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Probability of Encountering Coalbed Discontinuities During Vertical and Horizontal Borehole Drilling

By David W. Houseknecht

UNITED STATES DEPARTMENT OF THE INTERIOR

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PROBABILITY OF ENCOUNTERING COALBED DISCONTINUITIES DURING VERTICAL AND HORIZONTAL BOREHOLE DRILLING

By David W. Houseknecht [1]

ABSTRACT

Probabilities of encountering coalbed discontinuities during vertical or horizontal drilling in a specific coalbed can be estimated based on analysis of mined-out areas of the coalbed where the size, shape, orientation, and distribution of discontinuities are known. The resultant probability estimates can be applied to cost-risk evaluations of drilling programs proposed for exploratory, developmental, or methane drainage purposes in undeveloped areas of that coalbed.

Data compiled from mine maps of the Beckley Coalbed in southern West Virginia were used to estimate the probabilities that discontinuities would be encountered in two illustrative hypothetical drilling programs--one for drilling vertical boreholes and the other for drilling horizontal boreholes. Analysis based on a mined-out area of the Beckley Coalbed indicated that vertical methane drainage boreholes spaced 1,000 feet apart in a square grid pattern would each have a 29 percent probability of encountering a discontinuity in a geologically unexplored area of the coalbed. It was also determined that exploratory vertical drilling could locate most of the discontinuities if a borehole spacing of 2,500 feet were used. For horizontal drainage boreholes in the Beckley Coalbed, the analysis indicated a linear relationship between hole length and the probability of encountering a discontinuity.

[1] Geologist, Department of Geology, University of Missouri, Columbia, Mo.; faculty advisor with the Bureau of Mines, Pittsburgh Research Center, Pittsburgh Pa.

INTRODUCTION

Coalbed discontinuities are a major problem encountered during the drilling of methane drainage boreholes and during all phases of coal exploration and development. Specific problems related to discontinuities are numerous. The presence of undetected discontinuities can result in overestimation of a property's reserve and production potential. Discontinuities encountered during developmental mining can result in delays in entry development and in the completion of ventilation circuits. In certain geologic settings, natural gas may be emitted from discontinuities into a mine atmosphere (6).[2] Discontinuities can obstruct methane drainage borehole drilling and block anticipated gas migration paths to methane drainage boreholes. Roof instability and the presence of excess water are often related to lithologic facies changes in roof strata associated with discontinuities (6).

As part of its methane control program, the Bureau of Mines has addressed the problem of anticipating coalbed discontinuities because these discontinuities frequently have adverse effects on methane drainage drilling programs. This report summarizes a method for estimating probabilities of encountering discontinuities during drilling so that cost and risk factors can be more thoroughly analyzed in advance of major drilling programs, whether they are for methane drainage, exploratory, or developmental purposes. The procedure described can be completed with a modest investment of time and money, and yet it provides a quantitative estimate of the probabilities of encountering discontinuities when various vertical borehole spacings and various horizontal borehole lengths are used.

ACKNOWLEDGMENTS

Mine maps and other information pertaining to Beckley Coalbed discontinuities were provided by The New River Co., Piney Creek Coal Co., and Westmoreland Coal Co.

THE BECKLEY COALBED

The Beckley Coalbed of southern West Virginia is used as a model for this study. This coalbed lies within the New River Formation of the Pottsville Group (fig. 1) and attains a minable thickness in large areas of West Virginia's Raleigh, Wyoming, and McDowell Counties (7). Beckley coal is a high-quality metallurgical coal, typically ranging between low- and medium-volatile bituminous rank with the following average characteristics: Fixed carbon, 74 to 77 percent; volatile matter, 16 to 18 percent; total sulfur, less than 1 percent; total ash, 3 to 6 percent; calorific value, 14,500 to 15,000 Btu/lb; and mean vitrinite reflectance, 1.50 to 1.55 percent.

Mining operations in the Beckley Coalbed have long been plagued by severe mining problems, including coalbed discontinuities, roof instability, excessive methane emission from the coalbed and enclosing strata (8), and excessive ground water migration into mine entries

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

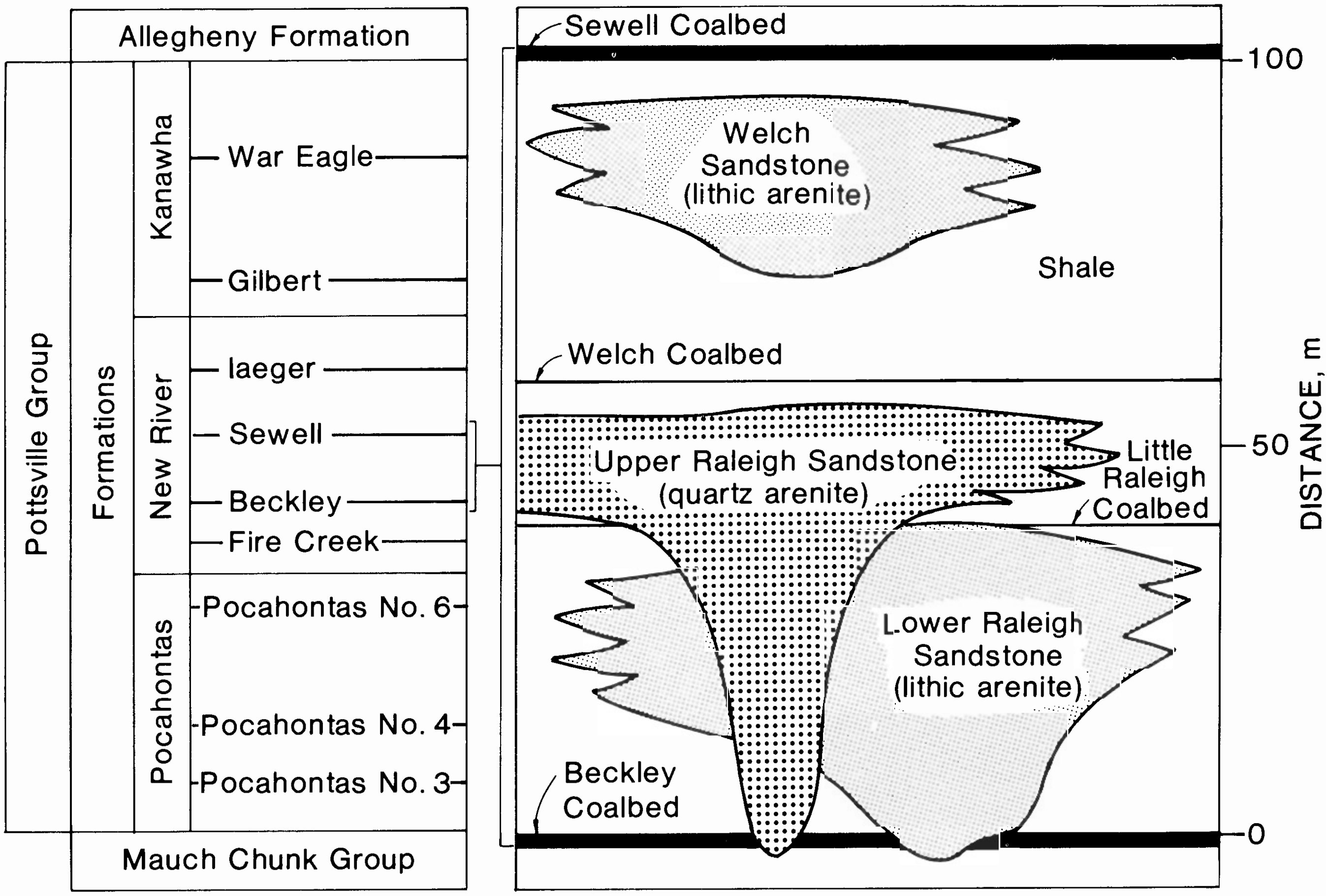


FIGURE 1. - Generalized stratigraphic column showing position of Beckley Coalbed (modified from reference 5).

from enclosing strata. Continuous mining activity since early in this century has resulted in large mined-out areas, most of which were accurately mapped as mining progressed. The coalbed's mining problems (especially the discontinuities) and the existence of accurate maps of the mined-out areas make the Beckley an ideal coalbed to use as an example of how to estimate the probability of encountering discontinuities during drilling.

Figure 2 is a map of a large area in portions of the Beckley, Crab Orchard, Lester, and Eccles 7-1/2-minute quadrangles of southern West Virginia. Within this area, the Beckley Coalbed has been mined out in five large mines, as shown on the map. Figure 3 shows the locations of approximately 300 boreholes which have been drilled into the Beckley Coalbed during exploration and development (in the same area as is shown in figure 2) since the early part of the century. Figure 4 is a map of discontinuities that have been delineated within the Beckley Coalbed (again in the same area), partly during mining and partly as a result of drilling.

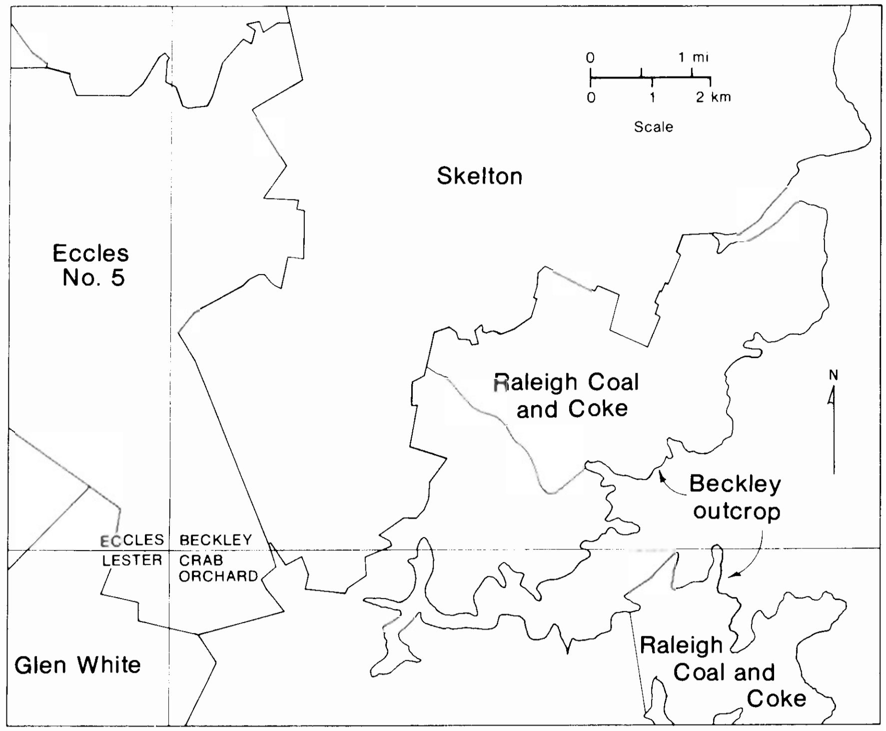


FIGURE 2. - Map of study area showing mines that have encountered discontinuities in the Beckley Coalbed.

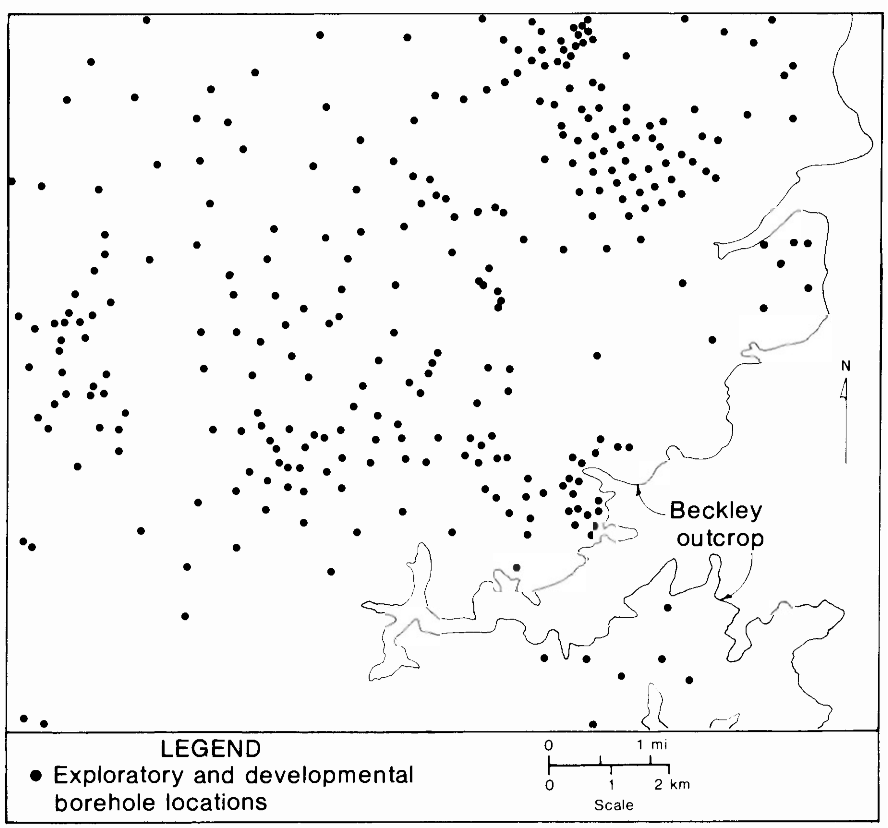


FIGURE 3. - Location of approximately 300 boreholes drilled within the study area for exploratory and/or developmental purposes.

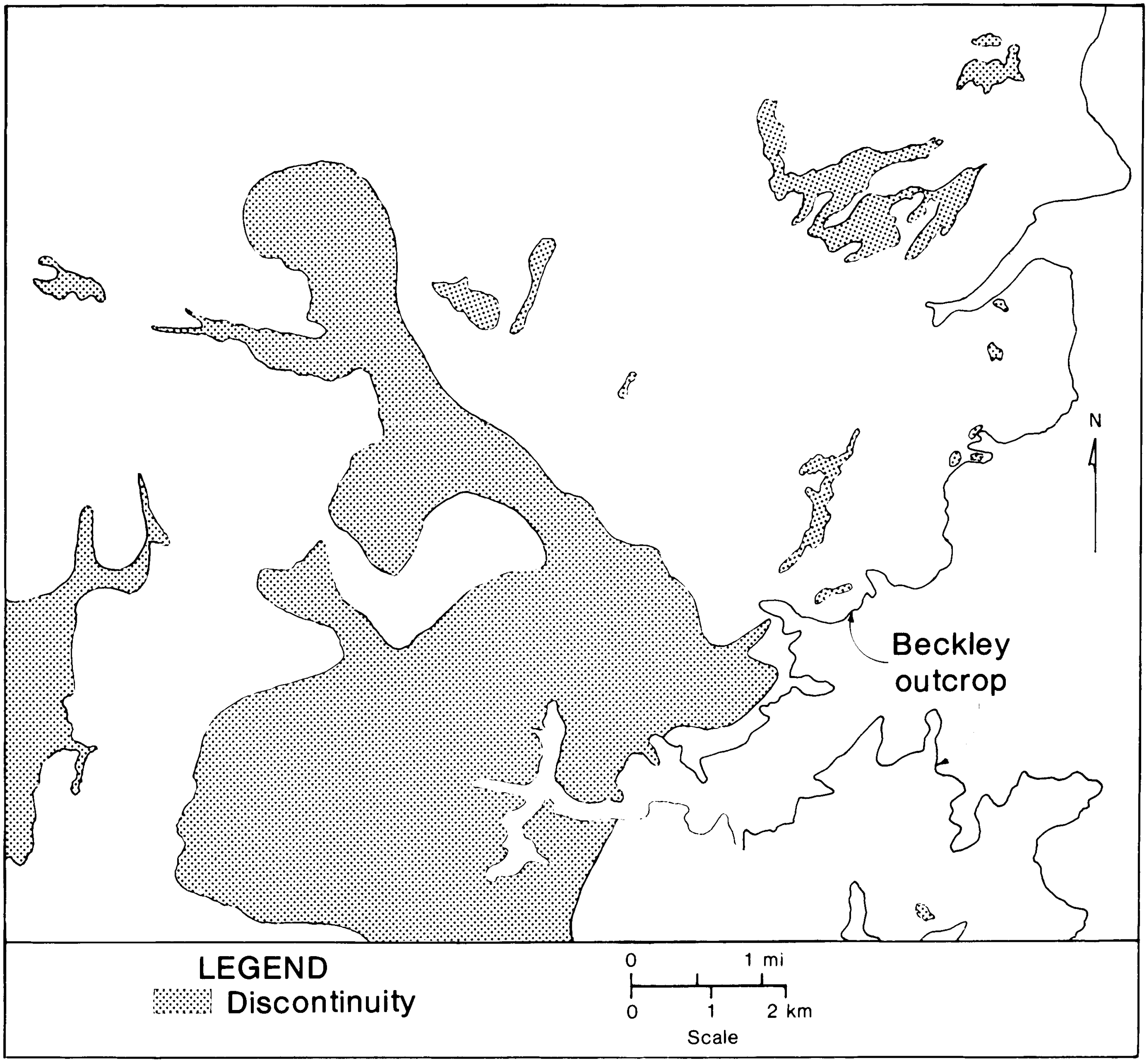


FIGURE 4. - Map of Beckley Coalbed discontinuities compiled from individual mine maps.

QUANTIFICATION OF DISCONTINUITIES

Working Definition

Discontinuities differ in mode of origin and physical dimensions. Unfortunately, detailed descriptions of discontinuities are generally not recorded on mine maps or in mine records. For this reason, an estimate must be made (for purposes of analysis), as to what has been considered to constitute a discontinuity on a specific mine property or within a specific coalbed. By inspecting coal thickness records and talking with mine personnel, it is usually possible to determine what has historically been considered a discontinuity on any specific property.

In the case of the Beckley Coalbed, coal thicknesses less than 28 inches have generally been mapped as discontinuities. Although these areas of thin coal are usually different in origin than discontinuities in which coal is totally absent (channel-phase sandstone bodies, normal faults, etc.), the two are commonly not distinguished from one another on mine maps. Because these two types of discontinuities cannot easily be distinguished using the available data, all areas labeled as discontinuities on mine maps (wants, normal faults, etc.) are used in the following analysis, despite the fact that this procedure may result in considering unlike features as belonging to a single category.

Sources of Data

Maps from mined-out areas and borehole data serve as the primary sources of data for the calculation of probabilities of encountering discontinuities. Most of the mine maps include areas of discontinuities encountered during mining or during exploratory and/or developmental drilling. A few detailed mine maps also show coal thickness and/or lithologic descriptions in areas adjacent to discontinuities. It is advisable to make underground visits to verify the accuracy of mine maps, but this is seldom possible in extensively mined-out areas because mines may no longer be open or discontinuity areas may have been sealed off or may be unsafe to visit.

After mine maps of large mined-out areas have been compiled, all discontinuities should be clearly identified for measurement purposes. The assumption made in using data from mined-out areas is that discontinuity size, shape, orientation, and distribution in mined-out areas are similar to those in undeveloped areas of the coalbed.

Definition and Measurement of Size, Shape, and Orientation

Discontinuity size, shape, and orientation are defined as illustrated in figure 5. Since discontinuities are usually irregular in shape, their sizes and shapes are not conveniently measured. To standardize measurement procedure and eliminate ambiguity in measurement technique, a smallest possible tangential rectangle is constructed around each individual discontinuity on the discontinuity map (as shown in figure 5). Two axes are defined for measurement of size; the long axis of the rectangle is defined as the a-axis, and short axis is defined as the b-axis. These two axes can also be defined as the major and minor axes of an ellipse. Because the shape of most discontinuities approximates an ellipse, the long and short axes of the tangent rectangle are appropriate representatives of the actual discontinuity dimensions.

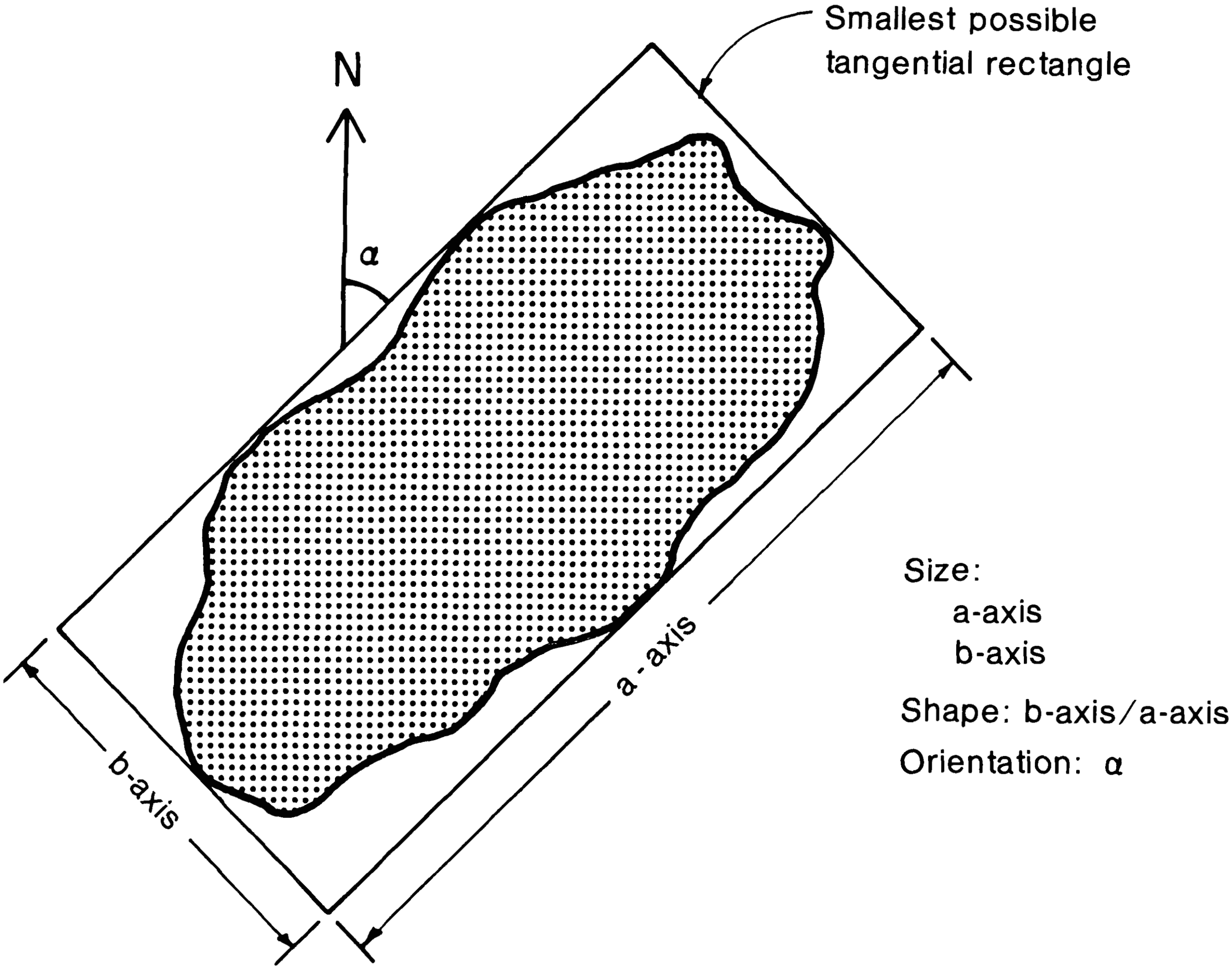


FIGURE 5. - Definition of discontinuity size, shape, and orientation.

Shape is defined as the ratio b-axis/a-axis. Figure 6 illustrates discontinuities of various shapes for reference purposes.

The final parameter to be quantified is orientation. This is important to measure because discontinuities are locally preferentially oriented, and this fact needs to be taken into account during exploration and development. Orientation is herein defined as the angle, measured clockwise, between north and the long axis (a-axis) of the tangent rectangle of each discontinuity (fig. 5). Because only orientation, and not vector direction, can be measured, all values are limited to a 180° portion of the compass and can therefore be plotted as shown in figure 7.

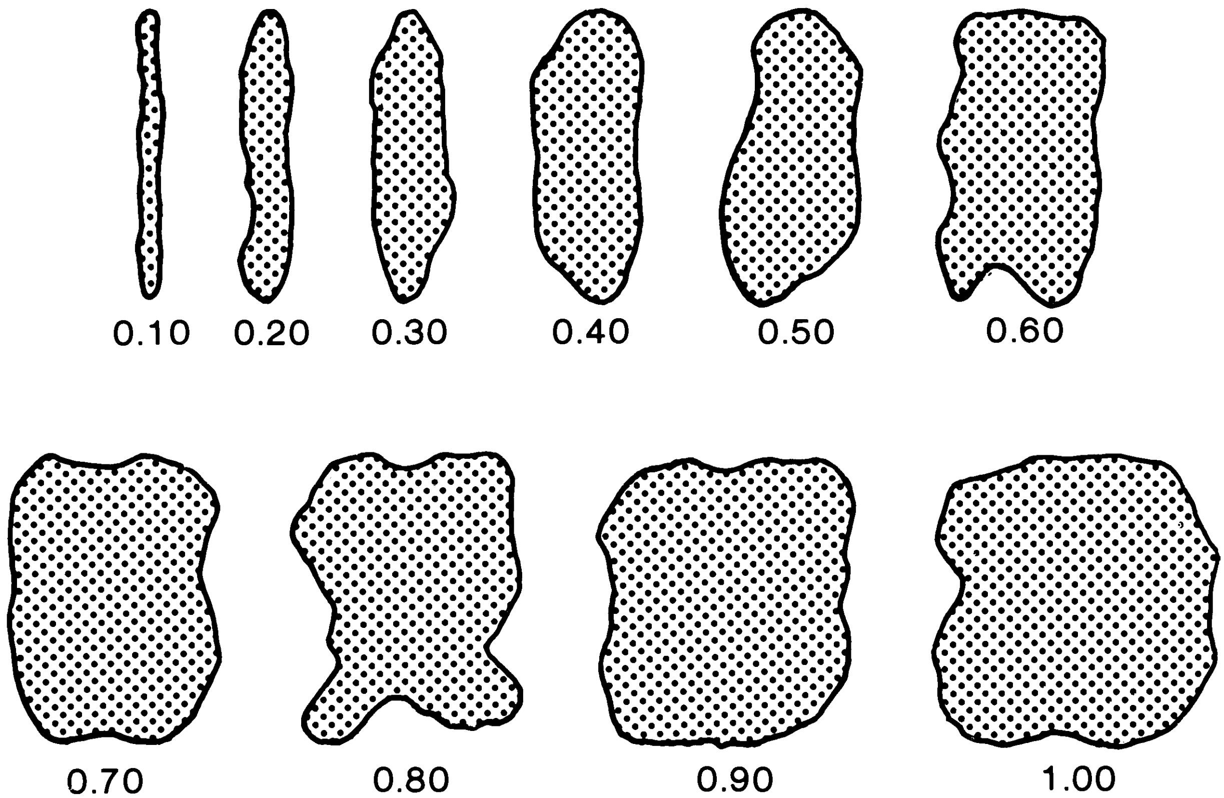
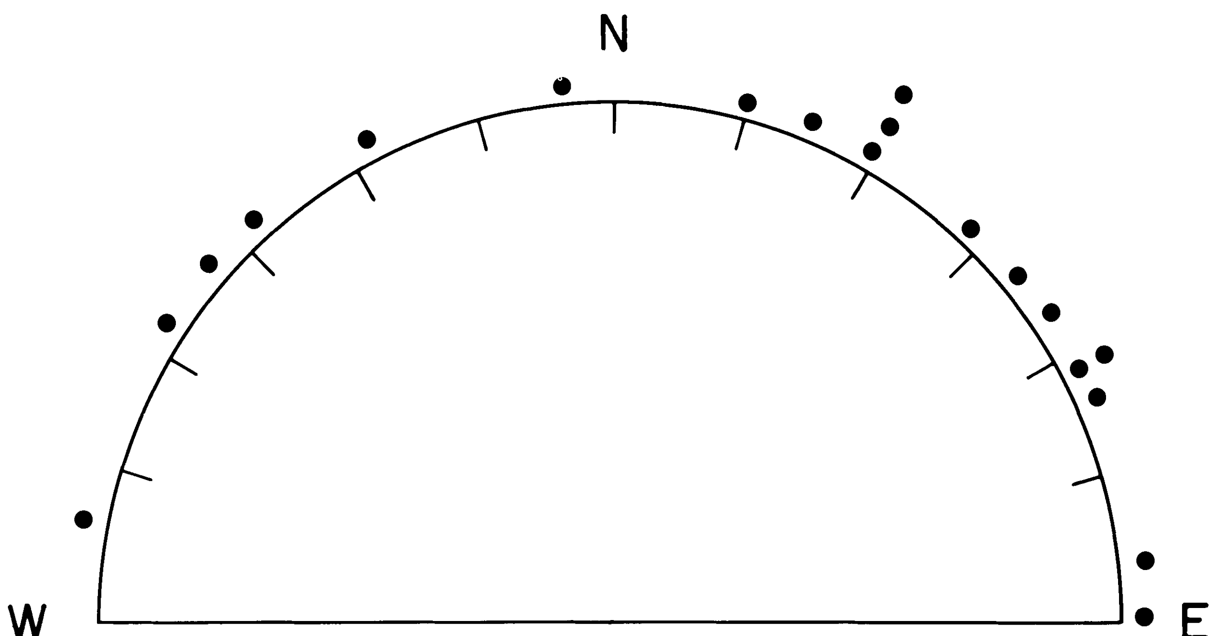


FIGURE 6. - Examples of discontinuities of various shapes with a-axes of equal lengths. The numerical values below each example are quantitative representations of shape (the ratio b-axis/a-axis).



LEGEND

● Measured orientations of long axes of discontinuities

FIGURE 7. - Orientations of Beckley Coalbed discontinuities.

The size, shape, and orientation of each discontinuity on the base map (fig. 4) are measured, and the results are compiled (table 1). Discontinuities with a-axis lengths greater than 10,000 feet have been omitted from table 1 because it is assumed that such large discontinuities would have been located during exploratory drilling. This assumption is demonstrated to be valid in a later section of this report.

TABLE 1. - Characteristics of coalbed discontinuities in study area of Beckley Coalbed and results of hypothetical vertical drilling program

Discontinuity reference number	A-axis length, ft	B-axis length, ft	Shape $\left(\frac{\text{b-axis}}{\text{a-axis}}\right)$	Orientation (deg clockwise from north, except where otherwise indicated)	Borehole spacing necessary to achieve 100 pct probability of encountering discontinuity[1]	Located by hypothetical drilling program
1	875	525	0.60	132	921	No
2	1,415	550	.39	65	1,088	No
3	600	310	.52	15	545	No
4	500	170	.31	31	324	No
5	725	400	.55	89	725	No
6	770	515	.67	153	856	No
7	600	320	.53	138	600	No
8	6,050	2,050	.34	28	4,033	Yes
9	3,800	1,100	.29	175	2,235	Yes
10	6,650	1,675	.25	62	3,325	Yes
11	3,250	2,250	.69	50	3,824	Yes
12	1,150	450	.39	61	885	Yes
13	4,650	1,525	.33	43	3,100	Yes
14	2,790	1,760	.63	55	3,100	Yes
15	1,115	500	.45	83	1,014	No
16	790	300	.38	29	608	No
17	3,740	785	.21	22	1,800	No
18	2,910	1,185	.41	124	2,238	No
19	2,730	1,650	.60	101	2,874	Yes
Mean	2,377	948	.45	N 20 E	1,798	NAp

NAp Not applicable.
[1]Calculated from published probability tables (9).

PROBABILITY OF ENCOUNTERING DISCONTINUITIES DURING VERTICAL DRILLING

Vertical drilling is the most commonly used method of obtaining geologic data during coal exploration and development and is also widely used for coalbed methane drainage. In each of these applications, it is important to quantitatively evaluate the probability of encountering coalbed discontinuities during drilling. During exploratory and/or developmental drilling, it is generally advantageous to encounter any discontinuities present on a property so that accurate reserve estimates can be made and so that potential mining problems can be anticipated and minimized during mine planning. In contrast, it is detrimental to encounter discontinuities during methane drainage drilling because discontinuities can obstruct methane drainage boreholes and block anticipated gas migration paths to the boreholes. The following discussion outlines how probabilities of encountering discontinuities during vertical drilling are estimated. Also discussed is the importance of these estimates to both methane drainage and exploratory and/or developmental drilling programs.

Probability Analysis

Assumptions and Variables

After the size, shape, and orientation data have been compiled, estimating the probability of encountering coalbed discontinuities during vertical drilling is simply an exercise in statistics. The size, shape, and orientation data are collected from mined-out areas as previously described. Then, the assumption is made that similar discontinuities exist in unmined areas of the coalbed. Probabilities are calculated from the mined-out area and then applied to the unmined area.

Other investigators have provided the mathematical proof and probability tables necessary to determine the probability of encountering any elliptical target using drilling grid patterns with various spacings between boreholes (9). Before these probability tables can be used, the following questions must be considered:

1. Will a square, rectangular, or hexagonal drilling grid pattern be used?

2. Are the targets (discontinuities) preferentially distributed within the area?

3. Are the discontinuities preferentially oriented?

4. What are the shapes of the discontinuities?

5. What discontinuity sizes may be expected and, more importantly, what is the smallest discontinuity that those carrying out the drilling program must be aware of in order to accomplish the objectives of the drilling program (or, conversely, what is the largest discontinuity the drillers can afford not to know about, considering the drilling objectives)?

6. What spacing will (or must) be used between adjacent boreholes?

Each of these variables is considered in the following discussion, which demonstrates how probabilities of encountering discontinuities are determined for the Beckley Coalbed within the study area shown in figures 2-4. The effects of these variables on probability estimation have been discussed by others (4, 9).

Determination of Probabilities for the Beckley Coalbed

Drilling Grid Pattern

Coalbed drilling for purposes of methane drainage, exploration, and/or development is rarely carried out on the basis of a regular geometric borehole pattern for a variety of strategic, economic, and logistic reasons. In most cases, however, existing borehole patterns approximately fit some regular geometric pattern so that probability analysis can be performed with some degree of confidence. In order to maintain simplicity and because the probability tables (9) used in this analysis are calculated on the basis of regular geometric drilling patterns, a square drilling grid pattern is used throughout this analysis.

Discontinuity Distribution and Orientation

Examination of the Beckley Coalbed discontinuity map (fig. 4) and the discontinuity orientation plot (fig. 7) suggests that the discontinuities are neither preferentially distributed nor preferentially oriented. Therefore, the analysis may proceed under the assumption that the Beckley's discontinuities are randomly distributed and oriented.

Discontinuity Shape

Because shape is a major variable in the probability tables (9) used in this analysis, discontinuity shapes within the study area are analyzed first. Figure 8 is a plot of shape (b-axis/a-axis) versus long axis (a-axis) length for the 19 discontinuities listed in table 1. Shape ranges from approximately 0.20 to approximately 0.70 overall, but there appears to be a significant relationship between shape and size: Discontinuities with a-axis lengths greater than 3,300 feet display little variability in shape, with values ranging from approximately 0.20 to approximately 0.35; whereas smaller discontinuities display much variability in shape, with values ranging from

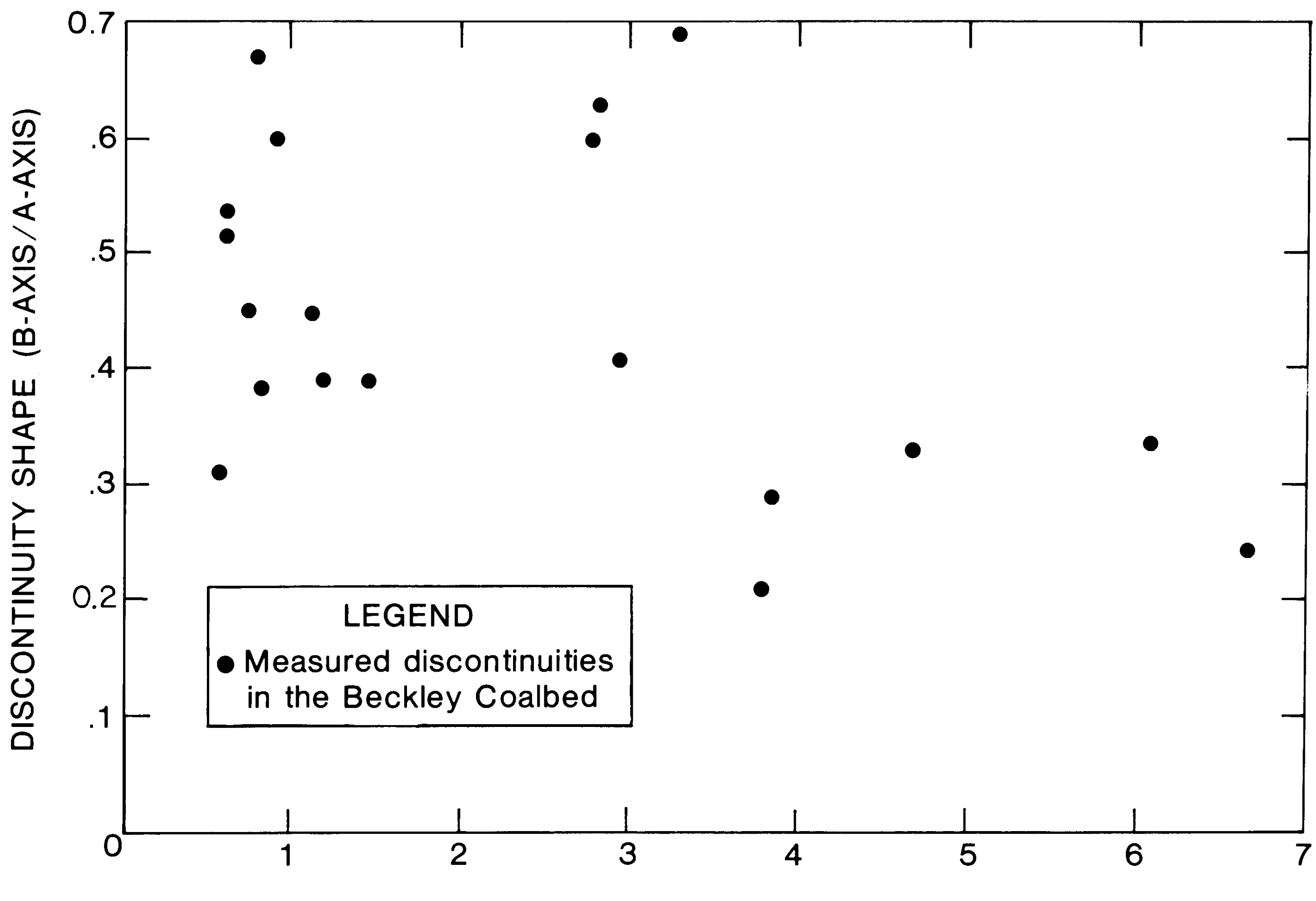


FIGURE 8. - Size versus shape of Beckley Coalbed discontinuities.

approximately 0.30 to approximately 0.70. This size-shape relationship may have genetic significance, but this cannot be confirmed because detailed geologic information on the area in the vicinity of these discontinuities is not available. This relationship must be taken into account, however, when estimating probabilities of encountering discontinuities using the previously cited probability tables.

Discontinuity Size and Borehole Spacing

Discontinuity size and borehole spacing can be considered simultaneously because they are closely related in the probability tables (9) and because one is often a known (or assumed) quantity while the other is an unknown quantity. For example, by assuming the size of discontinuities in an area, the borehole spacing required to locate discontinuities during exploratory drilling in that area can be determined. This can be illustrated by examining a probability table that has been modified from the probability tables in reference 9 to be directly applicable to the Beckley discontinuity problem. This modified probability table, table 2, summarizes the probabilities of encountering discontinuities of various sizes using various borehole spacings for discontinuities of shapes 0.30, 0.50, and 0.70.

The first set of probability values in table 2 (under the heading "SHAPE 0.30") can be directly applied in estimating the probabilities of encountering discontinuities with a-axis lengths greater than 3,300 feet in the Beckley Coalbed using various borehole spacings. This is because discontinuities of the Beckley Coalbed that are longer than 3,300 feet in a-axis length have shapes of approximately 0.30, as previously shown in figure 8. Table 2 shows, for example, that where a 4,000-foot (a-axis) discontinuity of shape 0.30 is present, boreholes spaced 5,000 feet apart in a square grid pattern would each have a 55.4 percent probability of encountering the discontinuity. It can also be seen from table 2 that for a discontinuity of this same size and shape (4,000 feet long, shape 0.30), the probability of encountering the discontinuity increases as the distance between boreholes decreases, as follows: the probability is 75.8 percent for boreholes spaced 4,000 feet apart, 84.3 percent for boreholes 3,500 feet apart, 94.3 percent for boreholes 3,000 feet apart, 99.4 percent for boreholes 2,500 feet apart; and for any smaller spacings between boreholes the probability of encountering a discontinuity is 100 percent. As illustrated by this example, table 2 can be used to estimate the probabilities of encountering various-size discontinuities of shape 0.30 using any borehole spacing (and assuming a square grid pattern). Using the second and third sets of probability values in table 2, the probabilities of encountering various-size discontinuities of shapes 0.50 and 0.70 can be similarly estimated.

A comparison of the probability values for shapes 0.30, 0.50, and 0.70 in table 2 reveals that as discontinuity shape values increase (or as shape becomes more equant), there is a greater likelihood that discontinuities will be encountered. This means that for discontinuities of equal a-axis length, it takes a smaller borehole spacing (that is, more boreholes) to encounter an elongate discontinuity than to encounter a more nearly equant discontinuity. For example, in order to be sure (or to have a 100 percent probability) that a drilling program will encounter all discontinuities that are 2,000 feet long, table 2 shows that the *maximum* borehole spacing must be 1,000 feet for discontinuities of shape 0.30, 1,500 feet for discontinuities of shape 0.50, and 2,000 feet for discontinuities of shape 0.70.

TABLE 2. - Probabilities of encountering discontinuities of various shapes during vertical drilling[1]

Discontinuity length (a-axis), ft	Borehole spacing, ft: 5,000	4,000	3,500	3,000	2,500	2,000	1,500	1,000	500
SHAPE 0.30									
500	NZ	NZ	NZ	NZ	NZ	NZ	0.115	0.236	0.758
1,000	NZ	NZ	0.085	0.115	0.151	0.236	.388	.758	1.000
1,500	0.085	0.115	.191	.236	.335	.499	.758	.982	1.000
2,000	.151	.236	.284	.388	.554	.758	.943	1.000	1.000
2,500	.236	.335	.443	.608	.758	.906	1.000	1.000	1.000
3,000	.335	.499	.608	.758	.906	.982	1.000	1.000	1.000
3,500	.443	.608	.758	.906	.965	1.000	1.000	1.000	1.000
4,000	.554	.758	.843	.943	.994	1.000	1.000	1.000	1.000
5,000	.758	.906	.965	1.000	1.000	1.000	1.000	1.000	1.000
6,000	.906	.982	1.000	1.000	1.000	1.000	1.000	1.000	1.000
7,000	.965	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
8,000	.994	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
9,000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
SHAPE 0.50									
500	NZ	NZ	NZ	NZ	NZ	0.098	0.192	0.393	0.993
1,000	NZ	0.098	0.141	0.192	0.251	.393	.633	.947	1.000
1,500	0.141	.192	.318	.393	.552	.788	.993	.993	1.000
2,000	.251	.393	.472	.633	.854	.993	1.000	1.000	1.000
2,500	.393	.552	.713	.908	.993	1.000	1.000	1.000	1.000
3,000	.552	.788	.908	.993	1.000	1.000	1.000	1.000	1.000
3,500	.713	.908	.993	1.000	1.000	1.000	1.000	1.000	1.000
4,000	.854	.993	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5,000	.993	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
6,000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
SHAPE 0.70									
500	NZ	NZ	NZ	NZ	NZ	0.137	0.269	0.550	1.000
1,000	NZ	0.137	0.198	0.269	0.353	.550	.854	1.000	1.000
1,500	0.198	.352	.445	.550	.760	.980	1.000	1.000	1.000
2,000	.352	.550	.658	.854	.996	1.000	1.000	1.000	1.000
2,500	.550	.760	.932	1.000	1.000	1.000	1.000	1.000	1.000
3,000	.760	.980	1.000	1.000	1.000	1.000	1.000	1.000	1.000
3,500	.932	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
4,000	.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5,000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

NZ Near zero.
[1]1.000 = 100 percent probability.

Application of Probabilities: Hypothetical Drilling Program for Vertical Boreholes

Description of Hypothetical Program

For study purposes, a vertical borehole drilling program was hypothesized for the Beckley Coalbed study area and then analyzed. Considering the size and shape of the Beckley's discontinuities (table 1), it was decided that a 2,500-foot borehole spacing would provide a good compromise between the number of boreholes drilled (a consideration related to cost) and the size of discontinuities that would be detected (a consideration related to risk) in a hypothetical program. The hypothetical drilling program is illustrated in figure 9.

As shown in figure 9, a square drilling grid with 2,500-foot spacing between boreholes was superimposed on the Beckley discontinuity map. Because an

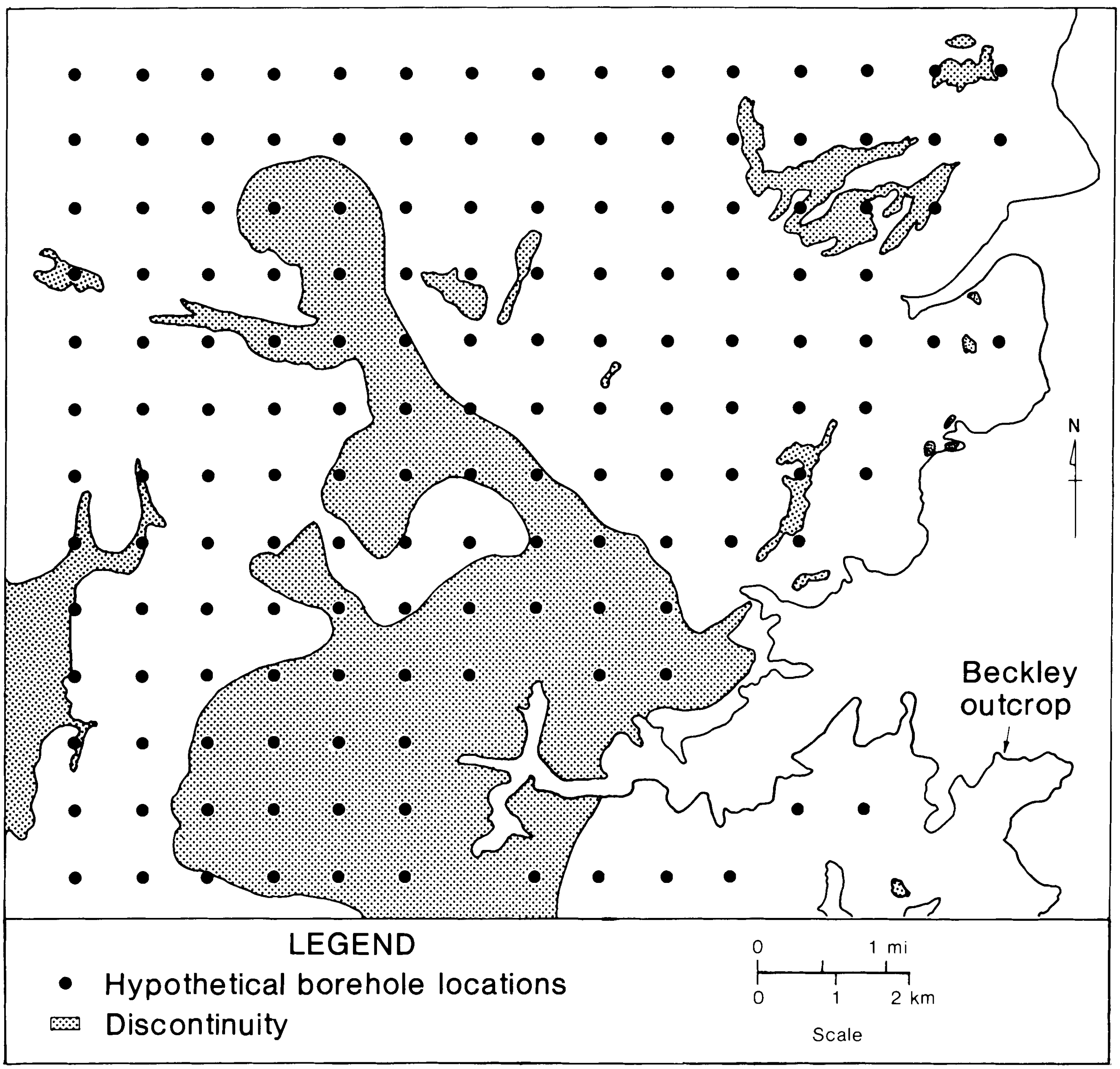


FIGURE 9. - Beckley Coalbed discontinuity map showing locations of hypothetical vertical boreholes.

assumption was previously made that Beckley discontinuities are randomly distributed and oriented, the drilling grid was arbitrarily oriented north-south. The grid was offset 2,500 feet from the north and west boundaries of the study area because boreholes are seldom drilled on boundaries of mine properties. Similarly, no hypothetical boreholes were "drilled" within 2,500 feet of outcrop because coal thickness data can be collected at numerous locations along the outcrop line. In all, the hypothetical drilling program simulated the drilling of 153 boreholes.

Results

Figure 9 shows that 45 of the 153 simulated boreholes would have encountered discontinuities. Thus, if the study area is representative of unexplored and/or undeveloped areas of the Beckley Coalbed, there is a 29 percent probability of encountering a discontinuity during vertical drilling in untested areas.

Discussion of Results

The probability of encountering a discontinuity is actually an estimate of the following ratio for the study area: total area of discontinuities/total area. For this reason, a square drilling grid pattern that covers the *entire* study area will encounter discontinuities in 29 percent of its boreholes, regardless of the spacing between boreholes. A simple mathematical proof of this relationship is available (2).

The hypothetical drilling program located most of the discontinuities that are large enough to seriously affect methane drainage or mining activities, as shown in table 1 and in figure 9. Of the 11 discontinuities not located, all but four are less than 1,000 feet long, and six are within 500 feet of outcrop. Only two of the undetected discontinuities would pose serious problems to methane drainage and mining efforts. These two discontinuities are located just north of the center of the study area; one is 3,740 feet long with a shape of 0.21, and the other is 2,910 feet long with a shape of 0.41 (reference numbers 17 and 18, respectively, in table 1). In order to be sure these two discontinuities would be detected, the borehole spacing would have to be reduced to 1,800 feet, and the result would be a significantly larger number of boreholes and a concomitant cost increase.

An exploratory drilling program similar to the one described above should precede methane drainage drilling so that tentative mine projections can be taken into consideration when the locations of methane drainage boreholes are planned. Assuming that geologic data concerning the distribution of coalbed thickness and discontinuities have been obtained from such an exploratory drilling program, methane drainage borehole patterns (commonly square grids with 1,000-foot spacing between boreholes) can be sited with little chance of encountering discontinuities during drilling. However, if a methane drainage borehole pattern with 1,000-foot spacing were drilled across the entire Beckley Coalbed study area, there would be a 29 percent probability that a given borehole would encounter a discontinuity, and 29 percent of all the boreholes drilled could be expected to encounter discontinuities. If relatively small borehole patterns (for example, 5 by 5 boreholes with 1,000-foot spacing) were drilled with no data input from exploratory drilling, the probability of encountering discontinuities would range from zero to 100 percent depending on the location selected, but these probabilities could not be estimated before drilling commenced without exploratory information.

The foregoing discussions demonstrate how systematic analysis of discontinuity characteristics, together with application of the probability tables from reference 9, can be used to quantitatively estimate the probabilities of encountering discontinuities during vertical drilling. This procedure can be used in the analysis of cost-risk factors involved in designing a drilling program and can be directly applied to determination of the borehole spacing and drilling pattern to be used in methane drainage and exploratory and/or developmental drilling.

PROBABILITY OF ENCOUNTERING DISCONTINUITIES DURING HORIZONTAL DRILLING

In recent years, there has been a significant increase in the use of horizontal drilling both for coalbed methane drainage (1) and for mine development work such as locating abandoned mine workings. For this reason, it is increasingly important to be able to predict probabilities of encountering discontinuities in advance of initiating a horizontal drilling program.

Probability Calculation

This section describes a method of probability calculation that can be used in estimating the probabilities of encountering coalbed discontinuities during horizontal drilling. For purposes of illustration, this method is then used in an analysis of a hypothetical drilling program for horizontal boreholes. Again, the mined-out area of the Beckley Coalbed (figs. 2-4) is used as an example; that is, data from the Beckley study area are used as the basis for the hypothetical program.

Considerations

In analyzing the probabilities of encountering discontinuities during horizontal drilling, two major questions must be considered. They are:

1. How will drilling locations be decided upon?

2. Once the location decisions are made, how will the probabilities of encountering discontinuities be calculated?

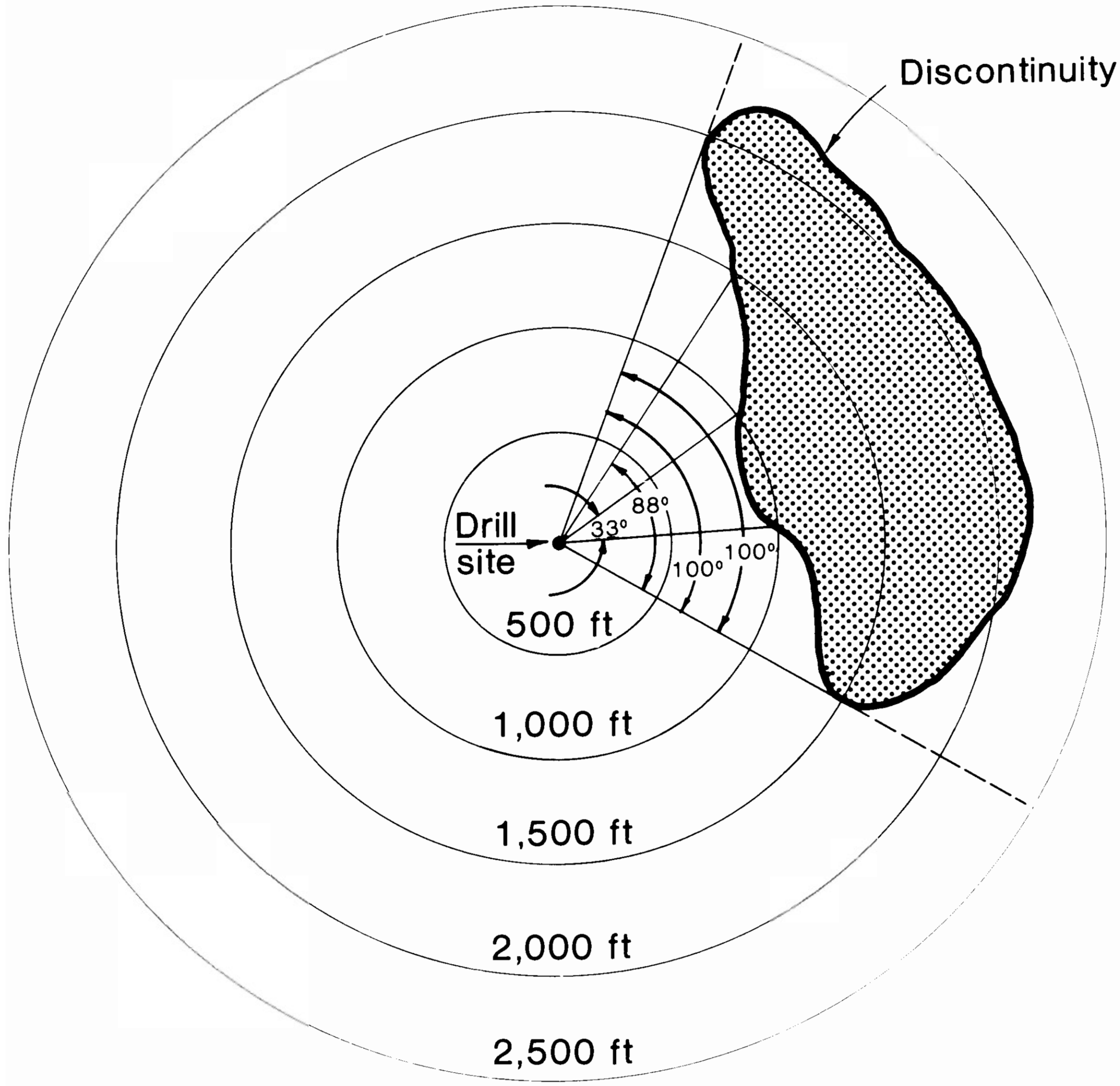
In practice, drilling locations are determined on the basis of existing and projected mine layouts. For the purpose of methane drainage, drilling locations for horizontal boreholes are chosen so that the boreholes will be drilled into blocks of coal that will not be mined for some time, thus allowing methane drainage in advance of mining. For developmental purposes, drilling locations are determined by the presence of potential problem areas such as abandoned mine workings.

A method of probability calculation applicable to horizontal borehole drilling is described below.

Method of Calculation

Probabilities are individually calculated for each proposed drilling site, based on data from mined-out coalbed areas. In order to analyze the probabilities that horizontal boreholes of various lengths will intercept a discontinuity, circles of 500-, 1,000-, 1,500-, 2,000-, and 2,500-foot radii are drawn around the drilling site to be analyzed, as shown in figure 10. These circles define the areas that could be intersected by horizontal holes of various lengths (that is, the same lengths as the radii). Theoretically, a horizontal hole could be drilled in any direction from the drilling site, so the circle with a radius of 500 feet, for example, delineates the area that would be intersected by 500-foot holes drilled in all possible directions from the site. Actual horizontal drilling directions would be considerably limited if drilling were to be done from the entries of an existing mine because boreholes would be drilled only in the directions of unmined coal. In contrast, horizontal drilling directions would not be limited at all if drilling were to be done from the bottom of a newly constructed shaft (3) because unmined coal would be present in all directions.

For each of the circles that intersects a discontinuity, radius lines are drawn from the drilling site to the two points where the circle and the



Hole length, ft	Angle of intersection, deg	Probability, pct $\left(\frac{\text{angle of intersection}}{360^\circ}\right)$
500	0	0
1,000	33	9
1,500	88	24
2,000	100	28
2,500	100	28

FIGURE 10. - Method of calculating probabilities of encountering discontinuities with horizontal boreholes of various lengths.

discontinuity intersect, as shown in figure 10. Any horizontal hole of a length equal to the radius of a circle that intersects a discontinuity, when drilled in a direction that lies between these two radius lines, will encounter the discontinuity. For each drilling site, the angle between the two radius lines (hereafter called the angle of intersection) is measured for each circle that intersects a discontinuity. For example, in figure 10, the 500-foot radius circle (representing boreholes 500 feet long) does not intersect a discontinuity, so the angle of intersection is zero. The 1,000- and 1,500-foot circles do intersect a discontinuity, and their respective angles of intersection are 33° and 88°.

In certain cases, the angle of intersection must be measured to allow for a "shadow effect." This effect involves two possible cases. In the first case, a circle may intersect a discontinuity across a smaller angle of intersection than a circle of smaller radius. For example, the circle of 2,000-foot radius in figure 10 intersects the discontinuity across a smaller angle of intersection than the circle of 1,500-foot radius. However, any 2,000-foot-long horizontal borehole that is drilled within the angle of intersection of the 1,500-foot circle would encounter the discontinuity. This is because the maximum length of the discontinuity lies closer to the drilling site than the circle of 2,000-foot radius. In the second case, a circle may not intersect a discontinuity although a circle of smaller radius does. For example, the circle of 2,500-foot radius in figure 10 does not intersect the discontinuity but circles of smaller radii do. In this case, the angle of intersection for the 2,500-foot circle must include the entire area where horizontal boreholes 2,500 feet long will encounter the discontinuity. In both of these cases, the following rule *must* be followed: As circles of larger radii are drawn, the measured angles of intersection can never become smaller; they can only remain constant or become larger. Thus, the angle of intersection for both the 2,000-foot circle and the 2,500-foot circle in figure 10 is 100°.

Once an angle of intersection has been measured for a circle of a given radius, it is converted to a probability of encountering a discontinuity simply by dividing the angle by 360°. If a circle intersects a single, irregularly shaped discontinuity in more than one location along the circumference of that circle, an angle of intersection is measured for each area where the circle intersects the discontinuity. Similarly, if more than one discontinuity is intersected by a circle, an angle of intersection is measured for each discontinuity. In both cases, all angles of intersection measured for a circle of given radius are summed before dividing by 360°. This procedure is repeated for each circle of each drilling site in order to arrive at mean values for the entire study area. The mean probability value calculated for each circle corresponds to the probability that a discontinuity would be encountered by a borehole the same length as the radius of the circle.

Application of Probability Calculation Method: Hypothetical Drilling Program for Horizontal Boreholes

The probability calculation method described in the previous section is applied in this section to a hypothetical horizontal drilling program for the Beckley Coalbed study area. For study purposes, the entire study area is considered to be a single mine property, when in fact, the area includes portions of five separate mines (as shown in figure 2). For this reason, it is not possible to locate hypothetical horizontal drilling locations on the basis of actual mine planes. In order to circumvent this problem and to analyze the entire study area, hypothetical horizontal drilling sites are located at each of the hypothetical *vertical* borehole locations that did not intersect a discontinuity. (See figure 9.) This provides 108 locations that are evenly distributed throughout the area of minable coal, so the study area is analyzed as if it were being developed by a single mine.

Table 3 summarizes the calculated probabilities of encountering discontinuities during horizontal drilling at the 108 drilling sites in the study area. The probabilities presented in table 3 are mean values based on calculations from all 108 hypothetical drilling locations. As the borehole length increases, there is a systematic increase in the probability of encountering a discontinuity; the mean probability is 4.16 percent for a 500-foot hole, 9.44 percent for a 1,000-foot hole, 13.71 percent for a 1,500-foot hole, 17.09 percent for a 2,000-foot hole, and 21.41 percent for a 2,500-foot hole. A bivariate plot of horizontal borehole length versus probability of encountering a discontinuity (fig. 11) demonstrates that there is a remarkably linear relationship between the two variables. This linear relationship provides a meaningful basis for the evaluation of cost-risk factors in advance of initiating horizontal drilling programs in other areas of the Beckley Coalbed, assuming that the study area is representative of the rest of the coalbed.

TABLE 3. - Horizontal borehole length and probability of encountering a discontinuity for hypothetical horizontal drilling program

Horizontal borehole length, ft	Mean probability, pct
500	4.16
1,000	9.44
1,500	13.71
2,000	17.09
2,500	21.41

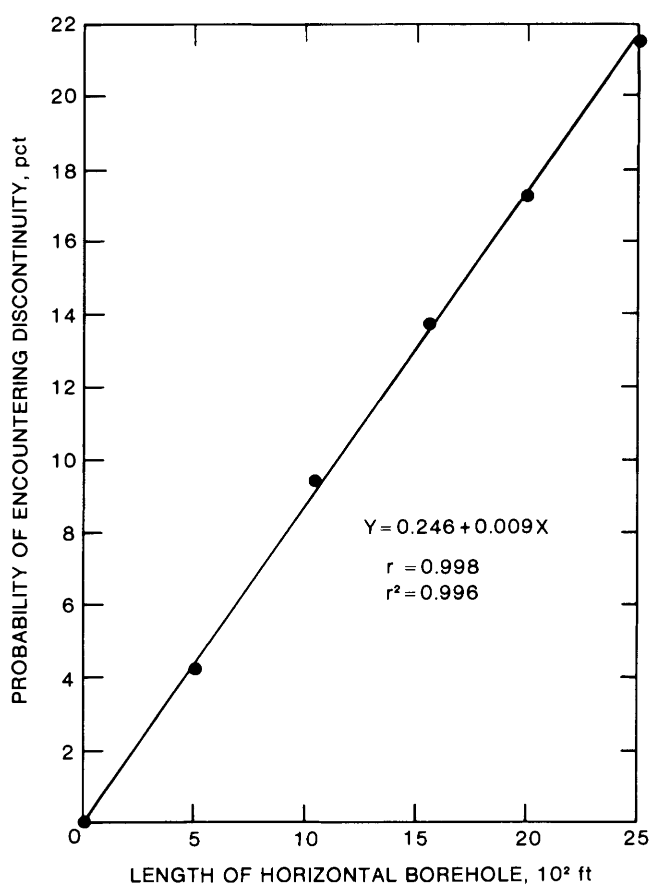


FIGURE 11. - Horizontal borehole length versus probability of encountering a discontinuity in the Beckley Coalbed. (The value r is the correlation coefficient and is used to test the statistical significance of the relationship between borehole length and probability of encountering a discontinuity; r^2 is a measure of the proportion of the total variation in these two variables that is accounted for by the calculated regression line.)

SUMMARY AND CONCLUSIONS

The probability of encountering coalbed discontinuities during vertical drilling in a specific coalbed can be estimated from statistical analysis of discontinuity size, shape, orientation, and distribution in mined-out areas of that coalbed. Published probability tables (9) allow determination of the size of discontinuities that will be encountered using various spacings between vertical boreholes, and conversely, what borehole spacings are necessary to assure detection of various-size discontinuities. In unexplored areas of the Beckley Coalbed, there is a 29 percent probability that a vertical borehole will encounter a discontinuity. A square grid exploratory drilling pattern with 2,500-foot spacing between boreholes assures detection of most discontinuities that are large enough to cause serious problems for methane drainage and mining programs in the Beckley Coalbed.

The probability of encountering coalbed discontinuities during horizontal drilling in a specific coalbed can be estimated from systematic analysis of hypothetical drilling sites in mined-out areas of that coalbed. The radii of various-size circles constructed around the drilling sites represent horizontal boreholes of various lengths. The part of a given circle that intersects a discontinuity, expressed as a circular percentage of all possible horizontal drilling directions, represents the probability of encountering a discontinuity with a horizontal borehole equal in length to the radius of that circle. Calculations of the probabilities for circles of various radii at drilling sites throughout a mined-out area allow estimation of mean probabilities for boreholes of various lengths. In the Beckley Coalbed there is a linear increase in the probability of encountering a discontinuity as the length of the borehole increases.

Calculations of the probabilities of encountering coalbed discontinuities can be used in cost-risk analysis in advance of initiating a drilling program, whether it be for methane drainage, exploratory, or developmental purposes. This procedure does not result in the prediction of discontinuity locations and is not intended to replace detailed geologic investigations. This paper has demonstrated, however, that probability calculations can be used to augment the knowledge obtained from detailed geologic mapping and depositional environment reconstructions; and in this role, the probability approach can serve as a valuable tool that can be used to help accomplish the safe and economical exploitation of coal resources.

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