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Use of Surface Joint and Photolinear Data for Predicting Subsurface Coal Cleat Orientation

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USE OF SURFACE JOINT AND PHOTOLINEAR DATA FOR PREDICTING SUBSURFACE COAL CLEAT ORIENTATION

by

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

ABSTRACT

Coalbeds exhibit a directional permeability, with the maximum permeability oriented parallel to the face cleat. Thus, the most efficient pattern of vertical degasification holes for a coalbed is dependent upon cleat orientation. Surface joints, infrared photolinears, and Ronchi grating photolinears were investigated as potential estimators of subsurface cleat orientation. Cleat orientations were measured in 18 mines in the Pittsburgh coalbed in southwestern Pennsylvania and northern West Virginia to be used as a standard against which prediction techniques would be evaluated. Two cleat systems with a strong geographic segregation were measured in the study area: N 67° W - N 28° E (95° separation) for the north, and N 76° W - N 17° E (93° separation) for the south.

Directional data obtained from the three techniques investigated yielded satisfactory regional predictions of cleat orientation. Analysis of surface joints was the only technique considered sufficiently reliable on a local basis. Prediction of cleat orientation is based on the pairing of the principal directional sets into all reasonable combinations of fundamental systems. The system or systems composed of the most dominant sets nearest to 90° separation are likely to be a reliable prediction of cleat orientation. The most dominant set of the system selected is likely to be the face cleat.

INTRODUCTION

Cleat is the naturally occurring vertical fracture in coal. Two cleat sets are commonly oriented perpendicular to each other to form a fundamental system (4).[2] The more dominant fracture is the face cleat, which cuts across bedding surfaces in the coal and may extend for many feet horizontally. The butt cleat is a short, poorly developed fracture that commonly is truncated by the face cleat.

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[1] Geologist.
[2] Underlined numbers in parentheses refer to the list of references at the end of this report.

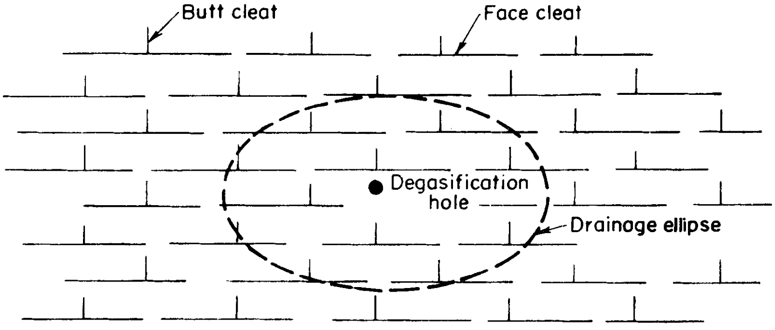

FIGURE 1. - Plan view of directional permeability due to cleat orientation.

It has been demonstrated by the Bureau of Mines (1) that coalbeds exhibit a directional permeability directly related to the cleat system. Degasification experiments conducted underground in coal mines have shown that horizontal holes drilled perpendicular to, and therefore intersecting, the largest number of face cleats will yield 2.5 to 10 times as much gas as holes drilled perpendicular to the butt cleat. This observation can in turn be related to the placement of vertical degasification holes drilled from the surface into a coalbed. A vertical hole into a coalbed with a well-developed face and butt cleat (for example, the Pittsburgh coalbed) will collect gas at a higher rate from the face cleat direction than from the butt cleat direction. Therefore, an elliptical drainage pattern (fig. 1) will be developed with the long axis parallel to the face cleat.

To determine the most efficient pattern for vertical degasification holes in an area of virgin coal, the subsurface cleat orientation must be determined. In conjunction with an extensive investigation of the Pittsburgh coalbed in a 39-quadrangle area in southwestern Pennsylvania and northern West Virginia, a study was undertaken to evaluate several techniques for estimating cleat orientation. The area of study was particularly well suited for the proposed investigation owing to the well-developed cleat system of the Pittsburgh coal and the numerous underground mines, which provided excellent control data on cleat orientation.

DETERMINATION AND ANALYSIS OF CLEAT ORIENTATION

Cleat orientations were measured in 18 mines operating in the Pittsburgh coalbed (fig. 2). Data were plotted on a semicircular rose diagram for evaluation of cleat orientation for each mine. A single, well-defined cleat system, such as for the Osage No. 3 mine (fig. 3), was typically observed. The mean face and butt cleat orientation of each mine was plotted on a composite rose diagram (fig. 4) to demonstrate the regional trends.

The composite rose diagram (fig. 4) indicates the presence of two nearly orthogonal cleat systems. The two fundamental cleat systems calculated for the study area are N 67° W - N 28° E (95° separation), and N 76° W - N 17° E (93° separation). The first system is composed of the readings from mines located in the northern part of the study area (Nos. 1-7, fig. 2) plus one mine (No. 9) more closely associated geographically with the southern part. The second system is composed of readings from the mines (Nos. 8 and 10-18) located in the southern part of the area.

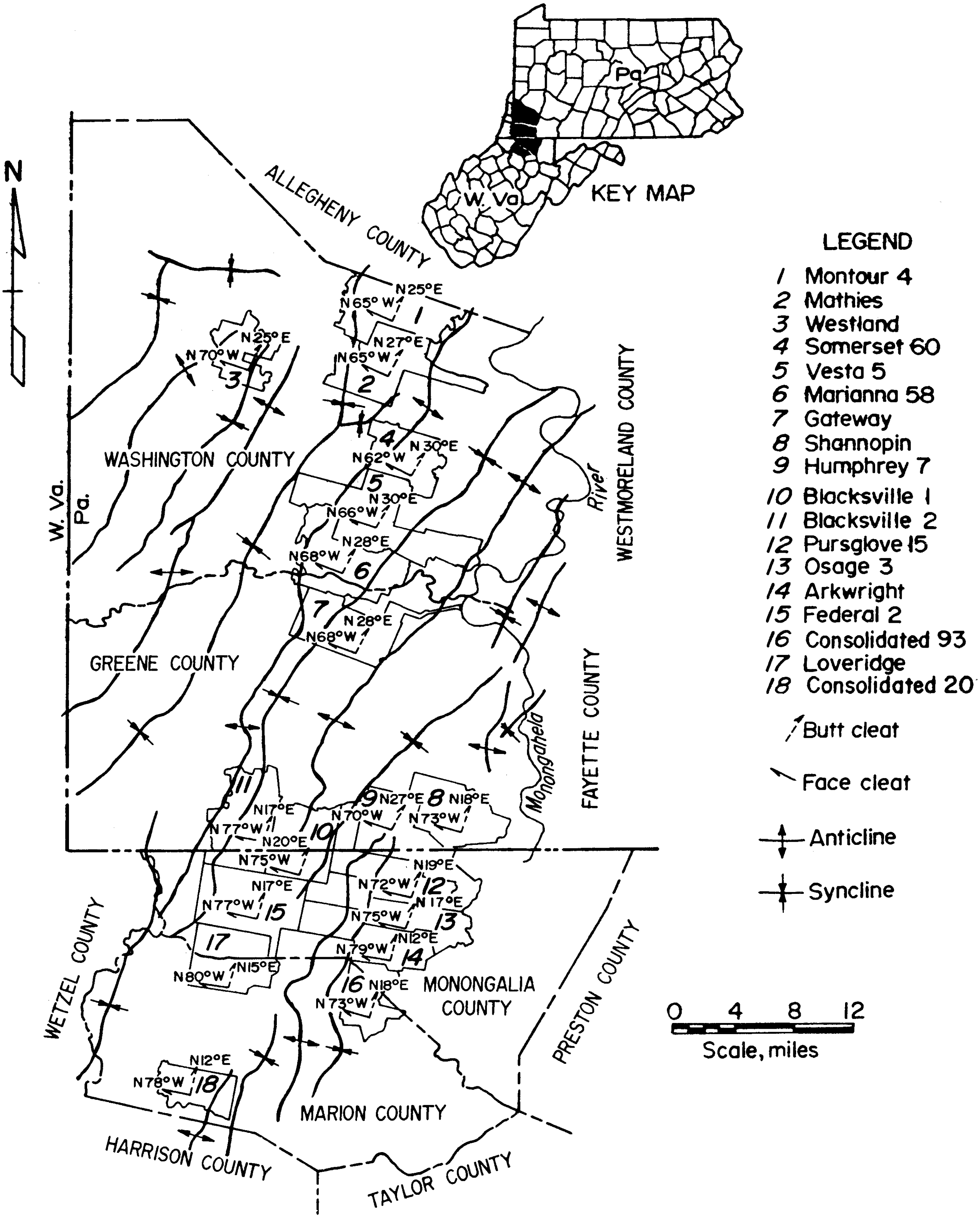

FIGURE 2. - Structure, cleat orientation, and mine locations in study area.

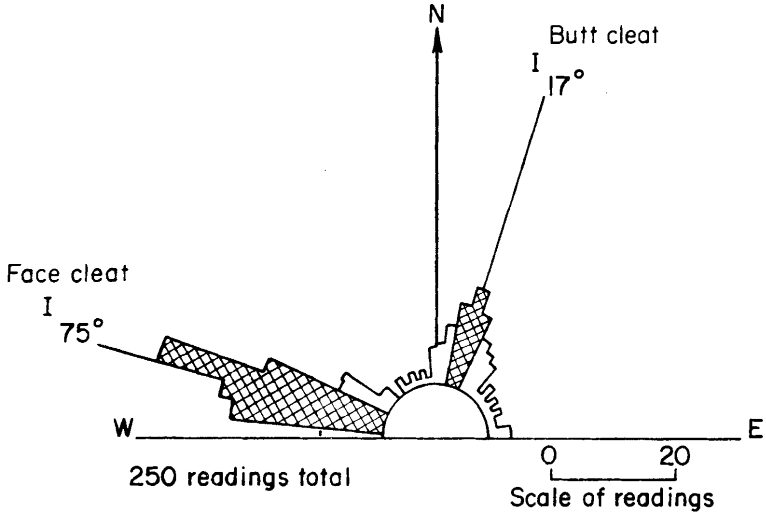

FIGURE 3. - Cleat orientation, Osage No. 3 mine, Monongalia County, W. Va.

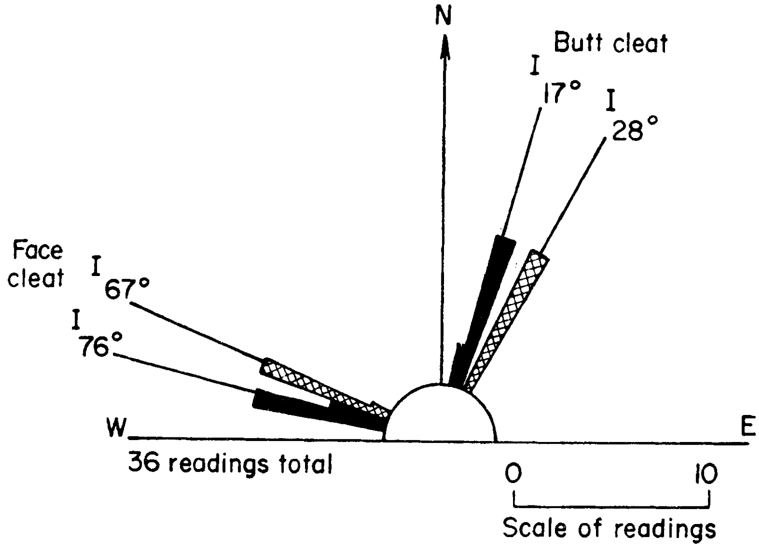

FIGURE 4. - Composite rose diagram of cleat orientation.

Nickelsen and Hough (4), in their study of jointing in the Appalachian Plateau of Pennsylvania, reported similar segregations, concluding that there existed a "number of locally dominant trends." They also noted an "overlap of trends dominant in adjacent local areas and that isolated occurrences of any given joint set may occur far from the area of its greatest dominance." The latter conclusion was observed for the Humphrey No. 7 mine (No. 9), which was geographically within the southern group of mines, but the cleat orientation was similar to those of the northern mines. The Blacksville No. 1 mine (No. 10) to the west of the Humphrey No. 7 mine has a bimodal face cleat peak (fig. 5). The most dominant face cleat, N 75° W, is similar to that of the southern group of mines where the mine is geographically located. The secondary face cleat, N 63° W, is similar to that observed in the northern group of mines. The Pursglove No. 15 mine (No. 12), located adjacent to mines 9 and 10, has a suggestion of a bimodal face and butt cleat similar to that of the Blacksville No. 1 mine. However, the separation of the peaks is not considered sufficient to calculate two separate fundamental systems.

The separation of the cleat readings into two distinct systems indicates approximately a 10° rotation of the cleat system, clockwise northward through the area. The rotation of the cleat system is similar to the change in trend observed for the fold axis of the area (fig. 2). The butt cleats are essentially parallel to the axial trends of folds, and the face cleats are perpendicular to them. It has been proposed by Nickelsen and Hough (4) and reiterated by McCulloch and others (3) that the face cleats were formed as

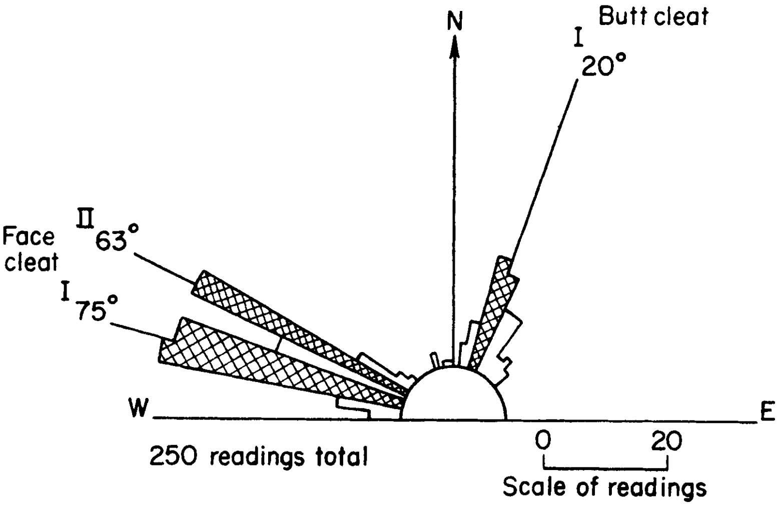

FIGURE 5. - Cleat orientation, Blacksville No. 1 mine, Greene County, Pa., and Monongalia County, W. Va.

extension fractures oriented parallel to the greatest principal compression stress axis that produced the area's folds. The origin of butt cleats is obscure, but they are possibly release fractures formed perpendicular to the greatest principal compressional stress axis during erosion and uplift. If this is true, then rocks other than coal potentially have similar joint orientation and dominance, hence the study of surface joints and photolinears to determine if they can be used to predict cleat orientation in virgin coal areas.

TECHNIQUES FOR PREDICTION OF CLEAT ORIENTATION

Three techniques were investigated for possible use in cleat prediction. Surface joints were measured for each of the 39 quadrangles of the study area. A minimum of 10 sample locations per quadrangle, with at least 10 readings per location, were obtained. Joints of varying prominence were measured in all lithologies in varying bed thicknesses to obtain a broad estimate of joint sets present in each quadrangle. Infrared aerial photographs were examined stereoscopically for linears. Owing to the masking effect of the urban and mining culture on the area, photolinear interpretation was based predominantly on straight water courses, stream valleys, and abrupt right-angle bends of streams. Thirteen photoindex sheets covering the study area were inspected for photolinears using a Ronchi defraction grating. This technique (5) combines many indistinguishable small parallel linear features into a more readily observable directional trend. Because the scale of the photoindex sheets is 1 inch equals 1 mile, only very general trends can be differentiated; individual linears, which could be seen with the infrared photographs at a scale of 1 inch equals 2,000 feet, could not be identified.

ANALYSIS OF REGIONAL DIRECTIONAL DATA

For the three techniques investigated, the directional data were originally compiled and plotted on rose diagrams for individual 7-1/2-minute quadrangle or photoindex sheet areas. Peaks 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° intervals. A decline of one-third the number of readings comprising a high point was used to define the limits of an individual peak, with the first 5° interval containing less than two-thirds of the high point not being included within the peak. However, if the first 5° interval to decline one-third the number of readings, and the next adjacent

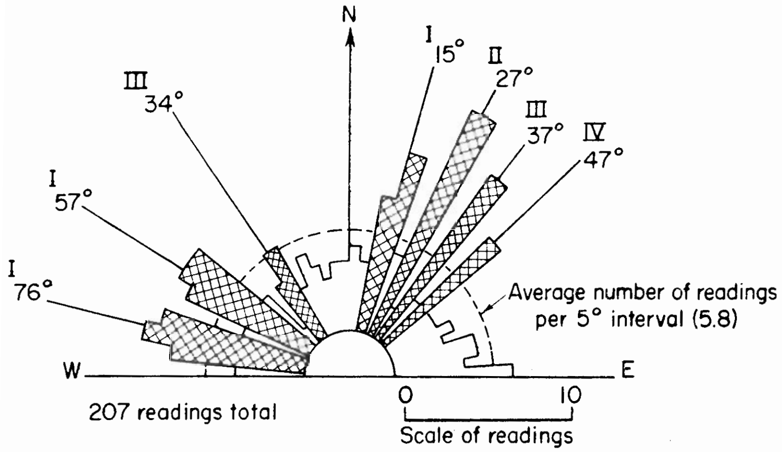

FIGURE 6. - Composite rose diagram of principal surface joint trends.

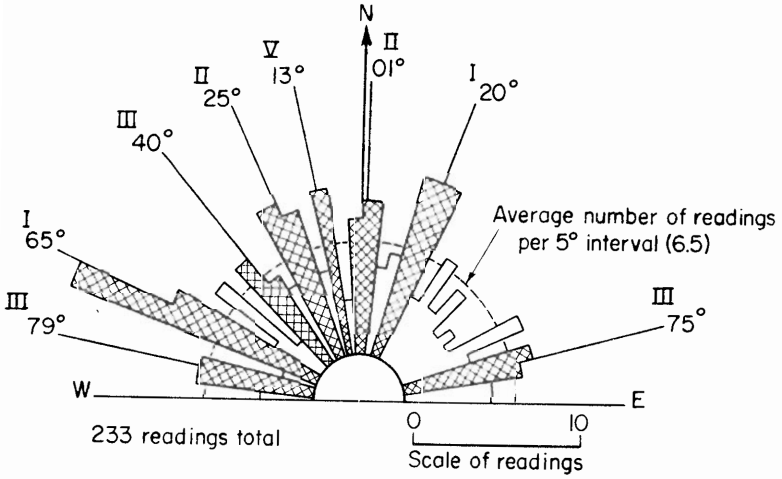

FIGURE 7. - Composite rose diagram of principal infrared photograph photolinears.

5° interval declines an additional one-third, then the first 5° interval to decline one-third is included 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 percent of the total number of readings.

The values of the trends from all individual areas were plotted on a single regional composite rose diagram for each technique (figs. 6-8). Trends on the composite rose diagrams of the surface joint and infrared photo data were assigned orders of dominance (table 1) based on the total number of readings comprising each peak. A difference of 10 percent in the number of readings is considered sufficient to assign different orders of dominance.

Trends established by the Ronchi inspection of photoindex sheets could not be assigned meaningful orders of dominance based on the composite rose diagram. This is the result of a small number of readings and the high degree of similarity between trends obtained from all photoindex sheets, which precludes the enhancement of one trend over another. However, it was possible to assign orders of dominance to the data based on a visual impression of image "strength" as each index sheet was viewed through the Ronchi grating.

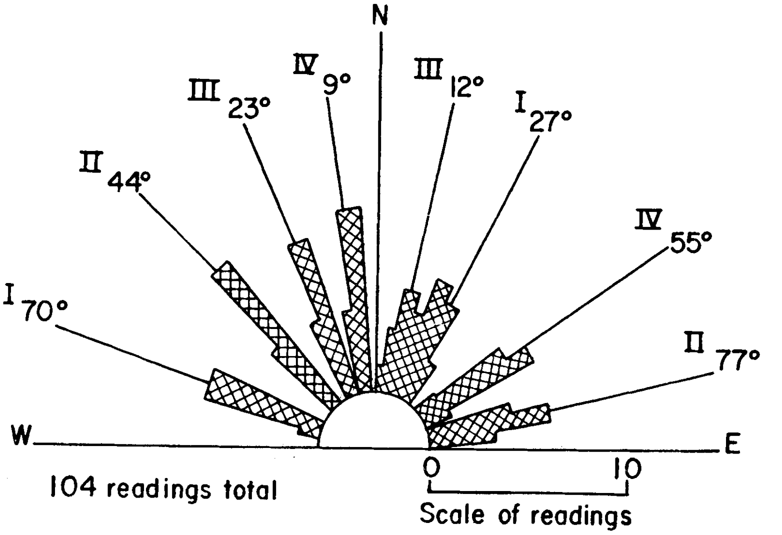

FIGURE 8. - Composite rose diagram of principal photoindex photolinears.

The principal regional sets of table 1 are paired into combinations of fundamental systems in table 2.

Two surface joint systems (Nos. 2 and 4) are composed only of joint sets of the first order of dominance. Both systems are composed of the N 15° E' set. System 4, with a 91° separation, more closely approaches the ideal fundamental system's 90° separation than does system 2, which has a 72° separation. System 4 (*N 76° W' - N 15° E') is quite similar in orientation to the *N 76° W' - N 17° E' cleat system established underground. The N 76° W' set of system 4 is the most dominant set of system 4, and it parallels the face cleat. The N 76° W' set could also be paired with the N 27° E'' set (system 5), but the separation of 103° is greater and the N 27° E'' set is less dominant than the N 15° E' set.

TABLE 1. - Principal directional sets in order of dominance

Data source	West				
	I	II	III	IV	V
Surface joints	N 57° W	-	N 34° W	-	-
	N 76° W	-	-	-	-
Photolinears (IR photographs)	N 65° W	N 25° W	N 79° W	-	N 13° W
	-	-	N 40° W	-	-
Photolinears (photoindex sheets)	N 70° W	N 44° W	N 23° W	N 09° W	-
	East				
	I	II	III	IV	
Surface joints	N 15° E	N 27° E	N 37° E	N 47° E	
Photolinears (IR photographs)	N 20° E	N 01° E	N 75° E	-	
Photolinears (photoindex sheets)	N 27° E	N 77° E	N 12° E	N 55° E	

NOTE.--Sets of equal dominance are listed in the same column of a data source.

TABLE 2. - Fundamental regional systems from directional data

Data source	System: West	System: East	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 (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 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 09° 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 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}), though 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 first infrared photolinear system (*N 65° W^{I} - N 20° E^{I}) is composed of the most dominant westerly set and the most dominant easterly set. This system best estimates the established *N 67° W^{I} - N 28° E^{I} coal cleat system. The *N 65° W^{I} set is the most dominant of the system, and it nearly parallels the face cleat. The N 20° E^{I} set, if not paired with N 65° W^{I}, could be paired with N 79° W^{III} (system 2), which is similar to the *N 76° W^{I} - N 17° E^{I}

cleat system. However, photolinear system 2 contains one set of the third order and has a larger divergence from 90° than does system 1. The N 79° W''' set can also be paired with N 01° E'' (system 3) for an 80° separation. This system, while having one set (*N 01° E'') that diverges 16° from the butt cleat of the *N 76° W' - N 17° E' cleat system, has one set (N 79° W''') that only diverges 3° from the face cleat. However, system 3 is composed of one set of the third order, and more significantly the most dominant set of the system *N 01° 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.

The first photoindex system (*N 70° W' - N 27° E') is composed of the two most dominant sets. This system is similar to the *N 67° W' - N 28° E' cleat system. The *N 70° W' set is the most dominant of the system, and parallels the face cleat. The *N 70° W' set could additionally be paired with N 12° E''' set to approximate the *N 76° W' - N 17° E' cleat system. This second system, however, contains one component of the third order. The remaining three photoindex systems are composed of sets of second and lower orders of dominance and are not similar to the established cleat systems.

ANALYSIS OF LOCAL DIRECTIONAL DATA

The relationship between coal cleats measured in individual mines and the directional trends established by measuring joints and photolinears directly overlying the mines is given in table 3. Surface joints provided the best estimator of cleat, averaging 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 set in the vicinity of N 15° - 30° W. This is similar to the *N 25° W'' set observed on the photolinear composite rose diagram (fig. 7), and the N 34° W''' set on the surface joint composite rose diagram (fig. 6). Lattman and Nickelsen (2), in an investigation of the correlation between surface joints and photolinears in a small (6-square-mile) area of central Pennsylvania, determined that even though the face cleat generally correlated with the dominant surface joint and photolinear sets, coal cleat orientations were not necessarily reflected in surface joints in shale and sandstones. It was also found that the joints in shales and sandstones produced the strongest photolinears. It seems possible that in light of these observations, a surface joint trend that is not parallel to a cleat orientation may be intensified as a photolinear in local areas.

TABLE 3. - 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	West	East	West	East
1	Montour 4..........	*N 65° W	N 25° E	N 55° W	*N 37° E	10	12	([1])	([1])	-	-
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	([2])	([2])	-	-
4	Somerset No. 60....	*N 62° W	N 30° E	*N 65° W	N 27° E	3	3	N 06° 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	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
11	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
12	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
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 03° E	13	9	*N 53° W	N 32° E	25	20
-	Average divergence.	-	-	-	-	7.4	6.6	-	-	23.7	19.4

[1] Insufficient data.
[2] Indeterminate.

NOTE.--An asterisk indicates the dominant set of each system. If no asterisk appears, both sets are of equal dominance.

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 areas of interest. As outcrops become less numerous and farther away from the area, the validity of the analysis decreases. Under these conditions, photointerpretation would perhaps be beneficial because it does not rely on outcrops for data. However, photoanalysis, which depends on the availability of quality photographs and an experienced photointerpreter, was significantly less reliable than field measurements of joints in the area investigated. Both methods are limited by the small number of directional measurements usually obtainable for a small area. With small samples, individual trends stand out less clearly, which makes analysis difficult.

CRITERIA FOR CLEAT PREDICTION

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 predict the cleat orientations 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 latter 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 since the two cleat systems are separated by only 10°. The directional systems not correlative with established cleat systems were rejected in all cases because they did not meet the dominance requirements.

CONCLUSION

The regional orientation of subsurface cleat systems in southwestern Pennsylvania and northern West Virginia is reflected in the fracture trends of other rock types. An analysis of the directional trends of surface joints, linears determined from examination of infrared photography, and linears observed on photoindex sheets using a Ronchi grating should provide a reliable estimate of cleat orientation in areas of virgin coal where similar geologic conditions exist. The procedure depends upon assigning a relative dominance to the principal directional sets obtained by the three methods and pairing them into fundamental systems. The analysis of surface joints is the only technique considered sufficiently reliable to be used on a local basis, but even this may fail if there is a strong divergence between cleats in coal and joints in the overburden. Reliable cleat prediction for a small area depends on the measurement of enough linear features to permit differentiation of individual trends.

Even though inspection of photoindex sheets with a Ronchi grating did allow prediction of one of the regional cleat systems, less confidence is placed on this technique than in the analysis of surface joint data and infrared photolinears. This is because the dominance of Ronchi grating trends is based on a visual impression of image "strength" as opposed to a more analytical approach for the other techniques.

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