PHOTO-LINEAR CHARACTERIZATION, LITHOLOGIC VARIABILITY, AND THE EFFECTS OF MINING ACTIVITY BY FRACTURE STUDIES AND IN SITU, AIR-INJECTION, PERMEABILITY TESTING[1]

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ABSTRACT

Highwall fracture studies and a novel permeability testing technique were used in a study of the subsurface character of a photo-linear "fracture trace". This study focused on a topographic-tonal, photo-linear feature that intersected the highwall of an active surface coal mine working the Freeport-Mahoning coals near Clearfield. Aerial photographs at 1:12,000 scale were used for the photo-linear analysis, and critical features were examined in the field. Fracture data on joints and faults were gathered in traverses along highwall exposures of a relatively uniform siltstone unit overlying the Upper Freeport Coal, and hydrologic tests through borehole packers were conducted in overburden shotholes and selected monitoring boreholes drilled into the siltstone. The orientation of photo-linear and joint distribution maximas compare well, both falling between 320 - 340 degrees. Joint frequency analysis indicated that fracturing increased slightly near the photo-linear feature's subsurface projection. However, the correlation of this feature with a swale in the Mahoning Coal (possibly an old distributary channel) indicated that fracture frequency increases are probably related to stratigraphic phenomena rather than "fracture traces". The air-based packer test technique used for the permeability testing was designed to gather data rapidly from available boreholes, especially those in unsaturated units adjacent to the mine pit. A total of 55 permeability values were obtained from the siltstone. These values defined the permeability variation within the siltstone (probably 1.0 to 7.0 x 10^{-13} ft^2), evaluated the effect of mining activity on bedrock permeability (2x + increases extending 20-30 ft from the highwall), and enabled the air-permeability values to be correlated with the hydraulic conductivity values (3.9 to 5.1 x 10^{-7} ft/sec) derived from water-based tests. In addition, air-injection test factors (such as Klinkenberg slippage, partial saturation, and turbulent flow) and some additional uses of the technique were given a preliminary evaluation.

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INTRODUCTION

One topic which has recently received more than passing attention from hydrogeologists is the movement of ground water through subsurface fractures. This interest is due to the ubiquitous nature of geologic fractures, their generally permeable character, and the fact that they can interfere with the application of Darcy's Law. By studying the nature of fracture flow, as well as the distribution and character of fracture features, ground-water scientists can better adapt porous media theory, based on Darcy's Law, to fit particular geologic situations. This will improve understanding and prediction of ground-water flow in many geologic systems. However, a great deal of information on the subsurface nature of fracture features and their effects on porous media must be gathered before consistent evaluation of these systems will be generally possible.

The primary objective of this study was a quantified evaluation of the geologic and hydrologic character of the subsurface expression of a photo-linear "fracture trace" feature. Because these features have been correlated with zones of weakness and increased ground-water flow (Lattman and Matzke 1961, Parizek 1976), it was expected that this research would yield valuable field data on the nature of these features that could be applied in other areas. This was to be achieved by fracture studies and in situ permeability tests that could be focused where a mapped feature intersected the highwall of a surface coal "strip" mine. Secondary objectives to be studied included the variability of permeability within a fractured lithology, the effects of mining on permeability, and the factors affecting the field use of air-injection permeability tests.

This study was conducted in Clearfield County in the Appalachian Plateau region of Pennsylvania. The Browncrest III surface coal mine, operated by the Central Pennsylvania Coal Company of Clearfield, was selected as the study site because of the availability of recent aerial photograph coverage of the mine, the presence of a photo-linear feature that intersected the mine pit, the relatively uniform and undisturbed nature of the exposed lithologies, as well as the cooperative attitude of the mine operator.

RESEARCH TECHNIQUE

As illustrated by figure 1, the research technique employed in this study had three phases: 1) identification of a photo-linear fracture trace feature where it crossed a mine highwall, 2) measurement of joints and faults in traverses of a suitable highwall lithology near the fracture trace and in other areas of the pit, and 3) development and application of the permeability testing technique in available overburden shotholes and monitoring boreholes drilled in the vicinity of the feature. By examination

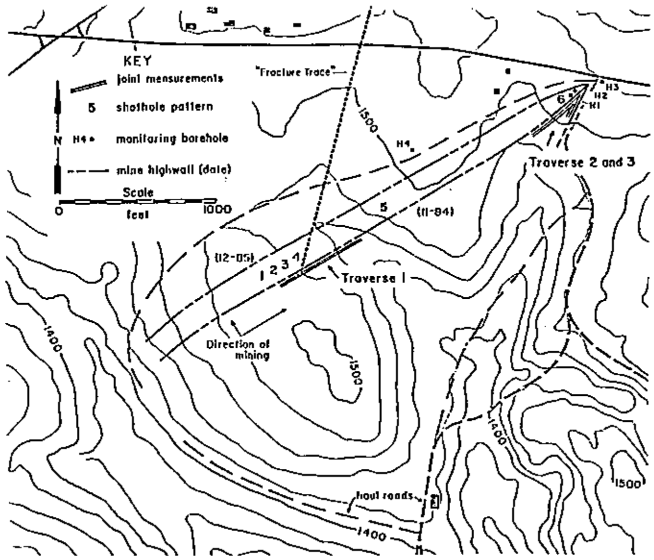

Figure 1 -- Location map of study area features.

of the exposed lithologies (from the Lower Freeport Coal to a sandstone above the Mahoning Coal), it was decided to concentrate the fracture studies and hydrologic testing on a siltstone unit that overlies the Upper Freeport coal (see figure 2). This unit was selected because of the number of drillholes into it, as well as its consistent character and exposure across the mine.

Photo-linear Fracture Trace Analysis

The fracture trace analysis was done in order to characterize the overall distribution of photo-linear features and to provide a basis for comparision with other available data on joints and fracture traces for this region. The technique used to map the photo-linear fracture trace features at the mine site

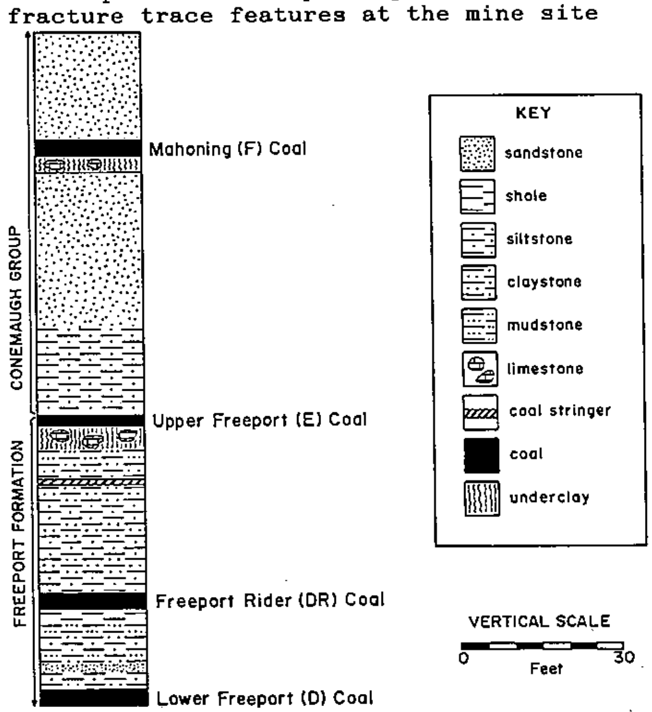

Figure 2 -- Composite stratigraphic section for the study area.

was derived from Lattman (1958) and Meiser and Earl (1982). Aerial photographs at 1:12,000 scale were studied individually and in stereo with the aid of a mirror stereoscope. The ends of observed features were marked on acetate overlays and the fracture trace feature shown in figure 1 was then field-checked for accuracy. Previous mining activity to the south and east of the mine pit made the analysis difficult. However, the three images which provided the photographic base for this analysis were of excellent quality, revealed land surface details with great clarity, and were only a few months old when this study began.

Highwall Fracture Studies

In order to determine if the photo-linear fracture trace feature intersecting the mine pit was related to a subsurface zone of fracture concentration, highwall fracture studies were conducted. The objective of this phase of the research was a qualitative and quantitative evaluation of joints and other geologic fractures that could be observed in highwall traverses. Joint measurements were made in 3 traverses, in the vicinity of the mapped feature as well as in areas thought not to be affected by linear features. Joint and fault planes were distinguished from blasting related fractures on the basis of their extent, regularity, degree of weathering, and relationship to remanents of shotholes visible along the highwall. The mapped joint and fault features were located along the 3 traverses with a fiberglass measuring tape. A Brunton compass, scale, and set of descriptive criteria were used to characterize each joint or fault identified along a traverse.

Air-Injection Permeability Testing

In order to conduct the density of permeability tests necessary to quantify the subsurface nature of the mapped photo-linear fracture trace, a novel air-injection permeability measurement technique had to be developed. This technique, illustrated in figure 3, was designed to quickly and accurately gather bedrock permeability values from test intervals at the bottom of overburden shotholes drilled in the siltstone. By testing in the patterns of these shotholes (closely spaced boreholes with similar characteristics), information on the spatial variation and factors affecting in situ permeability determinations was gathered.

Due to the nature of the surface mine environment, the technique had to be mobile, durable, and designed to operate in unsaturated conditions. The equipment item which made this possible was the borehole packer. By using a single packer to isolate the bottom of the borehole, permeability values were obtained from the constant-head (steady-state) air-pressure and corresponding air-flow conditions that could be developed in each test interval. These air tests were patterned on constant-head water tests used to gather hydraulic conductivity data under saturated conditions (Houlsby 1976).

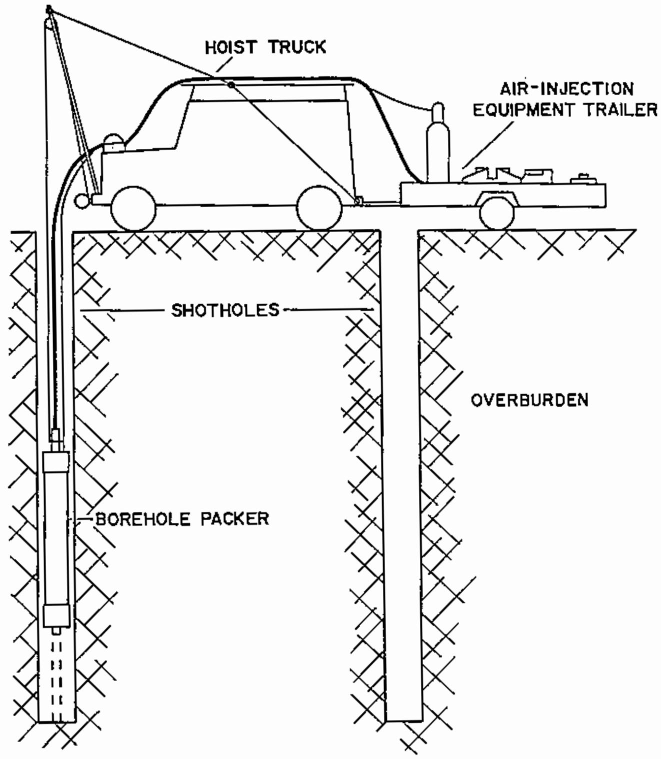

Figure 3 -- Schematic of air-injection permeability test.

Because of the severe limits on testing time imposed by the active mining, as well as equipment and manpower restrictions, it was not possible to gather subsurface fracture data from tested intervals with an impression packer.

The standard testing format, following insertion and inflation of the single packer, was a multiple step (abcba) test conducted in a sequence of pressures of approximately 10, 20, 30, 20, and 10 lb/in² (psi). For each injection pressure step, a flow rate in ft³/min (cfm) was recorded. Following completion of the last pressure step, the packer was deflated, withdrawn, and the testing apparatus was moved to the next shothole. All data were analyzed by the equation:

$$k=[uQ/[2\pi h(P_w-P_a)]]\ \ln(r_e/r_w)$$

where k is material permeability, u is dynamic viscosity, Q is fluid flow rate, π is pi, h is tested length of bore-hole, P_w is average borehole pressure, P_a is atmospheric pressure, r_e is the effective borehole radius, and r_w is the actual borehole radius (Blankenship and Stickney 1983). The multiple-pressure step method was designed to yield data on the behavior of test factors such as Klinkenberg slippage, turbulent flow, partial saturation, and other complicating factors (Klinkenberg 1941, Pearson and Money 1977).

The tests were usually run in the overburden shotholes (20 to 40 holes in a pattern) in the time between drilling and detonation. This restriction prevented all retesting of the boreholes as well as borehole development. However, the method proved capable of providing numerous permeability values from the siltstone unit (average borehole spacing of approximately 15 ft). Other tests were conducted in monitoring boreholes outside the immediate mining area. Unfortunately, these holes were not as close to the mine highwall and were partially saturated with water which made them unsuitable for air-testing. They were suitable for the more traditional hydrologic tests which were conducted as a check of the air-injection technique's accuracy.

Other Hydrologic Tests

In order to obtain hydraulic conductivity values from the siltstone unit which could then be compared to the air-based permeability data, both falling-head (slug) and constant-head (steady-state) water injection tests, using standard methods and analysis routines, were conducted in the available monitoring boreholes (Fetter 1980, Cooper et al 1967, Price et al 1982). These boreholes served as the site for tests of other applications of the air-injection system, such as falling-head air-injection tests and air-injection interference tests between adjacent boreholes.

RESULTS AND DISCUSSION

Photo-Linear Fracture Trace Analysis

The results of this phase of the research are presented in figure 4 which shows the orientation diagram for the 24 features observed in the vicinity of the mine site. These features showed a broad orientation maxima between 300 and 340 degrees of azimuth with a peak between 320 and 330 degrees. The features ranged in length from 2,000 to 5,500 ft and were defined by alignments of topographic, tonal, and or vegetative features. The photo-linear feature of interest to this study was identified by a combination alignment of topographic and tonal elements trending to the northeast of the mine. The orientation results compare well to other published results (Lattman and Nickelsen 1958) and the distinct orientation of several local tributary streams.

Highwall Fracture Studies

Prior to the fracture mapping of traverses along the siltstone unit, an anomalous zone was identified between the Lower Freeport and Upper Freeport Coals. As this zone was in close proximity to the surface swale which defined the topographic element of the photo-linear feature of interest, it was initially thought to be the subsurface expression of the photo-linear fracture trace. However, closer examination of the zone revealed several vein-like clastic infillings similar in character to the local underclay and that the zone was offset to the east of the photo-linear feature. Other areas of the mine contained concentrations of these "clay vein" structures which were also not apparently related to fracture trace features.

The three traverses of the siltstone unit also provided information on the fractures related to the mapped photo-linear feature as well as on the general distribution of joints in the area. In a total of 1,200 ft of highwall, 360 joints were identified. These features revealed a dominant orientation maximum between 320 and 340 degrees (figure 5) which compares well with the orientation data provided by the previous analysis as well as other published joint surveys. Although there is variation between the three traverses, the orientation data are dominated by this distinct peak. It should be noted that the highwall was controlled by a face joint set which had a trend at approximately 90 degrees to the joint orientation maxima. The joint data is biased, therefore, because traverses along the highwall were much more likely to observe face perpendicular joints than face parallel joints.

The joint data were also examined by preparing histograms of the number of joints per traverse interval (figure 6). This graphical technique revealed a peak to the east of the intersection point between the highwall and the mapped photo-linear feature. The number of joints per 20 ft traverse interval ranged from 2 to 11 with a mean of 6. This compares well to data for joint frequency in shales included in Nickelsen and Hough (1967). The peaks in figure 5 are not thought to be related to distinct fracture zones; rather they appear to be related to stratigraphic features like the ones previously noted.

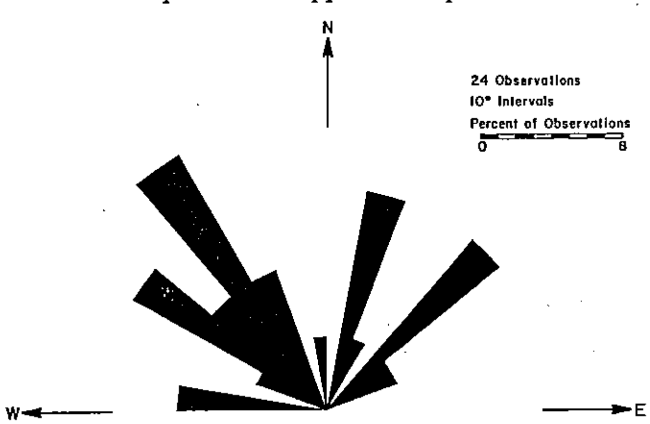

Figure 4 -- Orientation rose of photo-linear fracture trace features.

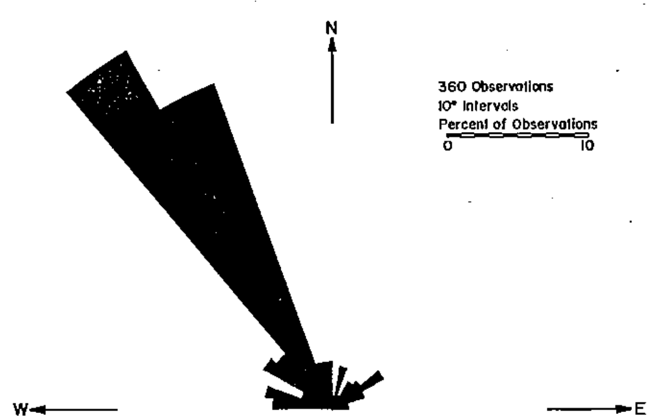

Figure 5 -- Orientation rose of all joint data.

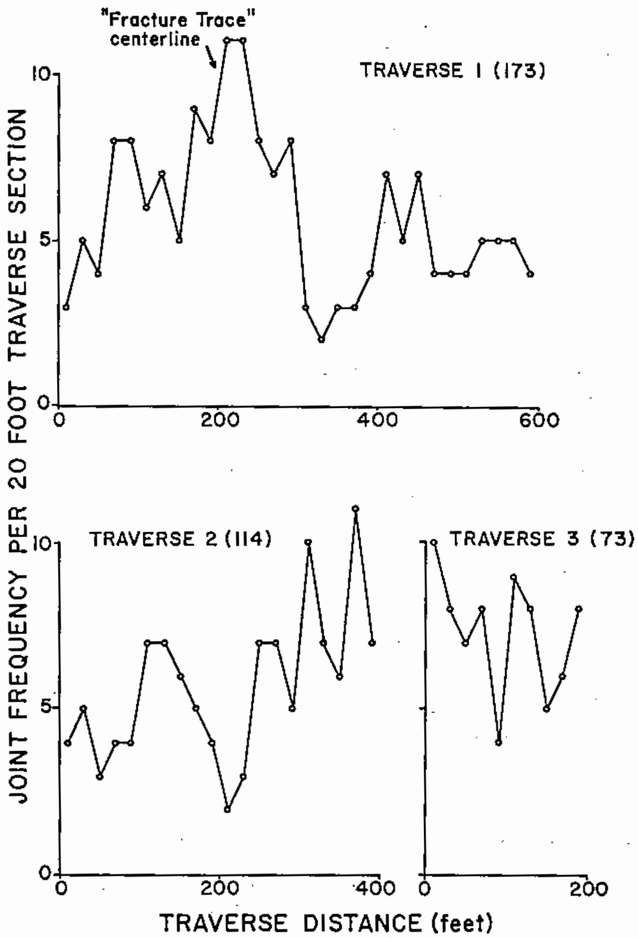

Figure 6 -- Traverse joint frequency distributions.

Air-Injection Permeability Testing

Because these air-injection tests make up the bulk of the quantitative data that was collected in this study, their analysis was critical to the objectives of this project. A total of 55 air-injection tests were conducted in six patterns of shotholes drilled into the siltstone unit. This particular aspect of the study gained importance with the discovery, by visual inspection of the highwall during the testing of Shothole Pattern 4 (see figure 1), that the photo-linear "fracture trace" was actually the surface expression of a stratigraphic swale in the Mahoning Coal. Although this discovery provided evidence that photo-linear features are related to geologic structures, this discounted even further the "fracture trace" nature of the feature.

The total range of permeability values determined in these tests is shown in figure 7. (1 foot squared (ft^2) = 929 centimeters squared (cm^2)) These values are averages of each of the step values produced during the multiple-step (abcba) tests. The data appear to be log-normally and possibly bi-modally distributed. This variability is probably the result of several factors, the most important of which is the natural variations of the siltstone's permeability. A secondary factor affecting the data is the impact of mining activity (primarily blasting) on

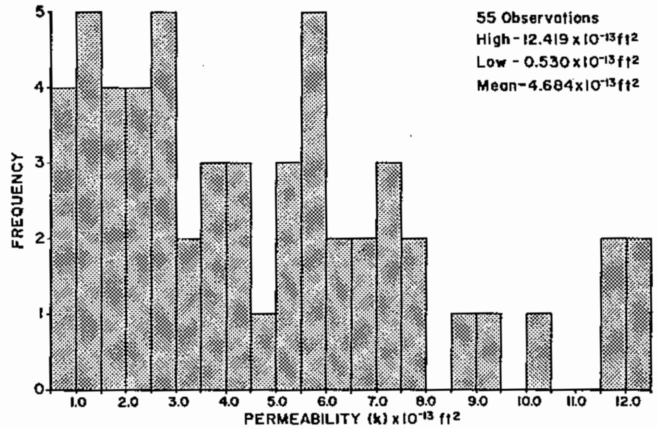

Figure 7 -- Distribution of air-injection permeability values.

the in situ permeability values of the siltstone. This factor can be given a qualitative analysis by examination of a data subset, the permeability values obtained from Shothole Pattern 5 (Figure 8). The distribution of values for the pattern reveals that permeability increases are highest along the highwall faces of the pattern. The data indicate that increases extend primarily from the recently shot area and that values higher than about 7 x 10^{-13} ft^2 are probably significantly blasting affected. Analysis of other patterns supports these results and indicates that 2x + increases are likely 20 to 30 ft from the shot faces of the tested pattern. This relationship is probably dependent on the thickness of the shot overburden (O'Regan and Nguyen 1981).

The multiple-step nature of the air-injection testing technique made it possible to examine other factors which could influence the permeability data. By preparing test step plots (see examples in figure 9), departures from the ideal linear relationship between flow rate and pressure could be examined (Houlsby 1976). Test 22 had one of the highest permeability values and steepest slopes recorded in this study. Of interest is the fact that the slope of the plot decreases with increasing pressure and flow. This slope change is also

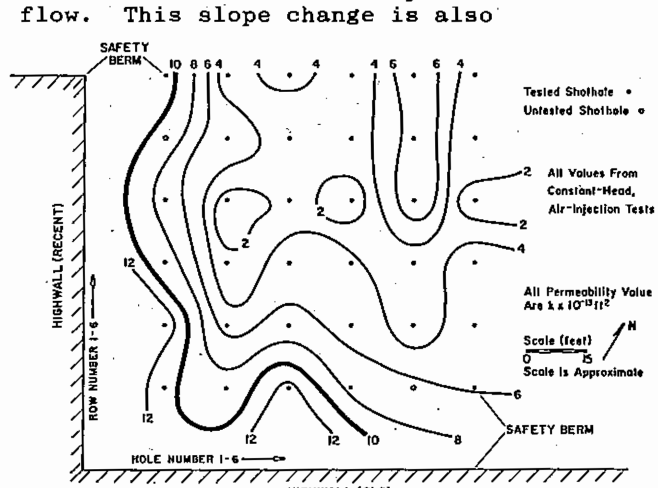

Figure 8 -- Isopermeability map of Shothole Pattern 5.

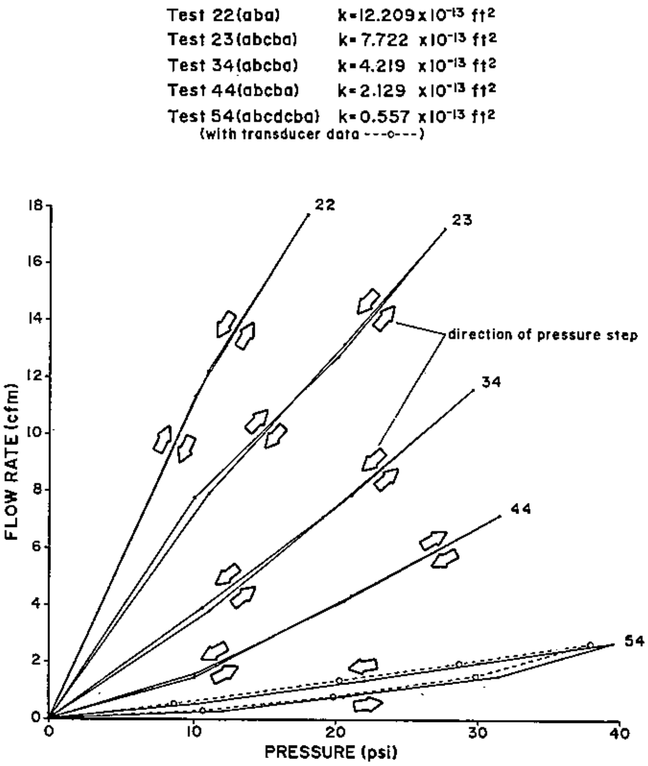

Figure 9 -- Step plots of selected air-injection tests.

illustrated by other high permeability tests, such as Test 23, and it is attributed to either turbulent flow conditions developing in the fractured porous media or to an improved packer seal in the borehole. Test 34, which has a moderate slope and permeability value, illustrates the idealized Darcian relationship between pressure and flow rate. As pressure increases in the test interval, the flow of injected fluid from the test interval increases in an amount which is dependent on the permeability of the material. Test 44 records a slope increase with increasing pressure and flow for a relatively low permeability test. This change is probably the result of the widening of a fracture in the siltstone or the leakage of fluids past the packer unit. Test 54 recorded a very low permeability value and step plot slope. This test was designed to test uphole pressure gauging equipment with downhole transducer readings. The test was conducted in a wet shothole, and the gradual increase in the observed permeability values with increasing pressure and testing time is thought to be due to the displacement of water from pores and fractures which resulted in increasing gas transmission from the test interval. Further analysis to determine the degree of influence of these test factors was not possible with the available testing technique.

Although it should have been possible to apply a Klinkenberg gas slippage correction term to the multiple-step test data, it proved to be impractical due to non-linear variations in the permeability values. The gas slippage correction was developed by Klinkenberg (1941) to account for the increasing interference, and related decrease in observed permeability, between gas molecules as increasing injection pressure makes them behave as an incompressible liquid. In this situation, because the air was not sufficiently compressed to behave as a liquid in these tests, it is possible that the measured permeability values are affected by Klinkenberg slippage.

Other Hydrologic Tests

Because of the restricted number of monitoring boreholes available to be tested by the falling head and constant head water-based tests, as well as field conditions which made some of the holes unsuitable for testing, only two hydraulic conductivity values could be obtained for the siltstone unit. However, the close correlation between these values from Hole 2 (3.9 and 5.1 x 10^{-7} ft/sec for a falling-head and constant-head test respectively) indicates that methods are comparable in this environment. These data and methods may also be comparable to the air-injection technique. This is supported through the use of a data table from Freeze and Cherry (1979) that allows all the air- and water-based test values to be compared. This table (figure 10) shows that the permeability and hydraulic conductivity values are limited in range and appear to represent the equivalent of a permeable sandstone. This does not seem unreasonable because the fractured siltstone unit may be hydrologically similar to such a lithology.

Additional uses of the air-injection technique provided some interesting results. Falling-head air-injection tests

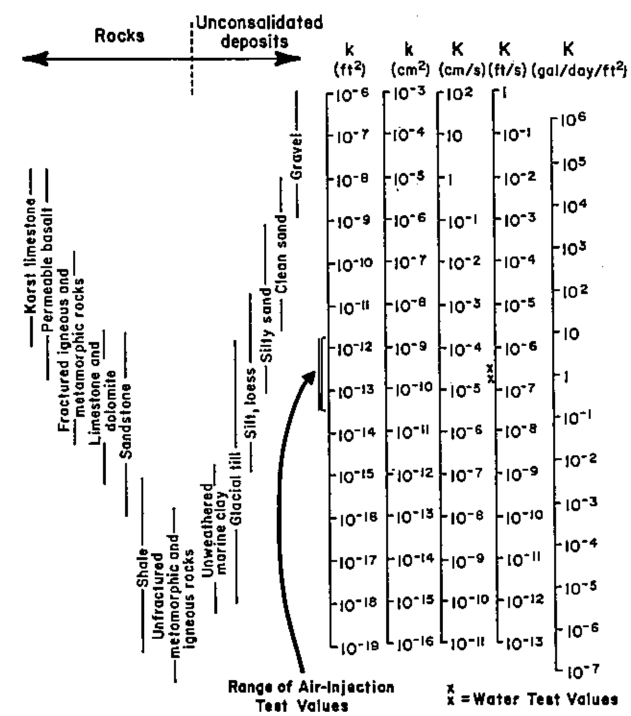

Figure 10 -- Range of test values for permeability (k) and hydraulic conductivity (K) (modified from Freeze and Cherry 1979)

(Blankenship and Stickney 1983) appeared to underestimate permeability values by two orders of magnitude. Air-injection interference testing conducted in Holes 1 and 2 (see figure 1) was more successful. During injection of air through a borehole packer inserted in Hole 2 while monitoring water levels about 20 ft away in Hole 1, it was observed that a water level fluctuation occurred in less than 10 minutes in the monitored hole. This was surprising as it had taken nearly 90 minutes for water injected in Hole 2 (at nearly the same pressure as the air) during the constant-head water-injection test, to cause even a minor change in the water level of Hole 1. The air-injection test also caused a much more substantial change in the observed water levels, nearly 1.7 ft as opposed to a few tenths of a foot. While the significance of these results is unclear, it is clear that injected air is capable of markedly affecting a ground-water flow field under some circumstances.

CONCLUSIONS AND RECOMMENDATIONS

The investigation of fracture features and in situ permeability values conducted at the Browncrest III surface coal mine succeeded in addressing a number of research objectives. The conclusions and recommendations of this work may assist future studies.

Conclusions

1. The photo-linear "fracture trace" orientation peak, between 320 and 330 degrees, compares well to the orientation of local tributary streams and the maxima of other fracture trace studies for this area.

2. The joints mapped in this study had an orientation maxima between 320 and 340 degrees. This agrees well to the fracture trace orientation peak, as well as to the orientation of the local stream valleys and to other published joint data. As a result, it is believed that all the features may be related to a common structural origin.

3. Measurements of joint frequency per highwall traverse interval revealed that joint concentrations appear to be related to specific stratigraphic features rather than fracture traces.

4. The photo-linear feature that was to be the focus of this study was found to be unrelated to a zone of fracture concentration. This feature was found to be related to a stratigraphic swale, possibly an old distributary channel, in the Mahoning Coal.

5. The air-injection technique was found to be quite consistent, durable, and mobile in operation. It was capable of conducting tests for a specific range of conditions: a) boreholes at depths of up to 70 ft, b) hole diameters of 4 to 7 inches, and c) injection pressures and flow rates well in excess of test parameters.

6. The in situ permeability values observed in this study ranged from 0.5 to 12.5 x 10^{-13} ft^2 and appeared to be log-normally and possibly bi-modally distributed. Mining activity was determined to affect the permeability values, increasing values by 2x + up to 30 ft from mine highwalls. As a result, the background permeability of the siltstone unit is probably in the range 1.0 to 7.0 x 10^{-13} ft^2.

7. Factors affecting the air tests were examined through graphical analysis of the test data. Turbulent flow conditions are thought to have the greatest impact on the values, although partially saturated conditions (water in the siltstone) and Klinkenberg slippage may also significantly affect the values.

8. Hydraulic conductivity values obtained by falling-head and constant-head water-based tests from the siltstone unit compare well to the air-based permeability values. These values indicate that the fractured siltstone unit has a character similar to a moderately permeable sandstone.

9. Additional uses and modifications of the air-injection technique were also investigated. Interference testing offers interesting data, although it is not possible to evaluate this information at this time.

Recommendations

Although this study was not able to quantify the subsurface nature of a photo-linear fracture trace, the methods presented here define a means of achieving this objective. However, the reliability, speed, safety, precision, and economics of these techniques may require further investigation. The photo-linear analysis may identify geologic structures, as well as nongeologic ones, that are not related to zones of fracture concentration in the subsurface. The highwall surveys are time consuming, occasionally dangerous, and are complicated by blast fractures and the relationship of the fractures to the highwall orientation. Many factors affect the air-injection technique. However, most of them are inherent to the technique and can only be corrected with improved analysis routines or increasingly costly instrumentation. Therefore, although this technique may be appropriate under circumstances where a high density of data is required, it may not be appropriate for more general investigations (Shuman 1987).

ACKNOWLEDGEMENTS

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