Experimental Verification of Acoustic Waveform and VSP Seismic Tube Wave Measurements of Fracture Permeability

by

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ABSTRACT

A variety of established and experimental geophysical techniques was used to measure the vertical distribution of fracture permeability in a 229-meter deep borehole penetrating schist and quartz monzonite near Mirror Lake, New Hampshire. The distribution of fractures in the borehole was determined by acoustic borehole televiewer and other geophysical logs. Fracture permeability was estimated by application of two experimental methods: (1) Analysis of tube-wave-amplitude attenuation in acoustic full-waveform logs; and (2) interpretation of tube waves generated in vertical seismic profiles. Independent information on fracture permeability was obtained by means of packer-isolation-flow tests and flowmeter measurement of vertical velocity distributions during pumping in the same borehole. Both experimental methods and packer-isolation-flow tests and flowmeter data indicated a single, near horizontal zone of permeability intersecting the borehole at a depth of about 45 meters. Smaller values of transmissivity were indicated for other fractures at deeper depths, with details of fracture response related to the apparent volume of rock represented by the individual measurements. Tube-wave-amplitude attenuation in full-waveform acoustic logs, packer-isolation flow tests, and flowmeter measurements during pumping indicated transmissivity values for the up-

per permeability zone within the range of 0.6 to 10.0 centimeters squared per second. Vertical seismic-profile data indicated a relative distribution of fracture permeability in agreement with the other methods; however, the calculated values of transmissivity appeared to be too small. This disagreement is attributed to oversimplification of the model for fracture-zone compressibility used in the analysis of vertical seismic-profile data.

INTRODUCTION

Many important geotechnical applications require an understanding of fracture permeability, including regional ground-water circulation, contaminant migration, nuclear-waste repository siting, and earthquake seismology. However, reliable estimates of fracture permeability are difficult to obtain. Large volumes of fractured rock need to be sampled to characterize the permeability of a representative volume. Therefore, small fracture segments recovered in cores are not likely to provide a representative sample of fractures, even when complete cores are recovered from fractured intervals. In addition to the problems associated with the size of fractured-rock samples, previous results indicate that the permeability of fractures depends on the in situ state of stress (Witherspoon et al., 1981). Damage to fractures during drilling and core recovery further complicates the interpretation of in situ fracture permeability based on recovered cores. All of these factors indicate that the in situ measurement of fracture permeability in rock masses surrounding exploratory boreholes is one of the most effective ways to characterize the permeability of otherwise nearly impermeable rocks.

The recognized need for in situ permeability measurements in fractured rocks has resulted in several new methods for estimating fracture permeability in boreholes in addition to established, qualitative methods for fracture characterization described by Keys (1979). Established methods include various combinations of geophysical well logs (CGWL), and acoustic borehole televiewer logs (ABTVL). Full-waveform acoustic logs (FWAL) and vertical seismic profiles (VSP) provide two new, quantitative methods for fracture-permeability estimation. These methods can be compared to the results of the more conventional, but time-consuming, packer-isolation flow tests (PIFT) and crosshole pumping tests using a slow-velocity, heat-pulse flowmeter (HPFM). Each of these methods has been described in the geophysical literature by numerous authors, but few references have compared the results of all of these measurements applied in the same borehole. This paper presents a systematic comparison of the fracture permeability measurements made using all of these methods in a single borehole where much additional information about fracture distribution and permeability is available.

Fracture-permeability-characterization methods used in this report are summarized in Table 1. These methods have been documented in the references cited in the table.

Most of the measurements described in this report have been analyzed in detail in other reports. The primary purpose of this report is the comparison of all of these different results using comparable scales and fracture-permeability measurements. One of the most important considerations in presenting such a comparison is consistency in characterization of fracture permeability; two different measures of fracture permeability were used to present these results. The measurements were selected because a major problem in such a comparison is relating the different intervals of a borehole used for different measurements. Fracture transmissivity was used because transmissivity values for adjacent fractures may be summed to determine the combined effect of both fractures on flow rates. The aperture of an equivalent single fracture also was used, because it would account for the measured permeability of a given interval of borehole because the results of such an equivalent single-fracture model could be applied to all of the measurements. An equivalent single-fracture aperture provides an easily understood indication of fracture permeability to potential readers with a variety of backgrounds who are familiar with differing units of fracture permeability.

Another important consideration in comparing various fracture permeability measurements is the markedly different volume of rock investigated by each of the different measurements. Because the volume-of-investigation effect appears to be the primary factor accounting for different results obtained for the same borehole, results of the permeability measurements are presented here according to increasing size of the appropriate volume of investigation. The approximate size of the volumes of investigation for each measurement also are given in Table 1.

DESCRIPTION OF STUDY SITE

The fracture-permeability measurements presented in this report were obtained in a set of boreholes at the Hubbard Brook Experimental Forest near Mirror Lake, New Hampshire (Figure 1). The site was selected because of the available data on background hydrology, ease of access, and initial indications of isolated, permeable fractures. Preliminary study indicated a geological environment with many features such as lithologic contacts, intrusions, and foliation that might complicate permeability interpretation in fractured crystalline rocks, but without extensive alteration zones that could severely affect the interpretation process.

At the study site, four boreholes were drilled in a square pattern, with about 10 m between boreholes on each side of the square. Three boreholes–EBR1, EBR2, and EBR3–penetrate to a depth of 107 m, the fourth borehole–EBR4–penetrates to a depth of 229 m. The data used to determine fracture permeability were obtained in borehole EBR4, except for the data obtained from the HPFM tests, which required data from the shallower boreholes. The boreholes are all about 16 cm in diameter, with

relatively rough borehole walls produced by percussion drilling. The fine scale of this borehole roughness does not appear on the caliper logs for the boreholes, but is apparent in the ABTVL as a background variation in the intensity of acoustic reflectivity. These borehole conditions have some effect on the various fracture-permeability measurements through mechanisms such as packer seating and acoustic scattering, but are considered typical of actual conditions encountered during a study of fractured crystalline rocks. The rocks penetrated by the boreholes are foliated, micaceous schists, extensively intruded by quartz monzonite. The foliation in the schists is important to identify because foliation could be mistaken for fracturing by such borehole wall viewing devices as downhole television and the ABTVL. Further details on the properties and geological history of the rocks at the Mirror Lake study site are given by Billings et al. (1979). Winter (1984), Likens (1985), and Paillet (1985a) give additional information on the hydrogeology and fracture distribution at the Mirror Lake study site.

FRACTURE PERMEABILITY REPRESENTATION

Fracture permeability is studied by geoscientists from a variety of disciplines, each with their own preferred units of measure for fracture permeability. Fractured-rock reservoirs represent an especially difficult problem, because fracture permeability is concentrated in a small volume of the rock mass. However, one of the most critical aspects of fracture-permeability measurement in such rocks is the separation of spatial variability in the permeability of the fracture network from variability in measurements related to the scale of the rock volume being sampled (Witherspoon et al., 1981). In borehole measurements, this problem has a more specific form. The volume of adjacent unfractured rock to be included in the cross-sectional area, A, needs to be determined when calculating fracture permeability according to the formula:

$$K = \frac{Q}{(H'A)} \tag{1}$$

where Q is the measured flow in the fracture; and H' is the measured hydraulic-head gradient causing the flow. The distinction is difficult for fractures with irregular surfaces, multiple cross-connections between parallel fractures, and zones of alteration surrounding the fracture plane (Paillet, 1985b).

The problem of fracture-zone identification was approached by selecting representations for fracture permeability that are independent of adjacent intervals of unfractured rock. That is, effective fracture permeability was represented in units other than those used for hydraulic conductivity so that values did not depend on the volume of unfractured rock involved in the measurement. A critical aspect of this approach was selection of a study site where isolated fractures or sets of fractures have been defined. Conventional geophysical well logs and ABTVL were used to indicate fracture locations

in the study borehole. Then each fracture-permeability measurement was transformed into two scales that could be compared for all methods: fracture-zone transmissivity and aperture of an equivalent, single fracture capable of conducting the same flow at the measured hydraulic-head gradients.

Transmissivity, T, is defined as the product of permeability and fracture zone thickness, b:

$$T = K\, b \tag{2}$$

However, transmissivity may be derived directly from measured flows according to the formula:

$$T = \frac{Q}{DH'} \tag{3}$$

where D is the lateral extent of the fracture. Furthermore, the effective transmissivity of two adjacent fractures contributing flows $Q1$ and $Q2$ to the borehole can be obtained by summing the individual values of transmissivity:

$$Tc = \frac{(Q1 + Q2)}{DH'} = T1 + T2 \tag{4}$$

where $T1$ and $T2$ are the transmissivities of the two fractures. This equation is important because comparison of different fracture-permeability measurements with different volumes of investigation requires grouping several individual fracture measurements into a single value.

Some fracture-permeability measurements cannot be used to determine flows in fractures directly; in these instances, flow in fractures is determined using a fracture model. Such models usually involve a single infinite fracture plane of uniform, fluid-filled aperture, b. The aperture of the model can be used as an alternative representation of fracture permeability. The relation between fracture aperture (b) and transmissivity is given by the equation for laminar flow in such a plane:

$$Q = \frac{\rho A g b^2 H'}{12\mu} \tag{5}$$

where g is the acceleration of gravity, μ is the viscosity of water, ρ is the density of water. Using the definitions for hydraulic conductivity and transmissivity:

$$T = \frac{(\rho g b^3)}{12\mu}. \tag{6}$$

This is the cubic law for flow in fractures given by Snow (1965). The relationship between flow and fracture aperture indicates that the effective aperture of two fractures can be combined according to the rule

$$bc = (b1^3 + b2^3)^{1/3}. \tag{7}$$

Both equations (4) and (7) have been used to relate different fracture-permeability measurements to uniform borehole intervals.

CONVENTIONAL GEOPHYSICAL AND ACOUSTIC BOREHOLE TELEVIEWER LOGS

The boreholes were logged with a full suite of conventional geophysical well logs and the borehole acoustic televiewer before conducting the fracture-permeability measurements. The conventional geophysical logs indicated the presence of fractures according to the various fracture responses described by Keys (1979), Nelson et al. (1983), and Hillary and Hayles (1985). However, the variable lithology, foliation, thin intrusions, and rough borehole wall make these fracture responses difficult to recognize in some cases, and make confirmation that specific anomalies are related to fractures impossible without additional information. ABTVL were used to construct a detailed distribution of fractures in the boreholes. A representative interval of a televiewer log is compared to acoustic transit-time, single-point resistivity, and caliper logs in Figure 2; the figure shows several of the typical isolated fractures intersecting borehole EBR4. Most of the fractures identified on the ABTVL are dipping steeply to the east and west.

Acoustic transit-time and single-point resistance logs appeared especially well correlated with fractures, but these fracture responses apparently depend on detection of altered rock adjacent to fractures in addition to fracture porosity and permeability (Figure 2). The caliper log does not show a distinct fracture response, apparently because caliper arms cannot easily extend into the small opening where isolated fractures intersect the borehole unless some erosion of altered rock or mechanical breakage have occured adjacent to the borehole. Additional descriptions of the geophysical logs obtained in the Mirror Lake boreholes are given by Winter (1984) and Paillet (1985).

Inspection of the complete televiewer log for borehole EBR4 indicates an irregularly decreasing number of fractures with depth. Few fractures occur below a depth of 150 m, but one large, southeastward-dipping fracture was detected within a few meters of the bottom of the borehole. The televiewer log provides a qualitative indication of the size of a fracture by the apparent width of the fracture image on the ABTVL (Figure 2). However, the image represents the convolution of the fracture opening with an acoustic beam nearly 1 cm in width, so no simple quantitative relation exists between fracture-image width on the ABTVL and actual fracture aperture.

One fact apparent from the ABTVL for the boreholes is the lack of continuity in fractures between the four boreholes. Discrete fractures apparent on one televiewer log either cannot be projected to adjacent boreholes, or they correspond to fracture images with different appearance or orientation. The discontinuous nature of the fracture network in these boreholes was confirmed later by the cross-hole pumping tests (Paillet et al., 1987).

FULL-WAVEFORM ACOUSTIC LOGS AND TUBE-WAVE AMPLITUDE LOGS

Full-waveform acoustic logs were run in borehole EBR4 using a 15 kHz source, 0.60 m source-to-receiver separation, 2 μs digital sampling, and recordings at 0.15-meter vertical intervals (Paillet, 1980, 1983). Numerical models (Cheng and Toksöz, 1981; Paillet and White, 1982) indicate that the late, large-amplitude part of the pressure signal in the acoustic waveforms consists of the tube-wave mode superimposed on the lowest guided shear mode (described in the literature as pseudo-Rayleigh or normal modes). Both tube waves and guided shear modes have dominant frequencies similar to the 15 kHz centerband frequency of the acoustic energy source. The superposition of guided-shear modes complicates the interpretation of tube-wave amplitude, because borehole-wall irregularities and lithologic contacts affect the guided-shear modes much more than the tube-wave mode. This problem was resolved in the calculations made for this report by inspecting both ABTVL and waveform plots to determine which waveform-amplitude decreases were related to tube-wave-amplitude attenuation attributed to fracture permeability and which were related to factors other than tube-wave-amplitude attenuation at fractures. After the attenuation unrelated to fractures was removed, the analysis was made as described by Paillet and Hess (1986).

An example of the tube-wave analysis is illustrated in Figure 3. The tube-wave amplitude plot in the figure shows multiple lows, but only the single amplitude minimum at a depth of about 225 m is related to the fracture indicated on the ABTVL. Inspection of the waveform plots indicates that this is the only point on the record where acoustic wave transmission in both tube-wave and guided-shear modes is interrupted. The tube-wave-amplitude log further indicates that an 80 percent attenuation of wave energy occurred in the tube-wave time window. Comparison of this attenuation with the calculations given by Mathieu and Toksöz (1984) and Mathieu (1984) indicates that the tube-wave-amplitude attenuation in Figure 3 is equivalent to that of a single, infinite fracture with a uniform aperture of 0.4 mm, and a transmissivity of 0.3 cm^2/s.

Analysis of the FWAL data for borehole EBR4 is described in more detail by Hardin et al. (1987). The results indicate that about 20 fractures are present with equivalent single-fracture permeability values ranging from 0.1 to 0.4 mm intersecting borehole EBR4. Most of these fractures are located in the depth interval from 30 to 130 m, most of the fracture permeability is concentrated in the interval from 40 to 60 m.

PACKER ISOLATION-FLOW TESTS

The most direct measurement of fracture permeability is obtained by measuring the rate of flow into or out of a pressurized interval of borehole previously isolated by the inflation of downhole packers. Additional details of the PIFT procedures and analysis are given by Davison et al. (1982) and Hsieh et al. (1983). The analysis of PIFT data used for this report is based on the equation

$$T = \frac{Q}{2\pi H} \ln\left(\frac{Re}{R}\right) \tag{8}$$

where Q is the measured flow rate, H is the hydraulic head increase or decrease in the isolated zone, R is the borehole radius, and Re is an effective radius of influence for the test. Re is not known, but a value of 10 m is used on the basis of the results of cross-hole testing. Note that the logarithmic dependence in equation 8 indicates that the results are not sensitive to the exact choice of Re.

The PIFT data for borehole EBR4 were obtained by using a 6 m isolation interval in the upper part of the borehole, and larger isolation intervals in the lower part of the borehole. PIFT test results indicated that most fracture permeability was concentrated in the interval from 40 to 60 m. No measurable fracture permeability was indicated below a depth of 70 m, with the exception of one 6 meter interval at a depth of about 135 m, corresponding to a prominent fracture on the acoustic borehole televiewer log, and an isolated fracture assigned an equivalent single fracture aperture of 0.6 mm on the basis of tube-wave-amplitude attenuation. The PIFT tests indicated negligible permeability for the fracture at a depth of about 225 m; however, PIFT tests were not made for depth intervals below 150 m where all other logs indicated no fracturing.

HEAT-PULSE FLOWMETER MEASUREMENTS DURING CROSSHOLE PUMPING TESTS

A recently developed, heat-pulse flowmeter was used to measure the vertical distribution of inflow and outflow in the boreholes during pumping tests. The operation and calibration of the flowmeter are described by Hess (1982, 1986) and Paillet and Hess (1986). Pumping tests were conducted by pumping from one of the four EBR boreholes and then measuring the vertical flow distribution in all four boreholes. Steady pumping rates during the tests varied from 5 to 40 L/min. Other details of the pumping tests and HPFM data analysis are given in Paillet et al. (1987).

HPFM test results indicated that almost all hydraulic connection between the four EBR boreholes was a single zone of fracture permeability. This zone of fracture permeability apparently is composed of multiple intersecting parts of steeply-dipping fracture

segments (Figure 4). Comparison of ABTVL indicates that none of the fractures associated with inflow or outflow during the pumping tests project continuously between adjacent boreholes. Various models of the pumping tests yield estimates of equivalent single fracture apertures for the permeable zone ranging from 0.7 to 1.2 mm. These values are given as upper limits because the data analysis assumes that all of the imposed flow is conducted by the permeable zone, whereas other fractures must have contributed to at least some of the inflow.

VERTICAL SEISMIC PROFILE DATA

The hydrophone vertical seismic profile data obtained at the Mirror Lake study site were based on seismic arrivals at the borehole from four different seismic shot holes (Figure 1). In the VSP procedure, explosives repeatedly are fired in shallow boreholes, and seismic signals measured at stations located in borehole EBR4. The use of several seismic shot holes permits calculation of both fracture permeability and fracture strike and dip according to the methods given by Hardin and Toksöz (1985). Fracture permeability is determined by the relative amplitude of tube waves generated when seismic waves encounter the intersection of fractures with the borehole. Examples of fracture-permeability calculations using the VSP data obtained at the Mirror Lake study site are given by Hardin et al. (1987).

The VSPs for borehole EBR4 indicate a single major zone of fracture permeability at a depth of about 44 m. One of the four VSPs is illustrated in Figure 5, showing a large tube wave generated by the passage of seismic waves across the intersection of the fracture zone and borehole EBR4. A much smaller tube wave originates at the isolated fracture at a depth of about 225 m, and two other minor tube waves are associated with fractures at depths of 105 and 135 m on other VSPs presented in Hardin et al. (1987). The VSP data are consistent with the pumping test results in that both indicate an almost horizontal zone of fracture permeability in the upper part of the borehole. However, the calculated values for fracture zone transmissivity were much smaller than the value estimated from the pumping tests.

COMPARISON OF FRACTURE-PERMEABILITY MEASUREMENTS

Fracture-permeability measurements obtained with FWAL tube-wave analysis, HPFM measurements during cross-hole pumping tests, PIFT tests on individual fracture zones, and VSPs are compared in Figure 6. These data are compared to the distribution of fractures identified on the ABTVL, with fracture distribution given as the number of

fractures in each 5 m interval of borehole. The various fracture-permeability measurements are given in order of increasing scale of investigation as listed in Table 1.

Results presented in Figure 6 indicate that the FWAL, PIFT, HPFM, and VSP data indicate consistent distributions of fracture permeability. All four methods indicate the major zone of fracture permeability is at a depth of about 45 m and all but the HPFM results indicate at least some of the other permeable zones at greater depths. Three of the methods (FWAL, PIFT, and HPFM) also indicate similar values of fracture permeability. Exact correspondence between numerical measurements is not expected because of the different volumes of investigation. However, the analysis indicates that the values determined by HPFM likely will be interpreted as upper limits; this indication appears in Figure 6.

In order to at least partially compensate for the different scales of investigation for the different measurements, the transmissivity values for all measurements have been combined into the effective transmissivity for 6 m depth intervals in Table 2. The apparent vertical extent of the horizontal fracture permeability zone indicated by the PIFT data in Table 2 may be related to the presence of secondary fractures that permit leakage of flow around the packers adjacent to the primary fracture zone. Results of the FWAL analysis for individual fractures identified on the ABTVL otherwise appear consistent with the fracture-permeability values for the principal fracture zone by the PIFT and HPFM methods.

One major inconsistency in the data presented in Figure 6 and in Table 2 is the small value for fracture permeability determined from the VSP; this inconsistency could be attributed to the much larger scale of investigation represented by the VSP data. That is, the permeability of the fracture zone may be much smaller at points located farther from the four EBR boreholes. However, the consistency of the other measurements makes such a scale effect appear unlikely. Hardin et al. (1987) propose that the determination of permeability from VSPs may be more complicated than the determination proposed by Hardin and Toksöz (1985). The model of fracture compressibility used in generating the VSP permeability data may require modification to account for the effects of wave propagation across asperities. Therefore, the actual compressibility of permeable fractures may depend on the properties of the strongest asperities in contact, rather than upon the average compressibility and permeability of the fracture zone in the vicinity of the borehole. Underestimation of fracture strength could account for underestimation of fracture permeability using the VSP data in Figure 5.

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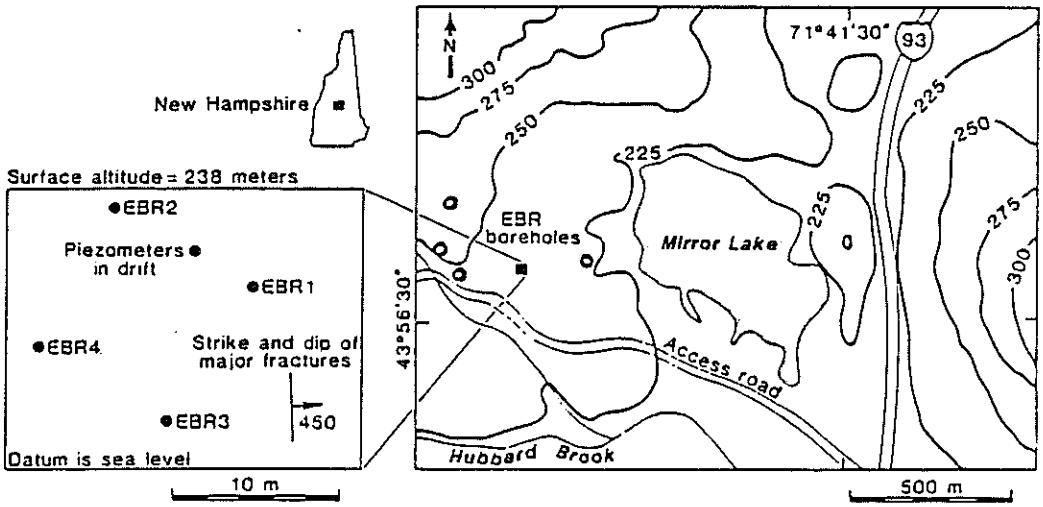
Table 1. Summary of fracture characterization methods used in this study

Method	Description	Mechanism	Scale of Investigation (meters)	Refs.
ABTV	Acoustic reflectivity image of borehole wall	Scattering of acoustic energy by fracture-borehole intersection	< 0.02	Keys (1979) Paillet et al. (1985) Zemanek et al. (1969)
FWAL	Acoustic tube-wave attenuation in full waveform logs	Viscous fluid dissipation in fracture openings	.10–.50	Rosenbaum (1974) Paillet (1980, 1983, 1985a) Hardin et al. (1987)
CGWL	Conventional well log response to fractures	Anomalous response at fractures	.1–1.0	Nelson et al. (1983) Keys (1979) Hillary & Hayles (1985)
PIFT	Pressure slug test in interval isolated by packers	Fracture flow away from isolated interval	10–20	Davison et al. (1982) Hsieh et al. (1983) Zeigler (1985)
HPFM	Flowmeter measurement of vertical permeability distribution	Identification of inflow and outflow during pumping	20–50	Hess (1982, 1986) Paillet & Hess (1986) Paillet et al. (1987)
VSP	Tube-wave generation in hydrophone vertical seismic profiles	Fluid pulses in borehole produced by seismic wave intersecting permeable fracture	50–200	Hardin & Toksöz (1985) Huang & Hunter (1981) Hardin et al. (1987) Levine et al. (1984)

Table 2. Comparison of fracture-transmissivity values determined by various methods for selected depth intervals in borehole EBR4

Interval (m)	Transmissivity, in centimeters squared per second, determined by indicated methods			
	PIFT	FWAL	HPFM	VSP
20–26	$9.8\ e^{-3}$	0	0	0
26–32	$1.0\ e^{-2}$	$2.7\ e^{-1}$	0	0
34–40	$1.3\ e^{-3}$	$3.6\ e^{-1}$	0	0
40–46	$6.3\ e^{-1}$	1.0	2.0–12.0	$2.0\ e^{-4}$
46–52	$4.9\ e^{-1}$	$6.4\ e^{-1}$	0	0
60–66	0	0	0	0
67–73	0	$9.0\ e^{-2}$	0	0
76–82	0	$1.0\ e^{-2}$	0	0
88–94	0	$1.2\ e^{-1}$	0	0
101–107	0	$1.8\ e^{-1}$	0	0
122–128	0	$2.3\ e^{-1}$	0	0
131–137	$3.0\ e^{-4}$	$3.3\ e^{-1}$	0	0



EXPLANATION

SEISMIC SHOT HOLE

BOREHOLE

Figure 1: Location of boreholes EBR1, EBR2, EBR3, and EBR4, and seismic shot holes near Mirror Lake, New Hampshire (modified from Paillet et al., 1987).

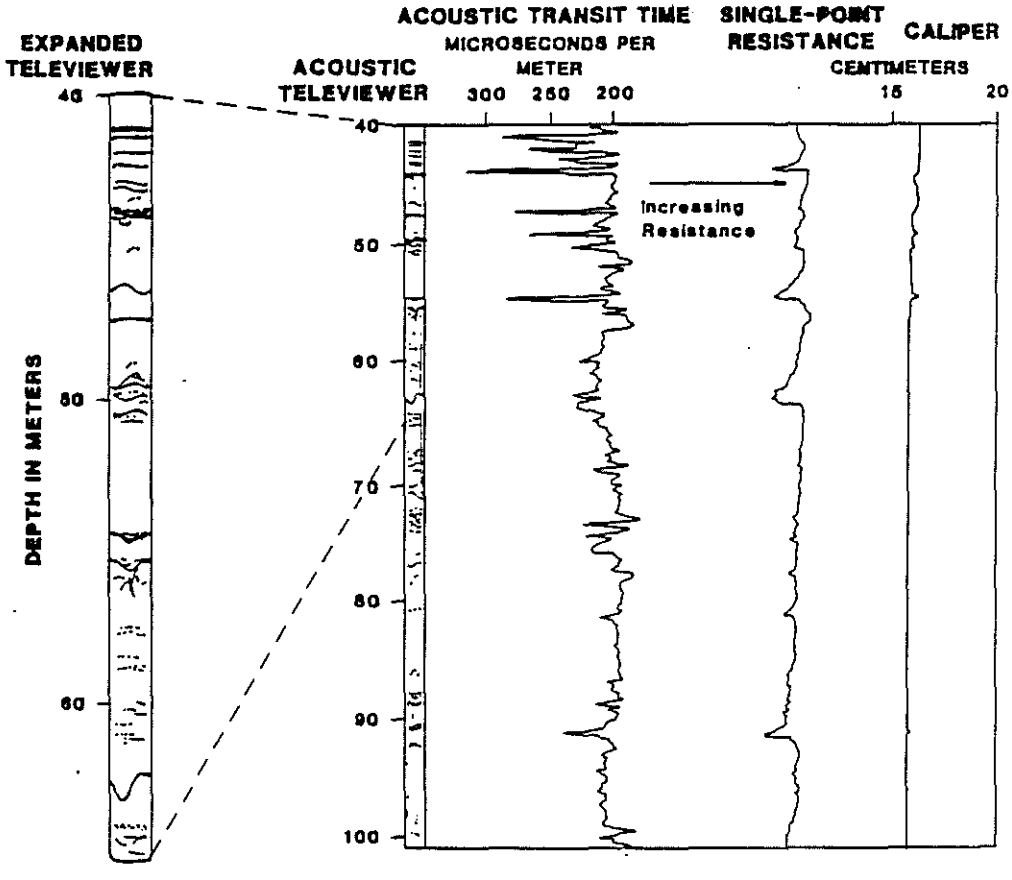


Figure 2: Acoustic-borehole-televiewer-log data and conventional geophysical well logs for the upper portion of borehole EBR4.

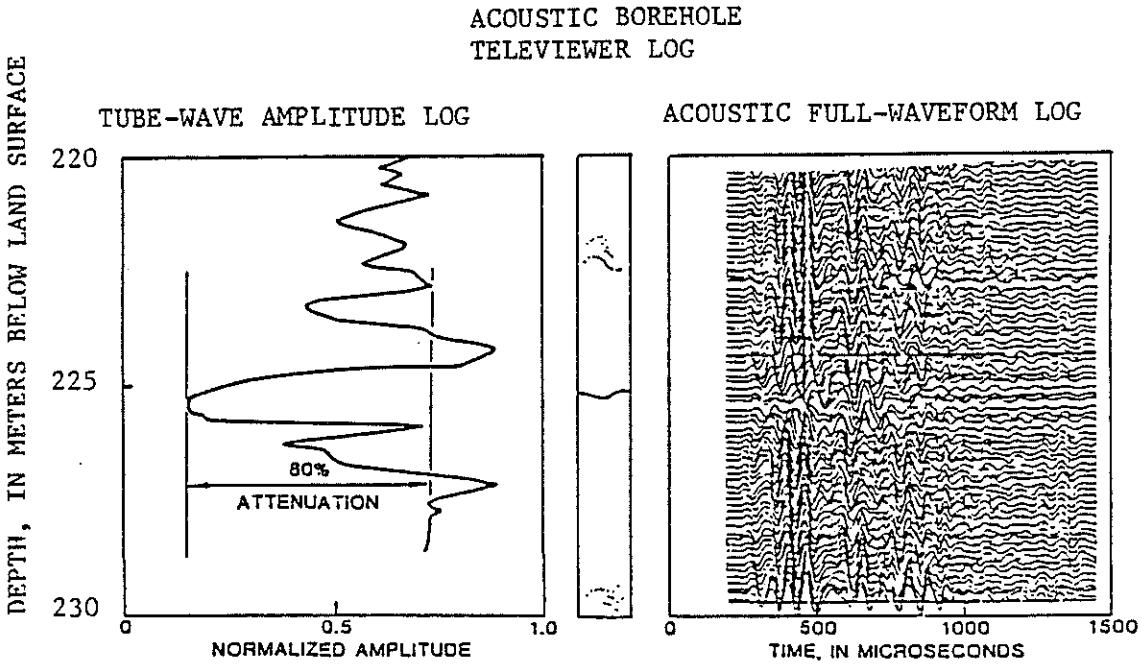


Figure 3: Tube-wave amplitude logs, ABTVL, and FWAL for the lower part of borehole EBR4, indicating calculation of tube-wave attenuation (modified from Paillet et al., 1987).

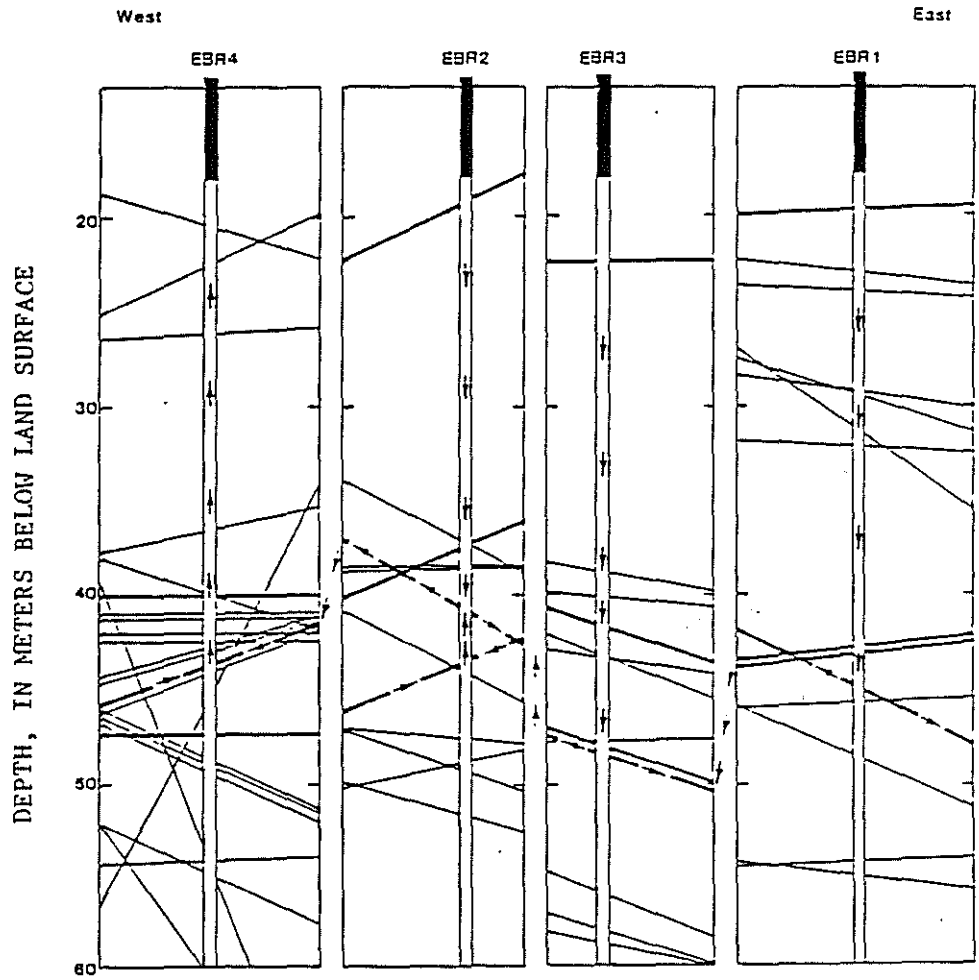


Figure 4: Cross-section through the EBR boreholes, indicating projection of fractures identified on ABTVL, and showing results of cross-hole pumping tests; note that vertical-scale projection decreases apparent dip of fracture planes (modified from Paillet et al., 1987).

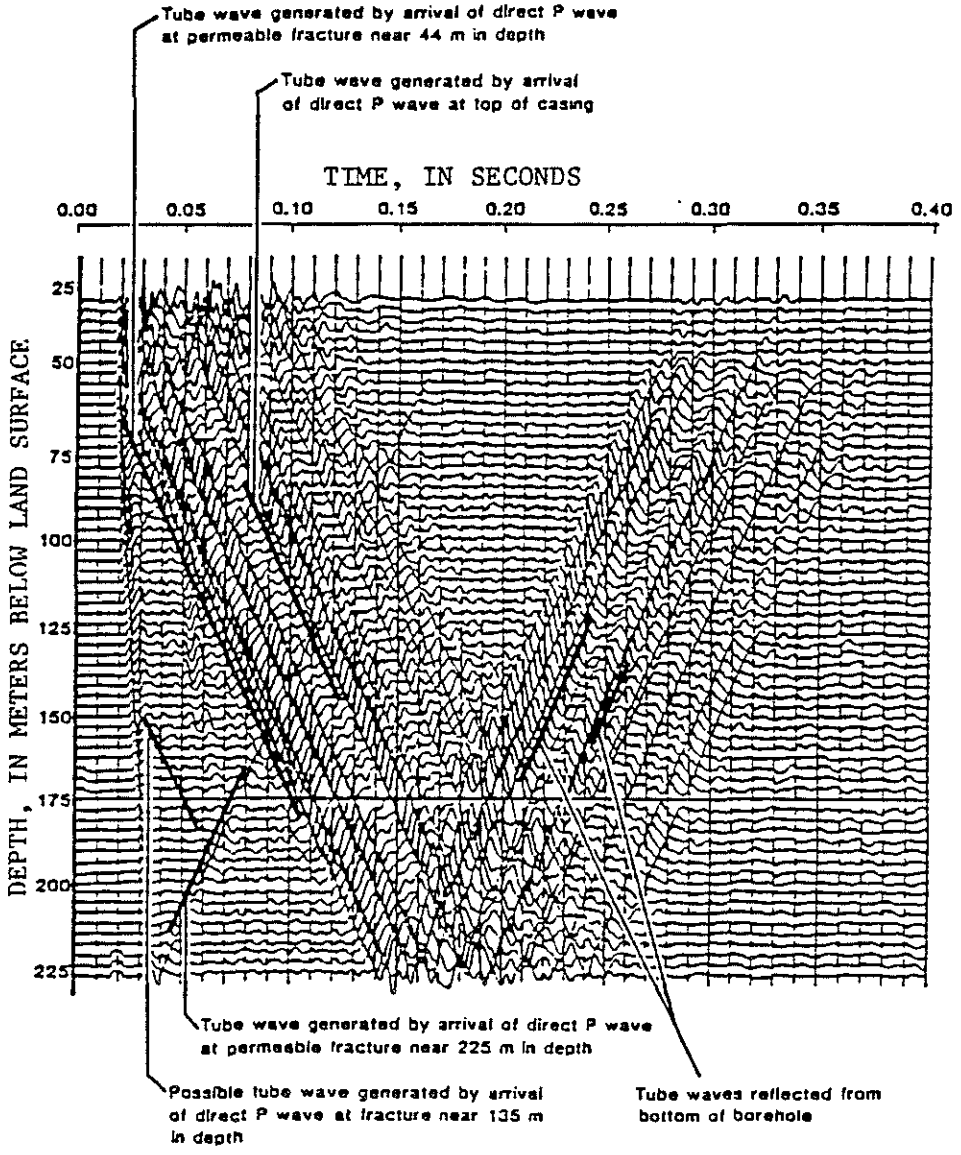


Figure 5: Vertical seismic profile section showing identification of tube waves generated when seismic waves from surface sources encounter the point where permeable fractures intersect the borehole (modified from Paillet et al., 1987).

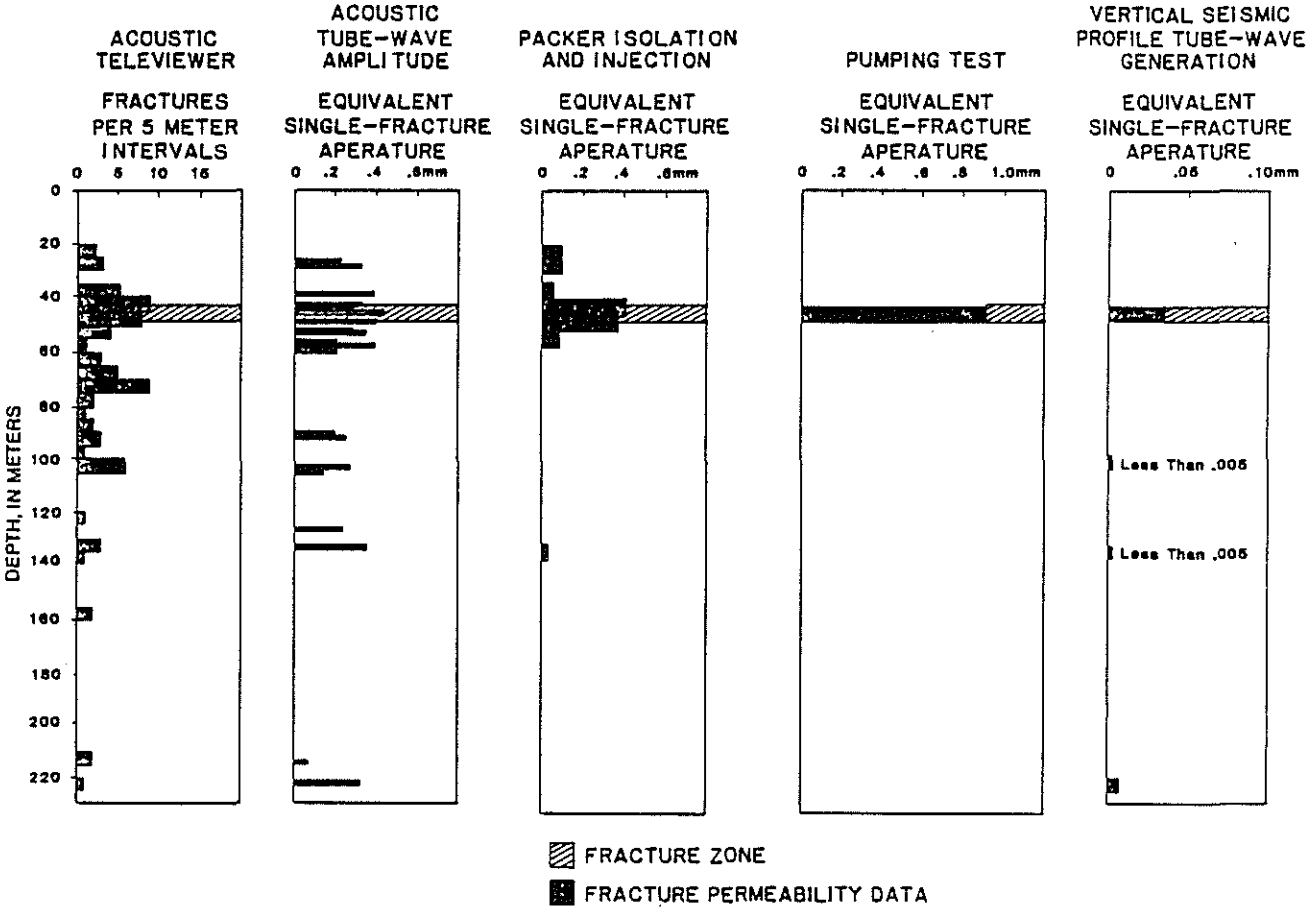


Figure 6: Comparison of fracture frequency determined from ABTVL with fracture permeability measurements determined from FWAL, PIFT, HPFM and VSP analysis.