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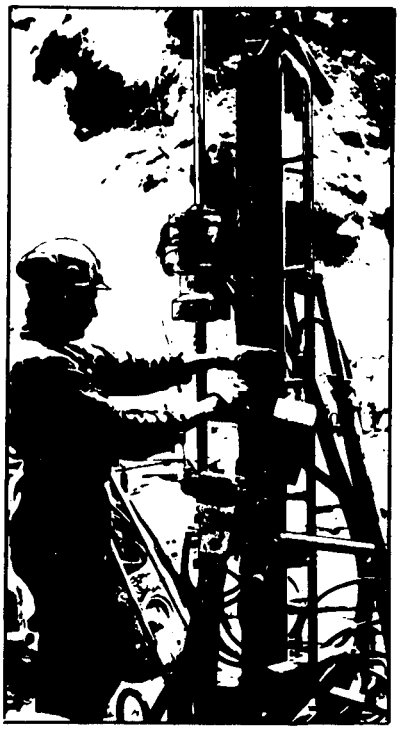
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PROGRESS IN THE HYDROGEOLOGICAL CHARACTERIZATION OF THE STRIPA SITE

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PROGRESS IN THE HYDROGEOLOGICAL CHARACTERIZATION OF THE STRIPA SITE

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PREFACE

This report is one of a series documenting the results of the Swedish-American cooperative research program in which the cooperating scientists explore the geological, geophysical, hydrological, geochemical, and structural effects anticipated from the use of a large crystalline rock mass as a geologic repository for nuclear waste. This program has been sponsored by the Swedish Nuclear Power Utilities through the Swedish Nuclear Fuel Supply Company (SKBF), and the U.S. Department of Energy (DOE) through the Lawrence Berkeley Laboratory.

The principal investigators are L.B. Nilsson and O. Degerman for SKBF, and N.G.W. Cook, P.A. Witherspoon, and J.E. Gale for LBL. Other participants will appear as authors of the individual reports.

Previous technical reports in this series are listed below.

1. Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns by P.A. Witherspoon and O. Degerman. (LBL-7049, SAC-01).

2. Large Scale Permeability Test of the Granite in the Stripa Mine and Thermal Conductivity Test by Lars Lundstrom and Haken Stille. (LBL-7052, SAC-02).

3. The Mechanical Properties of the Stripa Granite by Graham Swan. (LBL-7074, SAC-03).

4. Stress Measurements in the Stripa Granite by Hans Carlsson. (LBL-7078, SAC-04).

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10. Mechanical and Thermal Design Considerations for Radioactive Waste Repositories in Hard Rock. Part I: An Appraisal of Hard Rock for Potential Underground Repositories of Radioactive Waste by N.G.W. Cook; Part II: In Situ Heating Experiments in Hard Rock: Their Objectives and Design by N.G.W. Cook and P.A. Witherspoon. (LBL-7073, SAC-10).

11. Full-Scale and Time-Scale Heating Experiments at Stripa: Preliminary Results by N.G.W. Cook and M. Hood. (LBL-7072, SAC-11).

12. Geochemistry and Isotope Hydrology of Groundwaters in the Stripa Granite: Results and Preliminary Interpretation by P. Fritz, J.F. Barker, and J.E. Gale. (LBL-8285, SAC-12).

13. Electrical Heaters for Thermo-Mechanical Tests at the Stripa Mine by R.H. Burleigh, E.P. Binnall, A.O. DuBois, D.O. Norgren, and A.R. Ortiz. (LBL-7063, SAC-13).

14. Data Acquisition, Handling, and Display for the Heater Experiments at Stripa by Maurice B. McEvoy. (LBL-7063, SAC-14).

15. An Approach to the Fracture Hydrology at Stripa: Preliminary Results by J.E. Gale and P.A. Witherspoon. (LBL-7079, SAC-15).

16. Preliminary Report on Geophysical and Mechanical Borehole Measurements at Stripa by P. Nelson, B. Paulsson, R. Rachiele, L. Andersson, T. Schrauf, W. Hustrulid, O. Duran, and K.A. Magnussen. (LBL-8280, SAC-16).

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18. Rock Mass Characterization for Storage in Nucler Waste in Granite by P.A. Witherspoon, P. Nelson, T. Doe, R. Thorpe, B. Paulsson, J.E. Gale, and C. Forster. (LBL-8570, SAC-18).

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26. Part I: Some Results From a Field Investigation of Thermo-Mechanical Loading of a Rock Mass When Heater Canisters are Emplaced in the Rock by M. Hood. Part II: The Application of Field Data from Heater Experiments Conducted at Stripa, Sweden for Repository Design by M. Hood, H. Carlsson, and P.H. Nelson. (LBL-9392, SAC-26).

27. Progress with Field Investigations at Stripa by P.A. Witherspoon, N.G.W. Cook, and J.E. Gale (LBL-10559, SAC-27).

28. A Laboratory Assessment of the Use of Borehole Pressure Transients to Measure the Permeability of Fractured Rock Masses by C.B. Forster and J.E. Gale. (LBL-8674, SAC-28).

29. Thermal and Thermomechanical Data for In Situ Heater Experiments at Stripa, Sweden by T. Chan, E. Binnall, P. Nelson, O. Wan, C. Weaver, K. Ang, J. Braley, and M. McEvoy. (LBL-11477, SAC-29).

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51. Seismic Velocities and Attenuation in a Heated Underground Granitic Repository by B.N.P. Paulsson (LBL-16346 1/2, SAC-51).

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ABSTRACT

A comprehensive program of fracture hydrology investigations has been carried out in a granitic rock mass at the Stripa mine in Sweden. Sources of data included a limited number of outcrops, surface and subsurface boreholes, and fracture maps of rooms and drifts at a depth of about 340 m. The research program consisted of: (1) the collection of fracture geometry and borehole injection test data to determine directional permeabilities, (2) a macropermeability experiment to determine the bulk rock mass permeability, (3) ground-water sampling for investigations of geochemistry and isotope hydrology, (4) pump testing of surface wells, and (5) tracer tests to determine effective porosity. This report summarizes results from all but the last item, the tracer work, which had not been carried out when the field work ended in 1981.

Analysis of a large array of fracture statistics has revealed the existence of four fracture sets. Distributions of spacings and trace lengths were determined for each set. The trace-length data are best fitted by a negative exponential distribution, while the fracture-spacing data are best fitted by a lognormal distribution.

A comparison of the borehole injection test data with the results from the macropermeability experiment provides a unique opportunity to evaluate two different methods of measuring permeability in fractured rocks. The average permeability of 1×10^{-13} cm^2 obtained from the macropermeability experiment compares quite favorably with the average value of 8.9×10^{-13} cm^2 determined from borehole testing.

The geochemistry and isotope hydrology data support the concept that the waters found in the granite rock mass at Stripa, especially at the deepest levels (811-838 m), are many thousands of years old. They also support the conclusion that the shallow and deep ground-waters are isolated. Investigations of this kind provide independent approaches to evaluating the degree of isolation in a ground-water system.

The hydrogeological investigations at Stripa have demonstrated the value of coordinated surface and underground testing in site characterization. Proper evaluation of rock mass properties will require detailed studies of the influence of discontinuities, and will involve adequate sampling of their geometric and hydraulic properties from both surface-based and at-depth tests. The work at Stripa has shown that surface and underground tests provide complementary information and that the complete suite of data needed cannot be obtained from one approach alone.

1.0 INTRODUCTION

In the past few years a number of countries have shown increasing interest in using granitic rocks for nuclear waste repositories. Thus, when the Stripa mine became available in 1977 providing immediate underground access to a large mass of granite (Witherspoon and Degerman, 1978); it was obvious that important problems in waste management could be addressed with a minimum of delay. One of these problems was to understand the factors that control the rate at which radionuclides in groundwater can migrate through rock systems.

Discontinuities are the key to migration through crystalline rock. Flow through the intact rock matrix will be so low that significant movement can take place only through the fracture system. Hence fractures represent the primary flow paths along which radionuclides may migrate from the repository to the biosphere. Therefore, to characterize the hydrogeology of a granitic rock mass, one must understand the flow properties of a complex network of fractures.

To investigate the factors that control seepage in a granitic rock mass, we adopted a comprehensive program of fracture hydrology investigations (Gale and Witherspoon, 1979). This program consisted of: (1) the collection of fracture geometry and borehole injection test data to determine directional permeabilities, (2) a macropermeability experiment to determine the bulk rock mass permeability, (3) ground-water sampling for investigations of geochemistry and isotope hydrology, (4) pump testing of surface wells, and (5) tracer tests to determine effective porosity. This report summarizes results from all but the last item, the tracer work, which had not been carried out when the field work ended in 1981.

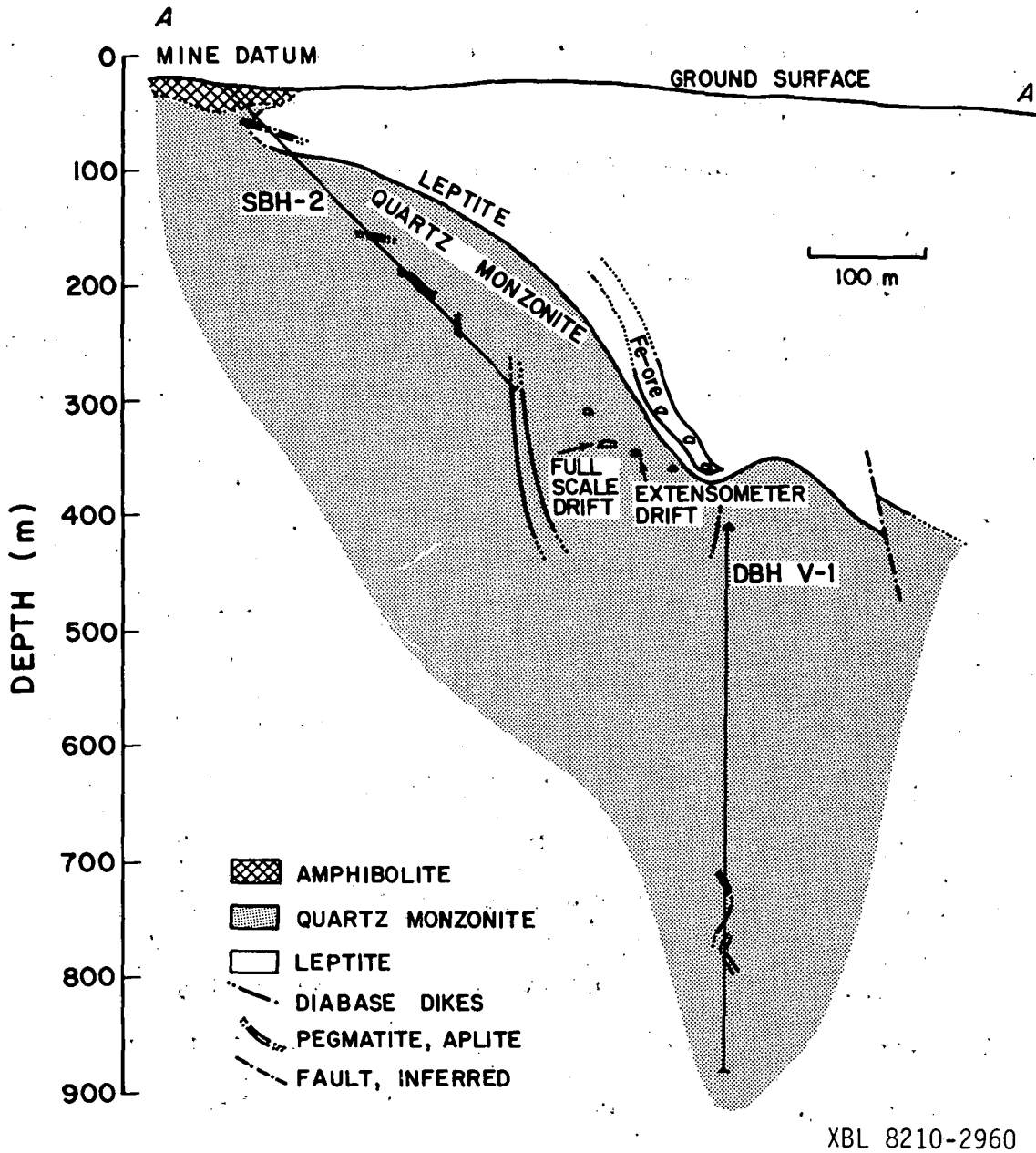


Fig. 1. Vertical cross-section bearing N89°E (from Wollenberg et al., 1980). See Fig. 2 for location.

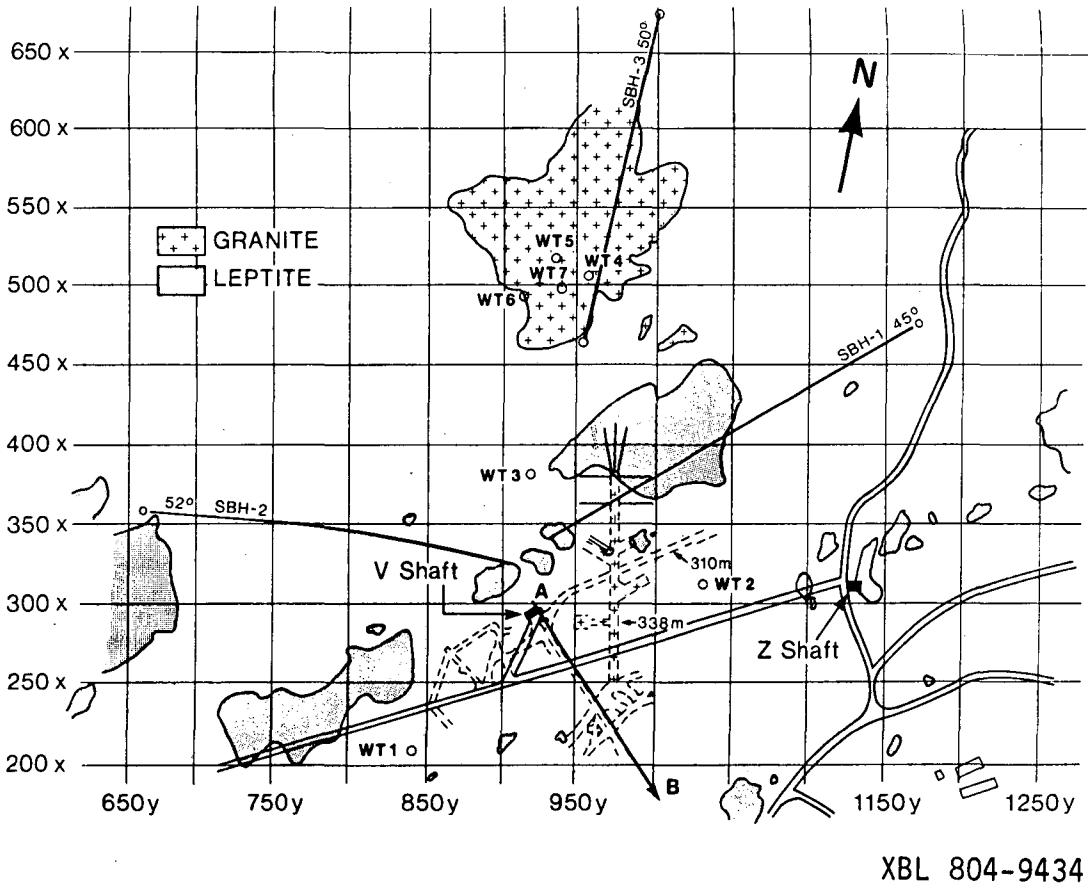


Fig. 2. Locations of hydrological boreholes and general site geology. The coordinates are in meters.

2.0 GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The Stripa site is located in south central Sweden about 150 km west-northwest of Stockholm. The bedrock geology is typical of highly folded and deformed shield terrains. The regional geology is characterized by a northeast-southwest trending suite of folded metamorphic rocks that have been intruded by a series of granitic rocks. The local bedrock structure around Stripa is dominated by a northeast-southwest trending syncline. Additional smaller synclines, one of which contains the Stripa ore zone (Fig. 1), trend both parallel and perpendicular to the major southwest trending syncline and add to the overall structural complexity of the region. Super-imposed on the regional fold pattern is a series of fracture zones and lineaments with at least one major fracture zone following the trend of the major synclinal feature (Olkiewicz et al., 1979).

The experimental rooms for much of the research program were excavated at a depth of 338 m below surface under the north limb of the syncline (Fig. 1), in a small body of granite (quartz monzonite) adjacent to the metasedimentary - metavolcanic sequence in which the mined-out ore body was located. The general geology of the test site area and the general fracture system are described by Olkiewicz et al. (1979). The petrology of the granite body is discussed by Wollenberg et al. (1980).

Sources of data for the fracture geometry investigation included a limited number of surface outcrops (Fig. 2), three oriented surface boreholes, 15 subsurface hydrology boreholes, and a large number of boreholes drilled for the thermomechanical experiments (Thorpe, 1979, and Paulsson et al., 1980). Fracture maps of walls and floors of experimental rooms,

especially the maps of the drift (Rouleau et al., 1981) for the macropermeability experiment, provided another important source of data.

The surface boreholes used in the fracture hydrology work consisted of three long (315-385 m) inclined boreholes, shown as SBH-1, SBH-2, and SBH-3 in Fig. 2. These three boreholes were oriented to maximize their intersection with the major fracture sets (Gale and Witherspoon, 1979). The subsurface hydrology boreholes consisted of 15 diamond coreholes 30-40 m in length. They were drilled at the north end of the underground test rooms within the quadrant bounded in Fig. 2 by mine coordinates 350-400 in the x direction and 950-1000 in the y direction. The last 33 m of this main drift was used for the macropermeability experiment (Wilson et al., 1981, 1982). All boreholes were 76 mm in diameter, and the drill cores were oriented and reconstructed to enable determination of true fracture strikes and dips.

An extensive series of measurements and observations was made in the boreholes, including (1) in-situ pore water pressure measurements during drilling, (2) measurement of the variation in water levels in boreholes open at the surface, (3) water outflow measurements from instrument and heater boreholes in conjunction with the thermal experiments, (4) measurements of water pressures and flow rates during both injection and withdrawal packer tests, and (5) measurements of water levels during pumping-out tests in several surface water wells. The raw data from these observations and measurements as well as the methods used to collect and process both the fracture and hydrology data have been described (Gale, 1981). They serve as the basis for this investigation of the fracture and hydrogeological characteristics of the Stripa site.

The most significant perturbation on the hydrologic regime at Stripa has been that produced by excavations made during the mining operations. Mining started as an open-pit operation some 400 years ago and continued as an underground operation for about the last 40 years. At the beginning of the Stripa program, it was proposed that the mine was acting as a major drain, decreasing the pore pressures in the surrounding rock mass. Thus, an attempt was made to measure in-situ pore pressures during the drilling of the three surface wells, SBH-1, SBH-2, and SBH-3.

The in-situ pore pressures for SBH-1 and SBH-3 are plotted in Fig. 3. The deviation of the fluid pressures from hydrostatic conditions in SBH-1 indicates a strong downward gradient starting about 100 m below ground surface. During the drilling of SBH-2, no measurements were made below the 100 m level. However the data from SBH-3 show downward gradients starting at the surface. These hydraulic gradients confirmed the expected drainage effect of the old mine workings. Moreover, measurements made by the Swedish Geological Survey in DBH V-1 (Fig. 1), a flowing borehole at the 410 m level, indicate upward-acting gradients, which suggests that ground waters from a deep flow system are discharging upward into the mine.

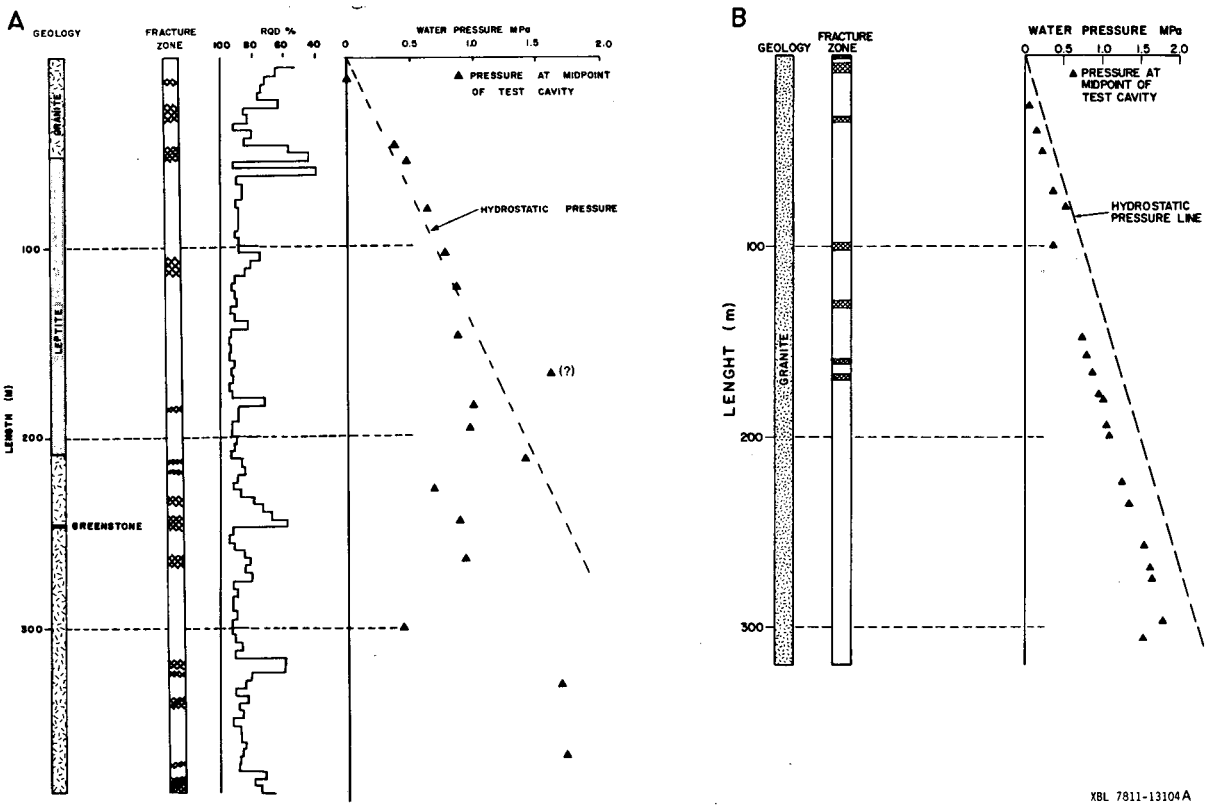


Fig. 3. Summary of geology, fracture data, and in-situ fluid pressures in boreholes SBH-1 (A) and SBH-2 (B).

3.0 CHARACTERISTICS OF THE FRACTURE SYSTEM

To determine the characteristics of the fracture system, data have been obtained from: (1) surface and subsurface hydrology boreholes (Gale, 1981); (2) boreholes drilled for the thermomechanical experiments (Olkiewicz et al., 1979; Thorpe, 1979; Paulsson et al., 1980); and (3) maps of the walls and floor of the ventilation drift, where the macropermeability experiment was conducted (Rouleau et al., 1981). The drill cores from both surface and subsurface boreholes were oriented, allowing the true orientations of the fractures intersecting the cores to be calculated. These data sets have been combined to define the orientations of the fracture sets within the test area and their spacing and trace-length distributions.

3.1 Fracture Orientations

Rouleau and Gale (1982a) have made a detailed analysis of the fracture measurements; from this analysis, the geometry of the fracture network has been deduced. Approximately 10,000 individual fracture measurements were analyzed. Figure 4 summarizes the fracture orientation data in the form of lower-hemisphere, equal-area contour plots of poles to fracture planes. Individual plots are given for data from the full-scale drift, the time-scaled drift, the R and HG holes, the walls and floor of the ventilation drift, and the lower part as well as the total length of the three SBH boreholes. It should be noted that the orientation of the boreholes and of the surfaces from which the fracture data were collected introduces a considerable bias into these data.

The contour diagram in Fig. 4 for the time-scaled drift was constructed from vertical borehole data only (Thorpe, 1979), while the data to construct the diagram for the full-scale drift were obtained from both vertical and

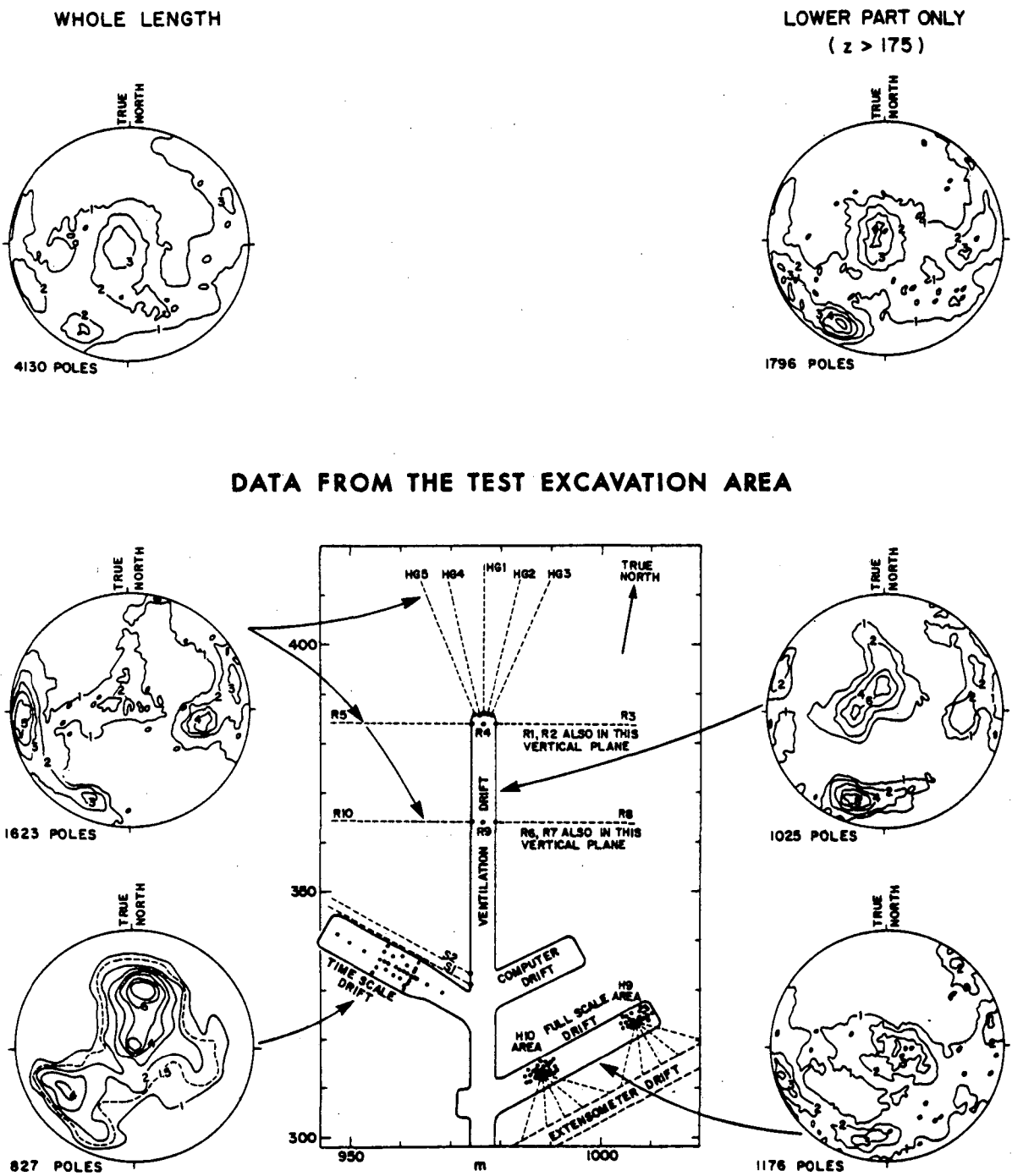


Fig. 4. Contoured stereonet plots to joint planes measured in different areas of test excavation. The contoured values are in percent of points per 1% area (from Rouleau and Gale, 1982a).

horizontal boreholes. In areas of complex fracturing and folding, such as the Stripa site, more scatter is introduced into the data as the volume of rock increases. This is evident when we compare the two contour plots for the SBH boreholes. When data from the entire length of the SBH boreholes are included, the fracture sets are very poorly defined or missing, with considerable scatter evident in the result. However, by using data from only the bottom portions of the three SBH boreholes (i.e., from depths greater than 175 m), we achieve a significant reduction in scatter and a considerable improvement in the definition of the fracture sets.

Figure 5 is a contour plot of fracture data from both the R and HG holes and the walls and floor of the ventilation drift. Given the variation in sampling orientation provided by the boreholes and the mapped surfaces, this plot can be assumed to give a relatively unbiased sample of the fracture system in the immediate area of the ventilation drift. The linearized boundaries of the four fracture sets that have been defined are superimposed on this contour diagram. Visual inspection shows that the pole clusters for these four sets correspond fairly closely with the clusters defined on the orientation diagram for the bottom part of the SBH holes (Fig. 4).

3.2 Fracture Trace Lengths

With the fracture orientations in hand, the next step was to investigate trace lengths. During the mapping of the ventilation drift, the length of each fracture trace was measured (Rouleau et al., 1981). On the basis of known orientation, each fracture was assigned to one of the fracture sets identified in Fig. 5. Then, for each set, the trace lengths were plotted as frequency histograms (Fig. 6). Besides showing the distribution

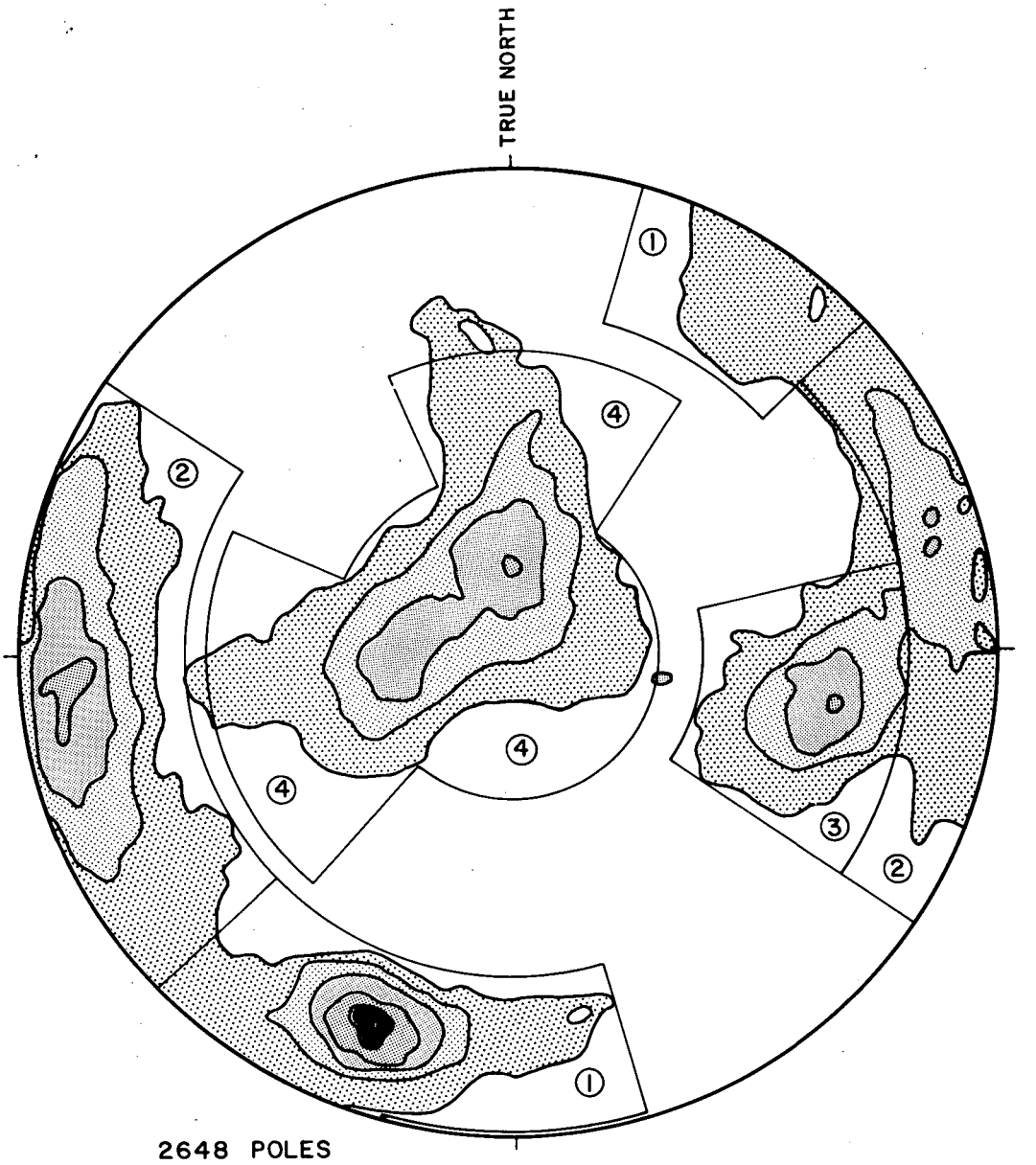


Fig. 5. Lower hemisphere plot of poles to fracture planes for walls of the ventilation drift and HG and R drill cores (after Rouleau and Gale, 1982a).

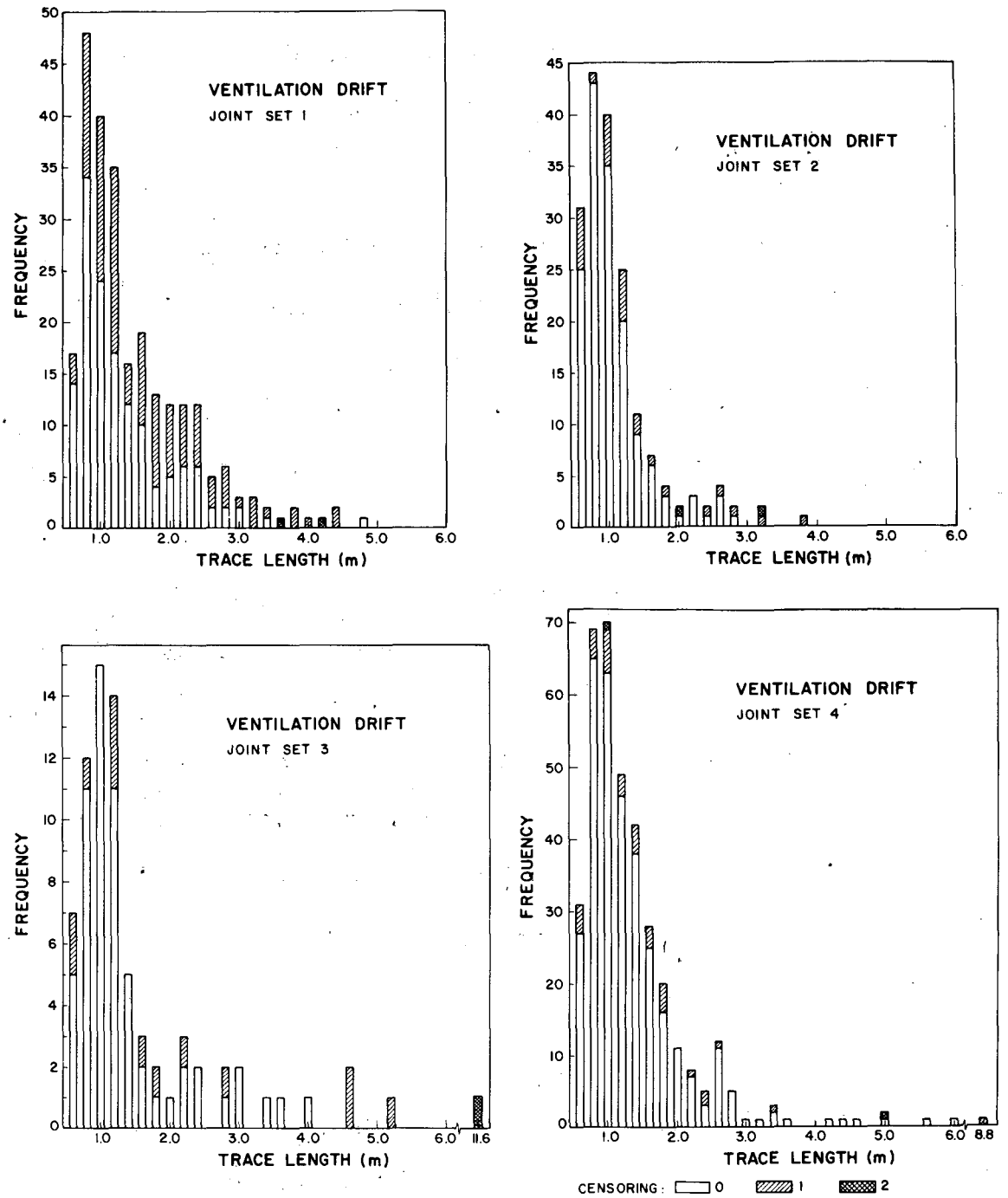


Fig. 6. Frequency histograms of the fracture trace lengths measured on the walls of the ventilation drift (after Rouleau and Gale, 1982a).

of fracture lengths, Fig. 6 also indicates the degree of censoring, i.e., 0 for the case when both ends of the fracture trace are visible on the mapped surface, 1 when only one end is visible, and 2 when neither end is visible. A summary of the statistics computed for the trace length distributions is given in Rouleau and Gale (1982a).

The censoring and other sampling biases such as truncation and size bias (Baecher et al., 1978, and Rouleau and Gale, 1982b) make the statistical analysis of trace length distributions relatively difficult. A maximum-likelihood approach to estimate the parameter of an exponential distribution accounting for censoring (Baecher, 1980) has been applied to our data. The probability density function of an exponential distribution is given by:

$$f(x) = \lambda\, e^{-\lambda x}$$

The mean of this distribution is $1/\lambda$. Although no test has been carried out for the goodness-of-fit of this distribution to the data, the distribution shown in Fig. 6 suggests that there is a significant difference in mean trace lengths from one fracture set to another. For example, the computed estimates of the mean values of trace lengths for the four different sets range from 1.3 to 2.7 m. The complete statistics for trace length data are given in Table 1.

3.3 Fracture Spacings

The spatial locations of the fractures intersecting the drill cores have been used to compute the spacing between every pair of consecutive fractures of the same set. We define the spacing here as the distance between consecutive intersections of two fractures of the same set with a sampling line (i.e., a borehole axis), multiplied by the cosine of the

Table 1. Trace-length statistics by degree of censoring for the four fracture sets.

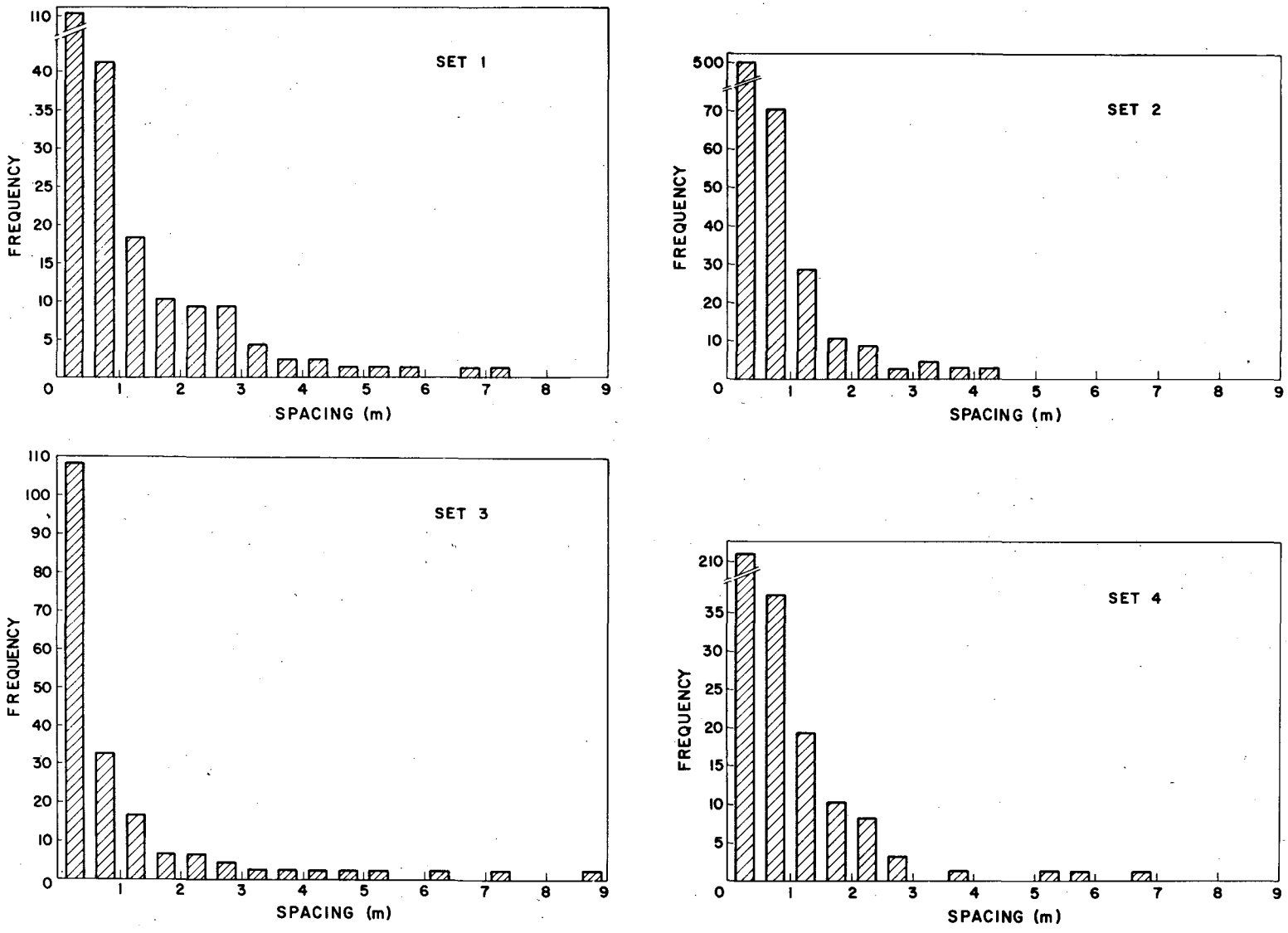
	SET 1			SET 2			SET 3			SET 4		
Censoring[1]	0	1	2	0	1	2	0	1	2	0	1	2
M	140	109	2	150	26	2	61	13	1	327	35	2
Sum	181.55	183.25	7.89	158.12	36.38	5.04	62.40	28.79	11.51	435.42	59.14	5.96
Max, m	4.78	4.44	4.28	2.93	3.85	3.11	3.95	5.22	11.51	6.04	8.88	5.02
Mean, m	1.30	1.68	3.95	1.05	1.40	2.52	1.35	2.22	11.51	1.33	1.69	2.98
Std. Dev, m	0.68	0.86	----	0.45	0.88	----	0.77	1.71	----	0.73	1.53	----
Skewness, m	1.76	1.15	----	1.78	1.42	----	1.76	0.98	----	2.58	3.53	----
Kurtosis m	4.40	1.00	----	3.52	1.34	----	2.60	-0.48	----	10.23	14.77	----
θ		0.376			0.752			0.497			0.653	
$1/\theta^2$		2.660			1.330			2.012			1.531	
$V[\theta]$[3]		0.0010			0.0038			0.0041			0.0013	

Note; 1. Degree of censoring is 0 when both ends of the fracture trace are visible, 1 when only one end is visible, and 2 when neither end is visible.
2. Theoretical measure of the mean of the exponential distribution [1].
3. Variance.

angle made by the sampling line and the pole of the average plane of the fracture set. Figure 7 shows the frequency histograms of spacings for every fracture set that has been defined for the rock mass surrounding the ventilation drift (Rouleau and Gale, 1982a). The spacing data from all the oriented HG and R cores were combined to construct the histograms of Fig. 7. A summary of the statistics computed for these spacing distributions is given in Table 2.

These empirical distributions as shown by the shape of the histograms in Fig. 7, have been compared to various theoretical models that are bounded by zero to the left and skewed to the right. The distributions were tested against exponential, lognormal, and Weibull models. The analysis and goodness-of-fit tests presented in Rouleau and Gale (1982b) indicate that the exponential distribution does not fit the data at all. The Weibull model passes the tests for two of the four fracture sets at a level of significance larger than 0.05. However, the lognormal distribution fits the data very well at a level of significance larger than 0.15.

To assess the variability in fracture spacing around the ventilation drift, a one-way analysis of variance was made. This analysis also tested the hypothesis that, for each fracture set, all populations of spacings sampled from the different drill cores have the same mean. The analysis indicated that, except for Set 3, the fracture sets definitely do not have the same population mean (Rouleau and Gale, 1982b). This result suggests that each borehole samples a volume of rock that is <u>smaller</u> than the scale of variability in fracture density for the whole rock mass.



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Fig. 7. Frequency histograms for the spacing between consecutive fractures of the same set measured on the oriented cores from HG and R boreholes (from Rouleau and Gale, 1982a).

Table 2. Summary statistics of the distributions of spacing (SPAC) and logarithm of spacing (LSPAC) for each fracture set for oriented HG and R holes.

	SET 1		SET 2		SET 3		SET 4	
	SPAC	LSPAC	SPAC	LSPAC	SPAC	LSPAC	SPAC	LSPAC
N	209	208	619	614	177	177	319	316
Max, m	7.08	1.96	4.42	1.49	8.59	2.15	9.29	2.23
Min, m	0.0	-5.51	0.0	-6.21	0.003	-5.82	0.0	-4.85
Mean, m	0.93	-0.88	0.36	-1.74	0.79	-1.08	0.51	-1.50
Std. Dev., m	1.21	1.40	0.54	1.23	1.25	1.36	0.92	1.20
Skewness, m	2.42	-0.34	3.58	-0.11	3.51	-0.17	5.21	0.15
Kurtosis, m	7.03	-0.22	16.50	0.23	15.00	0.25	37.13	0.04
Weibull, m								
Shape (λ)	.830		.856		.797		.796	
Scale (σ)	.796		.317		.625		.406	
Model	D-STATISTICS[1] AND [P(>O)][2]							
Exponential	.126 [.002]		.126 [<.001]		.182 [<.001]		.200 [<.001]	
Normal		.043 [>.15]		.019 [>.15]		.048 [>.15]		.055 [>.15]
Weibull	.043 [>.15]		.066 [<.01]		.075 [>.15]		.095 [<.01]	

Note: 1. Measure of goodness of fit for assumed model according to Kolmogorov-Smirnov D statistics [11].
2. Probability that value of ν is greater than observed value if the empirical distribution was exactly following the theoretical model.

A similar analysis was carried out for the following borehole groups: (1) HG boreholes, (2) R1, R2, R3 and R5, and (3) R6, R7, R8, and R10. This analysis did not indicate significant differences between the population means, except for Set 4. These results suggest that, as opposed to individual holes, each of these groups sampled a volume of rock larger than the scale of variability in fracture density for the whole rock mass. Thus, combining the spacing values from the HG and R boreholes for all the fracture sets should yield spacing distributions that can be considered representative of the rock mass in any portion of the ventilation drift.

4.0 HYDROGEOLOGICAL RESULTS FROM BOREHOLES

4.1 Permeability

Injection tests were made with packed-off intervals 2 m long over the total lengths of the three SBH surface boreholes and over 2-m and 4-m lengths in the R and HG subsurface boreholes. A detailed discussion of the equipment and testing procedures is given by Gale (1981). About 850 intervals were tested, many of them at several different pressures. Equivalent porous media permeabilities have been computed for each interval, and the results from the 2-m spacings in SBH-1 are shown in Fig. 8. Although there is considerable scatter in the results, a least squares fit to the data does indicate a general trend of decreasing permeability with increasing depth (Gale, 1982).

The effect on permeability of the number of fractures intersecting the test interval in the HG and R boreholes is shown in Fig. 9. This figure shows that, with an increase in the number of fractures intersecting a test interval (increase in fracture frequency), there is a general increase in the permeability. However, if all fractures were contributing equally to the flow behavior, the correlation should have been much stronger.

The overall variation in rock mass permeabilities in the walls of the ventilation drift is shown by the histogram in Fig. 10. This histogram was compiled using data from 148 individual tests in the HG and R boreholes (Gale, 1982). The geometric mean is 8.9×10^{-13} cm^2.

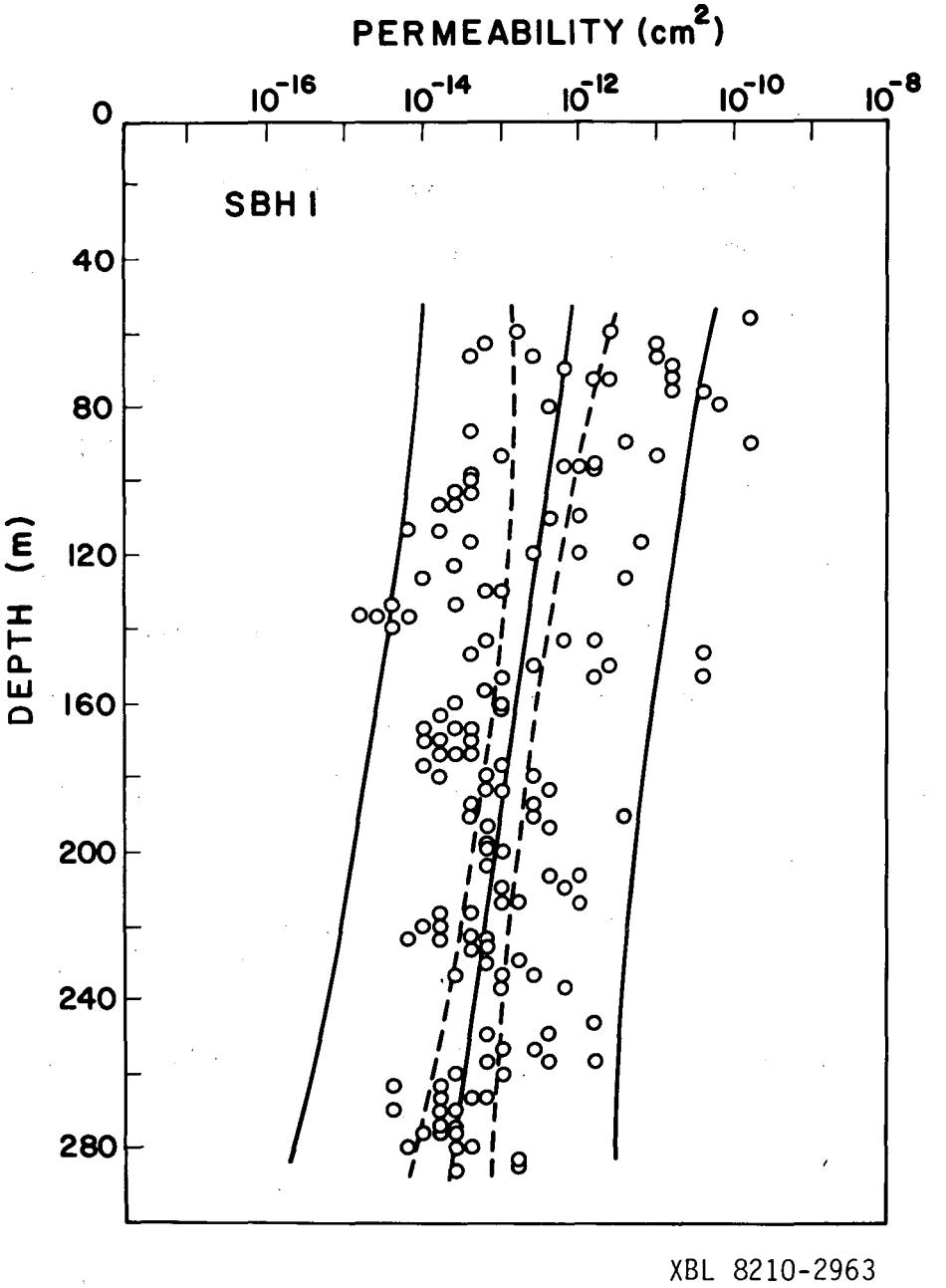
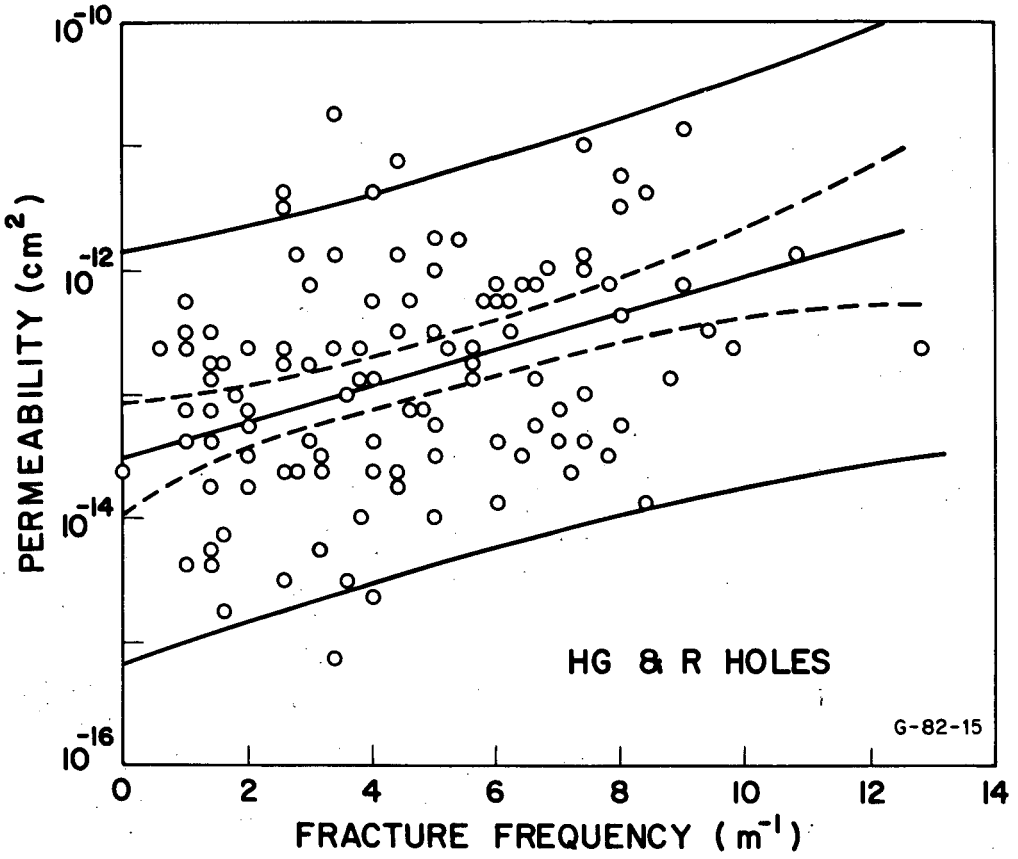


Fig. 8. Permeability versus depth from injection tests in SBH-1 (after Gale, 1982).



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Fig. 9. Permeability versus fracture frequency for all HG and R boreholes (after Gale, 1982).

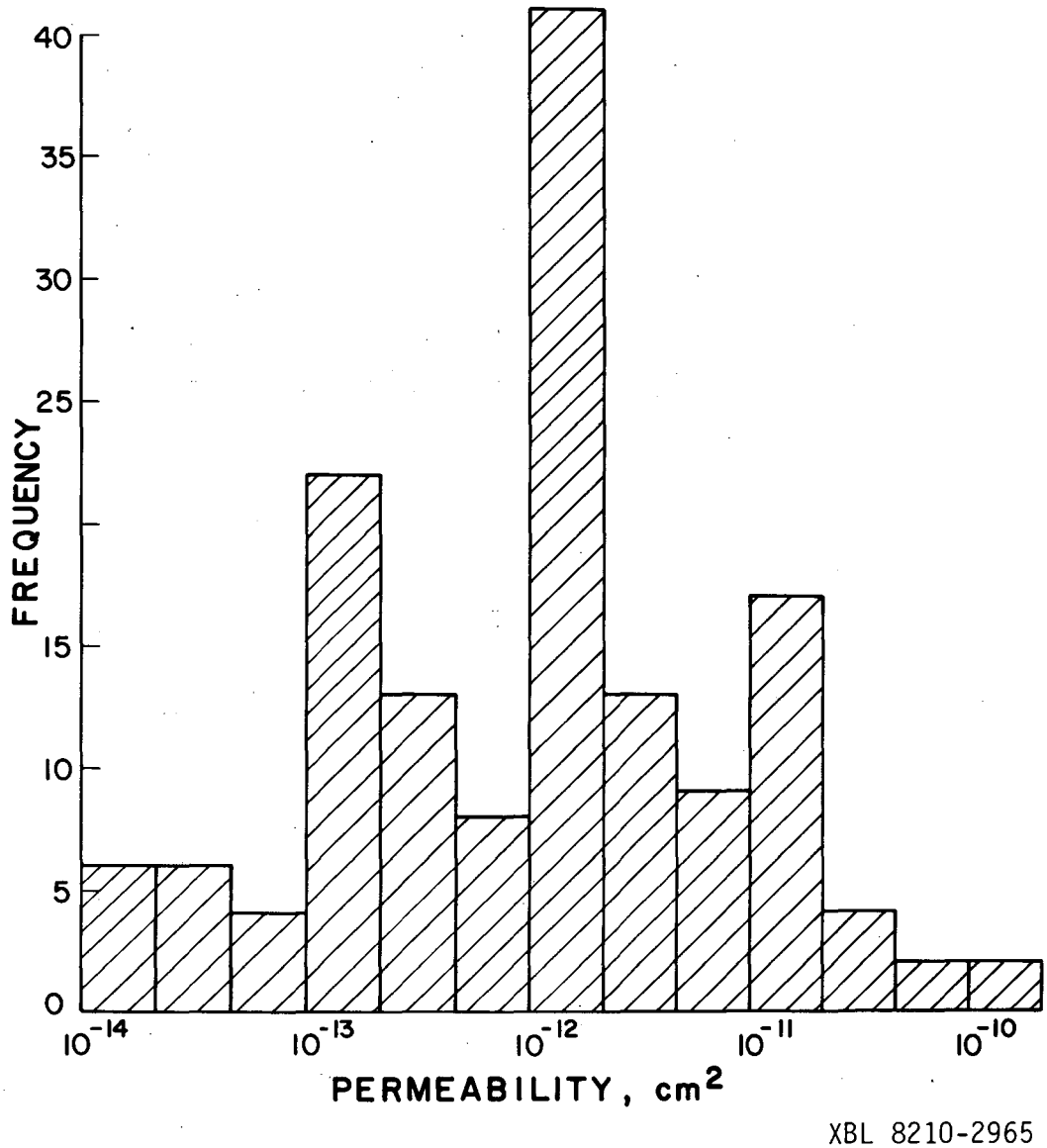


Fig. 10. Permeability distribution computed for the HG and R boreholes (after Gale, 1982).

4.2 Fracture Porosity

A fundamental problem in fracture hydrology is to determine the volume of pore space that controls fluid movement. This is called the "effective," or "flow," porosity, but there can also be a significant amount of pore space that does not affect fluid movement because of the dead-end spaces. The "total" fracture porosity includes all fracture openings whether they contribute to the flow process or not.

Fracture porosity, at least with regard to the crystalline rocks being considered for waste isolation, is normally far less than the matrix porosity. Hard crystalline rocks, for example, have matrix porosities of 0.01 to 0.02 (Knapp, 1975) or possibly as much as 1.0 (Baker, 1981). Fracture porosities are typically less than 10^{-4}. Thus, there are inherent problems in measuring fracture porosities in the field, especially when the methods are influenced by the relatively large volume of pore space in the matrix. As a result, not many in-situ determinations of fracture porosity have been made.

A new procedure using the wealth of data collected at Stripa is being developed to determine fracture porosity. Figure 11 is a probability plot of apertures that was computed using the injection test data from the HG and R boreholes. The solid circles represent results from about 100 tests where single fractures were isolated and tested. The open squares represent results from about 120 tests using a fixed spacing of 2 m. The computed results for this second correlation were based on the assumption of a single fracture within the 2-m interval regardless of the actual number.

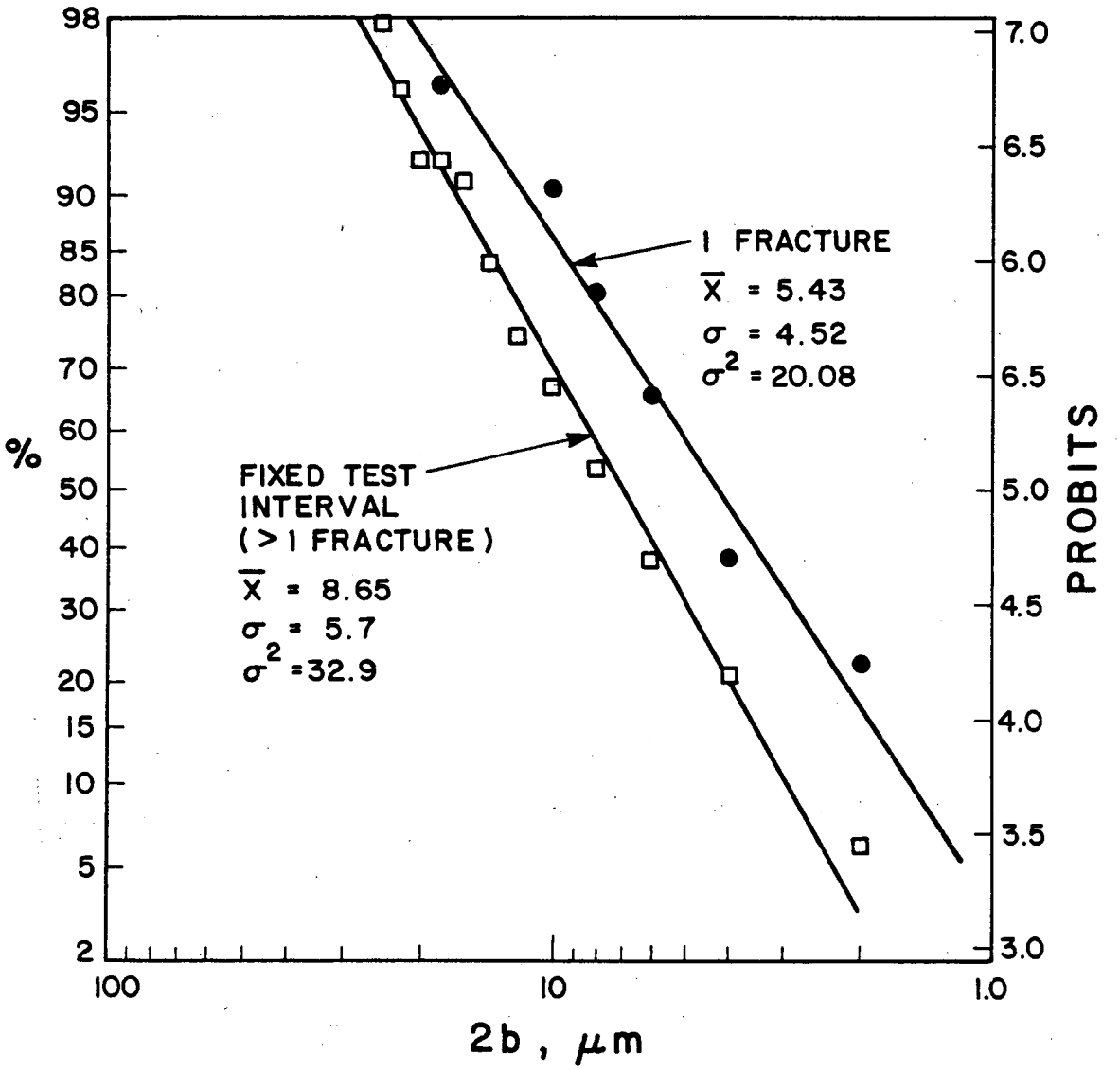


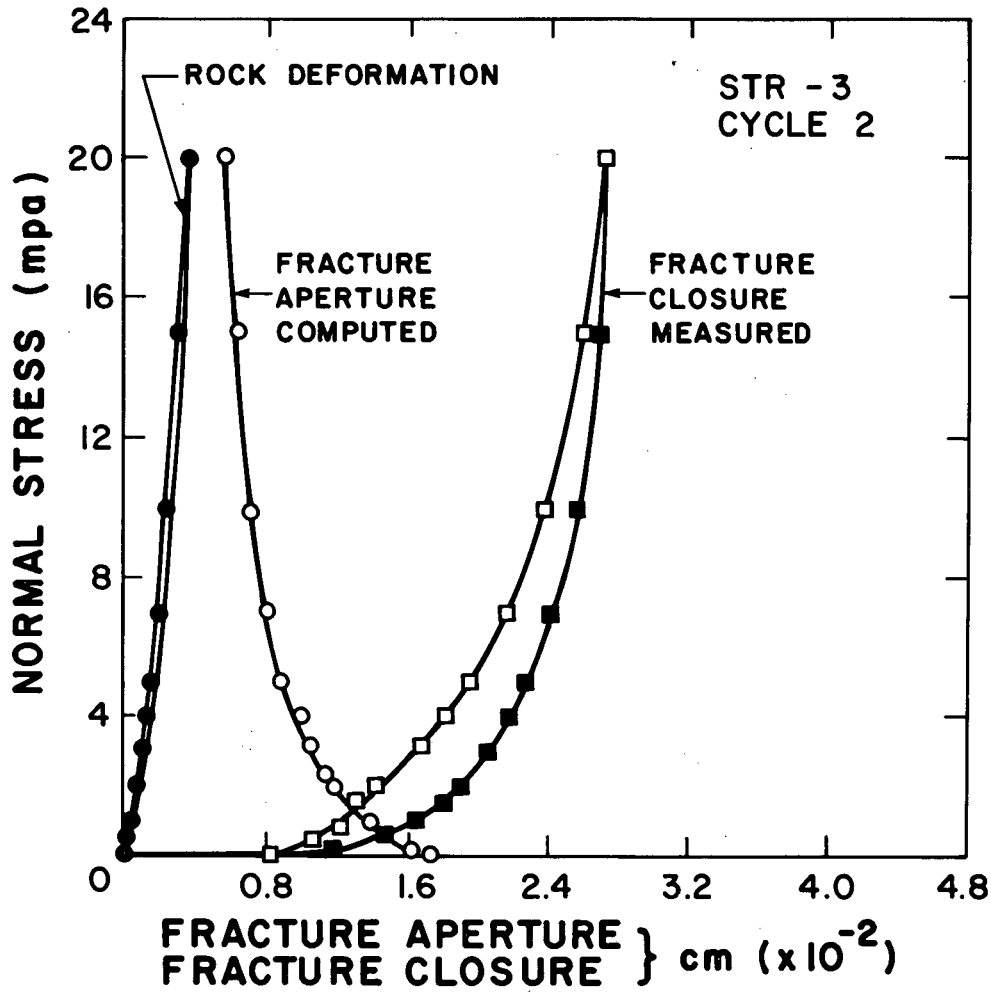
Fig. 11. Distribution of fracture apertures from 2-m and single-aperture injection test data collected in the HG and R boreholes (after Gale, 1982).

In both correlations in Fig. 11, the aperture results are reasonably close to a straight line, and we interpret this to mean that the fracture apertures are lognormally distributed. From this interpretation, we have computed mean values of 5.8 micrometers for the single-fracture data and 8.3 micrometers for the 2-m interval tests.

The apertures in Fig. 11 were calculated from the injection test data using the standard assumption of smooth parallel walls, but it can be demonstrated that this assumption may introduce an error because it ignores the effects of roughness (Gale, 1982). Furthermore, the calculated results depend on the degree of interconnection between the fractures within the test interval and the rest of the network.

Some idea of the actual size of the fracture apertures has been obtained from an analysis of laboratory tests of a natural fracture in a core of Stripa granite with a diameter of 0.15 m (Gale, 1982). In the laboratory situation, the single fracture is continuous between the imposed pressure boundaries, and the problem of fracture interconnection does not arise. Figure 12 shows the relationship between measured fracture closure and normal stress across the single fracture. Apertures were computed from the flow data on the assumption of smooth parallel walls.

The in situ injection tests in the HG and R boreholes were conducted in the rock mass where the estimated in situ stress is in the range of 10-20 MPa. From Fig. 12, this corresponds to a parallel-plate fracture aperture of about 80 micrometers; this aperture would be somewhat larger if the effects of roughness were taken into account. Thus, once corrections



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Fig. 12. Results of laboratory testing of a natural fracture in a Stripa core sample, showing effect of normal stress on fracture behavior.

for roughness are made, the field data in Fig. 11 and the laboratory data in Fig. 12 can be used to develop a fracture distribution model for this granitic rock mass.

The final step in this new procedure is to combine the aperture data with the fracture statistics to determine the effective and total porosities. Fig. 13 illustrates the approach we are investigating. The process is as follows: (1) identify the set to which each fracture belongs; (2) from the statistical correlations for that set, randomly select a trace length and spacing for the given fracture; and (3) randomly select an aperture for each fracture from the fracture distribution model. The final step in this new procedure is to combine the aperture data with the fracture statistics to determine the effective and total porosities. One can then estimate the total porosity using aperture data as interpreted from laboratory results (Fig. 12) and effective porosity using aperture data computed from borehole tests (Fig. 11). This procedure has been used to determine fracture porosities for six of the 15 boreholes in the ventilation drift (Gale, 1982). The results indicate that the rock mass has a mean effective fracture porosity on the order of 10^{-5} and a mean total fracture porosity on the order of 10^{-4}. Further work is needed to verify the applicability of this new approach to evaluations of fracture porosity.

4.3 Pump Testing of Surface Wells

Four wells 15-30 m apart were drilled into a surface outcrop of granite approximately 100 m north of the underground test facility to determine if pump testing could indicate directional permeability. The wells, shown as WT4, WT5, WT6, and WT7 in Fig. 2, were sited according to the orientations of the dominant fracture sets. The central pump well, WT7, was 100 m deep,

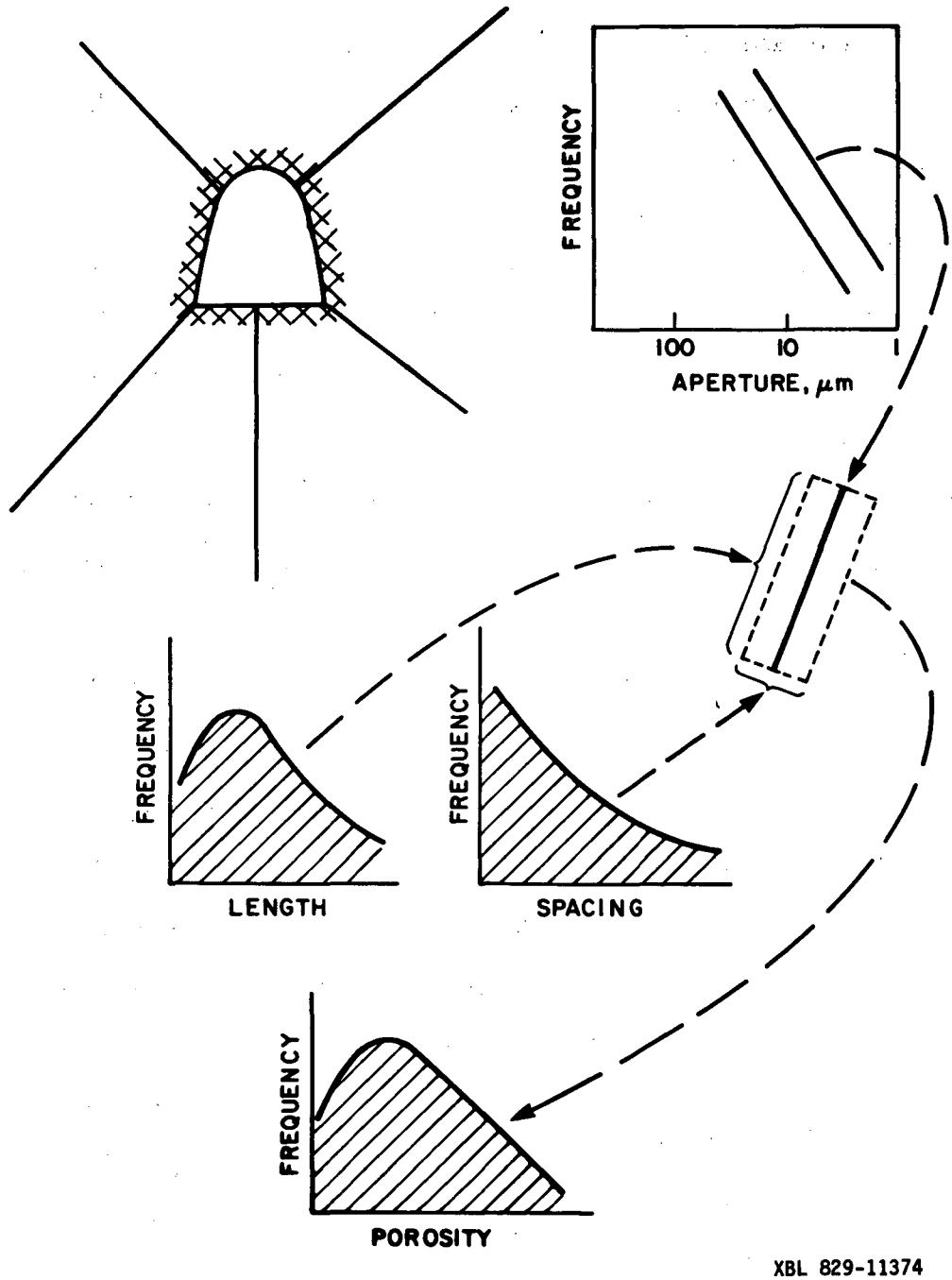


Fig. 13. Graphical representation of method for computing fracture porosity from aperture data and fracture statistics.

and the observation wells were each 50 m deep. All wells were vertical. Test results indicated that the local hydrologic system was dominated by a fracture zone interconnecting the pumped well with one of the observation wells; the other two observation wells did not appear to be hydraulically connected to the pumping well. The dominant effects of this single fracture zone did not permit the tests to be interpreted in terms of directional permeability, which suggests that the wells may not have intersected a representative number of fractures. Additional information on these tests has been published (Witherspoon et al., 1979).

5.0 GEOCHEMISTRY AND ISOTOPE HYDROLOGY

Geochemistry and isotope hydrology of ground waters provide an independent approach to the problem of the overall permeability of a rock system. If surface waters moved rapidly to the experimental level (338 m), shallow and deep waters should be similar in chemistry and age. On the other hand, if the deep waters had entered the ground-water system many thousands of years before the shallow waters or at a considerable distance from the present site, to which they percolated slowly, there should be significant chemical differences between waters at different depths.

A comprehensive program of geochemical investigations of the Stripa ground waters has been carried out by Fritz et al. (1979). Water samples were collected from the surface, shallow private wells, and boreholes drilled in the heater drifts at the 338-m level. In addition, samples were collected from a deep borehole drilled by the Swedish Geological Survey from 410 m (the deepest operating level in the mine) to about 840 m below the surface.

The high chloride concentrations and relatively low deuterium and oxygen-18 contents of the deep mine waters, compared with near-surface waters, indicate that these waters followed different flow paths and/or had a different geochemical history. The low deuterium and oxygen-18 values also indicate that when the deep waters were originally at the surface (that is, before they seeped into the ground-water system), their temperatures were considerably cooler than that of present-day conditions. The high chloride contents suggest a much different geochemical environment than presently exists at Stripa. These conclusions are substantiated by

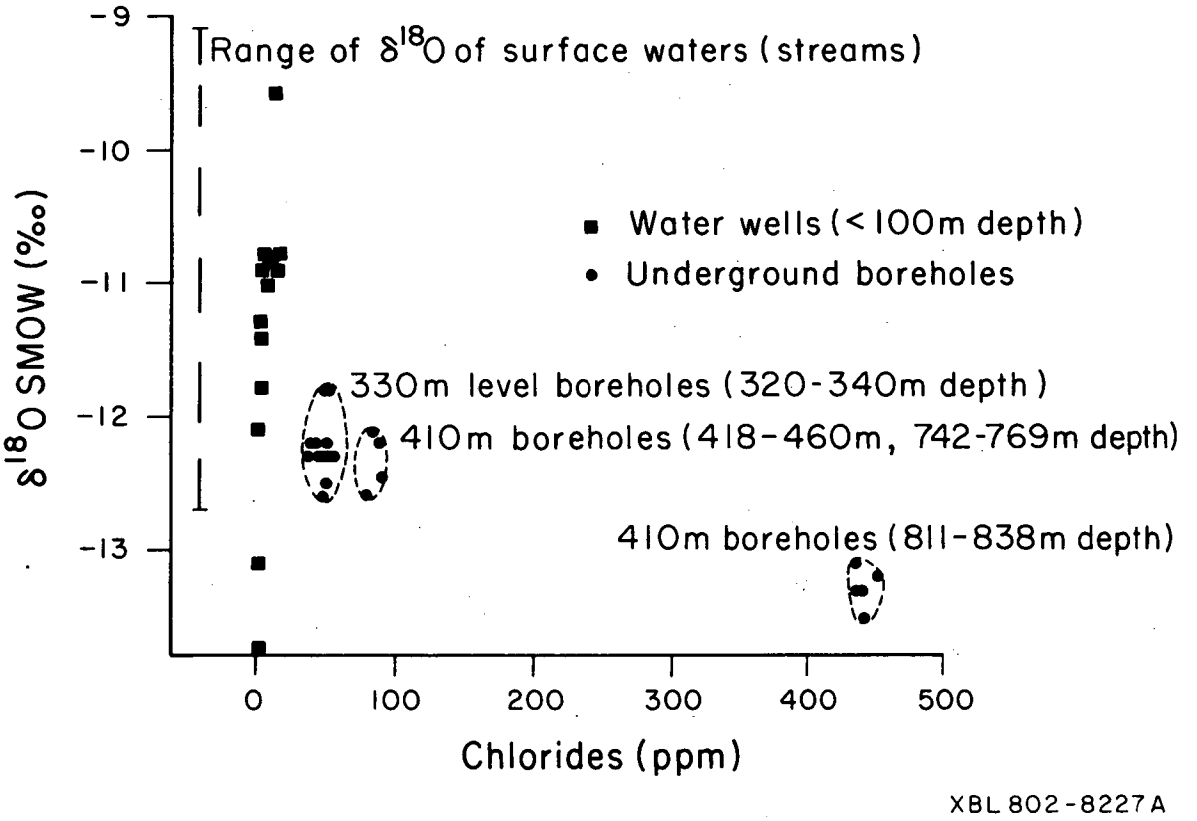


Fig. 14. Comparison of chloride concentrations with $\delta^{18}O$ values from geochemical investigations shows there are distinct differences between waters at different depths. Oxygen isotope values are referred to standard mean ocean water (SMOW).

comparing $\delta^{18}O$ with the chloride concentrations, as shown in Fig. 14. It is apparent that the deep ground waters, especially those at 811 to 838 m, are chemically distinctly different from the shallow ground waters. We interpret this as indicating that the shallow and deep ground-water systems are hydrologically isolated from each other.

Isotopic dating of the various ground waters was also carried out (Fritz et al., 1979). In contrast to the surface waters, where appreciable amounts of tritium were observed, the deep ground waters from the quartz monzonite are essentially devoid of tritium, which indicates that they are at least 30 to 40 years old. Waters from the deep levels are also very low in dissolved inorganic carbon; 2000 to 3000 liters of water were needed for ^{14}C analysis. On the basis of this method, the age of the waters at the 330 m level, and probably also from the 410 m borehole, exceeds 20,000 years.

Three different approaches to dating based on the uranium decay series were also investigated; these involved: (1) uranium activity ratios, (2) helium contents, and (3) radium-radon relations (Fritz et al., 1979). Although the $^{234}U/^{238}U$ method is still under development and is subject to some uncertainties, ages exceeding 100,000 years have been inferred from these data. Similar ages have been determined from ^{4}He concentrations. A method proposed by Marine (1976), relating ^{4}He to its parent ^{238}U, yields ages ranging from tens of thousands to hundreds of thousands of years. The results of the radium-radon method indicate ages for the ground waters ranging from 8,000 to 35,000 years.

Both the ^{14}C and the uranium decay series are dating tools that consider dissolved constituents in the water rather than the water itself.

Thus, geochemical reactions can affect isotopic distributions and, hence, inferred water ages. Despite this caveat, the data support the conclusion that the waters found in the quartz monzonite rock mass at Stripa, especially at the deepest levels (811 to 838 m), are indeed many thousands of years old. They also support the inference from the geochemical data that the shallow and deep ground waters are isolated. It is apparent that geochemical and isotope hydrology investigations provide independent and complementary approaches to evaluating the degree of isolation in a ground-water system.

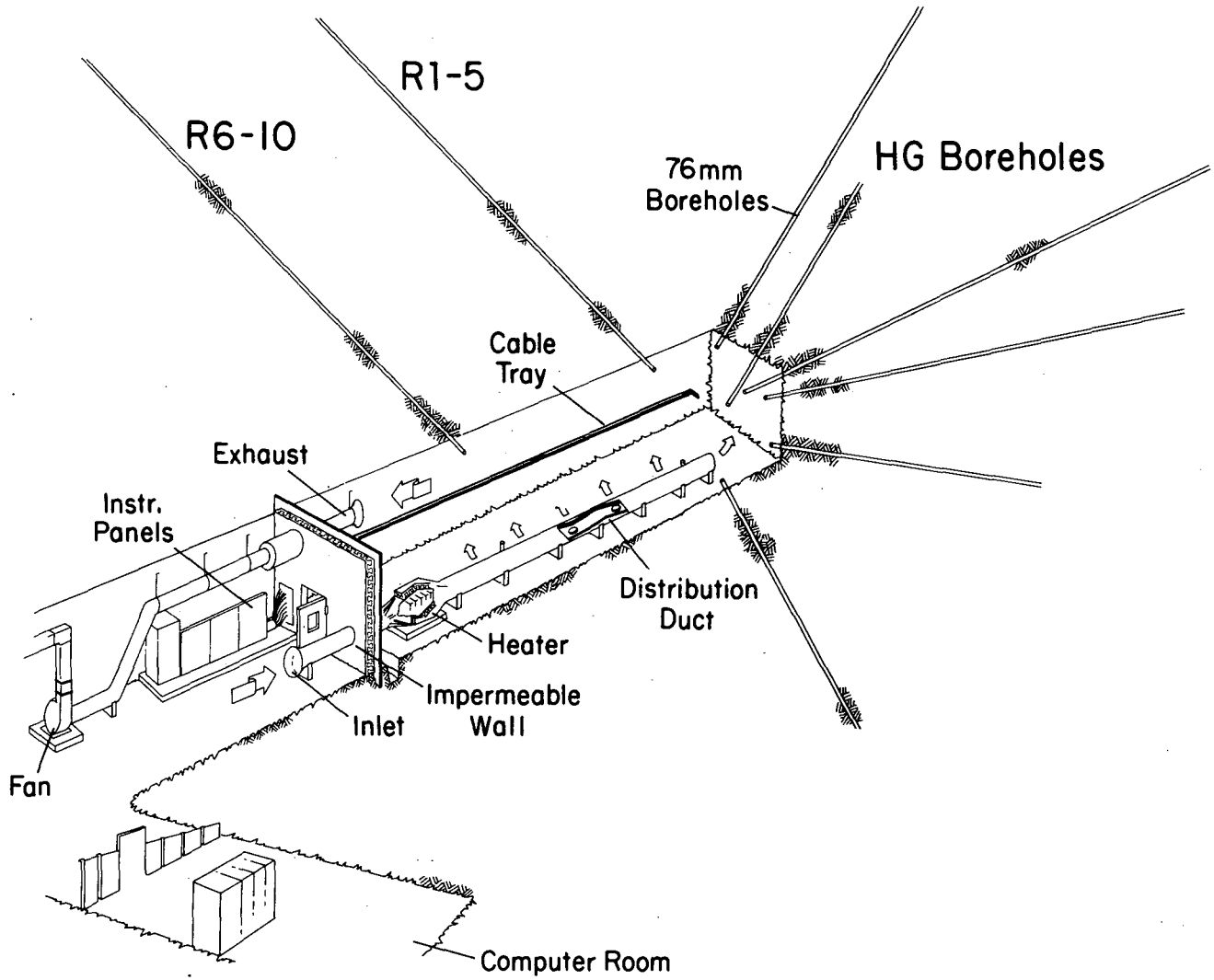
6.0 THE MACROPERMEABILITY EXPERIMENT

The macropermeability experiment was an attempt to measure the permeability of a large volume of fractured rock. The experiment was conducted in a 5 m x 5 m x 33 m room known as the ventilation drift (Fig. 4) at the 338-m level of the Stripa mine. Water flow and pressure were monitored for an 11-month period from November 1979 to September 1980.

The primary objective of the experiment was to improve techniques for permeability characterization of large volumes of low-permeability rock. In meeting this objective, the results were expected to: (1) give a measure of the average permeability of some 200,000 cubic meters of rock, (2) provide a basis of comparison with estimates of rock-mass permeability from the conventional borehole tests, and (3) evaluate the ventilation technique for monitoring seepage into a large, open drift.

Discussions of the theoretical basis for the experiment and the need for this type of research were presented in earlier papers (Gale and Witherspoon, 1979; Wilson et al., 1981; Witherspoon et al., 1980; and Long et al., 1980). An analysis of the steady-state, radial component of seepage into the drift has also been carried out (Wilson et al., 1982).

A schematic drawing of the experimental setup is presented in Fig. 15. Water inflow was measured as the net moisture pickup of the ventilation system inside a sealed portion of the ventilation drift. The ventilation air was heated to improve its moisture-carrying capacity and to improve the accuracy of the measurements. Hydraulic gradients were determined by measuring water pressure in 90 isolated intervals in the 15 HG and R boreholes (Fig. 15). Each isolated interval was about 5 m long, a length intended to



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Fig. 15. Schematic drawing of the macropermeability experiment in the ventilation drift, showing installed equipment and boreholes that were packed off to obtain pressure measurements.

include sufficient numbers of open fractures (generally 15 to 20) within each zone to provide reasonable assurance that the pressure data would be sufficiently averaged to produce smooth pressure profiles.

Tests were run at three nominal room temperatures -- 20°, 30°, and 45°C -- followed by a cool-down test back to 20°C. The 20°C test most closely reproduced the ambient air conditions under which the earlier borehole permeability tests were performed in the R and HG boreholes of the ventilation drift. The two higher temperature tests provided more accurate measurements and permitted investigation of thermal effects on the measured inflow and on the ventilation techniques for monitoring seepage. The first three tests were continued until essentially steady-state conditions were reached. Because of time constraints, the cool-down test was stopped while still clearly in a transient state.

Net moisture pickup from the ventilation system measurements is shown in Fig. 16 for the period 15 November 1979 to 30 September 1980. Net moisture pickup was determined from the difference between the exhaust and inlet ducts in the water content of the air streams. This net pickup was interpreted as a measure of the average seepage rate into the sealed portion of the ventilation drift.

Net moisture pickup for the initial 20°C test averaged about 50 ml/min, although the data show considerable scatter due to low measurement accuracy at this temperature. This first test was actually run at an average room temperature of about 18°C, which was as close to the ambient mine air temperature of 15°C as could be attained while still evaporating all incoming moisture. Figure 17 shows a distance-drawdown, semi-log plot of the pressure data from the radial boreholes. On such a plot, the

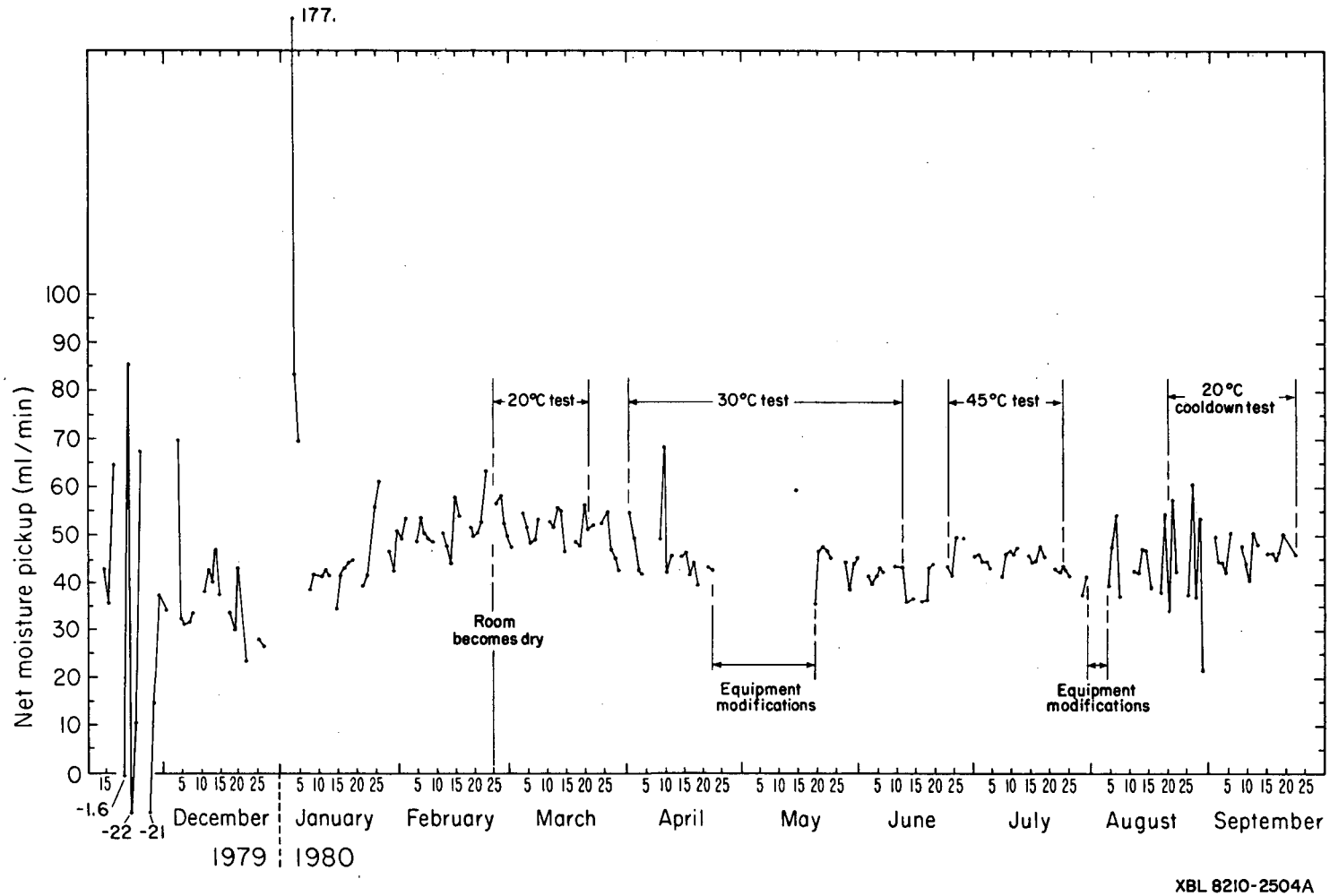


Fig. 16. Net moisture pickup by the ventilation system from 15 November 1979 to 30 September 1980. Lines join data taken on consecutive days.

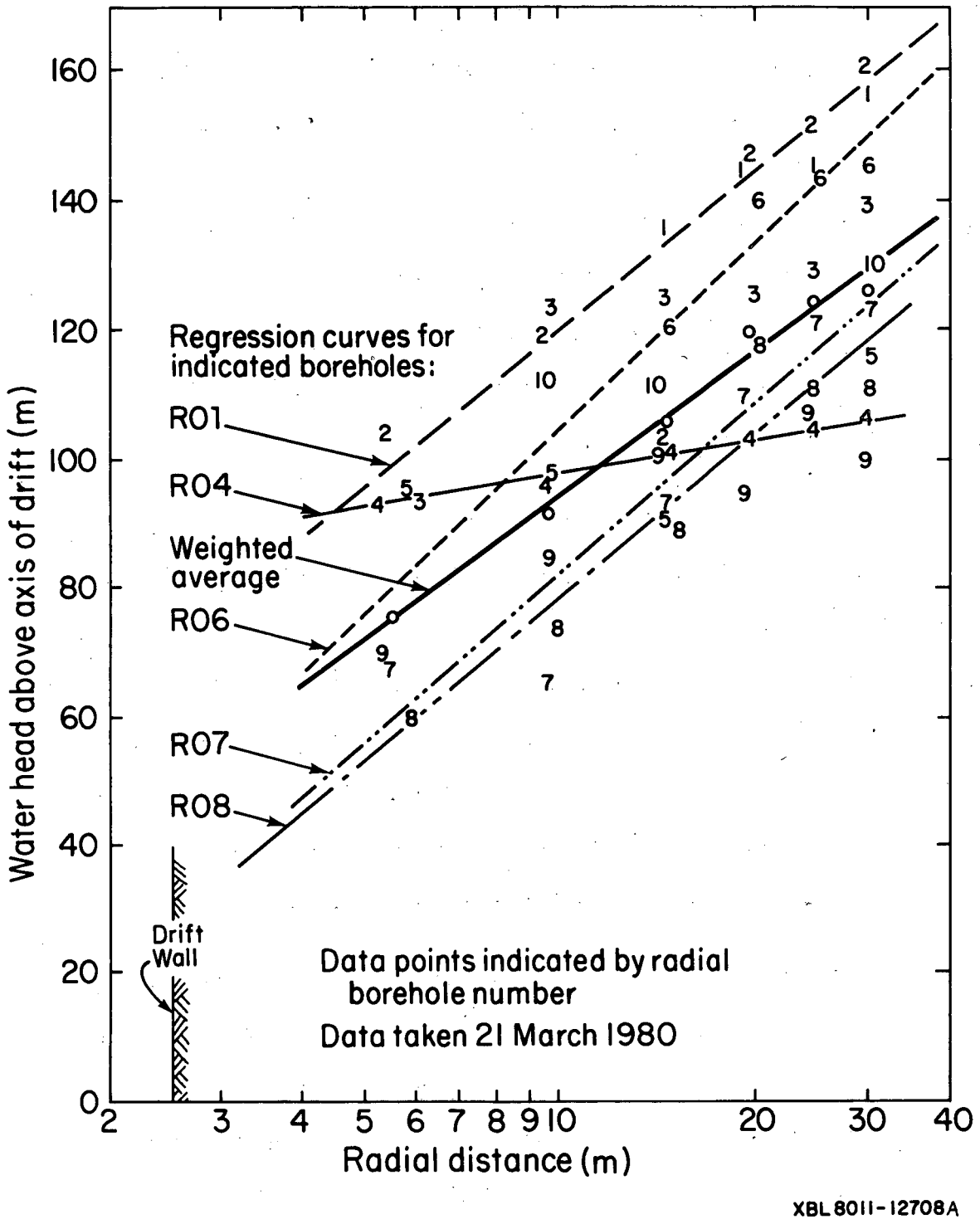


Fig. 17. Distance-drawdown plot for permeability test with nominal room temperature of 20°C.

normal porous-media-type flow will appear as a straight line. Data from four of the 10 boreholes do plot as rather well defined straight lines, with correlation coefficients on the order of 0.9 or better (dashed lines, Fig. 17). The weighted average of all data points also plots as a straight line, with a correlation coefficient of 0.98 (Fig. 17). If we assume that 80% of the observed 50 ml/min net moisture pickup occurred as radial flow (as estimated from a simplified analysis of flow into the entire drift), the average hydraulic conductivity of the monitored rock mass is about 1.0 x 10^{-10} m/s, which for water at ambient conditions is equivalent to an intrinsic permeability of 1.0 x 10^{-13} cm^2.

It may be noted that in Fig. 17 the weighted average line and the lines for each borehole indicate a water head significantly higher than the actual head if projected to the wall of the drift. This suggests that a skin of lower permeability rock exists between the drift wall and the location of the closest measurements. If this skin is assumed to be homogeneous and about 2.5 m thick, its hydraulic conductivity would be about 3.5 x 10^{-11} m/s, or about one-third of the average conductivity of the rock mass. If the skin thickness were less, its conductivity would be even smaller.

At the end of the 20°C test, air temperatures were raised successively to 30°C and 45°C and then reduced back to 20°C. Table 3 summarizes the permeability results obtained from the four tests; essentially the same results were obtained at all temperatures. Ground-water pressures tended to increase in the vicinity of the drift with increasing air temperatures. This resulted in slightly smaller gradients, which were reflected in the decreased flow rates. The mean hydraulic conductivity for all the tests is 9.8 x 10^{-11} m/s, equivalent to an intrinsic permeability of 9.8 x 10^{-14} cm^2.

Table 3. Results of permeability tests in the ventilation drift.

Test	Nominal Temp. °C	Average Flow Rate ml/min	Hydraulic Conductivity m/s
1	20	50	1.0×10^{-10}
2	30	42	9.4×10^{-11}
3	45	43	1.0×10^{-10}
4	20[a]	47	9.8×10^{-11}

[a]Cool-down temperature.

7.0 DISCUSSION AND CONCLUSIONS

Because of the importance of the fracture system, for both mine stability and ground-water flow, a careful analysis of the fracture system is mandatory if we are to compare the characteristics of one site with those of another. Such analysis becomes even more important when we consider the number of sites currently being studied in different countries. On the basis of our work at Stripa, several points can be made that will be of assistance in selecting a repository site.

The data needed to evaluate fractured rock masses are quite considerable, and their collection and preservation are of utmost importance. To answer questions relevant to site assessment, a careful and systematic method of field operations must be adopted. Maps of the drift walls should be user-oriented. This involves careful photographing of drift surfaces, followed by mapping of the fracture traces on a grid system. Each trace should be assigned a number so that data for any particular fracture, such as strike, dip, trace length, etc., can be located. This will make it relatively easy for other workers to use the fracture maps and data files to compare fracture characteristics at one site with those at another.

The drill core is another source of valuable basic data. The boreholes should be oriented to optimize intersection with the principal fracture sets. The cores should be oriented, photographed, and carefully mapped so that the true orientations of the fractures intersecting the drill core can be calculated. This requires the use of improved core orientation devices, triple-tube core barrels, and impression packers in conjunction with a sustained effort at core reconstruction and mapping.

At Stripa, user-oriented maps (Rouleau et al., 1981) were prepared for the ventilation drift. These maps were used to determine the number of fracture sets present in the rock mass and the distribution of trace lengths for each fracture set. Trace lengths can be measured only at surface exposures or on the walls and floors of subsurface drifts. A sufficient area of exposure is necessary to minimize the censoring problem and to insure that an adequate sample has been obtained.

The oriented HG and R drill cores provided an independent set of data that confirmed the existence of the four fracture sets. In addition, we were able to use the oriented drill cores to determine the distribution of spacings for each fracture set. Analysis (Rouleau and Gale, 1982a) of the fracture data from the drift walls suggests that the trace length data and fracture spacing data are best fitted by log-normal distributions. This analysis also showed that significant differences exist between the mean values of the trace lengths and spacings for the different fracture sets.

It is obvious that reliable data are required from both surface and subsurface exposures and oriented drill cores if one is to determine the type of statistical distribution that best fits the trace length and spacing data from different sites. It is essential that the appropriate distributions be identified so that their statistical parameters may be used in simulations of fracture networks. This will enable one to assess flow pathways, hydraulic interconnections, directional permeabilities, and fracture porosities. Fracture data will also provide valuable input for the general problem of rock mass stability and questions of thermomechanical

behavior. In this context, the new approaches used in collecting and analyzing the fracture data at Stripa, when modified by the experience gained, should provide a statistically meaningful basis for site comparisons.

The fracture hydrology program at Stripa was also designed to explore new techniques for evaluating the fluid flow properties of discontinuous rock masses of low permeability. A fundamental question in such evaluations is whether the fractured rock can be analyzed using porous-medium concepts. What measurements should one make to verify that a porous-medium equivalent exists for a network of discontinuous fractures? To provide new insight into this problem, the field program at Stripa was deliberately designed to include permeability measurements on a wide scale ranging from individual fractures to the very large scale macropermeability experiment. Further analysis of the fracture statistics is needed, however, to shed more light on the question of the porous-medium equivalence of the fracture network. New methods of investigating this problem are now available (Rouleau and Gale, 1982a and Long et al., 1982). Fracture porosity is another important component of this problem. Porosity values can be computed using the techniques discussed above, but the field measurement of effective porosity will require appropriate tracer studies.

The testing equipment developed for the fracture hydrology measurements in boreholes worked satisfactorily with steady-state flow and 2-m intervals for hydraulic conductivities as low as 10^{-11} m/s. Increasing the test interval to 20 m would have enabled an evaluation of conductivities as low as 10^{-12} m/s, but the longer interval would have been many times greater

than the average fracture spacing. This was not desirable because it would have decreased the statistical information on aperture distributions. Pressure pulse techniques applied to 2-m intervals could decrease this limit down to 10^{-12} m/s and lower, but the application of this method to fractured rocks needs extensive evaluation (Gale, 1982).

The new technique of measuring the average rock mass permeability that was obtained from the macropermeability experiment can also be improved. The final result of about 10^{-10} m/s could be decreased by one order of magnitude simply by making the drift 10 times longer. By improving the method of detecting low flow rates, it should be possible to detect seepage rates as low as 5 ml/min, and, as the depth of the test chamber increases, the effective hydraulic gradients could be 5-10 times greater than those measured at Stripa. Thus, hydraulic conductivities on the order of 10^{-12} m/s should be measurable within reasonable time periods.

Comparison of the borehole results with those of the macropermeability experiment provides a unique opportunity to evaluate two different methods of measuring fractured rock permeabilities. The average permeability of 10^{-13} cm^2 from the macropermeability experiment data compares quite favorably with the average of 8.9×10^{-13} cm^2 determined from borehole test data in the rock walls of the same room. The higher average value determined with the latter method probably reflects differences in test mode. For example, testing in boreholes required fluid injection, whereas fluid was being withdrawn from the system in the large-scale experiment. Also, the lengths of the boreholes, which radiated in all directions from the drift, increased the possibility that the holes would intersect more

high-permeability fractures than the drift itself. The macropermeabilty method, however, appears to be the one technique that could be used during development of actual repository sites to determine the acceptability of individual storage drifts.

Although the procedures that will be used to characterize a repository site have yet to be decided, it seems likely that they will include some form of probability analysis. This will require that the pertinent properties of the rock mass be described in terms of appropriate statistical distributions. The borehole testing program has demonstrated how data on the variation in fracture permeabilities can be obtained. Ultimately, one needs to be able to predict the rate of movement of radionuclides through the rock mass, and this will require data on fracture apertures. The testing program at Stripa has demonstrated how different interpretational models can be used to compute the statistical distributions of fracture apertures. As discussed above, we are also investigating a new method of computing fracture porosity, a parameter necessary to determine true velocities. In addition, when fracture apertures are combined with fracture orientations and spacings, it will be possible to determine directional permeabilities. The macropermeability method, which yields an average rock mass permeability for a very large volume of rock, will provide a necessary check on the results calculated from borehole data.

The approach taken to develop the fracture hydrology data base at Stripa will also enable one to evaluate the degree of hydraulic anisotropy within the rock mass. This can then be used to determine the distribution of velocities within the fracture system and the most probable fracture pathways for radionuclide migration. This level of understanding of the

fracture hydrology should also be a necessary prerequisite to the planning and execution of any tracer studies. Completion of the originally planned tracer experiments would permit a comparison of predicted versus measured transit times and thus serve as a check on the validity of our interpretations of the fracture hydrology at Stripa.

A more complete understanding of the effective transit time within the fractured rock mass at Stirpa is necessary if we are to properly interpret the apparent groundwater ages determined by analysis of the isotopes and the groundwater residence times. This will certainly require a thorough analysis of fracture porosity and permeability. It is obvious, given the complexity of the highly disturbed flow system at Stripa, that a necessary objective of the fracture hydrology program should be an attempt to reconcile the measured porosities, permeabilities, and flow system boundary conditions with the distribution of isotopes and ground-water chemistry. Such an attempt, even if only partially successful, will provide considerable insight into the nature of flow systems in fractured rocks and should enhance the overall problem of selecting sites for nuclear waste disposal.

Finally, the hydrogeological investigations at Stripa have demonstrated the value of coordinated surface and underground testing in site characterization. It is recognized that the logical sequence proceeds from surface work to the subsurface with appropriate analysis of results at key points in the total process. The hydrological as well as the thermomechanical behavior of the rock mass is controlled by fractures and other discontinuities, and predictions made using standard continuum assumptions are

often not valid. Proper evaluation of rock mass properties will require detailed studies of the influence of these discontinuities, and will involve adequate sampling of their geometric and hydraulic properties from both surface-based and at-depth tests. The work at Stripa has shown that surface and underground testing provide complementary information, and that the complete suite of data needed cannot be obtained from one approach alone.

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