# RELATION OF FRACTURE SYSTEMS TO TRANSMISSIVITY OF COAL AND OVERBURDEN AQUIFERS IN PRESTON COUNTY, WEST VIRGINIA

by W. A. Hobba, Jr.

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## CONVERSION FACTORS AND ABBREVIATIONS

For use of readers who prefer to use metric (International System) units, rather than the inch-pound terms used in this report, the following conversion factors may be used:

| Multiply Inch-Pound Unit | By | To Obtain Metric Unit |
|---|---|---|
| inch (in.) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |
| gallon (gal) | 3.785 | liter (L) |
| gallon per minute (gal/min) | 0.06308 | liters per second (L/s) |
| foot squared per day ($ft^2/d$) | 0.09290 | meters squared per day ($m^2/d$) |

**Sea level:** In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "sea level datum of 1929."

## ACKNOWLEDGMENTS

The author wishes to thank Patriot Mining Company for allowing access to their property, for providing geologic information of the area, for giving the author permission to use two boreholes on their property, and for providing a tank truck to flush the boreholes. The author also wishes to thank Peter Lessing and Michael Peck, both with the West Virginia Geological and Economic Survey, for assisting with data collection and analysis, and the personnel from the U.S. Bureau of Mines, Bruceton, Pa., for providing video logs of two boreholes.

# RELATION OF FRACTURE SYSTEMS TO TRANSMISSIVITY OF COAL AND OVERBURDEN AQUIFERS IN PRESTON COUNTY, WEST VIRGINIA

**By W. A. Hobba, Jr.**

## ABSTRACT

Aquifer tests were conducted on a leaky confined coal aquifer and the associated sandstone and shale overburden water-table aquifer in Preston County, West Virginia. The Preston County aquifer-test site is located on a relatively flat hilltop. The site is not undermined, there are no surface indications of faults or lineaments, and the water table is less than 10 feet below land surface. The site is underlain by a 4.5-foot-thick coal bed—the Upper Freeport coal of the Pennsylvanian Allegheny Formation. The coal bed lies beneath about 57 feet of alternating beds of shale, sandstone, and coal of the Conemaugh Group of Pennsylvanian age.

Five test wells were constructed at the site. Drilling at three of the test wells was interrupted at 10-foot intervals to run constant-head permeability tests in the overburden. The more permeable rock was within 33 feet of land surface. The horizontal hydraulic conductivities of the overburden aquifer ranged from 0.05 to 0.90 feet per day.

Aquifer tests indicate that the 4.5-foot-thick coal aquifer is almost as transmissive as the 50-foot-thick overburden aquifer. The average direction of maximum transmissivity in the coal aquifer is about N. 75° W., which nearly parallels the direction of dominant face cleat orientation—N. 65° W. The median maximum transmissivity in the coal aquifer was 91 $ft^2/d$ (feet squared per day) or about three times greater than the minimum transmissivity. The direction of maximum transmissivity in the overburden aquifer also trends to the northwest and nearly parallels that for the coal aquifer. The median maximum transmissivity in the overburden aquifer was 97 $ft^2/d$ and about seven times greater than the minimum transmissivity. The average storage coefficients for the coal and overburden aquifers were $9.4 \times 10^{-3}$ and $1.1 \times 10^{-2}$, respectively. The equipotential lines for both aquifers, when affected by the injection or withdrawal of water, was elliptical with the long axes trending to the northwest-southeast, indicating increased permeability in this direction.

# INTRODUCTION

## Background

Some coal beds in West Virginia are productive aquifers, in which water flows primarily through fractures. Kulander and Dean (1980) mapped the orientation of dominant fracture systems or face cleats in coal beds throughout the State. They found that the orientation of the face cleats was nearly constant over broad areas, and they delineated six regions in the State where the face cleats had similar orientations (fig. 1). Because ground-water flows primarily through these fracture systems, then the permeability in coal aquifers may be greatest parallel to the regional trend of the face cleat. If the maximum transmissivity in the coal aquifer parallels the face cleat, then the direction of maximum transmissivity could be predicted from the existing map showing the orientation of face cleat.

## Purpose and Scope

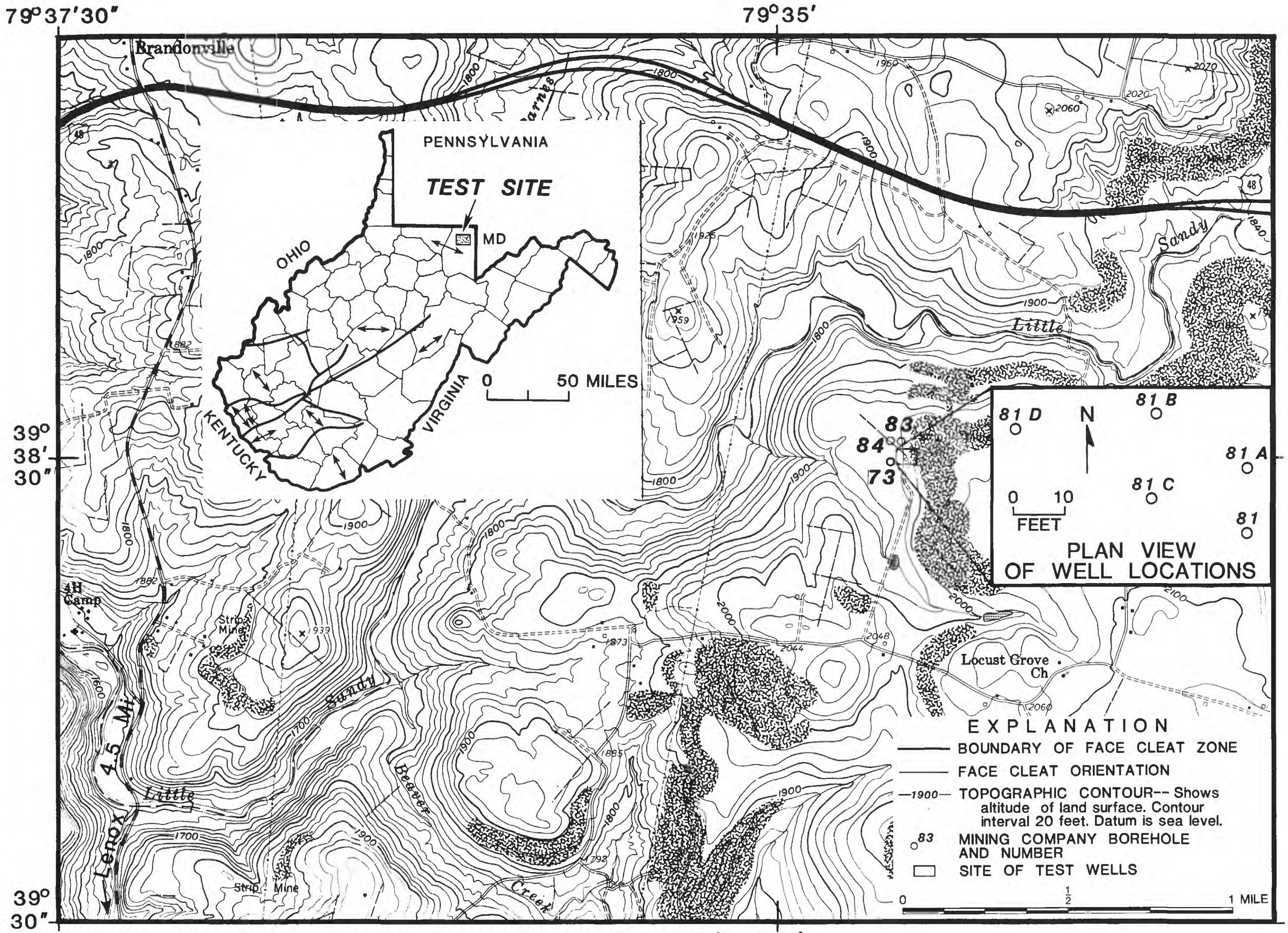
This report presents the results of the study at a test site in Preston County, West Virginia, to determine if a correlation exists between the direction of maximum transmissivity in a coal aquifer and the orientation of the face cleat in the coal bed. A secondary objective was to determine the direction of maximum transmissivity and variation in hydrologic conductivity with depth in the overlying rock (overburden) aquifers. The results are based on multiple-well aquifer tests in the Upper Freeport coal bed and overburden. The report describes (1) the geology and the occurrence and movement of ground water in the coal and overburden aquifers, (2) aquifer- test design and methods of data analyses, (3) hydraulic properties of the coal and overburden aquifers, and (4) orientation of the face cleat in the Upper Freeport coal bed.

## Previous Investigations

Way and McKee (1982), using the method described by Papadopulos (1965), determined that the direction of maximum hydraulic conductivity of two sandstone aquifers near Rawlins, Wyoming, was generally aligned with the regional pattern of sediment deposition. Using data from seven observation wells and analyzing 35 possible 3-well combinations, they found that only 19 of the 35 combinations gave viable results for directional hydraulic conductivity and storage coefficient. They concluded that 16 of the 3-well combinations did not yield viable results because the aquifer was both heterogeneous and anisotropic.

Way, McKee, and Wainwright (1984) analyzed data from an aquifer test in Australia in which seven observation wells were used. They concluded that the trend of the maximum hydraulic conductivity was N. 2° E. and 2 to 5 times greater than the minimum hydraulic conductivity. At this site, 27 of the 35 possible 3-well combinations gave viable results for directional hydraulic conductivity and storage coefficients.

The relation between face-cleat orientation and the direction of maximum hydraulic conductivity has been investigated by several researchers. In Wyoming, Stone and Snoeberger (1977) concluded that the direction of maximum horizontal hydraulic conductivity (N. 59° E.) approximately corresponded to the trend of the prominent, nearly vertical face-cleat system (N. 70° E.). The maximum hydraulic conductivity was 0.89 ft/d (feet per day) or 1.8 times greater than the minimum hydraulic conductivity (0.49 ft/d). In Montana, Stoner (1981) concluded that the average maximum horizontal hydraulic conductivities of two coal seams were oriented (1) N. 83° E., with a maximum hydraulic conductivity of 2.1 ft/d or 2.5 times as great as the minimum hydraulic conductivity (0.85 ft/d), and (2) N. 32° W. with a maximum hydraulic conductivity of 0.66 ft/d or 2.9 times greater than the minimum hydraulic conductivity (0.23 ft/d).




Base from U.S. Geological Survey Brandonville 1:24,000, 1959 (Pr 1976)

**Figure 1.—The location of the test site, the surrounding area, and the location of known nearby boreholes drilled by the mining company. (Index map shows the location of test site, county boundaries, and zones of different face-cleat orientations—Modified from Kulander and Dean, 1980).**

# DESCRIPTION OF SITE

The test site is in the Allegheny Mountain section of the Appalachian Plateaus physiographic province in northern West Virginia near the village of Brandonville in Preston County (fig. 1). The site is in a rural area that is characterized by relatively broad hills; local relief in the area is less than 200 ft. The test site is on a relatively flat hilltop that is about 1,000 ft wide and 1,500 ft long, as indicated by the contours in figure 1. The water table is less than 10 ft below land surface, and there is no surface indication of faults or linear features that pass through the site. Although there is active surface mining of coal near the test site, the test site has never been undermined.

## Geology and Fracture Systems

The test site is underlain by gently to moderately folded, consolidated sedimentary rocks (Hennin and Reger, 1914) (stratigraphic nomenclature used is that of the West Virginia Geological Survey.) of the Allegheny Formation and the Conemaugh Group. These Middle and Upper Pennsylvanian rocks are comprised chiefly of alternating beds of sandstone, shale, and coal that are usually underlain by clay layers.

The Upper Freeport coal is about 4.5 ft thick and lies about 60 ft below land surface at the top of the Allegheny Formation (fig. 2). The Upper Freeport coal is underlain by about 15 ft of shale. During this study, the Upper Freeport coal was being stripmined at its outcrop about 1,000 ft north of the test site.

The orientation of the face cleat in the Upper Freeport coal was measured at three exposures within 2,500 ft of the test site. Two orientations were measured—N. 65° W. and N. 74° W. Face cleats in the N. 65° W. orientation were the more predominant. The face cleats shown on the map for this area (Kulander and Dean, 1980) range from N. 66° W. to N. 69° W. In November 1982, when surface mining approached to within 150 ft of the test wells, orientations of N. 68° W. and N. 65° W. were measured in the coal bed at the base of the high wall. The N. 65° W. orientation was determined to be the predominant orientation. On the average, there were 20 easily identified face cleats per inch or about 240 per foot of width of coal. The much less prominent butt cleat, which is nearly perpendicular to the face cleat, could not be counted with certainty.

At the test site, the overburden rock above the Upper Freeport coal is the Conemaugh Group. Although the group reaches a maximum thickness of about 640 ft in Preston County, at the test site, only the lower 57 ft of the group is present. Wells at the test site penetrated 30 ft of alternating beds of shale, sandstone, clay, and coal (less than 1.5 ft thick) before penetrating about 20 ft of hard massive sandstone and 1 ft of black shale and then the Upper Freeport coal.

## Occurrence of Ground Water

Two aquifers occur within 65 ft of land surface at the test site. The overburden aquifer is the water-table aquifer and it consists of about 50 ft of mainly shale and sandstone beds. The leaky confined coal aquifer lies immediately below the overburden aquifer, and it consists of 4.5 ft of coal.

Water occurs in both joints and intergranular openings in the overburden aquifer. Sandstones that contain both intergranular and joint openings, generally, will yield the most water to wells. However, at the test site, intergranular openings are commonly filled with secondary minerals and the vertical joints and horizontal bedding-plane joints are poorly developed; thus, the sandstones yield little water to wells. In general, shales do not yield large quantities of water, except in areas where the rocks are intensely fractured. Friel and others (1967, p. 93) report that yields of wells tapping the Conemaugh Group ranged from less than 1 to 400 gal/min (gallons per minute). The highest yields are reported for wells that are situated in valleys and that tap the massive basal sandstones.

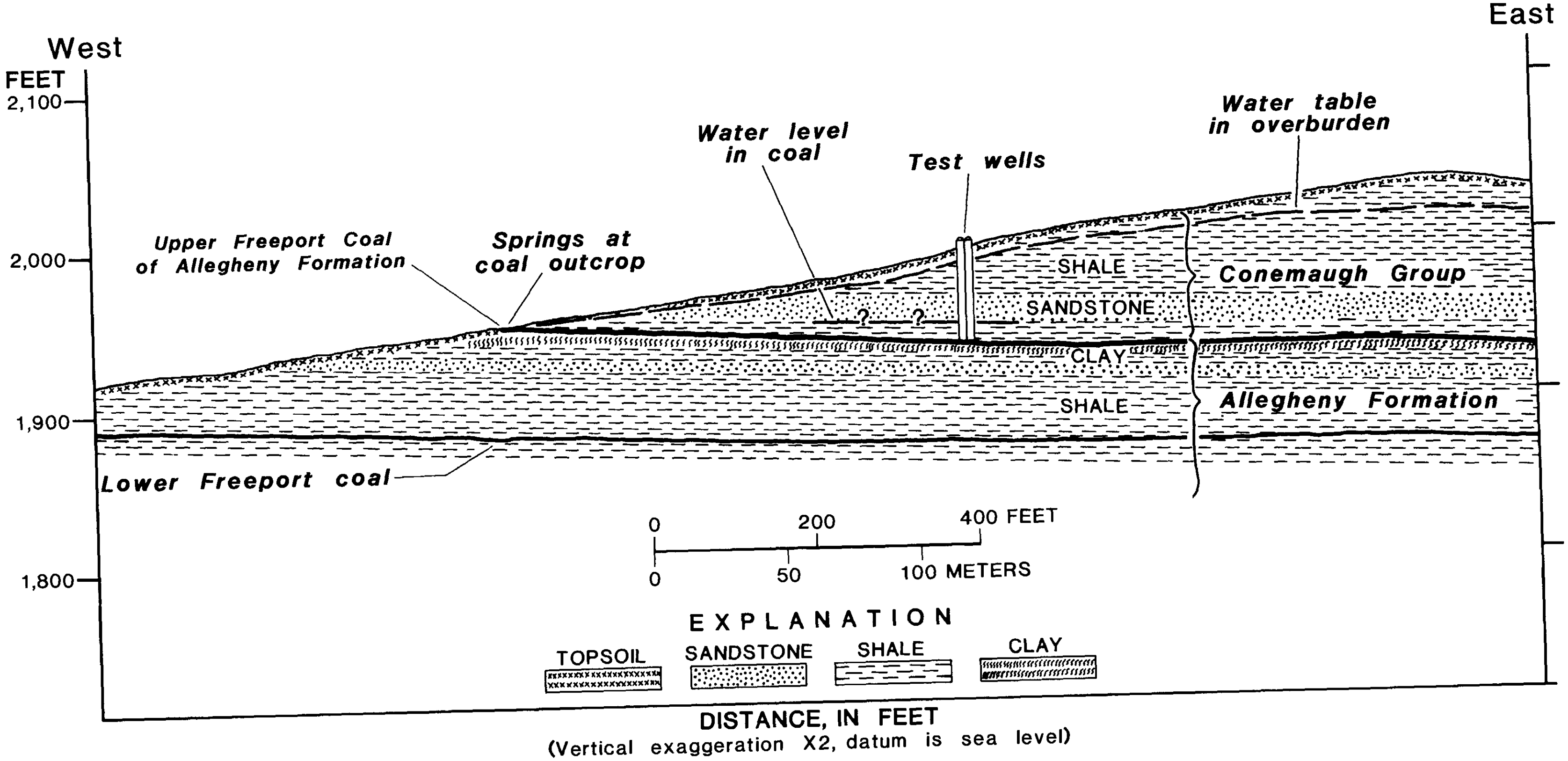



Figure 2.—General hydrogeologic section through the test site.

Water is present primarily in vertical joints in the coal aquifer where intergranular porosity is essentially zero. In the coal beds, these joints or face cleats may be fractions of an inch apart. Face cleats generally cut through the entire thickness of the coal bed, whereas butt cleats, which form at nearly right angles to the face cleat, are less pronounced and do not cut through the entire thickness of the coal bed.

## Water Levels and Ground-Water Movement

The water table in the overburden slopes to the northwest at about 0.11 ft/ft (feet per foot), which correlates to the general slope of the land surface in the area. However, the potentiometric surface for the confined water in the coal bed slopes to the east at about 0.025 ft/ft. One possible explanation for this difference in slope direction may be the existence of old test borings east of the test site. If these old borings penetrate permeable rock below the Upper Freeport coal, they could drain water from the coal aquifer downward into a zone of lower head. If enough water was being drained from the aquifer, this would tend to reverse the gradient.

Drainage to a lower aquifer occurred at well 83 just after the well was drilled. The well, which was about 250 ft northwest of the test site, was drilled to a depth of 125 ft. During drilling, a water-bearing or productive zone or layer, which yielded about 50 gal/min, was reportedly penetrated at about 75 ft below land surface. On Oct. 12, 1981, the water level in the well was 56.15 ft below land surface; the top of the Upper Freeport coal is 56 ft below land surface. The well was backfilled with drill cuttings and bentonite clay pellets to 67.5 ft below land surface. By Oct. 29, the water level had recovered to 18.75 ft below land surface. Prior to backfilling, water from the coal bed and the overburden was draining down the borehole and out the permeable zone at 75 ft.

The water level of 18.75 ft below land surface in well 83 is a combination of the head in the overburden and the head in the coal aquifer. The combined head is about 10 ft less than the head in the overburden aquifer, which shows that water is moving from the overburden aquifer downward into the coal aquifer. This may be occurring at wells 83, 84, and 73 (fig. 1). The recharge to the coal aquifer through these wells west of the site plus possible drainage from the coal bed at abandoned test holes east of the site could explain the eastward slope of the potentiometric surface in the coal aquifer.

# WELL INFORMATION

Preliminary hydraulic characteristics of the combined overburden and coal aquifers and/or coal aquifer were determined from a test performed on two wells, 13 ft apart, that were drilled by the coal company (81, 81A). A short aquifer test (1/2 hour) on these wells was used to estimate the distance the cone of depression would expand from the pumped well over time. This information was used to determine well spacings for other wells at the site.

Table 1 shows information for the five wells (81, 81A, 81B, 81C, 81D) at the test site and information on the three nearby wells (73, 83, and 84), which are too far away to be used during the aquifer tests.

## Well Construction

Wells 81, 81A, and 81D were cased through the soil zone (less than 4 ft) with 6-in. diameter steel casings. The wells were then drilled through the overburden and coal and 3 in. into the underlying shale. Plastic piezometers, 1.5 in. in diameter, were installed with perforated screened sections open to the coal bed. The annular space between the coal and the screen was filled with coarse-grained white silica sand. About 1.5 to 2 ft of bentonite clay pellets were placed on top of the sand at the level of the overlying black shale layer to hydraulically isolate the overburden aquifer from the coal aquifer. Generalized well construction is shown in figure 3.

Wells 81B and 81C, 8-in. diameter wells, were drilled through the overburden into the shale that overlies the coal bed. Six-in.-diameter steel casings were set in clay pellets in the shale (fig. 3). A 5-5/8-in. drill bit was used to drill through the pellets and the coal bed. Head in the overburden aquifer was measured in the annular space between the steel casing and the wall of the well. Head in the coal aquifer was measured inside the steel casing.

On Dec. 15, 1981, after the aquifer tests were completed on the coal aquifer, wells 81B and 81C were modified so that aquifer tests could be performed on the overburden rocks. The 6-in. diameter steel casings were removed, and that part of the well open to the coal aquifer was filled with sand; 1-1/2 to 2 ft of clay pellets were placed above the sand for a hydraulic seal. A 4-in.-diameter plastic pipe liner, perforated over its entire length and capped at the bottom, was placed in each well. The plastic liner was used to prevent any loose rock on the wall of the well from caving in on the pump when the overburden aquifer was tested.

## Well Logs

Geophysical logs were run on test wells 81A, 81B, and 81C. Figure 4 shows the rock types penetrated by wells 81B and 81C, and representative caliper, resistivity, and gamma logs. Wells 81 and 81A, were drilled prior to the study by the coal company; therefore, detailed lithologic logs were not available. Because all wells are located within 30 ft of wells 81B and 81C, the geologic section penetrated by wells 81B and 81C was assumed to be representative of the test site.

The caliper log shows variations in hole diameter with depth. Well 81C was 56 ft deep when caliper logged. The log shows that the borehole is as much as 14 in. in diameter from 12 to 26 ft. Drill cuttings indicate that the shale, siltstone, and clay in this part of the well are soft and highly weathered. As a result the surging of water and mud by compressed air during drilling caused this zone to cave and wash out. Several other hard and soft layers are indicated by the variations in hole diameter at 30 to 33 ft. Note that the hole diameter changed little in the massive hard sandstone found below 37 ft. A slightly smaller drill bit was used to drill below 50.5 ft.

A down-hole television camera was used to scan the walls of wells 81 and 81A. Two fractures were seen in well 81 (at 25.5 ft and 30.7 ft); only one fracture was seen in well 81A (at 12.3 ft). These scans suggest that the rock in the study area is not heavily fractured.

The resistivity log is shown for well 81A. This log was run when the well was 70.3 ft deep. Note that the positive peaks correspond to the coal bed, 59 to 63.2 ft deep, and to the massive sandstone bed, 38 to 58 ft deep. Other positive peaks at depths of 27, 33, and 37 ft probably correspond to thin beds of coal shown at well 81B. The negative peaks from depths of 19 to 26 ft and from 63 to 70 ft correspond to shale and clay beds. Note that this log shows that the zone containing the most clay and shale is the zone that washed out in well 81C (fig. 2).

The spontaneous-potential log is roughly a mirror image of the resistivity log. Although the log is less useful in pinpointing changes in lithology, its negative peak nicely matches the 20 ft of sandstone just above the Upper Freeport coal and its positive pulses correspond to the mainly shale beds above a depth of 25 ft.

**Table 1.—Data for wells located at or near the test site.**

| Well number | Drilled by | Date drilled | 6-inch casing: Casing length (feet) | 6-inch casing: Open interval (feet below land surface) | 6-inch casing: Water level (feet below land surface) | 6-inch casing: Date measured | 1 1/2-inch casing: Casing length (feet) | 1 1/2-inch casing: Open interval feet below land surface) | 1 1/2-inch casing: Water level (feet below land surface) | 1 1/2-inch casing: Date measured |
|---|---|---|---|---|---|---|---|---|---|---|
| 73 | Patriot Mining Company | -81 | 0 | 0 to 49.0 | 7.0 | 10-09-81 | 0 | ---- | ---- | ---- |
| | Patriot | 10-11-81 | 9.7 | 9.7 to 66.3 | 51.86 | 10-12-81 | 0 | ---- | ---- | ---- |
| 81[1] | Mining | ---- | 9.7 | 9.7 to 65.4 | 10.00 | 11-19-81 | 0 | ---- | ---- | ---- |
| | Company | ---- | 9.7 | 9.7 to 58.0 | 8.15 | 12-10-81 | 59.0 | 59.0 to 63.0 | 52.30 | 12-10-81 |
| | Patriot | -81 | 0 | 0 to 79.5 | 24.50 | 10-21-81 | 0 | ---- | ---- | ---- |
| 81A[2] | Mining | | 2.5 | 2.5 to 73.1 | 27.15 | 11-19-81 | 0 | ---- | ---- | ---- |
| | Company | -81 | 2.5 | 2.5 to 58.0 | 7.30 | 12-10-81 | 59.0 | 59.0 to 63.3 | 52.11 | 12-10-81 |
| | | 11-12-81 | 56.0 | 56.0 to 61.1 | 49.40 | 11-19-81 | 0 | ---- | ---- | ---- |
| 81B[3] | USGS | ---- | 56.0 | 56.0 to 61.1 | 49.15 | 12-10-81 | 0 | ---- | ---- | ---- |
| | | | 2.5 | 2.5 to 56.9 | 6.93 | 12-17-81 | | | | |
| | | 11-14-81 | 56.0 | 56.0 to 61.2 | 49.97 | 11-19-81 | 0 | ---- | ---- | ---- |
| 81C[3] | USGS | ---- | 56.0 | 56.0 to 61.2 | 49.57 | 12-10-81 | 0 | ---- | ---- | ---- |
| | | | 2.5 | 2.5 to 56.8 | 5.94 | 12-17-81 | | | | |
| | | 11-16-81 | 2.5 | 2.5 to 58.7 | 16.45 | 11-19-81 | 0 | ---- | ---- | ---- |
| 81D[4] | USGS | ---- | 2.5 | 2.5 to 52.7 | 6.60 | 12-10-81 | 53.7 | 53.7 to 58.7 | 46.04 | 12-10-81 |
| 83[5] | Patriot Mining Company | 10-10-81 | 0 | 0 to 119.1 | 56.15 | 10-12-81 | 0 | ---- | ---- | ---- |
| | Patriot | 10-10-81 | 0 | 0 to 118.3 | 33.13 | 10-12-81 | 0 | ---- | ---- | ---- |
| 84[6] | Mining Company | ---- | 10 | 10.0 to 64.0 | 24.00 | 10-16-81 | 0 | ---- | ---- | ---- |

[1] Well originally drilled to 79 feet. Backfilled from 66.3 to 63 feet 11-19-81 when 1 1/2-inch casing installed.
[2] Well originally drilled to 80 feet. Backfilled from 79.5 to 63.3 feet 11-19-81 when 1 1/2-inch casing installed.
[3] Pulled 6-inch casing. Backfilled to 56.9 feet 12-15-81.
[4] Installed 1 1/2-inch casing 11-19-81.
[5] Well originally drilled to 125 feet.
[6] Well originally drilled to 125 feet. Backfilled with drill cuttings to 64 feet on 10-15-81.

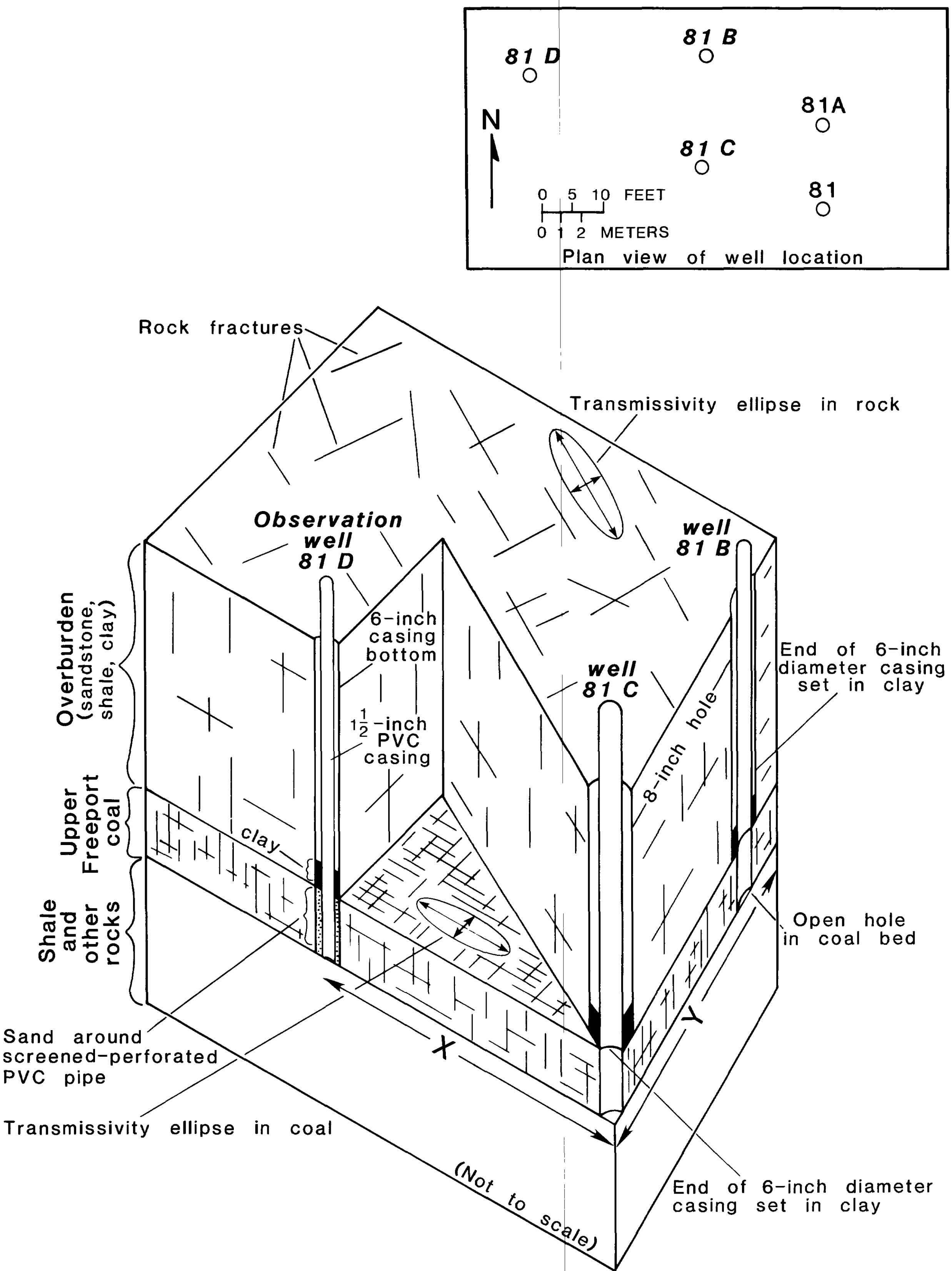



**Figure 3.—Schematic diagram showing three test wells, their construction when testing the coal aquifer, and the orientation of maximum and minimum transmissivities for the overburden and coal aquifers. (The "X" line parallels the face cleat and the "Y" line nearly parallels the butt cleat in the coal.)**

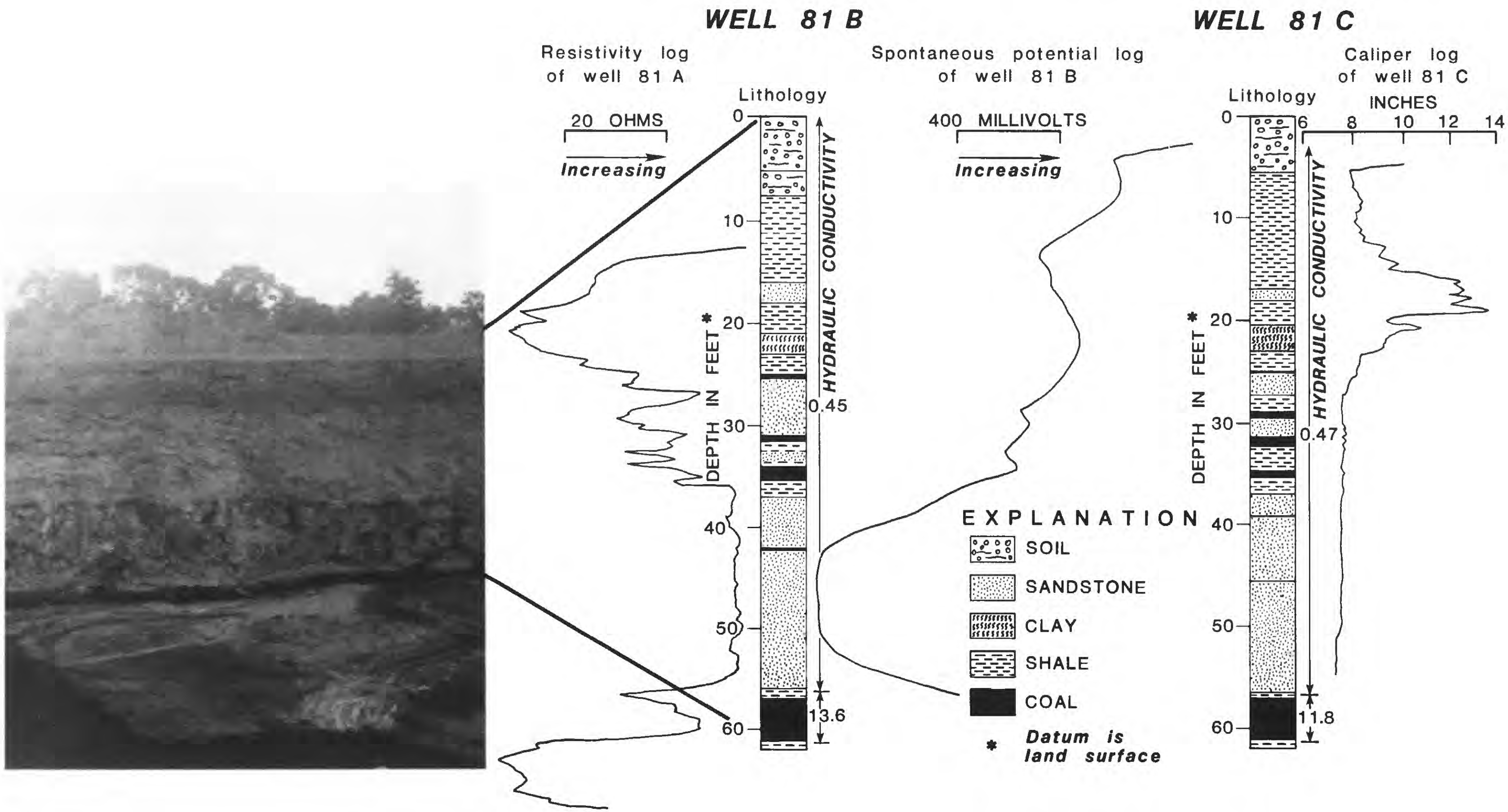



**Figure 4.—Photograph of stripmine highwall (about 300 feet north of the test site), geophysical and lithologic logs from selected test wells, and horizontal hydraulic conductivities determined for the coal and overburden aquifers at wells 81B and 81C.**

# TESTS USED TO DETERMINE HYDRAULIC PROPERTIES

Two types of tests were used to evaluate the hydraulic properties of the coal and overburden aquifers at the test site—constant-head injection and multiple-well aquifer tests. The constant head injection tests were used to detect permeable zones in the wells as they were drilled through the overburden. After well completion and development, multiple well aquifer tests were performed to determine the directional transmissivity and the storage coefficients.

The coal beds in West Virginia, which generally are underlain by clay and overlain by shale and sandstone, contain well-developed face cleat(s) oriented in a persistent direction over broad areas. The aquifer analysis method derived by Papadopulos (1965) was used to test the directional transmissivity of the Upper Freeport coal at the test site. Papadopulos (1965) derived an equation that could be used to analyze aquifer-test data from three or more observation wells located around a well that was being pumped at a constant rate from a confined, infinite, anisotropic aquifer. This analysis permits the determination of the components of the transmissivity tensor along an arbitrarily chosen set of orthogonal axes. These components in turn are used to determine the axes of maximum and minimum transmissivity (assuming minimum transmissivity lies at right angles to the maximum). Theoretically, the analysis of combinations of data from any three wells in the same homogeneous, anisotropic aquifer, should yield similar results. The shape of the contours of the recharge mound or drawdown at various times during aquifer testing also was used to graphically indicate permeability of the rocks at the test site.

## Depth-Interval Test

Wells 81B, 81C, and 81D generally were drilled in 10-ft intervals. After advancing the hole 10 ft, a constant-head injection test was done on the entire length of the hole in the overburden. These tests were used to determine which 10-ft increments of the well were permeable. The depth intervals from 3-13 ft, 3-23 ft, 3-33 ft, 3-43 ft, and 3-56 ft (a 13-ft interval) in wells 81B, 81C, and 81D were tested.

After cleaning the hole with water and compressed air, the well was filled with water to the top of the surface casing, and a measured amount of water was added to keep the water in the well level with the top of the casing over a measured period of time. When testing the less permeable sections of the well, the water level in the well was maintained by adding water from a 250- or 500-milliliter plastic bottle. When testing the more permeable sections of the hole, the water was added through a 1-in. plastic pipe and a water meter connected to a large water tank.

The relation $K = C\,Q/H$ (U.S. Department of the Interior, 1974) was used to calculate the permeability of each succeeding section of the overburden,

where $K$ = hydraulic conductivity (ft/d),
$Q$ = injection rate into hole (gal/min),
$H$ = difference in head between static head and head maintained by injection (ft), and
$C$ = shape factor based on length and diameter of open hole being tested.

Figure 4 and table 2 show the hydraulic conductivities that were determined for the combined overburden and coal aquifers using wells 81B, 81C, and 81D.

The injection tests at wells 81B and 81C indicate that the most permeable zones in the overburden are in the top 30 ft of rock. Water loss in well 81D constantly increases with depth suggesting some permeability within each interval of the well.

Table 2.--Hydraulic conductivities (K) and water-loss rates (Q) in the overburden for various depth intervals in wells 81B, 81C, and 81D.
[ft=foot; ft/d=foot per day; gal/min=gallon per minute]

| Well depth interval (ft) | Well 81B | | Well 81C | | Well 81D | |
|---|---|---|---|---|---|---|
| | K (ft/d) | Q (gal/min) | K (ft/d) | Q (gal/min) | K (ft/d) | Q (gal/min) |
| 3-13 | 0.05 | 0.06 | 0.22 | 0.30 | 0.28 | 0.30 |
| 3-23 | .12 | .23 | .90 | 2.0 | .72 | 1.3 |
| 3-33 | .28 | .75 | .73 | 2.2 | .88 | 2.2 |
| 3-43 | .09 | .30 | .61 | 2.3 | .80 | 2.6 |
| 3-56 | .45 | 1.8 | .47 | 2.1 | .78 | 2.9 |

The depth-interval tests, conducted while drilling, probably yielded hydraulic conductivity values that are too low—primarily because of incomplete cleaning of drill cuttings and mud from the well. However, even if these values are low, they probably indicate relative permeabilities found at various levels in the hole. On the basis of these data, the more permeable rock is found between a depth of 6 ft (the top of the water table) and 33 ft.

## Coal-Aquifer Test

In wells 81B and 81C, the static water level in the leaky confined coal aquifer was about 7 ft above the top of the coal bed. Because the transmissivity and storage coefficient of the coal aquifer are relatively low, this is insufficient head to pump the aquifer for an adequate length of time and pumping rate to test the aquifer. Therefore, the aquifer was tested by injecting water into wells 81B and 81C in two separate tests at rates of 0.8 and 0.9 gal/min, respectively. Figure 3 shows the construction of wells 81B, 81C, and 81D at the time the coal aquifer was tested.

Water from two 55-gallon steel drums, connected in series, was injected through a 1-in.-diameter plastic pipe in the well. A gate valve was used to adjust and maintain a constant flow rate, which was measured with a standard "home-type" water meter. As water was injected into one well, the water levels were measured in the surrounding wells.

The aquifer-test data were analyzed by plotting and then contouring the water levels measured in the observation wells at various times during the aquifer tests and by analyzing the test data from sets of three observation wells to compute a direction for maximum and minimum transmissivity based on the technique proposed by Papadopulos (1965). Maslia and Randolph (1987) provided a computer program that greatly expedited the calculations required by the Papadopulos method. They also provided a least-squares optimization procedure whereby the data from all four observation wells could be used in a single analysis.

Figures 5 and 6 show the resultant water mound in the potentiometric surface around wells 81B and 81C, after 110 and 160 minutes, respectively. The injected water moves more rapidly away from the injection wells to the northwest and southeast—presumably along the face cleat in the coal. Thus, the mound around both injection wells is elongated to the northwest/southeast.

The injection aquifer-test data for the coal aquifer were analyzed using the standard type of aquifer analysis for the data from a single observation well (Cooper-Jacob and Theis methods.) The data were plotted on log-log or semilog graph paper and transmissivity and storage coefficients were determined. Because of the short duration of the aquifer tests, these transmissivity values are considered to be estimated ones. Estimated transmissivities of the coal aquifer ranged from 49 to 65 $ft^2/d$ and storage coefficients ranged from $3.8 \times 10^{-3}$ to $1.7 \times 10^{-2}$.

## Overburden-Aquifer Test

Wells 81B and 81C were modified and used to test the saturated overburden aquifer 7 to 57 ft below land surface. The coal zone was sealed with clay and the wells were cased through the overburden with 4-in.- diameter perforated plastic casings to keep soil from caving into the well when the 6-in.-diameter casing was removed. A centrifugal pump, with a pumping rate of about 11 gal/min, was used to pump the wells. A net pumping rate of 1 gal/min was maintained by discharging 10 gal/min back into the 4-in. perforated plastic casing in the pumped well. As the well was pumped, the water level could be measured in the annular space between the wall of the well and the 4-in. plastic liner. The net pumping rate of 1.0 gal/min permitted a sufficiently long period (more than 40 minutes) of pumping to cause a water-level decline in observation wells located from 17 to 30 ft away from the pumped wells.

Figures 7 and 8 show the resultant drawdown in water level around the pumped wells after 70 and 42 minutes of pumping the overburden aquifer. The water moves more rapidly to the pumped well from the northwest and the southeast—presumably along the joint system in the rock that is oriented N. 60° W. to N. 70° W. (Bench and others, 1977, p. 18). Thus the drawdown cone is elongated to the northwest/southeast.

The aquifer-test data for the overburden aquifer were analyzed using the standard type of aquifer analysis for the data from a single observation well (Cooper-Jacob and Theis methods). Time-drawdown data were plotted on log-log or semilog graph paper and values of transmissivity and storage coefficients were determined. Because of the short duration of the aquifer tests, these transmissivity values are considered to be estimated ones. Estimated transmissivities for the overburden ranged from 47 to 140 $ft^2/d$, and storage coefficients ranged from $2.9 \times 10^{-3}$ to $1.8 \times 10^{-2}$. Thus,the 4.5 ft of Upper Freeport coal is almost as transmissive as the 50 ft of sandstone and shale overburden.

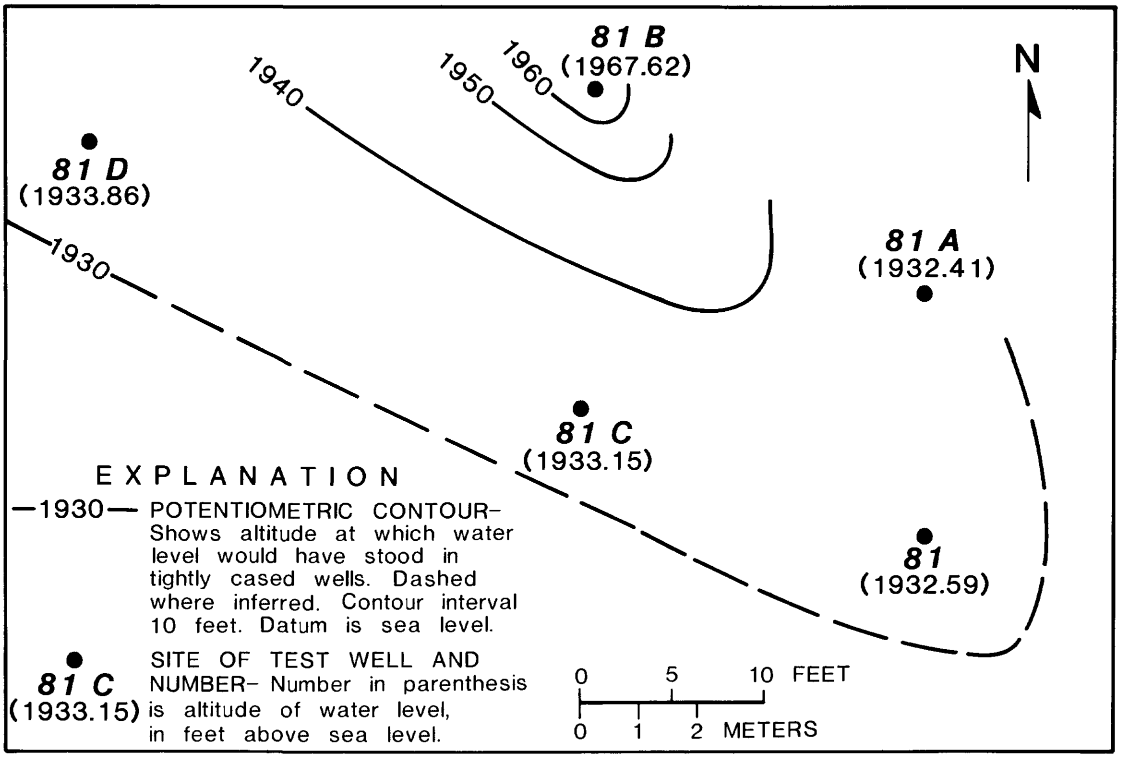



**Figure 5.—Equipotential lines in coal aquifer after 110 minutes of injecting water at well 81B at 0.8 gallons per minute.**

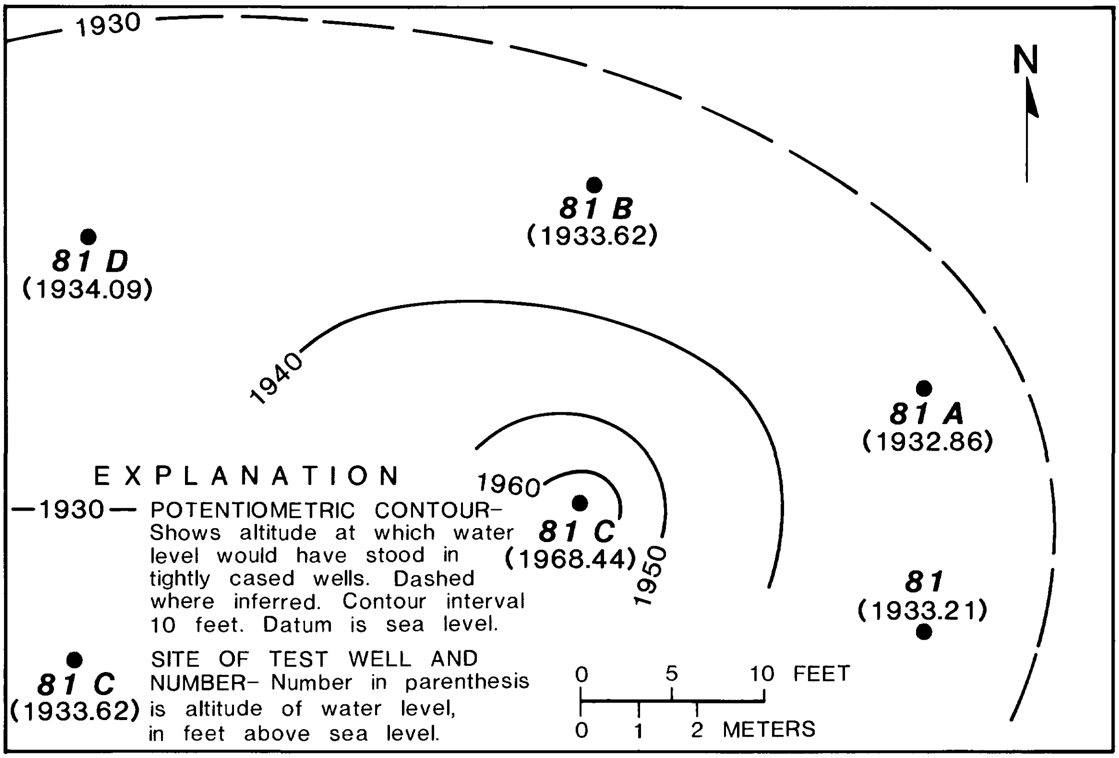



**Figure 6.—Equipotential lines in coal aquifer 45 minutes after cessation of injection of water at well 81C at 0.9 gallons per minute for 115 minutes.**

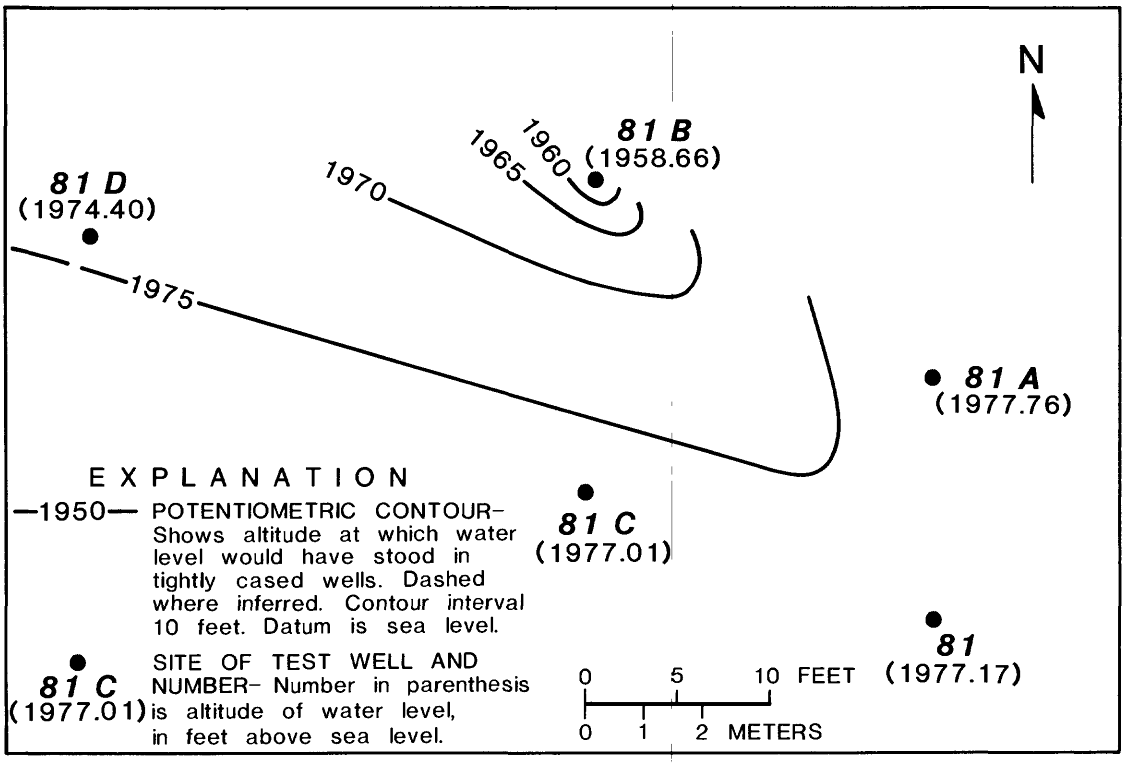



**Figure 7.—Equipotential lines in bedrock above coal after 70 minutes of pumping well 81B at 1.1 gallons per minute.**

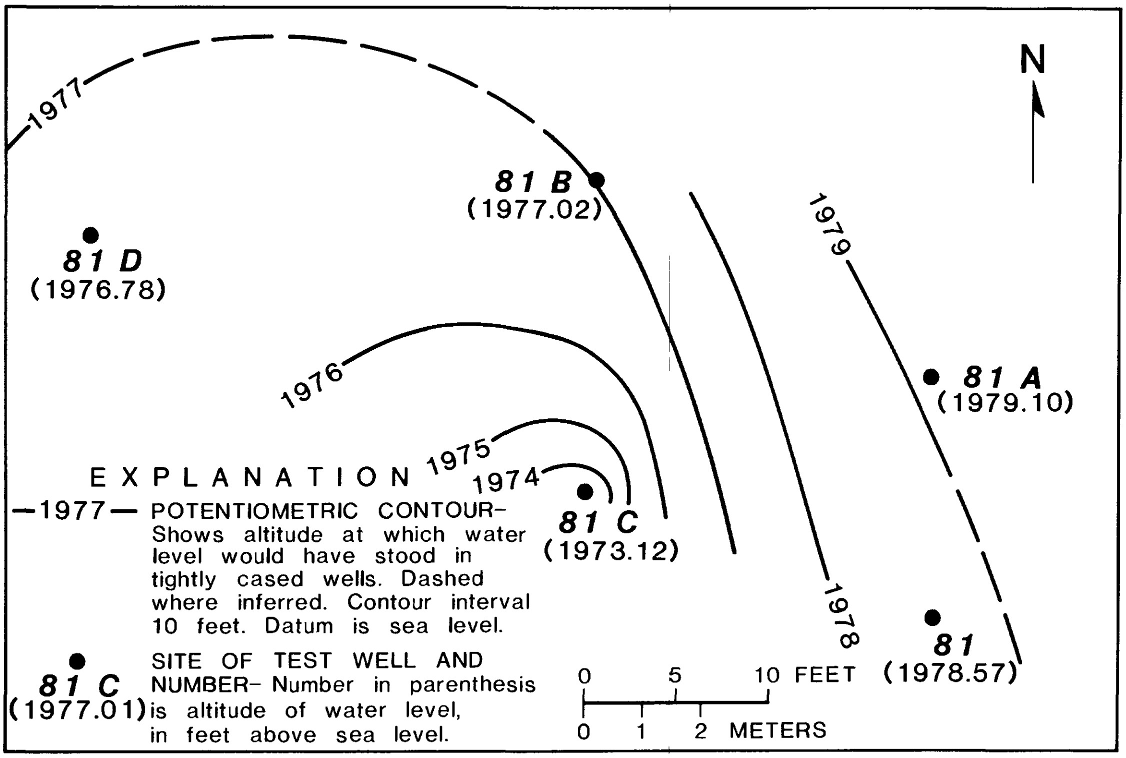



**Figure 8.—Equipotential lines in bedrock above coal after 42 minutes of pumping well 81C at 1.0 gallons per minute.**

# RELATION OF FRACTURE SYSTEMS TO TRANSMISSIVITY

The aquifer-test data were analyzed using the Papadopulos (1965) method for analyzing nonsteady flow to a well in an infinite anisotropic aquifer. The locations of the test wells were plotted to scale on arithmetic graph paper in their proper positions with respect to the pumped well. A set of X-Y axes was drawn with the origin at the center of the pumped well and the Y axis oriented in a north-south direction. X and Y coordinates were determined for each well. By using these coordinates and the drawdown data from various sets of three observation wells, the components of the transmissivity tensor along the X-Y axes were determined using the computer program (for the Theis type curve) by Maslia and Randolph (1987). These tensors were used to determine maximum and minimum transmissivities and the orientation of the axis of maximum transmissivity. The axis of minimum transmissivity is assumed to be at right angles to the axis of maximum transmissivity.

Each of the nine analyses indicated that the direction of maximum transmissivity for the coal aquifer was to the northwest. A rose diagram (fig. 9) was constructed using the nine determinations for the axis of maximum transmissivity (table 3) for the coal aquifer. The rose diagram indicates that the axis of maximum transmissivity averages about N. 75° W. at this site and nearly parallels the face cleat in the coal. The orientation of two face cleats in the coal are N. 75° W. and N. 64° W., an average of N. 69.5° W. Two face cleats measured in the coal about 150 ft from the test wells in the surface mine pit were oriented N. 68° W. and N. 65° W., an average of N. 66.5° W. The map by Kulander and Dean (1980) shows face cleats for this area are oriented from N. 66° W. to N. 69° W.

The maximum transmissivity direction, maximum and minimum transmissivity values, and storage coefficients determined while recharging well 81C (table 3) may be more reliable than those determined while recharging well 81B. When performing the test using well B a brief lowering of the recharge rate (after 30 minutes of recharging) caused a shift in the data curves for wells 81A and 81C. When analyzing these data curves with the Theis type curve to determine values of drawdown, time, W(u), and u, the late data plots were shifted, using the Theis type curve, so that they matched with the data obtained prior to the lowered recharge rate. After making this shift, the match point values of drawdown, time, W(u) and u were selected and values were computed (table 3). They compare favorably with the values obtained while recharging well 81C.

The ratios of maximum transmissivity to minimum transmissivity range from 2 to 15, with median of 3.4 for the coal aquifer (table 3). Therefore, the maximum transmissivity generally is 3.4 times greater than the minimum transmissivity. Figure 10 shows the transmissivity ellipse for the coal aquifer (and the overburden aquifer) as determined by the least squares analysis (Maslia and Randolph, 1987) of the data from all four observation wells. The ratio of the maximum to minimum transmissivity in this figure is 3:1, and the orientation of the axis of maximum transmissivity is N. 65° W.

Each of the seven analyses for the overburden aquifer indicated that the direction of maximum transmissivity was also northwest/southeast. A rose diagram was constructed using the seven determinations for the axis of maximum transmissivity (table 4) for the overburden aquifer (fig. 11A). The axis of maximum transmissivity averages about N. 52° W. and somewhat correlates with the orientation of the face cleat in the coal. A poorer correlation would be expected simply because there are fewer values determined for maximum transmissivity and because the aquifer test would be affected by open horizontal joints or faults, and bedding plane separations, and the lack of closely-spaced (face-cleat type) joints in the bedrock.

Figure 10 compares the least-squares transmissivity ellipses for the coal and overburden aquifers. This figure shows that the 4.5 ft of coal and approximately 50 ft of overburden have nearly the same transmissivity and nearly the same orientation of maximum transmissivity axes.

The ellipse axes drawn on the coal bed and the overburden in figure 3 show the general orientation and approximate relation of the maximum to minimum transmissivity. The orientation of the axis of maximum transmissivity agrees somewhat with the findings of Bench and others (1977, p. 18) who measured the orientation joints in the bedrock in nearby northeastern Monongalia County. Most of the 108 joints they measured were oriented between N. 60° W. to N. 75° W. and N. 15° E. to N. 45° E. (fig. 11B). They concluded that in their study area the principal bedrock joints and zones of weakness are nearly parallel to the cleats in the coal beds (Bench and others, 1977, p. 29).

**Table 3.—Hydraulic properties of the Upper Freeport coal aquifer.**
**[ft²/d, foot squared per day; ---, impossible values]**

| Aquifer | Observation wells | Direction of maximum transmissivity | Transmissivity Max. (ft²/d) | Transmissivity Min. (ft²/d) | Transmissivity Ratio | Storage coefficient | Method of analysis[1] |
|---|---|---|---|---|---|---|---|
| Upper | 81,81C,81D | N. 76° W. | 106 | 15 | 7.0 | $5.1x10^{-3}$ | Theis |
| Freeport coal | 81A,81C,81D | N. 84° W. | 104 | 23 | 4.6 | $7.4x10^{-3}$ | Theis |
| (Recharging | 81,81A,81D | N. 92° W. | 84 | 34 | 2.5 | $6.9x10^{-3}$ | Theis |
| well 81B on | 81,81A,81C | N. 62° W. | 91 | 29 | 3.1 | $1.1x10^{-2}$ | Theis |
| test date | 81,81A,81C,81D | N. 78° W. | 107 | 22 | 4.9 | $6.8x10^{-3}$ | Theis[2] |
| 12-2-81) | | | | | | | |
| Upper | 81A,81B,81D | N. 67° W. | 79 | 23 | 3.4 | $1.2x10^{-2}$ | Theis |
| Freeport coal | 81,81A,81D | --- | --- | --- | | --- | Theis |
| (Recharging | 81,81A,81B | N. 74° W. | 64 | 30 | 2.1 | $1.5x10^{-2}$ | Theis |
| well 81C on | 81,81B,81D | N. 42° W. | 144 | 9.3 | 15.5 | $8.4x10^{-3}$ | Theis |
| test date | 81,81A,81B,81D | N. 65° W. | 74 | 24 | 3.1 | $1.2x10^{-2}$ | Theis[2] |
| 12-10-81) | | | | | | | |

[1] Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage:American Geophysical Union Transactions, v. 16, p. 519-524.
[2] Least-squares technique used with the data from 4 observation wells.

**Table 4.--Hydraulic properties of the overburden aquifer.**
**[ft²/d, foot squared per day; ---, impossible values]**

| Aquifer | Observation wells | Direction of maximum transmissivity | Transmissivity Max. (ft²/d) | Transmissivity Min. (ft²/d) | Transmissivity Ratio | Storage coefficient | Method of analysis[1] |
|---|---|---|---|---|---|---|---|
| Overburden | 81,81A,81C | N. 33.5° W. | 97 | 13.6 | 7 | $9.9x10^{-3}$ | Theis |
| (Pumping | 81A,81C,81D | N. 95° SW. | 77 | 36 | 2.1 | $1.2x10^{-2}$ | Theis |
| well 81B on | 81,81C,81D | N. 62° W. | 155 | 17 | 9 | $6.4x10^{-3}$ | Theis |
| test date | 81,81A,81D | --- | --- | --- | | --- | Theis |
| 12-17-81) | 81,81A,81B,81C,81D | N. 59° W. | 77 | 30 | 2.5 | $8.1x10^{-3}$ | Theis[2] |
| Overburden | 81,81A,81B | N. 143° SW. | 42 | 32 | 1.3 | $9.3x10^{-3}$ | Theis |
| (Pumping | 81A,81B,81D | N. 52° W. | 259 | 52 | 5 | $1.7x10^{-2}$ | Theis |
| well 81C on | 81,81B,81D | --- | --- | --- | | --- | Theis |
| test date | 81,81A,81D | --- | --- | --- | | --- | Theis |
| 12-23-81) | 81,81A,81B,81C,81D | N. 45° W. | 203 | 50 | 4 | $1.6x10^{-2}$ | Theis[2] |

[1] Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: American Geophysical Union Transactions, v. 16, p. 519-524.
[2] Least-squares technique used with the data from 5 observation wells.

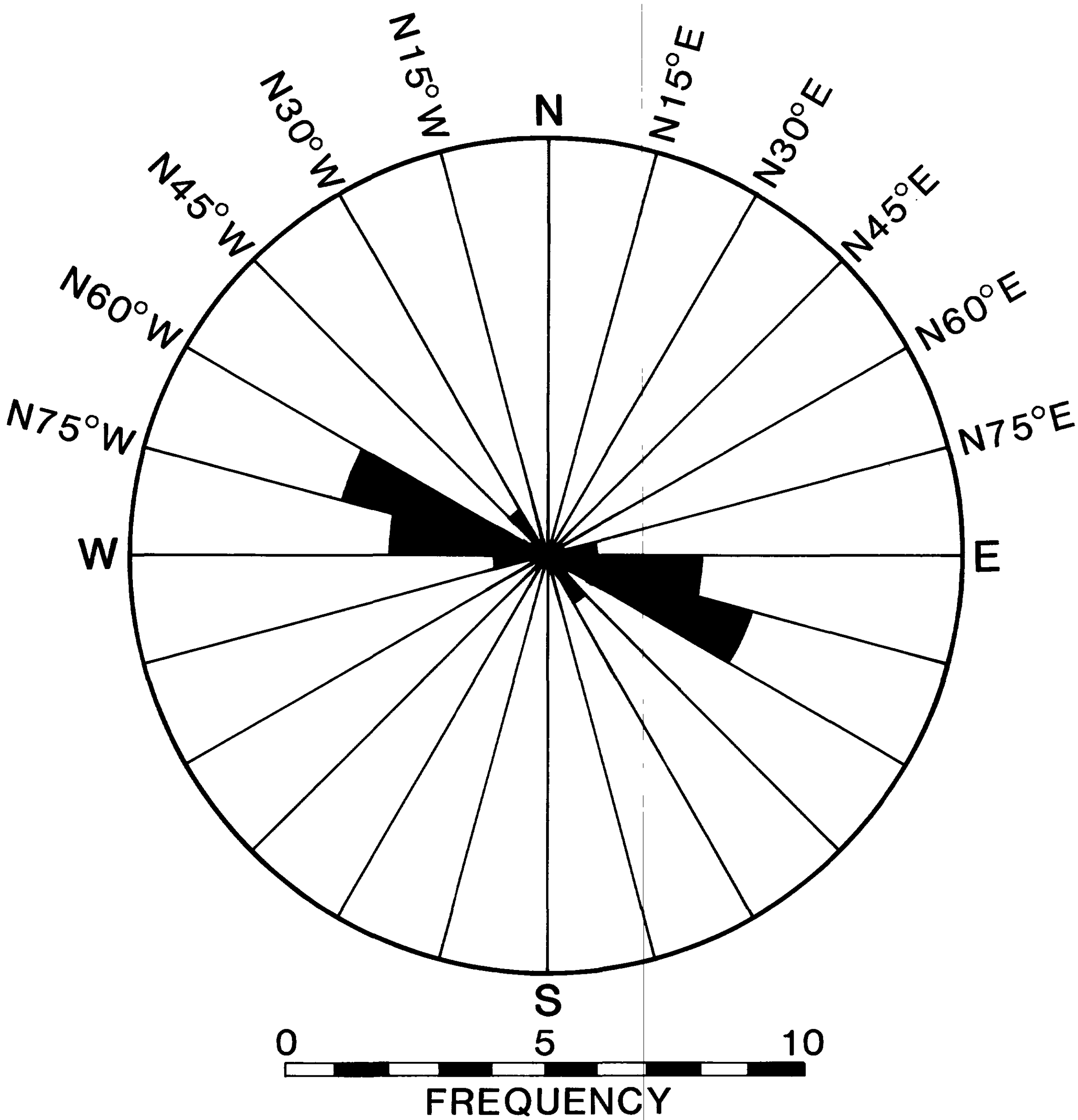



**Figure 9.—Rose diagram showing frequency of orientation of the major component of transmissivity in Upper Freeport coal aquifer.**

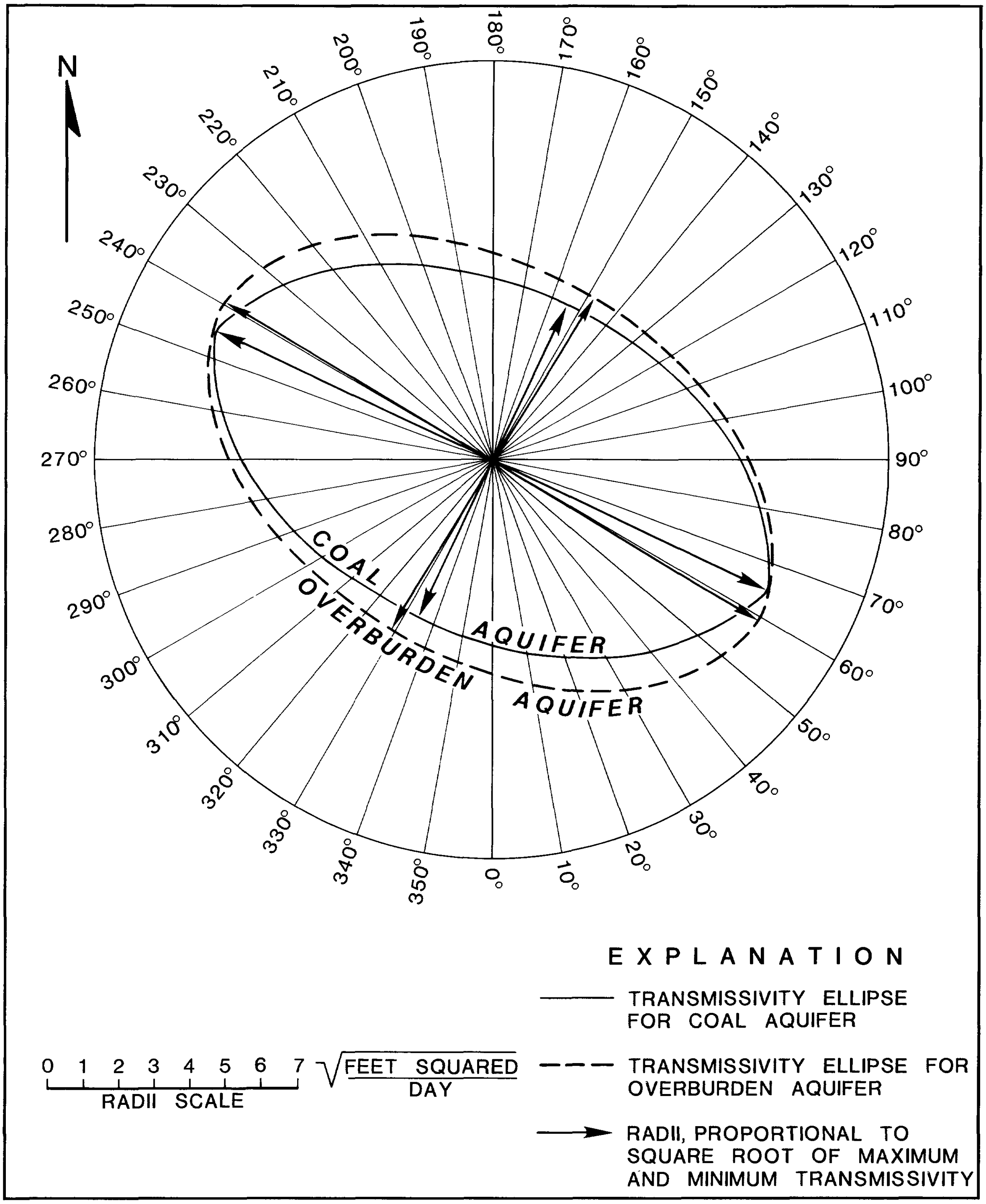



**Figure 10.—Least-squares transmissivity ellipses for coal and overburden aquifers for aquifer tests December 10 and 17, 1981, Preston County, West Virginia.**

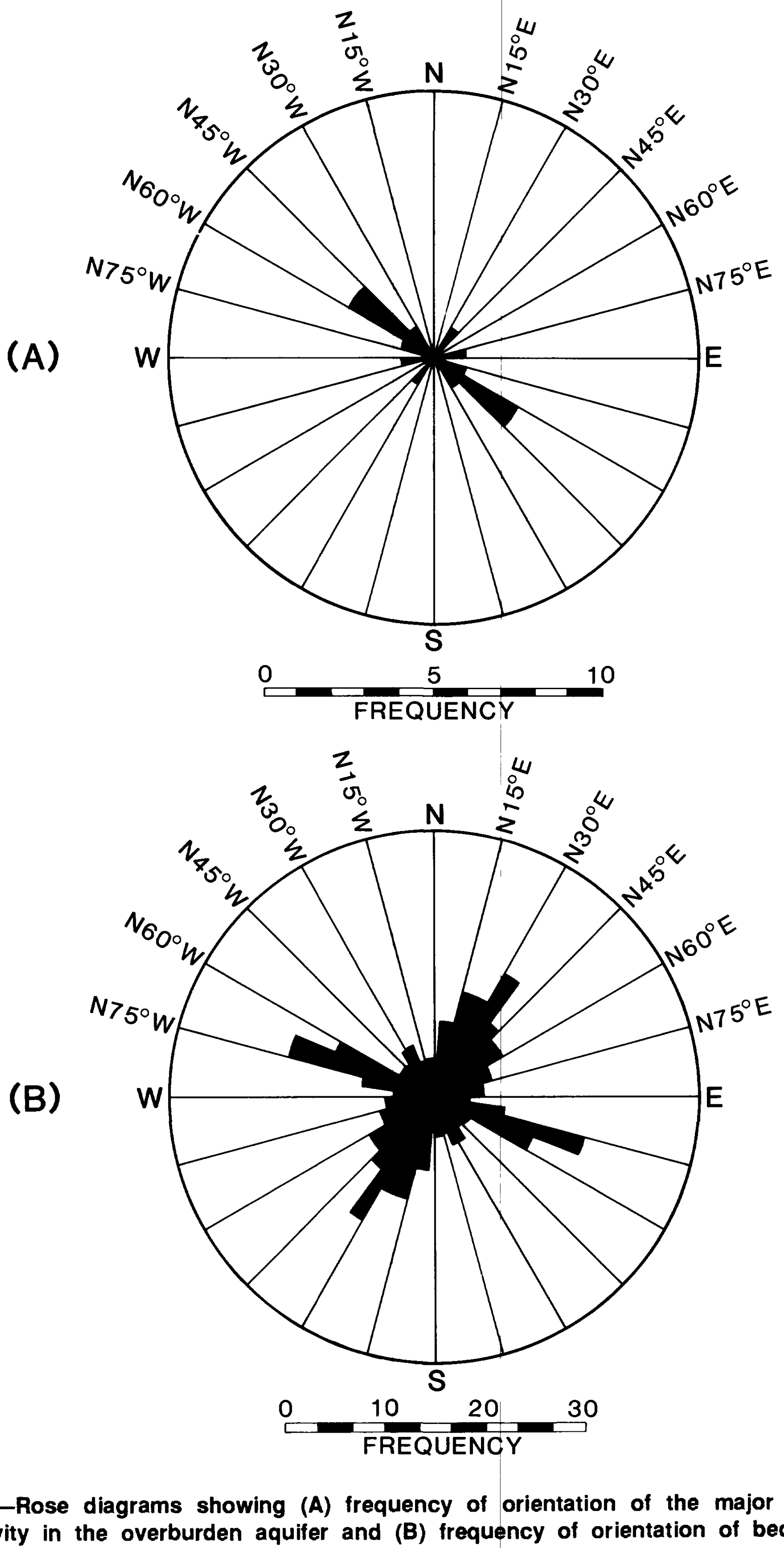



**Figure 11.**—Rose diagrams showing (A) frequency of orientation of the major component of transmissivity in the overburden aquifer and (B) frequency of orientation of bedrock joints in northeastern Monongalia County. (Modified from Bench and others, 1977, p. 18.)

## SUMMARY

Aquifer tests were conducted on a leaky confined coal aquifer and the associated sandstone and shale overburden water-table aquifer in Preston County, West Virginia. The test site is located on a relatively broad hilltop that has a shallow water-table aquifer. The ground water at the site is not influenced by fracturing along known faults or lineaments. Analysis of the data from tests used to evaluate hydraulic properties of anisotropic aquifers indicates that at this site—

1. The Upper Freeport leaky confined coal aquifer, which is 4.5 ft thick, is almost as transmissive as the 50 ft of overlying sandstone and shale.
2. The orientation of maximum transmissivity in the coal—N. 75° W.— approximately parallels the averaged direction of the major fractures (face cleat) in the coal—N. 65° W.
3. In the coal, the maximum transmissivity is about three times greater than the minimum transmissivity.
4. In the overburden, the maximum transmissivity is about seven times greater than the minimum transmissivity.
5. The directional maximum transmissivity in the coal and the overburden aquifers differ slightly, but both trend to the northwest and nearly parallel the face cleat in the coal.
6. The average storage coefficient is only slightly lower for the coal than for the overburden.
7. Major and minor fracture sets create anisotropic hydraulic characteristics that favor ground-water movement parallel to the major fractures in both the coal and overburden aquifers.

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