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Selected Geologic Factors Affecting Mining of the Pittsburgh Coalbed

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 8093

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SELECTED GEOLOGIC FACTORS AFFECTING MINING OF THE PITTSBURGH COALBED

by

C. M. McCulloch,[1] W. P. Diamond,[1] B. M. Bench,[1]
and Maurice Deul[2]

ABSTRACT

As part of the Bureau of Mines methane control program, the Pittsburgh coalbed was studied in Washington and Green Counties, Pa., and in Marion and Monongalia Counties, W. Va., where this coalbed is now being mined at its greatest depth. The coalbed thickness appeared to be structurally controlled; the bed was generally thinner near the axes of anticlines and thicker near the axes of synclines. The overburden isopach shows a similar relationship. Most of the clay veins in coal occur in the synclinal troughs, generally under sandstone roof.

Cleat orientations measured in 18 underground mines showed that face cleats are perpendicular to the axial trends of the folds, and the butt cleats are parallel to the axial trends, indicating structural control of the cleat.

Measurement and analysis of surface joint orientations provide a method for predicting the cleat orientations of the coalbed, but linears measured from infrared photographs and photoindex sheets helped only to determine regional trends.

The results of these investigations provide a geologic framework for rational planning for underground mine development to use the best available technology to cope with methane emissions, coalbed discontinuities, and related ground support problems.

INTRODUCTION

The Pittsburgh coalbed is one of the largest and most valuable mineral deposits in the world. It extends from the western tip of Maryland, west to Belmont County, Ohio, and from Allegheny County, Pa., southwest to Putnam County, W. Va. This report is focused on Washington and Greene Counties, Pa., and Monongalia and Marion Counties, W. Va., because this is the area of greatest active mining. Within this area (fig. 1) the coalbed crops out only

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[1] Geologist.
[2] Research supervisor.

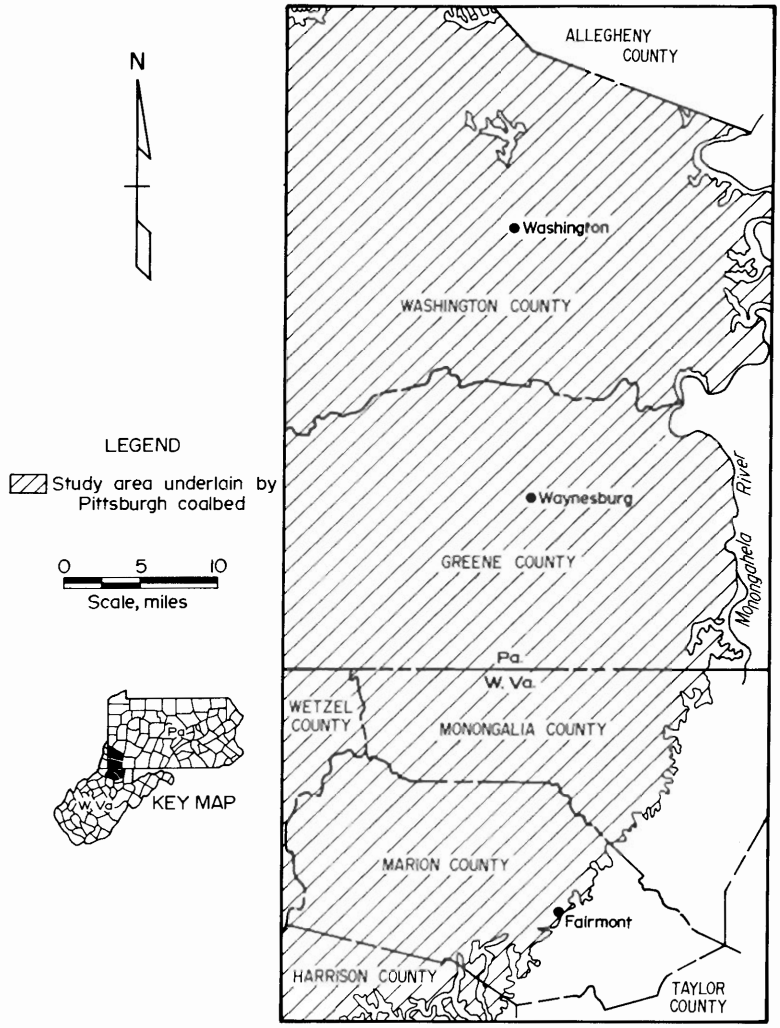

FIGURE 1. - Map of the study area and the portion underlain by the Pittsburgh coalbed.

in northern Washington County and along the Monongahela River, necessitating underground mining almost exclusively.

The Pittsburgh coalbed lies in an area known physiographically as the Allegheny Plateau and characterized by anticlines and synclines that normally dip less than 100 feet per mile. The strata above the Pittsburgh coalbed are composed predominantly of interbedded shales, sandstones, siltstones, and limestones with intermittent coalbeds. The critical vertical sequence above the coal is normally less than 50 feet.

In 1964, the U.S. Geological Survey (115)[3] determined from an extrapolation of data assembled by Latimer (71) that the Pittsburgh coalbed had yielded about 8 billion tons of coal from the beginning of mining in the early 1900's to January 1, 1965. This total was about 35 percent of the cumulative production of the Appalachian bituminous coal basin and 21 percent of the cumulative production of the United States. The coal reserves in western Washington and Greene Counties, Pa., and Marion and Monongalia Counties, W. Va., represent an important future source of coal. The coal here is deeper (up to 1,500 feet) than that previously mined in the Pittsburgh coal basin. Methane gas has been a continuing source of problems in the Pittsburgh coalbed, and such problems will probably increase with greater depth of mining. Roof instability and the occurrence of clay veins and sandstone channels are also possible.

This report deals with selected geologic factors that affect the mining of the Pittsburgh coalbed. Selected factors examined include structure,

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[3] Underlined numbers in parentheses represent items in the bibliography preceding the appendixes.

overburden, immediate roof strata, relation to joints and linears, and cleat orientations.

Much of the Bureau of Mines methane control research has been conducted in the Pittsburgh coalbed (25, 64, 75). The present report gives results of one phase of this research, which is seeking to identify the geologic factors that influence methane accumulations and emissions in coalbeds and which may be used in planning the degasification and ventilation of coal mines and the recovery of mine gas. Similar studies can be conducted on other coalbeds.

ACKNOWLEDGMENTS

This project could not have been completed without the assistance of many people and companies. We thank Consolidation Coal Co., Bethlehem Mines Corp., Eastern Associated Coal Corp., and Jones & Laughlin Steel Corp., who provided personnel to escort us in our underground studies and supplied core logs, mine maps, and other necessary data.

We especially thank James Marshalek, supervisory mining inspector for the Mining Enforcement and Safety Administration (MESA); S. M. Linger, W. C. Doran, Jr., J. G. Tilton, and J. C. Patton of the Equitable Gas Co.; James Barlow of the West Virginia Economic and Geologic Survey; Herb Steinman of Jones & Laughlin Steel Corp.; and W. Edmonds of the Pennsylvania Geological Survey for supplying information and reviewing the manuscript.

The contributions of C. H. Elder and P. W. Jeran, Bureau geologists are acknowledged. They have spent considerable time on investigations of the Pittsburgh coalbed and were most helpful with suggestions and supplying data for the preparation of maps.

HISTORICAL BACKGROUND

The first investigation of the Pittsburgh coalbed dates back to 1759 when Kenny (52) referred to a coal being mined on the hills around Pittsburgh. Since that time, numerous investigations have resulted in more than 100 publications. See Bibliography.

Nineteenth century investigators were concerned primarily with the stratigraphy of the area and the problems in working out stratigraphic boundaries (72, 85, 98-100, 107, 115). Rogers (100) in 1884 was one of the first to realize the importance of the Pittsburgh coalbed in the mining industry.

The most comprehensive single work on the Pittsburgh coalbed is that published in 1954 by Cross (21), who studied the stratigraphy, petrology, origin, composition, and mining problems of the bed. Much of Cross' work is pertinent today, and his paper has served as a model for the present report.

As would be expected for so important a deposit, mapping has been extensive. The early 1900's saw a flurry of activity, with the Pittsburgh coalbed being mapped in parts of all four counties of the study area by Clapp (18), Munn (79), Hennen (45), and Hennen and Reger (46). The first detailed map showing the area underlain by the Pittsburgh coalbed in West Virginia, Ohio, and Pennsylvania was published by Burrough (16) in 1914 and was a fairly accurate map for the small amount of data available.

The coal-bearing Upper Pennsylvanian and Lower Permian rocks of the Washington, Pa., area have been studied by Berryhill, Schweinfurth, and Kent (11), who prepared a number of isopach and lithofacies maps of the area.

In 1972 Roen and Farrel (96) published a structure map drawn on the base of the Pittsburgh coalbed using published geologic maps of Pennsylvania, county reports from West Virginia and Pennsylvania, and coal company data. The 7-1/2-minute geologic quadrangles of Amity, California, Ellsworth, Hackett, Mather, Monongahela, Prosperity, Washington East, Washington West, and Waynesburg have been mapped by the U.S. Geological Survey. The Carmichaels, Oak Forest, and Midway quadrangles have been covered in other studies. Geological maps of the Blacksville, Fairmont East and West, Grant Town, Morgantown North, Osage, and Rivesville 7-1/2-minute quadrangles have been prepared by graduate students at West Virginia University.

The stratigraphy of the Monongahela Group in West Virginia, Ohio, and Pennsylvania has been studied by Hoover (47), who prepared a series of isopachs on all major units from the Redstone to the Pittsburgh coalbed. The Pittsburgh-Redstone coal interval in West Virginia has also been studied by Conti (20).

In preparation for the present report, underground geologic investigations were conducted in 18 mines operating in the Pittsburgh coalbed. Coal cleat orientations were measured, and the location and trend of sand channels and clay veins were obtained. Surface joints were measured to evaluate their relationship to cleat directions underground. An aerial photoanalysis was conducted to locate lineaments and evaluate their relationship to surface joints. Geologic factors influencing roof control were also investigated.

STRUCTURE AND STRATIGRAPHY OF THE PITTSBURGH COALBED

Regional Structure and Paleogeography

Most of the Pittsburgh coalbed lies in a broad, gently dipping basin. The basin is a highly dissected region of gently folded anticlines and synclines that decrease in intensity westward from the Allegheny structural front (fig. 2). The area is known physiographically as the Allegheny Plateau. The fold axes generally parallel the axes of the basin. The dip of the rocks is generally less than 1°. The forces that produced the folding and subsequent erosion exposed, or brought near the surface, numerous coalbeds that otherwise would still lie deeply buried.

Figure 2 is a structural contour map of the Pittsburgh coalbed by Roen and Farrel (96). The Bureau has drilled approximately 20 holes to the Pittsburgh coalbed within the study area, but the additional information obtained did little to alter the interpretation of the structural trends.

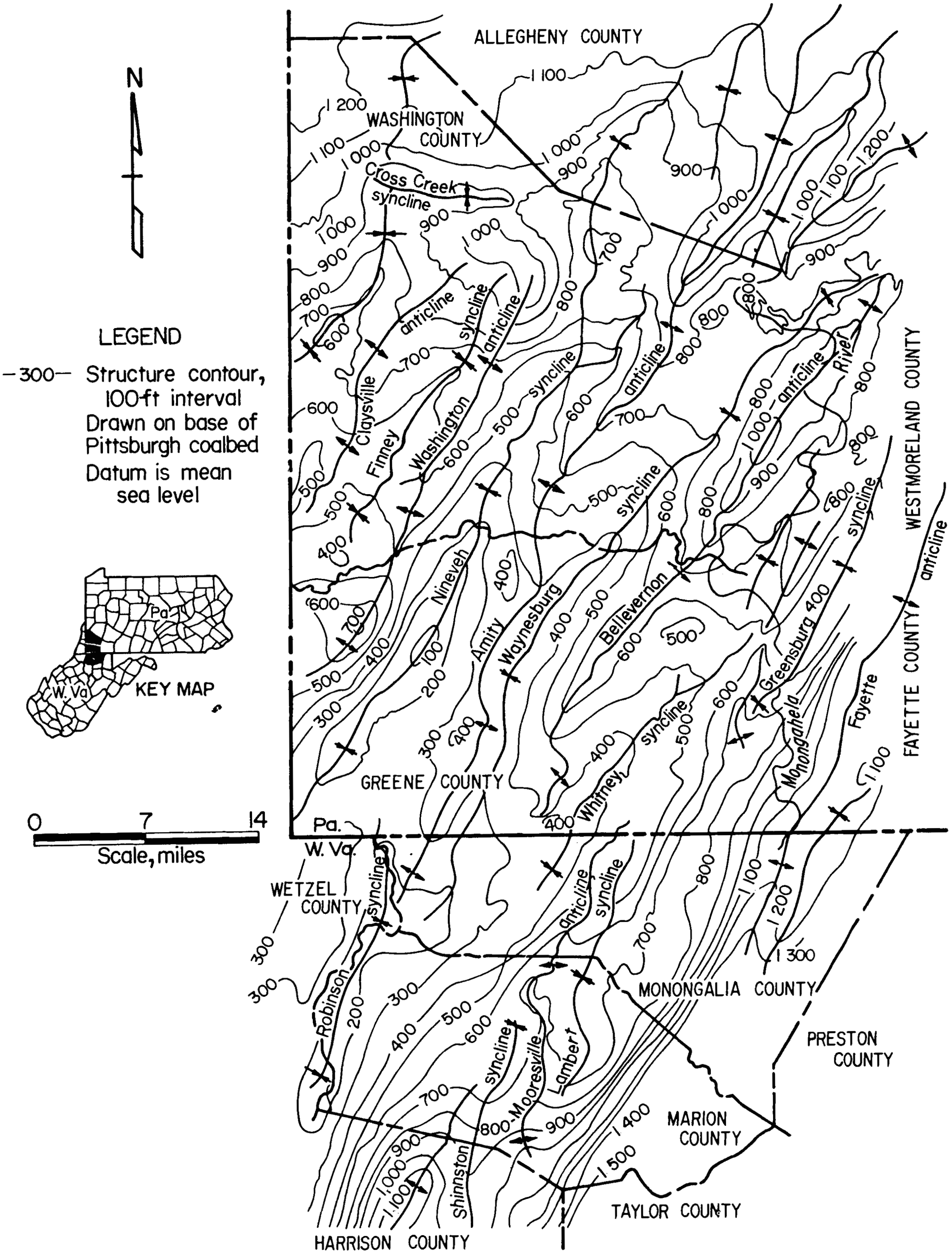

FIGURE 2. - Structure map drawn on the base of the Pittsburgh coalbed (97).

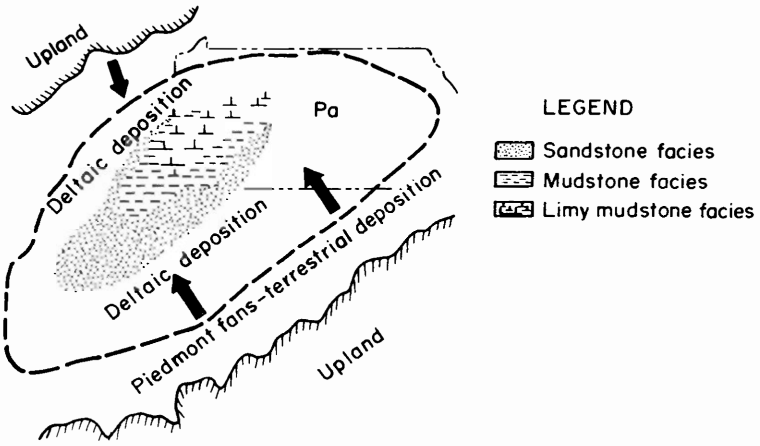

FIGURE 3. - Basin of deposition present in the study area during late Pennsylvanian time [taken from (12)].

The basin of deposition of the Pittsburgh coalbed during late Pennsylvanian time (fig. 3) occupied a large portion of Pennsylvania and adjacent areas of Ohio and West Virginia. The basin axis was defined by a bay which, according to Donaldson (26), expanded and contracted during Pennsylvanian time in response to the balance between tectonic subsidence, detrital supply, and eustatic changes in sea level.

Hoover (47) postulates a flood plain and interdistributary bay environment in the north and northwest part of the basin and a higher alluvial plain region along the south, southeast, and east side of the basin. Plant material, which eventually became the Pittsburgh coalbed, accumulated in a swamp environment associated with the deltaic sedimentation systems extending into the shallow bay. Darrah (23) notes that the climate of the area was probably moderate in temperature, rather than tropical as was once thought. Ferm and Cavaroc (32) and Conti (20) have made other paleogeographic investigations.

Thickness and Rate of Accumulation

A coal isopach (fig. 4) was prepared to give an idea of original minable coal in place. The interval measured included partings in the coal. It also included roof coal when not separated by more than 6 inches of shale or sandstone. It was constructed from more than 3,000 data points (fig. 5) derived from two sources, driller's logs of oil and gas wells and core logs from coal companies. The thickness data from the driller's logs, somewhat less reliable (probably ±2 feet) than those obtained from the detailed core descriptions, were mapped as reported. The reliability of the driller's logs depends in part on how long ago the wells were drilled, the type of equipment used, and the exactitude of the driller. Core data description generally correlated well with oil and gas well driller's logs. Mined-out areas are depicted on a separate map (fig. 6). Strip-mined areas, determined from the most recent topographic maps, are shown on the overburden isopach (fig. 7).[4]

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[4] Both the isopach of the coalbed and the overburden isopach are available from the authors'at scales of 1:24000 (one inch equals 2,000 feet). The isopach has a 100-foot contour interval on the 1:24000 maps. Also all other maps of the area are available on a scale of 1:96000.

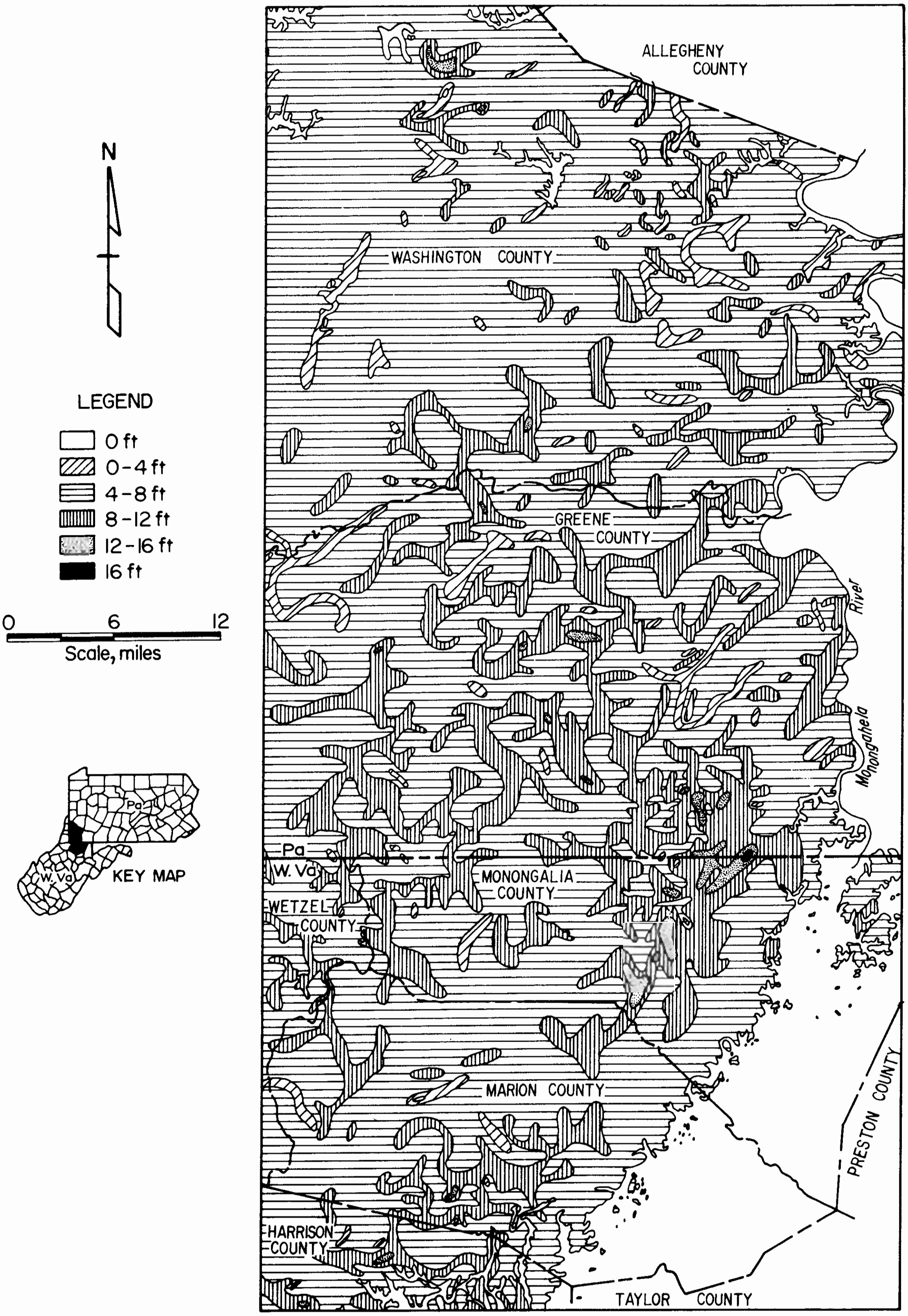


FIGURE 4. - Isopach of the Pittsburgh coalbed. (Sandstone cutouts are not included.)

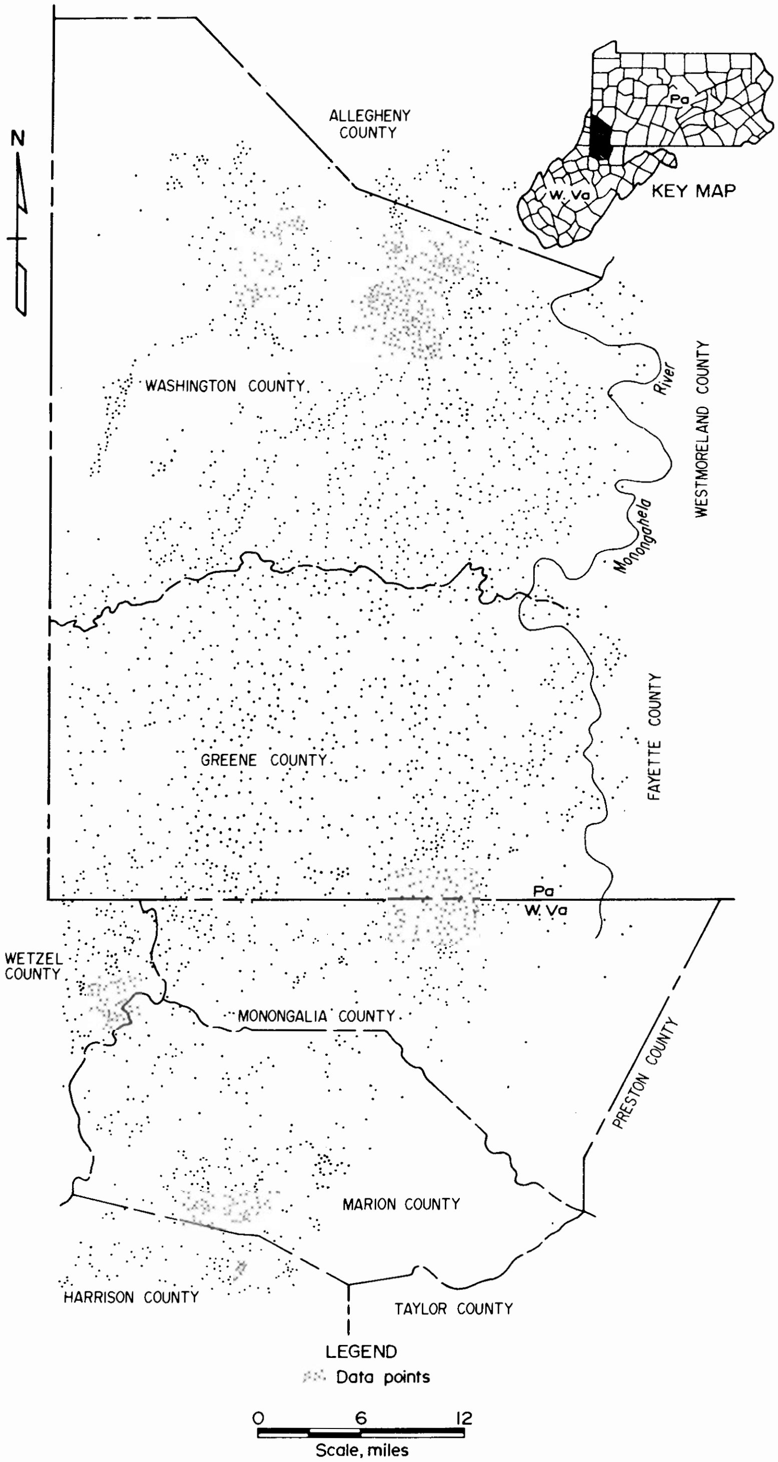


FIGURE 5. - Location of data points for the study area.

The areas of thicker coal (greater than 8 feet) do not directly overlie the regional synclinal troughs but are located generally on their flanks. It is suggested that the deposition of the Pittsburgh coal is in part structurally controlled, and that the axes of the principal structures have changed only slightly since deposition.

The dominant isopach trend (greater than 8 feet) coal begins in northern Harrison County, W. Va., runs through central Marion and Monongalia Counties, and extends into eastern Greene County, Pa. It is associated with the Shinnston and Greensburg synclines (fig. 2). Another trend, less distinct, about 10 miles to the west, begins in western Marion County, W. Va., and runs through central Greene County, Pa., into Washington County. This trend generally lies on the eastern flank of the Robinson and Waynesburg synclines. A third trend overlies the Nineveh syncline of western Greene and central Washington Counties, Pa.

The thickest coal measured was 16 feet in a core hole in northern Monongalia County, W. Va. (fig. 4), near the Pennsylvania border. Several thicknesses of 15 feet were also obtained from core descriptions in the same vicinity.

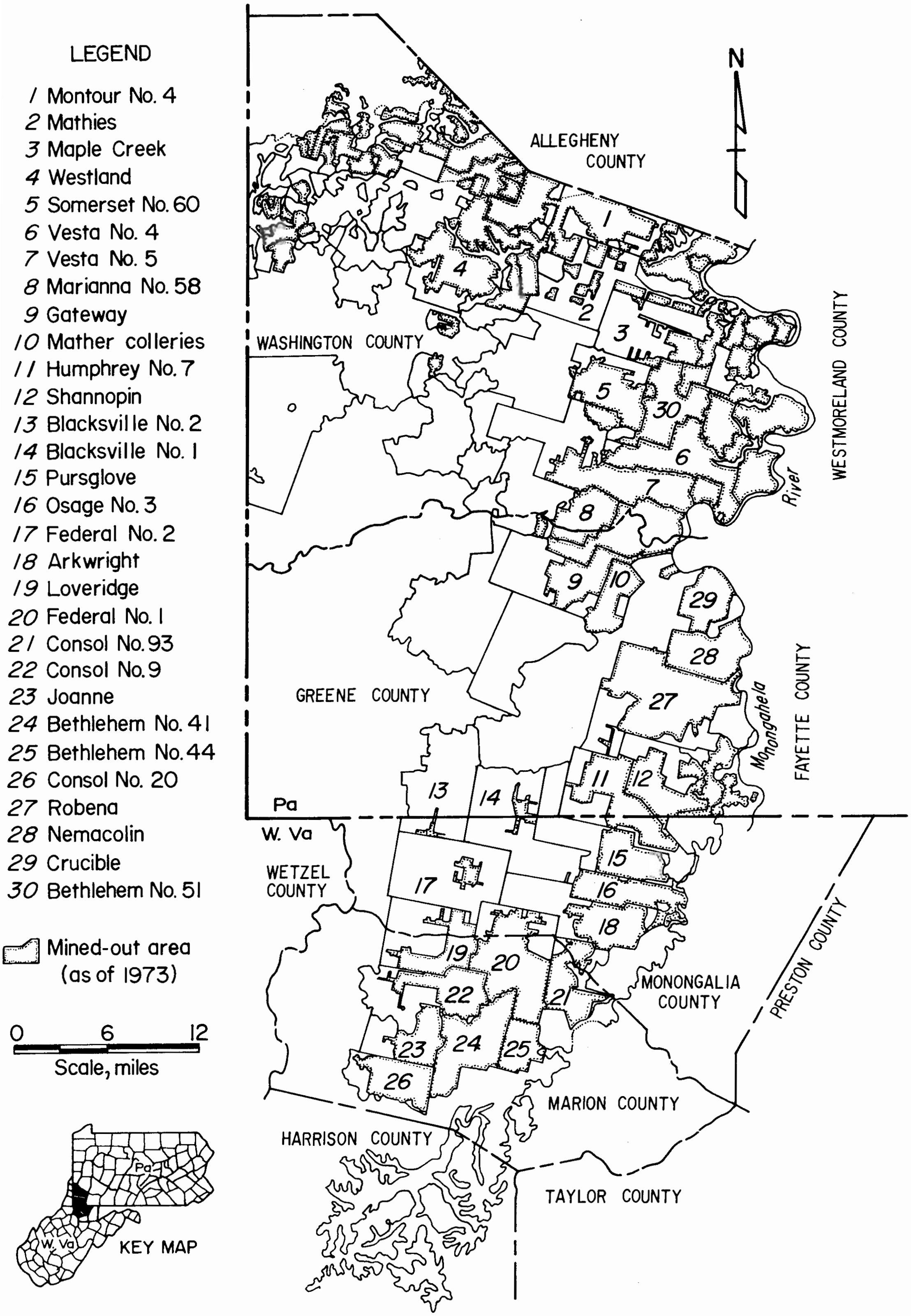


FIGURE 6. - Areas of the Pittsburgh coalbed that have been mined out.

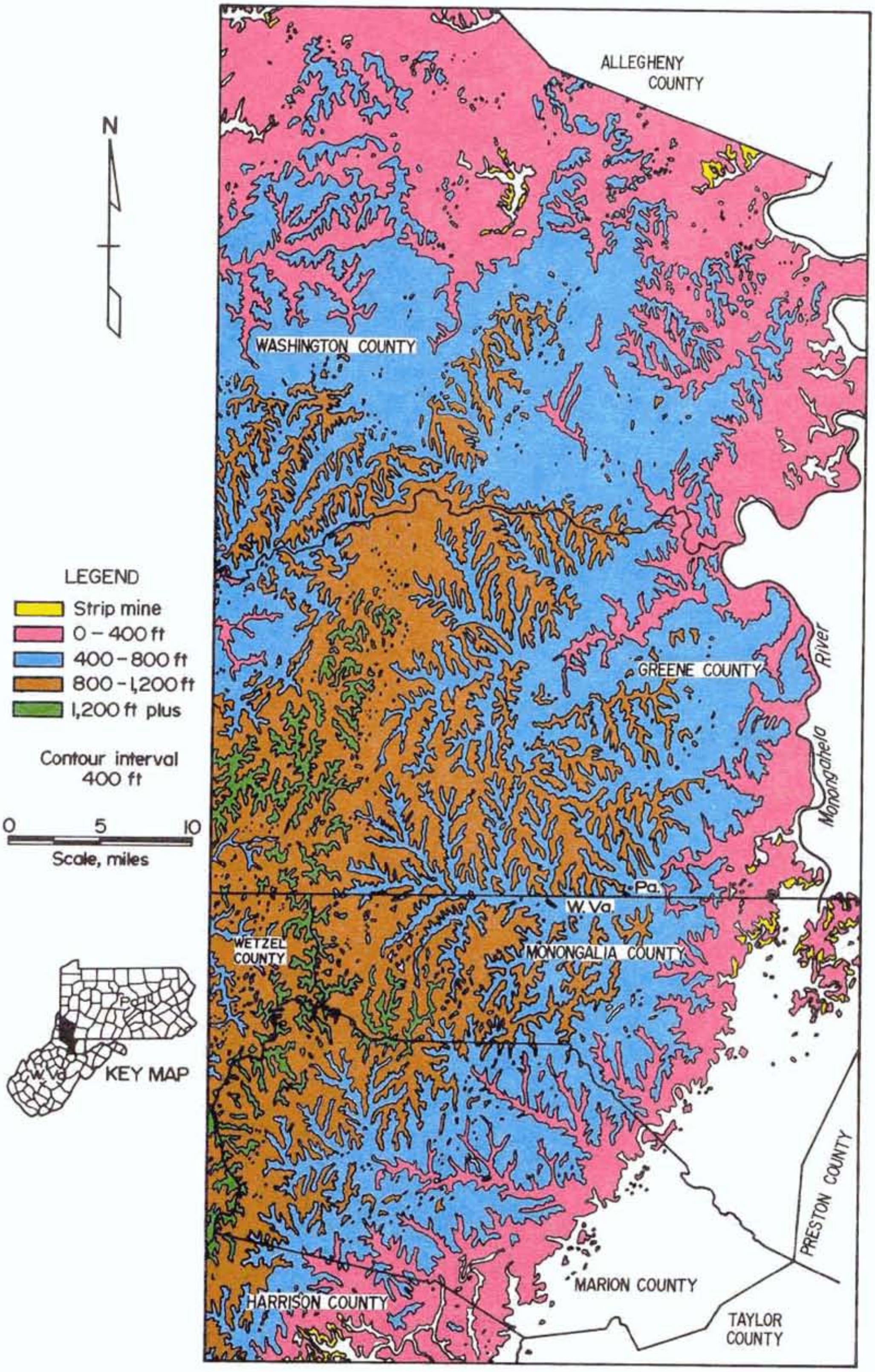


FIGURE 7. - Overburden isopach of the strata above the Pittsburgh coalbed.

Arkle (1) and Kent and Gomez (58) believe that the structures may have been "growing" during deposition, which could possibly explain the thinner coals near the axes of anticlines and the thicker coal deposits near the synclinal trough. Areas of low coal (less than 4 feet) are scattered throughout the area. Many have a preferred orientation, parallel to that of the regional structure. Some are closely associated with the anticlinal trends of the present structure. These thin areas may represent lower accumulation of plant material, greater erosion, or irregular surface of deposition. Several of the thin coal areas have a sinuous pattern suggestive of meandering streams and are probably the result of stream erosion.

Hoover (47) attributed the variations in thickness of the Pittsburgh coalbed to four possible causes: (1) Greater abundance of plant growth in some parts of the coalbed relative to others, (2) better preservation of accumulated plant debris in some areas, (3) influx of coarser detrital materials that may have diluted part of the peat already formed or terminated plant growth, and (4) the presence of deeper water, which prevented terrestrial vegetation from becoming established.

There were at least three other possible reasons for the variation in thickness: (1) Some parts of the swamp existed longer than others, (2) some areas may have been too high and dry to allow substantial plant growth, and (3) postdepositional erosion.

The time required for formation of the Pittsburgh coalbed can be estimated from the theoretical rate of accumulation for an ideal coalbed as determined by Ashley (3). Approximately 10 years would be required for 1 foot of peat to form from accumulated plant material. Since compaction and dewatering due to burial would reduce 1 foot of peat to 1-1/8 inches, approximately 100 years is required to produce 1 foot of compressed peat. The formation of 1 foot of coal requires between 3 and 3-1/2 feet of compressed peat, equivalent to at least 300 years. Thus, a 6-foot thickness of Pittsburgh coal would theoretically require 1,800 years of accumulation of plant material. This is only a reasonable estimate and cannot be considered a firm rule because the maximum thickness of 16 feet, which would require 4,800 years for deposition, is immediately adjacent to thinner coals. This maximum thickness may be due to greater accumulation of plant material in low areas as it was washed down from surrounding heights.

Generalized Stratigraphy of the Pittsburgh Formation

The Monongahela Formation in western Pennsylvania was raised to group rank by Berryhill and Swanson (12) who divided it into two formations, the Pittsburgh, which includes dominantly calcareous rocks with the Pittsburgh coalbed as its basal member and extends to the base of the Uniontown coalbed; and the Uniontown, which includes the Uniontown coalbed and the overlying predominantly sandy rocks to the base of the Waynesburg coalbed.

The Pittsburgh Formation (fig. 8) has five members: Lower, Redstone, Fishpot, Sewickley, and Upper. The Lower member includes the Pittsburgh coalbed at the base of the overlying Pittsburgh sandstone (when present). This

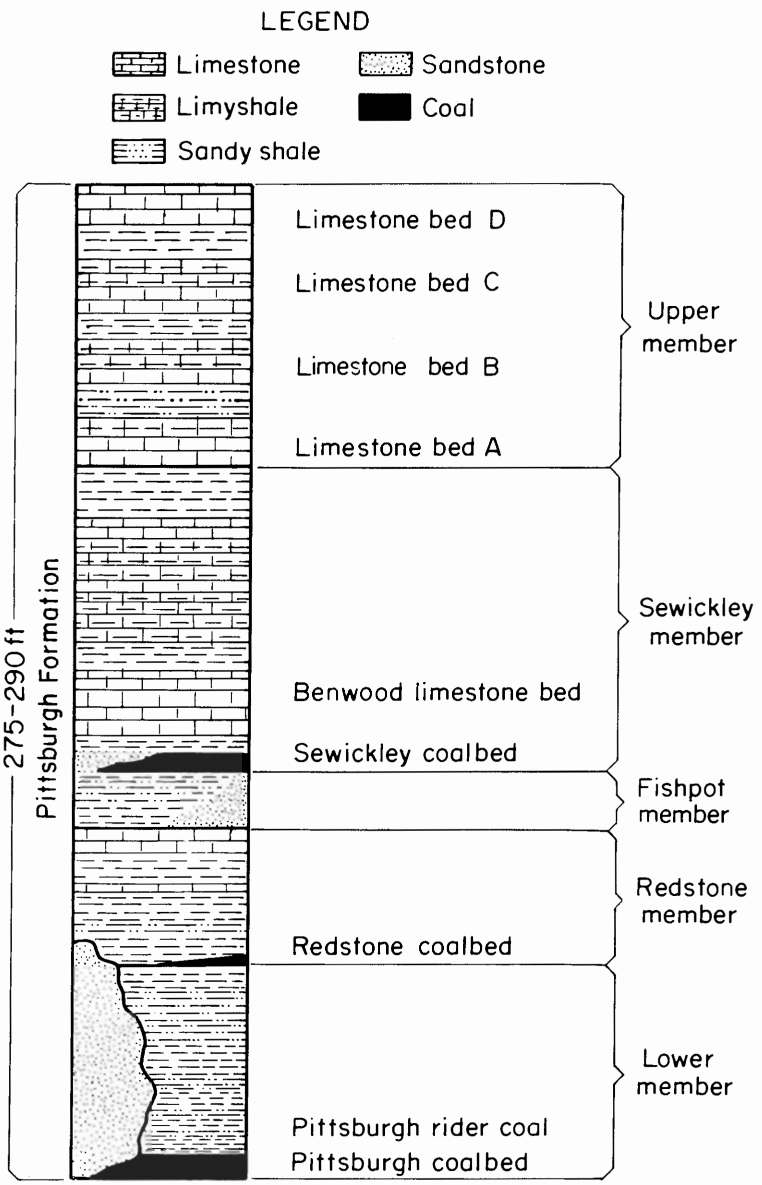


FIGURE 8. - Generalized stratigraphic column of the Pittsburgh Formation.

sandstone is the thickest and most extensive sandstone in the Monongahela Group.

The Redstone member is typically siltstone and mudstone overlain by a relatively persistent limestone. Its basal member is the Redstone coalbed. The Fishpot member is composed mainly of siltstone and mudstone. The Sewickley member has the thickest limestone sequence, and the Sewickley coalbed is at its base. The Upper member has four limestone units and no underlying coals; its top is the base of the Uniontown coalbed. According to Hoover (47), the Monongahela Group includes the strata from the base of the Pittsburgh coalbed to the top of the Waynesburg coalbed. The thickness ranges from 220 to 450 feet and consists mainly of interbedded sandstone, siltstone, limestone, and shale with lesser amounts of coal and clay. In general, throughout the section the coals overlie the calcareous units but are separated from them by underclays. The Pittsburgh coalbed is the most extensive and economically important part of the Monongahela Group.

Overburden Thickness Above the Pittsburgh Coalbed

An isopach (fig. 7) was prepared to display the thickness of rock overlying the Pittsburgh coalbed in the study area. The map was constructed by subtracting the elevation of the structure, drawn on the base of the coal from the topographic elevation. Overburden thickness ranged from zero, where the Pittsburgh coalbed crops out, to more than 1,500 feet. Generally, the coal is shallow on the axes of anticlines and deeper in the troughs of synclines. The deepest cover in the study area is in southwestern Greene County and western

Monongalia and Marion Counties, where it averaged 1,200 feet with a maximum thickness of slightly over 1,500 feet.

As mining progresses under deeper cover, methane control and other mining problems will undoubtedly intensify. As gas emission rates are measured by the Bureau for increasing depths, attempted correlations with overburden thickness will be made to develop a theoretical model of depth versus gas emission for the Pittsburgh coalbed.

In Washington County the Pittsburgh coalbed crops out and is strip-mined in three localities (fig. 7). One outcrop in the western part of the county has no structural dependence. The other two occur on the axes of the Amity anticline and the top of the Westland dome. Maximum overburden thickness is slightly over 800 feet in the southwestern part of the county. Average thickness is approximately 400 feet.

In Greene County the coalbed crops out and is strip-mined along the Monongahela River. The overburden reaches a maximum thickness of 1,400 feet in southwestern Greene County and averages approximately 800 feet. The area where the overburden is relatively shallow is roughly parallel to the axes of anticlines, and the areas of the greatest overburden are in the synclinal troughs. For example, the Nineveh syncline in the southwestern part of the county has an overburden of between 800 and 1,200 feet. Along the Washington anticline to the west, the overburden ranges between 400 and 800 feet.

In Monongalia County there is stripping along the eastern edge of the Pittsburgh coalbed where it crops out. Of the four counties, Monongalia has the most extensive stripping of the Pittsburgh coalbed. The coalbed rapidly increases in depth to a maximum of 1,500 feet of overburden in the western part of the county.

In Marion County the Pittsburgh coalbed crops out along the eastern part of the county. The central part of the county has an average of 400 feet of overburden, whereas the western part has between 800 and 1,200 feet of cover.

Only small sections of Harrison and Wetzel Counties are covered in this study. In Wetzel County, the eastern part of which is included in this study, the overburden averages between 800 and 1,200 feet. In Harrison County, there is some outcrop and strip mining. The overburden averages approximately 400 feet with a high of 1,300 feet along the border between Harrison County and Marion and Wetzel Counties.

GEOLOGIC FACTORS CONTRIBUTING TO MINING PROBLEMS

Geological investigations can identify many underground mining problems. Sand channels that may intersect and cut out the coal can be located in advance of mining by analysis of core hole logs, and their probable course and influence on future mining operations can be predicted (76). Clay veins can be located and their trends can sometimes be established so that high gas concentrations, frequently associated with clay veins, can be anticipated.

A detailed map of the rock above the coalbed can be used to determine the length of bolts needed to anchor into competent strata for proper roof support. Such a map can also help to locate rock known to deteriorate rapidly when exposed to air so that resin bolts can be used.

Abnormal accumulations of water can be evaluated and perhaps related to fracturing of the roof rock or to a fault zone. These zones of weakness may also be responsible for high gas concentrations.

A detailed analysis of surface joints above a mine area can be prepared and examined for a possible relationship to the coal cleat directions and roof joints. Local deviations in joint and cleat directions serve as a basis for modifying mine projections. The cleat and joint analyses also supply information related to roof stability. For example, excessive spalling of ribs when mining parallel to cleat directions can sometimes be corrected by rotating the direction of mining 45°.

Strata Above the Pittsburgh Coalbed

The strata overlying the Pittsburgh coalbed vary locally and regionally as shown in the fence diagram (fig. 9). This figure was prepared using 77 core logs, electric logs, and other data selected from more than 500 logs to best represent the regional stratigraphic trends. The most common rock type directly overlying the Pittsburgh coalbed is the "draw slate" or "roof slate" (miners' terminology), consisting of alternating thinly bedded, dark gray to black, fissile carbonaceous shale, coal stringers, and sandstone lenses. This draw slate unit is generally less than 4 feet thick, but thicknesses up to 12 feet have been observed.

In the central part of the study area, the most common rock types above the draw slate are limestone and calcareous and silty shales. Surrounding the central area is a sequence of shales and massive sands. Other areas of massive sand development are shown on the sandstone channel map (fig. 10).

In Monongalia and Marion Counties, W. Va., the rocks above the coal and draw slate are predominantly limestone and shale, although the "limestone" of older core logs is more likely interbedded limestone, shale, and siltstone; in earlier years these rock types were not usually differentiated. The only sand deposits in these two counties are along the eastern margin of the area.

The roof rock in Greene County, Pa., is similar to that in Monongalia and Marion Counties, W. Va. Limestone is still dominant in the south but decreases in importance toward the northern border where large sand bodies become more prominent. The Pittsburgh sandstone unit may be up to 80 feet thick.

In Washington County, Pa., limestone dominates the southwestern portion, sandstone the southern and central area, and shale the northern portion. Throughout the area, a few coals are detected, but there appears to be no pattern to their occurrence.

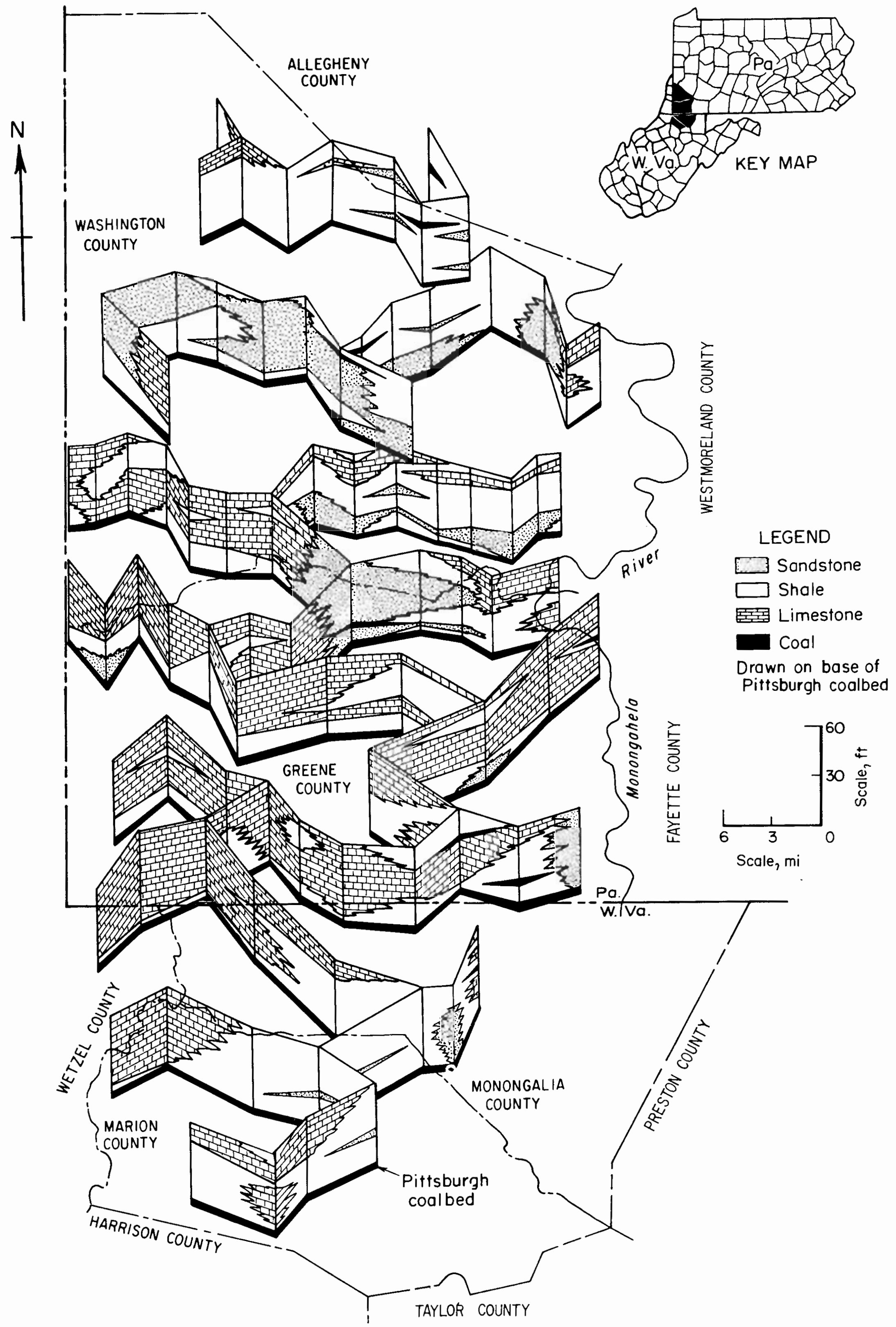


FIGURE 9. - Fence diagram of the strata directly above the Pittsburgh coalbed for the study area.

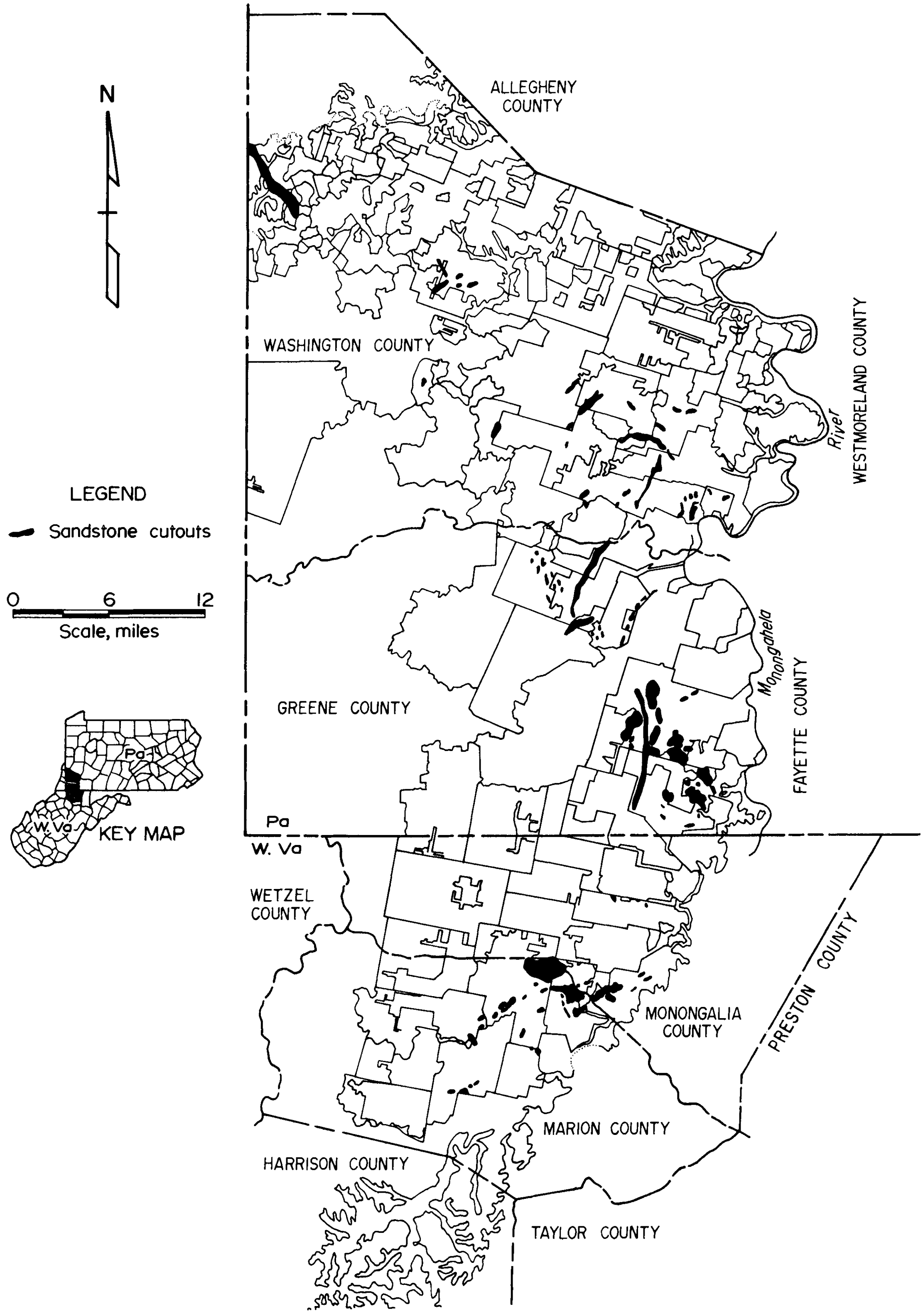


FIGURE 10. - Map of the known sandstone channels cutting into the Pittsburgh coalbed.

An isopach of the Pittsburgh sandstone prepared by Hoover (47) covers the known extent of the Pittsburgh sandstone in Monongalia and Marion Counties, W. Va., Greene County, Pa., and part of Washington County, Pa. (fig. 11). The sandstone bodies trend predominantly either to the northeast or northwest. The thin portions of the sandstone especially seem to be oriented to the northeast, as are the axes of the folds, which again suggests some structural control. There is also the possibility that the sandstone bodies are sedimentologically controlled, as suggested by W. Edmonds of the Pennsylvania Geological Survey (personal communication, available for consultation at Bureau of Mines Pittsburgh Mining and Safety Research Center, Pittsburgh, Pa.). The northeast-oriented bodies could be related to the strike of the strandline and could have formed as longshore bars. The northwest-oriented bodies could be down-paleoslope features such as alluvial valleys. A correlation may also exist between the thickness of the sandstone and areas of sandstone cutouts in the coal.

Sandstone Channels

Sandstone channels are lenticular, sometimes sinuous bodies of sandstone extending into, and sometimes completly through, a coalbed. Figure 10 is a map of known sandstone channels in the Pittsburgh coalbed, encountered in underground mining operations. Cross (21) also reports a channel extending from southwestern Pennsylvania to Monongalia County, W. Va., generally paralleling the Monongahela River. The channel then turns westward at the Monongalia-Marion County border.

Most of the known channels are within the present mine workings. Channels are difficult to detect in advance of mining because exploratory drilling of a mine property is frequently on 1-mile centers or more, whereas the channels are usually less than 2,000 feet wide. A much closer spacing, preferably 2,000 or 3,000 feet, will enable more detailed mapping and predicting of sandstone channel trends in advance of mining.

Even when a sandstone channel is not directly encountered in the core drilling, other evidence may suggest the proximity of one. The coal may become abnormally thick, sometimes even doubling in thickness near a sandstone channel by possibly washing to the side or by differential compaction. The sulfur content may increase toward channel areas. Channels can also possibly be detected by analysis of the related sediments using sedimentological and paleodepositional techniques, but this would be beyond the scope of this paper. Donaldson and Morton (27) listed five criteria that may be helpful in predicting channels: (1) Presence of clay veins, (2) change in coal type, (3) increase in the number and thickness of partings, (4) increase in detritals in the coal, and (5) a down-bowed parting.

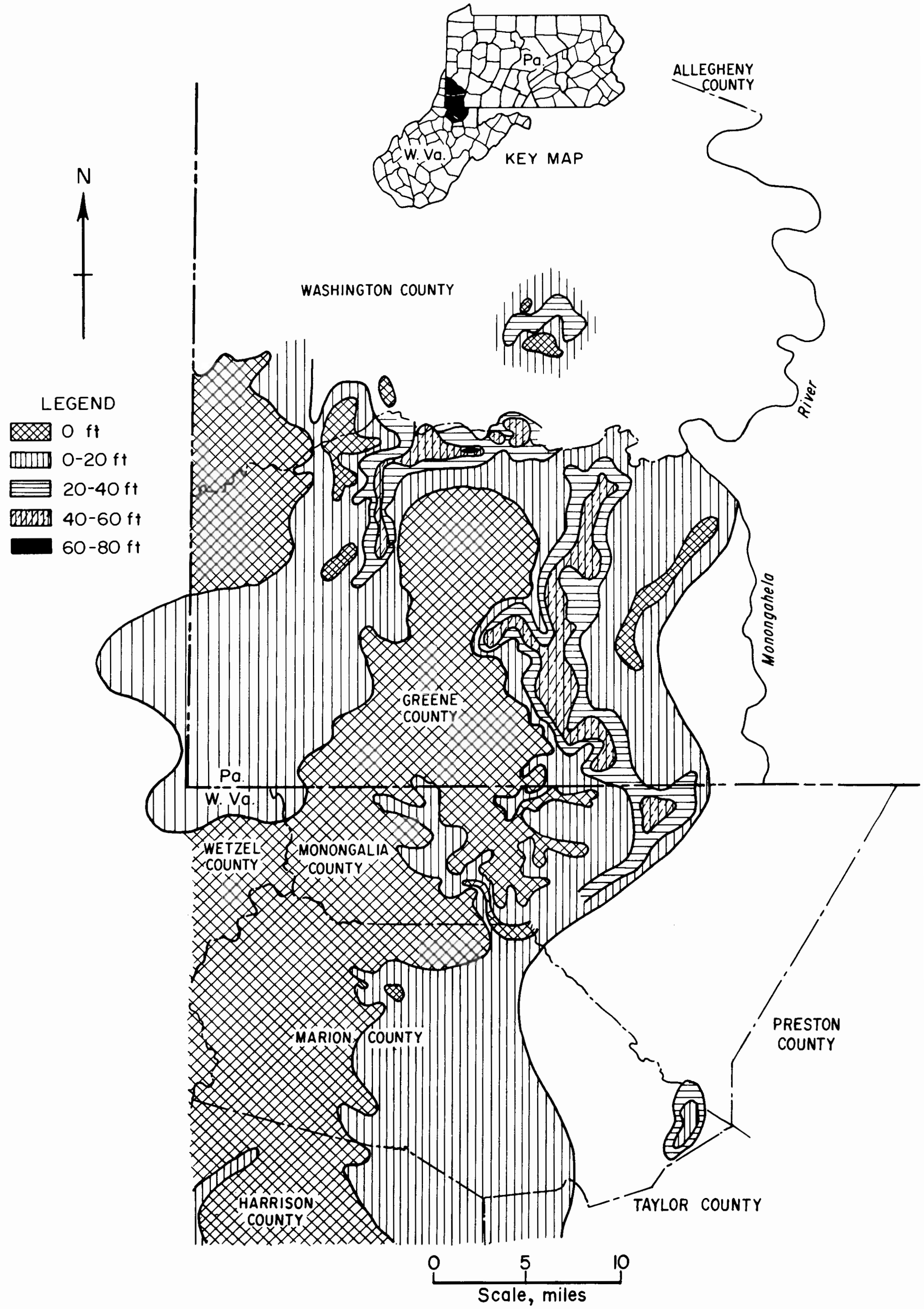


FIGURE 11. - Isopach of the Pittsburgh sandstone (48).

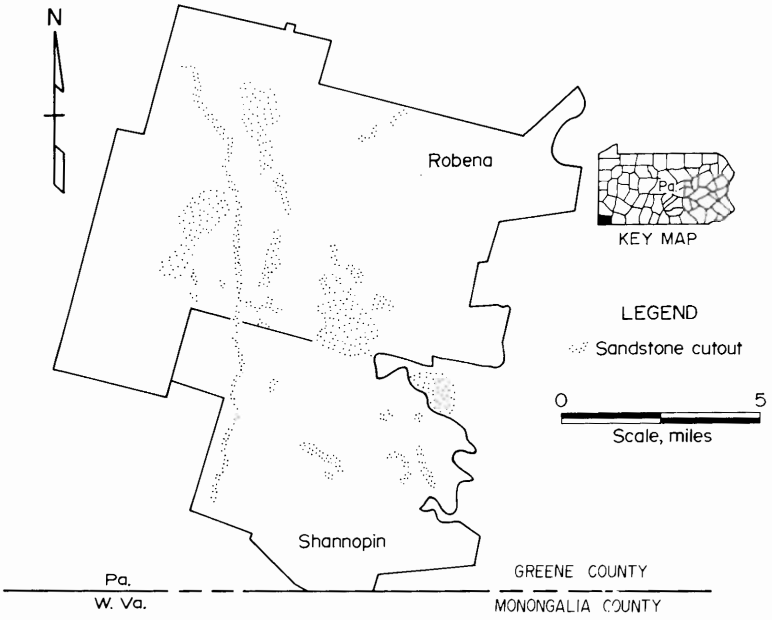


FIGURE 12. - Map of the Shannopin and Robena mines with sandstone cutouts.

At the Shannopin and Robena mines in Greene County, a number of channels intersect the coalbed (fig. 12). A fence diagram (fig. 13) of the area around the Shannopin mine shows a large lenticular sandstone body (Pittsburgh sandstone) overlying the coal. When the location of the sandstone channels that intersect the Shannopin and Robena mines are plotted on figure 11, these washouts are seen to occur in an area where the sandstone is 40 to 60 feet thick. Bureau geologists have found that when core logs indicate that such a sandstone body is approaching the coal, the coalbed is very likely to be cut out. Where the strata for approximately 40 feet above the Pittsburgh coalbed consist of limestone and shale, there is little chance of encountering a sandstone channel during mining. Figure 10 also shows other mines where sandstone channels have occurred.

Clay Veins

Clay veins are wedges of indurated clays and silts that penetrate the coalbed from either above or below. They can be vertical (parallel to the cleat directions) or form an angle of about 45° with the vertical (parallel to shear directions) (fig. 14).

Clay veins encountered in mines are usually crooked, are frequently angular, and interfinger with the coal rather than forming smooth contact surfaces. They may be hard enough to damage mining equipment. Thickness normally ranges from 1 inch to several feet but may be up to 15 feet. A total length of more than 1,000 feet has been observed underground.

There are two physical types of clay veins. The first occurs as inclusions within a clay-silt matrix and has a conglomeratic or brecciated appearance. The second type is composed of small interlocking lenslike masses of shale fragments with convoluted, slickensided surfaces.

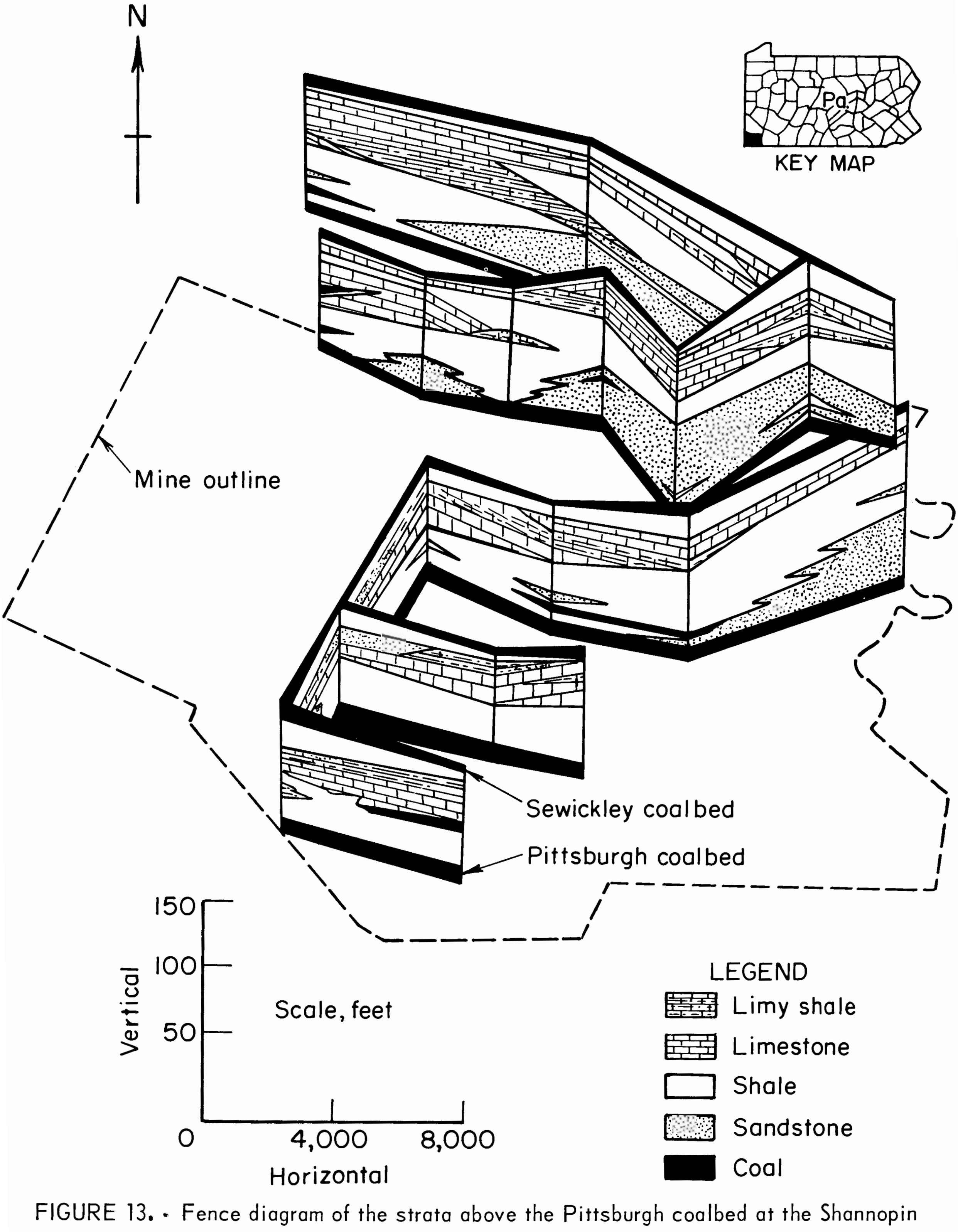


FIGURE 13. - Fence diagram of the strata above the Pittsburgh coalbed at the Shannopin mine.

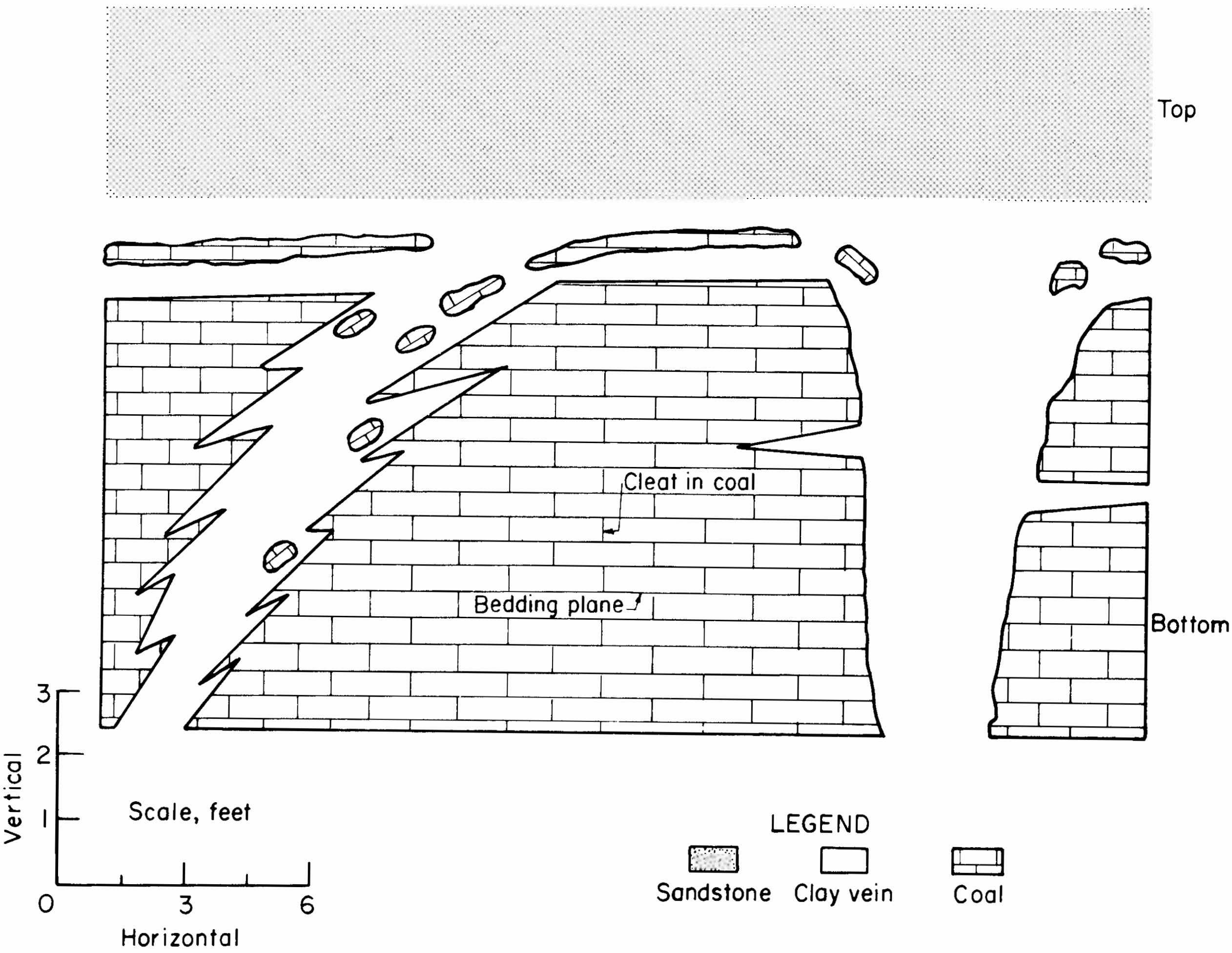


FIGURE 14. - Generalized cross section of clay veins intersecting coalbeds.

Clay veins were found in the following mines operating in the Pittsburgh coalbed (fig. 15): Mathies, Bethlehem Nos. 41 and 44, Marianna No. 58, Gateway, Shannopin, and Vesta No. 5; all these mines have a predominance of sandstone in the immediate roof. Two other adjacent mines, Loveridge and Federal No. 2, show no clay veins, and their roof strata are predominantly shale and limestone.

The presence of clay veins can greatly affect mining conditions. They often form cells within which large volumes of gas are isolated under high pressure. A test hole drilled into a cell enclosed by such a clay vein measured a confined pressure of 263 lb/in^2 (<u>41</u>). The gas flow from a 2-inch hole drilled horizontally into the coalbed through the clay vein at this point produced an average of 78,000 ft^3/d of gas for a short time. When mining encounters such a cell, large volumes of gas are released rapidly into the mine creating an explosion hazard. Also the chance of an explosion is increased by the sparks that are generated when mining into clay veins with both continuous miners and lognwall systems.

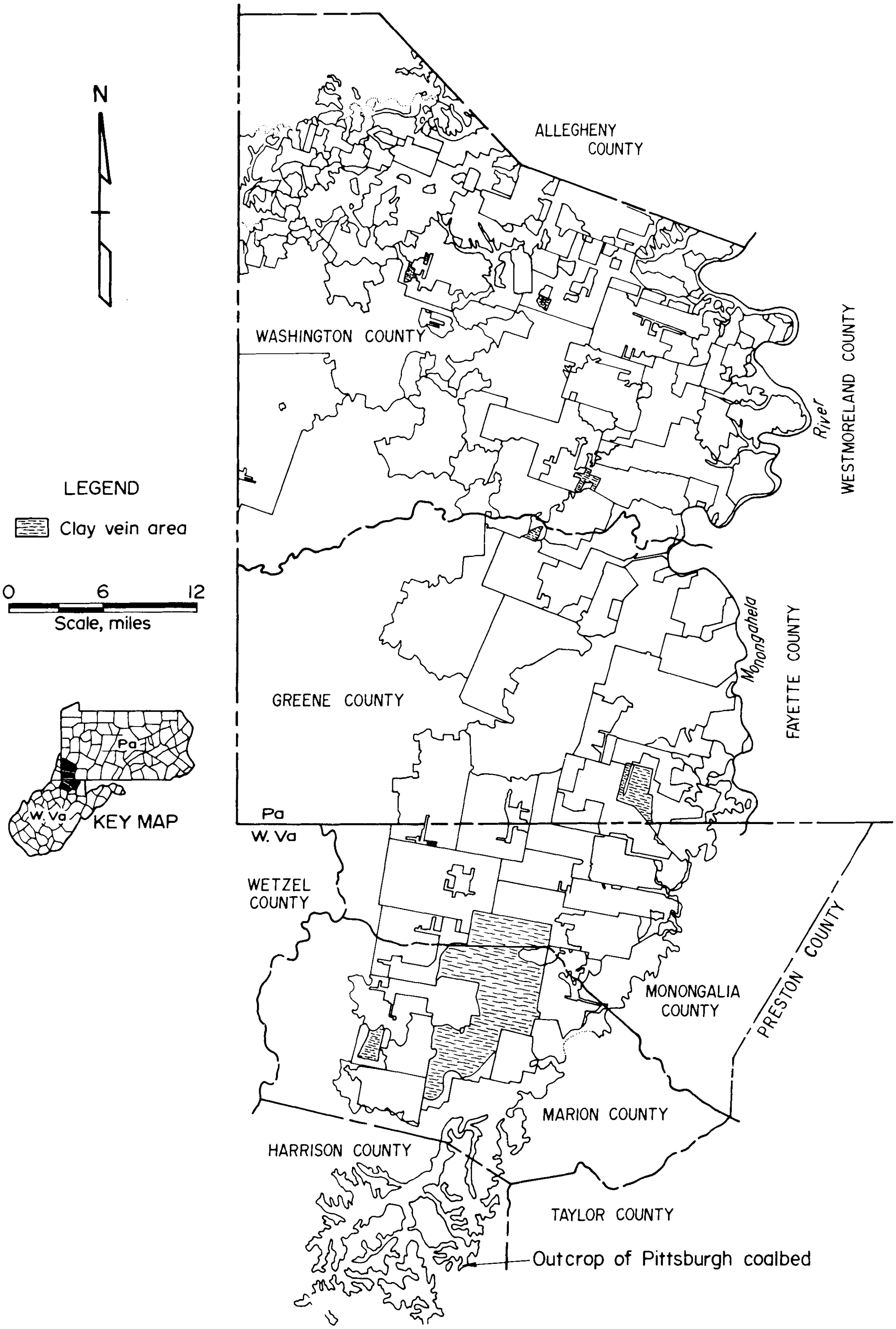


FIGURE 15. - Mines operating in the Pittsburgh coalbed with abundant clay veins.

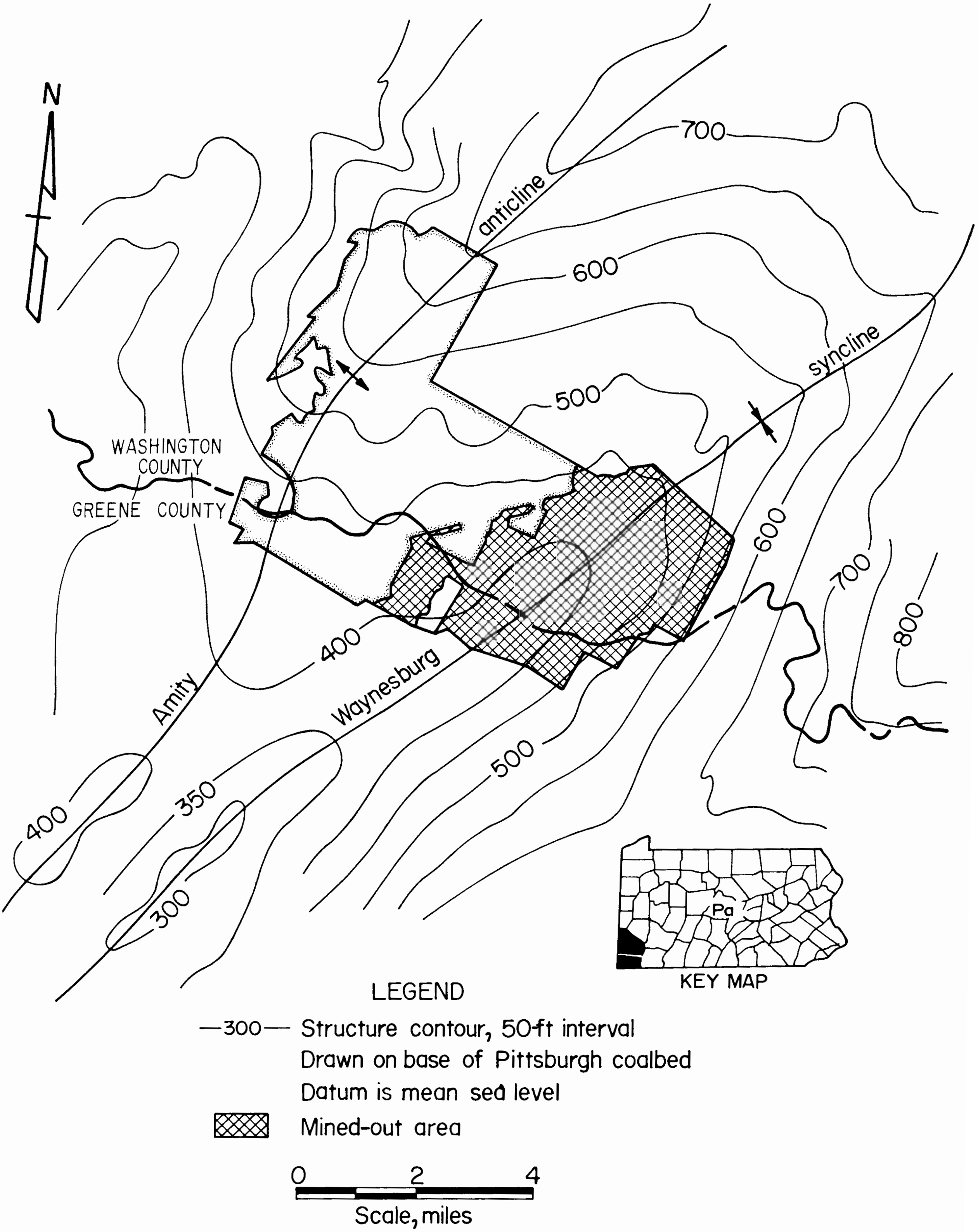


FIGURE 16. - Location and structure around the Marianna No. 58 mine.

Clay veins generally extend into strata immediately overlying the coalbed, sometimes for as much as 10 feet vertically. This breaks up the lateral continuity of the layered roof strata, causing roof instability. Roof failures tend to be more frequent when clay veins are almost parallel to the entry than when they are at right angles. Mining of clay veins also produces a marked increase in the percentage of rejects in the coal preparation plant.

The Marianna No. 58 mine is an example of a mine with clay vein occurrences. It is located in the trough of the Waynesburg syncline (fig. 16). The greatest frequency of clay veins occurred in a section of the mine located within the synclinal trough (fig. 17). The clay veins formed cells with sides oriented subparallel and subperpendicular to the axial trend of the trough.

Clay samples from the Marianna No. 58 mine were analyzed by X-ray diffraction to determine their mineralogical composition. Comparison of mineral compositions showed a near-perfect match between clay veins (fig. 18A) and the draw slate or roof rocks (fig. 18B) above. The major mineral peaks (quartz, kaolinite, and illite) all matched in intensity and slope. The floor rock samples (fig. 18C) showed a different composition, with calcite and quartz predominating, indicating that in this case the clay vein was injected from the roof rock, not from the floor rock. In some cases, clay veins are injected from underclays or shale lying below the coalbed up into it. Examples occur in the Redstone coalbed and in several coalbeds in western Kentucky.

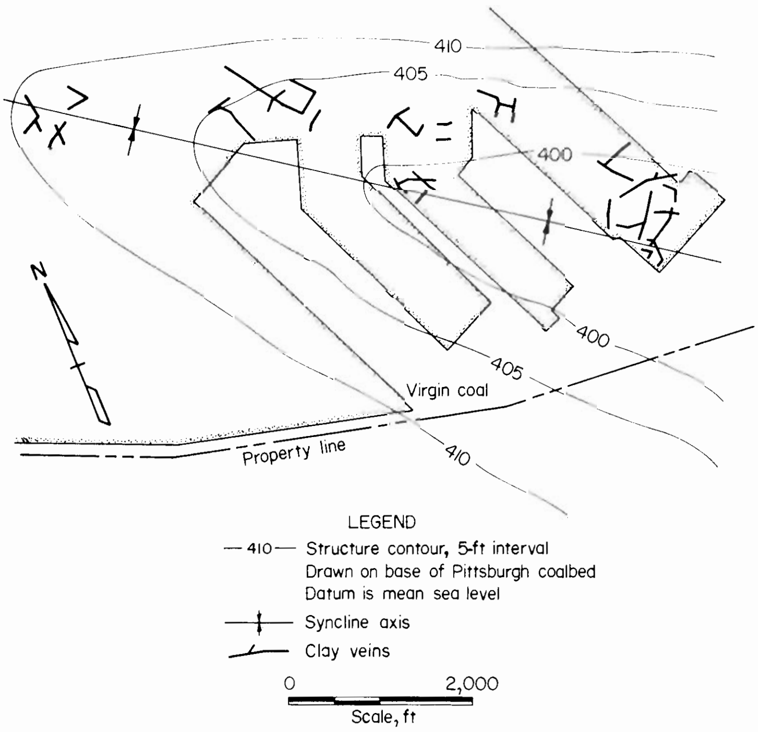


FIGURE 17. - Clay veins in synclinal trough at the Marianna No. 58 mine.

Based on Bureau research, it has been postulated that the clay veins intruded the coal after coalification had taken place. This conclusion is supported by the presence of coal fragments with good cleat development in clay veins. As the coal fragments were layered and the layers were parallel to the dip of the clay vein (fig. 14), it would appear that clay was not injected into cracks in peat as suggested by Raistrich and Marshall (90), but was forced into the coalbed after coalification.

It appears that the clay veins in the Pittsburgh coal bed are probably the result of tectonism, as in the Marianna No. 58 and

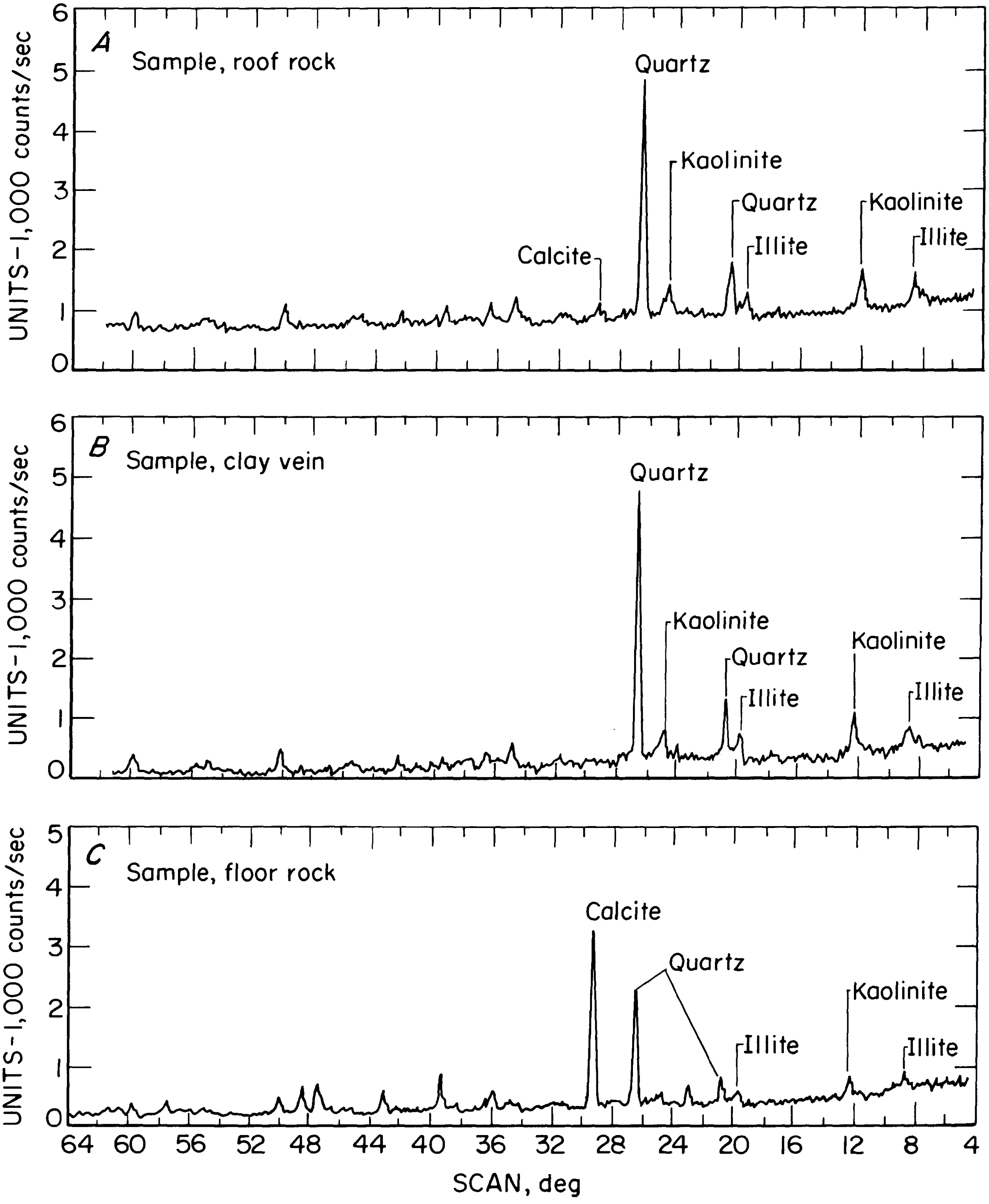


FIGURE 18. - X-ray diffraction charts of *(A)* the clay vein, *(B)* the roof rock, and *(C)* the floor rock lithologies.

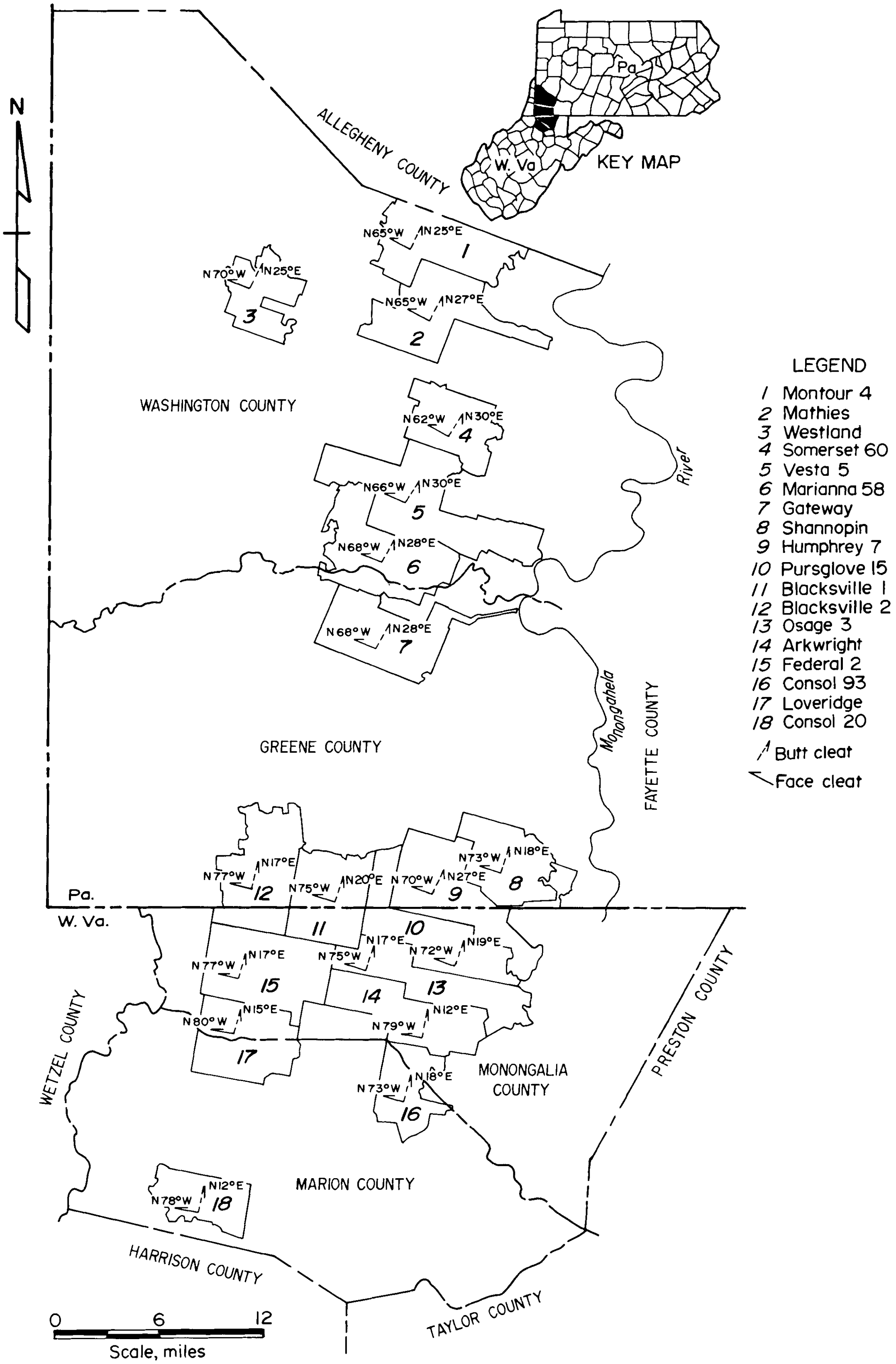


FIGURE 19. - Cleat systems in mines operating in the Pittsburgh coalbed.

Shannopin mines, although they may also be related to differential compaction in a depositional environment such as described by Wilson (124) in the central Missouri coals. This would explain the thick sandstone units found above them, whereas mines with limestone and shale roofs have no clay veins. The only known evidence of igneous activity within the study area is a peridotite dike found in Fayette and Greene Counties, Pa. The dike has been noted by Cross and others, and its presence has been confirmed by exposure in mine workings. The dike, which has been traced on the surface for approximately 15 miles, ranges in width from a few inches to several feet and tends to be perpendicular to the axial folds. The coal around the dike has been naturally "coked."

Cleat Within Mines

Cleat is the natural vertical fracture system in bituminous coalbeds. It is usually composed of a fundamental system of two components (sets) at 90° to each other. The more dominant fracture plane is the face cleat; the minor fracture plane is the butt cleat. The face cleat is more continuous, crossing bedding planes in the coal and extending for many feet, and tends to be perpendicular to the fold axes. The butt cleat is short, is often curved, and is a discontinuous feature that frequently terminates against the face cleat.

In the past, the orientation of the cleat in the Pittsburgh coalbed controlled the direction of mining. As coal tends to break along the cleats, it was easier to mine parallel to the cleat than at an angle to it. This has changed with the introduction of continuous miners, which mine as fast at an angle to the cleat as parallel to it. However, cleat is still very important because its orientation determines directional permeability which, in turn, determines the flow of methane and water into the mine workings (64, 75). When mining advances perpendicular to the face cleats, much more gas and water are emitted into mine workings than when the advance is parallel to the face cleat.

Determination and Analysis of Cleat Orientation

Cleat surveys were conducted in 18 mines operating in the Pittsburgh coalbed. The average cleat orientations were measured for each mine (table 1) and plotted according to geographic location (fig. 19). A composite rose diagram (fig. 20) was constructed using the values from table 1. Two distinct peaks are present in the face and butt cleat directions. Two equally dominant fundametal cleat systems with directional trends approximately perpendicular are calculated for the study area. These two systems are N 76° W - N 17° E, with a 93° separation; and N 67° W - N 28° E, with a 95° separation.

In southwestern Pennsylvania and northern West Virginia, the cleat systems rotate clockwise from south to north. In figure 20, the dominant N 17° E direction is composed of the measurements from mines in the southern portion of the area (Nos. 8 to 18 with the exception of No. 9), and the dominant N 28° E direction is composed of the measurements from mines in the northern portion of the area (Nos. 1 to 7 plus 9). The geographic plot of the cleat systems (fig. 19) gives a more detailed picture of the cleat rotation on a mine-to-mine basis.

TABLE 1. - Cleat systems of 18 mines surveyed

No.	Mine name	Face cleat	Butt cleat
North:			
1............	Montour 4.................	N 65° W	N 25° E
2............	Mathies...................	N 65° W	N 27° E
3............	Westland..................	N 70° W	N 25° E
4............	Somerset No. 60...........	N 62° W	N 30° E
5............	Vesta No. 5...............	N 66° W	N 30° E
6............	Marianna No. 58...........	N 68° W	N 28° E
7............	Gateway...................	N 68° W	N 28° E
8............	Shannopin.................	N 73° W	N 18° E
9............	Humphrey No. 7............	N 70° W	N 27° E
10............	Pursglove No. 15..........	N 72° W	N 19° E
11............	Blacksville No. 1.........	N 75° W	N 20° E
12............	Blacksville No. 2.........	N 77° W	N 17° E
13............	Osage No. 3...............	N 75° W	N 17° E
14............	Arkwright.................	N 79° W	N 12° E
15............	Federal No. 2.............	N 77° W	N 17° E
16............	Consol No. 93.............	N 73° W	N 18° E
17............	Loveridge.................	N 80° W	N 15° E
South: 18......	Consol No. 20.............	N 78° W	N 12° E

A slight counterclockwise rotation of the cleat from east to west was also noted. Starting in the eastern part of the study area with Humphrey No. 7 (N 70° W), and continuing westward to Blacksville No. 1 (N 75° W) and Blacksville No. 2 (N 77° W) mines, the face cleat rotates 7°. A similar rotation was detected between Consol No. 93 mine (N 73° W) and the Loveridge mine (N 80° W) to the west, and in the northernmost part of the study area between the Mathies mine (N 65° W) in the east and the Westland mine (N 70° W) in the west.

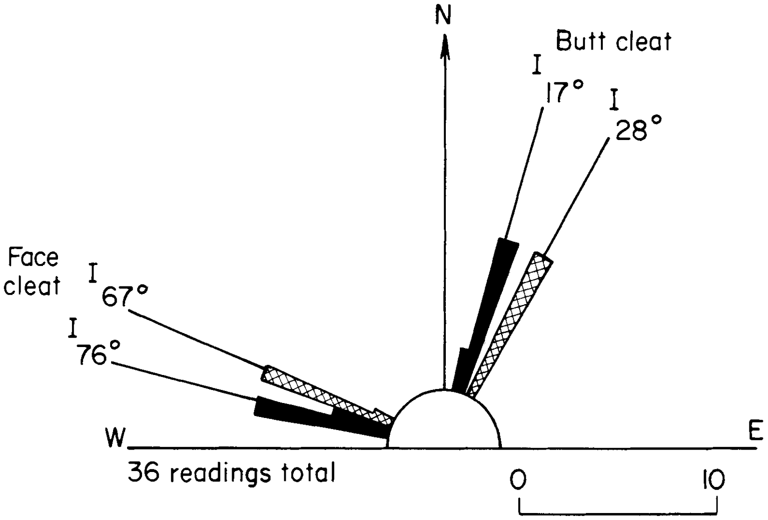


FIGURE 20. - Composite rose diagram of cleat orientation in 18 mines surveyed.

Relationship of Local Structure to Cleat Orientation

Cleat orientation and local structure are closely related. The butt cleats tend to be parallel to the axial trends of folds, whereas the face cleats are perpendicular to the axial trends. This has been noted not only in the Pittsburgh coalbed but also in the Pocahontas No. 3 (Virginia), the Lower Kittanning (Pennsylvania), and the Hartshorne (Oklahoma) coalbeds (75).

A good example of the relationship between local structure and cleat orientation in the Pittsburgh coalbed can be observed in the Pursglove No. 15 mine, located in Monongalia County, W. Va., between the area's two dominant structural features--the Fayette anticline and the Lambert syncline (fig. 21). Cleat orientations measured in the mine define a N 72° W - N 19° E fundamental system. The structural strike within this portion of the mine averages N 24° E, close to the N 19° E strike of the butt cleat. The structural dip is N 76° W, similar to the N 72° W trend of the face cleat. Similar (±10°) relationships between cleat orientation and local structural trends are observed for the majority of the mines surveyed.

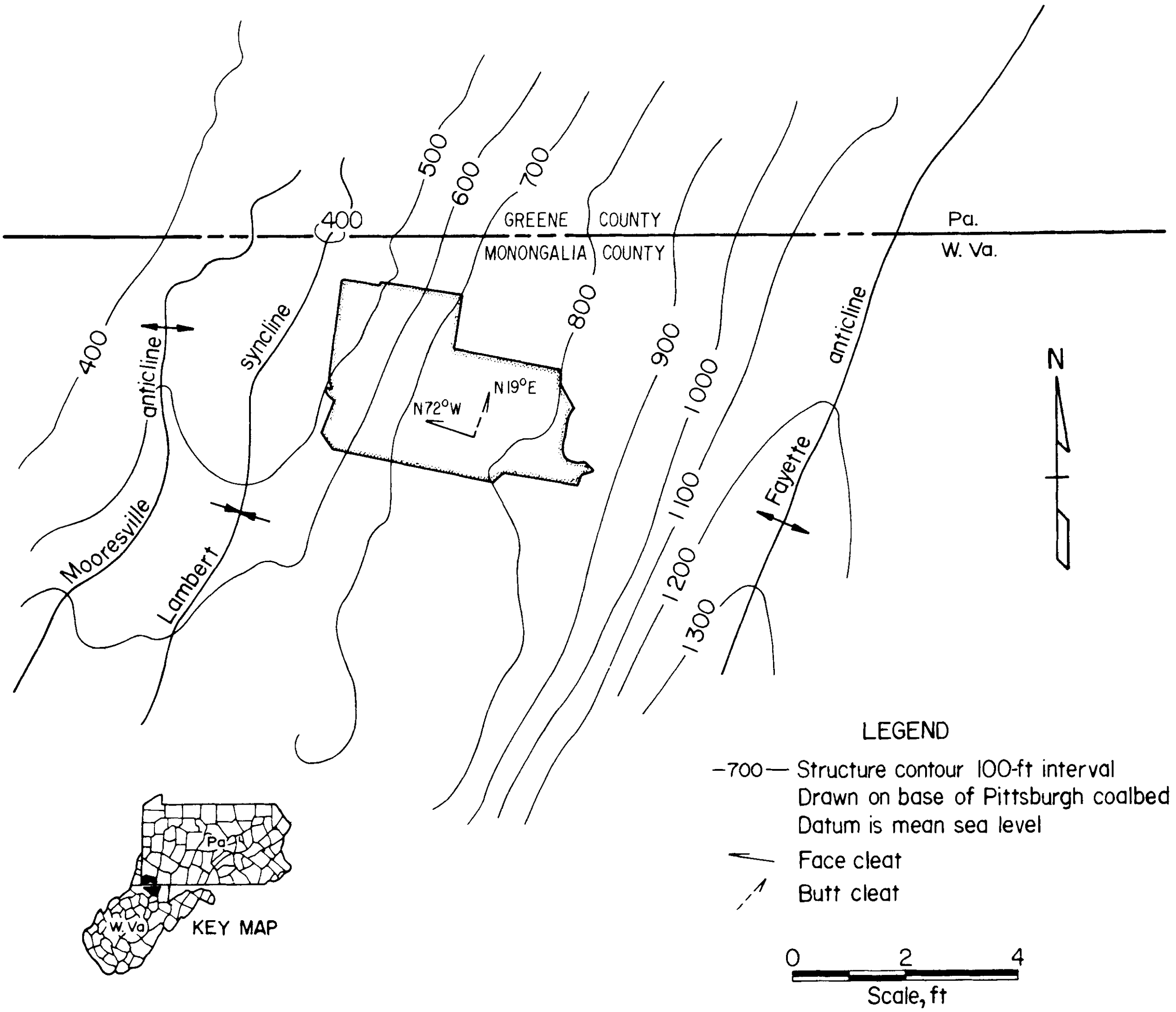


FIGURE 21. - Relationship between local structure and cleat orientation in the Pursglove No. 15 mine, Monongalia County, W. Va.

Geologic Factors Affecting Methane Emission

The Pittsburgh coalbed is a gassy coalbed. According to Irani (50-51) the five counties in the United States producing the most coal gas are--

	MM ft^3/d
Monongalia County, W. Va	40.7
Marion County, W. Va	23.1
Buchanan County, Va	22.1
Washington County, Pa	12.4
Greene County, Pa	11.7

Four of these counties are within the study area. They have a total gas production of 87.9 MM ft^3/d; approximately 95 percent is from mining in the Pittsburgh coalbed. Also Kim (60-61) has estimated that the Pittsburgh coalbed in southwestern Pennsylvania (over an area of 575 square miles) contains over 500 billion ft^3 of methane in the virgin coal.

Analysis of a number of gas samples collected from horizontal holes drilled from active faces into virgin coal (59) showed that their methane contents ranged from 84 to 96 percent (table 2).

TABLE 2. - Composition of gas from the Pittsburgh coalbed, percent

Gas	Sample 1	Sample 2	Sample 3	Sample 4
CH_4	88.91	95.86	93.85	84.4
C_2H_6	.04	1.08	.04	-
CO_2	10.97	2.54	4.75	14.75
O_2	.04	.06	.05	.02
N_2	.05	.46	1.20	.65

Although the total effect of the geology of a coalbed on its methane emission is still not completely understood, considerable progress has been made in identifying certain controlling factors. Kissell and Bielicki (64) have found that an unfractured "solid" block of coal has a very low permeability, in contrast to high permeability in the coalbed where fracturing is extensive. The density of the fractures and the permeability of the coalbed depend on the coal rank. The low-volatile coals tend to be the most highly fractured. In a given coalbed, fractures are not uniform in size or spacing. This could be due to such factors as the degree of folding and faulting, proximity to fold axes, and the thickness of overburden. The in situ fracture spacing calculated for the Pittsburgh coalbed is 8 cm, as compared with 4.5 cm for the Pocahontas No. 3 coalbed, although observed fracture spacings may vary widely from these calculations.

Permeability should be greatest in the face cleat direction. In one area of a mine operating in the Pittsburgh coalbed, the methane emission from the solid ribs was significantly higher than the emission from the working face. It was observed that the rib intersected the face cleats and that the working face was draining the less permeable butt cleats (64).

Measurements by Parsons and Dahl (82) of the lateral compressive stresses in strata adjacent to the Pittsburgh coalbed showed that the major lateral stress is in an east-west direction, nearly perpendicular to the butt cleat direction. They concluded that the butt cleats are squeezed more tightly, reducing the permeability even more.

These observations show the importance that cleat plays in determining "directional permeability." Any horizontal drilling in mines to degasify an area must take into account the preferred flow due to directional permeability. Bureau research has shown that a hole drilled into the coalbed perpendicular to the face cleat could yield from 2.5 to 10 times as much gas as a hole drilled perpendicular to the butt cleat. At the Federal No. 2 mine in Monongalia County, three holes were drilled perpendicular to the face cleat and a fourth was drilled parallel to it (fig. 22). The hole drilled parallel had the lowest gas pressure, whereas the holes drilled perpendicular to the face cleat maintained their sustained higher gas pressures even after producing gas for as much as 45 days. This difference in emission is undoubtedly due to the difference between the face cleats, which are much longer and more continuous fractures exposing larger surface areas, and the shorter butt cleats, which frequently terminate against the face cleat.

Other geologic factors also influence gas emission from the coalbed. The amount of overburden is known to be important, but no specific relationship can be established until more accurate gas emission data are available from operating mines. Greater overburden pressures that may tend to close fractures and reduce permeability may be compensated for by a greater gas content of the deeper coals.

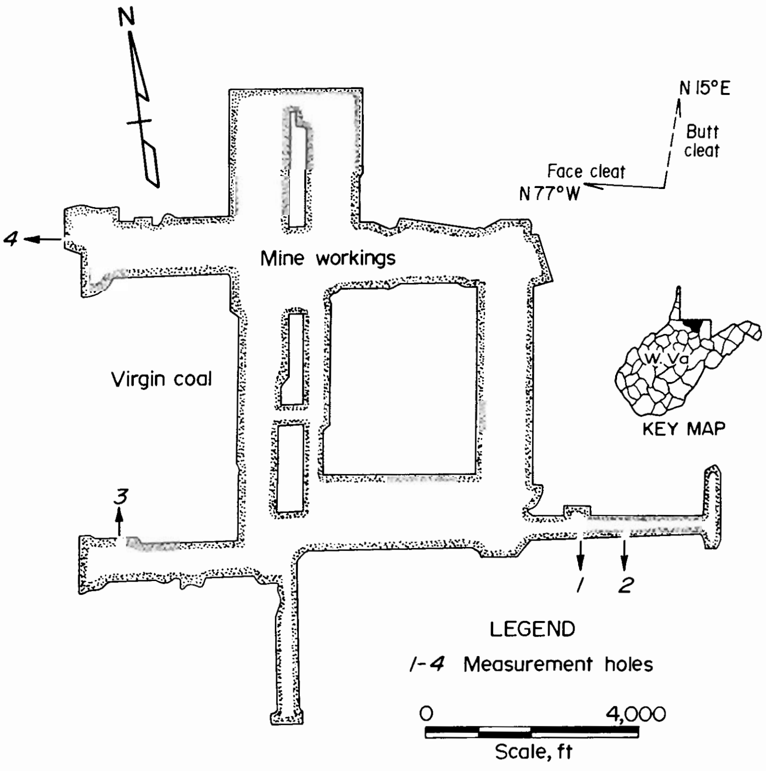


FIGURE 22. - Map of Federal No. 2 mine showing horizontally drilled holes and cleat directions.

Friability of the coal also affects methane emission. A core from the Beckley or Pocahontas No. 3 coalbed (both of which are friable), when allowed to degasify in a sealed container, gives off approximately 94 percent of its total gas content, whereas the same amount of Pittsburgh coal (which is blocky) under the same conditions gives off only 60 to 65 percent of its total gas. This also may be due to the closer cleat spacing in the

Beckley and Pocahontas No. 3 (1/4 inch) coalbeds, as compared with the Pittsburgh coalbed (1 inch).

Geologic structure can also affect gas emission through its effect on waterflow. Even a dip of less than 1° can decrease the flow of gas because any water in the coal must be displaced uphill before gas can flow freely.

Example of Geology-Related Problems in a Working Mine

Typical structure-related problems were studied at Somerset No. 60 mine (76), which was being developed down the northwest flank of the Amity anticline towards a syncline (fig. 23). Water has been accumulating at the face of entries being driven to the northwest, which dip into the working face. Once the axis of the syncline is crossed, the floor will dip away from the face, allowing the water to run off.

The N 62° W (face) and N 30° E (butt) cleat system is nearly orthogonal. The measured rock joint orientations are between N 57° W and N 75° W, corresponding roughly to the face cleat. Mining was originally parallel to the cleat orientations but at present is 45° to the previous working. According to the operators, this gives more stable ribs and roof.

The immediate roof is generally coal. A weak slickensided claystone, generally up to 12 inches thick and overlying the coal, is removed during mining, leaving the "stable" rider coal. Study of roof falls shows the weak strata to be either micaceous sandstone with thinly interbedded shale, or alternating coals and slickensided claystones.

In the western part of the mine workings there are sand channels that completely cut out the coal. To investigate roof conditions and the probability of sandstone channels in the area of future advancement adjacent to the active mine workings, a fence diagram (fig. 24) was constructed using data on the 40 feet of strata immediately above the Pittsburgh coalbed. The probability of the coal being cut out increases in areas where the rock type directly above the coal is predominantly sandstone and where the base of the sandstone approaches the top of the coal. Based on this consideration and on core data, a sandstone cutout probability map (fig. 25) was constructed.

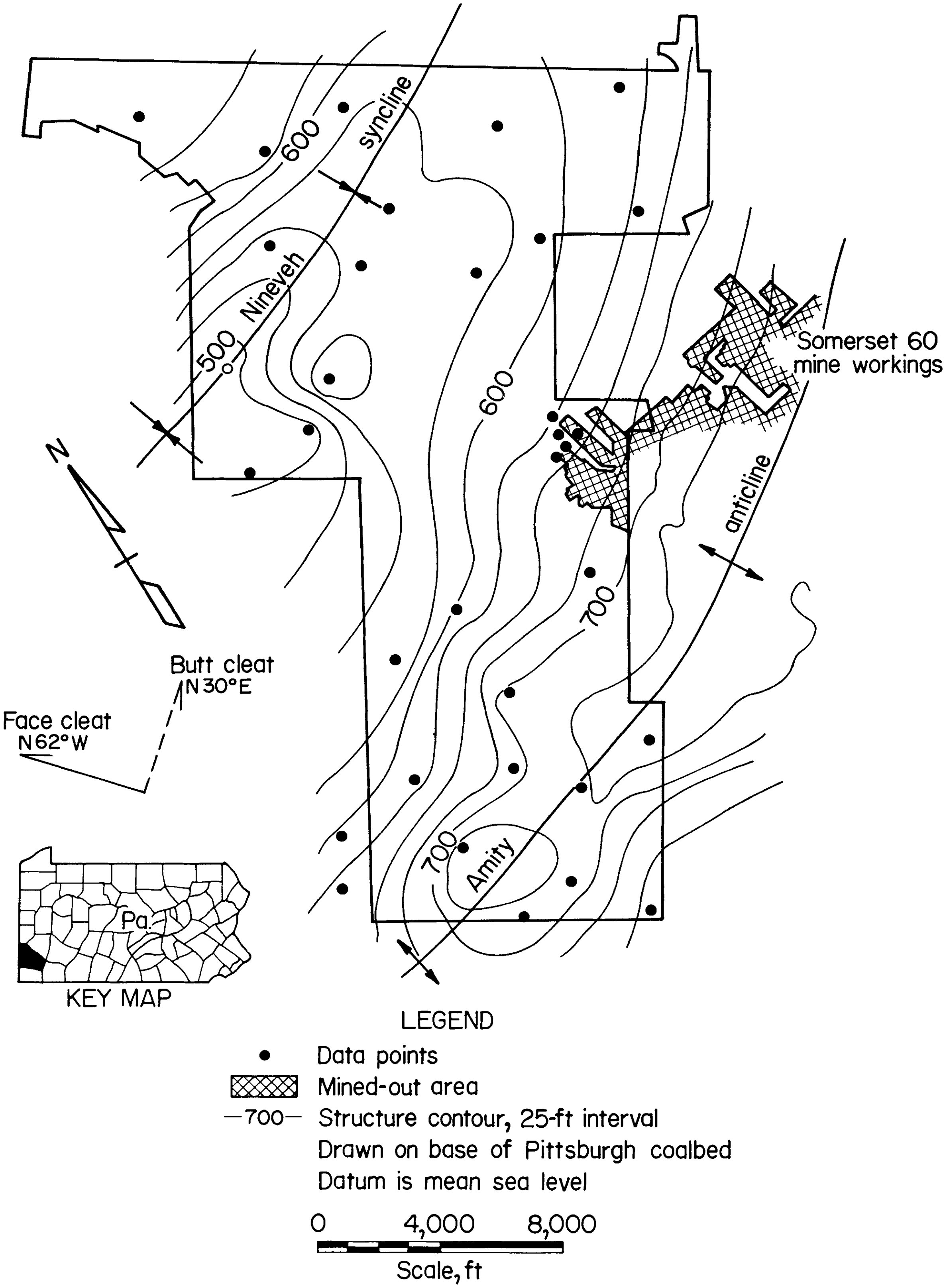


FIGURE 23. - Structure map drawn on the base of the Pittsburgh coalbed for the area adjacent to the active workings of the Somerset No. 60 mine.

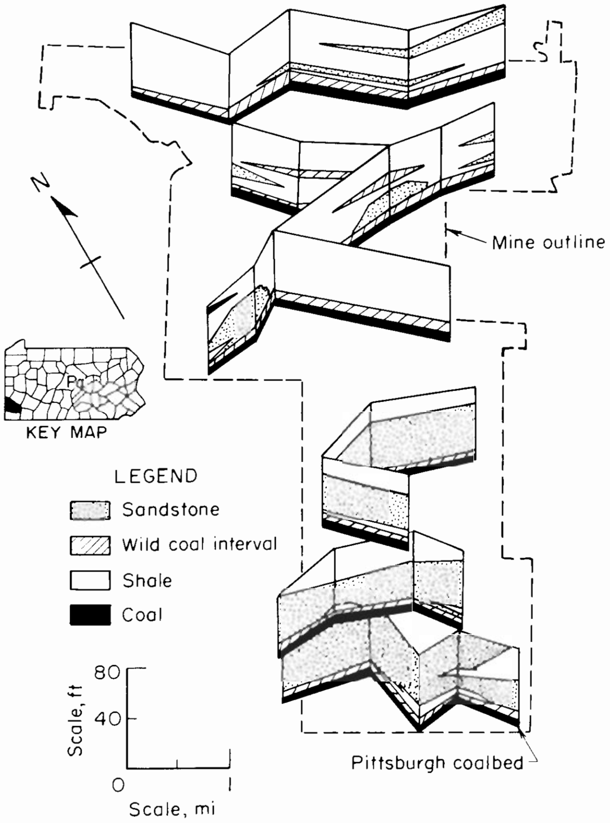


FIGURE 24. - Fence diagram of the strata directly above the Pittsburgh coalbed adjacent to the active workings of the Somerset No. 60 mine.

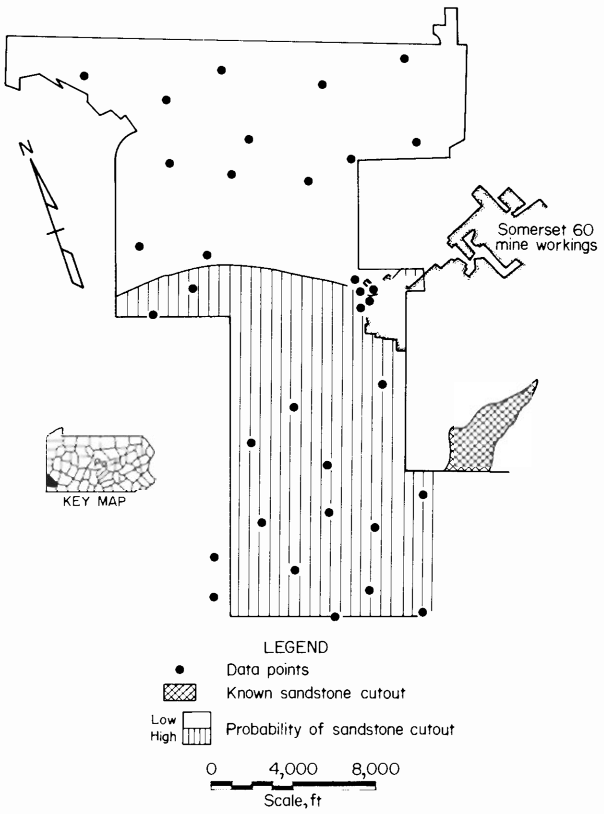


FIGURE 25. - Sandstone channel probability map of the area adjacent to the active workings of the Somerset No. 60 mine.

Zones of abrupt lithologic change often coincide with areas of unstable roof and high gas emission (53, 58, 75-76). The significant lithologic changes that can occur within a very short horizontal distance above the Pittsburgh coalbed are exemplified in figure 26 by two core holes (TH1 and TH2) 620 feet apart and on opposite sides of the boundary between the zones of low and high probability shown in figure 25. The rapid change in lithology is due to the removal of stream erosion of approximately 20 feet of original sediments at the location of the TH2 hole along a stream channel that was subsequently filled with sand. More core drilling in the area adjacent to the active workings of the Somerset No. 60 mine could provide additional data to substantially refine the prediction of specific problem areas. The practice of spacing core holes 3,000 feet or more apart makes correlations and predictions difficult, especially where there are rapid changes in lithology and sedimentation patterns.

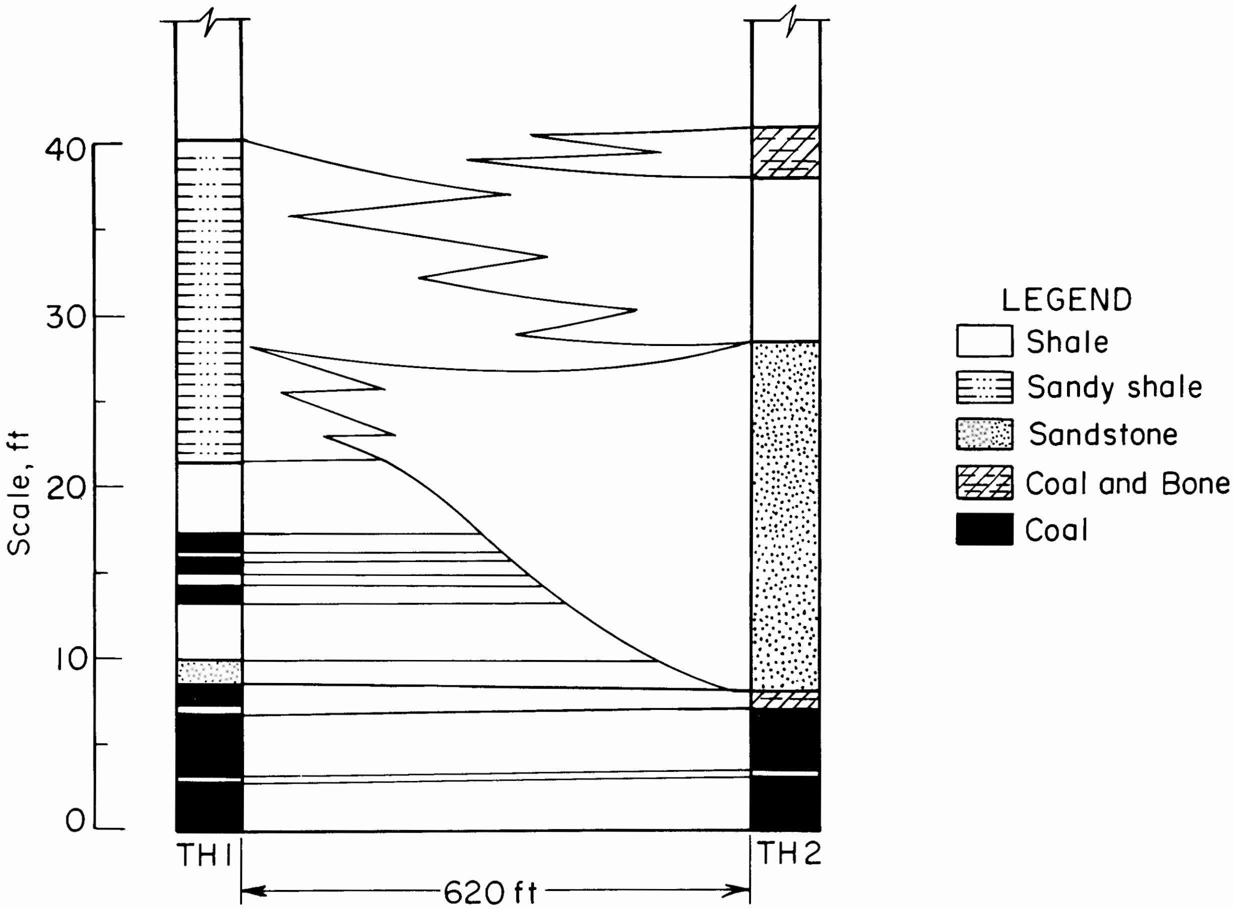


FIGURE 26. - Rapid lateral variation in the strata directly above the Pittsburgh coalbed.

Directly overlying the main bench (mined portion) of the Pittsburgh coalbed is an interval of variable thickness known as "draw slate" (fig. 27). This rock interval has very little strength and commonly fails, resulting in sudden gas emissions and rock haulage problems. Most miners prefer to anchor roof bolts in the more competent rock above the draw slate. The minimum bolt length that would be necessary to anchor into competent rock above the "draw slate" unit in any area can be determined from isopach maps like figure 27.

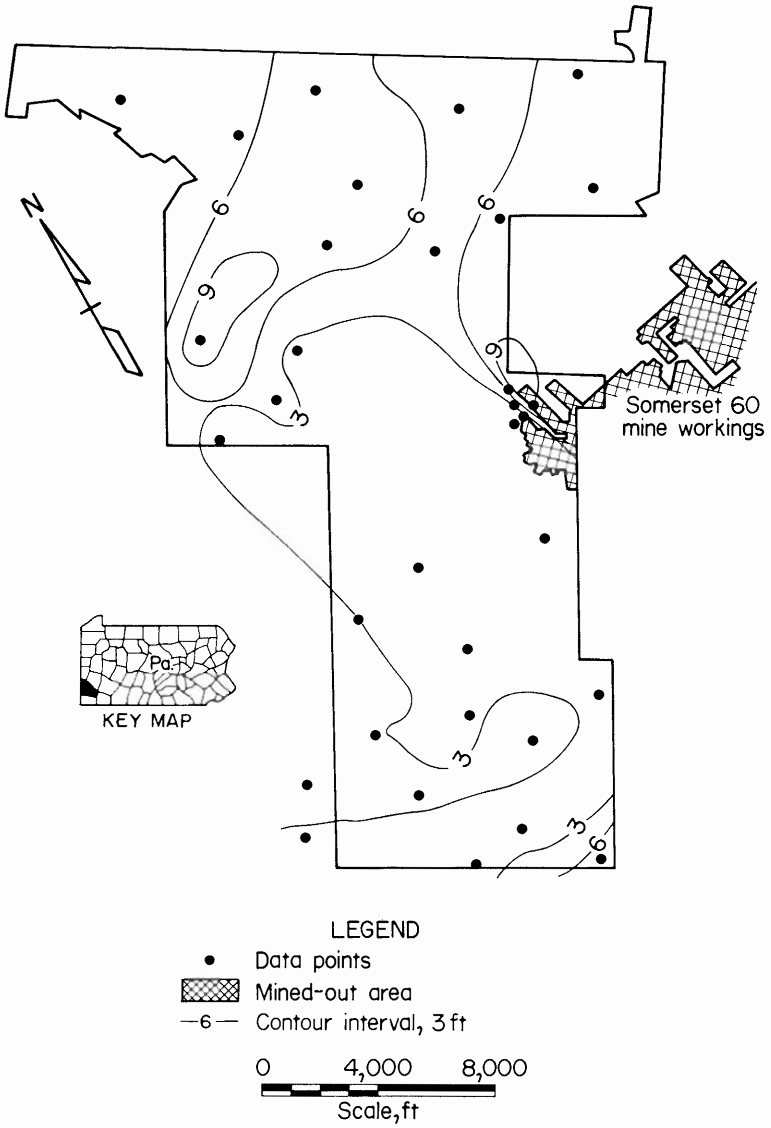


FIGURE 27. - Isopach of "draw slate" above the Pittsburgh coalbed in the area adjacent to the active workings of the Somerset No. 60 mine.

DETERMINATION AND ANALYSIS OF JOINTS AND PHOTOLINEARS

The frequency, character, and prominence of jointing in surface rock exposures vary greatly, depending on brittleness and on the susceptibility of each rock type to the compressional and tensional forces exerted on the earth's crust. According to Nickelsen and Hough (80), jointing due to increasing tectonic forces affects coal first, then shale and limestone, and lastly sandstone. This is evident from the relative spacing of joints in the various rock types. Coal cleats generally have the closest spacing, followed by shale, limestone, and then sandstone in which the joints are the most widely spaced and most prominent. Inspection of the joint measurements for each rock type gives an overall view of the principal trends.

Photolinears are zones of weakness that generally correlate with measured joint trends and may or may not be actual fractures observed in the field. In areas of heavy vegetation or few outcrops, or during periods of bad weather for fieldwork, photolinear analysis is an alternative to the measurement of surface joints.

The directional trends established by the various techniques indicate directions of inherent weakness in a coalbed and the rock surrounding it. An analysis of the fundamental directional systems in a virgin area prior to mine development can provide an estimate of the cleat system in a coalbed underground. This in turn determines the most efficient spacing of degasification holes for maximum gas flow, and to some extent, determines the most efficient mine development in directions that can minimize problems such as rib spalling and water and gas influx.

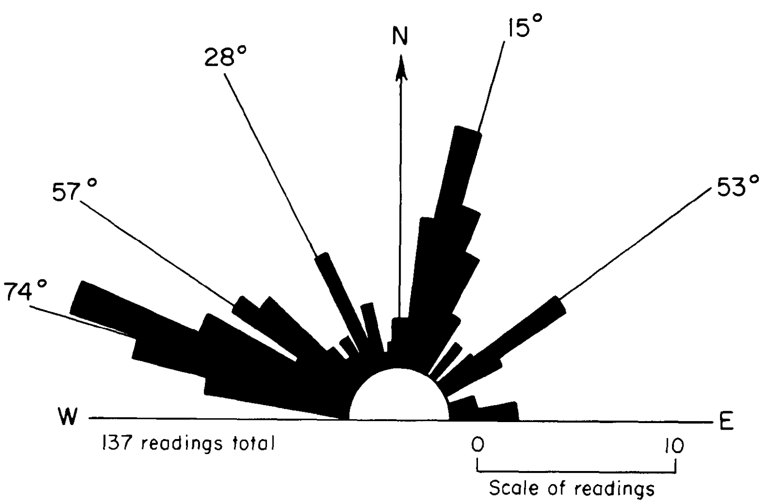


FIGURE 28. - Rose diagram of surface joint trends from the New Freeport quadrangle, Pennsylvania.

Coal is the rock type most susceptible to the tectonic forces that produce directional trends that reflect structural weakness. The face and butt cleats measured in coal underground are the direct result of these tectonic forces and are directly related to the regional structural trends. Because of the need to estimate the directional trend of cleat underground and the established relationship of cleat to structure, the cleat data are used as a standard against which to judge the reliability of data obtained by other methods.

Surface Joint Determination

Surface joints were measured over the thirty-nine 7-1/2-minute quadrangle study area in southwestern Pennsylvania and northern West Virginia. An average of 120 joint readings were taken per quadrangle with a minimum of 100 readings per quadrangle and no more than 10 readings at a single outcrop. Rock types and quality of joints were noted at each outcrop. The directions were read as azimuths using damped Brunton compasses corrected for magnetic declination. To evaluate the principal directional trends, the data from each quadrangle were plotted individually on rose diagrams (fig. 28). By plotting only the dominant trends from each individual quadrangle on a single rose plot, a composite rose diagram (fig. 29) of surface joint trends for the study area was constructed. Joint orientations by tier (fig. 30) and corresponding counties from north to south are given in table 3.

Surface Joint Analysis

It was determined from the data shown in figure 29 that there are three major directional trends to the west and four to the east (table 4). The number directly above the directional trends in table 4 gives the order of dominance within the group, based on the number of readings comprising the peaks on figure 29. The assigning of the same order of dominance to two readings in the same group indicates equally strong directional trends.

TABLE 3. - Average surface joint orientations, by county

Tier	County	1	2	3	4	5	6	7	8	9
					WEST					
1, 2, 3	Washington..........	N 6° W	N 21° W	N 33° W	-	N 49° W	N 57° W	N 73° W	-	N 85° W
4, 5	Greene..............	-	N 19° W	N 28° W	N 40° W	-	N 58° W	N 75° W	N 81° W	-
6	Wetzel and Monongalia	-	-	-	-	N 51° W	-	N 67° W	N 80° W	N 87° W
7	Marion and Monongalia	N 5° W	N 20° W	-	-	N 51° W	-	N 68° W	N 81° W	-
8	Marion and Harrison..	N 7° W	-	N 35° W	-	N 51° W	N 61° W	-	N 80° W	N 89° W
					EAST					
1, 2, 3	Washington..........	N 7° E	-	N 19° E	N 29° E	N 37° E	N 46° E	N 63° E	N 72° E	N 89° E
4, 5	Greene..............	N 2° E	N 14° E	N 22° E	N 28° E	N 38° E	N 49° E	-	-	N 80° E
6	Wetzel and Monongalia	N 5° E	N 13° E	-	N 27° E	-	N 53° E	-	N 72° E	-
7	Marion and Monongalia	N 2° E	N 15° E	-	N 25° E	N 37° E	-	-	N 68° E	N 86° E
8	Marion and Harrison..	N 5° E	N 14° E	-	N 27° E	N 39° E	-	N 59° E	N 72° E	N 83° E

NOTE.--Numbered trends are arranged within the 2 directional groups (east and west) by increasing divergence from north and not by their order of dominance. Trends within the same vertical column of a group are assumed correlative. Directional data from the individual quadrangles are tabulated in appendix B.

TABLE 4. - Principal surface joint trends in order of dominance

West		East			
I	III	I	II	III	IV
N 57° W	N 34° W	N 15° E	N 27° E	N 37° E	N 47° E
N 76° W	-	-	-	-	-

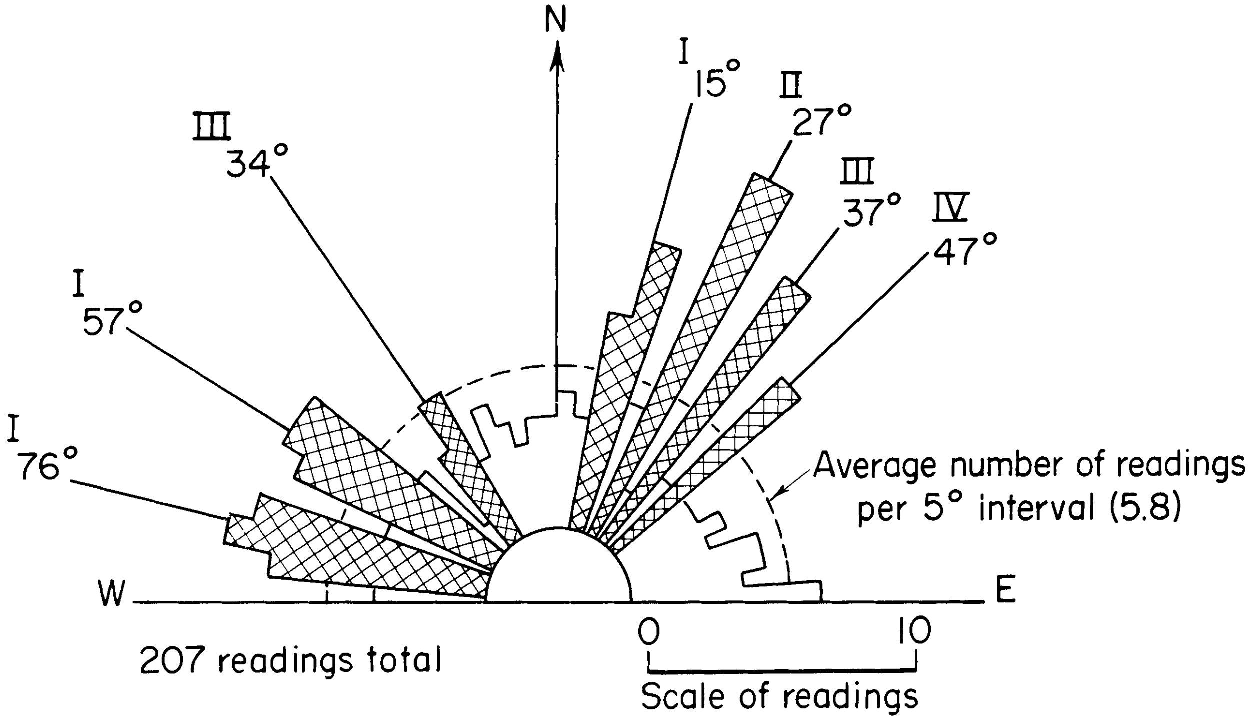


FIGURE 29. - Composite rose diagram of principal surface joint trends.

The principal directional trends listed in table 4 can be paired to form six fundamental joint systems:

1. *N 57° W^{I} and N 27° E^{II} with an 84° separation.
2. *N 57° W^{I} and N 15° E^{I} with a 72° separation.
3. *N 57° W^{I} and N 37° E^{III} with a 94° separation.
4. *N 76° W^{I} and N 15° E^{I} with a 91° separation.
5. *N 76° W^{I} and N 27° E^{II} with a 103° separation.
6. *N 34° W^{III} and N 47° E^{IV} with an 81° separation.

The superscripts in Roman numerals indicate the order of dominance, and the asterisks indicate the most dominant trend of each system. Two surface joint systems (Nos. 2 and 4) are composed of joint sets of the first order of dominance. Both systems are composed of the N 15° E^{I} set. System 4, with a 91° separation, more closely approaches the ideal fundamental system's 90° separation than does system 2 with a 72° separation. System 4 (*N 76° W^{I} - N 15° E^{I}) is quite similar in orientation to the *N 76° W^{I} - N 17° E^{I} cleat system established underground. The *N 76° W^{I} set of system 4 is the most dominant set of system 4 and parallels the face cleat. The N 76° W^{I} set could also be paired with the N 27° E^{II} set (system 5), but the separation of 103°

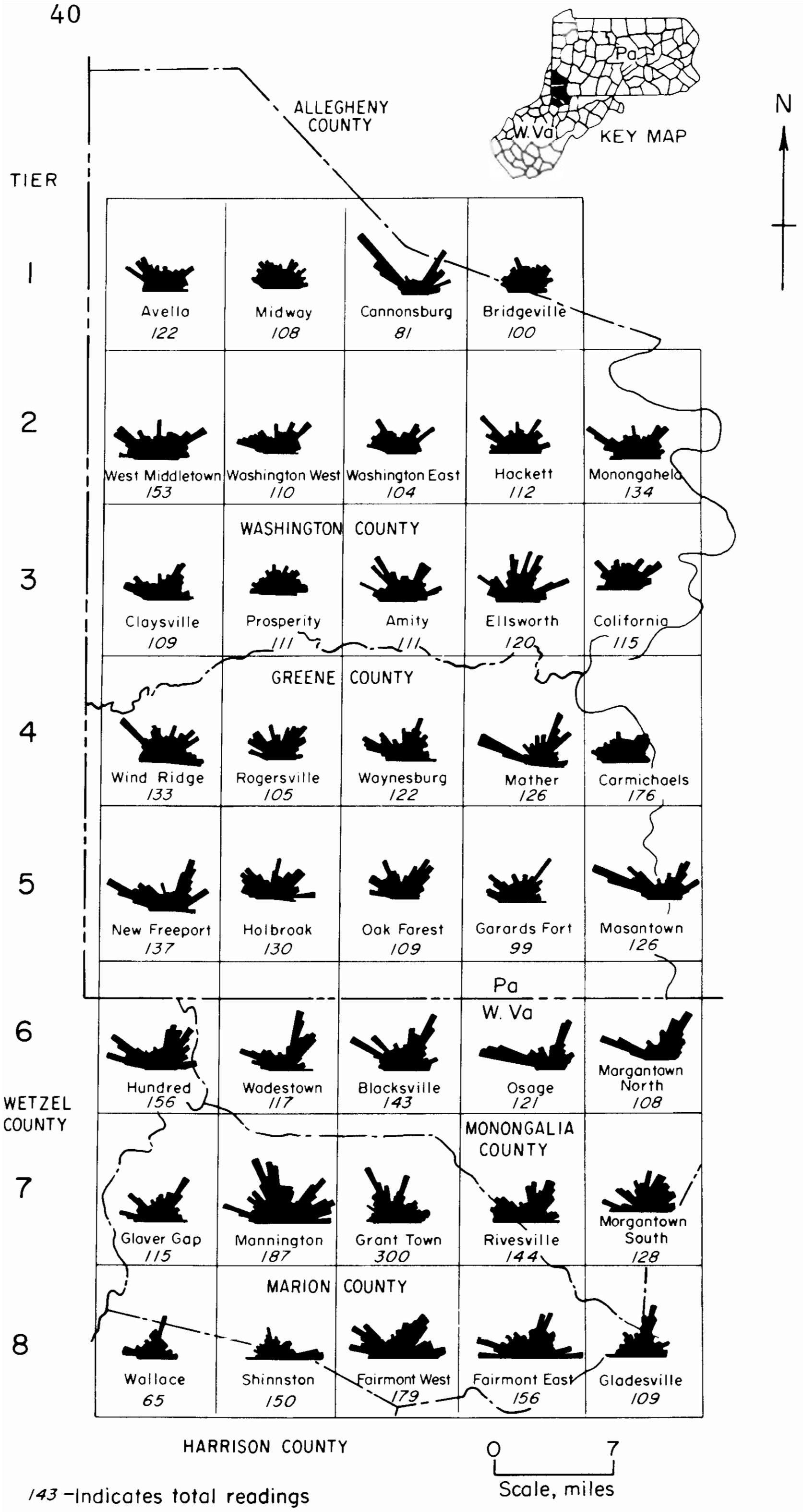
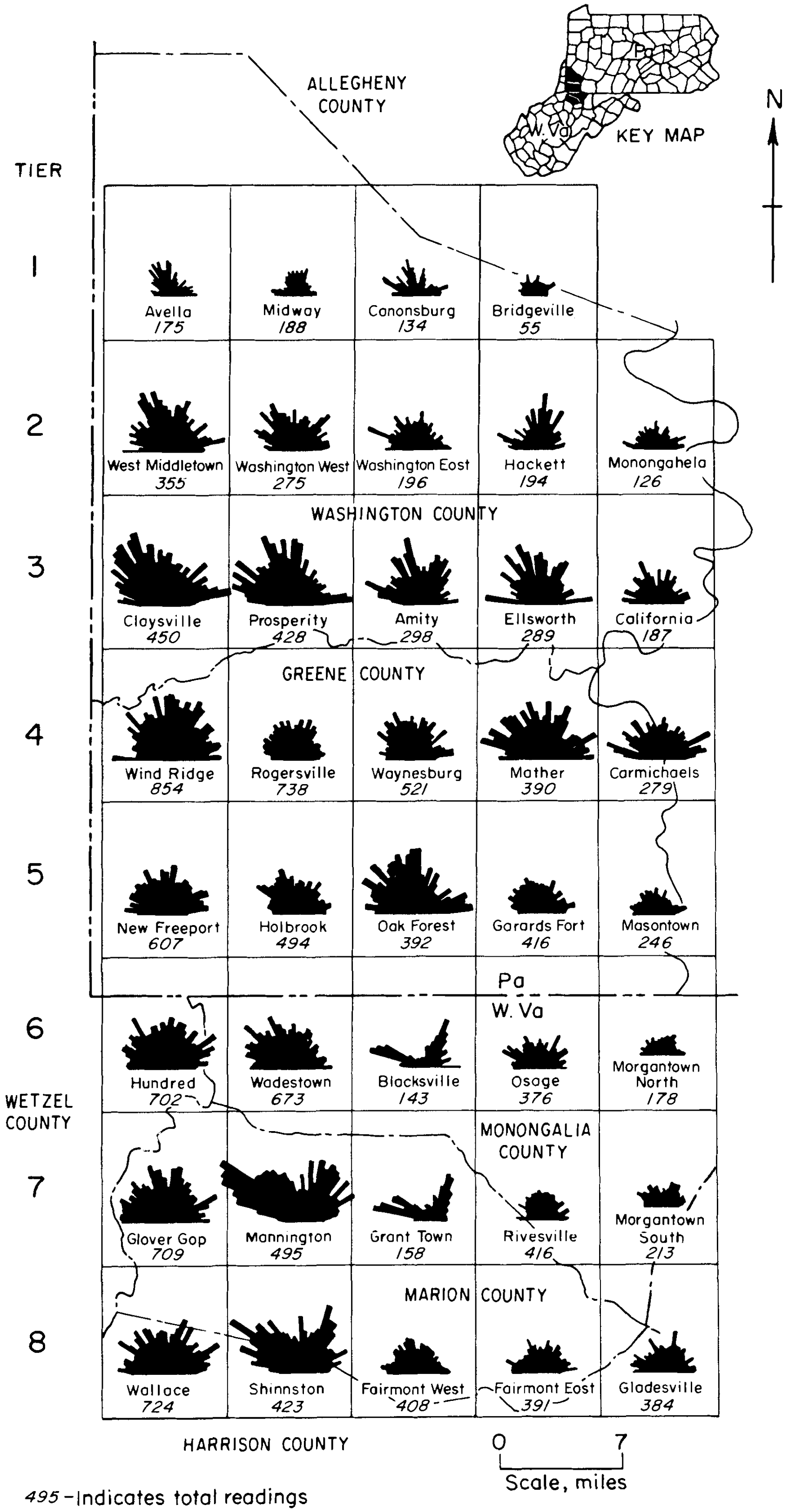


FIGURE 30. - Rose diagrams of surface joints for 39 quadrangles.

is greater and the N 27° E^{II} set is less dominant than the N 15° E^{I} set.

The N 57° W^{I} set, if not paired with N 15° E^{I}, can be paired with N 27° E^{II} (system 1) for an 84° separation or with N 37° E^{III} (system 3) for a 94° separation. System 1 (*N 57° W^{I} - N 27° E^{II}) is reasonably similar to the *N 67° W^{I} - N 28° E^{I} cleat system established underground. System 3 (*N 57° W^{I} - N 37° E^{III}), while not substantially dissimilar from the *N 67° W^{I} - N 28° E^{I} cleat system, is, however, composed of one set of the third order of dominance. The *N 57° W^{I} set of systems 1 and 3 is the most dominant set of the systems and is reasonably similar to the face cleat orientation.

The most dominant eastern components (N 15° E^{I} and N 27° E^{II}) closely parallel the strike of the major structural axes of the area, and the western trend is nearly perpendicular to the axes. Therefore, the systems are probably directly related to the regional structural deformation. The sixth surface joint system (*N 34° W^{III} - N 47° E^{IV}) may also be related to the regional structure, although it is composed of sets of the third and fourth order of dominance and not oriented parallel to the cleat directions. This system is oriented at approximately 45° to the *N 76° W^{I} - N 15° E^{I} system, which is within the theoretical angle of shears to the dominant trends.



495 – Indicates total readings

FIGURE 31. - Rose diagram of photolinears for 39 quadrangles.

Additional evidence for the correlation of jointing with regional structure is the clockwise rotation of the joint trends in the study area; this is also observed for the trends of the major structural axes. The rose diagrams of the joint measurements from the individual quadrangles assembled in figure 30 illustrate the shift of the joint trends throughout the area.

Photolinear Interpretation From Infrared Photographs

Aerial photographs covering the 39 quadrangles of the study area were examined stereoscopically for photolinears. Photolinears are combinations of a great number of individual surface fractures that form distinctive alinements discernible on the photographs. They are zones of weakness that generally correlate with measured joint trends. An excellent photolinear study of a small portion of the study area was done by Hough (48) in 1960.

In theory, photolinears that are a direct result of fracturing can be recognized as straight lines separating areas of tonal differences in open ground, linear topographic depressions, alinements of vegetation or taller than average trees, and shadow lines from cliff edges. In practice, farming, mining, and other manmade changes obscure most features that otherwise would be observable. Therefore the interpretation of photolinears depends largely on straight segments of valleys and stream courses and on abrupt right-angle turns in streams and rivers.

Photolinear Analysis

The data from the infrared photographs were used to prepare rose diagrams for each of the 39 quadrangles (fig. 31). The dominant photolinear directions for each quadrangle were determined from the rose diagrams (appendix C) and plotted on a single composite rose diagram (fig. 32). Directional data by tier and corresponding counties from north to south are given in table 5.

Figure 32 shows five principal photolinear trends to the west and three to the east. Their order of dominance is given in table 6.

The individual photolinear trends can be paired into six fundamental photolinear systems, with an asterisk indicating the dominant trend of each system:

1. *N 65° W^{I} and N 20° E^{I} with an 85° separation.
2. N 79° W^{III} and *N 20° E^{I} with a 99° separation.
3. N 79° W^{III} and *N 1° E^{II} with an 80° separation.
4. N 40° W^{III} and *N 20° E^{I} with a 60° separation.
5. *N 25° W^{II} and N 75° E^{III} with a 100° separation.
6. N 13° W^{V} and *N 75° E^{III} with an 88° separation.

TABLE 5. - Average photolinear orientations, by county

Tier	County	1	2	3	4	5	6	7	8
				WEST					
1, 2, 3	Washington...........	N 3° W	N 12° W	N 21° W	N 30° W	N 39° W	N 52° W	N 66° W	N 85° W
4, 5	Greene................	N 3° W	N 14° W	N 24° W	-	N 41° W	N 54° W	N 65° W	N 76° W
6	Wetzel and Monongalia.	N 4° W	-	N 18° W	N 29° W	N 44° W	N 51° W	N 65° W	N 74° W
7	Marion and Monongalia.	N 4° W	N 11° W	-	N 30° W	N 43° W	-	N 61° W	N 80° W
8	Marion and Harrison...	N 3° W	N 13° W	N 23° W	N 35° W	N 43° W	N 52° W	N 69° W	N 79° W
				EAST					
1, 2, 3	Washington...........	N 4° E	N 13° E	N 19° E	N 37° E	N 51° E	N 63° E	N 78° E	-
4, 5	Greene................	N 5° E	-	N 20° E	N 31° E	N 44° E	N 62° E	N 75° E	N 89° E
6	Wetzel and Monongalia.	N 2° E	N 15° E	N 24° E	N 32° E	N 54° E	-	N 72° E	N 88° E
7	Marion and Monongalia.	N 3° E	N 15° E	N 25° E	N 37° E	-	-	N 69° E	-
8	Marion and Harrison...	-	N 16° E	N 24° E	N 38° E	N 50° E	N 63° E	-	N 84° E

NOTE.--Numbered trends are arranged within the 2 directional groups (east and west) by increasing divergence from north and not by their order of dominance. Trends within the same vertical column of a group are assumed correlative.

TABLE 6. - Principal photolinear trends in order of dominance

West				East		
I	II	III	V	I	II	III
-	-	N 79° W	-	-	-	-
N 65° W	N 25° W	N 40° W	N 13° W	N 20° E	N 1° E	N 75° E

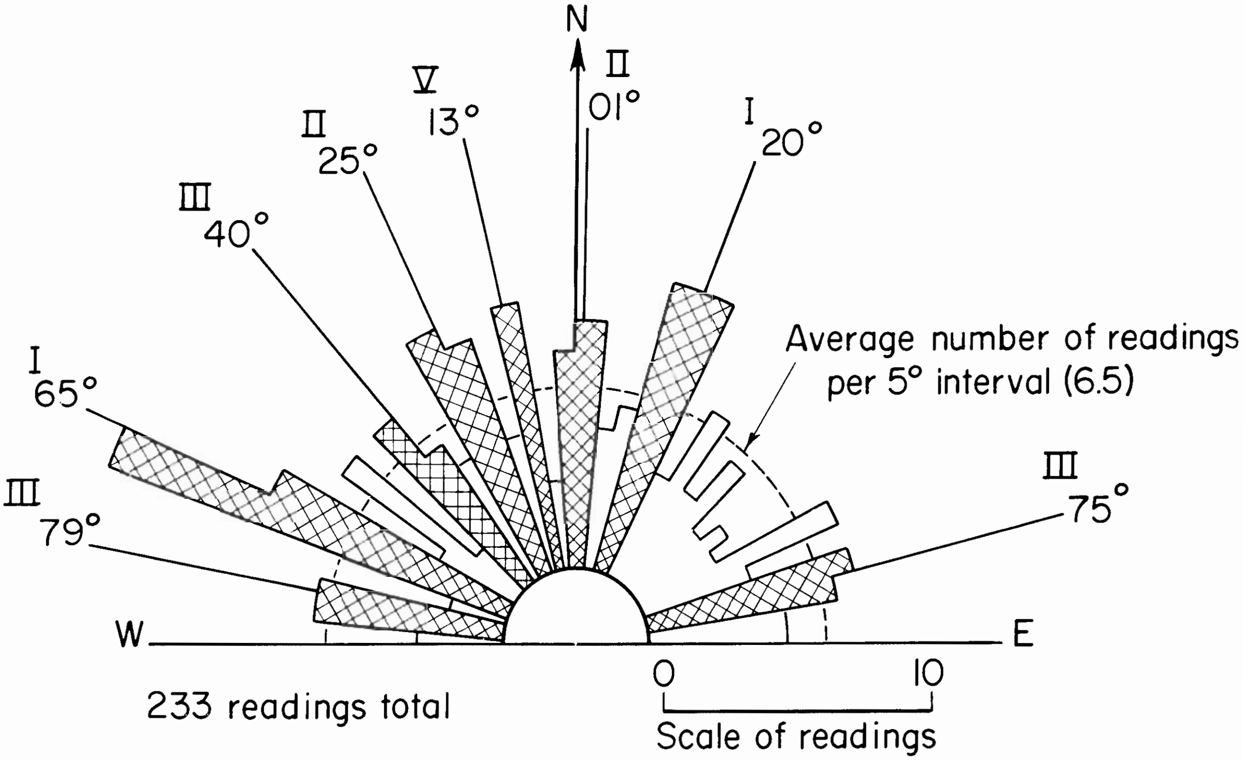


FIGURE 32. - Composite rose diagram of principal photolinear trends for entire area.

The first infrared photolinear system (*N 65° W' - N 20° E') is composed of the most dominant westerly set and the most dominant easterly set. This system best estimates the established *N 67° W' - N 28° E' coal cleat system. The *N 65° W' set is the most dominant of the system and it nearly parallels the face cleat. The N 20° E' set, if not paired with N 65° W', could be paired with an N 79° W''' (system 2) which is similar to the *N 76° W' - N 17° E' cleat system. Photolinear system 2, however, contains one set of the third order and has a larger divergence from 90° than system 1. The N 79° W''' set can also be paired with N 1° E'' (system 3) for an 80° separation. This system, while having one set (*N 1° E'') which diverges 16° from the butt cleat of the *N 76° W' - N 17° E' cleat system, has one set (N 79° W''') which diverges only 3° from the face cleat. System 3, however, is composed of one set of third order dominance, and more significantly, the most dominant set of the system (*N 1° E'') is in the butt cleat direction. The fourth, fifth, and sixth photolinear systems are each composed of one component of third or lower order of dominance and have no similarity to the established cleat systems.

Ronchi Inspection of Photoindex Sheets and Analysis of Trends

Thirteen photoindex sheets covering the study area were inspected for photolinears using a Ronchi-type defraction grating. The scale of the index sheets is 1 inch to 1 mile; hence only general trends can be differentiated, not specific linears. This method was investigated to determine its reliability as a relatively inexpensive, rapid reconnaissance procedure for delineating structural weakness.

Principal directional trends as interpreted from the 13 individual index sheets of the area were plotted on a composite rose diagram (fig. 33). The individual trends established for each of the 13 sheets are presented in appendix D. Directional data by county from north to south are given in table 7.

TABLE 7. - Average photoindex sheet linear orientations, by county

County	1	2	3	4
		WEST		
Washington............	N 10° W	N 24° W	N 45° W	N 70° W
Greene................	N 8° W	N 23° W	N 42° W	N 69° W
Monongalia............	N 8° W	N 22° W	N 43° W	N 70° W
Marion................	N 8° W	N 24° W	N 43° W	N 73° W
		EAST		
Washington............	N 19° E	N 30° E	N 51° E	N 73° E
Greene................	N 11° E	N 25° E	N 56° E	N 79° E
Monongalia............	N 8° E	N 23° E	N 58° E	N 80° E
Marion................	N 6° E	N 20° E	N 58° E	N 78° E

NOTE.--Numbered trends are arranged within the 2 directional groups (east and west) by increasing divergence from north, not by order of dominance. Trends within the same vertical column of a group are assumed to be correlative.

The rose diagram (fig. 33) shows four directional trends to the west and four to the east. Although the order of dominance of the directional trends does not stand out clearly in figure 33, it was established (table 8) for the data based on the strength of the image of the directional trends viewed through the Ronchi grating.

TABLE 8. - Principal photoindex trends in order of dominance

West				East			
I	II	III	IV	I	II	III	IV
N 70° W	N 44° W	N 23° W	N 9° W	N 27° E	N 77° E	N 12° E	N 55° E

The principal directional trends delineated by the Ronchi grating can be paired into five fundamental systems, with the superscripts again indicating the order of dominance and an asterisk the most dominant trend of each system.

1. *N 70° W^{I} and N 27° E^{I} with a 97° separation.

2. *N 70° W^{I} and N 12° E^{III} with an 82° separation.

3. N 23° W^{III} and *N 77° E^{II} with a 100° separation.

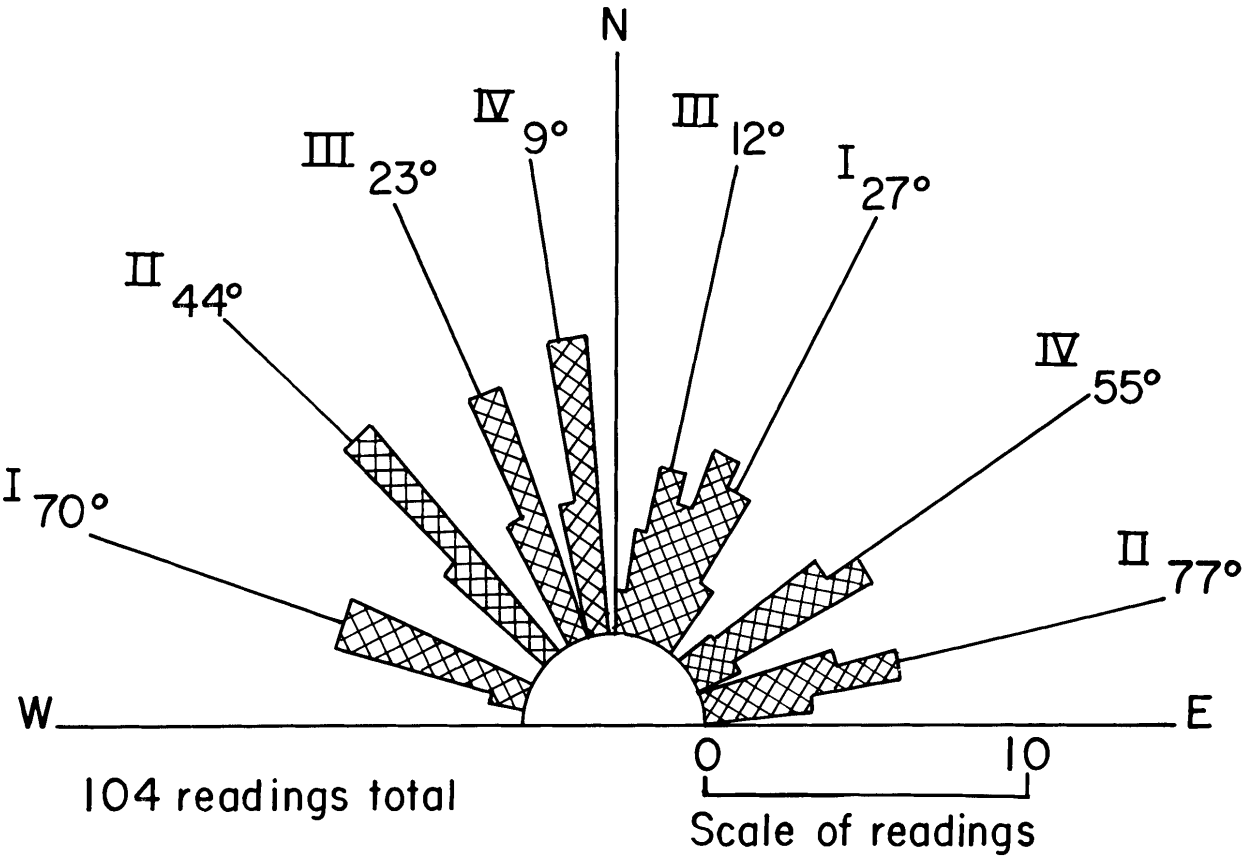


FIGURE 33. - Composite rose diagram of principal Ronchi trends for entire area.

4. *N 44° W^{II} and N 55° E^{IV} with a 99° separation.

5. N 9° W^{IV} and *N 77° E^{II} with an 86° separation.

The pairing of the most dominant westerly trend, *N 70° W^{I} with either N 27° E^{I}, the most dominant easterly trend, or N 12° E^{III} closely approximates the dominant trend of structural weakness as previously indicated from the analysis of cleat, surface joint, and photolinear orientations. The *N 70° W^{I} is the most dominant trend of the first system and correlates with the face cleat. The components of the less dominant systems 3, 4, and 5 appear to be related to shears to the principal directional trends.

A rotation of directional trends, similar to that observed for the cleat and surface joint trends, is apparent in a portion of the Ronchi derived data. The two trends at N 27° E^{I} and N 12° E^{III} on the composite rose diagram (fig. 33) appear to be parts of a weak bimodal peak. A review of the actual data for these two trends (appendix D, Nos. 1 and 3 east) shows that they are indeed two distinct trends with an easterly shift of the county directional means of 10° and 13°, respectively, from south to north.

Criteria for Cleat Estimation

The analysis of directional data yielded trends that could be paired into various combinations of fundamental systems (table 9). Two surface joint systems (1 and 4) correlated best with the established cleat systems. These two systems are composed of trends of the first and second order of dominance. Systems 2, 3, and 5 are composed of sets already paired in systems 1 and 4, and system 6 is composed of trends of third and fourth orders of dominance and is not similar to the cleat orientations. One infrared photolinear system (1) correlated with a cleat system and was composed of trends of the first order of dominance. An additional system (3) was reasonably correlative with the remaining cleat system, but was composed of second- and third-order trends. The second photolinear system is composed of trends already used in systems 1 and 3. Systems 4-6 are not correlative with a cleat system and are composed of at least one trend of third or lower order of dominance. One photoindex photolinear system (1) correlated with a cleat system and was composed of trends of the first order of dominance. Even though system 2 would correlate with a cleat system, it is composed of one trend already used in system 1 and one trend of the third order of dominance. Systems 3-5 are not correlative with a cleat system and are composed of at least one trend of third or lower order of dominance. In each case where a directional data system correlated with a cleat system and was composed of trends of the first or second order of dominance, the most dominant trend correlated with the face cleat.

TABLE 9. - Fundamental systems from directional data

Data source	System No.	System		Degrees of separation
Cleat	1	*N 67° W^{I}	N 28° E^{I}	95
	2	*N 76° W^{I}	N 17° E^{I}	93
Surface joints	1	*N 57° W^{I}	N 27° E^{II}	84
	2	*N 57° W^{I}	N 15° E^{I}	72
	3	*N 57° W^{I}	N 37° E^{III}	94
	4	*N 76° W^{I}	N 15° E^{I}	91
	5	*N 76° W^{I}	N 27° E^{II}	103
	6	*N 34° W^{III}	N 47° E^{IV}	81
Photolinears (infrared photographs).	1	*N 65° W^{I}	N 20° E^{I}	85
	2	N 79° W^{III}	*N 20° E^{I}	99
	3	N 79° W^{III}	*N 1° E^{II}	80
	4	N 40° W^{III}	*N 20° E^{I}	60
	5	*N 25° W^{II}	N 75° E^{III}	100
	6	N 13° W^{V}	*N 75° E^{III}	88
Photolinears (photoindex sheets)	1	*N 70° W^{I}	N 27° E^{I}	97
	2	*N 70° W^{I}	N 12° E^{III}	82
	3	N 23° W^{III}	*N 77° E^{II}	100
	4	*N 44° W^{II}	N 55° E^{IV}	99
	5	N 9° W^{IV}	*N 77° E^{II}	86

NOTE.--Superscripts indicate the order of dominance within the directional group (east or west) for each data source, and an asterisk indicates the dominant trend of each system.

The procedure proposed for the estimation of cleat orientation is based on the results of the directional data analysis summarized above. The pairing of the established sets into all reasonable combinations of fundamental systems is of primary importance in analysis of each type of directional data. Which system or systems are to be used to estimate the cleat orientation is based on the relative dominance of the sets of each system as determined by the number of readings comprising the corresponding peaks on rose diagrams. A system composed of the most dominant set and a perpendicular set of the first or second order of dominance will most likely give the best estimation of cleat orientation. The most dominant set of the selected system is most likely the face cleat direction.

Cleat systems of similar, but different orientation may be present. Here, two regional fundamental joint systems were in fact composed of sets of the required orders of dominance, and correlated with the observed cleat systems. In the analysis of linears from infrared photographs and linears on photoindex sheets, one system satisfied the dominancy requirements and was correlative with one cleat system, and other systems were reasonably correlative with the remaining cleat system. But these other systems would be rejected because one component lacks the necessary relative dominance. The rejection of an estimator for the second cleat system is not detrimental as the two cleat systems are separated by only about 10°. In all cases the directional systems not correlative with established cleat systems were rejected because they did not meet the dominance requirements.

Relationship of Cleat to Surface Joints and Photolinears Overlying Individual Mines

The relationship between coal cleats measured in individual mines and the directional trends established by measuring joints and photolinears directly overlying the mines was investigated utilizing the criteria established in the regional analysis. The most dominant directional systems measured with the degrees of deviation from the cleat directions are listed in table 10. An asterisk indicates the most dominant trend of each system. As with the regional data, surface joints provided the best estimation of cleat orientation. The most dominant surface joint system averaged within ±7.4° of the face cleat and ±6.6° of the butt cleat. It was possible to correctly predict the face cleat direction for 14 of the 18 mines using the surface joint data. The photolinear data were considerably less reliable, with averages of ±23.7° for the face cleat and ±19.4° for the butt cleat. The face cleat direction was correctly predicted in only 7 of the 18 mines.

The high degree of divergence observed for the photolinear analysis is primarily the result of a dominant westerly photolinear trend in the vicinity of N 15°-30° W. This is similar to the second most dominant *N 25° W'' trend observed on the photolinear composite rose diagram (fig. 32), and the N 34° W''' trend on the surface joint composite rose diagram (fig. 31). In several cases the second most dominant local photolinear system above the mine had an orientation similar to that of the cleat.

TABLE 10. - Coal cleat, dominant surface joint, and photolinear orientations of the study area

No.	Mine	Face cleat	Butt cleat	Surface joints		Degrees of divergence		Photolinears		Degrees of divergence	
						West	East			West	East
1	Montour 4..............	*N 65° W	N 25° E	N 55° W	*N 37° E	10	12	Insufficient data		-	-
2	Mathies................	*N 65° W	N 27° E	*N 60° W	N 27° E	5	0	*N 66° W	N 17° E	1	10
3	Westland...............	*N 70° W	N 25° E	*N 73° W	N 23° E	3	2	Indeterminate		-	-
4	Somerset No. 60........	*N 62° W	N 30° E	*N 65° W	N 27° E	3	3	N 6° W	N 82° E	56	52
5	Vesta No. 5............	*N 66° W	N 30° E	*N 76° W	N 14° E	10	16	N 53° W	*N 27° E	13	3
6	Marianna No. 58........	*N 68° W	N 28° E	*N 72° W	N 12° E	4	16	N 70° W	*N 22° E	2	6
7	Gateway................	*N 68° W	N 28° E	*N 78° W	N 13° E	10	15	N 18° W	N 75° E	50	47
8	Shannopin..............	*N 73° W	N 18° E	*N 80° W	N 23° E	7	5	N 26° W	N 71° E	47	53
9	Humphrey No. 7.........	*N 70° W	N 27° E	*N 80° W	N 20° E	10	7	N 27° W	N 55° E	43	28
10	Pursglove No. 15.......	*N 72° W	N 19° E	*N 78° W	N 17° E	6	2	N 28° W	N 54° E	44	35
11	Blacksville No. 1......	*N 75° W	N 20° E	*N 66° W	N 27° E	9	7	*N 68° W	N 24° E	7	4
12	Blacksville No. 2......	*N 77° W	N 17° E	N 65° W	*N 13° E	12	4	*N 66° W	N 17° E	11	0
13	Osage No. 3............	*N 75° W	N 17° E	N 82° W	N 17° E	7	0	N 51° W	N 34° E	24	19
14	Arkwright..............	*N 79° W	N 12° E	*N 76° W	N 19° E	3	7	N 59° W	*N 27° E	20	15
15	Federal No. 2..........	*N 77° W	N 17° E	*N 68° W	N 28° E	9	11	*N 66° W	N 25° E	11	8
16	Consol No. 93..........	*N 73° W	N 18° E	N 80° W	*N 17° E	7	1	*N 75° W	N 21° E	2	3
17	Loveridge..............	*N 80° W	N 15° E	*N 75° W	N 17° E	5	2	*N 57° W	N 22° E	23	7
18	Consol No. 20..........	*N 78° W	N 12° E	*N 91° W	N 3° E	13	9	*N 53° W	N 32° E	25	20
-	Average divergence.....	-	-	-	-	7.4	6.6	-	-	23.7	19.4

Analysis of directional data for a limited area is hampered by problems not normally encountered in a regional approach. Surface joint measurements are limited by the number and location of outcrops in the area of interest and at times by weather conditions. As outcrops become less numerous and farther from the area, the validity of the analysis decreases. Under these conditions, photointerpretation would perhaps be of benefit since it does not rely on outcrops for data, nor does it depend on the weather. However, photoanalysis, which depends on the availability of quality photographs and an experienced photointerpreter, is significantly less reliable than field measurements of joints. Both methods are limited by the small number of directional measurements usually obtainable for a small area. The fewer the data, the less likely are individual trends to stand out clearly, and this makes analysis difficult.

Summary of Directional Data Analysis

The estimation of regional underground cleat systems in coal by surface joint and photolinear analysis and Ronchi inspection is reliable within the established limits. The confidence level is least for Ronchi inspection results because the order of dominance of Ronchi trends is based largely on a visual impression of image "strength." Surface joint analysis is the only technique considered sufficiently reliable to be used on a local basis.

RELATIVE COSTS OF CLEAT ESTIMATION BY THE THREE METHODS OF ANALYSIS OF SURFACE DIRECTIONAL DATA

The relative costs and time requirements for the three analytical procedures are discussed below.

Field Mapping

The mapping of surface joints requires approximately 2 days of fieldwork per 7-1/2-minute quadrangle by an experienced two-man team. An additional day is required for tabulation and analysis of data. Salary or consulting fee and field expenses for such a two-man team would amount to approximately $650 per 7-1/2-minute quadrangle. An area of 39 quadrangles, like the one investigated in this report, would require 33 weeks to evaluate (table 11) for a total cost of $25,350.

TABLE 11. - Time and cost requirements for measuring joints and photolinears for the study area

Method	Cost	Time, weeks
Field measurement of surface joints...	$25,350	33
Measuring linears from infrared photographs..........................	25,460	39
Measuring linears from photoindex sheets............................	625	1

Infrared Photography Analysis

Interpretation of infrared photographs requires approximately 1 week per 7-1/2-minute quadrangle for delineation and analysis of directional trends. Cost in this case would include $110 for infrared photo coverage and the salary or consulting fee of an experienced photointerpreter and would total approximately $650 per quadrangle. Photolinear interpretation of a 39-quadrangle area would take 39 weeks and would cost $25,460.

Ronchi Inspection of Photolinear Sheets

As already noted, cleat estimation by Ronchi inspection of photoindex sheets is somewhat less reliable than the two other methods, but it is far less expensive and time consuming. The total cost per 7-1/2-minute quadrangle is about $15. This is essentially the salary or consulting fee of a geologist, since cost of the photoindex sheet coverage for the whole 39-quadrangle area was only $40. An 8-quadrangle area could be evaluated in 1 day and the entire 39 quadrangles in 1 week. Cost of the 1-week evaluation would be only $625.

Ronchi inspection is especially attractive because this rapid and inexpensive reconnaissance technique can provide a good initial estimate of the cleat underground for subsequent checking by one of the two other methods. In an area of unknown cleat orientation, a combination of two or perhaps all three of the methods would be advantageous in that it would greatly increase the confidence level of the results.

SUMMARY

The Pittsburgh coalbed is one of the largest potential fuel resources in the world with respect to total tonnage of coal and the associated gas reserves. To aid in the efficient utilization of this deposit, a study was made of the southwestern Pennsylvania and norther West Virginia area which it underlies. The primary objective was to identify geologic factors that interfere with efficient mining and especially those factors that influence gas migration in the coalbed.

For this purpose, a map was prepared of all known sandstone bodies that intersect the coalbed. A correlation was found between areas of thicker sandstone and the occurrence of sandstone channels cutting into the coal. Prediction of sandstone channel trends is commonly hindered by the lack of sufficient subsurface data. Core drilling on the usual mile centers may entirely miss some of the sinuous, narrow sandstone channels.

Clay veins were found and mapped in eight of the mines surveyed and tend to be clustered along the axes of synclines. Clay veins have been observed more frequently near channel sandstone bodies. Clay veins tend to intersect, forming boxlike cells that prevent gas migration. A hole drilled through two clay veins had pressures of 220 and 263 lb/in^2 on the virgin side and 0 lb/in^2 on the mined side (41). X-ray diffraction analysis of clay vein material and roof and floor rock indicates that in the mines investigated the clay material was injected after coalification from the roof and not from the floor.

An isopach map of the Pittsburgh coalbed was constructed from more than 3,000 data points. Wherever possible, strip mines were located and mapped. The coalbed thickness trends were oriented northeast to southwest, closely paralleling the regional structure. Areas of thick coal (8 feet plus) generally were located near synclinal troughs. Some areas of thin coal (less than 4 feet) were located near the axes of the anticlines. Several other areas of low or thin coal had a sinuous pattern, suggesting a possible relation to ancient stream systems.

A fence diagram was prepared of the strata above the Pittsburgh coalbed. The predominant rock type directly above the coalbed is a "draw slate" composed of thinly bedded, dark gray to black, fissile carbonaceous shale, coal, and sandstone. This unstable unit is generally less than 4 feet thick but may be as much as 12 feet thick. In Monongalia and Marion Counties, the rock above the draw slate is usually limestone and shale. In Greene County, limestone predominates in the south and sandstone in the north, reaching a maximum thickness of 80 feet. In Washington County there is a preponderance of limestone in the southwest, sandstone in the south and center, and shale in the north.

A close relationship between overburden thickness and structure was established in Pennsylvania. In general, the coalbed was nearer to the surface along the axes of anticlines and deeper along the troughs of synclines. The overburden thickness ranged from zero at outcrop along the eastern edge of the study area to a maximum of 1,500 feet in western Greene and Monongalia Counties. The relationship was less well developed in West Virginia.

Cleat surveys were completed in 18 mines operating in the Pittsburgh coalbed. Two similar, but slightly different cleat system (*N 76° W and N 17° E, *N 67° W and N 28° E) were established for the area, amounting to approximately a 10° clockwise rotation from south to north. A slight counterclockwise rotation of 4° to 7° was detected from east to west. A strong relationship was apparent between the cleat orientations and the local and regional structure. Face cleats tended to be perpendicular to the axial trends of folds, and the butt cleat tended to be parallel to the axial trends. The rotation observed for the cleat directions in general matches the rotation of the structural trends.

The need for estimating the cleat systems in areas of virgin coal prompted the measurement and analysis of surface joints and the analysis of photolinears from infrared photographs and photoindex sheets. Although all three techniques provide reliable regional estimates of the cleat systems, surface joints provide the best estimate, especially on a local basis. Ronchi inspection of photoindex sheets is the fastest and cheapest method, but the level of confidence is better for the two other techniques.

This report is a study of a large area and the problems that may be encountered in mining coal. The problems that can occur were noted, and possible solutions and methods of detection of the trouble areas are offered. The project was implemented because a number of studies had been conducted on individual mines in the area and on individual quadrangles and selected areas, but no overall geologic study of this important coalbed had been attempted. Eighteen coal mines were studied underground, 39 quadrangles were mapped for surface joints and photolinears, and more than 3,000 core log descriptions were collected.

It is hoped that the results presented in this report can serve as a framework for future mine planning and operations in the Pittsburgh coalbed. More detailed geologic studies dealing with specific problems of individual mines can be conducted as outlined by McCulloch and Deul (74). Because the methodology developed in this study can be applied to other areas, especially where there will be more underground coal mining, this approach is recommended for consideration by the mining geologists and engineers responsible for mine planning.

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APPENDIX A.--GLOSSARY OF TERMS

Anticline.--A fold in sedimentary rocks, convex upward with the sides dipping away from a common line or crest.

Autochthonous.--Describing coal that formed inplace, from the constituent plants that grew, accumulated, and degraded, without transport.

Axial plane.--A plane that intersects the crest or the trough of a fold in such a manner that the limbs, or the sides of the fold, are more or less symmetrically arranged with reference to it.

Axis.--The intersection of the axial plane with a particular bedding plane.

Basin of deposition.--Depression in which sediments accumulate.

Bedding plane.--A surface that visibly separates successive layers of stratified rock (of the same or different lithology).

Butt cleat.--A short, poorly defined joint or cleavage plane in a coalbed, usually oriented at right angles to the face cleat and terminating against it.

Clay vein.--A body of clay, usually inducted, tabular to irregular in form, which fills a fissure in a coalbed. Clay veins are also known by the following miner's terms: Clay dikes, clay slips, clay seams, clay cutouts, mud fills, spars, and horsebacks.

Coal cleat.--A joint or set of joints along which the coal is fractured. There are usually two cleat sets developed perpendicular to each other. (See butt cleat and face cleat.)

Detrital.--Applied to materials occurring in sedimentary rock that were derived from preexisting igneous, sedimentary, or metamorphic rocks and have usually been transported from place of origin.

Dip.--The angle at which a stratum or any planar feature is inclined from the horizontal. The dip is at a right angle to the strike.

Draw slate.--Soft shale that occurs above a coalbed and fails readily after the removal of the coal (also called roof slate).

Eustatic.--A worldwide change in sea level as opposed to a relative change in sea level resulting from local coastal subsidence or elevation.

Extension fracture.--Fractures that form parallel to the direction of a compressive force. In a sence they are tension fractures.

Face cleat.--A well-defined joint or cleavage plane in a coalbed. The major set of joints in a coalbed.

Fundamental system (joint system).--Two sets of prominent joints oriented at approximately 90° to each other.

Interdistributary bay.--Restricted body of shallow, brackish or marine water located between distributary branches of a river in a deltaic depositional system.

Isopach map.--A map that shows the variation of the interval (thickness) between two designated stratigraphic units or horizons or between any horizon and the surface; for example, a map prepared directly from two structure-contour maps by subtracting the elevations of the lower surface from those of the upper surface at each control point and drawing new contours.

Joints.--Fractures in rock, generally more or less vertical or perpendicular to bedding, along which no appreciable movement has occurred.

Linear or lineaments.--Straight or gently curved mappable physiographic features on the earth's surface.

Lithofacies map.--A map based on lithologic characteristics showing variation in the lithologic makeup of a selected stratigraphic unit. The map may emphasize the dominant, average, or specific lithologic aspect of the unit, and provides information on the changing composition of that unit.

Paleoslope.--The direction of initial dip of a former land surface.

Peridotite dike.--A vertical or nearly vertical igneous intrusion composed of coarse-grained plutonic rock composed chiefly of olivine.

Rank of coal.--A generalized classification of coals according to degree of metamorphism, or progressive alteration, in the natural series from lignite to anthracite.

Release fractures.--Fractures that form perpendicular to the major stress axes. These fractures are assumed to have formed when the load was removed, hence their name.

Rib.--The side wall of an outside entry in a coal mine.

Rider coal.--A thin unminable coal found closely above a thicker minable coalbed. Normally only a few inches thick.

Rose diagram.--Circular or semicircular diagram for plotting the frequency of measured strikes (or dips) of planar features, such as joints and cleats.

Sandstone channel.--A body of sand deposited in the channel of a stream or river.

Set.--A group of essentially parallel related planar features, such as joints or dikes or faults, or clay veins.

Shear fracture.--A fracture that results from opposed stresses which displace one part of a rock mass past the adjacent part.

Slickenside.--Polished and striated (scratched or grooved) surface that results from friction along a plane. The movement can be very slight.

Spalling of ribs or pillars.--The breaking off of layers of coal parallel to the surface of ribs or pillars in underground mines.

Strandline.--The line or level at which a body of standing water, such as the sea, meets the land; for example, the shoreline.

Strike.--The course or bearing of the intersection of an inclined bed or structure with the horizontal. It is perpendicular to the direction of dip.

Structure contour map.--A map that portrays by means of lines drawn through points of equal elevation the subsurface configuration of a stratum such as a coalbed.

Syncline.--A fold in sedimentary rock where the strata dip inward from both sides toward the axis.

Synclinorium.--A broad regional syncline on which are superimposed minor folds.

Tectonic forces.--The forces involved in deformation of the earth's crust, resulting in folding and faulting.

Washouts.--A channel cut into or through a coalbed during or after its deposition and generally filled with sandstone.

Wild coal.--Brittle shale interstratified with thin coalbeds.

APPENDIX B.--SURFACE JOINT READINGS OF INDIVIDUAL QUADRANGLES

Quadrangle	West							
	1	2	3	4	5	6	7	8
WASHINGTON COUNTY								
Tier 1:								
Avella............	-	-	-	N 37° W	-	N 56° W	-	-
Midway............	N 7° W	-	N 21° W	N 32° W	-	N 52° W	N 74° W	-
Cannonsburg.......	-	-	-	-	N 49° W	-	-	-
Bridgeville.......	-	-	-	N 26° W	-	N 60° W	-	N 87° W
Degrees separation	-	-	-	11	-	8	-	-
Directional mean..	N 7° W	-	N 21° W	N 32° W	N 49° W	N 56° W	N 74° W	N 87° W
Tier 2:								
West Middletown...	N 7° W	-	-	-	-	N 57° W	N 70° W	-
Washington West...	-	-	-	-	-	N 53° W	N 76° W	-
Washington East...	-	-	N 20° W	N 38° W	-	N 59° W	N 72° W	N 82° W
Hackett...........	N 8° W	-	-	-	-	N 52° W	N 67° W	-
Monongahela.......	-	-	-	N 31° W	-	N 64° W	-	-
Degrees separation	1	-	-	7	-	12	9	-
Directional mean..	N 8° W	-	N 20° W	N 35° W	-	N 57° W	N 71° W	N 82° W
Tier 3:								
Claysville........	-	N 12° W	-	-	-	N 60° W	N 76° W	-
Prosperity........	-	N 12° W	-	-	-	-	N 72° W	-
Amity.............	-	-	-	N 32° W	-	-	N 75° W	-
Ellsworth.........	N 4° W	-	N 23° W	N 33° W	-	-	N 72° W	-
California........	N 1° W	-	-	N 32° W	-	N 58° W	N 71° W	-
Degrees separation	3	0	-	1	-	2	5	-
Directional mean..	N 3° W	N 12° W	N 23° W	N 32° W	-	N 59° W	N 73° W	-
County separation...	5°	-	3°	3°	-	3°	3°	5°
County directional mean..............	N 6° W	N 12° W	N 21° W	N 33° W	N 49° W	N 57° W	N 73° W	N 85° W

	West					
	1	2	3	4	5	6
GREENE COUNTY						
Tier 4:						
Windridge.........	N 22° W	-	-	N 51° W	-	-
Rogersville.......	-	-	-	N 58° W	-	-
Waynesburg........	-	-	-	N 57° W	N 77° W	-
Mather............	N 15° W	-	-	-	N 77° W	-
Carmichaels.......	N 17° W	N 26° W	N 37° W	N 49° W	N 70° W	-
Degrees separation	7	-	-	9	7	-
Directional mean..	N 18° W	N 26° W	N 37° W	N 54° W	N 75° W	-
Tier 5:						
New Freeport......	-	N 28° W	-	-	N 74° W	-
Holbrook..........	-	-	N 43° W	N 61° W	N 77° W	-
Garards Fort......	-	-	-	N 61° W	-	N 81° W
Oak Forest........	N 19° W	N 32° W	-	N 64° W	-	-
Masontown.........	-	-	-	N 56° W	N 75° W	-
Degrees separation	-	4	-	8	3	-
Directional mean..	N 19° W	N 30° W	N 43° W	N 61° W	N 75° W	N 81° W
County separation...	1°	4°	6°	7°	0°	-
County directional mean..............	N 19° W	N 28° W	N 40° W	N 58° W	N 75° W	N 81° W

Quadrangle	West						
	1	2	3	4	5	6	7
	WETZEL AND MONONGALIA COUNTIES						
Tier 6:							
Hundred...........	-	-	-	-	N 64° W	N 81° W	-
Wadestown.........	-	-	-	N 47° W	N 70° W	N 85° W	-
Blacksville.......	-	-	-	N 50° W	N 66° W	-	-
Osage.............	-	-	-	N 57° W	-	N 77° W	-
Morgantown North..	-	-	-	-	-	N 76° W	N 87° W
Degrees separation	-	-		10	6	9	-
Directional mean..	-	-	-	N 51° W	N 67° W	N 80° W	N 87° W
	MARION AND MONONGALIA COUNTIES						
Tier 7:							
Glover Gap........	N 3° W	-	-	N 50° W	-	N 84° W	-
Mannington........	-	-	-	N 47° W	-	N 75° W	-
Grant Town........	-	N 23° W	-	N 52° W	-	N 80° W	-
Morgantown South..	-	N 17° W	-	N 54° W	-	N 84° W	-
Rivesville........	N 7° W	-	-	-	N 68° W	-	-
Degrees separation	4	6	-	7	-	9	-
Directional mean..	N 5° W	N 20° W	-	N 51° W	N 68° W	N 81° W	-
	MARION AND HARRISON COUNTIES						
Tier 8:							
Wallace...........	-	-	-	-	-	-	N 89° W
Shinnston.........	N 12° W	-	-	N 51° W	-	-	-
Fairmont West.....	-	-	-	-	N 60° W	N 80° W	-
Fairmont East.....	-	-	-	-	N 58° W	N 80° W	-
Gladesville.......	N 2° W	-	N 35° W	-	N 66° W	-	-
Degrees separation	10	-	-	-	5	-	-
Directional mean..	N 7° W	-	N 35° W	N 51° W	N 61° W	N 80° W	N 89° W

	East							
	1	2	3	4	5	6	7	8
	WASHINGTON COUNTY							
Tier 1:								
Avella............	-	-	-	-	N 46° E	-	-	-
Midway............	-	N 17° E	N 28° E	-	N 44° E	N 63° E	-	-
Cannonsburg.......	-	-	N 27° E	-	N 45° E	N 63° E	-	-
Bridgeville.......	-	N 19° E	-	N 37° E	-	N 57° E	-	-
Degrees separation	-	2	1	-	2	6	-	-
Directional mean..	-	N 18° E	N 28° E	N 37° E	N 45° E	N 61° E	-	-
Tier 2:								
West Middletown...	-	N 19° E	-	N 37° E	N 47° E	-	N 70° E	N 88° E
Washington West...	-	N 17° E	-	N 37° E	-	-	-	-
Washington East...	-	-	N 29° E	-	N 47° E	-	-	-
Hackett...........	-	-	N 27° E	-	N 47° E	-	N 69° E	N 89° E
Monongahela.......	-	-	N 27° E	N 37° E	-	-	N 69° E	-
Degrees separation	-	2	2	0	0	-	1	1
Directional mean..	-	N 18° E	N 28° E	N 37° E	N 47° E	-	N 69° E	N 89° E
Tier 3:								
Claysville........	-	N 19° E	-	-	-	-	N 75° E	-
Prosperity........	N 7° E	-	N 33° E	-	-	-	N 72° E	N 89° E
Amity.............	-	-	N 27° E	N 37° E	-	N 63° E	-	-
Ellsworth.........	-	-	-	-	N 47° E	-	-	-
California........	-	N 23° E	-	-	N 45° E	N 62° E	-	-
Degrees separation	-	4	6	-	2	-	3	-
Directional mean..	N 7° E	N 21° E	N 30° E	N 37° E	N 46° E	N 63° E	N 74° E	N 89° E

Quadrangle	East							
	1	2	3	4	5	6	7	8
WASHINGTON COUNTY--Continued								
County separation...	-	3°	2°	0°	2°	2°	5°	0°
County mean.........	N 7° E	N 19° E	N 29° E	N 37° E	N 46° E	N 63° E	N 72° E	N 89° E

Quadrangle	East						
	1	2	3	4	5	6	7
GREENE COUNTY							
Tier 4:							
Windridge.........	-	N 10° E	N 23° E	-	N 39° E	-	N 80° E
Rogersville.......	-	N 9° E	-	N 26° E	-	N 46° E	-
Waynesburg........	-	N 12° E	-	-	-	N 43° E	N 82° E
Mather............	-	N 13° E	-	-	-	-	N 76° E
Carmichaels.......	-	-	-	N 29° E	-	N 44° E	N 78° E
Degrees separation	-	4	-	3	-	3	6
Directional mean..	-	N 11° E	N 23° E	N 28° E	N 39° E	N 44° E	N 79° E
Tier 5:							
New Freeport......	N 2° E	N 16° E	-	-	N 37° E	-	N 77° E
Garards Fort......	N 1° E	-	-	N 27° E	N 37° E	-	N 85° E
Oak Forest........	-	-	N 18° E	N 27° E	N 37° E	-	-
Masontown.........	-	-	N 22° E	-	-	N 52° E	-
Degrees separation	1	-	4	0	0	1	8
Directional mean..	N 2° E	N 16° E	N 20° E	N 27° E	N 37° E	N 53° E	N 81° E
County separation...	-	5°	3°	1°	2°	8°	2°
County mean.........	N 2° E	N 14° E	N 22° E	N 28° E	N 38° E	N 49° E	N 80° E
WETZEL AND MONONGALIA COUNTIES							
Tier 6:							
Hundred...........	N 7° E	-	N 25° E	-	N 57° E	N 74° E	-
Wadestown.........	-	N 10° E	N 27° E	-	-	-	-
Blacksville.......	N 3° E	N 14° E	N 27° E	-	-	N 70° E	-
Osage.............	-	N 15° E	-	-	N 54° E	-	-
Morgantown North..	-	-	N 27° E	-	N 49° E	-	-
Degrees separation	4	5	2	-	8	4	-
Directional mean..	N 5° E	N 13° E	N 27° E	-	N 53° E	N 72° E	-
MARION AND MONONGALIA COUNTIES							
Tier 7:							
Glover Gap........	-	-	N 28° E	-	-	-	-
Mannington........	-	N 10° E	-	-	-	N 68° E	-
Grant Town........	-	N 17° E	-	-	-	-	-
Morgantown South..	N 2° E	-	N 22° E	N 37° E	-	-	N 86° E
Rivesville........	-	N 17° E	-	-	-	-	N 86° E
Degrees separation	-	7	6	-	-	-	0
Directional mean..	N 2° E	N 15° E	N 25° E	N 37° E	-	N 68° E	N 86° E
MARION AND HARRISON COUNTIES							
Tier 8:							
Wallace...........	N 7° E	-	N 24° E	-	-	-	-
Shinnston.........	N 3° E	-	-	-	-	-	N 89° E
Fairmont West.....	-	-	N 30° E	-	-	-	N 77° E
Fairmont East.....	-	N 13° E	-	N 39° E	-	N 72° E	N 83° E
Gladesville.......	-	N 14° E	-	-	N 59° E	-	N 82° E
Degrees separation	4	1	6	-	-	-	12
Directional mean..	N 5° E	N 14° E	N 27° E	N 39° E	N 59° E	N 72° E	N 83° E

APPENDIX C.--PHOTOLINEAR READINGS OF INDIVIDUAL QUADRANGLES

Quadrangle	West							
	1	2	3	4	5	6	7	8
WASHINGTON COUNTY								
Tier 1:								
Avella............	N 1° W	-	N 22° W	-	-	-	-	-
Midway............	-	-	N 22° W	-	-	-	-	N 80° W
Cannonsburg.......	-	-	N 18° W	-	-	N 47° W	N 64° W	N 89° W
Bridgeville.......	-	-	N 19° W	-	N 38° W	-	N 69° W	-
Degrees separation	-	-	4	-	-	-	5	9
Directional mean..	N 1° W	-	N 20° W	-	N 38° W	N 47° W	N 67° W	N 85° W
Tier 2:								
West Middletown...	-	N 10° W	N 24° W	-	-	N 57° W	-	N 88° W
Washington West...	N 3° W	-	-	N 29° W	N 43° W	-	N 62° W	-
Washington East...	-	-	N 23° W	-	N 40° W	-	N 67° W	N 90° W
Hackett...........	N 8° W	-	N 18° W	-	-	-	N 69° W	N 84° W
Monongahela.......	N 6° W	-	-	-	-	N 57° W	-	N 80° W
Degrees separation	5	-	6	-	3	0	7	10
Directional mean..	N 6° W	N 10° W	N 22° W	N 29° W	N 42° W	N 57° W	N 66° W	N 86° W
Tier 3:								
Claysville........	-	N 13° W	-	-	N 37° W	-	N 60° W	-
Prosperity........	-	-	N 20° W	-	-	N 53° W	N 67° W	-
Amity.............	-	N 14° W	-	N 30° W	-	-	N 69° W	-
Ellsworth.........	N 2° W	-	N 20° W	-	N 35° W	N 53° W	N 69° W	N 83° W
California........	-	-	N 20° W	-	-	-	N 68° W	N 84° W
Degrees separation	-	1	0	-	2	0	9	1
Directional mean..	N 2° W	N 14° W	N 20° W	N 30° W	N 36° W	N 53° W	N 67° W	N 84° W
County separation...	5°	4°	2°	1°	6°	10°	1°	2°
County mean.........	N 3° W	N 12° W	N 21° W	N 30° W	N 39° W	N 52° W	N 66° W	N 85° W

	West						
	1	2	3	4	5	6	7
GREENE COUNTY							
Tier 4:							
Windridge.........	-	N 13° W	-	N 43° W	-	N 61° W	-
Rogersville.......	-	-	N 29° W	-	-	N 66° W	-
Waynesburg........	-	N 12° W	-	N 35° W	N 53° W	-	N 73° W
Mather............	-	N 17° W	-	N 42° W	-	N 67° W	-
Carmichaels.......	-	N 13° W	-	N 34° W	N 54° W	-	N 77° W
Degrees separation	-	5	-	9	1	6	4
Directional mean..	-	N 14° W	N 29° W	N 39° W	N 54° W	N 65° W	N 75° W
Tier 5:							
New Freeport......	-	-	-	N 37° W	-	-	N 77° W
Holbrook..........	-	-	N 28° W	-	N 53° W	-	-
Oak Forest........	N 2° W	-	N 25° W	N 43° W	-	N 60° W	-
Garards Fort......	-	-	N 23° W	N 47° W	-	N 62° W	N 76° W
Masontown	N 4° W	-	N 29° W	-	-	N 69° W	-
Degrees separation	2	-	6	10	-	9	1
Directional mean..	N 3° W	-	N 26° W	N 42° W	N 53° W	N 64° W	N 77° W
County separation...	-	-	3°	1°	1°	1°	2°
County mean.........	N 3° W	N 14° W	N 24° W	N 41° W	N 54° W	N 65° W	N 76° W

Quadrangle	West							
	1	2	3	4	5	6	7	8
	WETZEL AND MONONGALIA COUNTIES							
Tier 6:								
Hundred..........	-	-	-	N 28° W	-	-	N 62° W	-
Wadestown.........	-	-	N 18° W	-	N 44° W	-	N 66° W	-
Blacksville.......	-	-	-	-	-	-	N 68° W	-
Osage.............	-	-	-	N 29° W	-	N 51° W	N 63° W	N 76° W
Morgantown North..	N 4° W	-	-	N 29° W	-	-	-	N 72° W
Degrees separation	-	-	-	1	-	-	6	4
Directional mean..	N 4° W	-	N 18° W	N 29° W	N 44° W	N 51° W	N 65° W	N 74° W
	MARION AND MONONGALIA COUNTIES							
Tier 7:								
Glover Gap........	N 6° W	-	-	N 32° W	-	-	-	N 77° W
Mannington........	-	-	-	-	-	-	N 61° W	-
Grant Town........	N 1° W	-	-	-	-	-	N 60° W	N 75° W
Rivesville........	-	-	-	N 30° W	-	-	N 59° W	N 84° W
Morgantown South..	-	N 11° W	-	N 29° W	N 43° W	-	N 65° W	N 85° W
Degrees separation	5	-	-	3	-	-	6	10
Directional mean..	N 4° W	N 11° W	-	N 30° W	N 43° W	-	N 61° W	N 80° W
	MARION AND HARRISON COUNTIES							
Tier 8:								
Wallace...........	-	-	N 20° W	N 36° W	-	N 50° W	-	N 76° W
Shinnston.........	N 3° W	-	-	N 33° W	-	N 53° W	N 68° W	-
Fairmont West.....	-	N 14° W	-	-	N 43° W	-	-	N 82° W
Fairmont East.....	-	N 14° W	-	-	-	-	N 69° W	-
Gladesville.......	-	N 12° W	N 25° W	-	-	-	N 69° W	-
Degrees separation	-	2	5	3	-	3	1	6
Directional mean..	N 3° W	N 13° W	N 23° W	N 35° W	N 43° W	N 52° W	N 69° W	N 79° W

	East						
	1	2	3	4	5	6	7
	WASHINGTON COUNTY						
Tier 1:							
Avella............	-	-	-	-	-	N 66° E	N 82° E
Midway............	N 3° E	-	N 19° E	-	-	-	-
Cannonsburg.......	-	-	N 15° E	-	-	-	N 73° E
Bridgeville.......	-	N 13° E	-	-	-	N 63° E	-
Degrees separation	-	-	4	-	-	3	9
Directional mean..	N 3° E	N 13° E	N 17° E	-	-	N 65° E	N 78° E
Tier 2:							
West Middleton....	-	-	N 20° E	-	N 53° E	-	N 73° E
Washington West...	-	N 14° E	-	N 40° E	-	N 59° E	-
Washington East...	N 3° E	-	N 22° E	-	-	N 60° E	-
Hackett...........	-	N 10° E	-	N 33° E	N 52° E	-	N 79° E
Monongahela.......	N 4° E	-	-	N 36° E	-	N 65° E	N 82° E
Degrees separation	1	4	2	7	1	6	9
Directional mean..	N 4° E	N 12° E	N 21° E	N 36° E	N 53° E	N 61° E	N 78° E
Tier 3:							
Claysville........	N 8° E	-	-	-	N 48° E	-	N 75° E
Prosperity........	N 4° E	-	-	-	-	-	N 80° E
Amity.............	-	-	N 19° E	N 39° E	-	-	-
Ellsworth.........	-	-	N 22° E	-	-	-	N 83° E
California........	N 5° E	-	N 19° E	N 35° E	-	-	N 73° E

Quadrangle	East						
	1	2	3	4	5	6	7
WASHINGTON COUNTY--Continued							
Degrees separation	4	-	3	4	-	-	10
Direction mean....	N 6° E	-	N 20° E	N 37° E	N 48° E	-	N 78° E
County separation...		1°	3°	1°	5°	4°	0°
County mean.........	N 4° E	N 13° E	N 19° E	N 37° E	N 51° E	N 63° E	N 78° E
GREEN COUNTY							
Tier 4:							
Windridge.........	N 3° E	N 24° E	-	N 50° E	-	N 73° E	N 89° E
Rogersville.......	N 3° E	N 22° E	-	-	-	-	-
Mather............	N 3° E	N 20° E	-	-	N 62° E	-	-
Carmichaels.......	N 8° E	-	-	N 44° E	N 63° E	N 78° E	-
Waynesburg........	-	N 18° E	-	N 48° E	-	N 79° E	-
Degrees separation	5	6	-	6	1	6	-
Directional mean..	N 4° E	N 21° E	-	N 47° E	N 63° E	N 77° E	N 89° E
Tier 5:							
New Freeport......	N 5° E	-	N 35° E	-	-	N 70° E	-
Holbrook..........	N 5° E	N 17° E	N 33° E	-	-	-	-
Oak Forest........	-	N 17° E	N 27° E	-	-	N 75° E	-
Garards Fort......	-	N 23° E	-	N 41° E	N 60° E	N 73° E	-
Masontown.........	-	-	N 30° E	-	-	N 75° E	N 88° E
Degrees separation	0	6	8	-	-	9	-
Directional mean..	N 5° E	N 19° E	N 31° E	N 41° E	N 60° E	N 73° E	N 88° E
County separation...	1°	2°	-	6°	3°	4°	1°
County mean.........	N 5° E	N 20° E	N 31° E	N 44° E	N 62° E	N 75° E	N 89° E
WETZEL AND MONONGALIA COUNTIES							
Tier 6:							
Hundred...........	-	N 17° E	-	-	N 58° E	N 68° E	-
Wadestown.........	-	N 13° E	-	-	N 49° E	N 74° E	-
Blacksville.......	-	-	N 24° E	-	-	-	N 87° E
Osage.............	N 2° E	-	-	N 34° E	N 55° E	N 73° E	-
Morgantown North..	-	N 15° E	-	N 30° E	-	-	N 89° E
Degrees separation	-	4	-	4	9	6	-
Directional mean..	N 2° E	N 15° E	N 24° E	N 32° E	N 54° E	N 72° E	N 88° E
MARION AND MONONGALIA COUNTIES							
Tier 7:							
Glover Gap........	-	N 17° E	-	-	-	N 64° E	-
Mannington........	-	-	N 27° E	-	-	-	-
Grant Town........	-	-	N 26° E	-	-	-	-
Rivesville........	N 3° E	-	-	N 41° E	-	N 75° E	-
Morgantown South..	-	N 12° E	N 22° E	N 33° E	-	N 67° E	-
Degrees separation	-	5	5	8	-	11	-
Directional mean..	N 3° E	N 15° E	N 25° E	N 37° E	-	N 69° E	-
MARION AND HARRISON COUNTIES							
Tier 8:							
Wallace...........	-	N 18° E	-	N 33° E	-	N 63° E	-
Shinnston.........	-	-	N 26° E	-	-	-	-
Fairmont West.....	-	-	N 23° E	-	N 50° E	-	-
Fairmont East.....	-	-	N 22° E	N 41° E	-	-	N 83° E
Gladesville.......	-	N 13° E	-	N 40° E	-	-	N 85° E
Degrees separation	-	-	4	8	-	-	2
Directional mean..	-	N 16° E	N 24° E	N 38° E	N 50° E	N 63° E	N 84° E

APPENDIX D.--PRINCIPAL DIRECTION FOR INDIVIDUAL PHOTOINDEX SHEETS OF THE STUDY AREA

	West				East			
	1	2	3	4	1	2	3	4
WASHINGTON COUNTY								
Sheet:								
1..........	N 7° W	N 19° W	N 45° W	N 67° W	N 23° E	N 30° E	N 51° E	N 72° E
2..........	N 10° W	N 24° W	N 43° W	N 67° W	N 23° E	N 32° E	N 52° E	N 74° E
3..........	N 13° W	N 20° W	N 44° W	N 68° W	N 18° E	N 27° E	N 49° E	N 70° E
4..........	N 9° W	N 28° W	N 45° W	N 70° W	N 17° E	N 34° E	N 50° E	N 77° E
5..........	N 10° W	N 27° W	N 47° W	N 77° W	N 12° E	N 27° E	N 53° E	N 73° E
Degrees separation..	6	9	4	10	11	7	4	7
Directional mean........	N 10° W	N 24° W	N 45° W	N 70° W	N 19° W	N 30° E	N 51° E	N 73° E
GREENE COUNTY								
Sheet:								
1..........	N 7° W	N 25° W	N 47° W	N 68° W	N 14° E	N 28° E	N 58° E	N 81° E
2..........	N 12° W	N 23° W	N 43° W	N 70° W	N 10° E	N 24° E	N 56° E	N 75° E
3..........	N 9° W	N 20° W	N 42° W	N 70° W	N 7° E	N 21° E	N 57° E	N 77° E
4..........	N 5° W	N 23° W	N 44° W	N 67° W	N 12° E	N 26° E	N 53° E	N 82° E
Degrees separation..	7	5	5	3	7	7	5	7
Directional mean........	N 8° W	N 23° W	N 42° W	N 69° W	N 11° E	N 25° E	N 56° E	N 79° E
MONONGALIA COUNTY								
Sheet:								
1..........	N 8° W	N 20° W	N 42° W	N 69° W	N 5° E	N 19° E	N 60° E	N 79° E
2..........	N 7° W	N 23° W	N 43° W	N 70° W	N 10° E	N 26° E	N 56° E	N 81° E
Degrees separation..	1	3	1	1	5	7	4	2
Directional mean........	N 8° W	N 22° W	N 43° W	N 70° W	N 8° E	N 23° E	N 58° E	N 80° E
MARION COUNTY								
Sheet:								
1..........	N 8° W	N 28° W	N 42° W	N 72° W	N 4° E	N 19° E	N 57° E	N 78° E
2..........	N 7° W	N 20° W	N 44° W	N 73° W	N 7° E	N 21° E	N 59° E	N 77° E
Degrees separation..	1	8	2	1	3	2	2	1
Directional mean........	N 8° W	N 24° W	N 43° W	N 73° W	N 6° E	N 20° E	N 58° E	N 78° E
OVERALL								
Degrees separation between counties....	2	2	2	3	13	10	7	7
Directional mean........	N 9° W	N 23° W	N 44° W	N 70° W	N 12° E	N 27° E	N 55° E	N 77° E