cm^3/g	cubic centimeter per gram	μm	micrometer
°C/km	degree Celsius per kilometer	pct	percent
ft	foot	pct/ft	percent per foot
in	inch	pct/km	percent per kilometer
km	kilometer		

GEOLOGIC FACTORS INFLUENCING THE GAS CONTENT OF COALBEDS IN SOUTHWESTERN PENNSYLVANIA

By James P. Ulery[1]

ABSTRACT

A Bureau of Mines geologic study of Pennsylvanian and Permian coalbeds in southwestern Pennsylvania was undertaken to determine the effects of coalbed geology and petrology on in situ coalbed gas contents. Data were obtained from 18 coreholes from parts of four 7.5 ′ quadrangles in southwestern Washington and northwestern Greene Counties, and from a single corehole in Westmoreland County.

A total of 88 samples from 24 coalbeds were collected for direct-method testing to determine gas content. The samples were also analyzed for petrographic composition, chemical composition, and vitrinite reflectance values. Corehole information was used to generate isopach maps and geologic cross sections useful in data interpretation.

Results of the investigation show that coalbed gas content is related to vitrinite reflectance, but not to petrographic composition. Gas contents are also influenced by other geologic factors such as roof rock lithology and competency, and location with respect to local fold structure.

INTRODUCTION

Because of the hazards associated with methane emissions and ignitions in underground coal mines, the Bureau of Mines conducts fundamental research regarding the occurrence, emission, and drainage of coalbed methane. Previous studies have demonstrated the feasibility of degassing virgin reserves and producing commercial-quality methane gas from horizontal or vertical boreholes. By using the direct-method to determine coalbed gas contents, geologic studies have established that methane content is related primarily to the rank of the coalbed and its depth (*27, 30*).[2] The direct-method developed by the Bureau measures gas released from a coal sample sealed in an airtight container. All gas contents in this study were determined by this direct-method, which is presented in more detail by Kissell (*27*).

The objective of this report is to provide an overview of coalification, coal petrography and the maceral concept, and to review theories regarding gas generation and storage by coalbeds. More importantly, this report will assess the effects of variations in petrographic composition, rank, and local geology on the gas contents of coalbeds from the Dunkard Basin in southwestern Pennsylvania. The report concentrates on a relatively small area in the basin to minimize the effects of regional variations on former depth and duration of burial, and paleogeothermal gradient. Subsequent reports will address variation in gas contents with petrographic features across a wider range of rank and geothermal conditions.

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[2]Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

ACKNOWLEDGMENTS

The author gratefully acknowledges the invaluable assistance of Donald G. Puglio, project geologist, of Consolidation Coal Co., Northern Appalachian Exploration Div., Library, PA, for securing permission to collect the samples, cooperation in sample collecting and logging, work on correlation of the Permian coalbeds, and innumerable helpful discussions and suggestions throughout the preparation of this report.

COAL PETROGRAPHY AND THE MACERAL CONCEPT

Coal petrography refers to the macroscopic and microscopic characterization and description of coal or coal fragments on the basis of one or more physical criteria such as reflectance, morphology, luster, or color. Characterization on the macroscopic scale includes the thickness, abundance, and luster of various coal bands, and includes a description of interbedded noncoal layers such as bone, pyrite, shale, or other rock types. Petrographic analysis on a microscopic scale is accomplished either by viewing coal thin sections in transmitted light or by viewing coal fragments on a polished pellet with reflected light. Currently most petrographic analyses are accomplished by reflected light techniques.

Pioneering work in the field of coal petrography was done in the United States by Reinhardt Thiessen (*50-51*), and in England by Marie Stopes (*44-45*). Because they were using two different methods of analysis (Thiessen, transmitted light; Stopes, reflected light), the classification systems developed by each investigator varied considerably.

Most modern classification systems stem from the Stopes system, and recognize three main groups of microscopic components or macerals. Macerals are the fundamental components of coal, roughly analogous to minerals in rocks (*45*). Macerals, however, are not crystalline and are classified on the basis of reflectance, morphology, origin, or mode of preservation (*42*).

The three maceral groups recognized are vitrinite, inertinite, and exinite (or liptinite). These three groups may be further subdivided into individual macerals, submacerals, and maceral varieties, the only limitations being the degree of alteration and the needs of the researcher. Figure 1 lists the important macerals of the three groups and gives brief descriptions of each.

Vitrinite occurs most frequently and accordingly is the most important maceral group found in bituminous coals. Most vitrinite originates from the trunks, branches, stems, leaves, and roots of various flora that existed in ancient coal forming swamps (*50-51*). In lower rank coals the vitrinite macerals, telinite and collinite, are often found in close association (*42*). Telinite refers to preserved cell wall material, whereas collinite refers to a structureless gel-like maceral often found filling the aforementioned cell structures. As rank progresses, cell structure is obliterated and the two macerals are referred to simply as vitrinite.

Maceral group	Maceral	Origin	Appearance	
Vitrinite	Telinite	Primarily roots, bark and woody material Also twigs, leaves	Medium bright	Preserved woody remains with cell structure
	Collinite	Formed from gels of humic materials excreted from plant material		Occurs infilling cell structure and as macerated material in attrital coal
Exinite	Sporinite	Spore and pollen cell walls	Least bright medium to dark gray	Identified by morphological characteristics
	Cutinite	Waxlike coating of leaves and stems		
	Resinite	Numerous material including primary resins, fats, and oils		
	Alginite	Algae		
	Bituminite	Probably related to decomposition of algae, faunal plankton and bacteria	Usually black	Usually very dark, occasionally mistaken for mineral matter or fracture
	Exudatinite	"Secondary" resinite formed during coalification, veinlets		Distinct organic origin seen by fluorescence Identified by morphological characteristics
	Fluorinite	"Secondary" resinite probably formed from plant oils during coalification, massive		
Inertinite	Semifusinite Fusinite	Formed from or vitrinitic material from one or more processes acting before and/or during coalification	Bright to very bright	Occurs as bands or lenses usually with a well developed pore system
	Micrinite	Formed by degradation and devolatilization of cell wall and exinitic material		Occurs as rounded grains, usually < 1 μm in diameter in groundmass
	Macrinite	Fusinitized collinitic (gel) material		Usually structureless, more or less amorphous nongranular groundmass; occasionally isolated particles
	Sclerotinite	Fungal remains in younger coals; fusinitized cell secretions (resins) in older coals		Identified by morphological characteristics, usually somewhat rounded with pore structure

Figure 1.–Common macerals and their possible origin.

Two other important vitrinite macerals are telocollinite and desmocollinite, also known as vitrinite A and B, respectively (*7*, *42*). Generally concentrated in attrital coal layers, desmocollinite (vitrinite B) has a lower reflectance and higher hydrogen content than telocollinite (vitrinite A), which is usually found in nonattrital coal layers. Consequently attrital coal or bands within coal may be important in assessing gas generation potential.

Important macerals of the inertinite group, so named for their relatively inert behavior in the coking process, include fusinite, semifusinite, and micrinite. Fusinite is a charcoal-like substance usually formed by rapid charring and alteration of cell wall material (vitrinite) prior to, or shortly after, incorporation into the enclosing sediment. This charring may be a result of paleo-forest fires (*42*), and an abundance of this maceral may indicate relatively dry conditions. Semifusinite is a less altered maceral and represents material intermediate between vitrinite and fusinite.

Micrinite is an atypical inertinite maceral because it generally does react during the coking process. The genesis of micrinite remains controversial and several modes of origin have been proposed. One school of thought suggests that micrinite originates from physical degradation and metamorphism of cell wall material (*39*, *41*). Another suggests a subaqueous formation via chemical-biological agents during the peat stage (*38*, *52*). A third hypothesis contends micrinite originates during coalification through metamorphism of exinite macerals (*48-49*).

The exinite group macerals, which may be very important in methane generation, are derived primarily from spores, cuticles, resins, waxes, fats, and oils present in the original plant material. The exinite macerals are relatively rich in hydrogen and volatile matter and readily react during coalification. Another feature of exinite macerals is their fluorescence when irradiated with ultraviolet light. Fluorescence microscopy has led to the discovery of some previously unrecognized exinite macerals, fluorinite, exudatinite, and bituminite (*48*). Exudatinite may be significant because it represents a mobile "secondary" maceral generated during the coalification process, and its formation is likely concurrent with oil generation in source rocks of the same region (*49*). Therefore exudatinite in coals suggests that certain primary exinite macerals have volatilized releasing significant methane.

Fluorescence tends to decrease with increasing coalification, concomitant with the gradual disappearance of the exinite macerals (*48*-49). Significant alteration of original exinitic material begins to occur in the upper high-volatile rank and by low-volatile rank exinite have virtually disappeared (*42*). The alteration of exinite may be partially responsible for the higher gas contents found in medium- and low-volatile rank coals.

COALIFICATION AND RANK

The importance of the coalification process on gas formation and maceral associations necessitates a brief discussion. The coalification process is the gradual, progressive alteration (metamorphism) of plant material to peat, lignite, bituminous, and higher rank coals (*42*). Coalification is achieved through the interaction of temperature, time, and pressure (*12*, *36*, *41-42*, *60-61*).

Coals form in low-lying swampy areas in which subsidence and sedimentation occur simultaneously. The continued subsidence of these areas results in thick accumulations of sediments and deep burial. Temperature and pressure increase proportionately with burial causing physicochemical reactions resulting in coalification. One would expect, then, that at any given location the rank of coal material should increase with depth. This premise has been substantiated in numerous borehole profiles and is known as Hilt's law (*42*).

The relative importance of the coalification variables – temperature, time, and pressure – is subject to various interpretations. Most researchers agree that temperature has a very significant influence on coalification as indicated by rank studies adjacent to igneous intrusives (*4*, *42*). The effects of intrusive bodies on coalification are generally localized, whereas regional coalification results from heat associated with an area's geothermal gradient and the heat conductivity of the enclosing strata. High geothermal gradients however, may be associated with very large, deep-seated intrusive bodies. Changes in temperature during coalification occur then in three primary ways: (1) at a constant geothermal gradient, temperature increases as depth of burial increases; (2) changes in geothermal gradient due to mantle processes or large, deep-seated plutonic intrusives; and (3) localized temperature increase adjacent to smaller igneous intrusions (dikes, sills).

The effect of time on coalification has been discussed by Bostick (*3-4*) and Stach (*42*), and is a significant factor in this process. For example, if two coalbeds were subjected to similar temperatures, the one subjected for the longest time (geological) should attain a higher rank.

The effect of pressure on coalification has been extensively discussed and remains controversial. White (*58-61*) in his pioneering work on the carbon-ratio theory, related the degree of coalification to the occurrence of oil and gas, and concluded that tectonic pressure was important in promoting coalification. This view has lost acceptability because recent experiments have suggested that static pressure inhibits chemical coalification reactions (*9*, *36*, *42-43*), possibly because the removal of gas and other volatiles becomes more difficult.

Various systems have been proposed to classify coals according to their rank or degree of metamorphism. Early classification systems were often based on volatile matter, fixed carbon, calorific value, caking or coking power, and agglomerating properties. Because these parameters can be determined by fairly simple procedures, and have close relations to important uses of coal, classification systems based on them have found great acceptability and are used today.

As coal research progressed, the need for a classification system applicable to scientific research as well as enhanced coal technologies was needed. It soon became obvious that comparative rank studies should be made on the basis of vitrinite only, since this tends to exclude the influence of the heterogeneity of most coals. Vitrinite is used because it is the most abundant and readily isolated maceral found in coal. Comprehensive, comparative studies of all rank parameters show that certain parameters are more applicable to particular ranks of coal, while no single parameter is relevant throughout the rank series.

Measurement of vitrinite reflectance has become increasingly popular as a means of determining coal rank by photometrically measuring the amount of light reflected from the maceral vitrinite. Numerous studies relating reflectance to other rank parameters have been completed and are summarized by McCartney (*29*) and Stach (*42*).

Mean-maximum vitrinite reflectance was used in this study and is a commonly used petrographic technique for rank determination in the United States. According to American Society for Testing and Materials (ASTM) standards, it is determined on 100 vitrinite points statistically distributed over the whole surface of the polished specimen. For each point, the stage is rotated through 360° and the maximum reflectance intensity recorded. During reflectance measurement, care must be taken to exclude any influence from relief or inhomogeneities (e.g., scratches, fine cracks, or minute mineral inclusions). The maximum reflectance readings are usually plotted on a histogram, and the values averaged to determine mean-maximum reflectance. Internationally, mean-random reflectance, determined on nonrotated vitrinite particles is commonly used. Figure 2 compares ASTM rank with various rank parameters including random and maximum reflectance and shows their ranges of applicability.

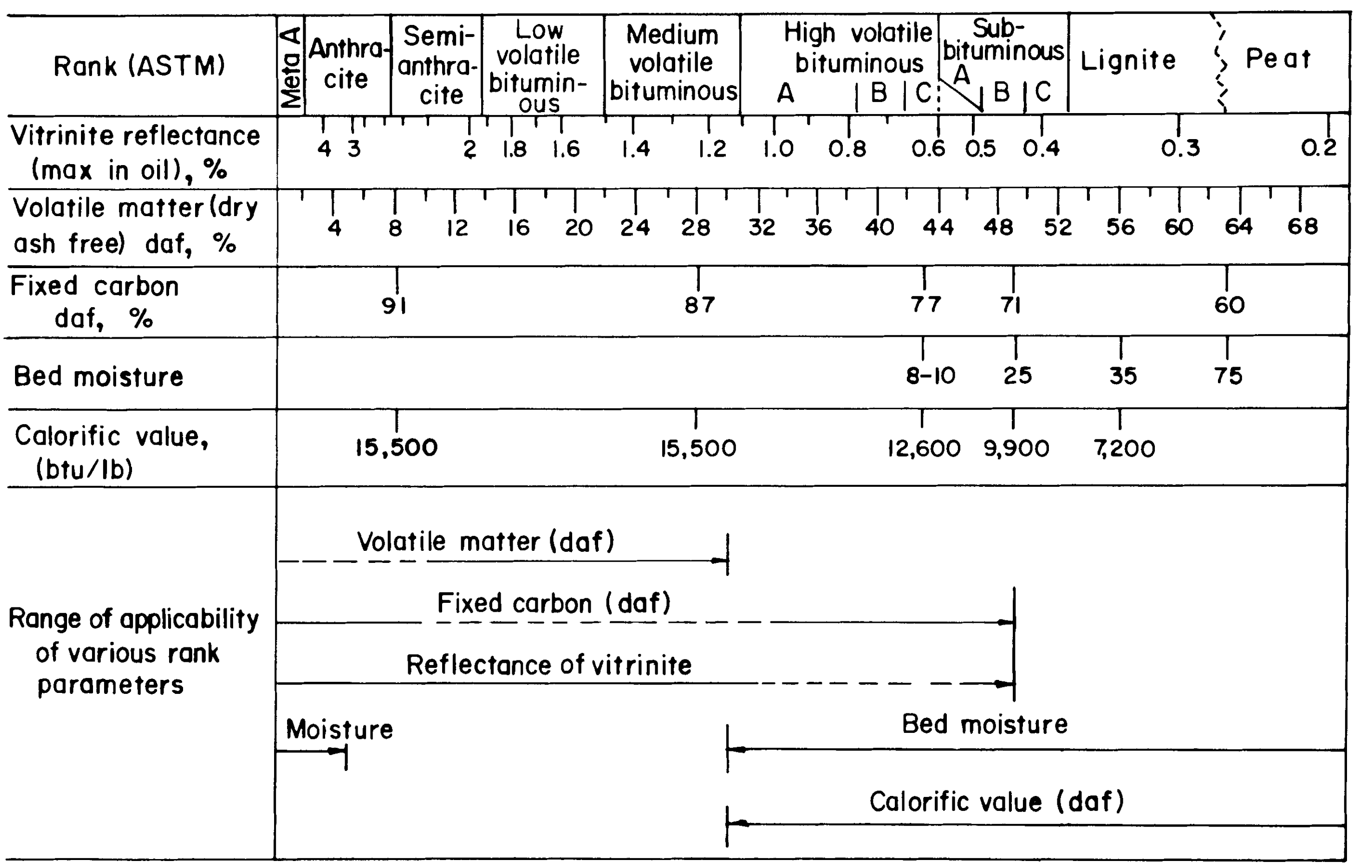

Figure 2.–ASTM rank classification; its relation to various ranking parameters and the range of applicability of these parameters.

COALIFICATION AND METHANE GENERATION

The occurrence of explosive gases or firedamp in coal mines has long been known in areas where bituminous coals are worked (*11*, *17*, *24*, *34*, *37*, *57*). The origin of these gases was once the subject of debate concerning whether or not they were generated in situ or migrated into the coalbed from adjacent strata (*11*, *37*). Today most researchers agree that the majority of the gases were generated within the coalbed during the coalification process (*17*, *25*, *34*, *57*). Some methane gas found in low-rank coals (lignites) was probably generated by biogenetic processes (*26*).

Formation of methane as well as carbon dioxide and water during the coalification process was hypothesized by White (*58-60*) and later by Kim (*25*), Patteisky (*34*), and Selden (*38*). In a review of European firedamp drainage, Venter (*57*) also concluded that most firedamp was probably generated from the organic matter during the coalification process. Hargraves (*17*), in studying outburst phenomena in Australian mines, also concluded that the methane contained in coal is a byproduct of coalification and attempted to estimate the volumes of methane, carbon dioxide, and water released during progressive coalification.

More recently, the work of Juntgen (*21*) and others (*6*, *15*, *18*, *22-23*, *32*, *40*) has provided conclusive evidence for the generation of coalbed gases as byproducts of the coalification process. The work of Juntgen (*21*) is particularly significant because a fundamental parallelism between coalification and pyrolysis is established. If one accepts this premise, there can be little doubt as to the in situ origin of coalbed gas. During pyrolysis (heating in an oxygen deficient atmosphere) coal releases H_2O, CO_2, N_2, H_2, CH_4, and heavier hydrocarbons, then tar; the coal eventually becomes coke. If the heating rate is decreased, tar formation likewise decreases, eventually to essentially zero, while production of methane and other volatiles increases. Using these observations, Juntgen (*21*) estimated that the volume of methane generated by the time a coal reached low-volatile bituminous rank was far in excess of the storage capacity of the coal.

Kroger (*28*) studied the behavior of the individual macerals during pyrolysis and demonstrated that exinite macerals generate the most volatile matter (water, hydrocarbon, and other gases) and inertinite macerals release the least. Similarly, if other coalification variables are equal (temperature, time, and pressure), one might expect exinite-rich coals to generate more methane than normal coals.

Finally, the work of Creedy (*10*) is noteworthy for the refinement in measurement of occluded gases in coal. Creedy's work on the relationship between petrographic characteristics and coalbed gas contents established that for bituminous coals, gas content generally increases proportionately with rank as determined by vitrinite reflectance. It was also concluded that gas emission rates increased in coal samples with higher fusinite contents.

RETENTION AND EMISSION OF COALBED METHANE

Most methane and other gases are retained in coal by the process of adsorption (*24*, *33*, *37*, *57*). Adsorption occurs when natural intermolecular attractions between the coal and gas molecules bond the gases to the walls of naturally occurring pores and fissures in coal. The packing together of the adsorbed gas molecules on the large internal surface area provided by pores and fissures enables large amounts of gas to be retained in a small volume of coal. Free gas also occurs in the fissure and pore systems and is believed to be in equilibrium with the gas in the adsorbed phase (*42*).

If the coalbed is capped by an impermeable layer, free gas in the fissure-pore network is also in equilibrium with the hydrostatic pressure of the surrounding strata. However, if the coalbed is capped by permeable strata, free gas will percolate upward, escaping from the coalbed. This loss of free gas destroys the equilibrium between free and adsorbed gas, allowing desorption to begin.

Desorption is the opposite of adsorption and occurs when the free gas pressure in fracture-pore system is lowered causing a disequilibrium between the free and adsorbed gas phases. Pressure changes in the free gas occur either by gradual percolation upward through permeable strata, or lateral migration through the coal caused by a pressure differential (*16*). Both of these processes require an interconnected fissure (fracture) system. This fissure system is known as cleat and occurs in most coalbeds of the United States.

According to Cervik (*8*), mass transport of gas through the fracture system is governed by Darcy's law, the driving force being a pressure gradient. Mass transport through the micropore system is governed by Fick's law of diffusion, where concentration gradient is the driving force.

STUDY AREA

The primary study area is part of the Dunkard Basin, located in southwestern Washington and northwestern Greene Counties, PA, and includes data from 18 coreholes from the Claysville, Prosperity, Wind Ridge, and Rogersville 7.5 ′ quadrangles (fig. 3). Samples were also obtained from a single corehole on the edge of the basin, near Greensburg, Westmoreland County, approximately 30 miles east of the main study area. Data from this corehole are used in conjunction with the general conclusions about coalification and gas content rather than site-specific conclusions.

The surficial rocks of Dunkard Basin consist primarily of alternating claystone, shale, siltstone, sandstone, limestone, and coal deposited during the Late Pennsylvanian and Early Permian. Vertical repetition of the rock types in a somewhat cyclic pattern is common, as are abrupt lateral facies changes due to the dynamic depositional environments coexisting with the coal-forming environment. There is also an upward increase in the amount of sandstones, siltstones, and shales relative to limestone.

Regionally these rocks resulted from sediment accumulation in an area of extensive shallow marine-limnic influence coexisting with swamp and fluviodeltaic environments. The area has been depicted as a northeasterly extension of an epicontinental sea, which was gradually cut off, forming an extensive shallow lake. The depth of the water probably never exceeded a few feet, and at times was a vast swamp, or even dried up completely (*2*). Subsidence of the Dunkard Basin appears to have occurred at a considerably slower rate than the Pocahontas Basin of southern West Virginia.

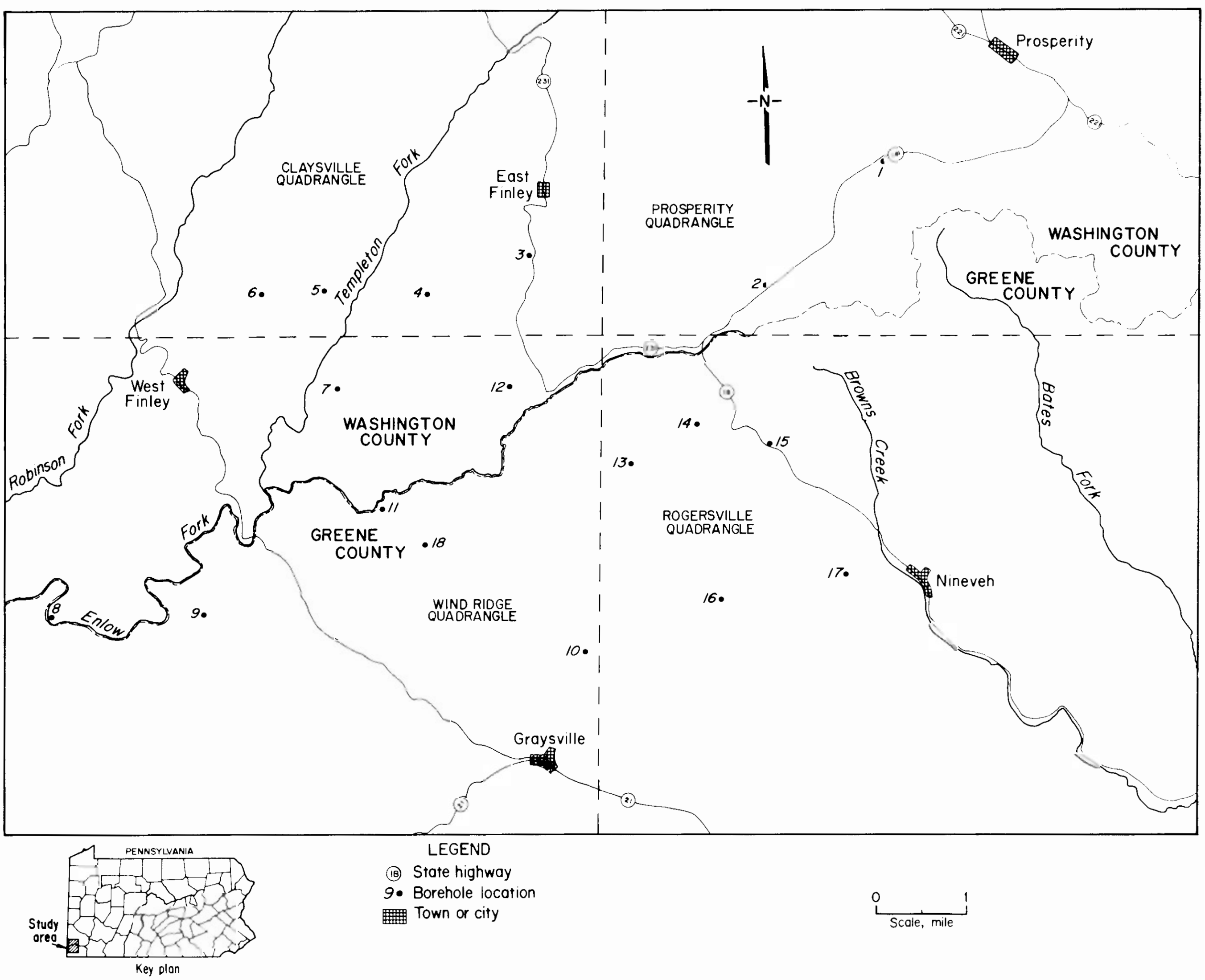

Figure 3.–Map of study area.

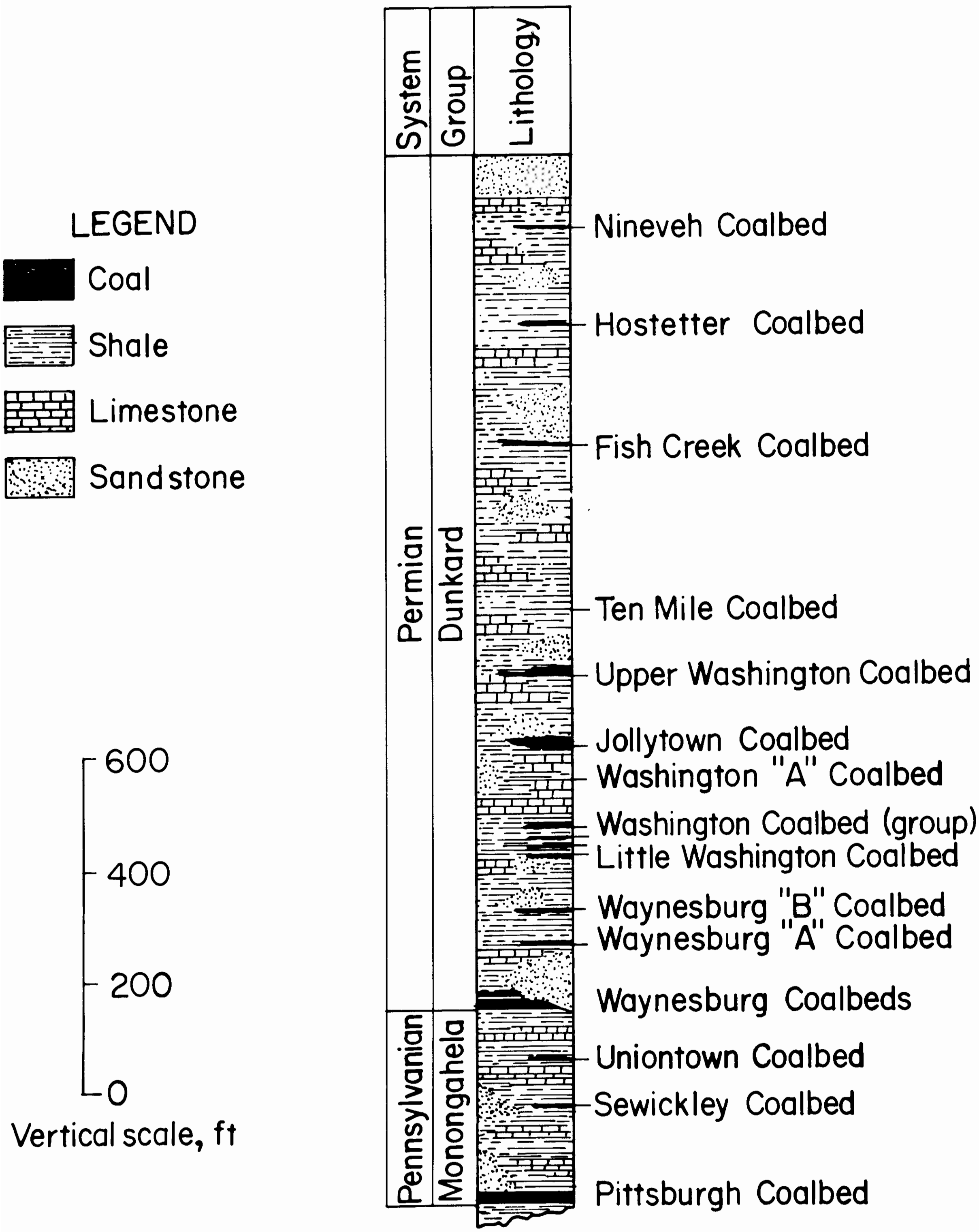

Figure 4.–Stratigraphic column of Monongahela and Dunkard Groups.

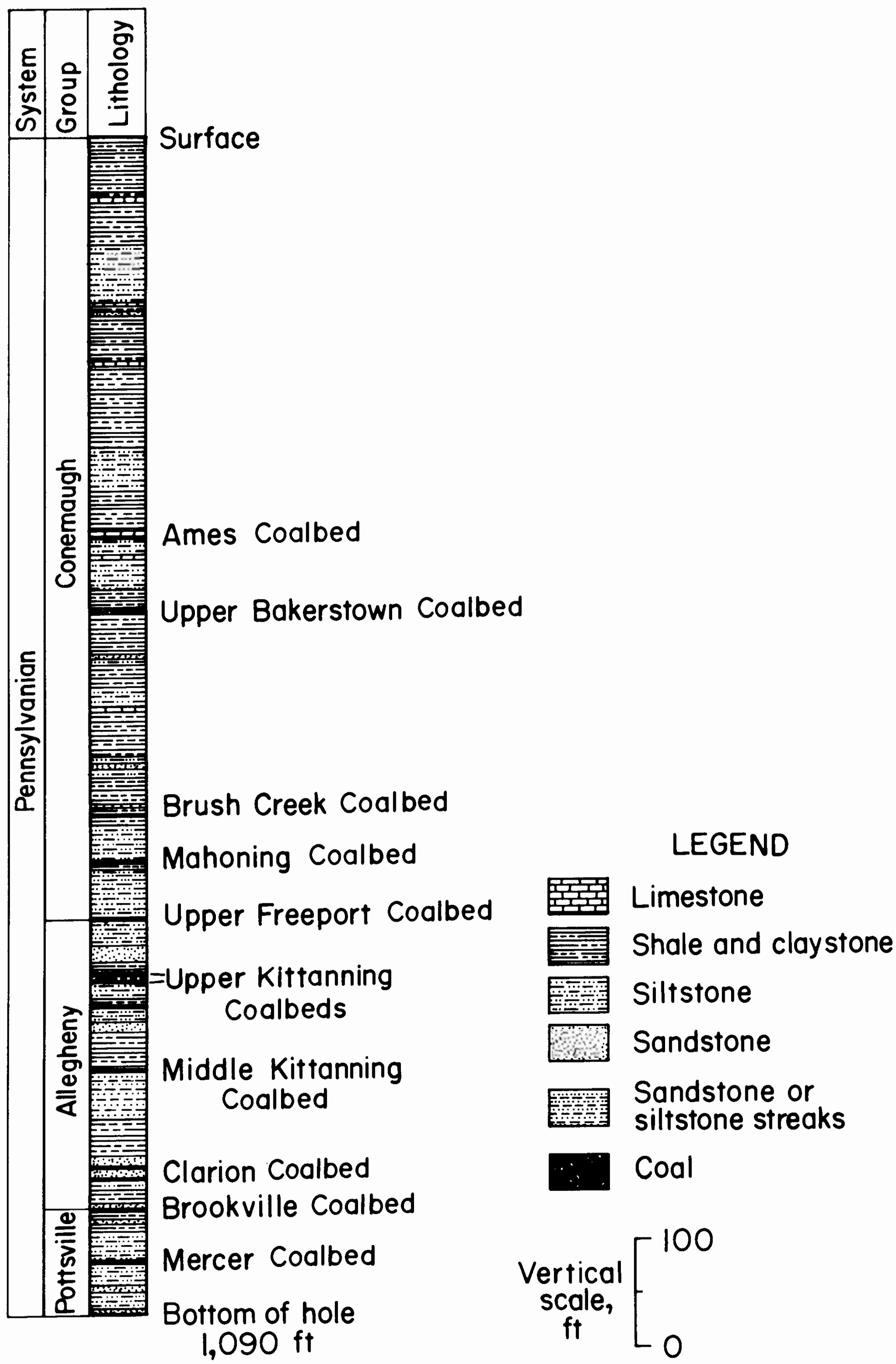

Figure 5.–Stratigraphic section penetrated by Westmoreland County, PA, corehole.

This report deals primarily with the rocks of the Pennsylvanian Monongahela Group and the Late Pennsylvanian-Permian Dunkard Group (*2*) of southwestern Pennsylvania. It also includes data from the Conemaugh, Allegheny, and Pottsville Groups of Westmoreland County. A generalized stratigraphic column of the Monongahela and Dunkard Groups in the main study area is shown in figure 4. A stratigraphic column of the lithologies penetrated in the Westmoreland County corehole is shown in figure 5.

Structurally the main study area is characterized by broad open folds whose flanks seldom dip more than 1° or 2°. Little or no faulting is associated with these features. Flexure occurred as a result of northwesterly directed compressive forces that were active during the Allegheny orogeny in the late Paleozoic (*31*). These forces ultimately culminated in large-scale regional uplift of the area.

Major structural features of the main study area are the Nineveh syncline, the Washington anticline, and the southern terminus of the Finney syncline. These structures are shown on a structural contour map (fig. 6) drawn on the base of the Pittsburgh Coalbed.

The Nineveh syncline is one of the more prominent structures of the Pittsburgh Plateaus physiographic province, extending more than 60 miles in a northeasterly direction across northern West Virginia and southwestern Pennsylvania. This syncline approximates the axis of the Dunkard Basin and is one of the deepest troughs in the region. In two areas along the syncline, just south of the study area, the Pittsburgh Coalbed is just 100 ft above sea level (*43*), its lowest point in the Dunkard Basin. Within the study area, the Pittsburgh Coalbed ranges from about 200 to 400 ft above sea level along this syncline.

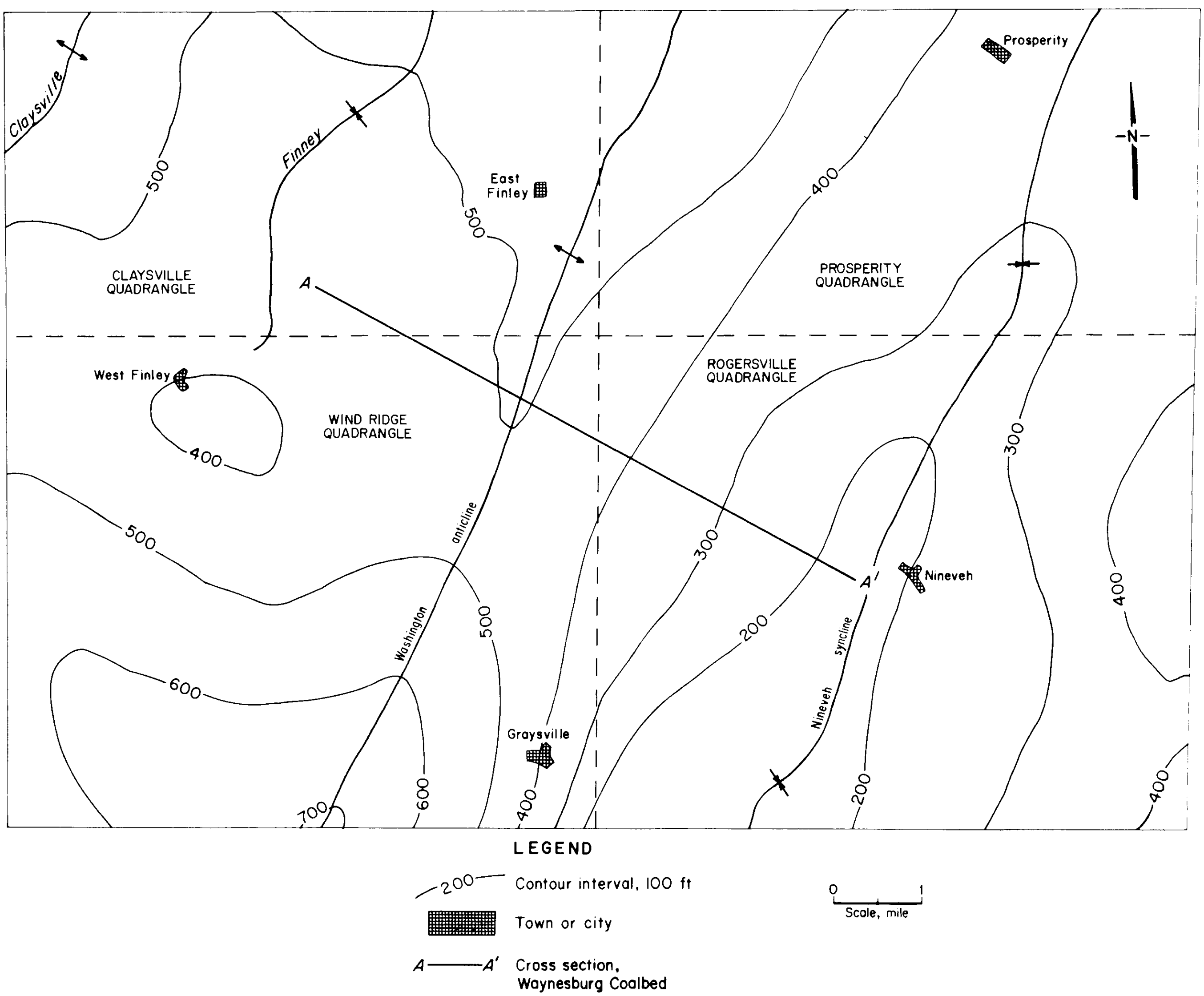

Figure 6.–Structural contour map of study area on base of Pittsburgh Coalbed.

West of the axis of the Nineveh syncline, the strata rise fairly rapidly and uniformly towards the axis of the Washington anticline, also a prominent structural feature. West of the crest of the Washington anticline, dips are much gentler, sloping northwestward to the weakly expressed terminus of the Finney syncline.

RELATION OF COALBED GAS CONTENT TO PETROGRAPHIC AND GEOLOGIC FACTORS

A number of researchers have related the methane content of coalbeds to various geologic factors associated with coal formation and occurrence (*10*, *15*, *17*, *21*, *26*, *34*). Previous work by the Bureau has established that gas content is chiefly a function of depth of cover and rank (*11*, *25*, *27*, *30*, *37*). Other workers (*10*, *53*, *55*) have noted similar relationships and detailed work is beginning to look more closely at the relationship between gas content and petrography.

A total of 88 samples were collected for gas content and petrographic analyses. Plotting of petrographic composition on ternary diagrams revealed that 92 pct of the samples fell within the area shaded in figure 7 as would most U.S. bituminous coals. The coals typically contained 75 to 90 pct vitrinite (by volume), 5 to 20 pct inertinite, and about 5 pct exinite. Most of the samples (78) were from the Pittsburgh through Nineveh Coalbeds (fig. 4), however, 10 samples from the Mercer through the Ames Coalbeds (fig. 5) were sampled from the Westmoreland County corehole.

In hand specimen, most samples would best be described as hard, blocky coals with mostly thin to medium bands of interbedded bright and dull coal. Most coalbeds had several distinct bone layers 1/4- to 1-in thick, as well as abundant pyrite streaks and lenses. Thin, 1/16- to 1/8-in fusain bands were occasionally noted.

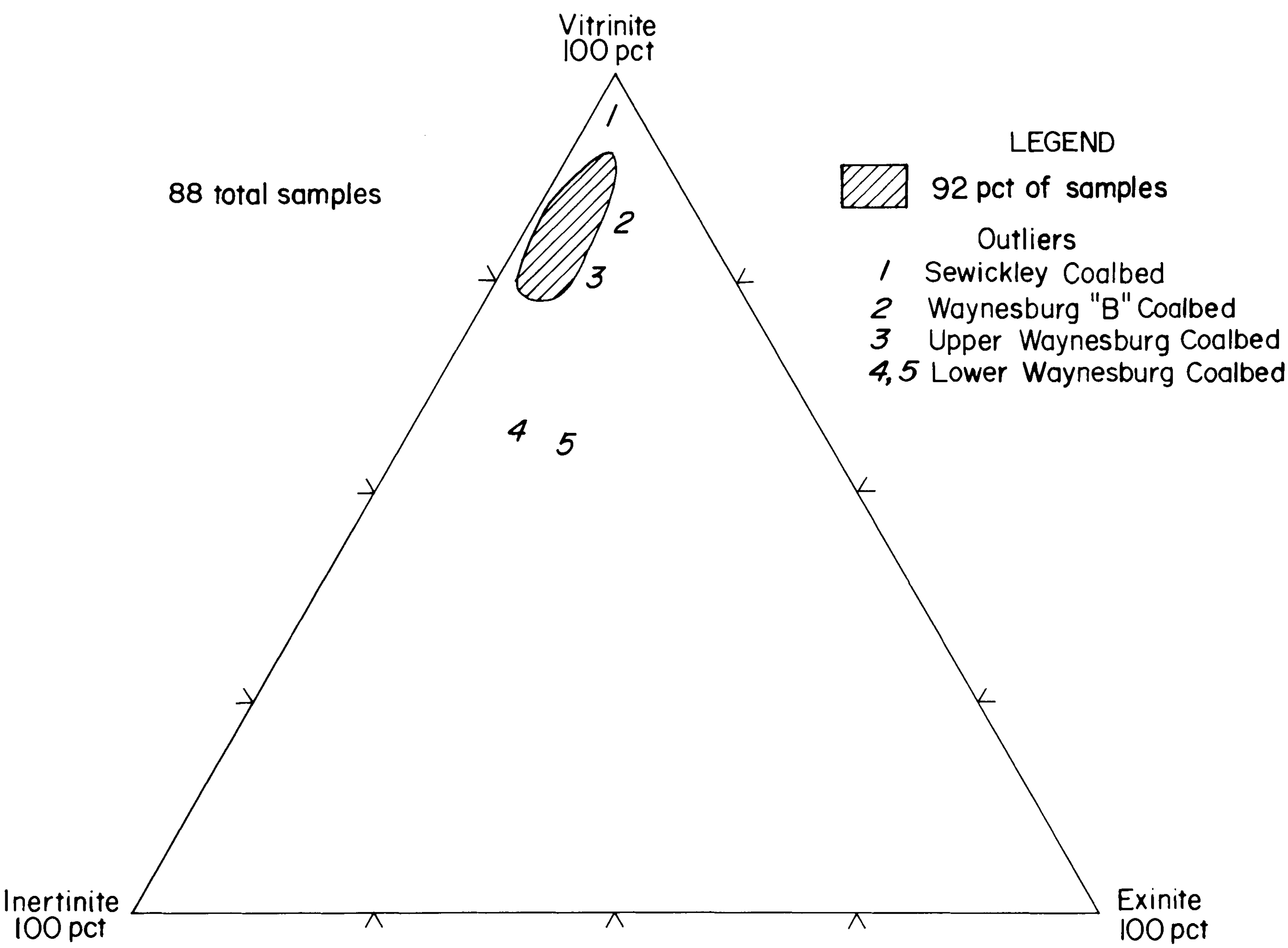

Figure 7.–Ternary plot of maceral composition of sampled coalbeds.

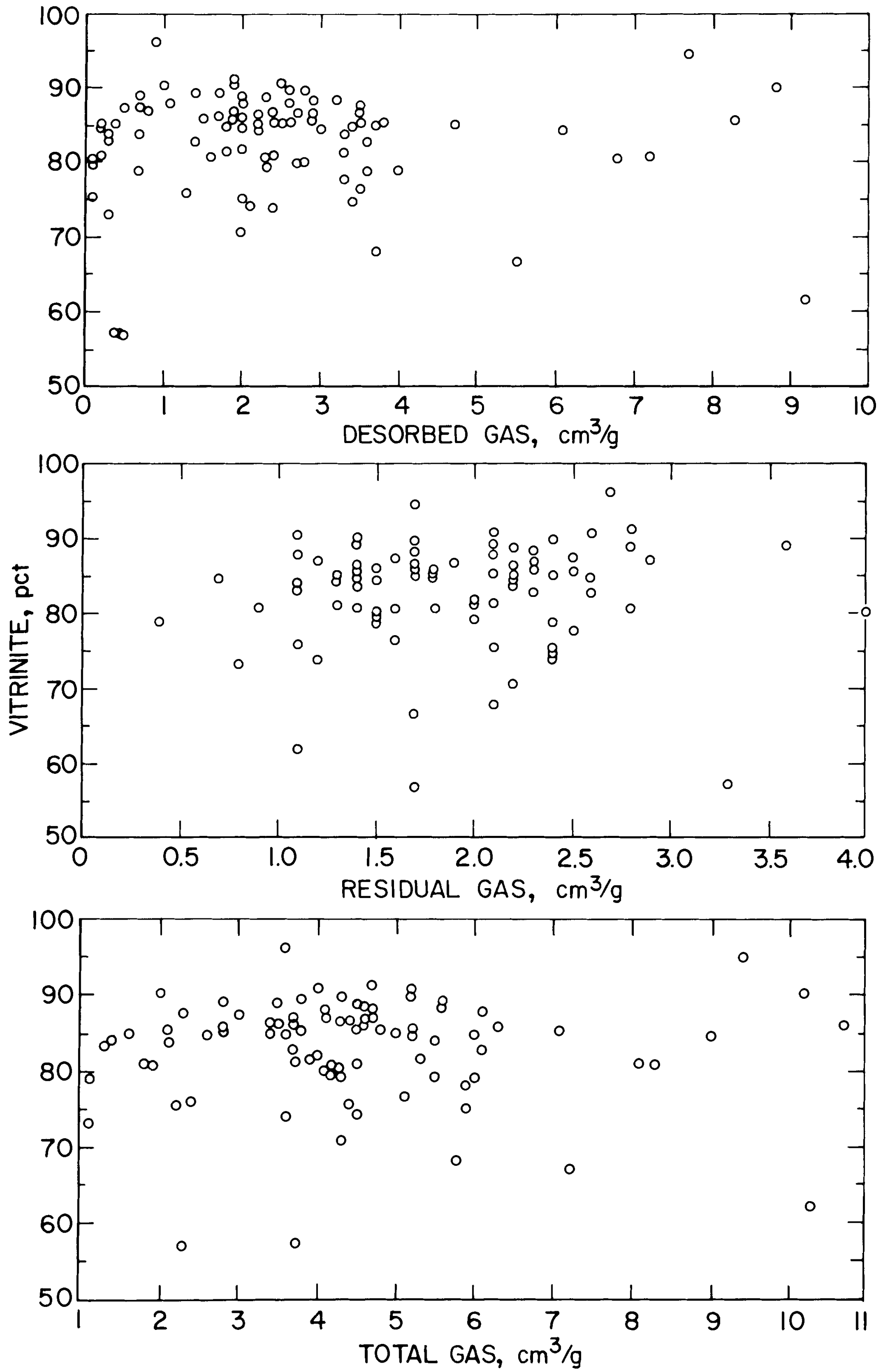

Figure 8.–Vitrinite percent versus total, desorbed, and residual gas contents.

Individual maceral compositions of samples from each coalbed were plotted graphically along with gas contents, (fig. 8). Additional graphs are given in the appendix. No correlation was found between desorbed, residual, or total gas content, and maceral composition. Complete data on maceral composition, chemical analysis and gas contents are also given in the appendix.

A better correlation appears to exist between gas content and vitrinite reflectance. Reflectance is used extensively in oil and gas exploration to determine the thermal maturity of potential source rocks (*4, 6, 15, 22-23, 40*). The degree of thermal maturity of the organic source material indicates the types and relative amounts of hydrocarbons that may be found in nearby reservoir rock.

Figure 9 depicts vitrinite reflectance plotted against gas content; the data set was analyzed by a computerized statistical program to determine the best fit function. Best fit was obtained with a linear regression that had a multiple correlation coefficient (R^2) of 0.73. Figure 10 depicts overburden versus gas content. This data set was also analyzed statistically and the best fit function was found to be a second degree polynomial with an R^2 value 0.31. Clearly, as a parameter for estimating gas content, vitrinite reflectance appears more useful than depth of cover.

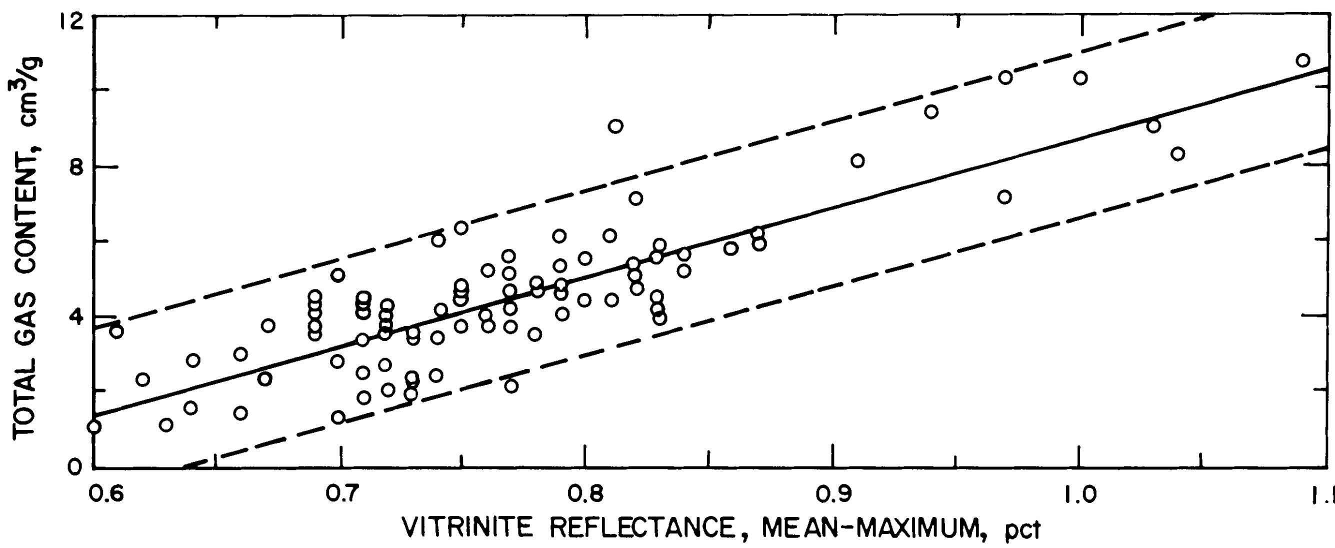

Figure 9.–Vitrinite reflectance versus total gas content.

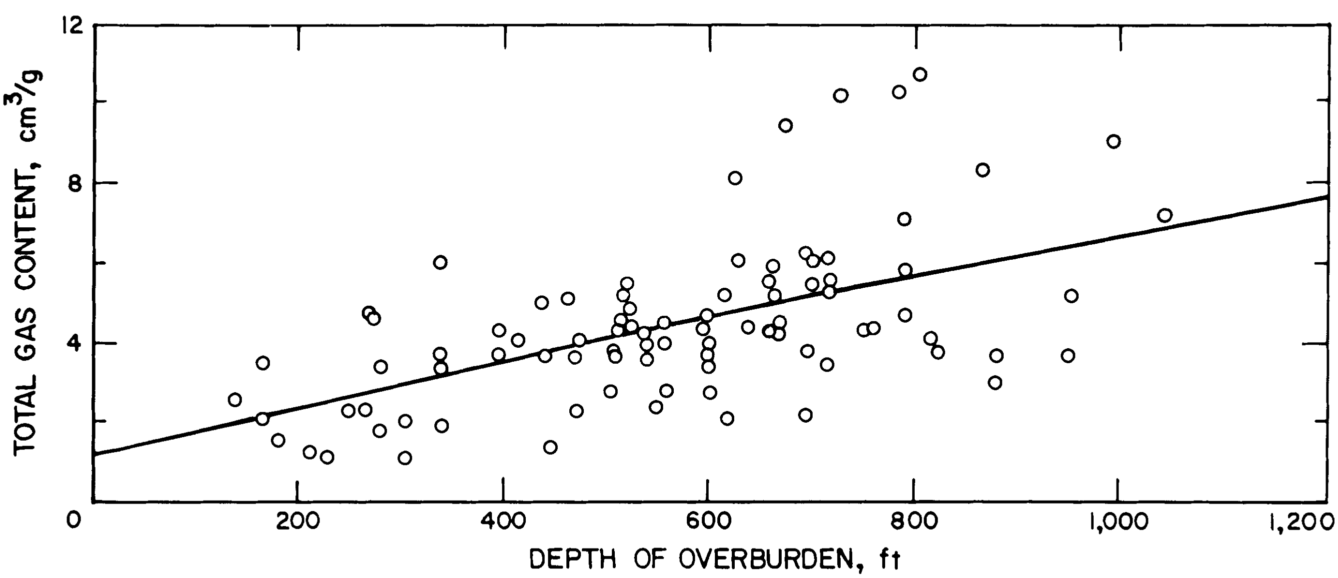

Figure 10.–Depth of cover versus total gas content.

The upper boundary shown in figure 9 may represent gas content values of relatively undisturbed coal capped by unfractured, impermeable strata, while gas contents near the lower boundary represent samples that have degassed naturally via fracturing or migration into porous, permeable, roof rock. By further refining the relation of reflectance and gas content by extending it into higher and lower rank coals, one may have a tool to accurately predict gas contents of coalbeds, given a knowledge of local geology.

Some early influential studies on the regional aspects of coalification invoked tectonic pressures (*57, 59*) as a mechanism for coalification. Some more recent studies still invoke pressure (*9*), however, most modern workers agree that pressures related to regional deformation have little to do with determining rank (*3, 12, 42*). Rather, as previously discussed, the determining factors are former depth of burial, paleogeothermal gradient (temperature), and time near maximum temperature.

Figure 11 could be construed to show that the structure does indeed influence coalification because of the uniform rank (reflectance) increase approaching the axis of the Nineveh syncline. A more acceptable explanation may be that the reflectance increase is merely the result of increasing former depths of burial. This implies that the Nineveh syncline was active during deposition and that the sediments deposited along its axis underwent deeper burial, and therefore were exposed to higher paleotemperatures. Structural activity during deposition of Upper Pennsylvanian-Lower Permian sediments in the Dunkard Basin has also been postulated by Hoover (*19*), while Berryhill (*1*) showed that no structural control on sedimentation existed.

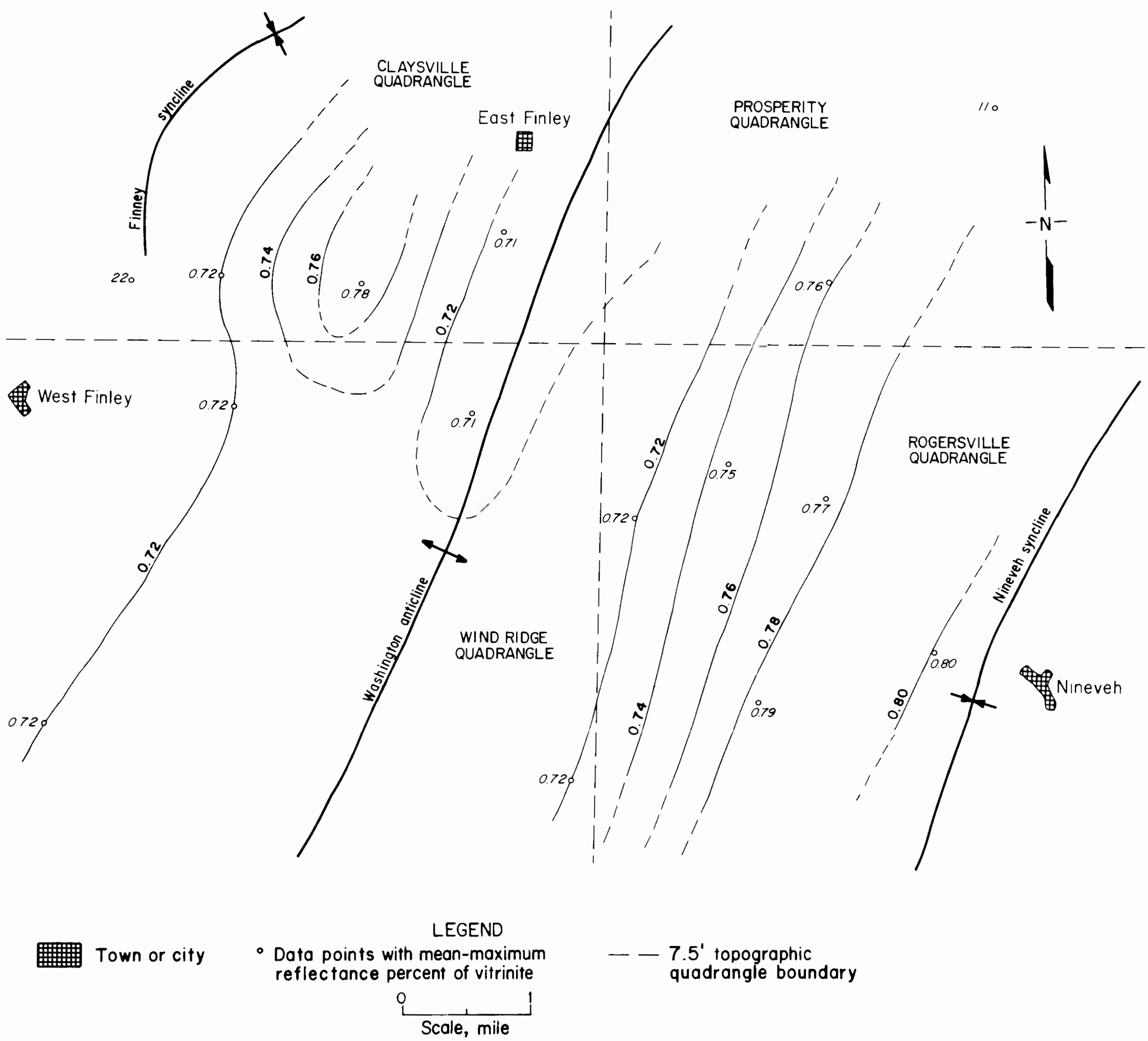

Figure 11.–Isoreflectance map of Lower Waynesburg Coalbed.

TABLE 1. - Gas content and vitrinite reflectance data for Upper and Lower Waynesburg Coalbeds in figure 12

Map key	Waynesburg Coalbed	Gas, cm^3/g Desorbed	Gas, cm^3/g Residual	Gas, cm^3/g Total	Mean-maximum vitrinite reflectance, pct	Roof lithology (caprock)
UW1 ...	Upper	1.9	1.8	3.7	0.75	Hard shale.
LW1A ...	Lower	2.3	1.2	3.5	ND	Claystone parting.
LW1B ...	...do	2.8	1.5	4.3	.72	Do.
UW2 ...	Upper	2.6	2.1	4.7	.75	Hard shale.
LW2A ...	Lower	2.7	1.9	4.6	.77	Claystone and shale parting.
LW2B ...	...do	2.9	1.7	4.6	.78	Do.
UW3 ...	Upper	.2	1.6	1.8	.73	Broken shale.
LW3	Lower	2.2	1.3	3.5	.71	Claystone parting.
UW4 ...	Upper	.1	2.1	2.2	.73	Shale.
LW4	Lower	2.5	1.3	3.8	.72	Shale parting.
UW5 ...	Upper	2.0	2.1	4.1	.77	Hard shale.
LW5A ...	Lower	2.1	1.9	4.0	ND	Claystone parting.
LW5B ...	...do	1.7	2.1	3.8	.75	Do.
UW6 ...	Upper	3.5	1.7	5.2	.76	Hard shale.
LW6	Lower	.3	1.8	2.1	.77	Broken shale and claystone parting.
UW7 ...	Upper	3.8	2.5	6.3	.75	Hard shale.
LW7A ...	Lower	4.0	1.5	5.5	.80	Broken claystone parting.
LW7B ...	...do	3.6	2.5	6.1	.79	Do.

ND Not determined.

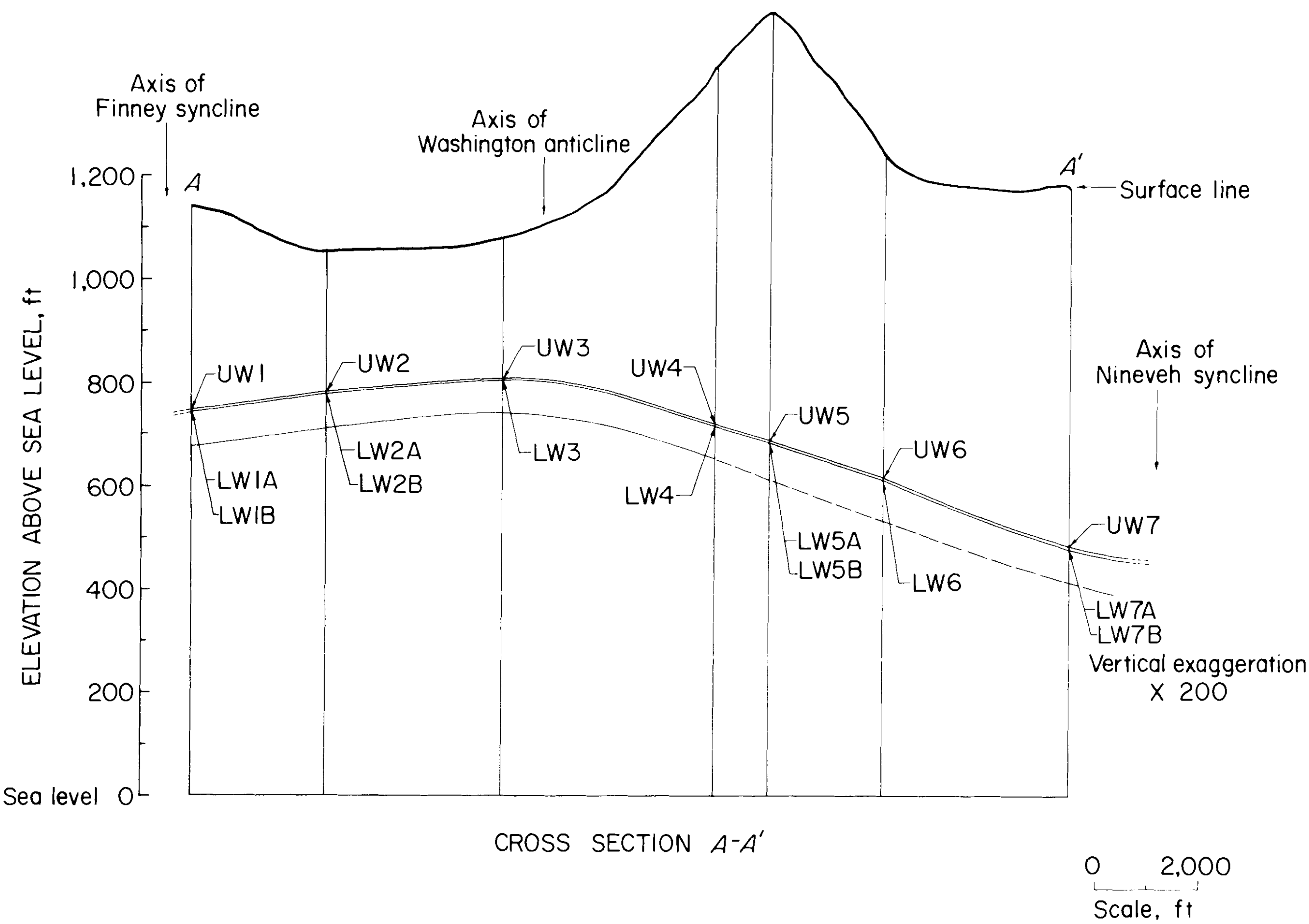

Figure 12.–Structural cross section of Upper and Lower Waynesburg Coalbeds showing gas contents.

TABLE 2. - Gas content and vitrinite reflectance data for Upper and Lower Waynesburg Coalbeds in figure 13

Map key	Waynesburg Coalbed	Gas, cm^3/g			Mean-maximum vitrinite reflectance, pct	Roof lithology (caprock)
		Desorbed	Residual	Total		
UW7 . . .	Upper	3.8	2.5	6.3	0.75	Shale.
LW7[1] . . .	Lower	3.7	2.0	5.7	.80	Broken claystone parting.
UW8 . . .	Upper	2.0	2.1	4.1	.77	Shale.
LW8[1] . . .	Lower	1.9	2.0	3.9	.75	Claystone parting.
UW9 . . .	Upper	.5	2.5	3.0	.66	Massive sandstone.
LW9	Lower	.8	2.9	3.7	.72	Shale parting.
LW10[1] . .	. . .do	.8	.8	1.6	.66	Massive sandstone.
UW11 . . .	Upper	1.7	1.7	3.4	.74	Shale with sandstone streaks.
LW11 . . .	Lower	1.4	1.4	2.8	.72	Shale parting.
UW12 . . .	Upper	2.1	1.5	3.6	.72	Shale with sandstone streaks.
LW12[1] . .	Lower	1.4	1.7	3.1	.71	Shale and claystone parting.
UW13 . . .	Upper	2.0	2.2	4.2	ND	Shale with sandstone streaks.
LW13 . . .	Lower	2.4	1.2	3.6	.76	Shale parting.

ND Not determined.
[1]Average gas content/reflectance values.

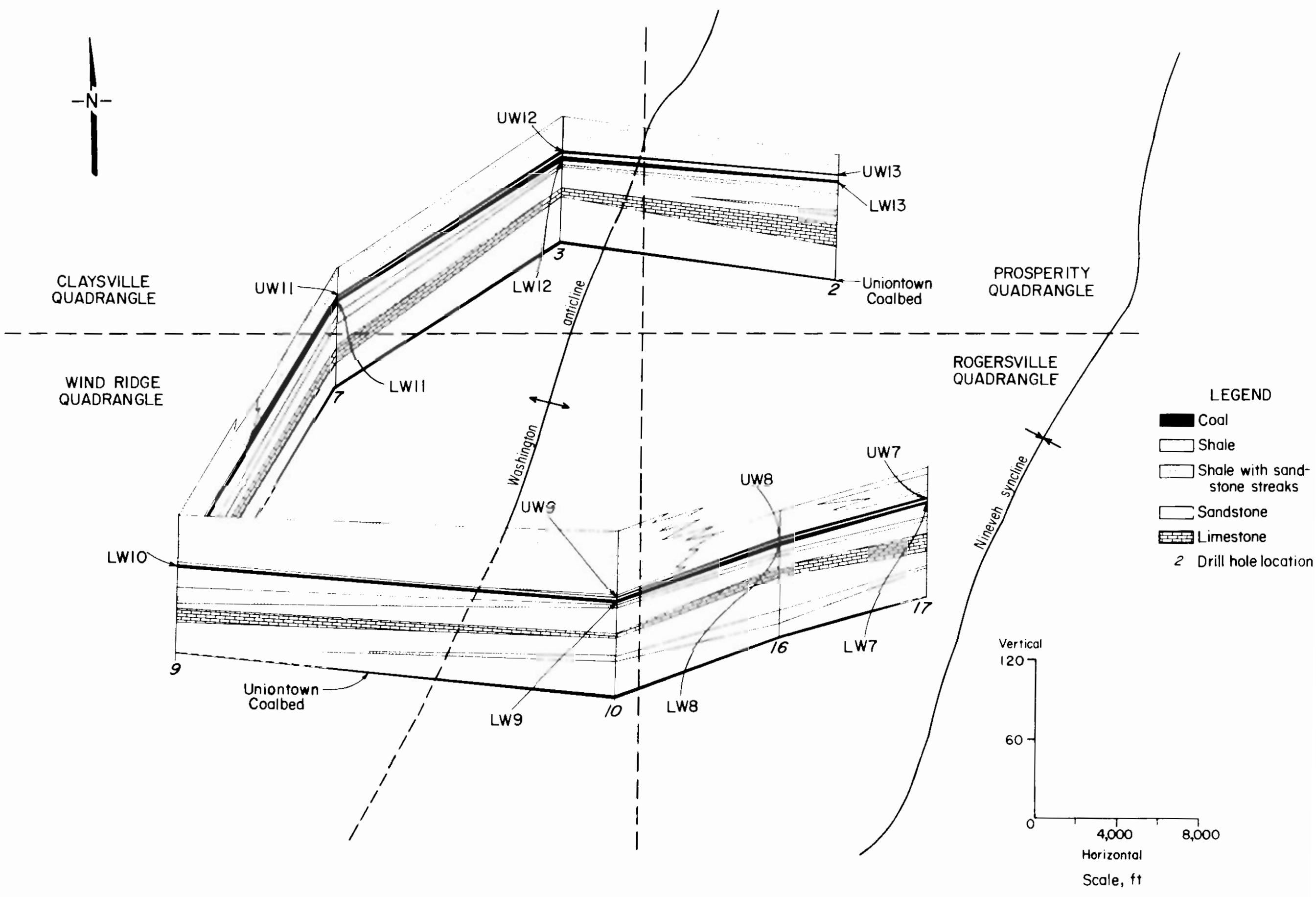

Figure 13.–Panel diagram of Uniontown and Upper and Lower Waynesburg Coalbeds.

The effects of structural position on reflectance values and gas contents is illustrated by table 1 and figure 12, which is a cross section of the Upper and Lower Waynesburg Coalbeds. This diagram shows that where the coalbeds are overlain by shale, gas content and vitrinite reflectance increase towards the synclinal axis except where the coalbeds are overlain by incompetent fractured strata. This difference in gas content may result from increased gas generation by the higher reflectance coals due to greater temperature and former depth of burial. The difference may be further influenced by the increased fracturing and destressing of the strata towards anticlinal crests. Figure 12 also illustrates that reflectance and structural position may be more influential on gas content than depth of cover (overburden).

Roof lithologies may also influence gas contents as shown in table 2 and figure 13. Core samples of Waynesburg Coalbed overlain by massive channel-phase sandstone (Waynesburg sandstone) show distinctly lower gas contents and reflectance values than do samples overlain by thick shale. The lower gas content then, may be due to gas migration into the porous sandstone and/or lower gas generation as indicated by lower reflectance. Significant gas emission from a sandstone overlying the Pittsburgh Coalbed in northern West Virginia (*54*) may support the migration theory. On the other hand, the sandstone may have in effect acted as a heatsink, its better thermal conductivity than shale allowing it to draw geothermal heat away from the coalbed, causing a lower degree of coalification (reflectance) (*5*, *42*). Another possibility is that paleocurrent action, in scouring the channel where the sandstone was later deposited, may have resulted in increased maceration and oxidation forming desmocollinite or vitrinite B, the lower reflectance vitrinite noted by Brown (*7*).

PALEOGEOTHERMAL GRADIENT AND FORMER DEPTH OF BURIAL

Vitrinite reflectance gradients were used in conjunction with a version of Karweil's coalification nomogram [as modified by Bostick (*3*)] to estimate former maximum depth of burial and paleogeothermal gradient influencing coalification of the organic material in the sedimentary sequence of the northern Dunkard Basin. In the modified Karweil nomogram (fig. 14), the coalification temperature can be estimated from vitrinite reflectance data if the length of time (geologic) the organic matter was near maximum depth of burial can be reasonably estimated.

By looking at the overall stratigraphic (vertical) variation in vitrinite reflectance values, one may calculate the reflectance gradient in terms of percent reflectance change per unit distance (vertical). The reflectance gradient can then be converted to a temperature gradient using the modified Karweil nomogram. By comparing the paleotemperature gradients responsible for coalification in different sedimentary basins or within a single basin, one may begin to explain the differences in overall gas content of similar coal-bearing sequences.

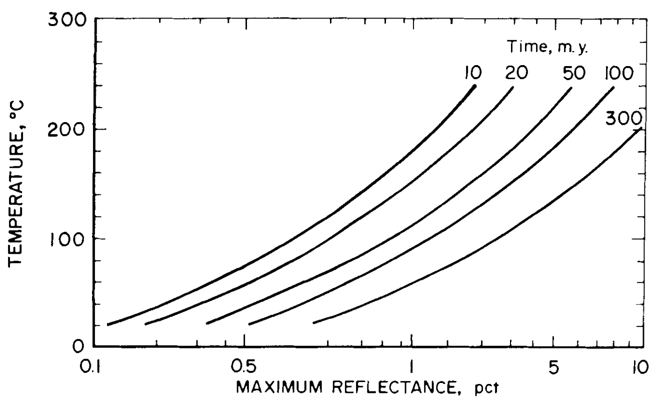

Figure 14.–Modified Karweil nomogram.

The coalbeds of the main study area were grouped stratigraphically and their average reflectances calculated and plotted versus depth, using average stratigraphic intervals for the study area. Average mean-maximum vitrinite reflectance values were determined for 11 coalbeds ranging from the Pittsburgh Coalbed upward to the Ten Mile Coalbed, a stratigraphic interval of about 750 ft. The Fish Creek Coalbed horizon, averaging 60 ft above the Ten Mile Coalbed, was used as a horizontal datum. The vitrinite reflectance gradient was calculated to be 0.288 pct per 1,000 ft (*55*) (fig. 15). Figure 15 also shows the number of samples for each coalbed and the range of reflectance values for that horizon. The circled anomalous reflectance values are those mentioned previously beneath thick Waynesburg Sandstone. The reflectance gradient of the coalbeds sampled from the Westmoreland County borehole shows a similar reflectance gradient of 0.295 pct per 1,000 ft (*53*), implying the gradient may be similar for the Pennsylvanian-Permian section throughout southwestern Pennsylvania.

In order to utilize the modified Karweil nomogram, the effective heating time or the length of geologic time that the sediments were within 15° C of their maximum temperature must be estimated. Essentially, this would also be the approximate length of geologic time that the sedimentary section remained at or near maximum depth of burial. For the coalbeds of the Dunkard Basin, this has been estimated to be 25 to 50 m.y. (*20*). Based on estimated paleotemperatures using 25, 35, and 50 m.y. effective heating times, it seems likely that the coalbeds investigated spent about 35 to 50 m.y. at or near their maximum depth of burial. Shorter times yield higher paleotemperatures that seem unlikely based on deeper oil-producing zones; longer times are probably inappropriate based on 250 m.y. before present timing of the Allegheny orogeny (*56*). The entire section studied (Pittsburgh to

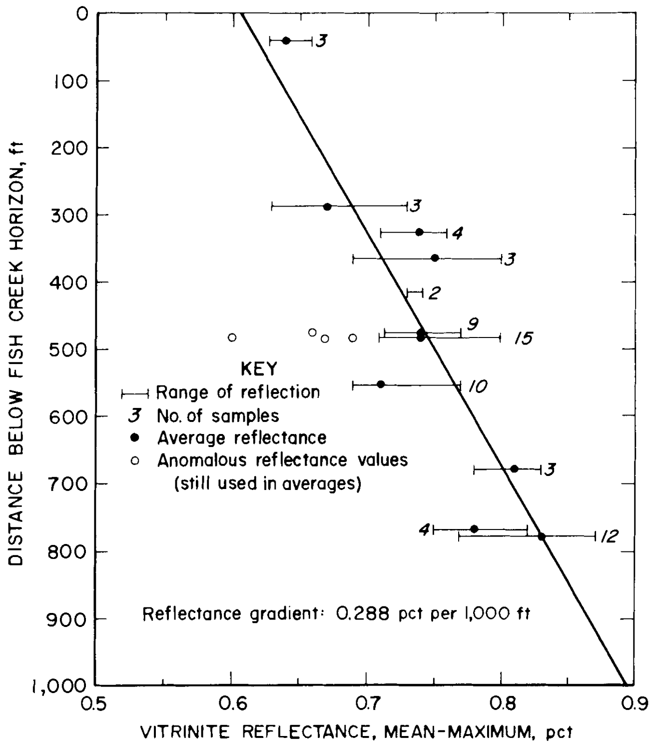

Figure 15.–Vitrinite reflectance versus depth below Fish Creek Coalbed horizon.

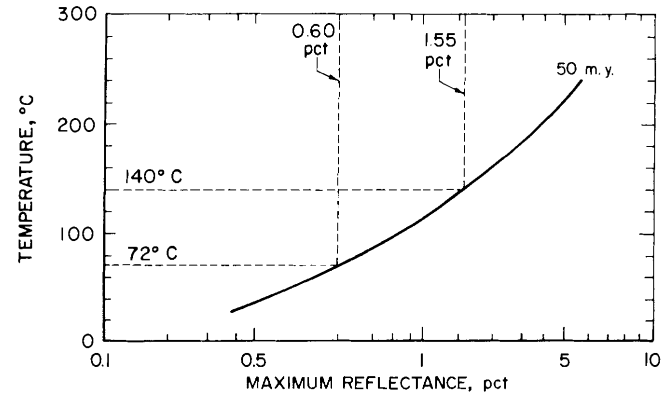

Figure 16.–Estimated paleotemperature at top and bottom of 1-km-thick sedimentary section.

Ten Mile Coalbeds) underwent the same effective heating time as evidenced by the continuous sedimentary record remaining above the Ten Mile Coalbed (minimum 600 ft). This indicates that subsidence was relatively continuous and the study section did not reach maximum depth of burial until well after deposition of the Ten Mile Coalbed. Therefore, the length of time each studied coalbed was at maximum depth of burial would be the same.

Because most geothermal gradients are expressed in metric terms (degree Celsius per kilometer) it would be convenient to work with reflectance gradients expressed in similar units. The measured reflectance gradient for about 800 ft of section above the Pittsburgh Coalbed was found to be 0.288 pct per 1,000 ft in Washington and Greene Counties. A similar gradient of 0.295 pct per 1,000 ft was found for a 1,100-ft section below the Pittsburgh Coalbed in Westmoreland County. This represents a measured reflectance gradient averaging 0.29 pct per 1,000 ft for about 1,900 ft or nearly 2/3 km of sediment above and below the Pittsburgh Coalbed. Therefore extrapolating this gradient to a full kilometer does not seem unreasonable. This average reflectance gradient (0.29 pct per 1,000 ft) converts to a reflectance gradient of 0.95 pct/km that was used in calculating the paleogeothermal gradients.

To calculate the paleogeothermal gradient, a lower reflectance value of 0.6 pct was chosen for the Fish Creek Coalbed horizon. This value seems reasonable based on the average reflectance of the Ten Mile Coalbed and the presence of a continuous section above it. Adding the reflectance change for a kilometer of intervening sediment yields an upper reflectance value of 1.55 pct. By inserting these values into the Karweil nomogram, using 50 m.y. effective heating time, paleotemperature of 72° C is estimated for 0.6 pct reflectance and a paleotemperature of 140° C is estimated for a reflectance of 1.55 pct (fig. 16). The difference in temperature then corresponds to the paleogeothermal gradient of 68° C/km, which is significantly higher than the 30° C/km paleogradient estimated by Hower (*20*). If shorter effective heating (burial) times are used (i.e., 25 and 35 m.y.), paleogeothermal gradients of up to 90° C/km are implied.

Substantiating this estimate is difficult. Thermal gradients measured in modern sedimentary basins are typically lower, on the order of 20° to 40° C/km (*15*, *22-23*), however, significantly higher gradients are not uncommon (*42*). Assuming the Earth has been steadily cooling since its origin, the overall geothermal heat flow would obviously have been greater 300 m.y.; however, it is unlikely that this alone would account for such a high gradient. Possibly this ancient, higher, background heat flow coupled with heat loss from a thermal event associated with the Appalachian orogeny produced the higher thermal gradient.

Projection of the reflectance gradient to deeper horizons seems to correlate well with the limited published data on the thermal maturity of these horizons. For example, projecting the reflectance gradient from the 0.6 pct average for the Fish Creek Coalbed horizon to the base of the Mississippian System (about 0.8 km lower) yields a projected reflectance of 1.36 pct for this horizon. The conodont color alteration index (CAI) for the Mississippian rocks of the study area is between 1.5 and 2.0 (*13*). This approximates a vitrinite reflectance of 0.85 to 1.3 pct (*13*), so the 1.36-pct projection is slightly high, but not unreasonable. Projecting the reflectance gradient farther down section to the base of the Devonian (about 2 km below the Pittsburgh Coalbed) yields an estimated reflectance of 2.7 pct. Measured mean-maximum vitrinite

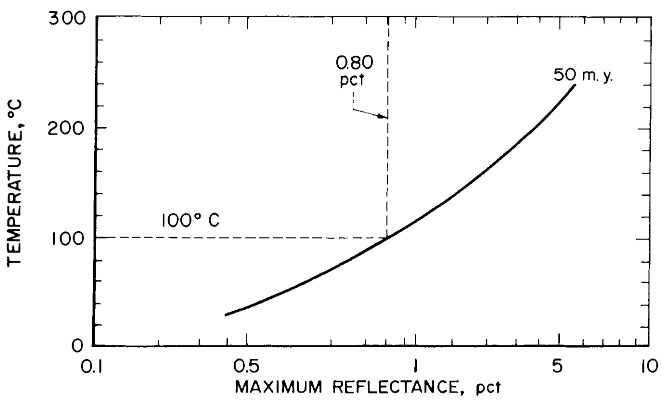

Figure 17.–Estimated maximum paleotemperature of Pittsburgh Coalbed.

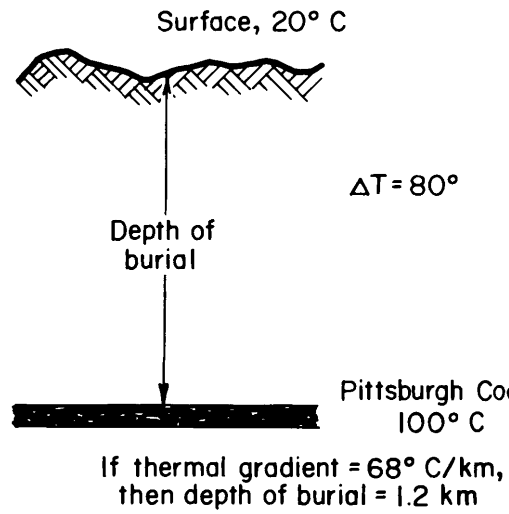

Figure 18.–Estimated former depth of burial of Pittsburgh Coalbed.

reflectance values of 2.4 and 2.6 pct have been recorded for Lower Devonian rocks in southwestern Pennsylvania and northern West Virginia (*46*), indicating that the calculated reflectance gradient may likely extend from the Permian through Devonian Systems in southwestern Pennsylvania.

Once the estimate of the paleogeothermal gradient has been established, estimating former maximum depths of burial becomes relatively simple. For example, typical vitrinite reflectance of the Pittsburgh Coalbed in the study area is 0.80 pct. Using this value with the Karweil nomogram and assuming 50 m.y. effective heating time, a 100° C maximum paleotemperature is suggested for the Pittsburgh Coalbed (fig. 17). Assuming a surface temperature of 20° C, the difference from the paleosurface to the Pittsburgh Coalbed is 80° C (fig. 18). If the paleogeothermal gradient was 67° C/km, then simple arithmetic indicates the former maximum depth of burial of the Pittsburgh Coalbed to be 1.2 km.

This estimated former maximum depth of burial agrees well with the estimates of McKee (*31*), who calculated a 1.5-km burial for the Pittsburgh Coalbed based on an average volatile matter content It also agrees well with the implied depth of burial suggested by Farrington's (*14*) estimates as to the original thickness of the Permian strata. The 1.2-km estimate is, however, significantly lower than the former depth of burial suggested by Hower (*20*), a 3.5- to 4.0-km burial for Allegheny Group coalbeds.

CONCLUSIONS

This report represents a Bureau of Mines preliminary investigation on the effects of petrographic characteristics on gas generation, storage, and emission by coalbeds. Further studies will attempt to carry the findings of this study into coalbeds of differing ranks and geologic settings. The following are the conclusions resulting from this investigation:

1. Review of pertinent literature shows that a relationship exists between the coalification process and hydrocarbon generation in coalbeds.
2. No correlation was found between methane content and petrographic composition of coalbeds.
3. A preliminary correlation was found in high-volatile rank coals between vitrinite reflectance and gas content. This correlation may also be valid for higher rank coals.
4. The primary vitrinite reflectance-gas content relationship may be influenced by such geologic factors as integrity and composition of the roof rock and position with respect to regional anticlinal and synclinal structures.
5. The coal-bearing sequence of the northern Dunkard Basin was subject to a calculated paleogeothermal gradient of 65° to 75° C/km. The Pittsburgh Coalbed was probably formerly buried under about 1.2 (this report) to 1.5 km (*31*) of overburden.

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APPENDIX A.-RESULTSOF PETROGRAPHIC AND CHEMICAL ANALYSES

TABLE A-1. - Maceral composition and gas content data

Coalbed	Sample depth, ft	County	Gas, cm^3/g (MMF) Desorbed	Residual	Total	Mean-max reflectance, pct	Total vitrinite, pct	Total exinite, pct	Total inertinite, pct	Sample No.
Lower Waynesburg	305	Greene	0.7	0.4	1.1	0.60	78.9	5.5	15.6	1467
Upper Washington	227	Washington .	.3	.8	1.1	.63	73.2	3.3	23.5	1472
Fish Creek	213	Greene	.3	1.1	1.4	.70	83.1	3.0	13.9	1588
Ten Mile	447	...do	.3	1.1	1.4	.66	84.0	2.8	13.2	1509
Do	181	...do	.2	1.4	1.6	.64	84.7	2.9	12.4	1561
Upper Waynesburg	278	Washington .	.2	1.6	1.8	.73	80.8	1.8	17.4	1585
Uniontown	341	...do	.1	1.8	1.9	.71	80.7	3.0	16.3	1587
Lower Waynesburg	306	Greene	1.0	1.1	2.1	.72	90.4	3.2	6.4	1468
Do.	619	...do	.3	1.8	2.1	.77	85.2	5.5	9.3	1580
Waynesburg A ...	165	Washington .	.7	1.4	2.1	.73	83.7	1.8	14.5	1584
Upper Waynesburg	695	Greene	.1	2.1	2.2	.73	75.5	10.0	14.5	1539
Lower Waynesburg	472	Washington .	.6	1.7	2.3	.67	56.9	18.4	24.7	1527
Washington A	247	...do	.7	1.6	2.3	.73	87.3	2.6	10.1	1534
Ten Mile	265	Greene	1.2	1.1	2.3	.62	87.8	2.4	9.8	1589
Washington	551	...do	1.3	1.1	2.4	.74	75.8	6.9	17.3	1538
Do	138	Washington .	2.0	.7	2.7	.71	84.6	5.6	9.8	1459
Lower Waynesburg	603	...do	1.4	1.4	2.8	.72	89.2	3.3	7.5	1505
Washington A	506	Greene	.4	2.4	2.8	.64	85.2	2.7	12.1	1537
Pittsburgh Rider ..	560	Washington .	1.4	1.4	2.8	.70	85.8	2.4	11.8	1749
Upper Waynesburg	881	Greene	.5	2.5	3.0	.66	87.3	4.6	8.1	1521
Do	601	Washington .	1.7	1.7	3.4	.74	86.3	1.7	12.0	1504
Lower Waynesburg	282	...do	2.2	1.3	3.5	.71	84.5	2.9	12.6	1586
Pittsburgh	339	...do	1.8	1.7	3.5	.73	84.9	4.5	10.6	1722
Pittsburgh Rider ..	715	...do	.7	2.8	3.5	.78	88.9	.8	10.3	1183
Waynesburg B ...	164	...do	2.0	1.5	3.5	.69	86.0	3.1	10.9	1460
Upper Waynesburg	469	...do	2.1	1.5	3.6	.72	84.5	3.3	12.2	1525
Lower Waynesburg	441	...do	2.4	1.2	3.6	.76	73.8	11.8	14.4	1543
Pittsburgh	338	...do	1.8	1.8	3.6	.76	84.7	4.8	10.5	1721
Pittsburgh Rider ..	540	...do	2.2	1.4	3.6	.61	84.9	3.0	12.1	1754
Sewickley	509	Greene	.9	2.7	3.6	.73	96.0	2.0	2.0	1642
Upper Waynesburg	394	Washington .	1.9	1.8	3.7	.75	86.9	3.2	9.9	1450
Fishpot	510	Greene	1.4	2.3	3.7	.67	82.8	2.4	14.8	1470
Lower Waynesburg	882	...do	.8	2.9	3.7	.72	87.1	3.3	9.6	1522
Uniontown	951	...do	2.4	1.3	3.7	.77	81.0	2.0	17.0	1523
Pittsburgh	340	Washington .	1.9	1.8	3.7	.72	85.9	3.1	11.0	1723
Waynesburg	599	Greene	.4	3.3	3.7	.69	57.2	11.5	31.3	1566
Lower Waynesburg	698	...do	2.5	1.3	3.8	.72	85.1	2.3	12.6	1540
Do	823	...do	1.7	2.1	3.8	.75	89.3	3.6	7.1	1560
Sewickley	539	Washington .	1.8	2.1	3.9	.83	81.4	9.1	9.5	1550
Lower Waynesburg	601	Greene	1.9	2.1	4.0	.79	90.8	2.9	6.3	1568
Washington	558	...do	2.0	2.0	4.0	.76	81.8	4.0	14.2	1591
Lower Waynesburg	475	Washington .	2.4	1.7	4.1	.74	86.7	6.6	6.7	1529
Uniontown	416	...do	.1	4.0	4.1	.72	80.0	3.1	16.9	1549
Upper Waynesburg	820	Greene	2.0	2.1	4.1	.77	88.0	3.5	8.5	1558
Uniontown	666	Washington .	2.3	1.8	4.1	.69	80.8	2.1	17.1	1506
Do	537	...do	2.7	1.5	4.2	.71	79.9	2.2	17.9	1530
Pittsburgh	660	...do	2.1	2.2	4.3	.83	70.7	8.9	20.4	1175

See explanatory note at end of table.

TABLE A-1. - Maceral composition and gas content data-Continued

Coalbed	Sample depth, ft	County	Gas, cm³/g (MMF) Desorbed	Residual	Total	Mean-max reflectance, pct	Total vitrinite, pct	Total exinite, pct	Total inertinite, pct	Sample No.
Lower Waynesburg	399	Washington .	2.8	1.5	4.3	0.72	80.1	6.1	13.8	1451
Waynesburg B . . .	752	Greene	2.6	1.7	4.3	.80	89.7	3.3	7.0	1520
Upper Waynesburg	596	. . .do	2.9	1.4	4.3	.77	86.4	2.5	11.1	1565
Uniontown	512	Washington .	2.3	2.0	4.3	.71	79.3	2.2	18.5	1544
Sewickley	639	. . .do	2.2	2.2	4.4	.81	86.5	5.5	8.0	1545
Uniontown	762	Greene	2.0	2.4	4.4	.69	75.3	3.7	21.0	1541
Pittsburgh	524	Washington .	2.4	2.1	4.5	.83	85.5	3.4	11.1	1133
Waynesburg A . . .	556	Greene	2.3	2.2	4.5	.75	88.7	3.2	8.1	1578
Pittsburgh	556	Washington .	2.1	2.4	4.5	.71	74.1	8.6	17.3	1752
Uniontown	671	Greene	1.7	2.8	4.5	.69	80.6	1.1	18.3	1569
Pittsburgh Rider . .	517	Washington .	2.9	1.7	4.6	.75	88.4	1.1	10.5	1128
Lower Waynesburg	274	. . .do	2.7	1.9	4.6	.77	86.7	4.2	9.1	1462
Do	275	. . .do	2.9	1.7	4.6	.78	86.0	4.0	10.0	1463
Pittsburgh	523	. . .do	2.4	2.3	4.7	.82	86.9	3.4	9.7	1132
Upper Waynesburg	270	. . .do	2.6	2.1	4.7	.75	88.0	3.2	8.8	1461
Lower Waynesburg	600	Greene	1.9	2.8	4.7	.79	91.1	4.1	4.8	1567
Sewickley	792	. . .do	3.5	1.2	4.7	.78	87.0	4.5	4.5	1573
Pittsburgh	521	Washington .	2.6	2.2	4.8	.79	85.3	1.5	13.2	1131
Upper Bakerstown	440	Westmoreland	3.7	1.3	5.0	.82	84.9	1.2	13.9	1715
Uniontown	465	Washington .	3.5	1.6	5.1	.70	76.5	1.2	22.3	1453
Pittsburgh Rider . .	518	. . .do	2.6	2.6	5.2	.77	90.6	.9	8.5	1129
Pittsburgh	665	. . .do	3.0	2.2	5.2	.82	84.5	4.2	11.3	1178
Upper Waynesburg	615	Greene	3.5	1.7	5.2	.76	85.4	2.6	12.0	1579
Clarion	957	Westmoreland	2.8	2.4	5.2	.84	89.7	.4	9.9	1765
Pittsburgh	718	Washington .	3.3	2.0	5.3	.79	81.3	1.8	16.9	1185
Do	520	. . .do	3.3	2.2	5.5	.77	83.8	3.1	13.1	1130
Lower Waynesburg	699	Greene	4.0	1.5	5.5	.80	78.9	8.1	13.0	1593
Sewickley	660	Washington .	2.0	3.6	5.6	.83	88.9	4.2	6.9	1531
Pittsburgh	720	. . .do	3.3	2.3	5.6	.84	88.3	2.4	9.3	1186
Do	793	. . .do	3.7	2.1	5.8	.86	67.9	9.6	22.5	1171
Do	661	. . .do	3.3	2.5	5.8	.87	77.7	3.8	18.5	1176
Do	663	. . .do	3.4	2.4	5.8	.83	74.7	4.9	20.4	1177
Do	630	. . .do	3.4	2.6	6.0	.87	84.8	3.7	11.5	1158
Uniontown	340	. . .do	3.6	2.4	6.0	.74	78.8	2.7	18.5	1464
Pittsburgh	717	. . .do	3.5	2.6	6.1	.81	82.8	4.7	12.5	1184
Lower Waynesburg	700	Greene	3.6	2.5	6.1	.79	87.5	5.6	6.9	1594
Upper Waynesburg	696	. . .do	3.8	2.5	6.3	.75	85.5	4.6	9.9	1592
Pittsburgh Rider . .	791	Washington .	4.7	2.4	7.1	.82	85.0	4.3	10.7	1170
Mercer	1,042	Westmoreland	5.5	1.7	7.2	.97	66.7	1.9	31.3	1768
Brush Creek	627	. . .do	7.2	.9	8.1	.91	80.8	.2	19.0	1731
Middle Kittanning .	866	. . .do	6.8	1.4	8.2	1.04	80.7	2.2	17.1	1744
Brookville	994	. . .do	6.1	2.2	8.3	1.03	84.3	2.5	13.2	1767
Mahoning	674	. . .do	7.7	1.7	9.4	.94	94.5	1.2	4.3	1732
Upper Freeport . . .	728	. . .do	8.8	1.4	10.2	1.00	90.0	1.6	8.4	1741
Upper Kittanning .	786	. . .do	9.2	1.1	10.3	.97	61.8	2.7	35.5	1742
Do	806	. . .do	8.3	2.3	10.6	1.09	85.7	1.5	12.8	1743

MMF Mineral matter free.

TABLE A-2. - Chemical data

Coalbed	Total gas, cm^3/g (MMF)	Ash (AR)	Sulfur (AR)	Fixed carbon (AR)	Fixed carbon (DMMF)	Volatile matter (AR)	Volatile matter (DMMF)	Apparent rank	Sample No.
Upper Washington	1.1	51.3	3.81	20.2	52.0	27.2	48.0	NAp	1472
Lower Waynesburg	1.1	28.0	5.72	40.6	58.8	29.5	41.2	HV-A	1467
Fish Creek	1.4	28.4	2.64	41.6	59.2	28.7	40.8	HV-A	1588
Ten Mile	1.4	26.8	4.24	40.0	58.9	31.6	41.1	HV-A	1509
Do	1.6	19.8	5.37	42.0	57.8	35.8	42.2	HV-A	1561
Upper Waynesburg	1.8	16.6	4.79	49.0	58.0	32.6	42.0	HV-A	1585
Uniontown	1.9	33.0	3.02	38.3	59.0	26.9	41.0	HV-A	1587
Lower Waynesburg	2.1	15.4	4.06	50.5	60.7	32.9	39.3	HV-A	1468
Do	2.1	19.2	4.08	46.9	57.9	32.6	42.1	HV-A	1580
Waynesburg A	2.1	15.4	3.37	51.4	60.9	31.3	39.1	HV-A	1584
Upper Waynesburg	2.2	17.1	5.14	47.9	57.4	33.5	42.6	HV-A	1539
Ten Mile	2.3	21.3	4.04	39.0	55.0	38.7	45.0	HV-A	1589
Lower Waynesburg	2.3	27.4	7.30	40.8	58.6	30.1	41.4	HV-A	1527
Washington A	2.3	36.0	4.06	36.8	59.4	24.9	40.6	HV-A	1534
Washington	2.4	22.4	4.87	46.7	60.3	29.5	39.7	HV-A	1538
Do	2.7	26.2	6.02	41.7	59.6	30.9	40.4	HV-A	1459
Pittsburgh Rider	2.8	19.0	4.38	49.2	64.9	30.3	35.1	HV-A	1749
Washington A	2.8	30.3	5.02	38.3	58.3	29.7	41.7	HV-A	1537
Lower Waynesburg	2.8	21.0	4.94	47.2	51.6	30.2	48.4	HV-A	1505
Upper Waynesburg	3.0	16.9	4.00	47.6	56.8	34.0	43.2	HV-A	1521
Do	3.4	16.4	4.87	49.5	59.2	32.9	40.8	HV-A	1504
Lower Waynesburg	3.5	23.4	3.91	44.0	57.2	31.6	42.8	HV-A	1586
Pittsburgh	3.5	7.6	3.58	58.0	61.6	32.9	38.4	HV-A	1722
Waynesburg B	3.5	19.9	4.33	45.9	60.4	32.9	39.6	HV-A	1460
Pittsburgh Rider	3.5	12.3	4.70	50.8	60.2	35.9	39.8	HV-A	1183
Sewickley	3.6	13.4	3.75	51.5	67.5	34.3	32.5	HV-A	1642
Pittsburgh Rider	3.6	23.2	3.71	46.0	67.1	29.5	32.9	HV-A	1754
Lower Waynesburg	3.6	20.1	3.88	45.3	58.3	33.3	41.7	HV-A	1543
Upper Waynesburg	3.6	15.4	3.94	50.8	60.4	32.4	39.6	HV-A	1525
Pittsburgh	3.6	10.3	2.12	56.7	61.3	31.5	38.7	HV-A	1721
Waynesburg	3.7	37.8	4.82	34.7	61.8	26.2	38.2	HV-A	1566
Lower Waynesburg	3.7	33.2	4.12	39.1	61.6	26.1	38.4	HV-A	1522
Upper Waynesburg	3.7	19.6	4.54	47.0	60.1	32.0	39.9	HV-A	1450
Fishpot	3.7	31.4	5.53	39.4	58.3	27.8	41.7	HV-A	1470
Uniontown	3.7	36.7	3.67	36.5	58.8	25.1	41.2	HV-A	1523
Pittsburgh	3.7	11.6	3.50	55.9	61.7	31.0	38.3	HV-A	1723
Lower Waynesburg	3.8	18.1	3.86	48.2	60.8	32.5	39.2	HV-A	1560
Do	3.8	22.4	4.86	46.2	61.1	30.1	38.9	HV-A	1540
Sewickley	3.9	8.9	2.63	52.7	58.0	37.2	42.0	HV-A	1550
Washington	4.0	22.9	2.16	46.0	61.5	30.1	38.5	HV-A	1591
Lower Waynesburg	4.0	16.9	4.27	49.3	59.9	32.8	40.1	HV-A	1568
Do	4.1	19.6	5.02	47.0	60.4	32.1	39.6	HV-A	1529
Upper Waynesburg	4.1	19.2	5.36	47.9	59.9	31.8	40.1	HV-A	1558
Uniontown	4.1	17.8	4.17	48.7	60.1	31.6	39.9	HV-A	1549
Do	4.1	19.5	2.70	46.7	59.7	32.4	40.3	HV-A	1506
Do	4.2	24.8	3.43	43.8	58.3	30.1	41.7	HV-A	1530
Do	4.3	21.6	4.22	46.1	60.5	31.0	39.5	HV-A	1544

See explanatory notes at end of table.

TABLE A-2. - Chemical data-Continued

Coalbed	Total gas, cm^3/g (MMF)	Ash (AR)	Sulfur (AR)	Fixed carbon (AR)	Fixed carbon (DMMF)	Volatile matter (AR)	Volatile matter (DMMF)	Apparent rank	Sample No.
Lower Waynesburg	4.3	19.1	3.75	48.6	61.5	30.9	38.5	HV-A	1451
Pittsburgh	4.3	5.3	1.40	55.4	59.5	37.8	40.5	HV-A	1175
Upper Waynesburg	4.3	21.6	5.77	45.6	58.7	31.9	41.3	HV-A	1565
Waynesburg B	4.3	20.7	1.52	48.7	60.5	29.1	39.5	HV-A	1520
Uniontown	4.4	16.6	4.10	49.0	60.2	33.1	39.8	HV-A	1541
Sewickley	4.4	13.0	3.69	52.7	61.0	32.9	39.0	HV-A	1545
Uniontown	4.5	30.4	4.27	38.6	67.1	29.8	32.9	HV-A	1569
Pittsburgh	4.5	6.7	3.24	57.5	67.1	34.4	32.9	HV-A	1752
Do	4.5	11.8	3.00	51.4	59.2	35.3	40.8	HV-A	1133
Waynesburg A	4.5	25.2	4.91	43.6	58.9	30.1	41.1	HV-A	1578
Lower Waynesburg	4.6	25.0	5.67	43.7	60.2	30.0	39.8	HV-A	1463
Pittsburgh Rider	4.6	27.4	3.60	39.5	55.6	31.7	44.4	HV-A	1128
Lower Waynesburg	4.6	19.5	4.90	46.4	58.4	32.7	41.6	HV-A	1462
Do	4.7	19.8	4.34	45.2	58.9	34.0	41.1	HV-A	1567
Pittsburgh	4.7	6.7	2.50	55.3	60.7	36.5	39.3	HV-A	1132
Sewickley	4.7	25.3	4.02	41.5	55.1	32.0	44.9	HV-A	1573
Upper Waynesburg	4.7	18.9	4.64	48.5	58.8	31.3	41.2	HV-A	1461
Pittsburgh	4.8	8.9	2.40	53.2	59.5	36.3	40.5	HV-A	1131
Lower Bakerstown	5.0	24.4	4.37	49.0	61.7	26.1	38.3	HV-A	1715
Uniontown	5.1	26.4	3.07	44.7	60.4	27.7	39.6	HV-A	1453
Clarion	5.2	22.8	5.51	47.2	69.3	25.7	30.7	MV	1765
Pittsburgh Rider	5.2	16.5	4.70	48.0	58.2	34.5	41.8	HV-A	1129
Pittsburgh	5.2	8.9	3.00	54.9	60.8	34.7	39.2	HV-A	1178
Upper Waynesburg	5.2	20.0	5.14	46.9	57.9	32.2	42.1	HV-A	1579
Pittsburgh	5.3	9.6	1.90	53.8	60.1	35.1	39.9	HV-A	1185
Do	5.5	6.4	4.60	52.7	57.1	39.5	42.9	HV-A	1130
Lower Waynesburg	5.5	20.0	4.77	46.9	58.7	32.2	41.3	HV-A	1593
Sewickley	5.6	13.6	2.90	50.4	59.5	34.0	40.5	HV-A	1531
Pittsburgh	5.6	9.2	2.50	55.1	55.4	34.1	44.6	HV-A	1186
Do	5.8	4.2	1.60	56.2	60.1	38.1	39.9	HV-A	1171
Do	5.8	12.7	2.10	51.9	62.3	34.0	37.7	HV-A	1177
Do	5.8	3.7	1.00	60.0	61.0	34.5	39.0	HV-A	1176
Do	6.0	5.9	0.90	58.7	63.1	34.4	36.9	HV-A	1158
Uniontown	6.0	28.9	3.47	42.2	59.5	27.2	40.5	HV-A	1464
Pittsburgh	6.1	5.9	2.30	55.4	59.1	37.3	40.9	HV-A	1184
Lower Waynesburg	6.1	17.6	3.70	49.1	59.4	32.4	40.6	HV-A	1594
Upper Waynesburg	6.3	20.4	6.14	46.9	59.9	31.9	40.1	HV-A	1592
Pittsburgh Rider	7.1	16.8	4.50	49.3	59.8	32.3	40.2	HV-A	1170
Mercer	7.2	24.2	4.87	53.7	65.5	21.8	34.5	MV	1768
Brush Creek	8.1	37.6	2.17	39.4	64.7	22.3	35.3	HV-A	1731
Middle Kittanning	8.2	14.4	4.23	60.8	69.9	24.5	30.1	MV	1744
Brookville	8.3	16.5	3.16	60.2	65.5	23.1	34.5	MV	1767
Mahoning	9.4	15.2	4.20	58.4	66.0	25.9	34.0	MV	1732
Upper Freeport	10.2	8.1	3.17	60.7	64.8	30.6	35.2	HV-A	1741
Upper Kittanning	10.3	27.4	6.45	50.0	66.1	22.2	33.9	MV	1742
Do	10.6	19.7	2.12	56.1	66.0	23.9	34.0	MV	1743

AR As received.
DMMF Dry mineral matter free.
HV-A High volatile A bituminous.
MV Medium volatile bituminous.
MMF Mineral matter free.
NAp Not applicable.

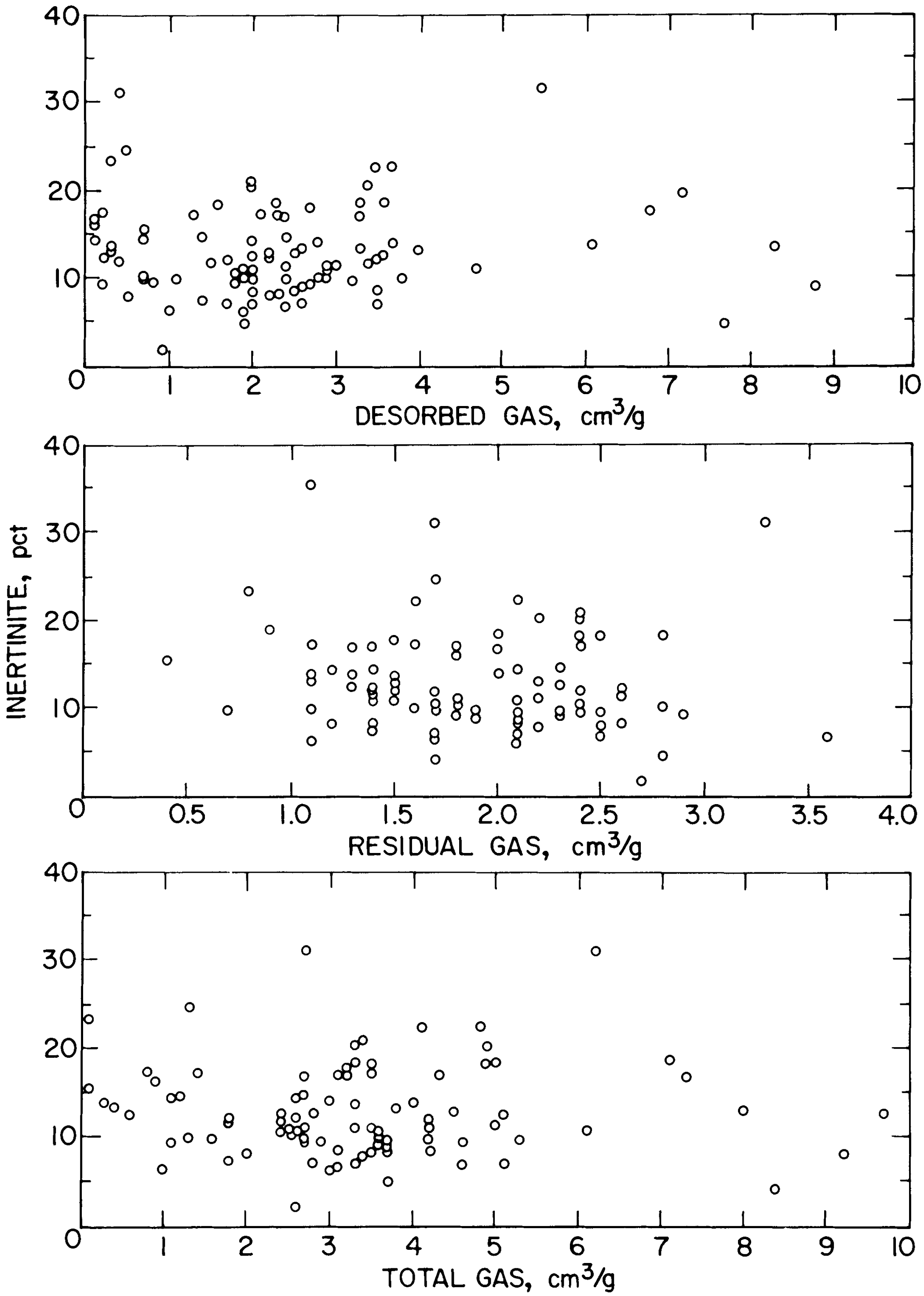

Figure A-1.–Relationship between inertinite and desorbed, residual, and total gas contents.

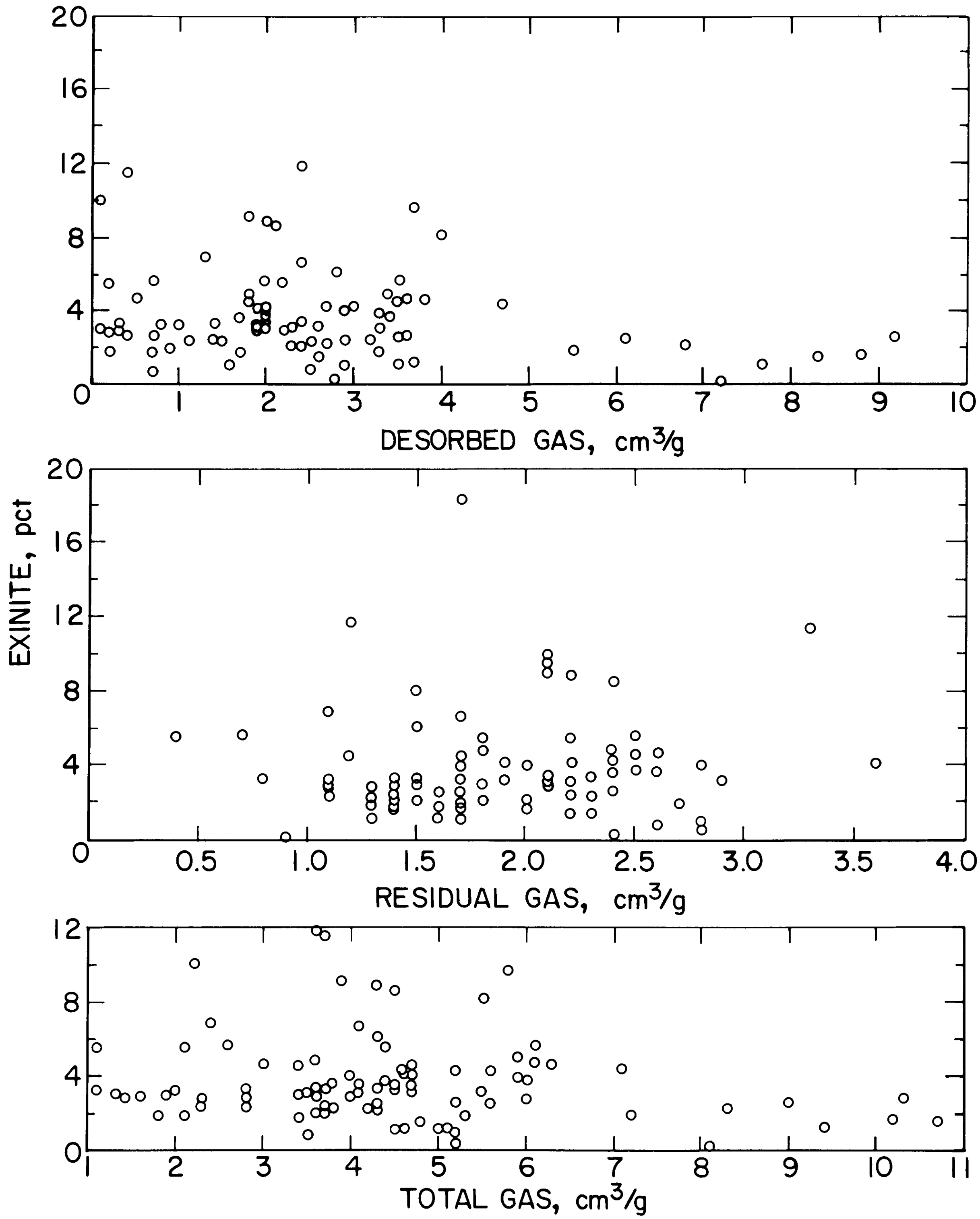

Figure A-2.–Relationship between exinite and desorbed, residual, and total gas contents.

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