Application of Borehole Geophysics in the Characterization of Flow in Fractured Rocks

by Frederick L. Paillet

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CONTENTS

FIGURES

TABLE

CONVERSION FACTORS

Multiply	By	To obtain
foot (ft)	0.3048	meter
gallon per minute (gal/min)	3.785	liter per minute (L/min)
gallon per minute (gal/min)	0.06308	liter per second
inch (in.)	25.4	millimeter (mm)
centimeter (cm)	0.3937	inch
meter (m)	39.37	inch

The following terms and abbreviations also are used in this report:

kilohertz (kHz)

megahertz (MHz)

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Abstract

Conventional geophysical well logs such as the gamma, neutron, and electric logs provide volume-averaged measurements that are often indicative of the presence of fractures, but the evidence of fractures usually is indirectly affected by drilling damage to the fracture mouth and by alteration minerals adjacent to the fracture and may not be a direct indication of fracture permeability. Borehole wall image logs obtained using optical, electrical, or acoustical methods provide a direct method for identifying fractures and interpreting their orientation, but drilling damage almost always affects the quality of the interpretation. Fracture interpretation can be significantly improved if fracture identification using image logs is combined with fracture interpretation using logs where the properties of fractures are measured over a larger sample volume. Conventional electric and nuclear logs can be used for this purpose. However, acoustic full-waveform logs provide the most effective characterization of fractures in volumes of rock surrounding the borehole. The Stoneley or tube-wave mode, one part of the composite acoustic waveform, is especially useful, and tube-wave amplitude attenuation can often be related to fracture permeability using various empirical and theoretical methods. A few specific mathematical models for the interpretation of fracture properties are given as examples of the techniques available in the literature. High-resolution flowmeter measurements during pumping provide another method for the identification of those fractures connected to large-scale flow systems. Examples of log interpretation show that conventional geophysical logs can be combined with borehole image logs, acoustic full-waveform logs, and high-resolution flowmeter logs to generate useful models for large-scale fracture flow systems at several different field sites.

INTRODUCTION

The determination of the hydraulic properties of fractured-rock aquifers present one of the most difficult problems in hydrogeology. This difficulty is associated with the heterogeneity of fracture distributions, which makes the distribution of permeability in fractured rocks extremely difficult to characterize using conventional drilling, sampling, and logging methods. Core sampling is not very effective in fractured rocks because recovery of samples is difficult in altered, brittle, or intensely fragmented rocks. There also are questions about the ability of small cores to effectively sample fractures, which may vary greatly in short distances along strike. At the same time, large-scale sampling using surface and borehole-to-borehole geophysical soundings almost always fails to provide the resolution needed to identify individual fractures. The best results obtainable with borehole-to-borehole radar reflection techniques can resolve individual fracture zones under optimum conditions of homogeneous, nonconductive crystalline rocks (Sandberg and others, 1991); in other situations, useful results are sometimes impossible to obtain.

Scale Considerations in Logging Fractured Rocks

Geophysical measurements in boreholes provide an effective compromise between depth of penetration and resolution and between large-scale sampling and individual fracture characterization. Logs provide access to the formation through the borehole as well as measurements of rock properties averaged over sample volumes from 0.3 to 1.0 m in diameter. This volume is more likely to provide a representative elementary volume of an aquifer than 3- to 10-cm-diameter cores but is small enough to resolve individual fractures and sets of fractures. For these reasons, well-logging techniques can make a significant contribution to fracture studies in hydrogeology. The analysis of geophysical logs in fractured-rock aquifers can be especially useful when the borehole measurements are compared to larger scale surface geophysical soundings, indicating how the individual sets of fractures intersecting boreholes are integrated into possible fracture flow systems extending across the study site.

Purpose and Scope

This report presents a detailed overview of the borehole geophysical methods available for the characterization of fractures in situ. The report reviews both qualitative and quantitative techniques for the interpretation of fractures intersected by boreholes. The review includes the fracture-interpretation applications of conventional geophysical logs and the interpretation of recently developed equipment designed specifically for fracture detection and characterization. Qualitative and quantitative interpretation techniques are reviewed on the basis of conventional and recently developed borehole geophysical techniques that are illustrated by describing their application at three different study sites where well logs have been used in intensive fracture-characterization studies and where geophysical well-log data have been integrated with surface geophysical and hydraulic test data. This report provides a thorough familiarization with techniques available for the interpretation of geophysical well logs in fracture characterization for hydrologists and geologists interested in the in-situ measurement of hydraulic conductivity in fractured-bedrock aquifers.

QUALITATIVE INTERPRETATION OF LOGS IN FRACTURED-ROCK AQUIFERS

Fracture Applications of Conventional Geophysical Logs

Under ideal conditions, geophysical measurements in boreholes are associated with three specific attributes that make them valuable in geological exploration: (1) Logs provide a continuous series of measurements made without missing or disturbed samples along a consistent depth scale; (2) logs provide measurements made in situ under natural stress conditions and where the sample volume is saturated with formation waters; and (3) logs provide multiple, independent measurements that can be used to separate such formation properties as lithology, mineralogy, porosity, and formation-water salinity. These three advantages of geophysical logging are associated with three important limitations: (1) Logs almost always measure physical properties only indirectly related to the hydraulic properties of sediments; (2) logs measure the properties of a sample volume that contains a fluid-filled borehole and that is subjected to drilling damage; and (3) sampling using logs is biased by the geometry of the borehole. The interpretation of geophysical logs in fracture characterization and most other applications in hydrogeology is largely the process of maximizing the use of the information provided by the positive attributes of geophysical measurements in boreholes, while minimizing the impact of the negative attributes.

The measurement of fracture properties in boreholes using conventional geophysical logs is shown in figure 1, and the classes of most common geophysical measurements and their most common fracture applications are listed in table 1. Geophysical logs can be divided into two classes: (1) Volumetric logs, which average physical properties over a definable sample volume; and (2) auxiliary logs, which do not. In some situations, this distinction is not exact. For example, the temperature log is a measurement of fluid temperature in the borehole but can often be related to the thermal conductivity of the rock adjacent to the borehole (Sass and others, 1988). Other logs, such as the caliper, provide useful information that is nearly impossible to interpret quantitatively because the measured value at any given depth cannot be related to the properties of a definable volume of rock.

The generalized measurement shown in figure 1 is averaged over a sample volume containing the borehole, surrounding unfractured rock, the fracture, and the borehole enlargement where the fracture intersects the borehole wall. The figure indicates that the fracture porosity represents a very small part of the sample volume. In the ideal situation where a single permeable fracture intersects the borehole in an otherwise homogeneous rock mass, that has no alteration adjacent to the fracture and no mechanical enlargement at the fracture mouth, the departure from constant background measurement (the anomaly) will be relatively small. Other, more volumetrically extensive properties of the fracture are more likely to generate a recognizable anomaly. Experience indicates that the effects of borehole enlargement and the distribution of alteration minerals in the rock adjacent to the fracture almost always are exhibited as fracture anomalies rather than as a direct indication of fracture porosity.

A few examples illustrate the difficulty of direct measurement of fracture porosity and permeability against a complicated background of borehole effects and alteration mineral distribution. Neutron porosity logs are sensitive to borehole wall rugosity even when borehole-compensated equipment is used so that this log is very sensitive to borehole wall enlargement at the fracture (Nelson and others, 1983). Clay alteration minerals in crystalline rocks are much more electrically

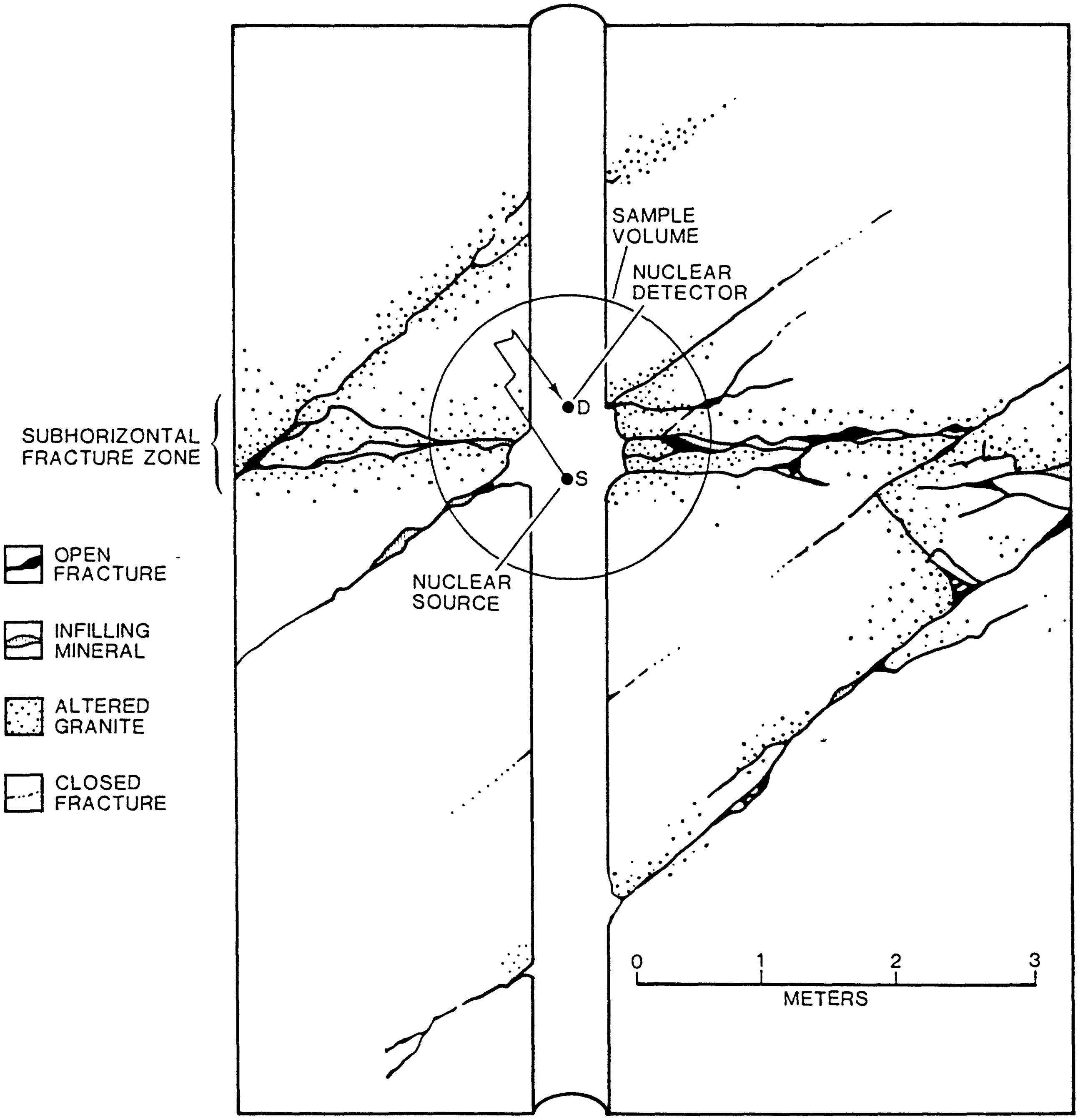

Figure 1. Schematic illustration of volume of investigation for typical geophysical measurements in a borehole.

Table 1. Summary of geophysical logs, their conventional application in sedimentary formations, and their application in fracture interpretation

Log type	Measurement	Conventional Interpretation	Fracture Interpretation	Reference
Natural gamma	Formation gamma emission	Clay mineral fraction	Radioisotopes as infilling	Keys, 1979; Aguilera, 1980
Neutron	Neutron flux attenuation	Porosity, clay fraction, water saturation	Alteration minerals and hole enlargements	Nelson and others, 1983; Paillet, 1991a
Resistivity	Formation electrical resistivity	Water salinity and lithology	Alteration minerals, hole enlargements, water quality, and permeability	Keys, 1979; Katsube and Hume, 1987
Gamma-gamma	Gamma flux attenuation	Density and porosity	Lithology and hole enlargements	Keys, 1979; Paillet, 1991a
Acoustic	Compressional wave travel time along borehole wall	Porosity and lithology	Alteration and fracture porosity	Paillet, 1991a; Keys, 1979
Acoustic waveform	Acoustic pressure signal	Shear velocity	Tube-wave attenuation, fracture transmissivity	Paillet, 1991a, 1983; Hornby and others, 1989; Tang and others, 1991
Temperature	Borehole fluid temperature	Thermal conductivity of formation	Inflow and outflow to borehole	Keys, 1979; Paillet, 1991a; Keys and Sullivan, 1979
Spontaneous potential	Natural shale "membrane" effect	Water salinity and clay mineral fraction	Streaming potential	Keys, 1979
Fluid conductivity	Electrical conductivity of borehole fluid	Salinity of borehole fluid	Inflow and outflow to borehole	Keys, 1979; Hess and Paillet, 1990; Paillet, 1991a
Caliper	Borehole diameter	Drilling damage and fractures	Hole enlargement	Keys, 1979; Paillet, 1991a
Flowmeter	Vertical flow in borehole	Permeability	Inflow and outflow to borehole	Hess, 1986; Hess and Paillet, 1990

conductive than the unaltered mineral so that electric logs often are more sensitive to alteration minerals than to fracture openings (Keys, 1979). In theory it is possible to use multiple logs to separate the effects of borehole enlargement and alteration minerals from those of fracture permeability, but most attempts to do so have not been very successful (Katsube and Hume, 1987; Paillet, 1991a).

Some of the earliest attempts to predict the fracture response of geophysical logs appeared to indicate that established models for predicting these responses were inadequate. Subsequent analysis demonstrates that the physical principles are correct but that fracture models were almost always oversimplified (Paillet, 1985, 1991b; Tang and others, 1991). For example, the fracture model most often used in predicting the acoustic-log response to fractures is a single, uniform-aperture opening separating two semi-infinite slabs of homogeneous rock (fig. 2*A*). The measured responses of logs to naturally occurring fractures differs substantially from those predicted by the theory. In particular, the theory indicates that very large fracture apertures are required to produce measurable effects at typical acoustic-logging frequencies of 10 kHz, and almost all of the response would involve reflected wave energy rather than attenuation and scattering. The model results are verified in laboratory experiments using scale models that are simple saw cuts in aluminum and plastic blocks of fractured rocks. The differences between results obtained for theoretical and laboratory models and measurements made in naturally fractured formations almost certainly results from the differences between artificial saw cuts and natural fractures (fig. 2*B*). Natural fractures consist of two irregularly broken fracture faces that make contact on asperities, leaving open pore spaces between the contact points. The fracture properties are further complicated by alteration of rock adjacent to the fracture faces and by the presence of infilling mineral deposits. Such a fracture is capable of transmitting shear stresses and otherwise exhibits physical properties very different from those of a slotlike, fluid-filled opening.

A typical example of conventional geophysical logs for a borehole drilled in fractured granitic schist can be compared to the distribution of fractures identified on the core in figure 3 (Paillet, 1991c). The logs indicate a number of fracture anomalies that can be related to specific fractures identified in the core, although one major fracture appears to exist in an interval where core was lost. Many of the fractures correspond with anomalies on the caliper log in figure 3 (denoted by A in fig. 3). However, caliper arms usually are about 0.5 to 1.0 cm in diameter and are too large to fit into the natural fracture openings. The anomalies on the caliper log apparently correspond to enlargement of the borehole where the fracture intersects the borehole wall. Therefore, the caliper anomalies are indirect indications of fractures. The neutron, gamma, and single-point resistance logs also show anomalies at some of the fractures (C, D, and E in fig. 3), and these anomalies can be taken as indicators of effects associated with borehole enlargement (as shown by the caliper log) and with the presence of alteration and infilling minerals. Together these logs can be taken as a qualitative indicator of the extent of alteration, especially if the data are corrected for borehole effects using information from the caliper log. The single-point resistance log is designed to give fine-scale, vertical resolution of electrical properties but is sensitive to small changes in borehole diameter and to the resistivity of the borehole fluid. For these reasons, the single-point log combines the functions of resistivity and fluid conductivity measurements shown in table 1.

The electrical-log anomalies associated with fractures shown in figure 3 indicate that the single-point device is very useful in characterizing fractures (Paillet, 1991a). In contrast, the long and short normal logs commonly used in hydrogeology produce anomalous results for thin beds such as in fractures for which bed thickness becomes smaller than electrode spacing (16 inches or about 40 cm for the short normal) (Keys, 1979, 1990). The sensitivity of the single-point resistance log to borehole-fluid conductivity also makes that device an effective indicator of contrasts in water quality in the well bore. The sharp deflection of the single-point log towards low resistance at about 41 m in depth denoted by F in figure 3 indicates just such a contrast. This information might be used to infer that relatively fresh water is flowing down the borehole and exiting at the fracture set identified on core at a depth of 41 m. Subsequent flow measurements confirmed that downflow was present but that water was entering at several fractures above 90 ft in depth and exiting at other fractures in addition to those near the abrupt change in borehole-fluid conductivity.

The suite of geophysical logs in figure 3 provides a typical example of how conventional geophysical logs can be used to characterize fractures in crystalline rocks. The analysis is most effective when various geophysical measurements are made because the ambiguity in the interpretation is reduced. However, the interpretation also shows that the logs are mostly indicating effects that are indirectly related to fractures rather than giving a direct sample of the hydraulic properties of fractures. At the same time, comparison of core fracture data with the logs demonstrates the effectiveness of this combination of data in the analysis. Core samples are used to identify the location of

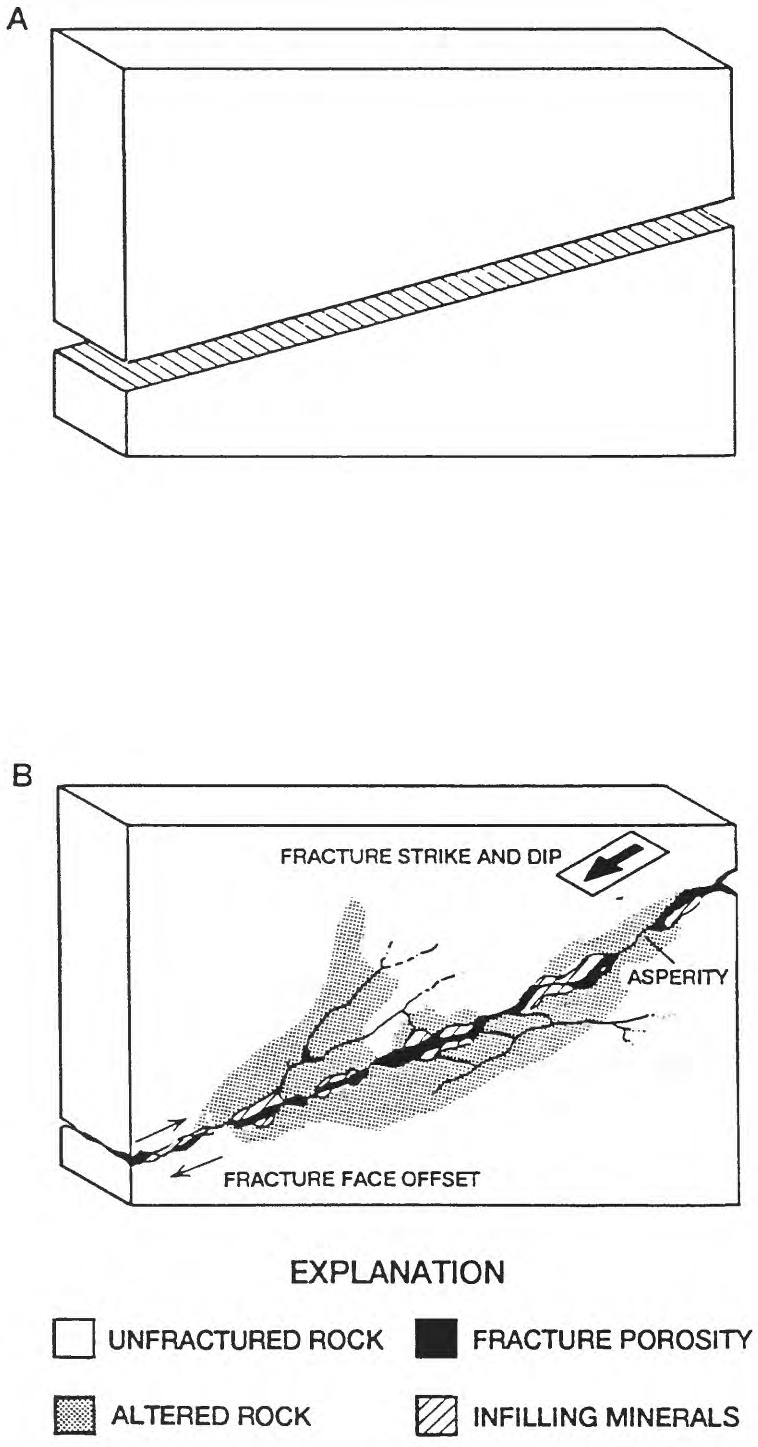

Figure 2. *A*, Idealized model of fracture as a planar, uniform-aperture opening between two parallel rock faces; and *B*, natural fracture model illustrating variable fracture aperture and contacts on asperities.

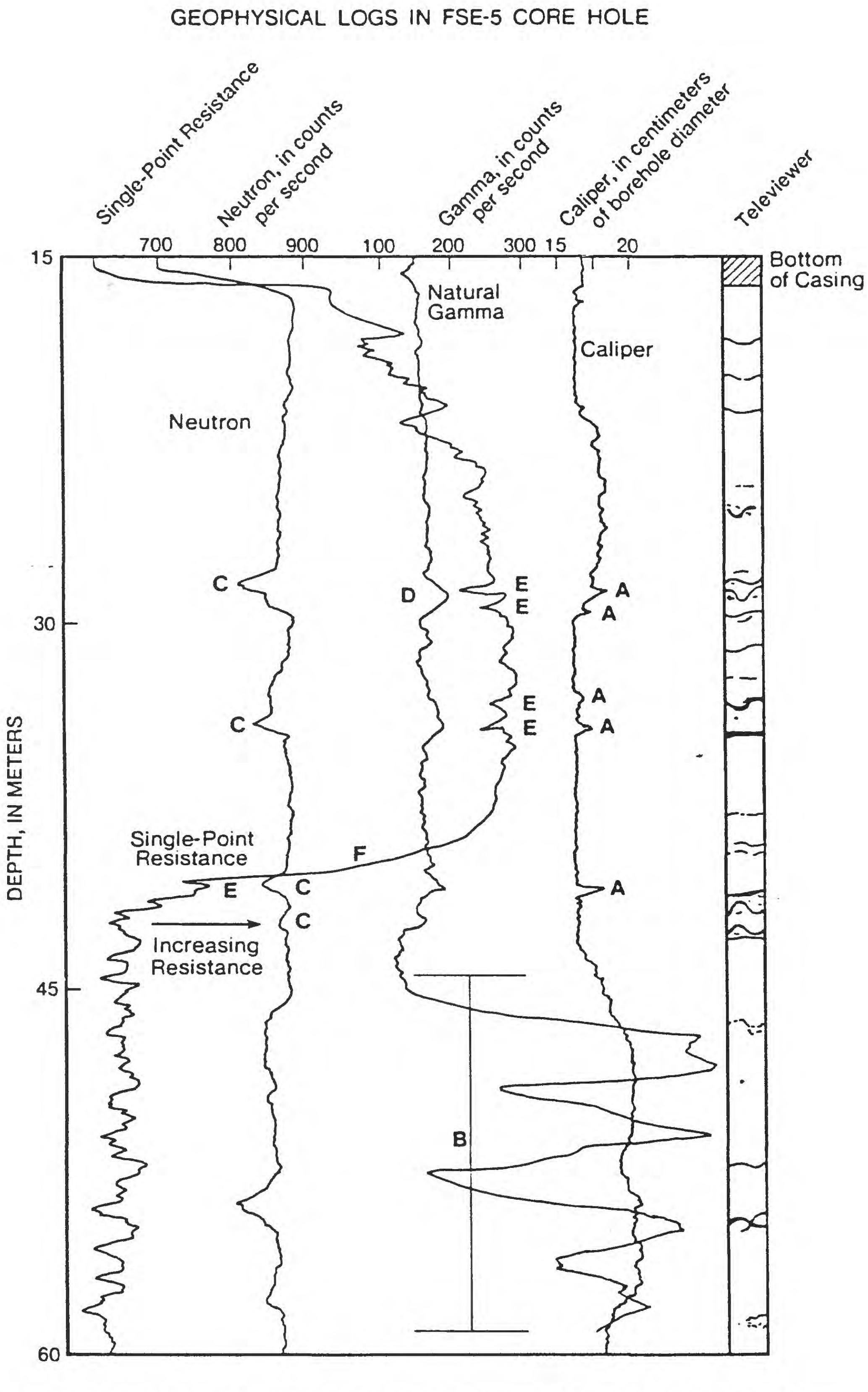

Figure 3. Example of conventional geophysical logs for a borehole in foliated granitic schist.

fractures, whereas logs are used to give a more representative sample of fracture properties over a volume extending away from the borehole. Geophysical logs also prove useful in identifying fractures in those intervals where core is not recovered.

Borehole Wall Imaging

Borehole wall imaging provides a direct way to circumvent the volumetric averaging of fracture properties shown in figure 1. Borehole wall image logs provide photographs or photographlike images of the borehole wall, allowing direct inspection of fractures where they intersect the borehole (Paillet and others, 1990). Images are produced using downhole optical cameras in either fluid-filled or air-filled boreholes and using acoustic and electrical imaging techniques in fluid-filled boreholes. Although direct optical imaging of fractures in boreholes would seem to be the simplest way to image fractures in situ, acoustic and electrical devices have been used much more extensively in borehole imaging than downhole video cameras (Keys, 1979; Paillet and others, 1990). Important limitations on the use of optical measurements include the need for a separate light source and clear borehole fluid and the inability to operate video cameras on conventional wireline logging systems. Most experience in borehole wall imaging in geophysics has been obtained using the borehole acoustic televiewer, an ultrasonic imaging system operating at a frequency of about 1 MHz (Zemanek and others, 1970). More recently, electric imaging systems have been developed using multiple electrodes on pads pressed against the borehole wall and operated on standard 7-conductor wireline (Ekstrom and others, 1987). In many applications, one or more of these imaging methods is used to identify fractures intersecting the borehole, and then other volumetric averaging logs are used to infer the properties of the volume of rock containing those fractures.

The acoustic televiewer operates by scanning the borehole wall with an acoustic beam generated by a rapidly pulsed piezoelectric source rotating at about 3 revolutions per second as the tool is moved along the borehole (Zemanek and others, 1970). The tool needs to be centralized in the borehole to function properly. The source crystal serves as the receiver for the reflected signal, which is transmitted uphole and recorded photographically. A smooth and hard borehole wall produces a uniform pattern of reflectivity. The intersection of a fracture with the borehole wall appears as a dark, linear feature (fig. 4*A*). The shape of this feature can be used to infer the strike and dip of the fracture. This dark feature (fig. 4*A*) appears because the fracture scatters incident acoustic waves, greatly decreasing the local intensity of the reflection and increasing the time delay between signal generation and arrival of the reflection. Borehole wall images usually are made by plotting the spatial pattern of the reflected signal but can be made by plotting the distribution of two-way travel time. The relative width of the fracture image can be related to the aperture of the fracture but only in a qualitative way. This restriction results from the convolution of the true fracture width having a nearly 1-cm-wide source beam and from the effect of drilling damage on the fracture at the borehole wall (Keys, 1979; Paillet and others, 1985). In spite of these difficulties, the televiewer log has served as the most frequently used fracture identification device in hydrogeology and has only recently come to share this application with electrical and optical imaging methods.

The effectiveness of televiewer logs in the interpretation of fractures can be illustrated by comparing examples of televiewer logs with fractures recovered in core samples. In the first example (fig. 4*B*), the televiewer log shows a single near-vertical fracture intersected by a pair of faint, subhorizontal fractures. The corresponding interval of core shows two large fractures separating intact sections of core and a much tighter fracture parallel to the core axis. The comparison of televiewer log with core indicates that the apparently open horizontal fractures were probably closed in situ but that the core sections separated along these planes of weakness during drilling and recovery. In contrast, the open vertical fracture is present in the core but has not been further opened by the drilling. The second example (fig. 4*C*) compares an interval of televiewer log with the description of fractures given by inspection of the corresponding interval of gravitationally orientated core. The core fracture description has been plotted in televiewer format using the independently measured orientations of the fractures given by the core log. The comparison indicates that the fractures listed as open on the core are clearly represented on the televiewer log. Many of the other closed fractures identified on core show up as discontinuous features on the televiewer log. The consistency between the orientations of the fractures on the core and televiewer logs also is apparent. The most significant difference between the core interpretation and the televiewer log is the association of apparently open fractures on the televiewer log with sets of parallel, closed fractures on the core log. This association results from the spalling of small pieces of borehole wall between the closed fractures, causing these closed fractures to appear as a single open fracture on the televiewer log (fig. 4*C*). These examples indicate the ques-

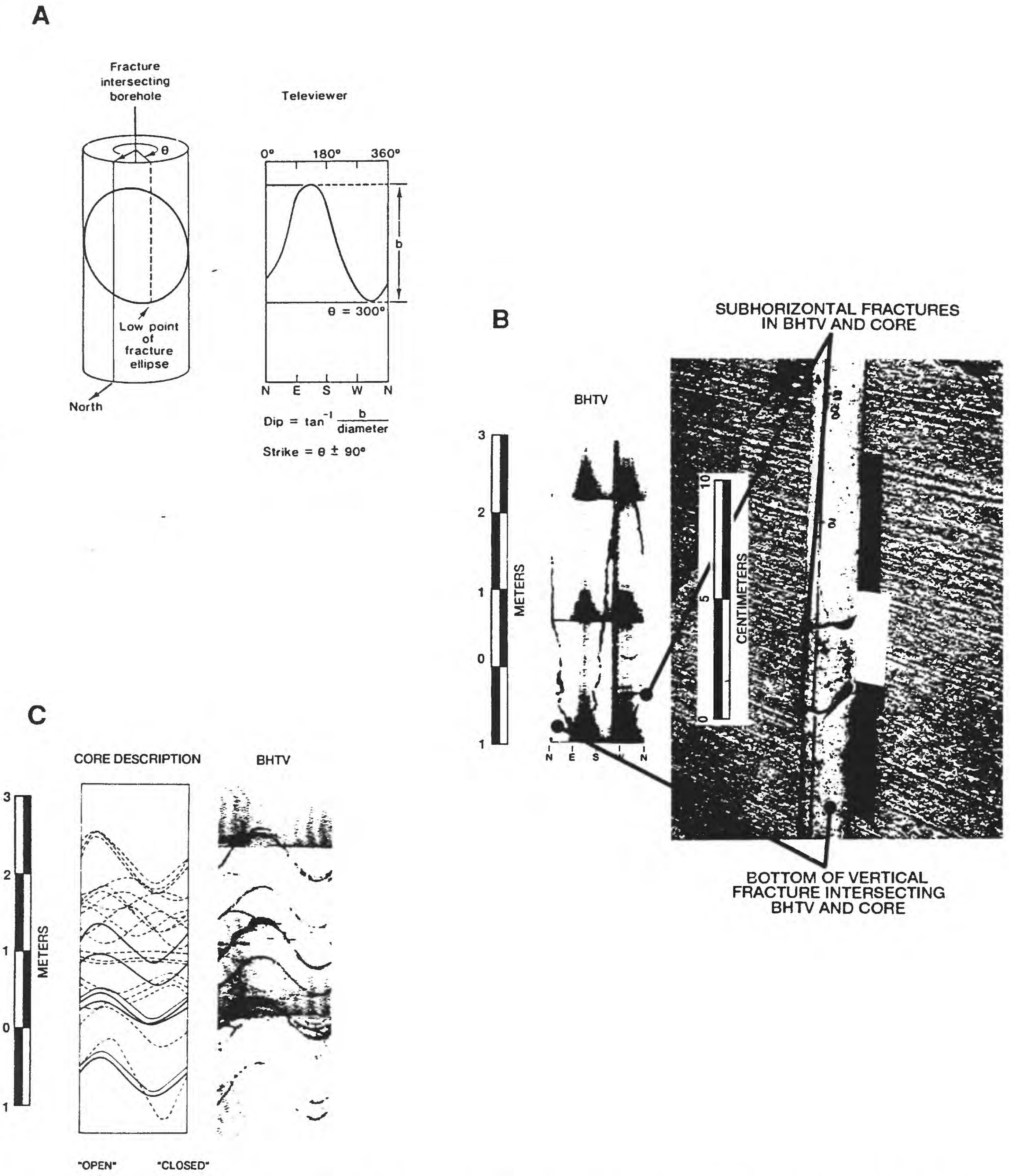

Figure 4. Examples of fracture imaging using the acoustic televiewer (BHTV): *A*, Schematic illustration of fracture strike and dip interpretation; *B*, comparison of core photograph with televiewer log for fractures in granite; and *C*, comparison of core fracture interpretation with televiewer log for a fracture zone in granite.

tions that can arise in the interpretation of televiewer logs in typical fracture studies.

Although direct imaging of fractures is the primary application of borehole wall imaging devices, borehole images also can be used to interpret the relation between fracture properties and the in-situ state of stress. Image logs can be used to investigate in-situ stress because the cylindrical geometry of the borehole concentrates stresses adjacent to the borehole, while the contrast between lithostatic stress in the borehole wall and hydrostatic pressure in the borehole can lead to shear failure in the borehole wall. This combination of differential loading at the borehole wall and geometric stress concentration results in the formation of breakouts orientated along the azimuth of least principal horizontal stress (Zoback and others, 1985). Therefore, these features are orientated 90 degrees from the azimuth where conventional hydraulic fracture techniques would induce fractures. The greater the anisotropy in the horizontal stress field, the smaller the total lithostatic loading required to generate breakouts. Oriented caliper logs can be used to identify the elliptical borehole cross section associated with breakouts (Gough and Bell, 1981; Plumb and Hickman, 1985), but there is considerable ambiguity in making such interpretations. Borehole wall images are much more effective in this situation and almost always allow positive identification of stress-induced breakouts if they are present (Paillet and others, 1990).

In-situ stress studies are beyond the scope of this review except where the relation between in-situ stress, fractures, and fracture transmissivity is concerned. The borehole wall breakout interpretation is not as effective in defining stress conditions as are other techniques such as hydraulic fracture and overcoring (Zoback and others, 1985). However, image logs provide detailed vertical profiles of the stress distribution in fractured rocks whenever breakouts are present. Typical examples of the appearance of stress-induced breakouts on televiewer logs obtained in massive and vesicular basalt are shown in figure 5. The breakouts appear as continuous or discontinuous strips of scattered acoustic energy in the otherwise reflective borehole wall. All three of the sample images in figure 5 indicate that a single fracture has relieved the in-situ stress so that the breakouts disappear either above or below the intersection of the fracture with the borehole. In each of these examples, the breakouts occur on the side of the fracture towards the center of the basalt flow where fracture density is low and the rock is capable of supporting large stresses. These examples indicate how image logs can be used to relate the state of stress to fractures in those situations where borehole wall breakouts are present.

Acoustic Waveform Measurement of Fracture Permeability

Perhaps the greatest difficulty in the application of borehole image logs in fracture studies is the limitation of these methods to fracture characterization in the immediate vicinity of the borehole wall. One approach to the improvement of image-log analysis is the use of televiewer, television (videos), or formation microscanner images (Ekstrom and others, 1987) in conjunction with acoustic waveform logs providing somewhat greater penetration into the borehole wall. These logs can be obtained by digitizing the entire pressure signal recorded by the receivers in an otherwise conventional acoustic-logging probe (Paillet, 1980, 1983; Paillet and Cheng, 1991). This approach is equivalent to performing an in-situ seismic refraction experiment on a small volume of rock containing the fracture (fig. 6). If the acoustic waveform logs are interpreted without the use of borehole wall images, the many variations in the data introduce a great deal of ambiguity into the interpretation so that effective fracture analysis is difficult or impossible. The combination of fracture identification with image logs and fracture characterization with acoustic waveforms provides information that could not be obtained using each of these logs independently.

Examples of acoustic waveform logs obtained for isolated fractures or fracture sets intersecting a borehole illustrate the effect of fracture permeability on seismic properties (fig. 7). Although borehole seismologists refer to both compressional and shear (P-wave and S-wave) arrivals in the data, the waveform actually represents the acoustic waves in the borehole fluid excited by the passage of critically refracted P-waves and S-waves traveling along the borehole wall. When fractures are transverse to the borehole, all wave energy is forced to travel across the fracture, and all parts of the waveform are attenuated by the fractures (fig. 7*A*). When the fracture is nearly parallel to the borehole, the fracture plane intersects the borehole over an extended interval so that there is always part of the borehole azimuth where seismic waves can travel from source to receiver without crossing the fracture. In this situation, the measured amplitudes of P-wave and S-wave energy are very irregular. There are even local increases in S-wave energy over background attributed to enhanced mode conversion; for example, when the acoustic receiver is located adjacent to the fracture mouth, shear energy is converted to acoustic energy in the borehole fluid. In general, there appears to be no direct relation between fracture permeability and amplitude or phase of the measured P-wave and S-wave arrivals in such data.

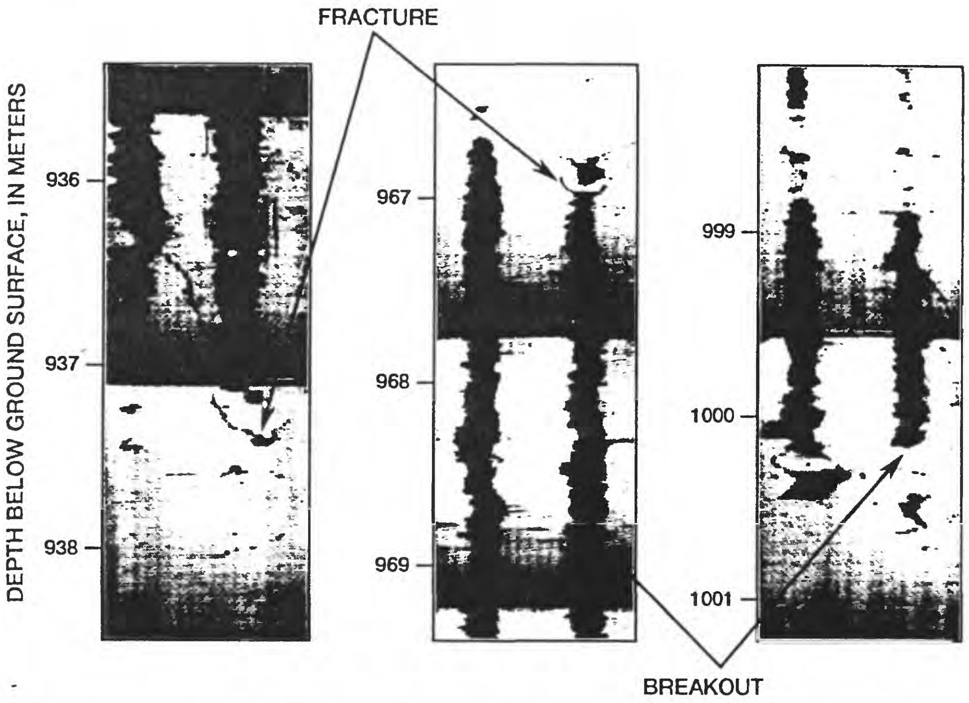

Figure 5. Examples of borehole wall breakouts induced by nonisotropic in-situ stress, illustrating termination of breakouts at natural fractures.

Much of the early literature on acoustic logging treated the measured waveforms as equivalent to compressional and shear body waves traveling along the borehole wall. A more thorough mathematical analysis of the wave-propagation problem demonstrates that the measured waveforms are a complex combination of seismic motion in the formation and acoustic motion in the borehole fluid (Paillet and White, 1982; Paillet and Cheng, 1986). In addition to the P-wave and S-wave arrivals in the waveforms, there is a series of trapped or guided wave modes traveling along the borehole waveguide. One of these, the Stoneley or tube wave, is relatively insensitive to all formation properties except permeability (Rosenbaum, 1974; Paillet and White, 1982). The relative insensitivity of the tube wave to fracture geometry is illustrated in figure 7, where the shape of the tube-wave-amplitude anomaly appears unaffected by the orientation of the fracture (Paillet, 1983, 1991a). The relation between tube-wave attenuation and fracture permeability has been the subject of numerous studies in the recent literature. Theoretical studies (Rosenbaum, 1974) indicate that borehole-wall permeability can be related to tube-wave attenuation, but that mudcake sealing of the formation would almost negate the effect in porous sandstones. Mudcake effects are not likely to be important in fractured crystalline rocks. Even in porous formations, recent studies indicate that excitation of nonaxisymmetric waves will result in nonaxisymmetric fluid motion in fractures and pores (Schmitt and others, 1988a, 1988b). In that situation, mudcake has only a small effect on tube-wave attenuation. These results support the otherwise strictly empirical relation between fracture transmissivity and tube-wave attenuation given by Paillet (1983, 1991a) and Burns and others (1988).

Attempts to generate a direct theoretical relation between tube-wave attenuation and fracture permeability have not been completely successful. Waveform data obtained in fractured intervals (fig. 7) indicate significant attenuation with almost no reflection for fractures having hydraulic apertures of less than 1 mm (Paillet, 1991a). In contrast, plane fracture models indicate that fracture apertures as large as 1 cm are needed to give significant tube-wave attenuation, whereas the computed attenuation is attributed to reflection rather than attenuation (Bhasavanija, 1983; Stephen and others, 1985). The difference between plane fracture theory and experiment is attributed to the nature of natural fractures because laboratory experiments using planar openings in aluminum blocks give measured tube-wave attenuation similar to that predicted by theory (Tang and Cheng, 1989). Further experiments demonstrate that the lack of measured tube-wave reflection is a function of frequency; reflections are measured and can be related to fracture permeability for frequencies less than 5 kHz (Hornby and others, 1989; Hornby and others, 1992). The observed frequency dependence of tube-wave reflection and attenuation is best explained by modeling the fracture as a thin porous layer rather than a planar opening of constant aperture. A representative example for the transition frequency of about 5 kHz demonstrates the agreement between theory and experiment that can be obtained with such a model (fig. 8; Tang and others, 1991).

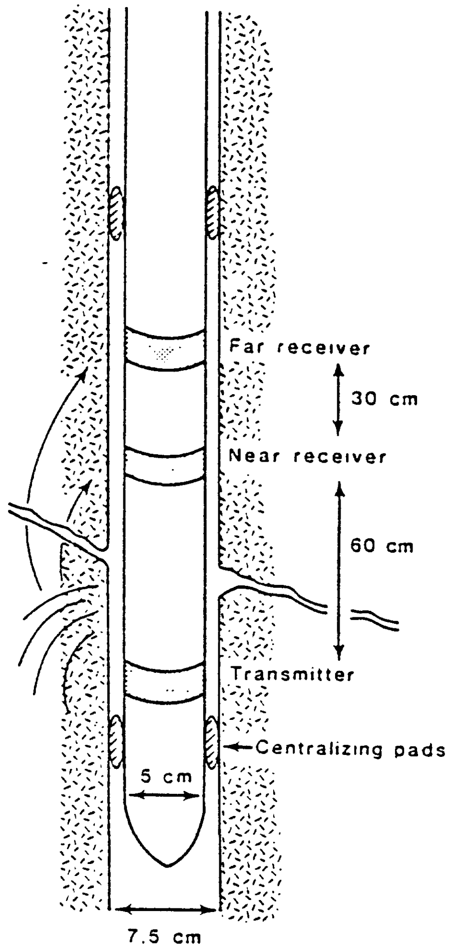

Figure 6. Schematic illustration of fracture characterization using the digitization of pressure signals received by a conventional acoustic logging system operating at about 20 kilohertz.

HIGH-RESOLUTION FLOW MEASUREMENTS IN BOREHOLES

Almost all geophysical measurements in fractured rocks involve measurement of physical properties that are indirectly related to fracture distributions and fracture permeability. However, borehole flow logs can provide information directly related to fracture permeability if discontinuities in the vertical distribution of flow can be related to inflow at specific fractures. Conventional spinner flowmeters have been used effectively in such studies (Keys, 1979; Keys and Sullivan, 1979), but relatively large borehole discharges are needed for effective operation of downhole spinners (Keys, 1990). Several methods for providing high-resolution flow measurements have been discussed in the literature. Most of these proposed methods are in the early stages of development, and limited information on their operation is available. The U.S. Geological Survey heat-pulse flowmeter can be used as a typical example of the results obtained using such vertical flow measurements in fractured rocks.

The heat-pulse flowmeter measures borehole discharge by indicating the time required for a small temperature pulse to be converted about 2 cm up or down through a cylindrical section of the logging tool. Flowmeter resolution is increased by forcing all flow through the measurement section of the tool using a downhole-inflatable packer to fill the annulus between the logging tool and the borehole wall. The flowmeter is calibrated using the measured response of the thermistor system in the laboratory under carefully controlled flow conditions (Hess, 1982, 1986). The current version of the U.S. Geological Survey heat-pulse flowmeter can measure borehole discharge as small as 0.04 L/min in boreholes ranging from 7.5 to 30 cm in diameter (Hess and Paillet, 1990).

The primary application of the heat-pulse flowmeter in fracture studies is in conjunction with borehole image logs to identify the individual fractures contributing to the total borehole discharge under ambient and pumped conditions. For example, the vertical flow in a deep borehole in the Canadian Shield was used to identify two large-scale fracture flow systems separated by a volume of sparsely fractured gabbro (fig. 9; Paillet and Hess, 1986). The measurements were made after a period of intense rainfall when surface fractures were recharged, and the borehole provided a hydraulic connection between the shallow and deep fracture systems. Such flowmeter measurements

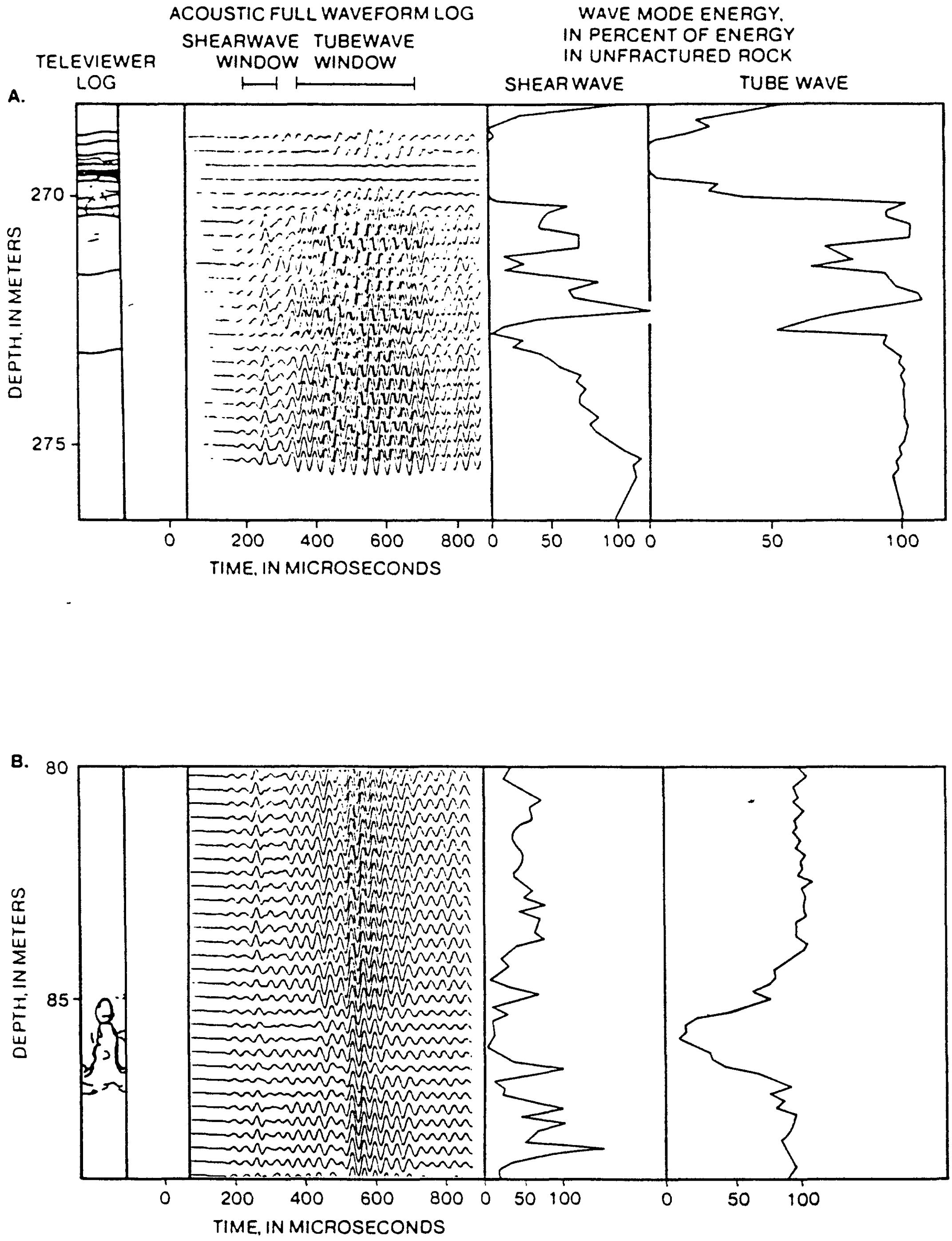

Figure 7. Examples of acoustic waveform data obtained for two different fracture zones in granite: *A*, Horizontal fractures transverse to a vertical borehole; and *B*, near-vertical fracture intersecting a vertical borehole (Paillet, 1991).

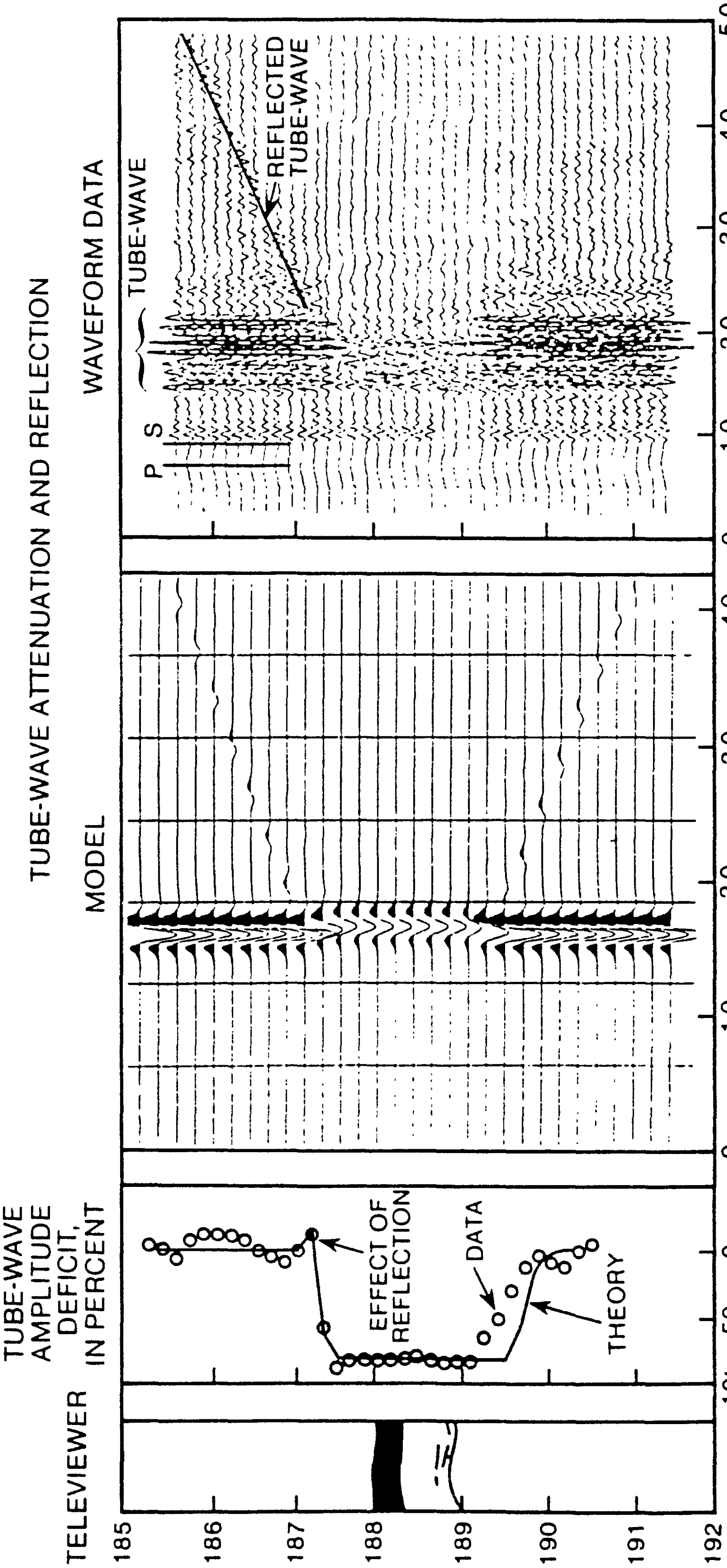

Figure 8. Relation of acoustic waveform attenuation predicted by a dynamic fracture model compared to waveforms obtained for propagation across a permeable fracture in granite; centerband frequency is about 5 kilohertz (Tang and others, 1991).

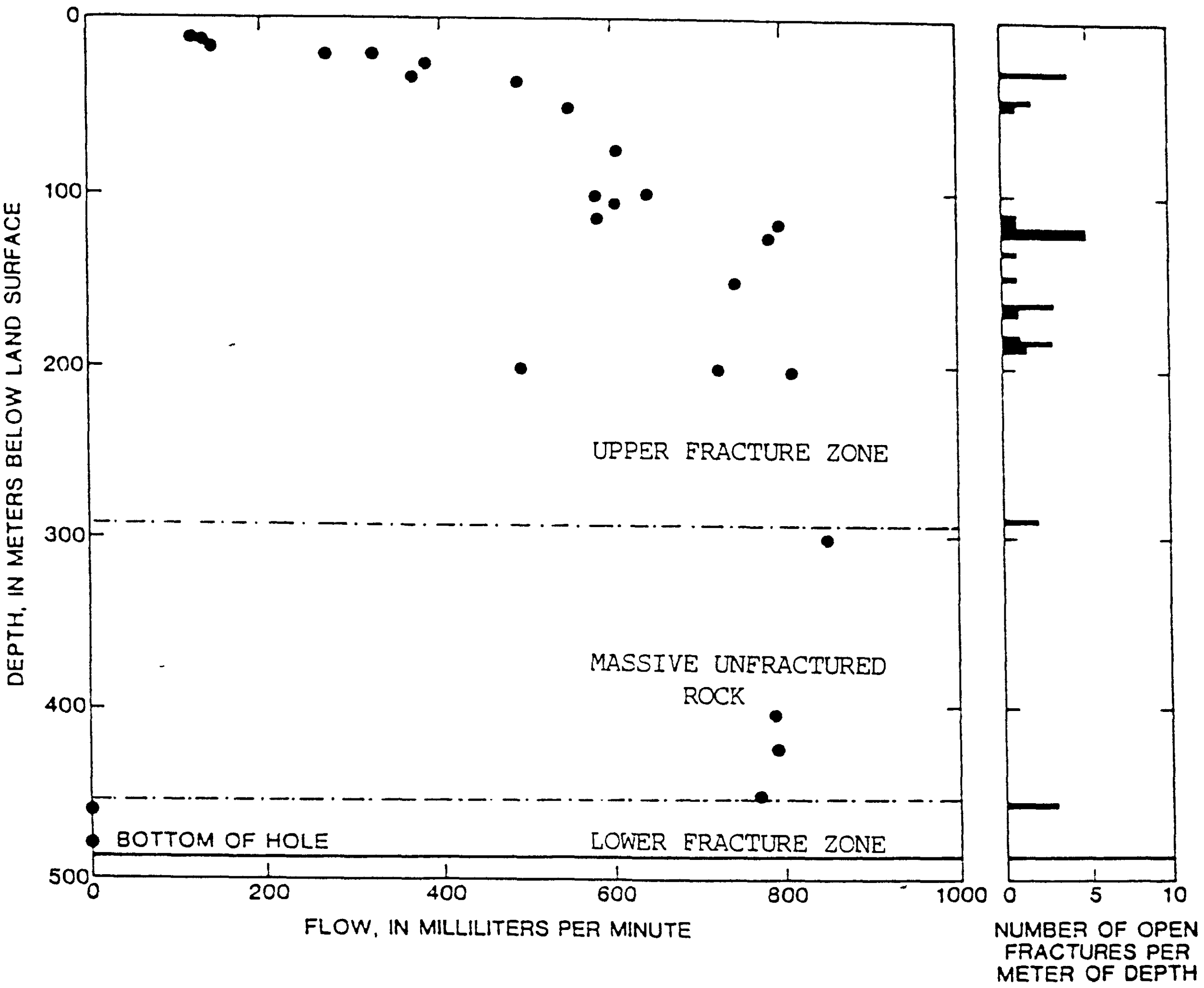

Figure 9. Relation of fracture frequency determined from core inspection to vertical flow measurements under ambient hydraulic-head conditions (Paillet and Hess, 1986).

do not require a great deal of geophysical sophistication to interpret and provide direct information about the larger scale connectivity of the fracture flow system.

One other recently developed technique, fluid-replacement logging (also denoted as hydrophysical logging), provides a practical method for the measurement of flow in boreholes (Tsang and others, 1990). In this technique, the borehole is filled with deionized water, and repeat fluid-conductivity logs are used to measure the rate of inflow of naturally occurring solutes from permeable fractures intersecting the borehole. Analysis of the changes in fluid-conductivity logs over time can be used to infer the permeability of fractures, the salinity of naturally occurring waters, and the rate of upflow or downflow in the borehole.

QUANTITATIVE INTERPRETATION OF LOGS IN FRACTURED-ROCK AQUIFERS

There are many interpretative models of fractures used in various applications of borehole geophysics in fractured rocks. Each model treats a specific application for a particular class of electrical, acoustic, or hydraulic measurement; many of these models have been discussed in a qualitative way in preceding parts of this review. Although most of these models are too specialized and the mathematics too complex to treat here, some examples can be cited to indicate the techniques available in the literature. This section discusses some of the most recent and most frequently used mathematical models applied in the interpretation of fracture properties.

Many applications in fracture hydrology are concerned with fractures as conduits for the movement of fluids or the migration of contaminants carried by fluids. The ability of a geologic formation to transport fluids is described by permeability, defined by Darcy's Law:

$$q = k \frac{P'}{\rho g} \tag{1}$$

where

- q is the volume-averaged flow per unit cross section,
- P' is the local pressure gradient,
- g is the acceleration of gravity,
- ρ is the density of the fluid in the fraction, and
- k is the permeability.

In this expression, k has units of velocity. Although equation 1 is given as a scalar equation, permeability is properly represented as a tensor relating the Darcian velocity vector to the pressure gradient. In equation 1 we assume q represents the component of flow along a fracture, and P' is the component of the pressure gradient in that direction. If a fracture is modeled as a planar channel of width a between two slabs of rock, the plane Poiseuille flow solution gives:

$$k = \frac{a^2}{12\mu} \tag{2}$$

where μ is the fluid viscosity. In general, it is difficult to restrict a downhole experiment to the fracture alone so that permeability of the adjacent rock becomes averaged with that of the fracture. If the adjacent rock is assumed to have negligible permeability, then fracture permeability is given by:

$$k = \frac{a^2}{12\mu} \frac{a}{b} \tag{3}$$

where b is the width of the interval over which permeability is averaged. In many situations, the hydrologist is concerned with the total amount of water transmitted by a horizontal layer. The transmissivity, T, is defined as the product of permeability and aquifer thickness, giving the cubic law for fracture transmissivity (Snow, 1965):

$$T = kb = \frac{a^3}{12\mu} \tag{4}$$

where b is the total thickness of the permeable fracture zone. Many applications compare fracture permeability estimates derived from geophysical well logs with permeability derived from hydraulic tests. In most hydraulic tests, fracture permeability is expressed as "equivalent plane fracture aperture" or "a" in equation 2. This expression results when drawdowns or pressure declines during pumping or slug tests are referenced to a plane-fracture model. In much of the literature, such equivalent hydraulic apertures are implied by the more general term "hydraulic aperture" of fractures. In considering such expressions, it is important to remember that a single aperture is derived to indicate the ability of a fracture to transmit water in a specific hydraulic test. The apertures of natural fractures measured in the field are variable along fracture strike so that a given hydraulic aperture represents a specific average of these variations of apertures obtained in a hydraulic experiment.

In some applications, the transmissivity of several fractures intersecting the borehole may be lumped together, as when intervals of borehole are isolated with straddle packers. In that situation, the transmissivity of the borehole interval (T_0) is given as the sum of the transmissivities (T_1, T_2, and so forth) of the individual fractures:

$$T_0 = T_1 + T_2 + ... \tag{5A}$$

If fracture transmissivity is expressed in the form of hydraulic aperture, a combined aperture (a_0) is given as the cube root of the sum of the individual apertures (a_1, a_2, and so forth):

$$a_0 = (a_1{}^3 + a_2{}^3 + ...)^{1/3} \tag{5B}$$

Another complication in the field measurement of fracture permeability is that some measurements are made at ultrasonic frequencies. The cubic law for fracture transmissivity in equation 4 is derived for steady viscous flow between two flat plates. The flow becomes much more complicated for oscillatory motion of the fluid. For low frequencies, there is no real change in the relation between pressure gradient and flow. However, at higher frequencies, the viscous flow becomes confined to boundary layers adjacent to the borehole wall, where the boundary layer thickness is given by:

$$\delta = \sqrt{\frac{2\mu}{\omega}} \tag{6}$$

where δ is the boundary layer thickness at frequency ω. This equation indicates that there will be a great difference between flow in pore channels and flow between two parallel plates at higher frequencies, even when the flow is described by similar transmissivities for steady flow for both situations. This difference is apparently one of the reasons why acoustic experiments in fractured rocks yield results different from those computed for parallel plate models and different from results obtained from experiments using saw cuts in the laboratory.

For the parallel plate model, Tang and Cheng (1989) showed that the dynamic permeability for oscillatory flow is a complicated function of frequency approaching the following form for large frequencies:

$$k = \frac{ia}{\rho\omega} \quad \delta \gg a \qquad (7A)$$

When the fracture is modeled as a plane porous layer rather than a planar opening, Tang and others (1991) show that the dynamic permeability is given by:

$$k(\omega) = \frac{k_o}{\left(1 - \frac{i\alpha k_o \omega}{3\mu\phi}\right)^{\frac{1}{2}} - \frac{i\alpha k_o \rho\omega}{\mu\phi}} \qquad (7B)$$

where α is the tortuosity of the pore spaces, ϕ is the porosity of the fracture, and k_o is the permeability of the fracture for steady flow. In practice, natural fractures will differ from both of these models, but it is assumed that the porous layer model will be more appropriate in a majority of applications, especially at ultrasonic frequencies.

A number of geophysical measurements are based on the electrical properties of fractured rocks or on a specific relationship between electric and hydraulic properties. In general, electrical resistivity of fractured rocks is assumed to be derived from parallel conduction along three different paths: rock matrix, fracture surface, and fluid-filled fracture opening. In typical fractured-rock applications, all three conduction mechanisms are assumed to be important, so that:

$$\frac{1}{R_t} = \sigma = \sigma_m + \sigma_s + \sigma_f \qquad (8)$$

where R_t is the resistivity of the fractured formation, and the subscripts *m*, *s*, and *f* denote electrical conduction through the rock matrix adjacent to the fracture, through the exchange ions associated with fracture surfaces, and through solutes in the fluid filling the fracture, respectively. Many crystalline rocks have negligible electrical conductivity, but alteration clays in the rocks adjacent to the borehole may be conductive and often contribute to the resistivity anomalies associated with fractures (Keys, 1979; Paillet, 1991a). Alteration clays also affect the ion exchange of pore surfaces in fractures, and the conductivity resulting from these exchange ions is a complicated function of water salinity (Worthington and Johnson, 1991). Finally, the relatively large transmissivity of some permeable fractures can provide low resistivity values, even when formation waters are relatively fresh.

Only the third electrical conduction mechanism in equation 8 is directly related to permeability, and there would be many situations where this permeability signal might not be identified in the geophysical data. Katsube and Hume (1987) attempted to separate the clay alteration mineral and surface conduction mechanisms from the permeability signal by correcting the measured resistivities using Archie's Law. They assume that a formation factor can be derived from the ratio of measured resistivity in the fracture zone (R_t) and the resistivity of the formation fluid (R_w):

$$F_a = \frac{R_t}{R_w} \qquad (9)$$

They further assume that a corrected formation factor can be derived:

$$F_c = \frac{F_a}{F_b} \quad F_b = c/\phi n \qquad (10)$$

where ϕ is porosity given by the density log and *c* and *n* are empirical constants. Values for the parameter F_c derived in this manner were then shown to correlate with independent measurements of fracture transmissivity according to the formula:

$$T = A \ (F_b/F_a)^{-S} \qquad (11)$$

where *A* is a constant equal to about 4.1×10^{-7} and *S* is about 1.06 for granite (Katsube and Hume, 1987). This relation was derived for fractured granite saturated with relatively fresh water near the southwestern limit of the Canadian Shield in Manitoba and might not necessarily apply to other rock types or other water salinities in the same rock type at other locations.

Models of the electrical conductivity of fractured formations also can be used to interpret the resistivity anomalies measured with electrical imaging devices. For example, Hornby and others (1992) report that the aperture of fractures (A) can be related to the microresistivity current anomalies (I_o) associated with fractures according to the equation:

$$A = cR_f I_o \left(\frac{R_f}{R_{xo}}\right)^{S-1} \qquad (12)$$

where R_{xo} is the resistivity of the fracture filled with borehole fluid, R_f is the resistivity of the borehole fluid, and c and S are empirical constants.

Acoustic logs have been used extensively to estimate fracture aperture. In most situations, the amplitude of the tube-wave mode is related to fracture permeability. Paillet (1983) found that for relatively large frequencies (15 to 35 kHz), tube-wave attenuation (expressed as the local tube-wave energy deficit) could be related to fracture transmissivity according to the formula:

$$T = c\,\frac{(A_0^2 - A^2)}{A_0^2} \qquad (13)$$

where A is the measured minimum amplitude of the tube wave, A_0 is the average amplitude of the tube wave in adjacent unfractured intervals, and c is an empirical constant.

Theoretical relations between fracture permeability and tube-wave attenuation have been much more difficult to derive. Hornby and others (1989) derived relationships for the transmission and reflection coefficients for tube waves propagating across the planar intersection between a horizontal fracture and a vertical borehole:

$$A_r = \frac{if(\omega)A}{1+if(\omega)} f(\omega) = \frac{aH_1^{\,1}(mr)}{rH_o^{\,1}(mr)}$$
$$A_t = \frac{1}{1+if(\omega)} m = \frac{\omega}{V_f} \qquad (14)$$

where A_r and A_t are the reflection and transmission coefficients, $i = \sqrt{-1}$ $H_o^{\,1}$ and $H_1^{\,1}$ are Hankel functions, r is the borehole radius, a is the fracture aperture, V_f is the acoustic velocity of the borehole fluid, and ω is the tube-wave frequency. Here the sum of A_r and A_t is unity because no energy is lost to outward propagating waves in the formation. These equations indicate that $A_r = 0$ and $A_t = 1$ in the low frequency limit, while A_r and A_t are complex functions of frequency in other situations. Equation 14 indicates that tube-wave reflections can be related to fracture permeability, and the technique seems to give good results at logging frequencies less than a few kilohertz. At higher frequencies, the tube waves are attenuated by propagation across fractures, but no reflections are detected. This attenuation can be accounted for using the approach of Tang and others (1991) where the fracture is modeled as a thin permeable zone rather than a planar fracture. Using that approach, reflection and transmission coefficients become:

$$A_r = \frac{2i(m_2^2 - m_1^2)\sin m_1 b}{(m_1+m_2)^2 e^{-im_2 b} - (m_1+m_2)^2 e^{im_2 b}}$$
$$m_1 = \frac{\omega}{V_{s1}}$$
$$(15)$$
$$A_t = \frac{4m_1 m_2 e^{-im_2 b}}{(m_1+m_2)^2 e^{-im_2 b} - (m_1+m_2)^2 e^{im_2 b}}$$
$$m_2 = \frac{\omega}{V_{s2}}$$

where b is the fracture zone thickness, and m_1 and m_2 give the wave numbers for the Stoneley waves traveling at the interface of the borehole fluid and unfractured formation (wave velocity is V_{s1}) and at the interface of the borehole and fracture zone (wave velocity = V_{s2}). These equations are applied to a typical set of tube waves in figure 8, where the theory appears to be in reasonable agreement with experiment for tube-wave attenuation at relatively high frequencies.

ADDRESSING THE SCALE PROBLEM IN THE INTEGRATION OF GEOPHYSICAL LOGS INTO GROUND-WATER FLOW MODELS

Borehole geophysical methods provide information about fractures in the immediate vicinity of their intersection with the well bore but do not indicate the properties and variability of fractures over distances more than 1 to 2 m from the borehole. Surface-to-borehole and borehole-to-borehole soundings and tomography can provide some of this information, although these methods rarely resolve individual fractures or fracture zones (Paillet, 1991b). However, combinations of large-scale soundings and local sampling of fractures can provide information that is unavailable from either set of data alone. For example, detailed information on fracture zones from well logs, such as extent and type of alteration, can be used to calibrate inversion models used in interpreting the soundings or tomography. Paillet (1991b) describes a generalized approach to multiple-scale interpretation of geophysical well logs in fractured aquifers. The approach is based on fracture characterization using a suite of conventional logs in conjunction with televiewer image logs and high-resolution flowmeter measurements (fig. 10). The method uses the large-scale drawdown from regional pumping (usually a water-supply well field) and transient drawdown from local pumping to investigate fracture flow on three different scales of investigation: (1) A small scale, associated with conventional geophysical log sample volumes less than 1 m in diameter; (2) an intermediate scale associated with the separation of 10 to 100 m between observation boreholes; and (3) a large or regional scale of 1,000 m or more associated with quasi-steady drawdown produced by the water-supply well field. In at least some situations, this application of three discrete scales of investigation seems to be an adequate approximation of the continuum of scales needed to characterize a heterogeneous distribution of fracture permeability.

A more specific issue in fractured-rock hydrology is that of fracture connectivity. Most geophysical measurements involve quantities that are indirectly related to permeability and fluid flow (Paillet, 1991a). There is often little direct evidence that a specific fracture indicated by well logs or imaged in a tomographic study is capable of conducting flow. Even when well-log data can be inverted for the local hydraulic aperture of fractures given at the intersection of the borehole and the fracture plane, theoretical studies indicate that fracture connectivity is as important as local aperture in determining large-scale flow or percolation in the rock mass (Long and others, 1982). Borehole geophysics can contribute to coordinated field studies designed to address the large-scale flow characterization in two ways: (1) Using local cross-borehole flow studies designed to characterize the nature of fracture connections in relatively small volumes of rock; and (2) using borehole geophysical data to guide the identification of test intervals during long-term interference and tracer studies in fractured-rock bodies.

Local cross-borehole studies involve the measurements of flow in observation wells while an adjacent borehole is being pumped. These measurements can be used to identify which of those fractures intersected by boreholes take part in the movement of water across a borehole array during pumping. Several examples of this approach are described by Paillet and others (1987a), Paillet and Hess (1986), Paillet (1989, 1991c), Griswold and others (1990), and Vernon and others (1992). Some of these field examples will be discussed in the next section of this review.

In larger scale studies of fractured aquifers, borehole geophysical measurements are important in designing fracture-monitoring programs and long-term pumping and tracer injection tests. Although most boreholes in fractured formations will intersect many fractures, hydrologists are limited by equipment requirements to the isolation (with packers) of only a few intervals in each observation well. Borehole measurements are used to identify unfractured intervals where packers can be seated and that separate zones of interconnected fracture permeability. These zones may be identified, for example, by detecting movement of water along the well bore between intervals characterized by different hydraulic heads under ambient conditions. This movement could be inferred from temperature and fluid-conductivity logs or measured directly with a flowmeter (Hess and Paillet, 1990). For this reason, it is important to consider the applications of borehole geophysics in interpreting large-scale geophysical sounding and long-term aquifer pumping and tracer tests, as well as applications of well logs in the direct detection and characterization of fracture populations.

RESULTS OF FIELD STUDIES

Comparing Fracture-Characterization Techniques in a Fractured Granite and Schist Aquifer Near Dover, New Hampshire

One way in which to compare the effectiveness of various borehole measurements is to illustrate the results obtained using each of these methods in a typical fractured-rock aquifer. An example is given for a borehole in fractured granite and schist near Dover in southeastern New Hampshire (fig. 11). This borehole was flowing at about 20 L/min during the logging. The

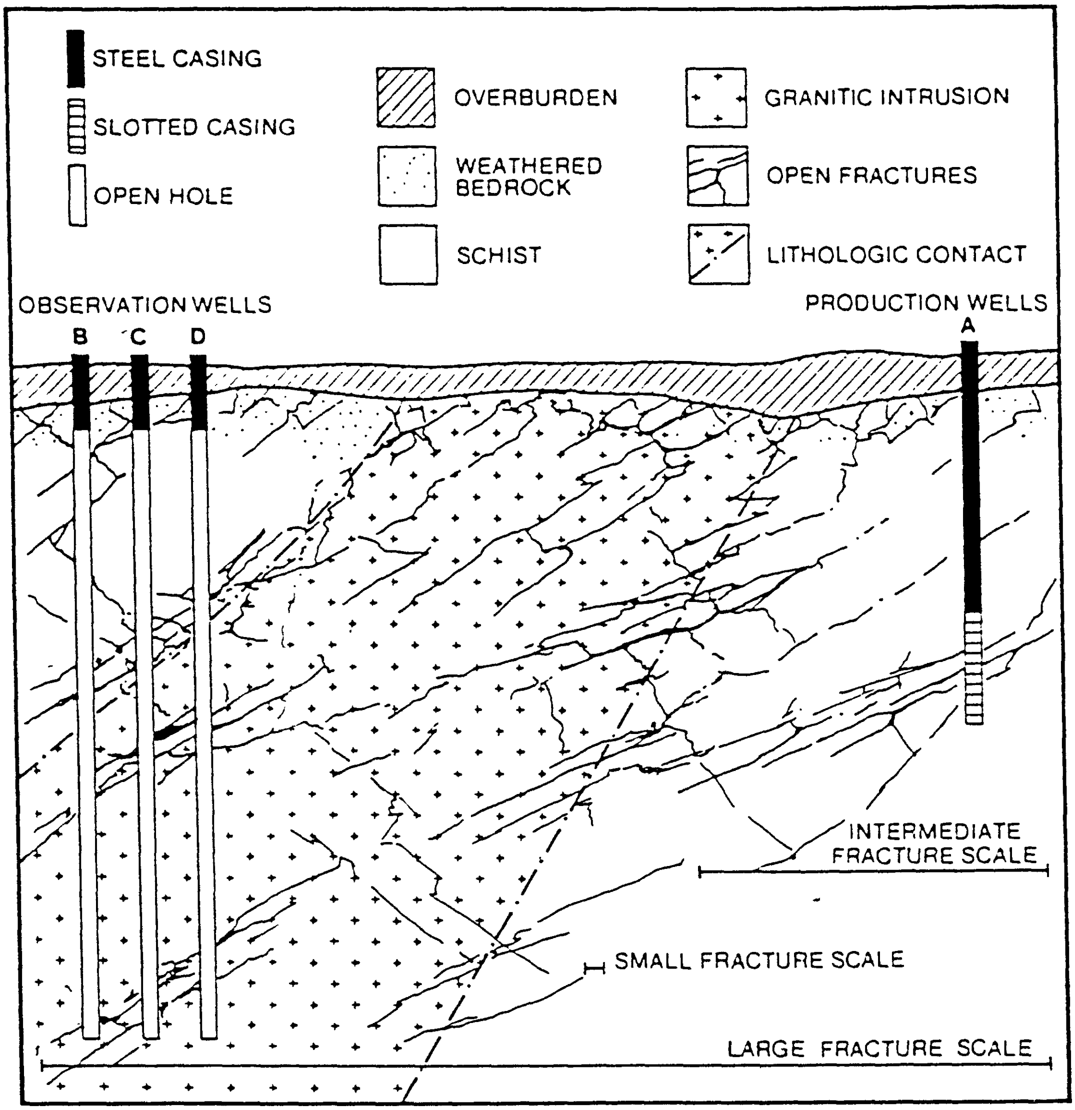

Figure 10. Schematic illustration of fracture flow characterization at three scales of investigation (Paillet, 1991).

lithology log (determined from inspection of cuttings, bit penetration, and rate of water production during drilling; Griswold and others, 1990) indicates that the borehole penetrated about 30 m of overburden and quartz monzonite overlying schist; the contact between quartz monzonite and schist is clearly indicated by the gamma log. The televiewer log indicates that the borehole intersects numerous fractures, many of which are indicated by the caliper log. In general, the distribution of fractures given by the televiewer log interpretation agrees with the distribution of fractures estimated from the rate of bit penetration and amount of chatter during drilling.

The temperature log for this borehole (not shown) indicates that most of the inflow occurs at about 100 m in depth. This distribution of inflow was further delineated by flowmeter measurements, indicating inflow at two major fractures (C and D in fig. 11). A small amount of scatter in the flowmeter data appears near 60 m in depth but is within the estimated error in the measurements and so is not interpreted as a definite indication of inflow at that depth. The fluid-replacement log agrees with the other logs in that most inflow is interpreted to occur at about 100 m in depth (fracture zones C and D), having minor inflow at fracture zones D and B. All of these results indicate that there is no measurable inflow or outflow at many other apparently

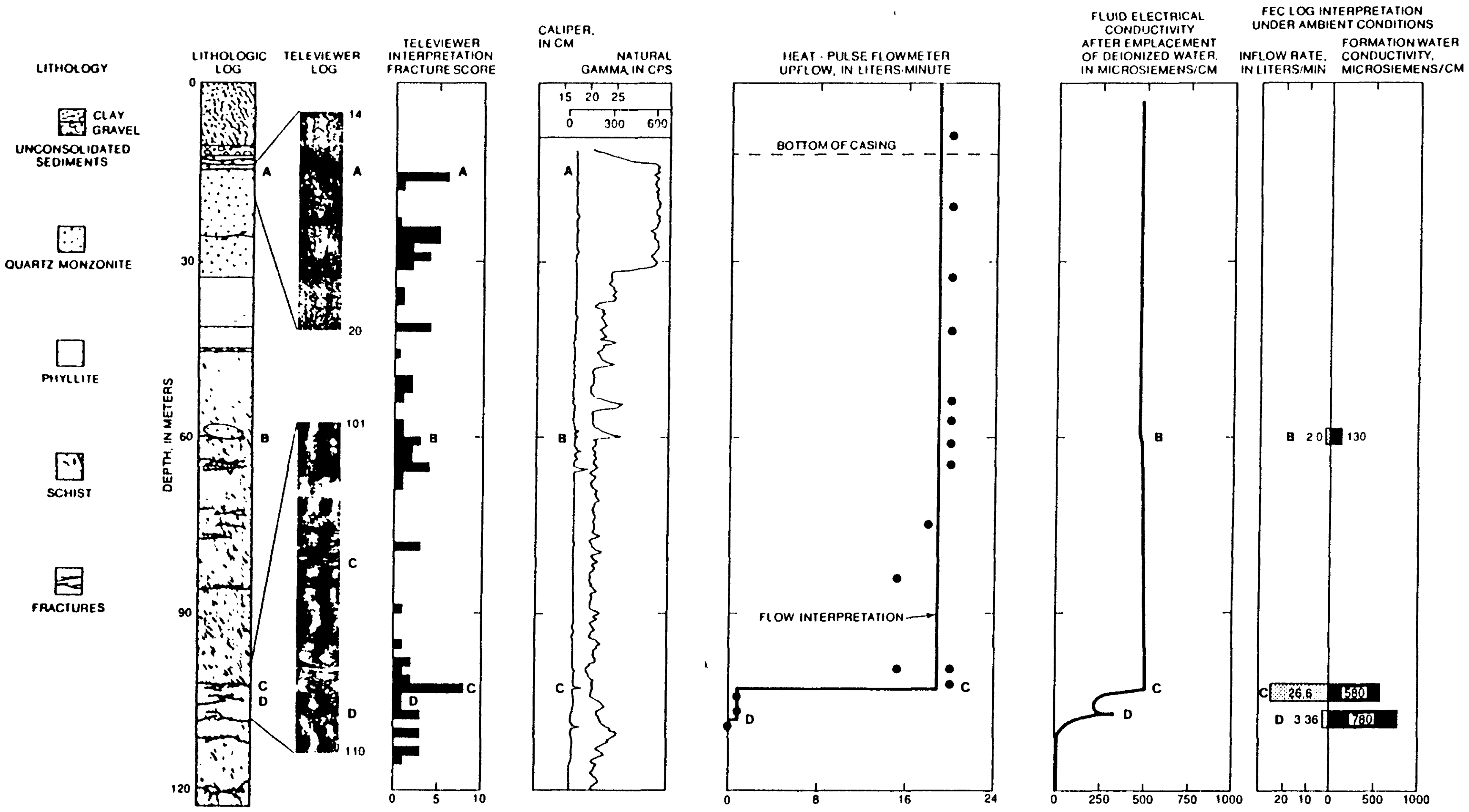

Figure 11. Relation of fracture characterization in a borehole in granite and schist using: Driller's log and water production during drilling, televiewer log data, caliper log, heat-pulse flowmeter logging during production, and fluid-replacement logging during production.

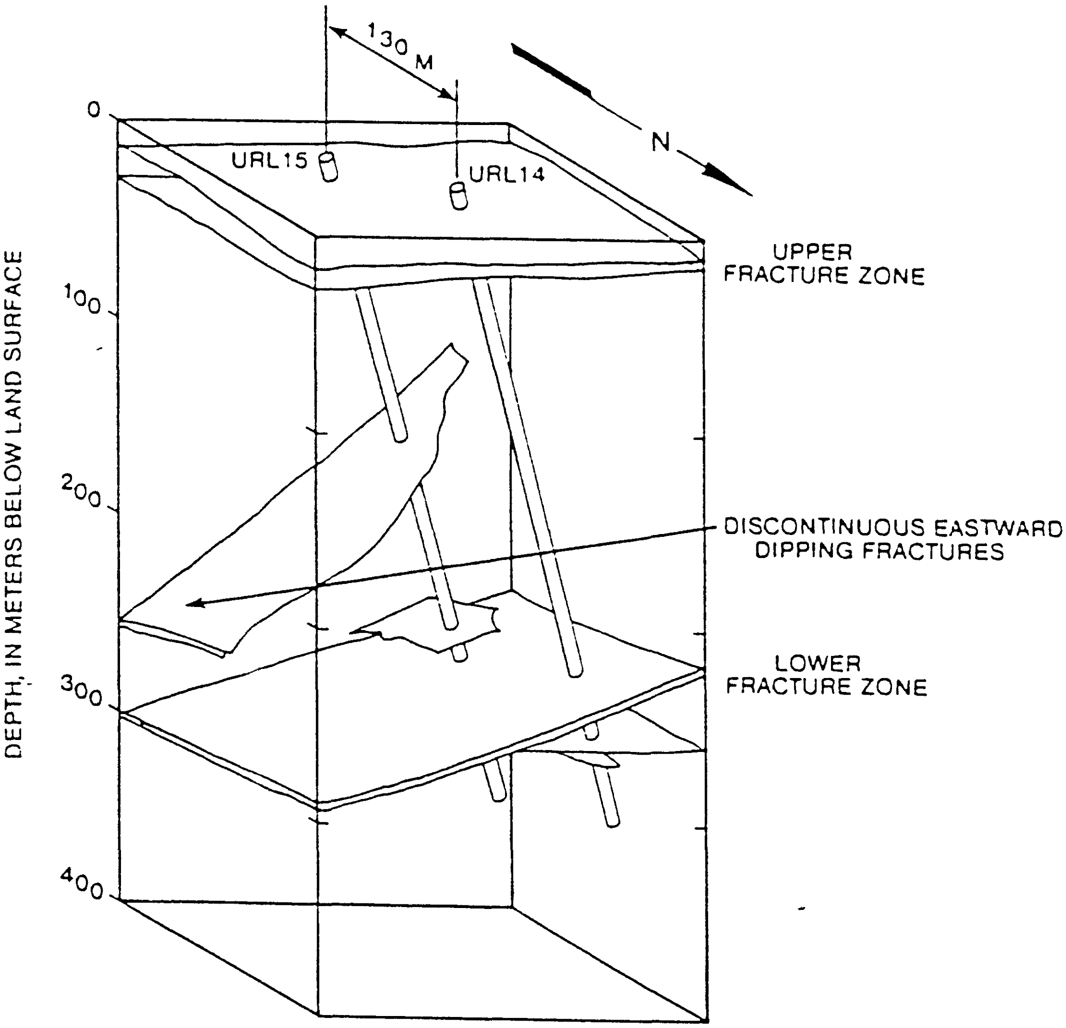

Figure 12. Schematic illustration of borehole pair used to conduct cross-borehole flow survey in a subhorizontal, permeable fracture zone at Lac du Bonnet, Manitoba, Canada (Paillet, 1990).

open fractures, such as those in fracture zone A. In addition, the fluid-replacement log shows the profile of electrical conductivity of the borehole in terms of both inflow rate and electrical conductivity of the inflowing water. In comparing these measurements with those given by the heat-pulse flowmeter, the additional time and effort required to obtain the fluid-replacement log in comparison with flowmeter logging needs to be balanced against the additional information provided by the former technique.

Fractured-Granitic Batholith near Lac du Bonnet in Southeastern Manitoba, Canada

Atomic Energy of Canada Limited is conducting a long-term site-characterization project at a location on the Canadian Shield typical of many such sites that might be useful for the construction of a radioactive-waste repository. Hydrogeologic and geophysical studies at this site are reviewed by Davison (1984), Soonawala (1983), and Paillet (1991a). An example of one geophysical and hydraulic study conducted at the Lac du Bonnet site is the characterization of flow in the volume of rock between two boreholes, URL14 and URL15 (fig. 12). A full suite of conventional geophysical logs was run in these two boreholes, and the logs were compared to fracture-frequency data obtained from core inspection. This volume of rock was of interest because a single fault zone was found to intersect the two boreholes; regional ground-water circulation is known to occur through similar faults at other locations in the batholith (Davison, 1984). The geophysical logs indicated the depths where the fault zone and a few isolated fractures in the adjacent granites intersected the two boreholes.

Acoustic full-waveform logs were run in both boreholes. Tube-wave amplitude analysis indicated that there were a number of distinct, permeable fractures within the fault where the fault was intersected by each of the boreholes and that some of the isolated fractures above and below the fault also were permeable (fig. 12). Although the distribution of fractures encountered in the vicinity of this fault is qualitatively similar in both boreholes, the quantities of water produced from each of these boreholes during drawdown tests were very different. Borehole URL15 was very productive, whereas borehole URL14 produced only a small fraction of a liter per minute at 50 m of steady drawdown. Furthermore, the flow between boreholes was found to occur through a relatively tight connection between discrete fractures beneath the fault, whereas there was no communication through the fault itself (fig. 13).

The results of the survey shown in figure 13 are not interpreted as a contradiction of the theory that ground-water circulation is controlled by the southeastward-dipping faults at the Lac du Bonnet site. Instead, it is assumed that these results are an indication of the heterogeneity of fracture permeability. The two boreholes in figure 12 sample the fault and adjacent fractures at only two points; however, the permeability of the fault may vary many orders of magnitude along strike and dip between these points. Probably the fault is relatively permeable, but borehole URL14 is locally isolated from the fault-zone aquifer.

One other result of the geophysical logs obtained in borehole URL14 is of interest. In-situ stress studies have indicated the presence of anomalous stress conditions in the vicinity of some of the faults in the Lac du Bonnet batholith (Martin, 1990); some of these disturbed stress regimes are indicated by the distribution of borehole wall breakouts (Paillet, 1989). A short interval of borehole wall breakout indicative of anomalous in-situ stress was identified just below the isolated set of fractures associated with inflow to borehole URL14 during the cross-hole pumping tests (fig. 14). We also note that core disking, a phenomenon associated with anomalous stress conditions (Paillet and Kim, 1987), corresponds almost exactly to the distribution of breakouts given on the televiewer.

Fractured Schist and Granite in the Mirror Lake, New Hampshire, Drainage Basin

The U.S. Geological Survey has established a long-term site for the study of flow in fractured crystalline bedrock at Mirror Lake, New Hampshire (Winter, 1984; Paillet and Kapucu, 1989). A typical suite of conventional geophysical logs are compared to the televiewer log for one of the Mirror Lake boreholes in figure 3. These data can be combined to generate various qualitative fracture permeability distributions (Paillet and Kapucu, 1989; an example is given in fig. 15) for several Mirror Lake boreholes. This distribution was generated by counting the number of fractures within 5-m intervals after weighting each fracture for relative size on a scale from 1 to 5. The weight for each fracture was determined by referring to the quality of the anomaly associated with each fracture on the conventional logs and by referring to the appearance of the fracture in the televiewer image. Production estimates from drawdown tests given in figure 15 indicate that there is almost no correlation between fracture density and production during pumping.

The qualitative distribution of fractures encountered by the borehole in one of the boreholes in figure 15 can be compared to the results of a vertical seismic-profile experiment in the same borehole (Hardin and others, 1987). This technique uses a conventional seismic source applied in a shallow borehole to generate seismic waves in the borehole (indicated schematically in fig. 16). When compression waves pass the location where permeable fractures intersect the well bore, fracture compression generates a pulse of flow into the well that propagates as a tube wave. The magnitude of this pulse can be related to fracture permeability (Huang and Hunter, 1981; Hardin and Toksoz, 1985). Furthermore, the results from several such tests having different source locations can be used to infer the strike and dip of permeable fractures. The results from such a measurement in the vicinity of borehole FSE4 appear to contradict some of the other geophysical log data. For example, the vertical seismic-profile data for borehole FSE4 at Mirror Lake indicate a single, nearly horizontal permeable zone near 45 m in depth, whereas the logs indicate numerous, steeply dipping fractures over the interval from the bottom of casing to more than 80 m in depth.

Cross-borehole flow measurements were conducted in borehole FSE4 and adjacent boreholes at the Mirror Lake site (fig. 17). The interpretation of these tests indicates that both the vertical seismic-profile and borehole-log data are correct and that the apparent contradiction is a result of the different scales of the two measurements (fig. 18). The flowmeter data indicate that water moves across the borehole array through individual, steeply dipping fractures but that the net flow is nearly horizontal. At the same time, most of the flow is carried by only a few of the apparently permeable fractures intersecting the boreholes, and none of

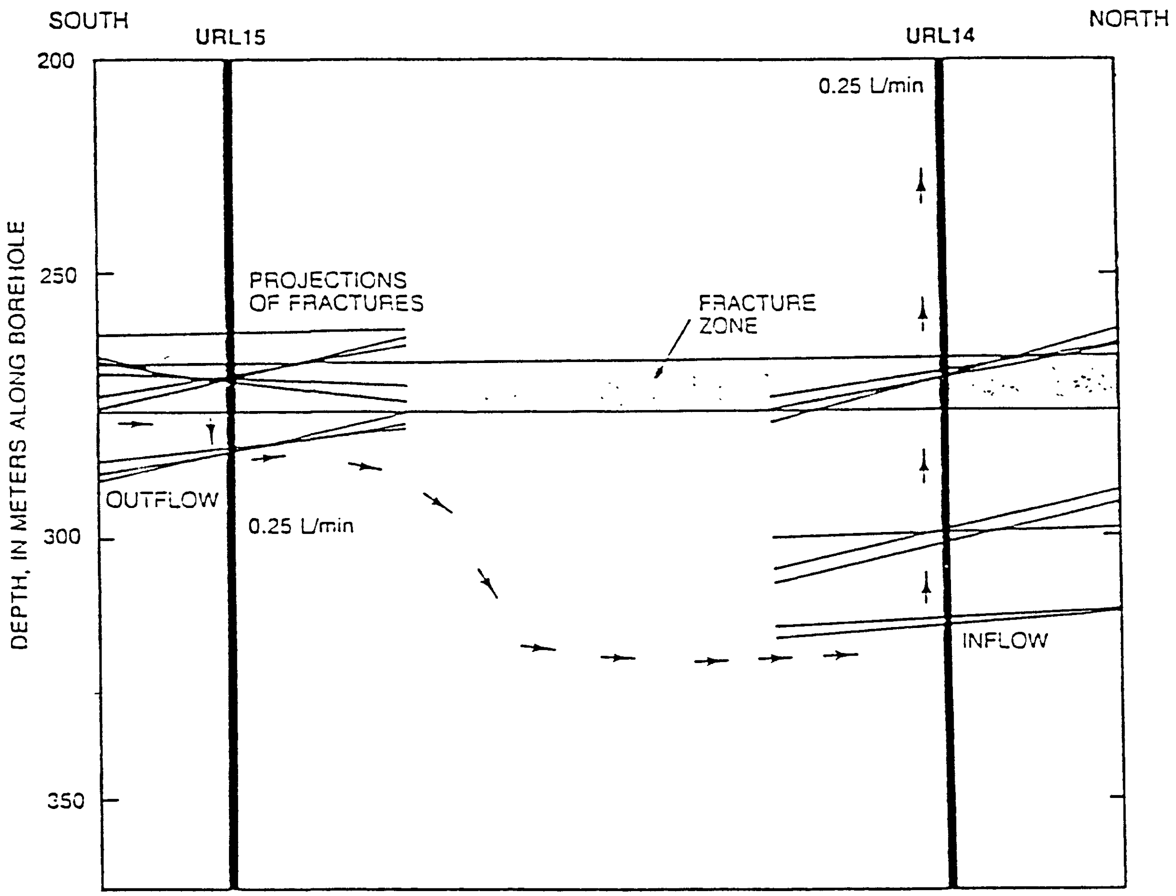

Figure 13. Results of cross-borehole flow survey at Lac du Bonnet, Manitoba, Canada, indicating distribution of flow measured in the observation and pumped boreholes and possible fracture flow path indicated by those measurements (Paillet, 1990).

the individual fractures identified on the televiewer logs appear to project from one borehole to the next. This result seems to confirm the theoretical result that fracture connectivity is more important in controlling large-scale flow than local fracture aperture (Long and others, 1982; Witherspoon and others, 1981). The importance of the scale effect in the interpretation of the geophysical data from the FSE boreholes at Mirror Lake is indicated by comparing the various measurements according to their scale of investigation (fig. 19). On the left, acoustic televiewer logs indicate numerous apparently permeable fractures at a scale of about 1 cm. As the interpretation shifts to larger scales of investigation (acoustic waveform and straddle-packer injection-test data), the distribution of fracture permeability appears to contract to a more limited depth distribution. When these intermediate-scale interpretations are considered, the single permeability zone indicated by the vertical seismic-profile data on the right appears consistent with the distribution of fractures given by the televiewer data. These results demonstrate the importance of obtaining geophysical data at several different scales in order to generate an effective interpretation of fracture permeability at a given site.

Hydraulic Stimulation of Fractured Granite in the Front Range Uplift, Colorado

Hydraulic stimulation is frequently used to increase productivity of wells developed in fractured-rock aquifers. In this procedure, packers are used to isolate a borehole interval, and borehole pressure is increased until an existing fracture is inflated or a new fracture forms by tensile failure. In commercial hydraulic-fracture operations, a single packer is used, and the entire depth interval below that fracture is subjected to the stimulation treatment. In this situation, it is assumed that there are existing fractures intersecting the borehole below the packer, so the procedure almost always acts to inflate and extend existing fractures.

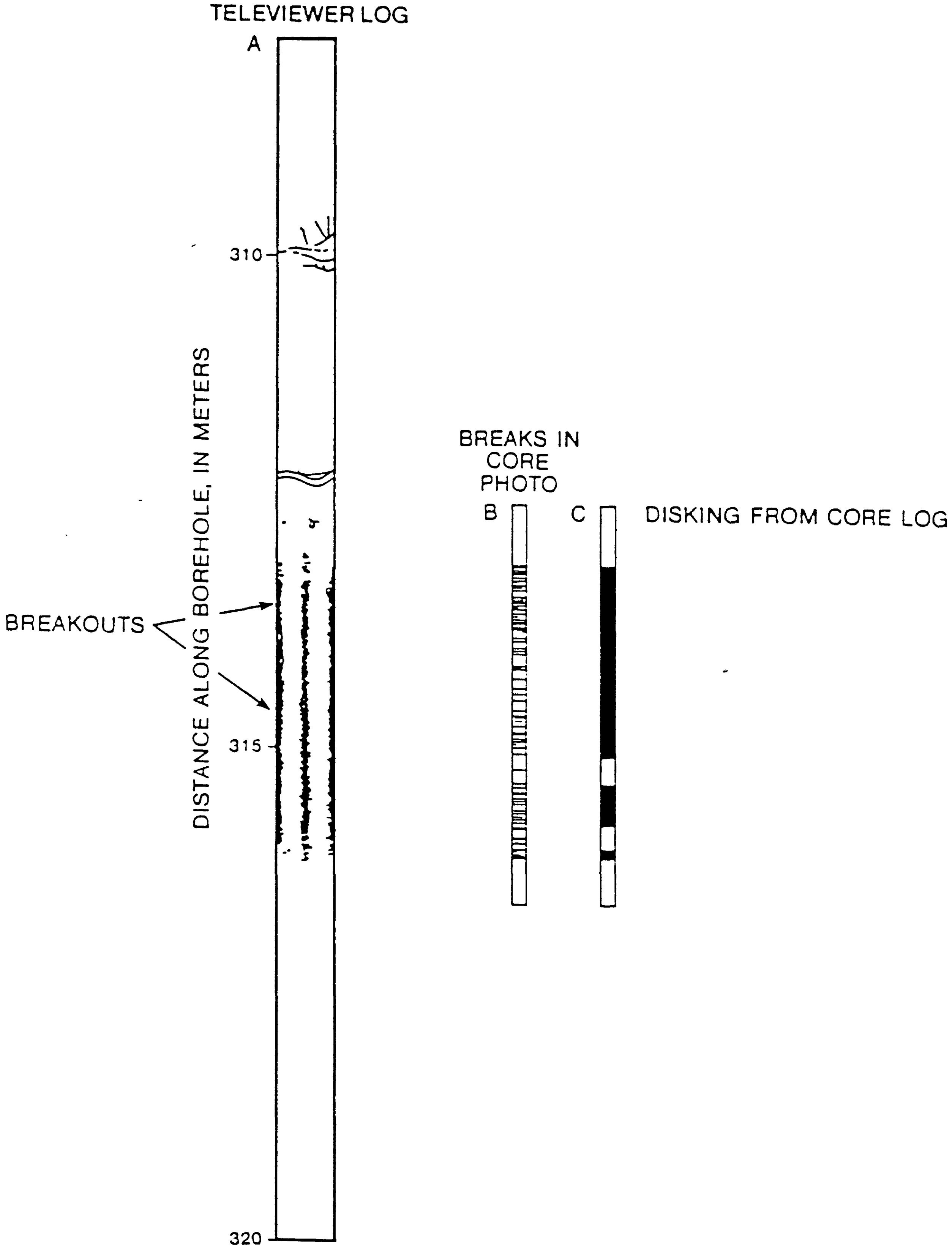

Figure 14. Distribution of borehole wall breakouts indicating anomalous stress conditions adjacent to a permeable fracture in borehole URL14 at Lac du Bonnet, Manitoba, Canada (Paillet, 1990).

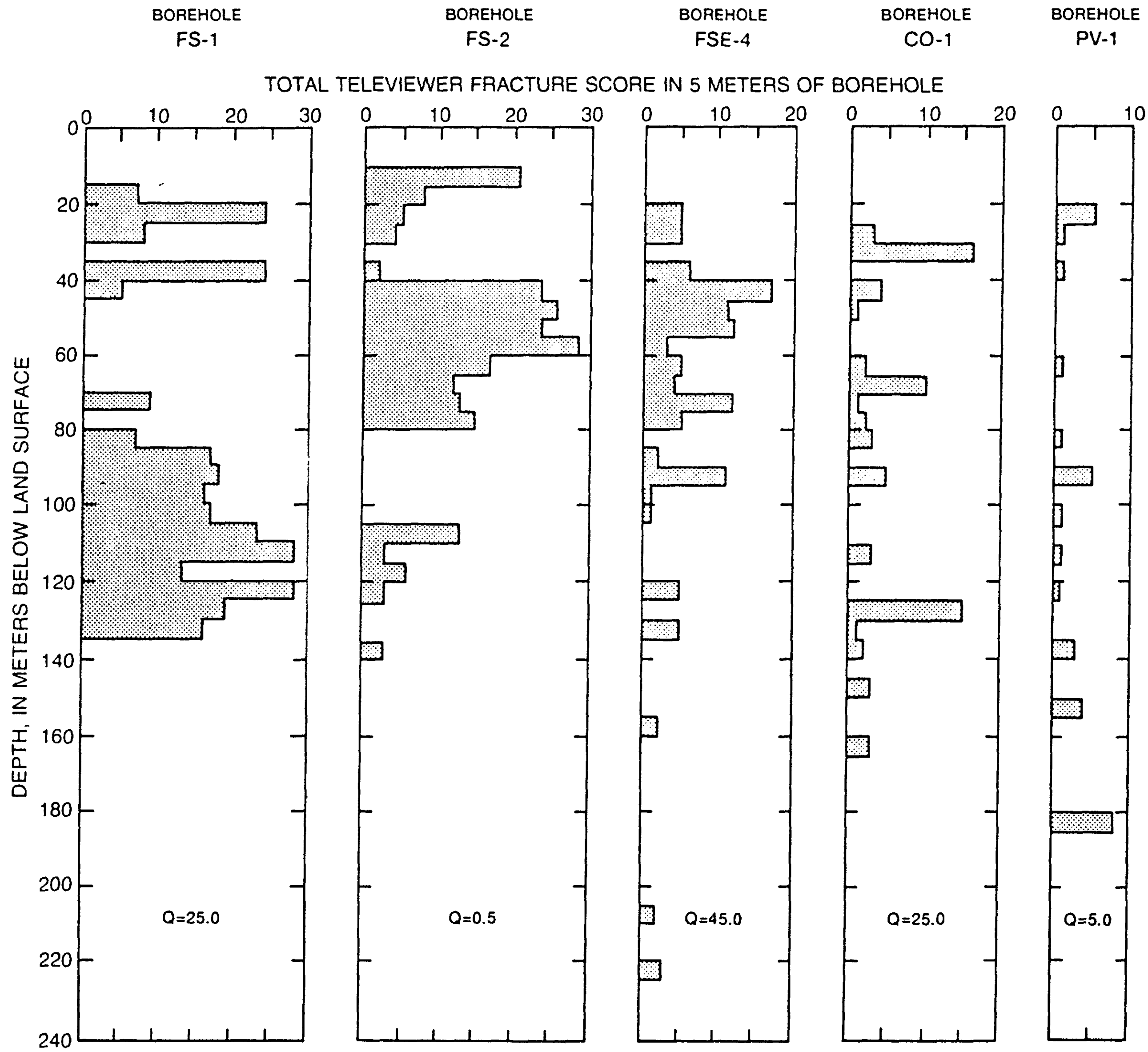

Figure 15. Distribution of fracture permeability interpreted from televiewer logs for five boreholes at the Mirror Lake, New Hampshire, site; Q denotes estimated production in liters per minute (Paillet and Kapucu, 1989).

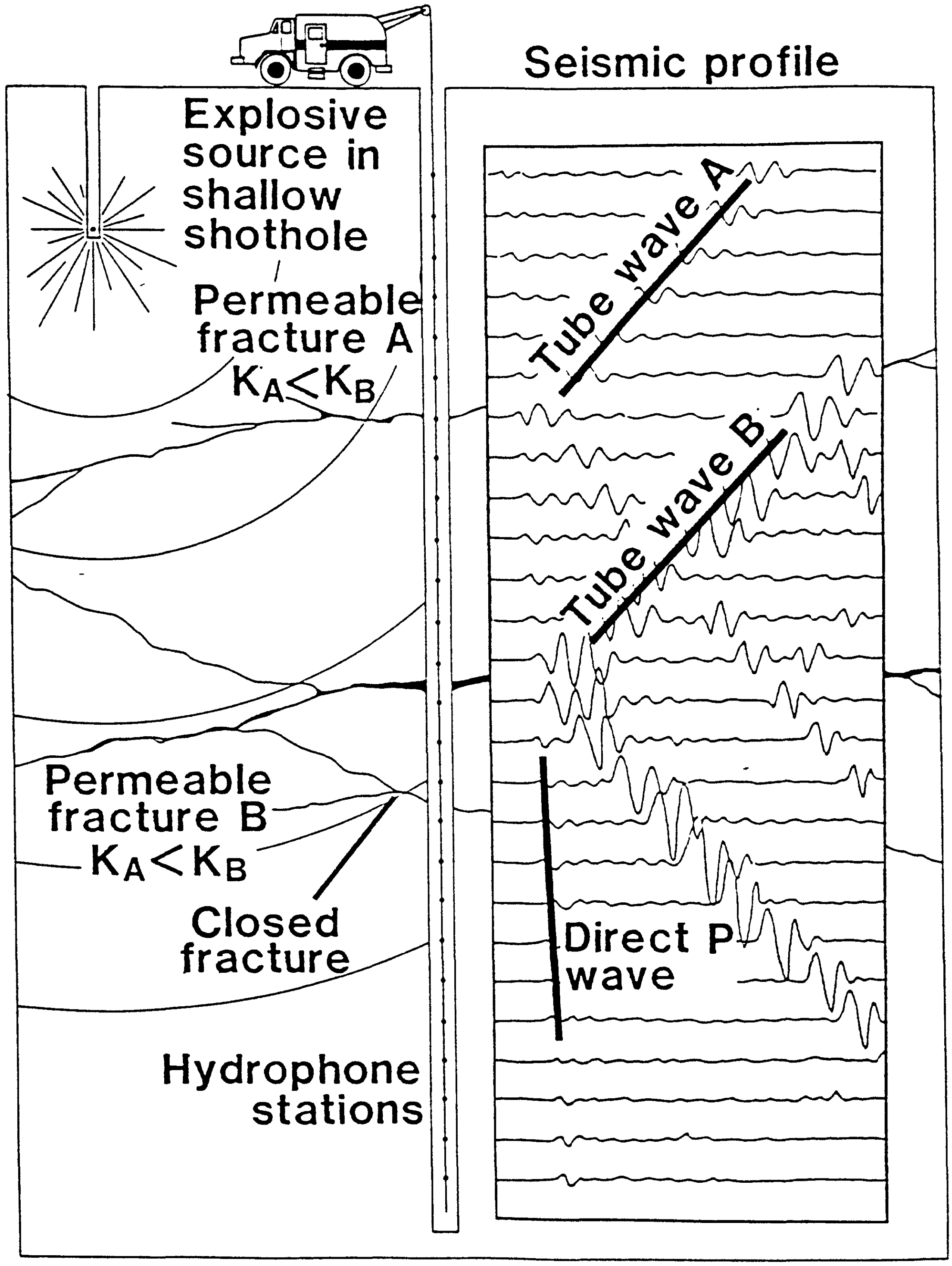

Figure 16. Schematic illustration of vertical seismic-profile, tube-wave analysis used to determine the permeability of fracture intersecting a borehole.

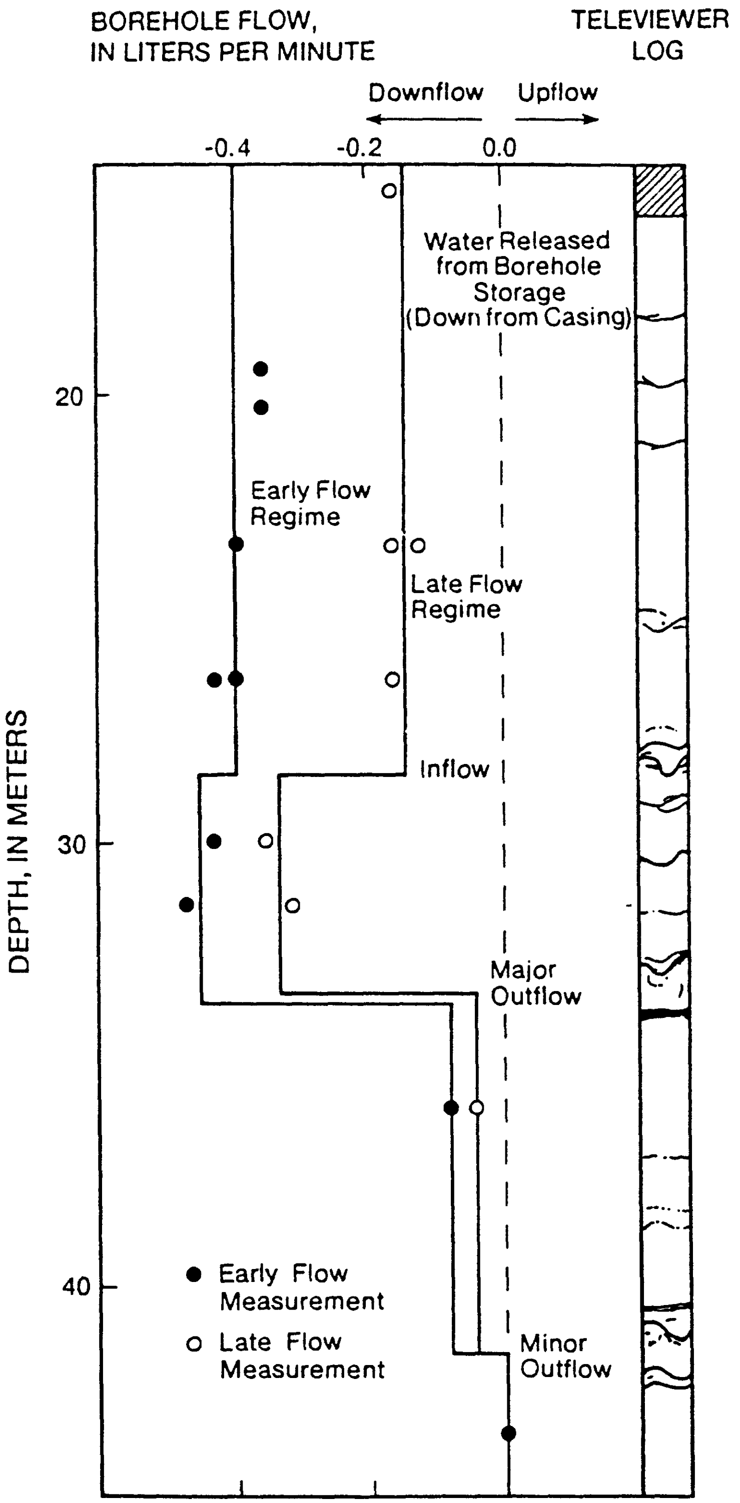

Figure 17. Example of vertical flow induced in an observation borehole as a result of pumping in an adjacent borehole (Paillet, 1991).

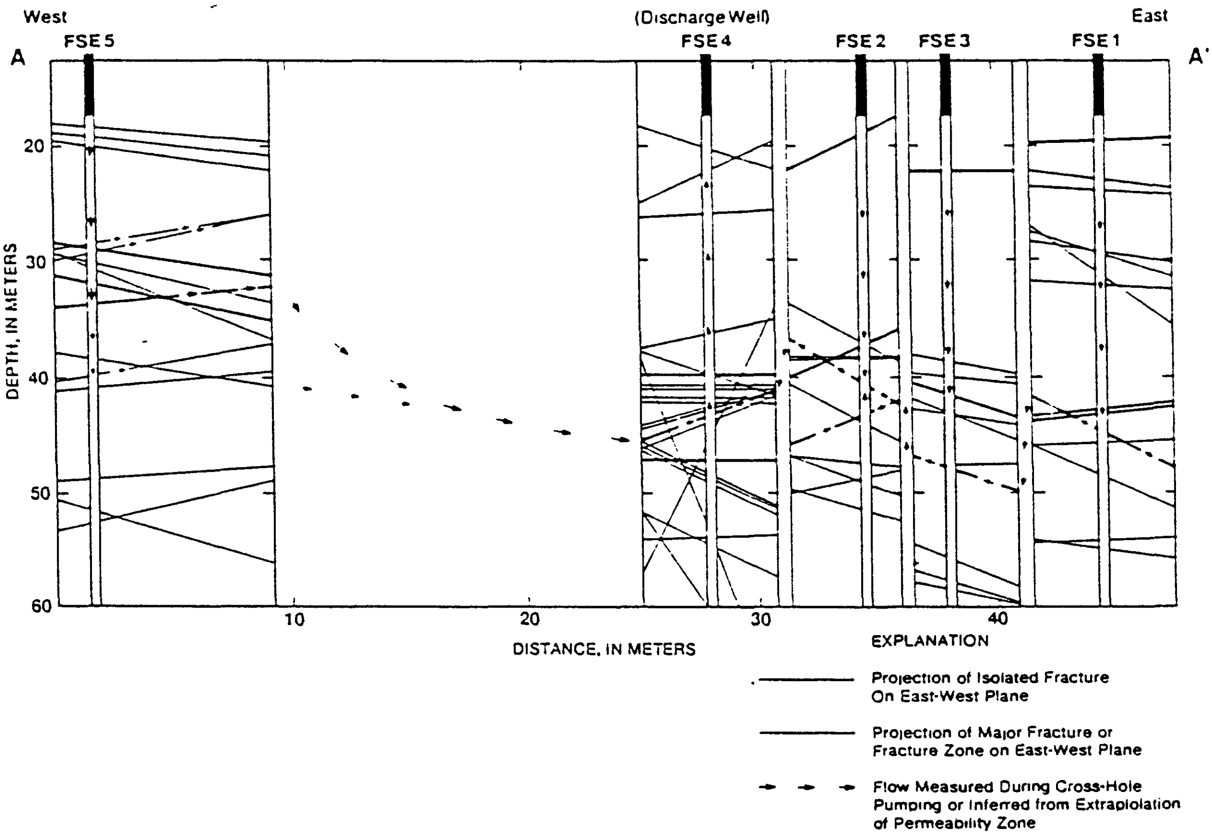

Figure 18. Projection of fractures in boreholes FSE1–FSE5 at the Mirror Lake, New Hampshire, site, into the vertical plane passing through the center of the array and movement of water across the array during pumping of borehole FSE4 inferred from heat-pulse flowmeter measurements (Paillet, 1991).

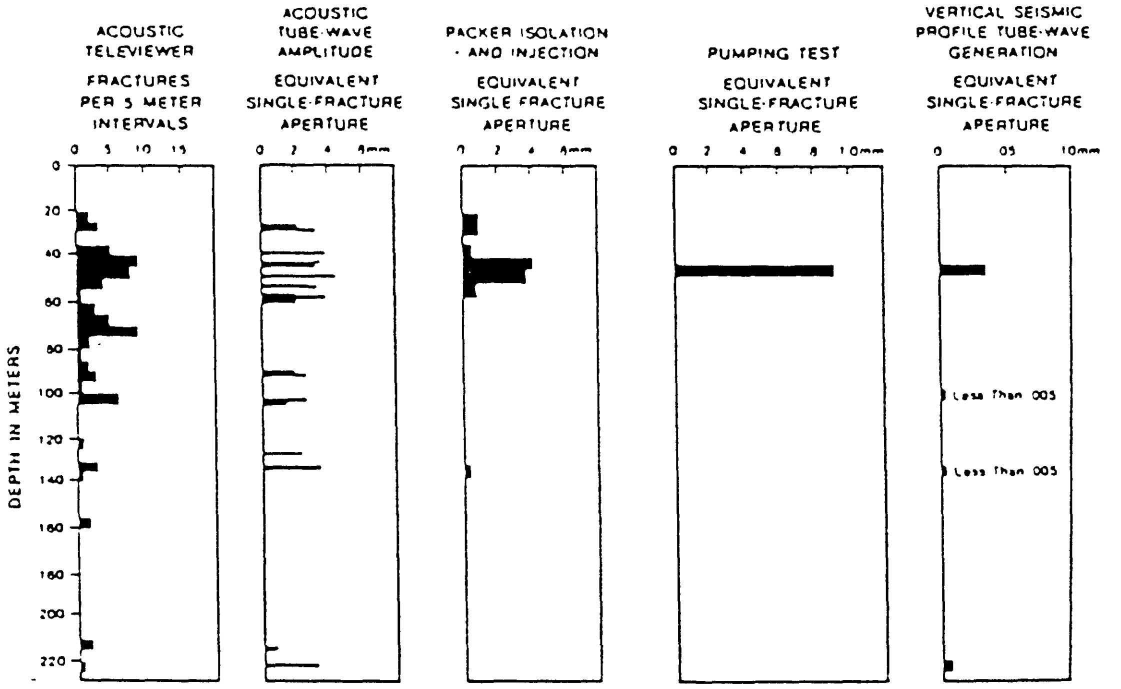

Figure 19. Comparison of geophysical measurements of fractures in borehole FSE4 at the Mirror Lake, New Hampshire, site, arranged in order of smallest scale of investigation on the left to largest scale of investigation on the right (Paillet and others, 1987).

The U.S. Geological Survey has investigated the effectiveness of hydraulic stimulation by logging boreholes before and after treatment. A typical example of a borehole studied in this way is illustrated in figure 20 (Paillet and others, 1989). Although this borehole was initially rated at a capacity of less than 1 L/min, televiewer and caliper logs indicate that the well bore is intersected by a number of apparently permeable fractures (A–G in fig. 20). The limited amount of water produced by this borehole during pumping tests was found to come from four relatively minor fractures (B, C, F, and G), whereas the two largest fractures indicated on the televiewer log (D and E) produced no measurable flow. This result is demonstrated by the profile of downflow during steady injection (fig. 21). Most of the measured downflow is shown to enter into storage in a formerly unsaturated fracture (A in fig. 20), whereas a small amount of downflow exits at each of the four minor producing fractures.

Hydraulic stimulation procedures were applied with the single packer set at the six depths indicated in figure 20. After stimulation, the profile of downflow under steady injection had changed significantly. The previously unsaturated fracture (A) was at least partially saturated as a result of an increase in static water level after stimulation. Furthermore, two of the previously productive fractures (B and G) were found to accept nearly 10 times as much flow under injection procedures identical to those used in the prestimulation injection test (fig. 21). No other measurable changes in the fractures intersected by this borehole can be found in comparing the geophysical logs obtained before and after stimulation. These results indicate that the stimulation has acted to increase borehole production during pumping by improving the hydraulic transmissivity of two relatively minor fractures. The effectiveness of the stimulation may have resulted from the favorable orientation of these fractures with respect to a large-scale flow system, rather than from the local hydraulic aperture of these fractures adjacent to the well bore.

SUMMARY

This review of the applications of borehole geophysics in hydrologic studies of fractured-rock aquifers indicates that both conventional well logs and some of the special logging techniques developed in recent years can be very useful in assessing flow patterns in fractured rocks. The typical fracture responses associated with each of the geophysical logging techniques mentioned in this review are summarized in figure 22. However, geophysical investigations of fractured rocks need not be restricted to borehole measurements alone. The most effective log analysis results when a number

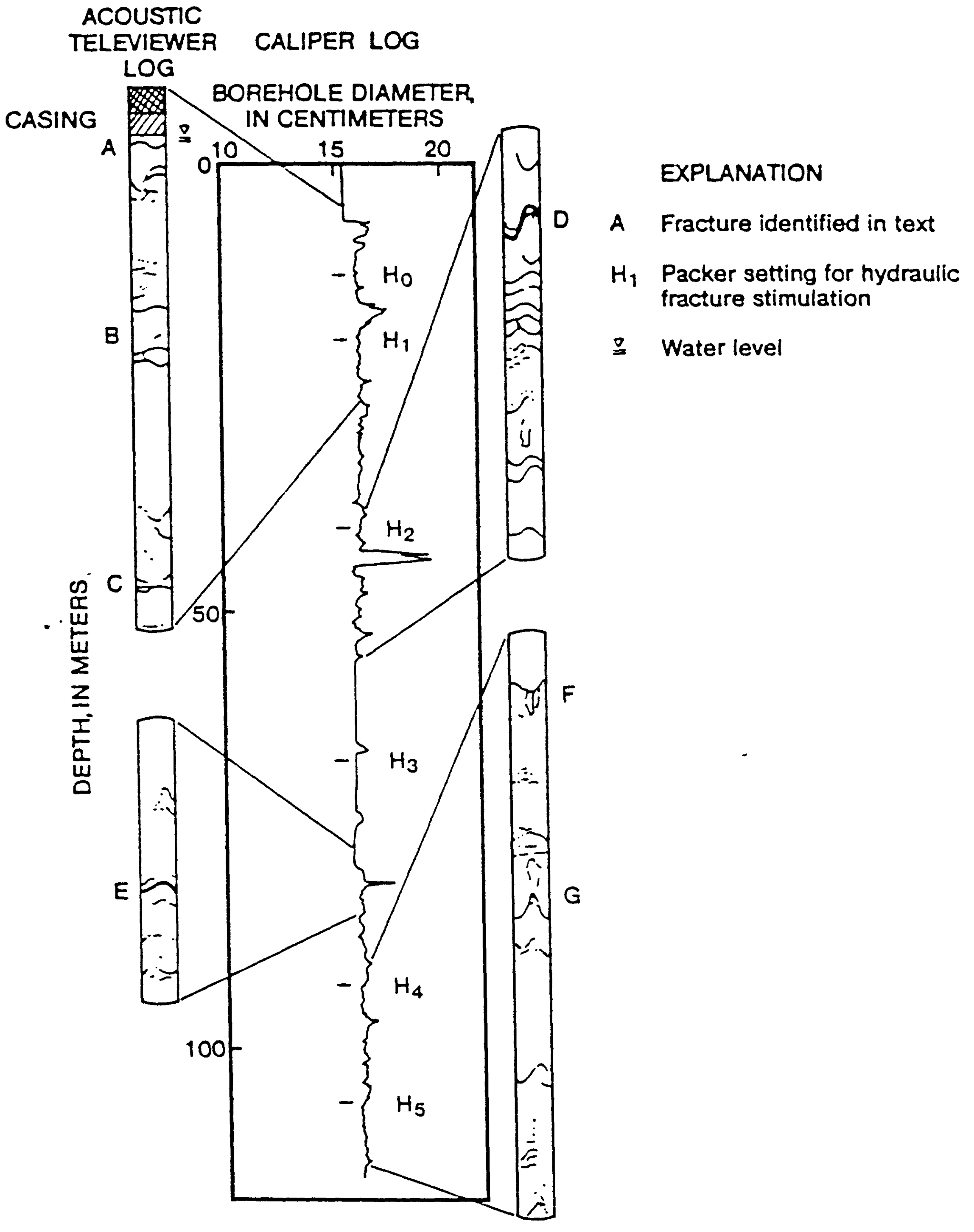

Figure 20. Distribution of fractures in a borehole in granitic rocks located near Denver, Colo., indicating televiewer image logs of some fractures and depth settings for packers during hydraulic-stimulation procedures H_0–H_5.

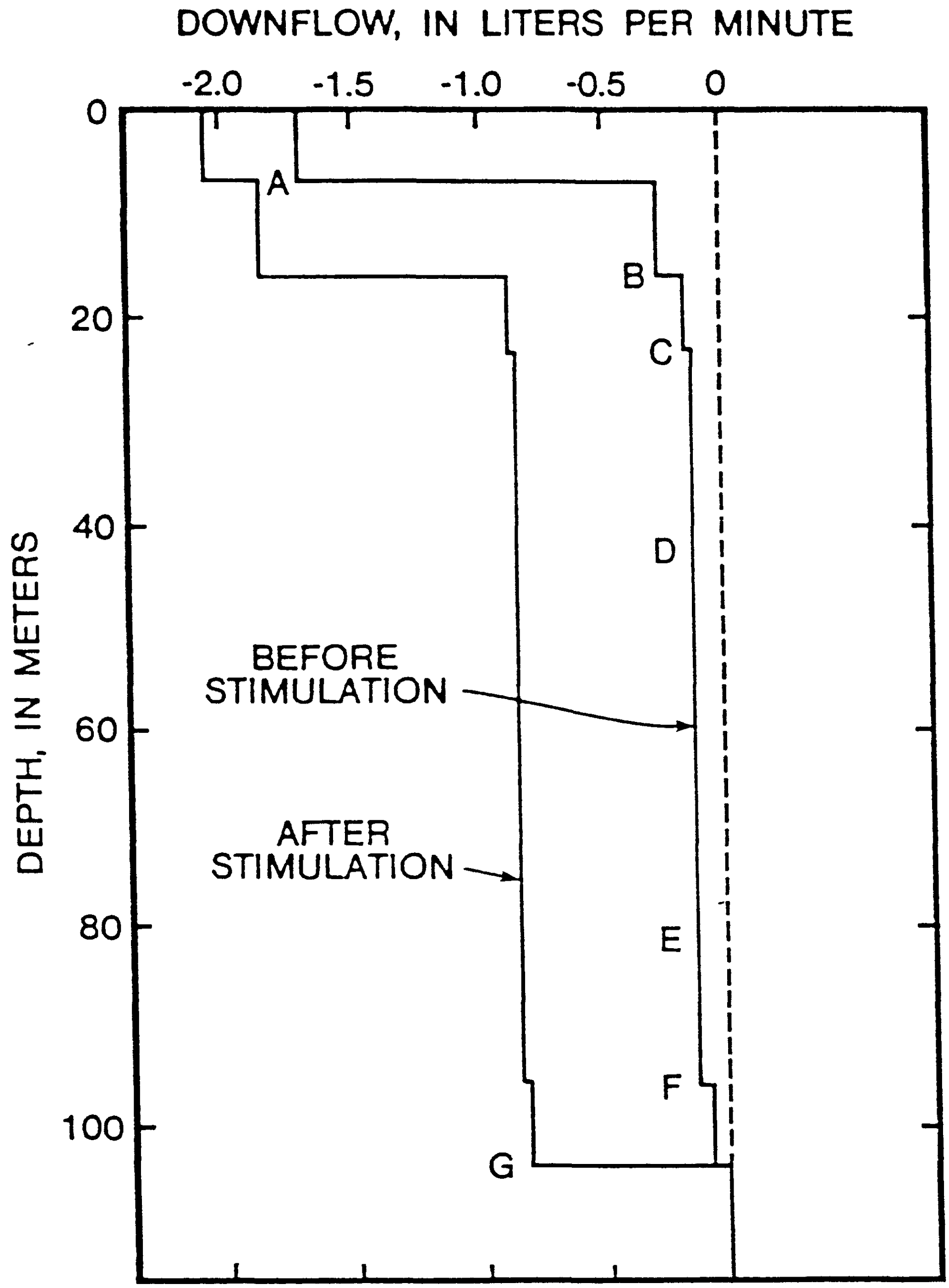

Figure 21. Vertical flow profiles obtained before and after hydraulic stimulation of the borehole described in figure 20 during quasi-steady injection tests.

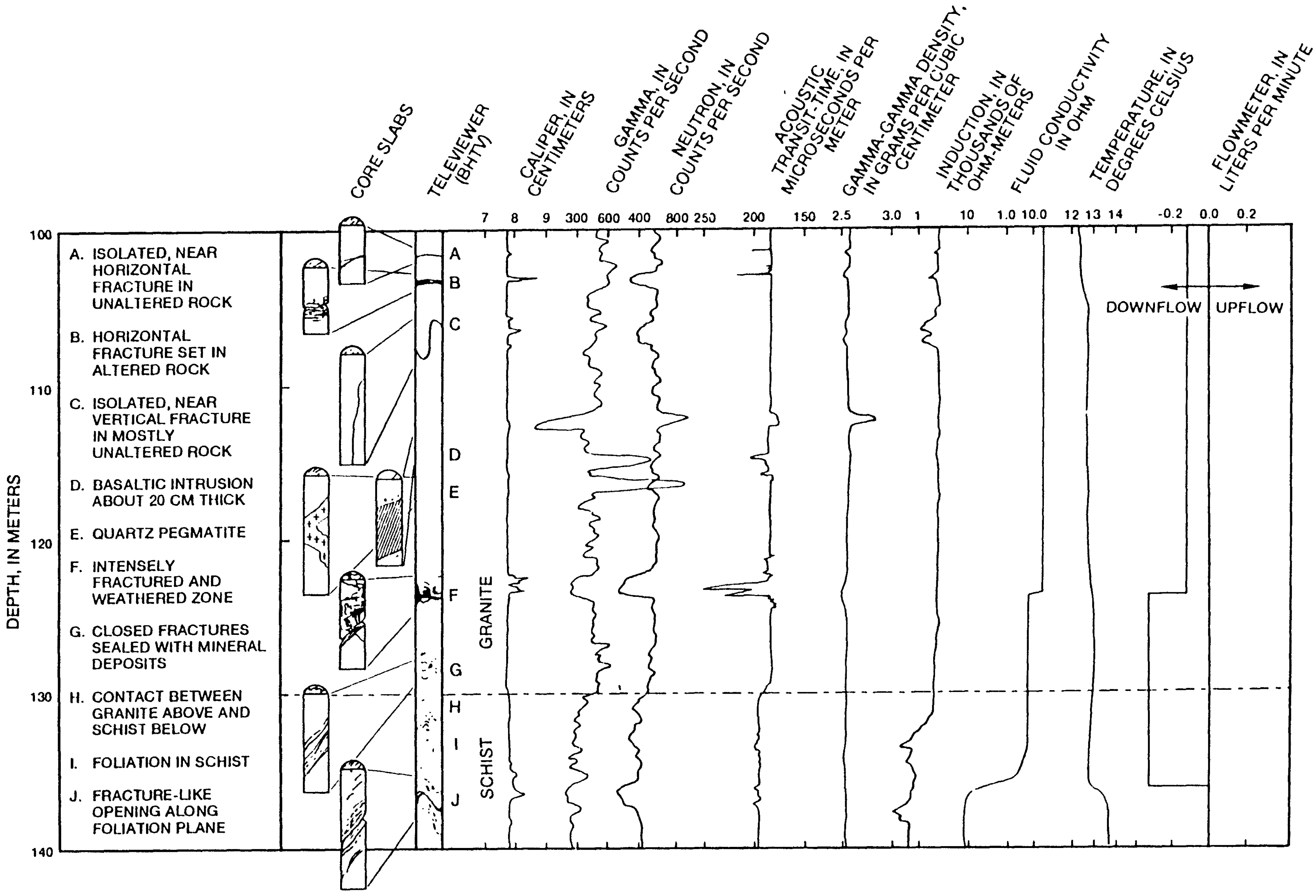

Figure 22. Summary of geophysical log responses for fractures in crystalline rock, illustrating most of the techniques used in fracture characterization in hydrogeology.

of different measurements obtained at different scales of investigation are combined in a single study. The combination of surface soundings, borehole-to-borehole tomography, cross-borehole flow measurements, geophysical logs, traditional bedrock mapping, and standard geologic analysis including statistical assessment of outcrop fractures can be especially effective in fracture characterization, as indicated by the various field studies described in this review.

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