RI 8217

Bureau of Mines Report of Investigations/1977

Methods of Determining the Orientations of Bedrock Fracture Systems in Southwestern Pennsylvania and Northern West Virginia

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 8217

Methods of Determining the Orientations of Bedrock Fracture Systems in Southwestern Pennsylvania and Northern West Virginia

By B. M. Bench, W. P. Diamond, and C. M. McCulloch

March 3, 1849

UNITED STATES DEPARTMENT OF THE INTERIOR
Cecil D. Andrus, Secretary

BUREAU OF MINES

This publication has been cataloged as follows:

Bench, Bernard M

Methods of determining the orientations of bedrock fracture systems in southwestern Pennsylvania and northern West Virginia / by B. M. Bench, W. P. Diamond, and C. M. McCulloch. [Washington] : Bureau of Mines, 1977.

35 p. : maps, graphs ; 26 cm. (Report of investigations - Bureau of Mines ; 8217)

Bibliography: p. 31-32.

1. Mining geology. 2. Coal mines and mining - Pennsylvania. 3. Coal mines and mining - West Virginia. I. Diamond, William P., joint author. II. McCulloch, Charles M., joint author. III. United States. Bureau of Mines. IV. Title. V. Series: United States. Bureau of Mines. Report of investigations - Bureau of Mines ; 8217.

TN23.U7 no. 8217 622.06173

U.S. Dept. of the Int. Library

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METHODS OF DETERMINING THE ORIENTATIONS OF BEDROCK FRACTURE SYSTEMS IN SOUTHWESTERN PENNSYLVANIA AND NORTHERN WEST VIRGINIA

by

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

ABSTRACT

This Bureau of Mines report describes photolineaments obtained from stereoscopic examination of vertical aerial photographs and by the Ronchi grating study of aerial photoindex sheets. The photolineaments are compared with the trends of oriented fracture systems procured by measuring the compass direction of joints in bedrock. The relative reliability of the methods is shown, and the results are presented in graphical, tabular, and written form.

Analyses of field measurements of strikes of bedrock joints in the project area indicate for the most part two intersecting sets of major joints oriented N 76° W - N 15° E, and N 57° W - N 27° E. The analyses of lineaments determined by stereoscopic examination of aerial photographs show dominant trends of lineament zones of weakness to be an average of N 65° W - N 20° E. Analysis of lineaments found by Ronchi grid viewing of aerial photoindex sheets indicate dominant trends of N 70° W - N 27° E. The three methods give similar findings and verify the work of previous authors.

The Ronchi grid method is a useful guide, but it cannot be substituted for the two more painstaking methods.

INTRODUCTION

The project includes Washington and Greene Counties and parts of Allegheny and Fayette Counties in southwestern Pennsylvania, and Monongalia and Marion Counties and parts of Wetzel, Preston, Taylor, and Harrison Counties in northern West Virginia. About 65 pct of the total project area is in Pennsylvania, and 35 pct is in West Virginia. This area of about 2,200 square miles is covered by thirty-nine 7-1/2-min quadrangles in the general rectangular region, 33 miles east to west and 69 miles north to south (fig. 1). The entire project is within the Appalachian Plateau province.

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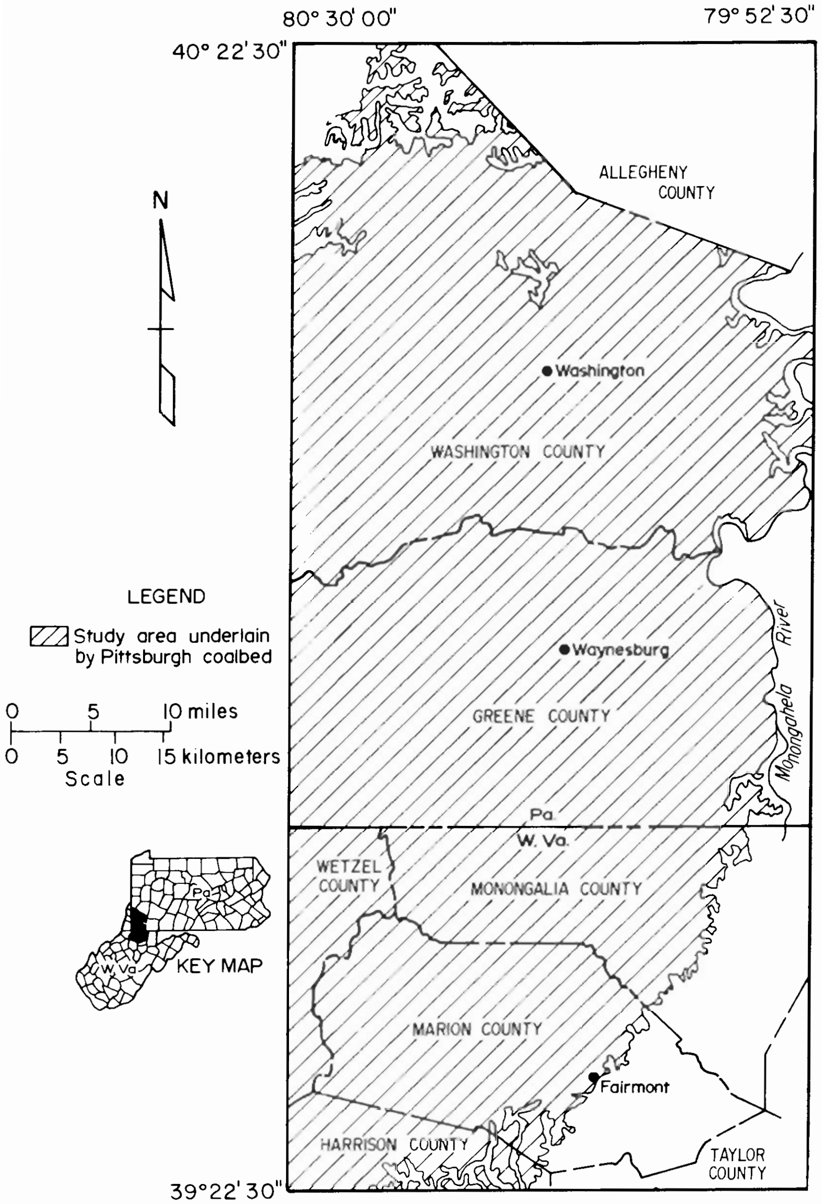

FIGURE 1. - Map of the project area and the portion underlain by the Pittsburgh coalbed.

In the project area, lineaments are important because they represent the significiant lines of landscape. The lineaments are generally rectilinear and sometimes reveal the structure of the basement rock. They are frequently surface expressions of fracturing and jointing that can be related to tectonic forces and observed on aerial photographs and other remote sensing images. These features are significant in the study of areas of underground coal mining since they indicate patterns of weakness that may extend into the subsurface coalbeds. The presence of lineaments has a direct relationship to and thus has a bearing on mining problems including roof instability (3, 7, 10)[2] and the emission of methane gas (3, 7-8, 11).

The measurements of surface joints is a procedure that is sometimes applicable in analyzing tectonic forces such as those of the Appalachian orogeny that affected various areas and produced structural trends. The use of aerial photographs provides a supplementary check system with a broad overall view. Aerial photographs permit examination of inaccessible terrain for lineaments that could be located in the field only by great expenditure of time and effort. The interpretation of aerial photographs also has the advantage of being independent of weather conditions.

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[2] Underlined numbers in parentheses refer to the list of references preceding the appendix.

Anticlinal and synclinal structures in the bedrock of the project area have a general trend of N 25° to 30° E. Field measurements of face cleat orientations of coal in underground coal mines denote a gradual variation in direction from N 76° W in the southern part of the area to N 67° W in the northern portion. Butt cleat orientations show a variation from N 17° E in the southern part to N 28° E in the northern part of the project. In the blocky Pittsburgh coal, the directions of underground room and pillar mining commonly follow the butt and face cleat directions to take advantage of the natural breaking of the coal.

The success of mining operations is dependent upon costs. For this reason, the determination of bedrock features that indicate underground conditions is often considered unnecessary. The cost of such investigations, however, is minor compared with the benefits derived.

The cost of data for a particular mining property would only be a small part of that required for the present study in the Allegheny Plateau. Here, the costs or consulting fees for determining the orientations of bedrock fracture systems by the three methods are estimated as follows:

Method		Total cost
1.	Measuring directions of bedrock joints by a team of 2 men, 2 days in field, and 1 day for tabulation and analysis of data per 7-1/2-min quadrangle, $650. Evaluation of 39 quadrangles in 33 weeks as in this report.	$25,350
2.	Stereo study for lineaments on infrared aerial photographs by 1 man, including field checking and $110 cost of photo coverage per 7-1/2-min quadrangle, $530. Study of 39 quadrangles in 32 weeks.	20,670
3.	Ronchi evaluation of lineaments on photoindex sheets by 1 man at rate of an area covering eight 7-1/2 min quadrangles per day, including a $40 cost of index sheets and covering entire 39 quadrangles in 1 week.	650

Ronchi inspection of photoindex sheets is helpful for reconnaissance work and corroboration, but it cannot replace the stereoscopic study of lineaments. The work must be confirmed by bedrock-joint directions in the field or by infrared photolineament analysis.

PREVIOUS WORK

Results of the study of lineaments in this paper were used in a more comprehensive study of the mining geology of the Pittsburgh coalbed (12), and the analytical techniques for evaluating the directional data were previously published in Geology (1) and in Bureau of Mines Report of Investigations 8120 (2). However, space limitations in these papers does not permit the type of discussion and explanation for the present purpose of describing and comparing the methods in more detail. Although most of the data and illustrations used were published previously (1-2, 12) they are included here for convenience.

Hough (5) published a comprehensive paper on photogeologic techniques for mapping rock joints. The area of his investigation included the Morgantown 15-min quadrangle, the western half of which is within the study area of this paper.

Kent and Pillmore (7) conducted a field and aerial photo study of the surface fracture system of the Pittsburgh coalbed area to evaluate the use of black-and-white infrared photographs for photolineament surveys and to determine the compass orientation of major joint sets. In addition, the study included data and geologic features of mine roof failure. Kent (6) made a similar study of the surface fracture system of southern Ashland County, Ohio, where terrain is similar to that of the project area.

Lattman (9), in his work on nomenclature, definition, and techniques, designated fracture traces of less than 1 mile in length as "linears," and those more than 1 mile long as "lineaments"; however, in this report all such alinements regardless of length are designated lineaments.

Nickelsen and Hough (13) made an extensive investigation of jointing in the Appalachian Plateau of Pennsylvania. They discussed the orientation and origin of joints in sandstone, shale, and coal, and also determined the orientations of major joints in shale and of systematic joints in coal. In addition, they attempted to classify some differences between their view of jointing, joint sets, and joint systems and the views of other authors. The work of Nickelsen and Hough is substantiated by a Bureau of Mines report (12) that presents new methods of attaining the same results of determining directions of oriented fracture systems.

Roen and Farrel (15) prepared a structure contour map of the Pittsburgh coalbed, southwest Pennsylvania and northern West Virginia. This very important and useful map was constructed on a scale of 1 to 125,000 with a contour interval of 100 feet.

FRACTURES AND PHOTOLINEAMENTS

Fractures include all types of discontinuity that result from mechanical failure in rock. They may be produced by either shear stress or tensile stress and include faults, shears, joints and fracture zones. Joints are fractures along which there has been no visible movement parallel to the joint surface. Many small irregular fractures cutting a mass of rock in a relatively restricted area comprise a fracture zone. In coal, joints and fractures are termed "cleats" (11).

Most rocks are fractured in varying degrees, depending on rock type and the nature of the regional and local stresses applied to the rock. Two or more principal directions of fracturing are normally present. Hough (5) and Kent (6-7) determined that photolineaments are the cumulative evidence of zones of linear weakness accentuated on the surface by erosional processes.

They have directional trends similar to those of the prominent sets of joints in rock outcrops. The recognition of photolineaments and their correlation with joint sets is possible because of the combined expression of numerous parallel joints that are collectively evident as a line or fracture belt when photographs are viewed stereoscopically (6). Straight portions of streams, long straight valleys, and right-angle bends of present or former stream channels originating from intersecting fractures are included within this category; they apparently result from lineament zones that were weakly resistant to erosion along which drainage was concentrated in the initial stages of stream flow (6-7).

The larger streams in southwestern Pennsylvania and northern West Virginia have been incised or entrenched as much as 150 feet since glacial times (18), indicating relatively rapid removal of overburden. Throughout uplift of the area, these streams have maintained their courses and meanders in places where they were first influenced by fracture systems (fig. 2).

Precautions were taken during the interpretation to avoid mistaking fracture and fault traces caused by valley stress release with structural lineaments. Ferguson (4), in his work on flood control and dams containing locks for navigation, describes compression faults in valley bottoms and tension fractures in the walls. Such fractures are mostly vertical, parallel to the strikes of the valleys, and generally of local and limited extent.

Actual joints are too small to be seen on photographs; therefore, interpretation of trends of structural weakness is based on lineament features believed to be related to fracture zones. The passage or presence of water in such zones accentuates lineaments that include the following: straight parts of streams, right-angle bends in streams and rivers that appear to result from the intersection of two joint or fracture zones, lines of trees taller than average, alinements of vegetation, dark zones caused by greater than normal moisture concentration, fairly straight color-tone differences in open ground, lineament depressions on sides or tops of divides, and straight portions of valleys (5, 7, 11).

Paleogeographic maps (16) indicate that no sediments younger than Permian have been deposited in the region. The same tectonic forces that produced fractures in sedimentary beds now exposed on the surface are believed to have been responsible for the cleats in the underlying coalbeds (11).

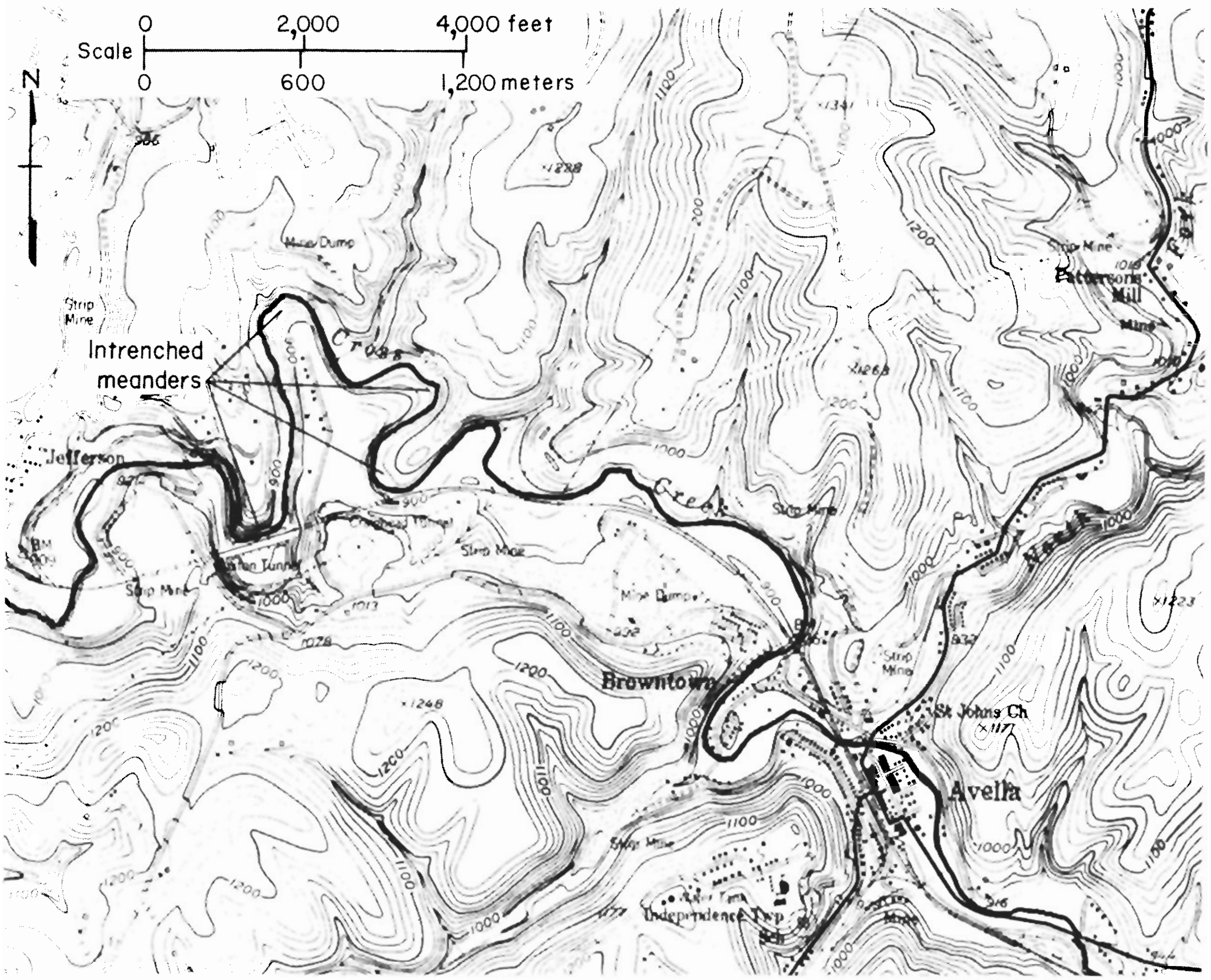

FIGURE 2. - Entrenched meanders, Cross Creek, Avella quadrangle, Washington County, Pa.

STEREOSCOPIC EXAMINATION OF AERIAL PHOTOGRAPHS

Photography

Two types of black and white film are generally used for aerial photography, panchromatic and infrared. The sensitivity of panchromatic films is exceptionally good. This sensitivity insures that the film will respond to all wavelengths of visible light, and that all tonal gradation in the original scene will be reproduced. Black-and-white infrared film is receptive to reflective infrared radiation in addition to the visible spectrum.

The infrared film is particularly well suited to the interpretation of lineaments related to slight differences in moisture content. Relative moist areas such as fracture zones appear dark in the images. Water photographs jet black because it absorbs almost all the radiant energy of infrared wavelengths (fig. 3). Ultraviolet radiation and blue light are filtered out to penetrate haze and to achieve high contrast in black and white tones. The cost of black and white infrared aerial photography by private companies is nearly four times that of the black and white panchromatic photography available from the Soil Conservation Service. However, the superior qualities of the infrared for photolineament enhancement and the factors of easier interpretation with better results more than justify the cost differential by the savings in salaries and time.

Procedure

The scale of the aerial photos used in this study is approximately 1/24,000 (1 inch=2,000 feet), similar to the scale of the 7-1/2-min topographic sheets on which the data were plotted. Photographs of individual quadrangles were assembled and cataloged in their proper positions. Approximately 21 photographs cover the area of one 7-1/2-min quadrangle.

Features identified as lineaments were marked on the photographs with colored pencils. Black was used for straight segments of streams and valleys believed to have originated from differential erosion along fracture zones. These were by far the most common lineaments observed. Less common features, such as right-angle bends in stream channels, soil tone differences, linear depressions, and vegetational indicators were marked in orange. The last three features are often obscured by the cultural development, coal mine operations, fences, powerlines, and pipelines, prevalent in the area.

The individual lineaments marked on the infrared photographs were transferred to 7-1/2-min topographic quadrangle maps (fig. 4) and the strike of each lineament was measured with a protractor and recorded. The individual measurements for each quadrangle were next plotted on a rose diagram (fig. 5) to be used in the analysis of the fundamental or orthogonal directional systems.

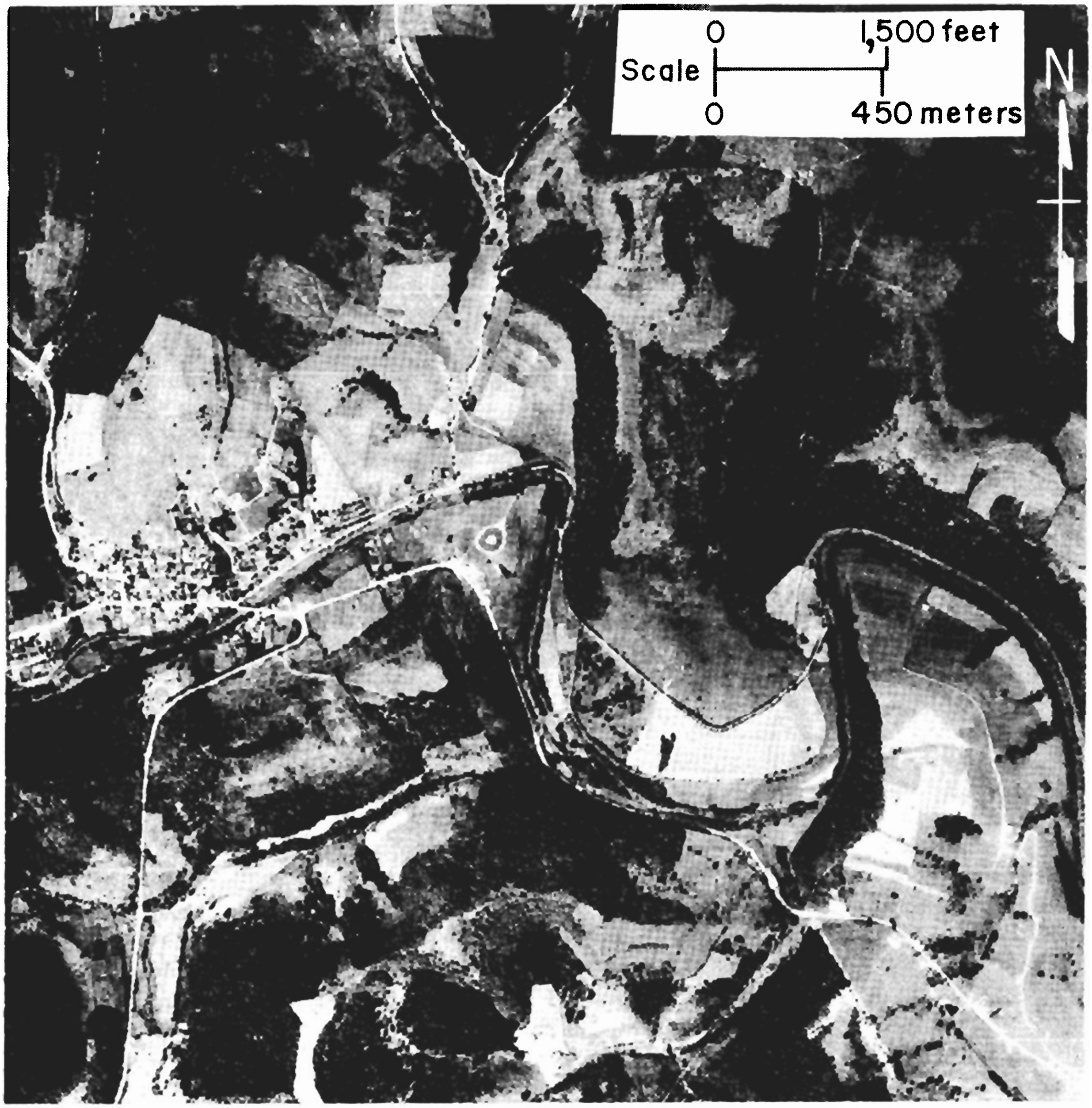

FIGURE 3. - Dunkard Creek and coal mine reservoirs, Blacksville quadrangle, Greene County, Pa., and Monongalia County, W. Va., project area. *A*, Photographed with panchromatic film in 1958.

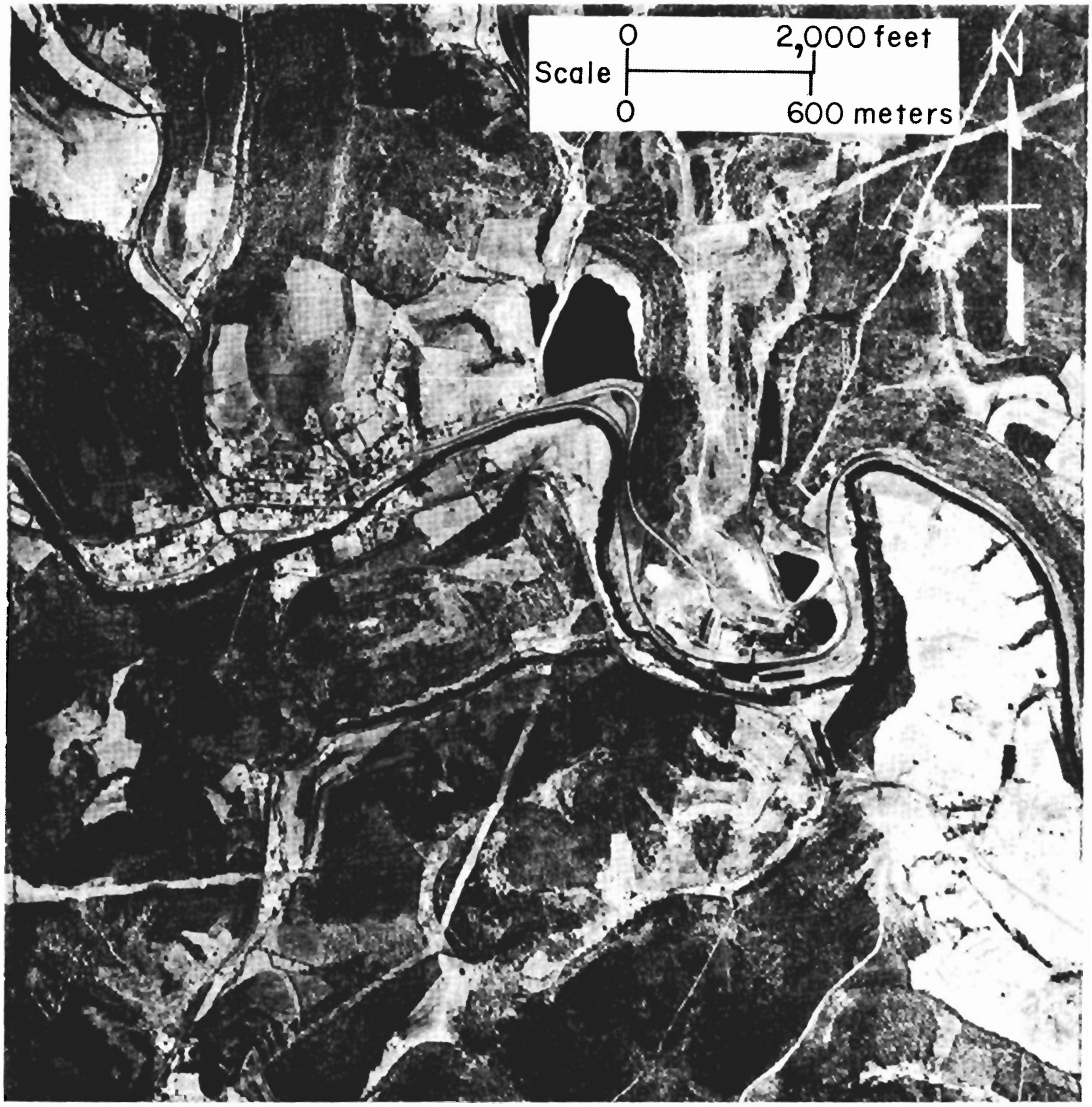

FIGURE 3. - Dunkard Creek and coal mine reservoirs, Blacksville quadrangle, Greene County, Pa., and Monongalia County, W. Va., project area. *B*, Photographed with infrared film in 1972.

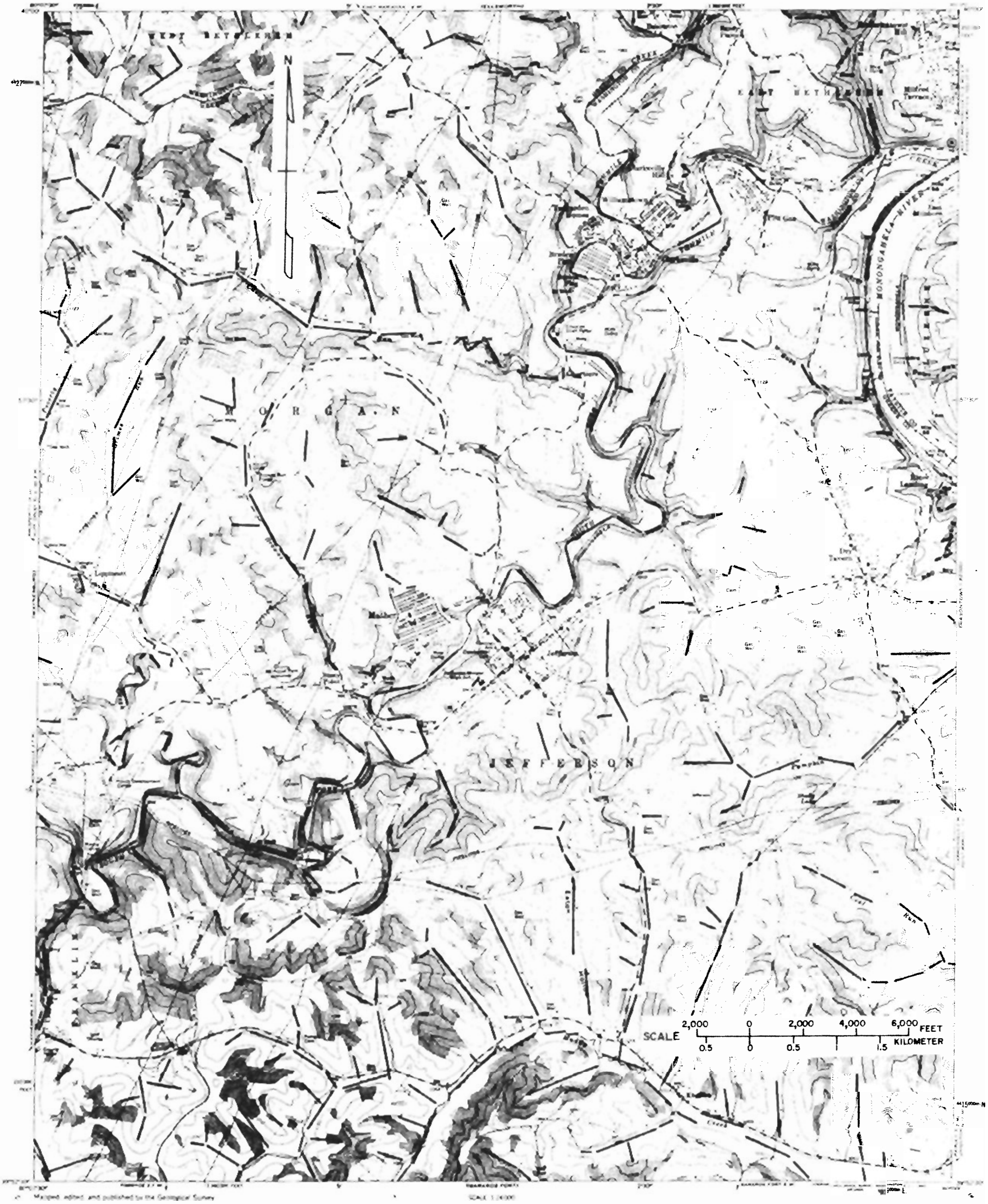

FIGURE 4. - Photolineaments plotted on Mather 7-1/2-min topographic quadrangle map.

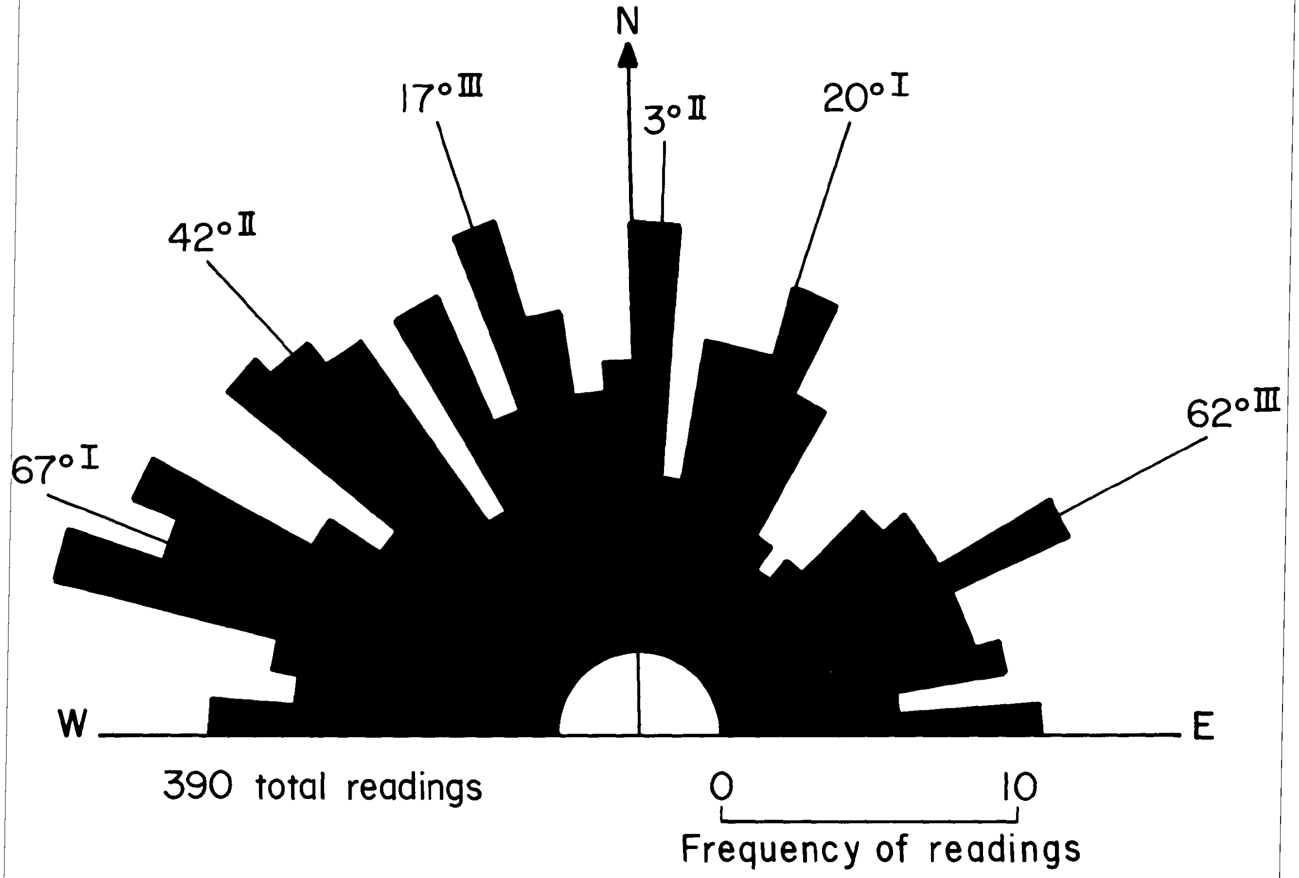

FIGURE 5. - Rose diagram of photolineaments in Mather quadrangle.

Regional Structure

In addition to lineaments, an impression of geologic structure was obtained from the stereoscopic examination of the aerial photographs. Structure in the study area shown in figure 6 is characterized by a broad basin, containing widely spaced, gently dipping anticlines and synclines. Dips are generally less than 1° or about 100 feet per mile. Beds having greater dip than this occur only on the west flank of the Chestnut Ridge anticline in Rivesville, Morgantown North, Morgantown South, and Gladesville quadrangles. Actual rock exposures in the area are scarce because of forest and soil cover. The hogback and cuesta topographic surface expression of the structure on the west flank of the Chestnut Ridge anticline, however, is clearly evident by the dip slopes recognized on the photographs (fig. 7).

Throughout most of the study area, a general impression of low dip attributed to nearly horizontal beds is interpreted from sedimentary layers observed as tonal contrasts in fields along hillsides and ridges. Individual beds with slightly different contents of water and mineral matter register on infrared film in varying shades of gray. Distinct bands of varying intensity

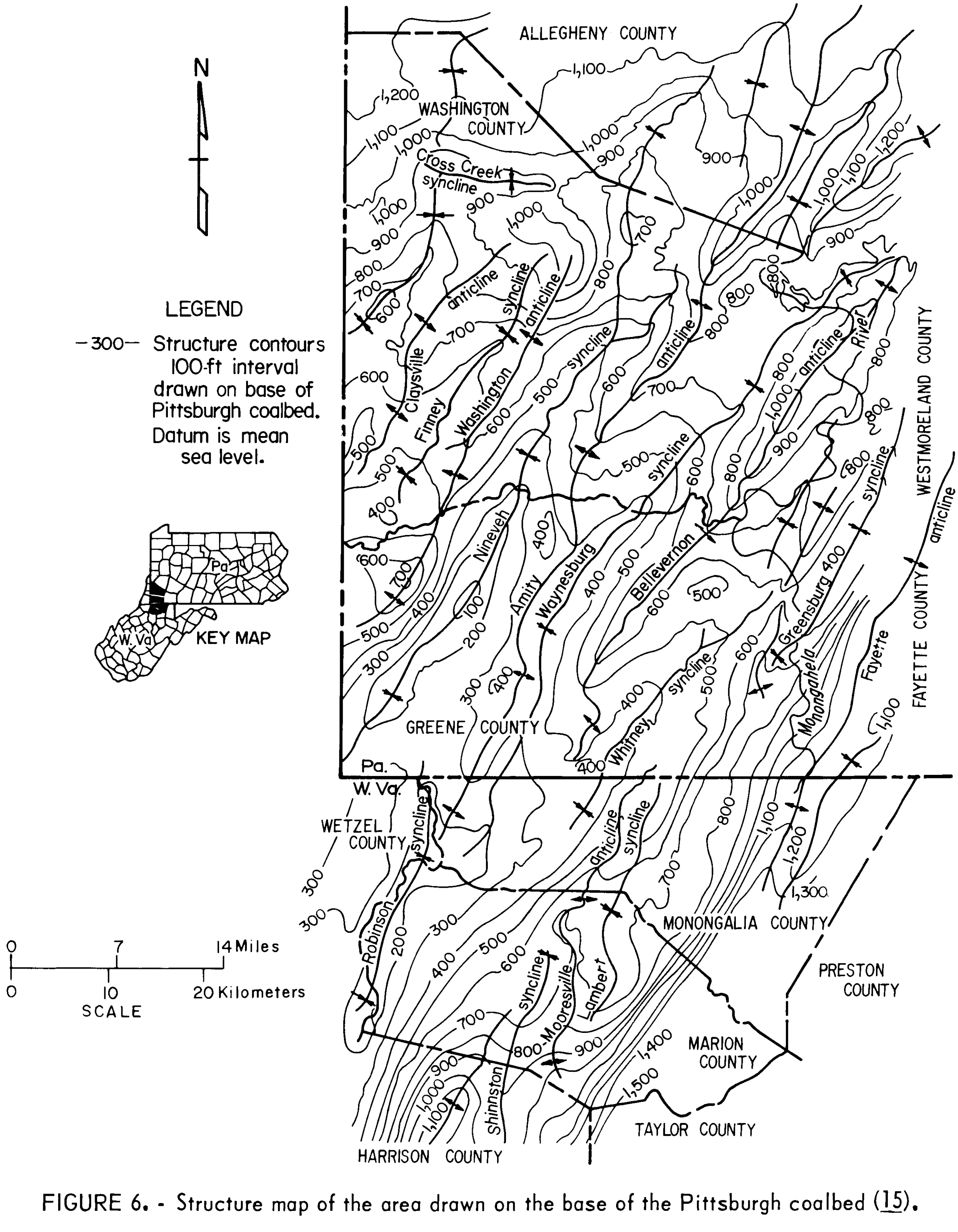

FIGURE 6. - Structure map of the area drawn on the base of the Pittsburgh coalbed (15).

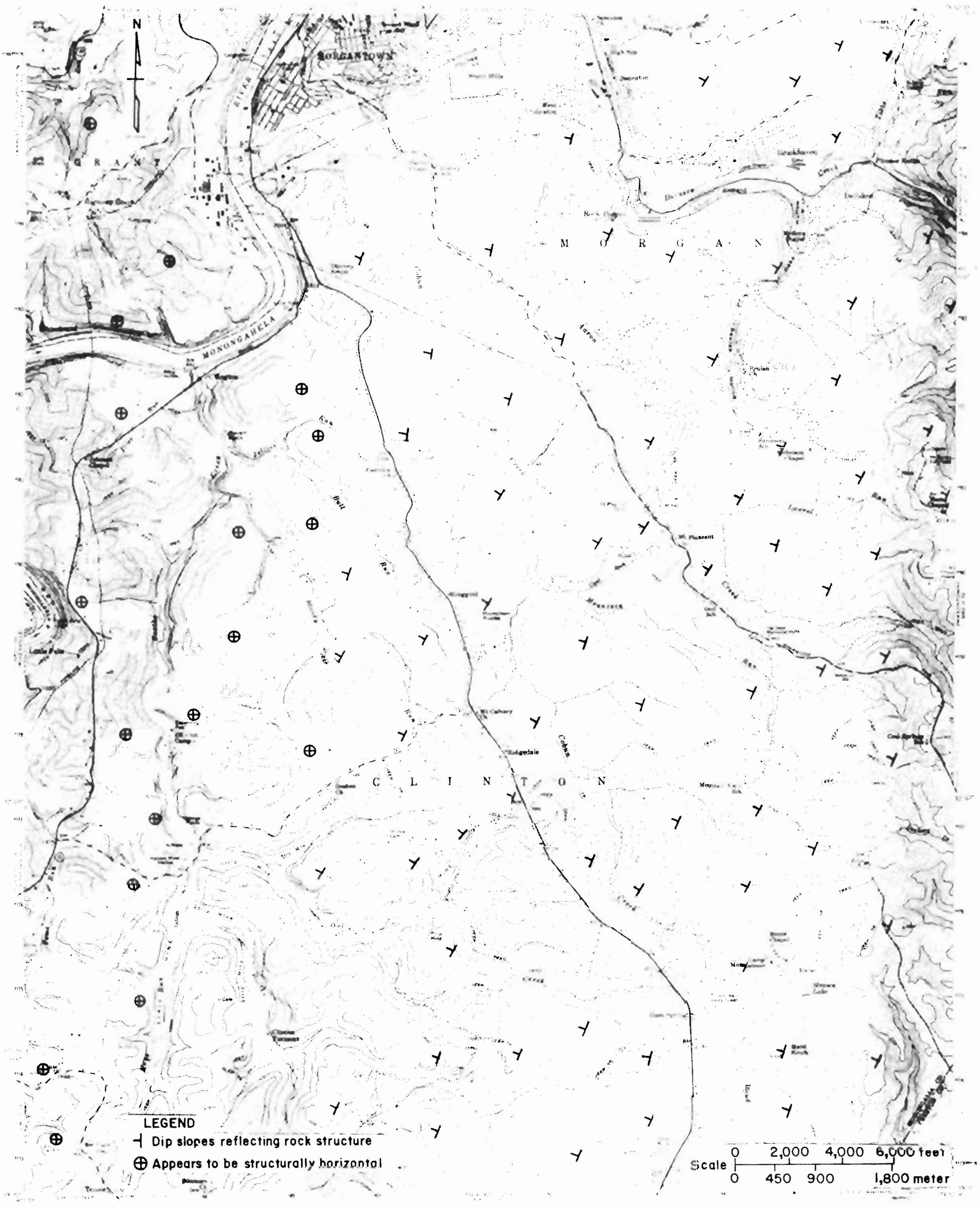

FIGURE 7. - Dip slopes and horizontal areas in Morgantown South quadrangle, West Virginia.

are normally continuous regardless of whether farm plowing is up and down slopes or on contour. Such small differences cannot be detected in the field where the only structural evidence to be seen is the attitude of rock exposures in road cuts, and in occasional outcrops in fields, on steep slopes, or in stream gullies.

The radial drainage in the south edge of Mather quadrangle (fig. 4) has developed in a large synclinal area of low dips. The axis of a small uplift extends southward about three-fourths of a mile from the northward curve of Muddy creek.

RONCHI GRID INSPECTION OF PHOTOINDEX SHEETS

The Ronchi grid is a device employed to identify lineaments occurring in a given direction by reinforcing their lengths on aerial photographs. It was used by Pohn (14) according to the principle of defraction grating to enhance edge contrast among numerous parallel lines. The grid consists of an optimum number of 200 equidistant parallel lines per inch ruled on a square of optical glass, usually 4 by 4 inches in size (fig. 8).

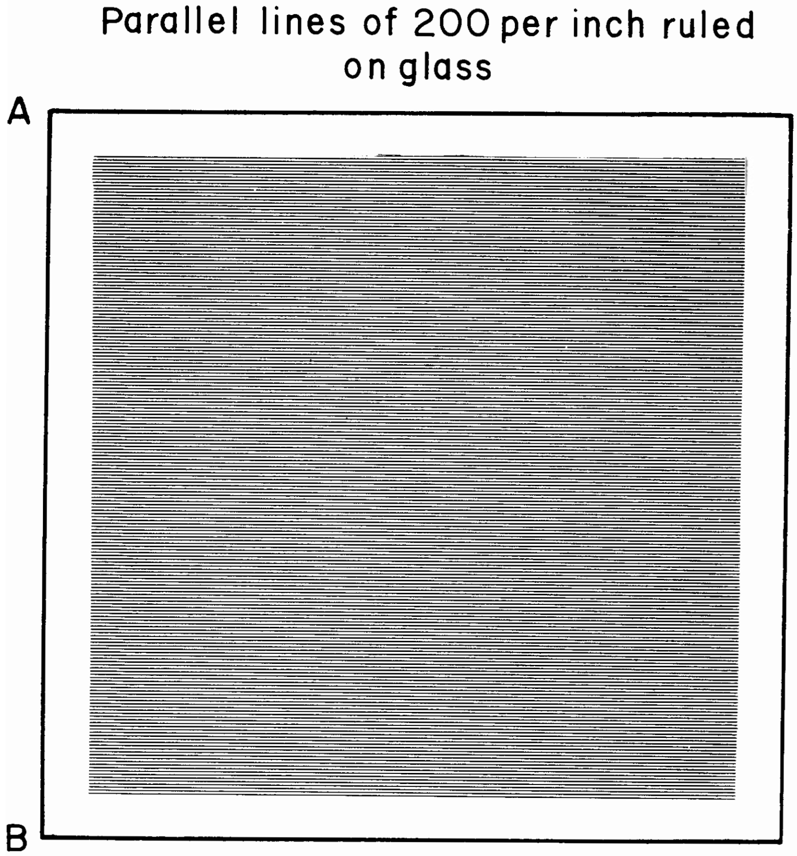

FIGURE 8. - Diagram of Ronchi grid. Enhancement of a set of photolineaments takes place when the Ronchi grid lines are perpendicular to the direction of the photolineaments. The compass direction of line A-B will show the bearing of the photolineament set.

Photography

The Ronchi grid was applied to locate lineaments on the photoindex sheets of Washington and Greene Counties, Pa., and Monongalia and Marion Counties, W. Va. Photoindex sheets are composed of individual photos, usually at a scale of 1 inch=1 mile, joined together at their edges.

The photoindex sheets are usually made by shingling or overlapping aerial photographs along or across flight lines, and the assembled index is then photographically reduced to an appropriate scale. The photoindex sheets of this study were constructed for the U.S. Department of Agriculture Commodity Stabilization Service from photographs of scale 1:20,000 and reduced to a scale of 1/62,500 (17).

Procedure

Photoindex sheets are generally attached to a wall or other flat vertical surface for convenience in viewing. Lineament trends are ascertained by slowly rotating the Ronchi grid while viewing an index sheet from a distance of 2 to 10 feet. The grid is best held inside the near focus of the eyes, 1 to 2 inches depending on the viewer's vision and personal preference. The enhancement of a set of lineament trends occurs when the lines of the Ronchi grid are perpendicular to the lineaments on the index sheets. The lineament images seen through the Ronchi grid differ from the narrow and discontinuous scattered lineaments seen with a stereoscope. The Ronchi images tend to fill the index sheet with relatively wide bands similar to a herringbone pattern.

A reconnaissance viewing of a sheet is made with the Ronchi grid to determine the number and general strike of lineament trends and the relative dominance of each trend based on image strength. A close measurement of the strike of each trend is made after rotating the grid back and forth to define the most prominent or distinct orientation of the intensified lineament image. A line is drawn on the photoindex sheet to indicate the strike of the trend and is measured with a protractor and recorded along with its relative dominance (fig. 9).

True lineaments create diffraction images only in the direction of the lineament itself, but buildings, trees, and all other fairly compact objects can form alinements in any direction the Ronchi is rotated. Roads, pipeline, and powerline clearings commonly give false lineaments that produce erroneous data if not recognized, or may enhance or strengthen valid trends if they are nearly parallel to a true one. Of particular concern are the north-south and east-west images formed by the edges of the individual photographs comprising the index sheets. These false lineaments also reinforce natural lineaments actually occurring in the same directions. Careful examination of the photographs and index sheets without the Ronchi grid can eliminate most other erroneous lineament features. True lineaments, both single or composites of many individual parallel features, generally produce more lengthy and stronger images than those produced by manmade objects.

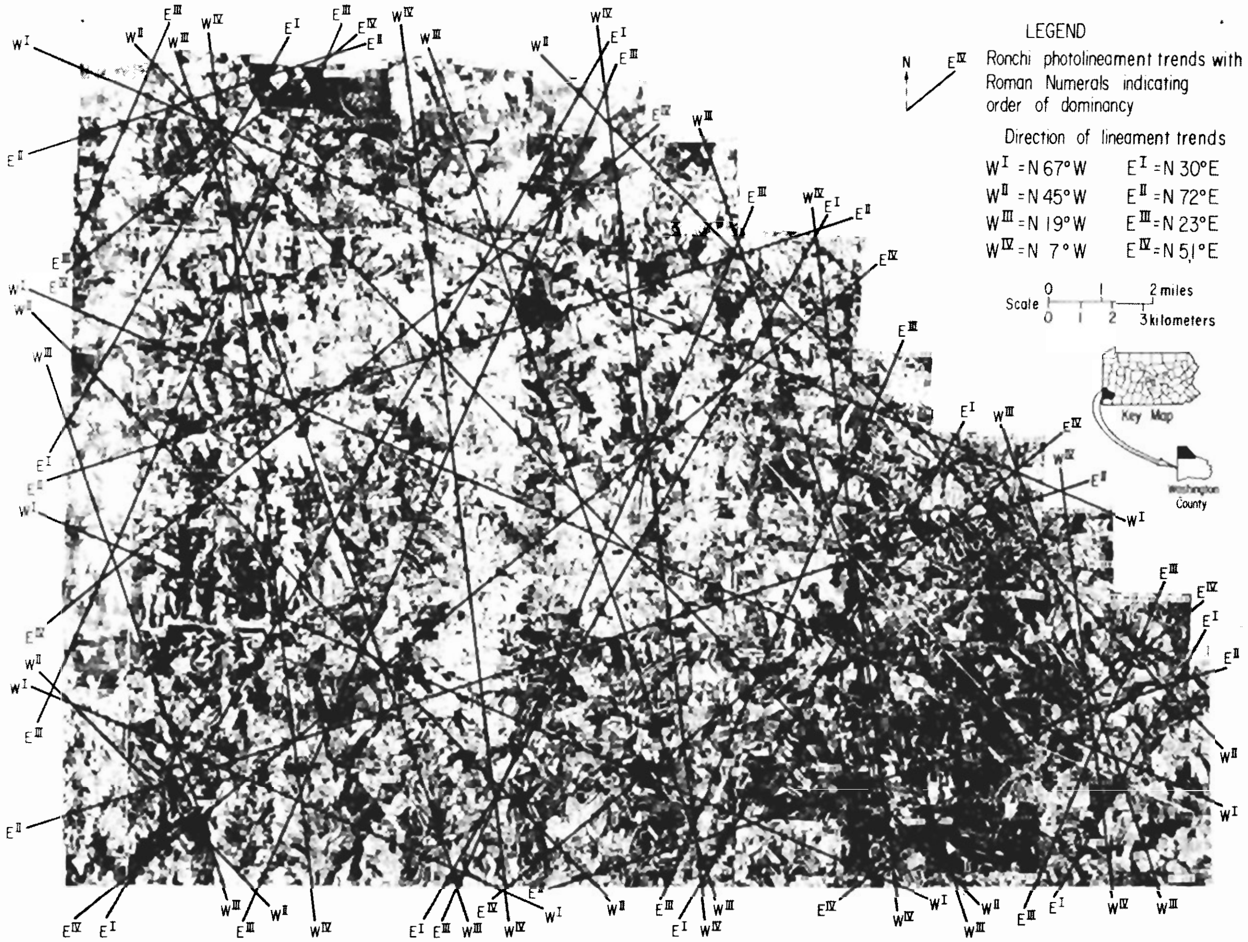

FIGURE 9. - Lineaments determined by Ronchi grid on photoindex sheet No. 1, Washington County, Pa. (17).

BEDROCK JOINT DETERMINATION

Joints in bedrock were measured in the field and corrected to true north with a Brunton compass in the thirty-nine 7-1/2-min quadrangles of the project area. A minimum of 100 joint readings were taken per quadrangle with an average of 120 readings for each quadrangle. No more than 10 readings were made at a single outcrop. Rock types and quality of joints were noted at every exposure.

The data from each quadrangle were plotted individually on rose diagrams as in figure 10 to evaluate the principal directional trends. Figure 11 shows the rose diagrams of the bedrock joint readings from the individual quadrangles assembled in their proper geographic position. From these data, a composite rose diagram (fig. 12) of bedrock joint trends for the entire study area was constructed by plotting only the dominant trends from each

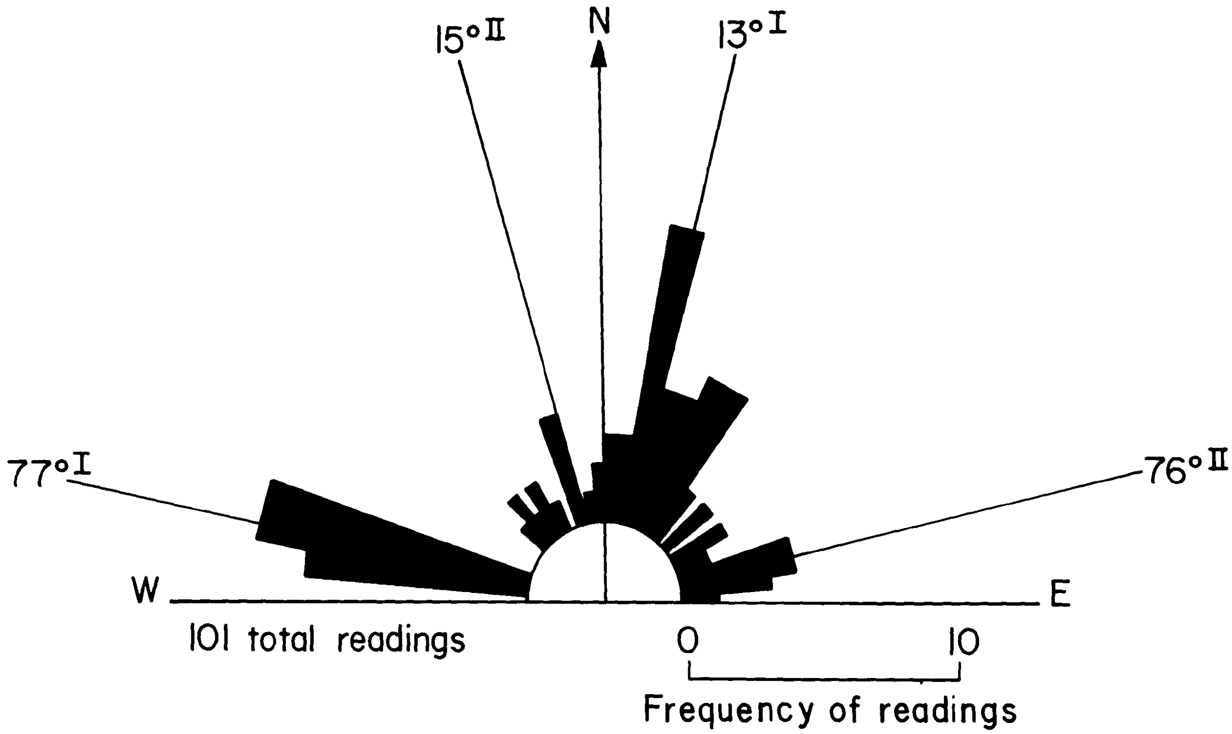

FIGURE 10. - Rose diagram of bedrock joints in the Mather quadrangle.

individual quadrangle on a single rose plot. Table A-1 in the present paper gives the averages of the bedrock joint orientations by county.[3]

The different trends are designated by numbers according to their divergence from north to the northwest, and by their divergence from north to the northeast. Trends in the same vertical column of a group correspond or are correlative through the six counties. Where blank spaces appear, no corresponding trends were found. The order of dominance of the trends is designated by superscipts I, II, III, and IV.

Peaks for the bedrock joint and infrared photolineament methods were defined by comparing the number of readings comprising each high point on a rose diagram with the number of readings in the adjacent 5° interval. A decline of one-third the number of readings comprising a 5° interval high point was used to define the limits of an individual peak.

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[3] The bedrock joint readings from individual quadrangles are shown in appendix B, pages 66 to 68, in Bureau of Mines RI 8093. They are listed according to counties in rows of quadrangles from north to south, figure 30, page 40. Separate tables contain the readings that are to the west of north and those to the east of north.

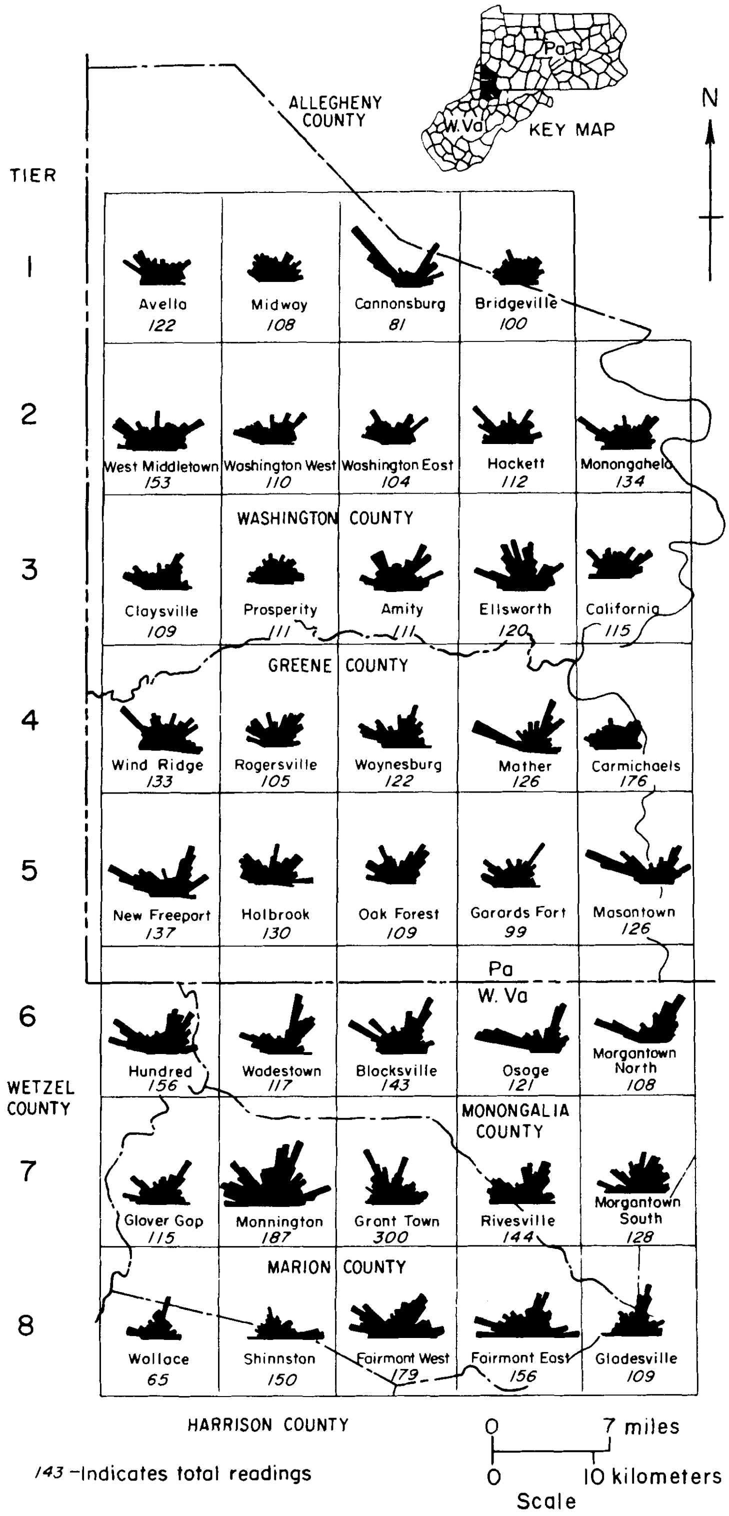


FIGURE 11. - Individual rose diagrams of bedrock joints in quadrangles of the project area.

The first 5° interval on each side containing less than two-thirds of the number comprising the high point was not included within the peak. However, if the first 5° interval to decline one-third the number of readings of the high point is above the line of the average number of readings, and the next adjacent 5° interval declines by an additional one-third, then the first 5° interval is considered as part of the peak.

To be included in the analysis of directional trends, the peaks as defined must (1) extend above the line of the average number of readings, and (2) be composed of at least 4 pct of the total number of readings. A difference of 10 pct in the number of readings was considered sufficient to assign different orders of dominance. The most dominant peak was assigned the first order of dominance, and the next most dominant was second order, etc.

Figure 12 illustrates the presence of three regional trends in the northwest quadrant and four in the northeast quadrant (table 1). The number directly above the directional trend in table 1 is the order of dominance of that measurement in relation to the others in the same group. The orders of dominance assigned to the trends are determined by the number of measurements comprising the peaks that correspond to the trends on the composite rose diagram. Two orientations, N 57° W and N 76° W in table 1 under the West I group, show equally strong directional trends.

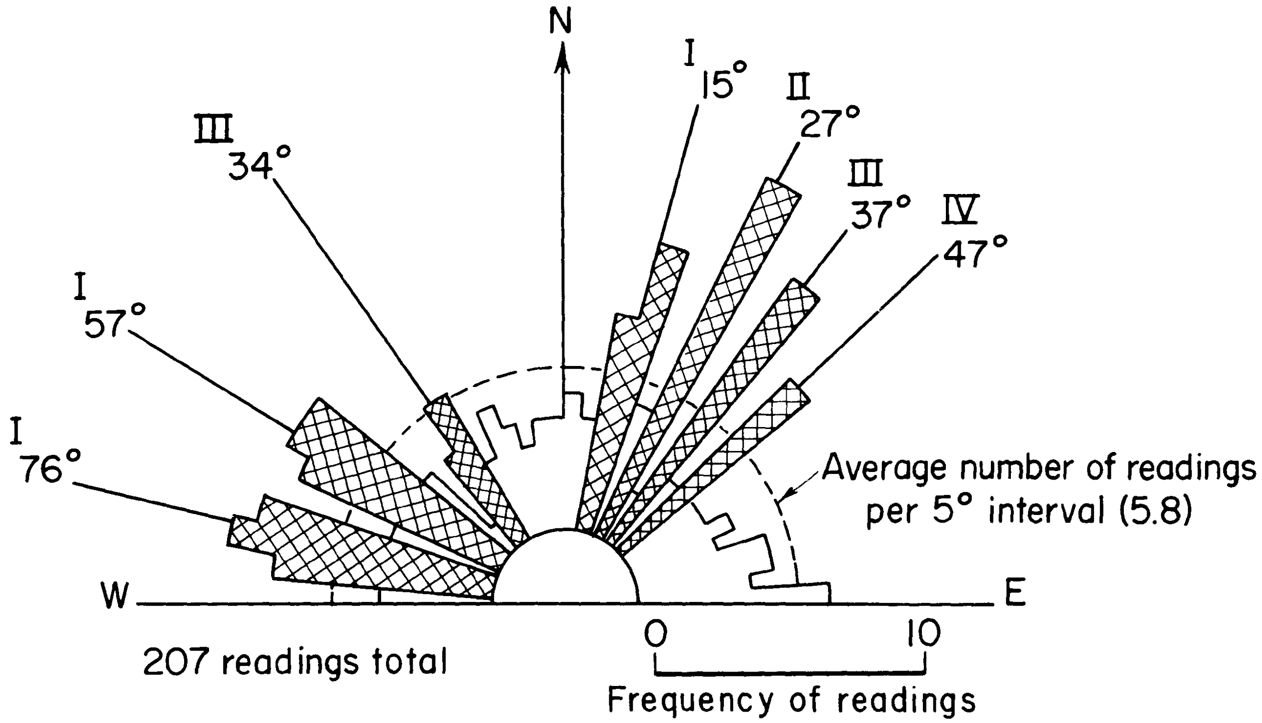


FIGURE 12. - Composite rose diagram of principal bedrock joint trends.

TABLE 1. - Principal bedrock joint trends, in order of dominance

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

The principal directional trends listed in table 1 form six fundamental or near orthogonal joint systems, composed of two trends each that are near 90° to each other as follows:

Systems

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

NOTE.--The superscripts in Roman numerals indicate the order of dominance.

Two bedrock joint systems (2 and 4) are composed only of joint sets of the first order of dominance and both systems contain the N 15° E^{I} set. System 4, with a 91° separation, more closely approaches the fundamental or near orthogonal system's 90° separation than does system 2 with a 72° separation.

System 5 also contains the N 76° W^{I} bedrock set but the eastward component of this system is less dominant than that of system 4, and its divergence from an ideal orthogonal system is greater. System 4 is thus considered the most dominant system containing the N 15 E^{I} and N 76° W^{I} sets.

The N 15° E directional trend is given the first order of dominance because it is composed of 19 readings compared with 15 readings for N 27° E. In the rose diagram (fig. 12), the N 27° E directional trend, which only spans a 5° interval, appears more prominent because of its length and the flaring at the top; however, the N 15° E direction spans a 10° interval and actually contains more readings. The average number of readings per 5° interval is 5.8.

Systems 1 and 3 contain a westward bedrock set (N 57° W^{I}) of equal dominance to that of N 76° W^{I} in system 4. Although both systems have nearly equal divergence from an ideal orthogonal orientation, system 1 with a higher order of dominance for the eastward set (N 27° E^{II}) is the most dominant system containing the N 57° W^{I} set. Systems 1 and 4 are therefore determined to be the most dominant bedrock systems that can be paired from the data in table 1.

The eastward trends of systems 1 and 4 closely parallel the strike of the major structural axes of the area, and the trends to the west are nearly perpendicular to the axes. These systems are thought to be directly related to the regional structural deformation.

The sixth bedrock joint system (N 34° W^{III} - N 47° E^{IV}) may also be related to the regional structure, even though 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.

INFRARED PHOTOLINEAMENT DETERMINATION

Rose diagrams were prepared for each of the 39 quadrangles using the data obtained from examination of infrared photographs. The individual rose diagrams are positioned in their proper geographic location within the study area in figure 13. The dominant trends of all the quadranges are plotted on a single composite rose diagram (fig. 14). Directional trends arranged by row and corresponding counties from north to south are given in the appendix, table A-2. Numbered trends are separated into west and east directional groups by their increasing divergence from north and not by their order of dominance. Trends within the same vertical column of a group are approximately correlative, being close to the same orientation.

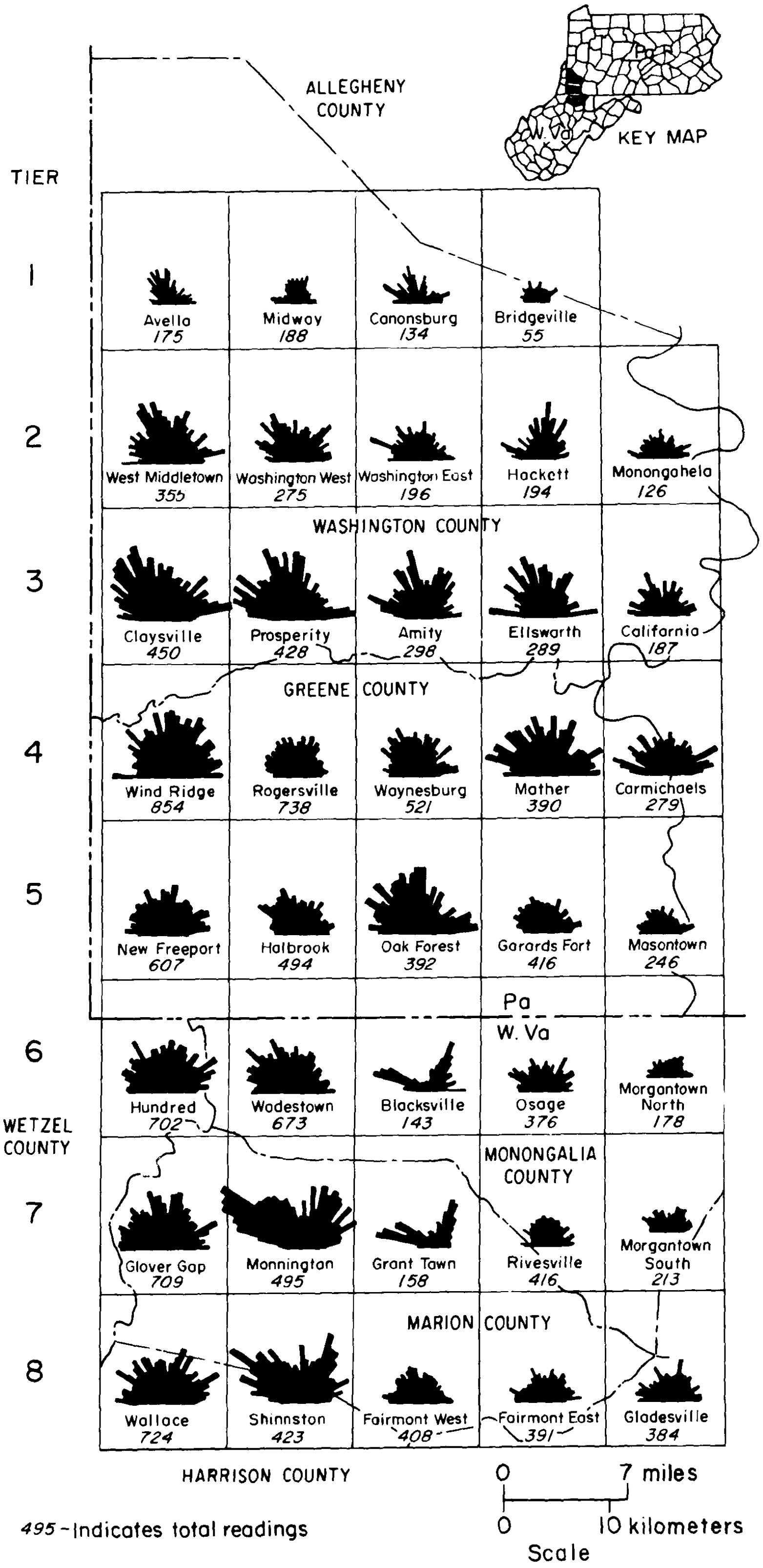


FIGURE 13. - Individual rose diagrams of photolineaments in quadrangles of the project area.

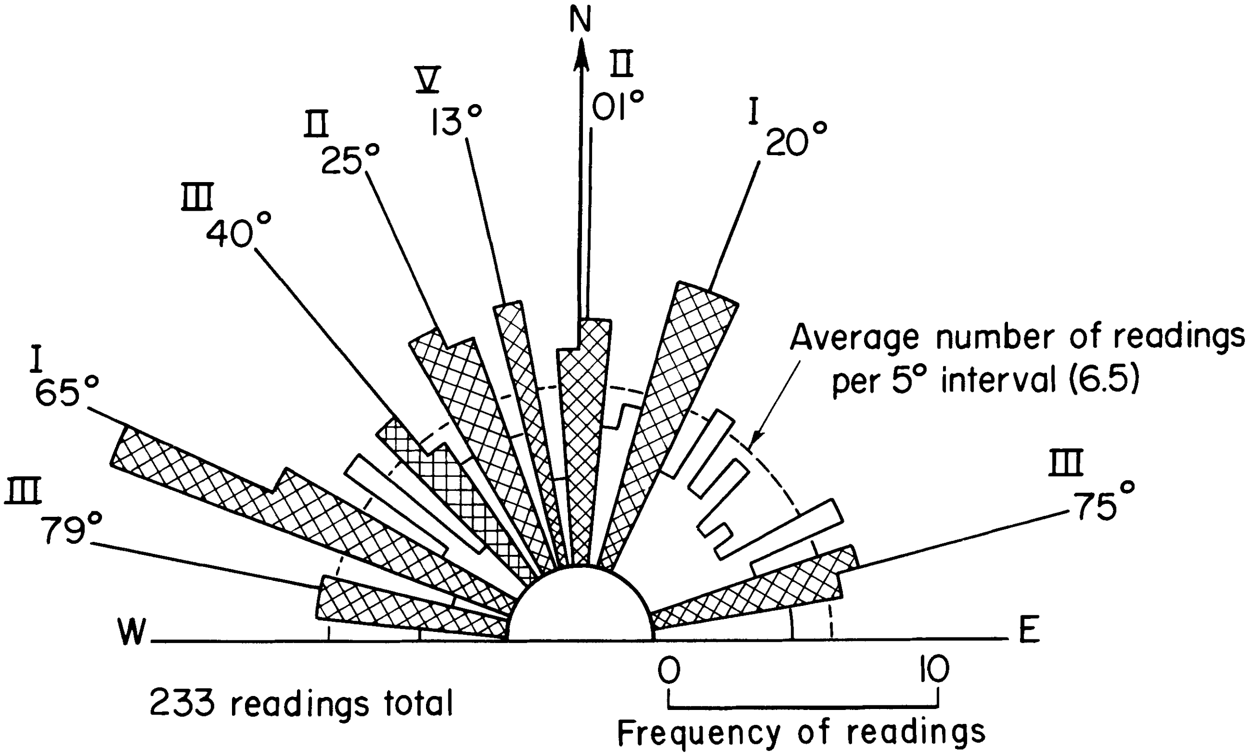


FIGURE 14. - Composite rose diagram of principal infrared photolineament trends.

Figure 14 indicates the presence of five regional photolineament trends in the northwest quadrant and three in the northeast quadrant. The order of dominance of these trends is presented in table 2.

TABLE 2. - Principal infrared photolineament trends, in order of dominance

West group				East group		
I	II	III	V	I	II	III
N 65° W	N 25° W	N 79° W	N 13° W	N 20° E	N 01° E	N 75° E
-	-	N 40° W	-	-	-	-

Individual photolineament trends are paired into five fundamental or near orthogonal infrared photolineament systems.

Systems

1. N 65° W^{I} and N 20° E^{I} (85° separation).
2. N 79° W^{III} and N 20° E^{I} (99° separation).
3. N 79° W^{III} and N 01° E^{II} (80° separation).
4. N 25° W^{II} aand N 75° E^{III} (100° separation).
5. N 13° W^{V} and N 75° E^{III} (88° separation).

NOTE.--Superscripts in Roman numerals indicate order of dominance.

The first infrared photolineament system (N 65° W' - N 20° E') is composed of the most dominant westerly set and the most dominant easterly set. This system is quite similar in orientation to the most dominant systems (1 and 4) paired in the bedrock joint analysis. The N 20° E' set, if not paired with N 65° W', could be paired with N 79° W''' (system 2) to approximate one of the dominant bedrock joint systems, but this system 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 01° E'' (system 3) for an 80° separation. System 3 is fairly close to one of the most dominant bedrock joint systems (system 4); however, it contains one set of the third order of dominance.

Systems 4 and 5 are within the theoretical limits for shears associated with the dominant systems. Both of these are composed of at least one set of third or lower order of dominance. System 1 is judged to be the most dominant photolineament system. No other photolineament system is considered to be of similar dominance.

RONCHI GRID PHOTOLINEAMENT DETERMINATION

Principal directional trends as interpreted from the 13 individual photoindex sheets of the area are plotted in a composite rose diagram (fig. 15).

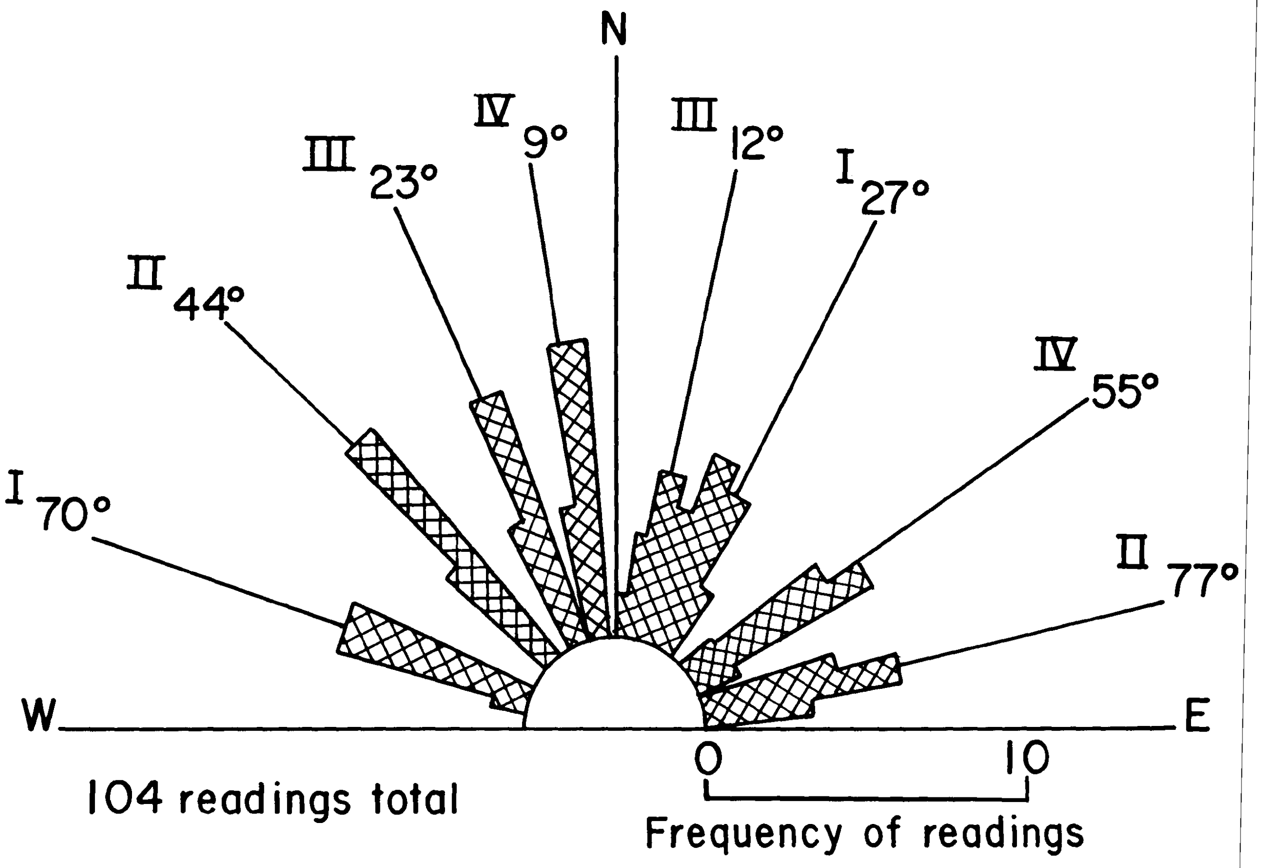


FIGURE 15. - Composite rose diagram of principal Ronchi photoindex sheet trends.

Directional data by county from north to south is given in the appendix, table A-3. Numbered trends are separated into west and east directional groups by their increasing divergence from north and not by their order of dominance. Trends within the same vertical column of a group are assumed correlative.

The composite rose diagram (fig. 15) 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 15, major trends were established (table 3), based on the strength of the alinements viewed through the Ronchi grid.

TABLE 3. - Principal Ronchi photoindex trends in order of dominance

West group				East group			
I	II	III	IV	I	II	III	IV
N 70° W	N 44° W	N 23° W	N 09° W	N 27° E	N 77° E	N 12° E	N 55° E

The 13 photoindex sheets used in the project cover Washington and Greene Counties, Pa., and Monongalia and Marion Counties, W. Va. Eight trends were measured on each sheet. The individual readings are indicated on figure 16 and in table 4. There are 13 readings for each general trend, and since all have the same number of readings, some reliance must be placed on the visual strength of the image. The general directional trends of N 70° W and N 27° E are very pronounced in viewing with the Ronchi grid.

The principal directional trends delineated by the Ronchi grid are listed in the appendix, table A-3, and can be paired into five possible fundamental or near orthogonal systems:

Systems

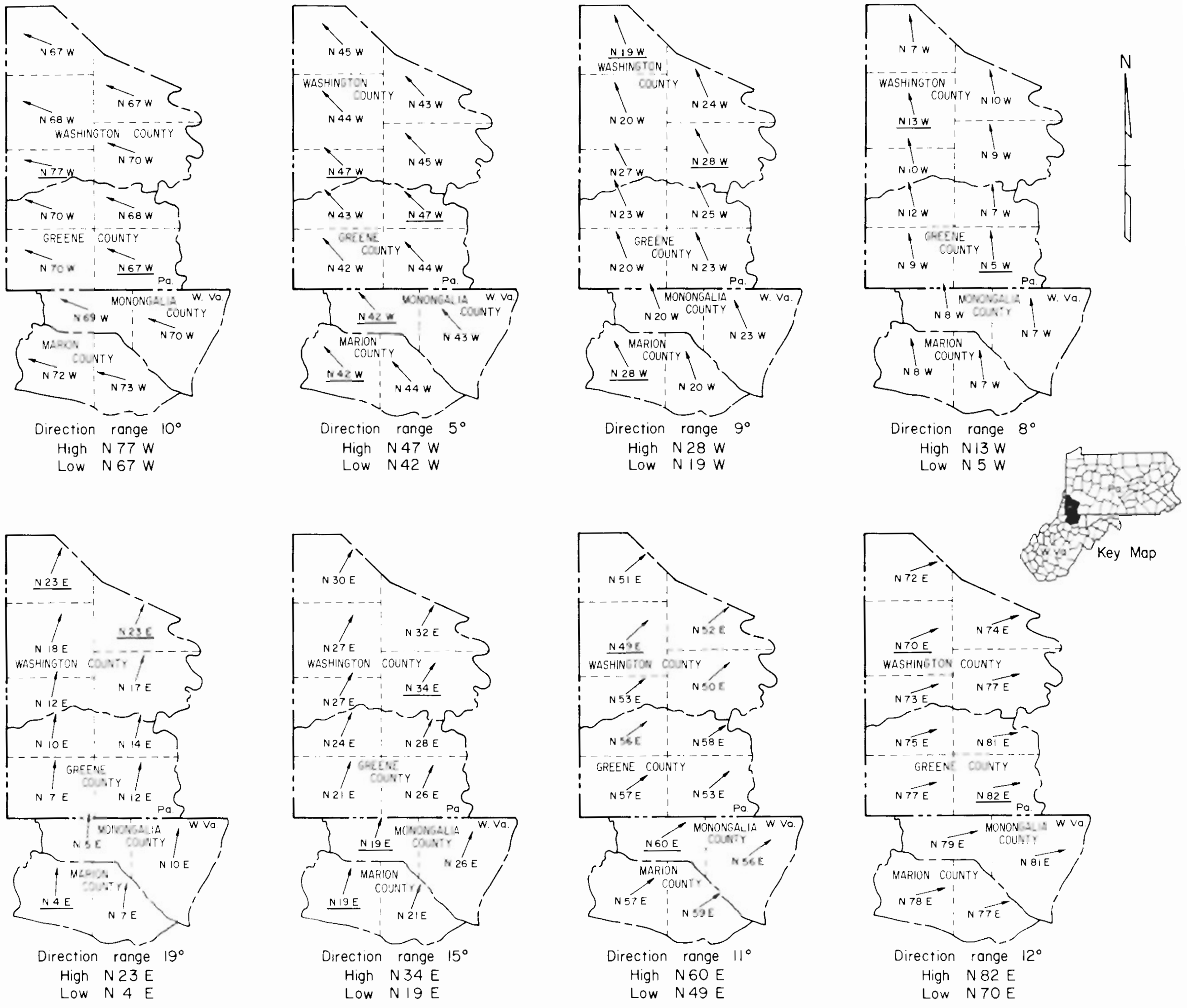
1. N 70° W^{I} - N 27° E^{I} (97° separation).
2. N 70° W^{I} - N 12° E^{III} (82° separation).
3. N 23° W^{III} - N 77° E^{II} (100° separation).
4. N 44° W^{II} - N 55° E^{IV} (99° separation).
5. N 09° W^{IV} - N 77° E^{II} (86° separation).

NOTE.--Superscripts in Roman numerals indicate order of dominance.

The most dominant westerly trend, N 70° W^{I}, can be paired with either N 27° E^{I}, the most dominant easterly trend, or with N 12° E^{III} to approximate nearly orthognal systems. The first system is by far the most dominant of the two. The last three Ronchi systems are not nearly as dominant as system 1, but they have components within the limits of the theoretical angles for shears. Ronchi photoindex system 1 is quite similar in orientation to the two bedrock systems and also to the single infrared photolineament system judged to be the most dominant.

TABLE 4. - Principal Ronchi directions on photoindex sheets of the project 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° E	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



Direction range 10°
High N 77 W
Low N 67 W

Direction range 5°
High N 47 W
Low N 42 W

Direction range 9°
High N 28 W
Low N 19 W

Direction range 8°
High N 13 W
Low N 5 W

Direction range 19°
High N 23 E
Low N 4 E

Direction range 15°
High N 34 E
Low N 19 E

Direction range 11°
High N 60 E
Low N 49 E

Direction range 12°
High N 82 E
Low N 70 E

FIGURE 16. - Maps of the four-county project area showing the eight principal Ronchi directions.

To obtain a pictorial view of the trends of the eight Ronchi alinements, the directions were plotted on small maps of a four-county area covering the principal part of the project (fig. 16). The angles and their directions are indicated at the center of the photoindex sheets in each county. The highest and lowest azimuths are underlined. On these maps, it is seen that the directions of the upper left and the two lower left rotate slightly clockwise from south to north in agreement with the butt cleat, joint, and structural axis directions.

ANALYSIS OF DIRECTIONAL DATA

As many as eight directional trends were established by the various techniques analyzed. Analysis was facilitated and made more meaningful by pairing the west and east trends into all possible combinations of potential fundamental or near orthogonal systems (two trends at 90° to each other). The fundamental or near-orthogonal systems obtained for each technique are listed in table 5.

TABLE 5. - Fundamental or near-orthogonal regional systems from directional data

Data source	System	Orientation		Degrees of separation
Bedrock 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
Photolineaments (IR 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 01° E^{II}	80
	4	N 25° W^{II}	N 75° E^{III}	100
	5	N 13° W^{V}	N 75° E^{III}	88
Ronchi photolineaments (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 09° W^{IV}	N 77° E^{II}	86

NOTE.--Superscripts indicate the order of dominance within the directional groups (west and east) for each data source.

Joints in the bedrock are believed to have resulted from the tectonic stresses and subsequent stress adjustments produced during the erosion and unloading that effected the southwestern Pennsylvania and northern West Virginia area, according to McCulloch and Nickelsen (11-13). Two fundamental or near orthogonal systems of joints, N 76° W^{I} - N 15° E^{I} and N 57° W^{I} - N 27° E^{II} composed of the most dominant trends to the west and to the east, are the bedrock expression of the principal trends and possibly of structural weakness. The bedrock joint data were then compared with the data derived from the photolineament and Ronchi grid methods.

In the analysis of both the infrared and Ronchi photolineaments, several systems (1, 2, and 3 of the infrared and 1 and 2 of the Ronchi) partially correlate with the two most dominant bedrock joint systems (1 and 4). With both the infrared photo and Ronchi photolineament methods, one each of the correlative systems (N 65° W^{I} - N 20° E^{I}, and N 70° W^{I} - N 27° E^{I}) are composed of sets only of the first order, and the other systems are composed of at least one set as low as third-order of dominance. All infrared and Ronchi photolineament systems that do not have similar orientations to the dominant bedrock joint system are composed of at least one set containing a third-order dominance.

Such observations can be used to formulate a set of procedures to be used in estimating the dominant trends of structural weakness from photolineament data. The procedure is (1) determine the relative dominance of all photolinear trends, (2) pair the trends into all fairly close combinations of fundamental or near orthogonal systems, and (3) select the system or systems composed of one set which is the most dominant (first order) and the other set which is of the first or second order, as the most likely estimate of the area's dominant trends of structural weakness.

Utilizing the procedures proposed and the data of this study, system 1 of the infrared photolineament and system 1 of the Ronchi photolineament systems are correlative with the two established dominant joint systems 1 and 4, and are thereby accepted as estimators of directions of structural weakness. In each case, the remaining systems are not used because of lack of dominance. The exclusion of the other correlative lineament systems is not considered particularly objectionable in this example since the two dominant bedrock joint systems are separated by less than 20°. Bedrock joint systems 1 and 4 listed on table 1 have a separation of 19° in the westerly direction (N 57° W to N 76° W) and 12° in the easterly direction (N 27° E to N 15° E).

Systems 2 and 3 of the infrared photolineaments, N 79° W^{III} - N 20° E^{I} and N 79° W^{III} - N 01° E^{II}, and system 2 of Ronchi photolineaments, N 70° W^{I} - N 12° E^{III}, correlate moderately well with system 4, N 76° W^{I} - N 15° E^{I} of the bedrock joints, but cannot be used as estimators because one of the sets in each case has a third order of dominance. It is important to note that only photolineament systems that are closely correlative with the two dominant bedrock joint systems are chosen as estimators, whereas those not correlative are excluded because they contain orders lower than I or II.

Even though the analysis of the Ronchi photolineaments correctly estimates one of the dominant joint systems under the proposed procedure, the confidence in this method is lower than that of the infrared photoanalysis. This is due to the necessity of partly determining the dominancy of Ronchi trends based on a strictly visual impression of image "strength" as opposed to a more analytical approach for the other technique.

GENERAL DISCUSSION OF JOINTING

Although jointing occurs in many types of rock, there is some question as to whether the greatest number of joints in certain azimuths are direct and simple indications of structural weakness. The types of rock and the forces that act upon them determine the joint systems that evolve. A massive sandstone, siltstone, or arenaceous shale may have characteristic directions at regular intervals. A joint system may have sets that were developed at varying times under different conditions. A sedimentary rock under compression by overburden can develop a set while consolidating. A joint set may form by release of pressure during erosion, and at other times through tensional movement. In folded rocks, the joint pattern can be related to stress directions in a very irregular manner.

The configuration of folds, character of bedding and lithology, and the dip of beds affect the spacing, orientation, and number of joints. Drainage development also influences the types, number, and proportions of lineaments as well as the size and manner in which outcrops are exposed. Furthermore, it is conceivable that some well-jointed rocks are so soft and friable that no exposures remain to measure.

The practice of combining joint trends of various directions from minor, widely scattered outcrops, formed at different times in various types of rocks, may include some intrinsic error, especially when considering effects of local conditions and limited areas of weakness within regional zones. Some geologists believe that joints form in the process of lithification and compaction and are not dependent orogenic forces. However, mountain building and directional tectonic forces such as provided by the Appalachian orogeny are believed to have had a part in the formation of major joints sets in the study area.

Pennsylvanian and Permian sediments account for practically all of the bedrock in the project area; sandstones and siltstones are the most common. The procedure in taking joint measurements was first to make a reconnaissance by automobile of the quadrangle to be investigated with the help of available geological and topographic maps, noting outcrops, access roads, and routes to be taken. The orientation of every joint was measured regardless of prominence and without selectivity in direction. For an overall evaluation, it was decided to include all joint directions; perhaps in this way, the most pronounced trends would emerge. This is seemingly what happened, even with the disparities and complexities of joint origin and occurrence. The results after tabulation and analysis indicate trends of structural weakness that appear to be dependable in the area of the Allegheny Plateau.

CONCLUSIONS

The three methods described in this paper produced essentially similar results, and these findings are substantially the same as those obtained by Nickelsen and Hough (13). Data on cleat directions in Bureau of Mines RI 8093 (12) and that determined by Nickelsen and Hough (13) are also in close agreement. The principal bedrock joints and zones of weakness in the area of the Pittsburgh coalbed are found to be almost parallel to the cleats in the coalbeds. It has also been observed that directions of coal cleats are more uniform and indicate less directional diversity than joint directions in surrounding rocks.

Zones of structural weakness in the earth's crust may be the cause of roof falls during underground mining of coal. Where these zones are observable as fractures in bedrock exposures, their directions can be measured directly in the field, or if difficult field conditions exist, directions can be estimated by the recognition of lineaments through stereoscopic examination of aerial photographs.

The strikes of joints occurring in bedrock were measured throughout the project area in southwestern Pennsylvania and northwestern West Virginia to compare with photogeologic methods for coal mining investigations. The procedure formulated for estimating zones of structural weakness were to (1) define the outstanding photolineament trends, (2) pair the trends into combinations of fundamental or near orthogonal systems (two trends, at near 90° to each other), and (3) select as the estimator of structural weakness the system or systems composed of one trend that is the most dominant and the other trend that is the first or second most dominant.

The measurement and analysis of bedrock joints in the field is believed to be the most direct and reliable method for determining dominant trends of structural weakness. Photolineament analysis through steroscopic viewing of infrared photographs is a useful substitute or complementary method, especially when field work is difficult owing to weather conditions, rugged terrain, lack of outcrops, or unavailability of field personnel.

The Ronchi grid examination of photoindex sheets closely estimated the dominant trends of structural weakness. However, less confidence is placed in this method owing to the necessity of determining dominancy of trends by a visual impression of image "strength." The primary function of the Ronchi method is for relatively fast and inexpensive reconnaissance on a regional basis. It is desirable for use in conjunction with the analysis of bedrock joint and photolineament data for comprehensive information. No one method is infallible; the three complement each other.

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APPENDIX

TABLE A-1. - Average bedrock joint trends, by county

County	Tier	Groups								
		1	2	3	4	5	6	7	8	9
				WEST						
Washington..........	1, 2, 3	N 6° W	N 21° W	N 33° W	-	N 49° W	N 57° W	N 73° W	-	N 85° W
Greene..............	4, 5	-	N 19° W	N 28° W	N 40° W	-	N 58° W	N 75° W	N 81° W	-
Wetzel and Monongalia	6	-	-	-	-	N 51° W	-	N 67° W	N 80° W	N 87° W
Marion and Monongalia	7	N 5° W	N 20° W	-	-	N 51° W	-	N 68° W	N 81° W	-
Marion and Harrison..	8	N 7° W	-	N 35° W	-	N 51° W	N 61° W	-	N 80° W	N 89° W
Directional mean..	-	N 6° W	N 20° W	N 32° W	N 40° W	N 51° W	N 59° W	N 71° W	N 81° W	N 87° W
				EAST						
Washington..........	1, 2, 3	N 7° E	-	N 19° E	N 29° E	N 37° E	N 46° E	N 63° E	N 72° E	N 89° E
Greene..............	4, 5	N 2° E	N 14° E	N 22° E	N 28° E	N 38° E	N 49° E	-	-	N 80° E
Wetzel and Monongalia	6	N 5° E	N 13° E	-	N 27° E	-	N 53° E	-	N 72° E	-
Marion and Monongalia	7	N 2° E	N 15° E	-	N 25° E	N 37° E	-	-	N 68° E	N 86° E
Marion and Harrison..	8	N 5° E	N 14° E	-	N 27° E	N 39° E	-	N 59° E	N 72° E	N 83° E
Directional mean..	-	N 4° E	N 14° E	N 21° E	N 27° E	N 38° E	N 49° E	N 61° E	N 71° E	N 85° E

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

TABLE A-2. - Average photolineament trends, by county

County	Tier	Groups							
		1	2	3	4	5	6	7	8
WEST									
Washington...........	1, 2, 3	N 3° W	N 12° W	N 21° W	N 30° W	N 39° W	N 52° W	N 66° W	N 85° W
Greene...............	4, 5	N 3° W	N 14° W	N 24° W	-	N 41° W	N 54° W	N 65° W	N 76° W
Wetzel and Monongalia.	6	N 4° W	-	N 18° W	N 29° W	N 44° W	N 51° W	N 65° W	N 74° W
Marion and Monongalia.	7	N 4° W	N 11° W	-	N 30° W	N 43° W	-	N 61° W	N 80° W
Marion and Harrison...	8	N 3° W	N 13° W	N 23° W	N 35° W	N 43° W	N 52° W	N 69° W	N 79° W
Directional mean...	-	N 3° W	N 13° W	N 22° W	N 31° W	N 42° W	N 52° W	N 65° W	N 79° W
EAST									
Washington...........	1, 2, 3	N 4° E	N 13° E	N 19° E	N 37° E	N 51° E	N 63° E	N 78° E	-
Greene...............	4, 5	N 5° E	-	N 20° E	N 31° E	N 44° E	N 62° E	N 75° E	N 89° E
Wetzel and Monongalia.	6	N 2° E	N 15° E	N 24° E	N 32° E	N 54° E	-	N 72° E	N 88° E
Marion and Monongalia.	7	N 3° E	N 15° E	N 25° E	N 37° E	-	-	N 69° E	-
Marion and Harrison...	8	-	N 16° E	N 24° E	N 38° E	N 50° E	N 63° E	-	N 84° E
Directional mean...	-	N 4° E	N 15° E	N 22° E	N 35° E	N 50° E	N 63° E	N 74° E	N 87° E

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

TABLE A-3. - Average Ronchi photoindex sheet lineament trends, by county

County	Groups			
	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
Directional mean	N 9° W	N 23° W	N 43° W	N 71° 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
Directional mean	N 11° E	N 25° E	N 56° E	N 78° E

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

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