GEOPHYSICAL WELL LOG DATA FOR STUDY OF WATER FLOW IN FRACTURES IN BEDROCK NEAR MIRROR LAKE, WEST THORNTON, NEW HAMPSHIRE

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U.S. GEOLOGICAL SURVEY

Open-File Report 85-340

Prepared in cooperation with
CORNELL UNIVERSITY and

INSTITUTE OF ECOSYSTEM STUDIES,
THE NEW YORK BOTANICAL GARDEN

Lakewood, Colorado
1985

UNITED STATES DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, Secretary

GEOLOGICAL SURVEY

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CONVERSION FACTORS

Multiply SI units	By	To obtain inch-pound units
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)		inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)		mile (mi)

The following units are listed to define abbreviations:

kilohertz (kHz)

ILLUSTRATIONS

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GEOPHYSICAL WELL LOG DATA FOR STUDY OF WATER FLOW IN FRACTURES IN BEDROCK NEAR MIRROR LAKE, WEST THORNTON, NEW HAMPSHIRE

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ABSTRACT

Four closely spaced boreholes were drilled through about 20 meters of till into schist bedrock near Mirror Lake, West Thornton, New Hampshire. The site was selected for borehole-geophysical research because it is included in a detailed ground-water study where the effects of flow in fractures on flow in overlying drift deposits is being studied. Three of the boreholes are about 100 meters deep and the fourth is about 230 meters in depth. All four boreholes were logged with caliper, natural gamma, single-point-resistivity, acoustic and acoustic televiewer logs. Fracture sets dipping about 45° to the east were detected in all four boreholes. Two sets of deeper fractures were detected near the bottom of the deepest borehole. Acoustic waveform logs were obtained in all boreholes using three different source frequencies, 34, 15, and 5 kilohertz, for future comparison between surface and borehole seismic data.

INTRODUCTION

Few studies have treated the flow in fractures in basement rocks that underlie more permeable surficial deposits as part of the overall ground-water-modeling problem. The majority of recent reports that consider fracture hydrology are concerned with deep flow systems during long periods of geologic time or with the aspects of such flow related to engineering properties and slippage along fault zones. One of the major reasons why fracture-hydrology studies have been extremely limited is the great complexity of natural fracture systems. Paillet and Keys (1984) review the difficulties in modeling the characteristics of fracture systems on the basis of limited borehole data. Davison (1984) describes in detail a Canadian project designed to monitor the hydrology of a fracture flow system during the construction of a deep excavation. This reference illustrates the elaborate test procedures and great expense needed to monitor such complex hydrological systems.

During the formulation of studies such as that reported by Davison, (1984), it has become clear that fracture flow systems probably are more complicated than originally expected. For example, borehole-televiewer and borehole-television logs of one of the major hydraulically conductive fractures zones at the Canadian site indicated more than a doubling in apparent fracture-zone thickness between boreholes less than 50 meters apart (Paillet and Keys, 1984). These initial results indicated that much additional information about the three-dimensional nature of fracture networks would be needed before the interaction between fracture flow and overlying aquifers can be understood.

This report describes the setting and initial borehole-geophysical data intended to provide the basis for studies of the interaction of fracture flow with ground-water movement in overlying unconsolidated sediments. The site near Mirror Lake was selected because it was readily accessible, and because it provided the relatively simple hydrogeological conditions of permeable glacial deposits overlying massive crystalline basement rock. The area adjacent to Mirror Lake is part of an intensive study of the interaction of Mirror Lake with ground-water (Winter, 1984). It is expected that the hydraulic head information provided by piezometers in till and shallow bedrock wells will be useful in characterizing the hydrological interaction between flow in surficial deposits and flow in fractures in bedrock. The geophysical data are being presented at this time in order to provide information for researchers who might be interested in applying their specialized fracture-characterization methods to this site. Tentative U.S. Geological Survey plans include at least cross-hole aquifer tests and surface-to-borehole seismic imaging to be conducted during 1985. These geophysical data are intended to supplement the information presented by Winter (1984).

LOCATION OF THE STUDY SITE

The study site is located in the Hubbard Brook Experimental Forest operated by the U.S. Forest Service in West Thornton, New Hampshire (fig. 1). The hydrology of the Mirror Lake area is described by Winter (1984) and Likens (1985). A set of four boreholes, designated the Eastern Bedrock or EBR series, were drilled as the basis for the fracture-characterization study. The boreholes were drilled about 10 meters apart because previous experience has indicated that commonly it is often very difficult to correlate individual fractures between boreholes even within these relatively short distances.

The four adjacent boreholes were constructed by deepening a set of three previously drilled boreholes, EBR1, EBR2, and EBR3 in figure 1, and drilling a fourth deeper borehole, EBR4. Data on depth and diameters, for these boreholes are given in table 1. All four boreholes are cased 3 meters into bedrock. The boreholes also are located within 5 meters of a set of 5 nested piezometers in the overlying till.

The geophysical logs and cuttings descriptions for the three original boreholes are given by Winter (1984). The three boreholes were later deepened to 107 meters during the summer of 1984. A summary of the geophysical logs made in 1984 are given in table 2. The additional borehole EBR4 was drilled to a depth of 229 meters, and logs were run over the full depth of that borehole during 1984. It is assumed that the primary interest in future fracture study will focus on sets of fractures that intersect the parts of the boreholes below a depth of 50 meters.

The basement rock underlying the Mirror Lake area is visible in a road cut along Interstate Highway 93 about 0.8 kilometers east of the EBR boreholes. This outcrop shows multiple natural fractures in the bedrock. A distinct zone of yellow-brown weathered and brecciated rock is included in the otherwise light-gray schist exposed along the east side of the south-bound lane of the highway. Various cross-cutting veins of quartz or pegmatite also are apparent in the road cut. A photograph of intersecting fractures and veins exposed along the west wall of the south-bound lane is shown in figure 2.

BOREHOLE EQUIPMENT

The four EBR boreholes were logged using conventional caliper, single-point-resistivity, gamma, and acoustic logs and using the acoustic borehole televiewer. The caliper log measures the diameter of the borehole by recording the average of three spring-loaded arms. The natural gamma log records the natural gamma activity of the rocks adjacent to the probe as it is withdrawn from the borehole. The single-point-resistivity log measures the potential difference between two electrodes adjacent to a single current electrode; a second return current electrode is located at ground level. The acoustic log measures the inverse of rock compressional velocity, usually known as acoustic transit time. All of these conventional types of logging equipment are described in more detail by Keys and MacCary (1971).

The acoustic borehole televiewer is described by Zemanek and others (1969). The televiewer is an acoustic device that produces a photographic image representing the pattern of acoustic reflectivity on the borehole wall. The image is oriented with respect to the component of the Earth's magnetic field in a plane perpendicular to the borehole axis. An example of the interpretation of fracture strike and dip on the basis of a televiewer-log image is shown in figure 3. In situations where the logging site is near one of the Earth's magnetic poles and the geomagnetic field has a steep inclination, or where the borehole axis is greatly deviated from vertical, apparent fracture strike and dip can be converted to true strike and dip by means of the methods discussed by Lau (1983) and Kierstein (1983).

GEOPHYSICAL LOGS FOR THE EASTERN BEDROCK BOREHOLES

Natural gamma, single-point-resistivity, and televiewer logs are shown for EBR1, EBR2, and EBR3 boreholes in Figures 4, 5, and 6. The figures also include descriptions of cuttings as recorded during drilling. Expanded televiewer logs for these boreholes are given in Figure 7. These logs indicate the same generalized relationship between quartz-monzonite intrusions and increased gamma counts, and between fractures and single-point-resistivity. The geophysical logs for borehole EBR4 are shown in figure 8. An expanded representation of the televiewer logs for this borehole is given in figure 9. For convenience of presentation, logs in figure 8 have been divided into 80-meter intervals. The figure also includes descriptions of cuttings as recorded during drilling. The quartz monzonite intrusions appear to have a much greater gamma activity, yet the cuttings description seems to show the quartz monzonite shifted downward with respect to the natural gamma log. This may represent the time required for the cuttings to arrive at the surface; that is, the drill bit probably had penetrated some distance into the quartz monzonite before quartz monzonite cuttings began to appear at the surface in the drilling fluid.

The single-point-resistance log was made with the assumption that the single-point log can be a good indicator of fractures. In crystalline rocks of relatively great resistivity, the single-point-resistivity log probably is affected by altered rock adjacent to fractures, and not directly by fracture porosity (Davison and others, 1982; Keys and MacCary, 1971). Clay minerals in altered feldspars provide exchange cations for the conduction of current even when adjacent rock is effectively non-conductive, and natural waters are very fresh. The single-point resistance log in Figure 8 shows significant anomalies at many of the larger fractures indicated on the televiewer log. The size and thickness of the single-point-resistivity anomalies probably can be assumed to be qualitative indicators of the extent of alteration in the vicinity of individual fractures, but this does not necessarily mean that the extent of alteration correlates with fracture permeability.

The acoustic log measures the inverse of rock compressional velocity, but the velocity-determining algorithm in the logging system may not function when acoustic waves are severely attenuated by fractures. Therefore, actual acoustic transit times recorded by the log adjacent to fracture zones are attributed to errors in arrival detection and do not represent a real rock property. The relative size of acoustic log anomalies therefore may provide a qualitative correlation with fracture permeability, but this relationship is not always accurate, and sometimes may be very misleading. Altered rock adjacent to fractures may likewise attenuate the acoustic signal, further complicating the relationship between apparent acoustic transit time and fracture permeability.

One of the important fracture characterization methods planned for the future at Mirror Lake is vertical seismic profiling (Paillet and Turpening, 1984). For this reason, accurate seismic background data is important, and acoustic waveform logs were made for all four boreholes using two conventional acoustic sources of 34 and 15 kilohertz, and a new low frequency source with a 5 kHz centerband frequency (Paillet and Turpening 1984). These logs are recorded by digitizing the entire pressure signal received by the acoustic-logging probe, rather than routing this signal through the acoustic-arrival detection system in the conventional acoustic logging system. Many of the considerations involved in comparing acoustic logs that have much lower frequency, surface seismic signals are discussed by Stewart and others (1984). Fracture characterization using acoustic-waveform logs is discussed by Paillet (1980) and Paillet and White (1982).

CORRELATION OF FRACTURES ON TELEVIEWER LOGS

The televiewer logs for the lower parts of the four EBR boreholes indicate that there are several sets of fractures, many of which dip at about 45° towards the east. The televiewer logs for adjacent parts of the four EBR boreholes are shown in Figure 10. The depths have been shifted in this figure so that fractures dipping to the east at 45° project horizontally. There apparently is some correlation between wells because some features do project from televiewer log to televiewer log. However, some apparent fractures on the televiewer log do not project from borehole to borehole.

The scaled drawings of televiewer logs given in figures 7 and 8 can provide only an approximate indication of fractures as they appear on the televiewer log. Examples of actual intervals of televiewer logs are given in figure 11, where the set of fractures in borehole EBR4 at a depth of about 77 meters in depth is compared to the fractures that apparently project into the other three boreholes in figure 10.

It is possible that fracture patterns might be related to trends in lithology, so an attempt was made to correlate natural gamma logs among the EBR boreholes (fig. 12). The best correlation among the gamma logs for the EBR boreholes is nearly horizontal and clearly different from the steeply dipping trend of the prominent major fractures on the televiewer logs.

Table 1.--Diameter and original and final depths of boreholes.

Borehole	Diameter (millimeters)	Original Depth (meters)	Final Depth (meters)
EBR1	153	47	107
EBR2	153	62	107
EBR3	153	62	107
EBR4	153	--	229

Table 2.--Geophysical logs made in boreholes.

Borehole	Log Type	Date Run	Interval logged (meters)
EBR1	Natural gamma	7-10	107-surface
	Single-point-resistance	7-10	107-casing
	Televiewer	7-11	107-17
	Acoustic waveform:		
	15 kHz	7-13	107-casing
	sparker	7-13	107-16
EBR2	Natural gamma	7-10	107-surface
	Single-point-resistance	7-10	107-casing
	Televiewer	7-11	107-16
	Acoustic waveform		
	sparker	7-13	107-19
EBR3	Natural gamma	7-10	107-surface
	Single-point-resistance	7-10	107-casing
	Televiewer	7-11	107-17
	Acoustic waveform		
	Sparker	7-13	107-23
EBR4	Caliper	7-11	229-surface
	Natural gamma	7-10	229-surface
	Single-point-resistance	7-10	229-casing
	Acoustic velocity	7-12	229-casing
	Televiewer	7-11	229-casing
	Acoustic waveform		
	34 kHz	7-12	229-casing
	15 kHz	7-12	229-casing
	sparker	7-12,13	229-casing

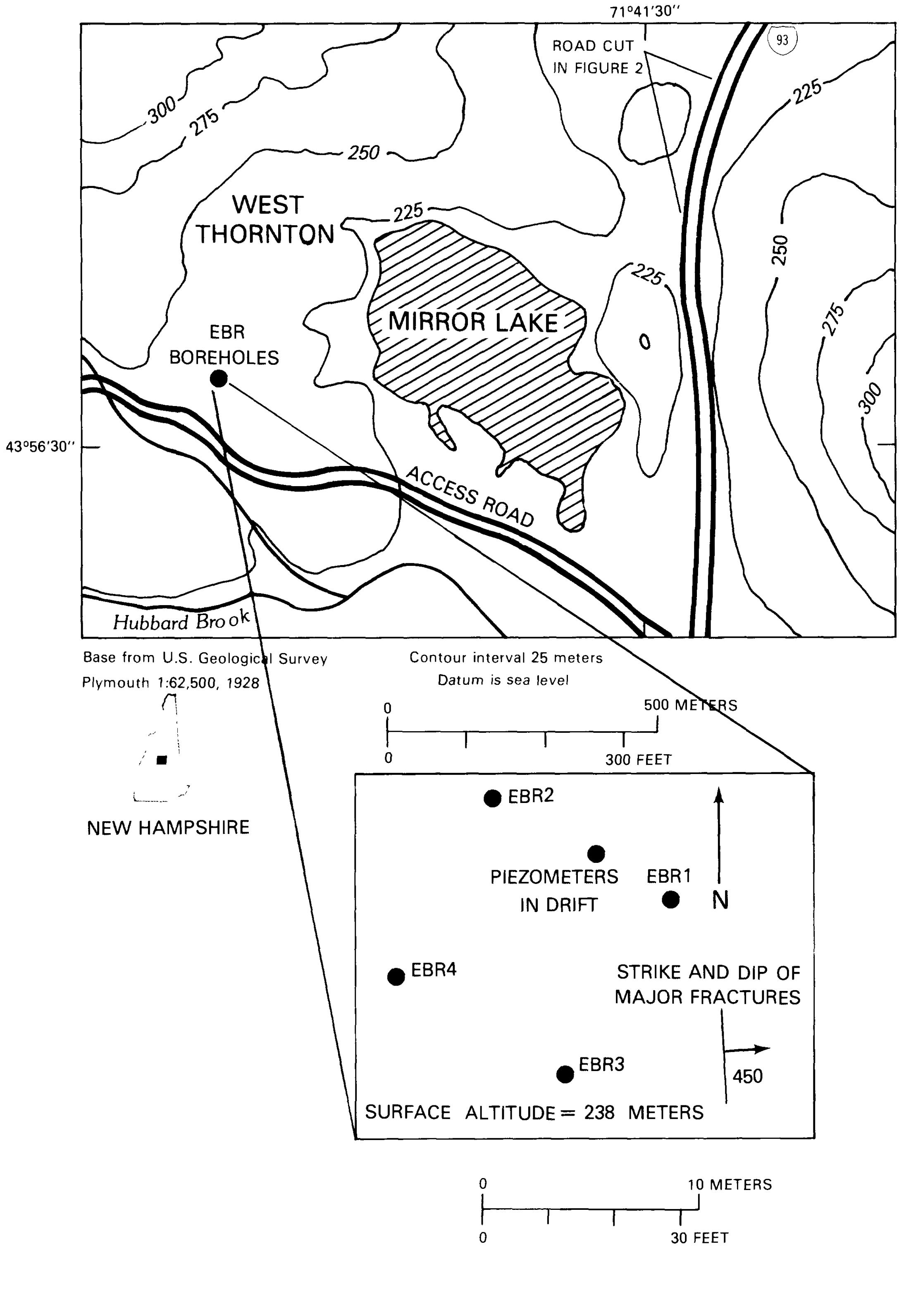

Figure 1.--Location of (EBR) boreholes near Mirror Lake.

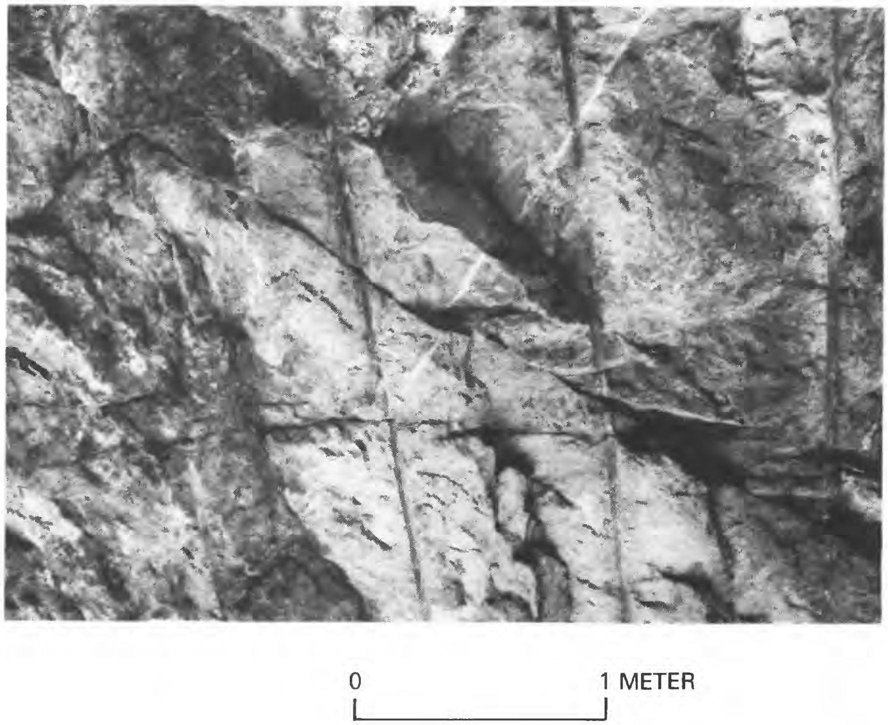

Figure 2.--Fractures and quartz veins in road cut along Interstate Highway 93, 0.5 kilometer northeast of the EBR boreholes.

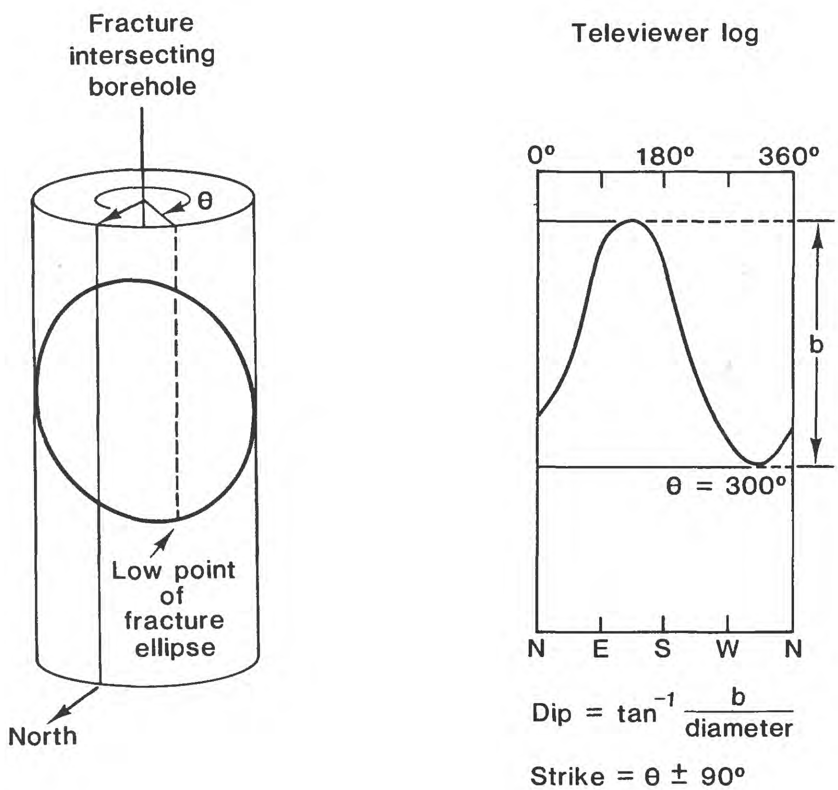

Figure 3.--Schematic illustration of fracture image in televiewer log display.

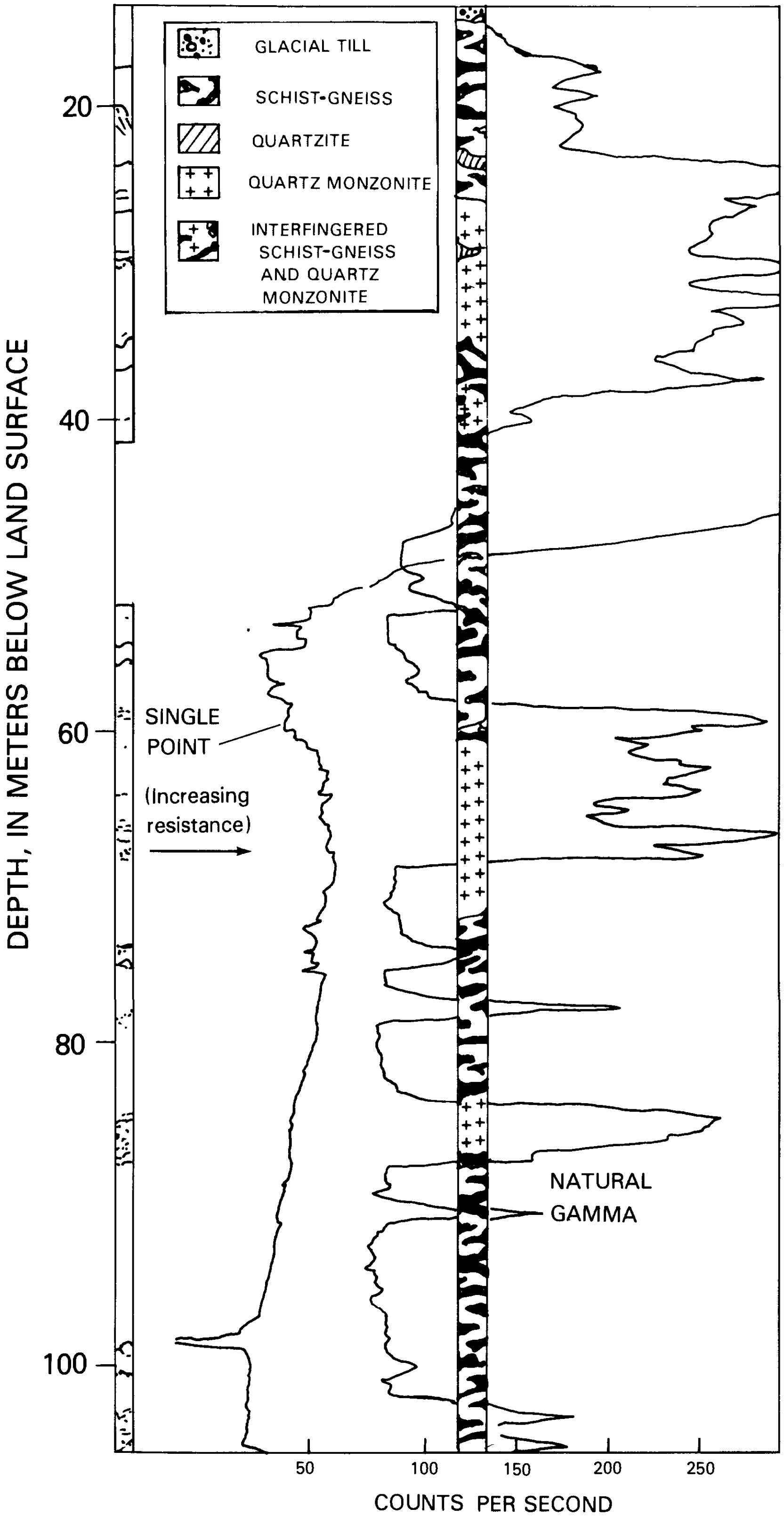

Figure 4.--Summary of geophysical logs and cuttings description for boreholes EBR1.

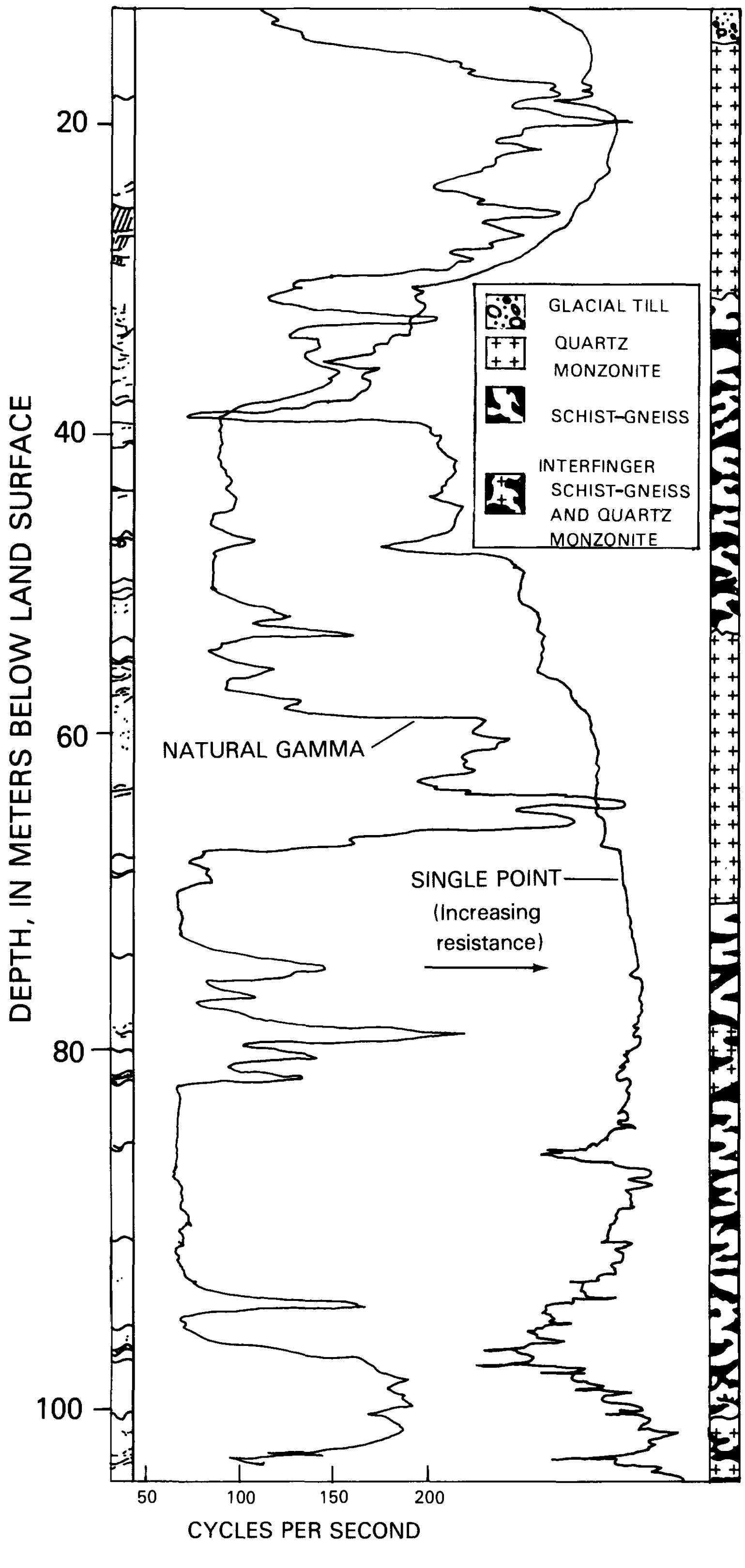

Figure 5.--Summary of geophysical logs and cuttings description for boreholes EBR2.

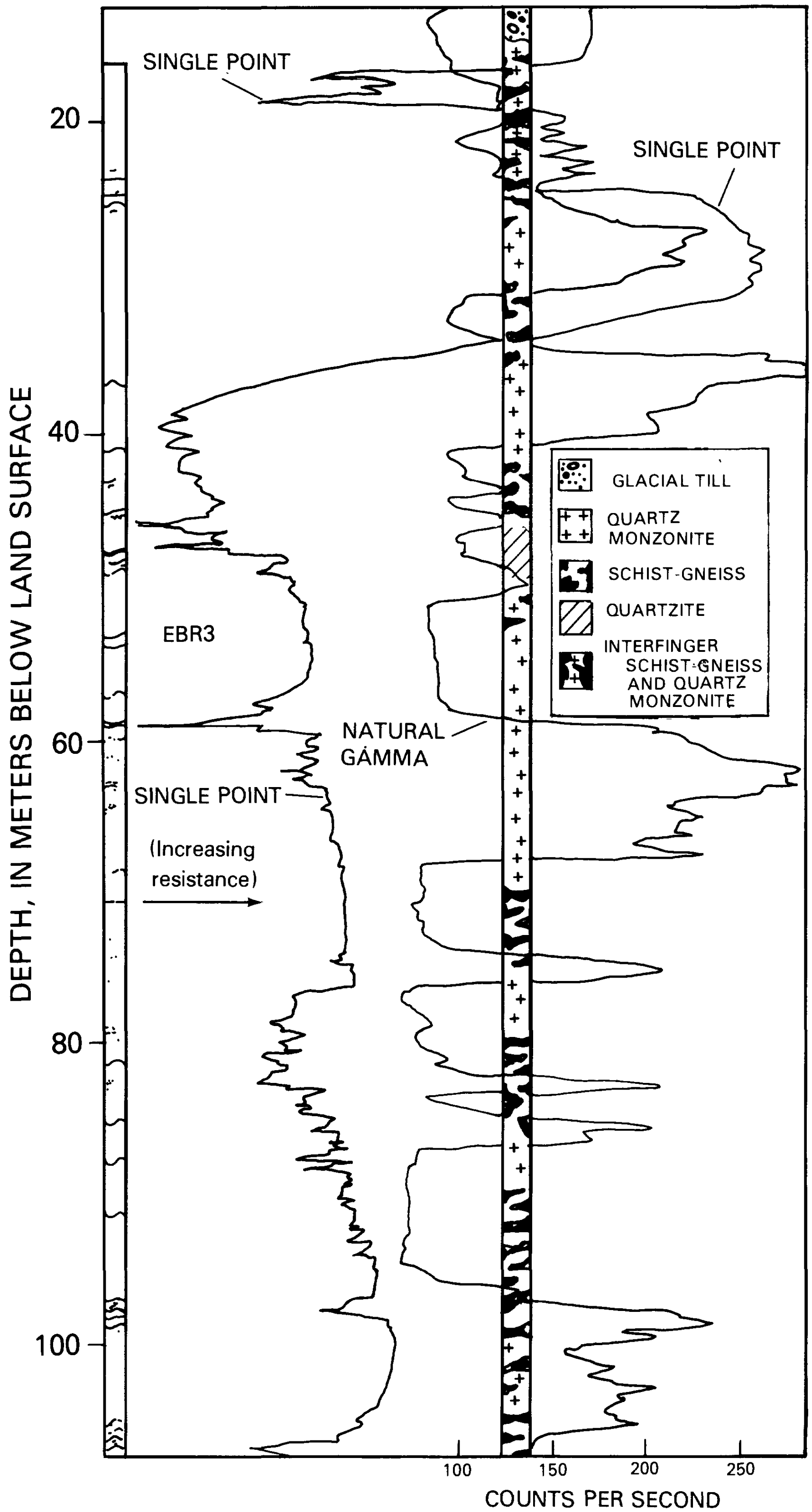

Figure 6.--Summary of geophysical logs and cuttings description for borehole EBR3.

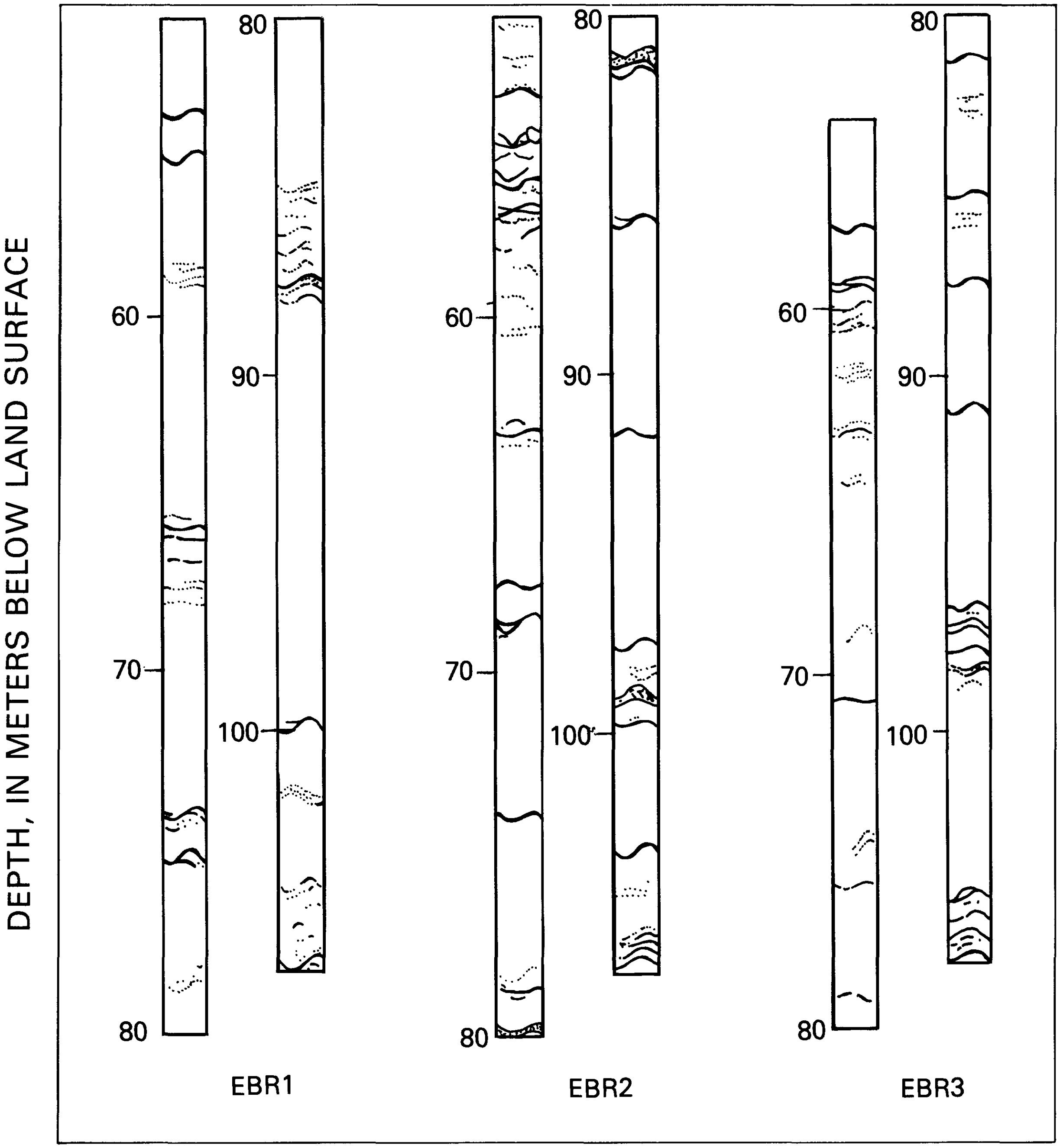

Figure 7.--Televiewer logs for boreholes EBR1, EBR2, and EBR3.

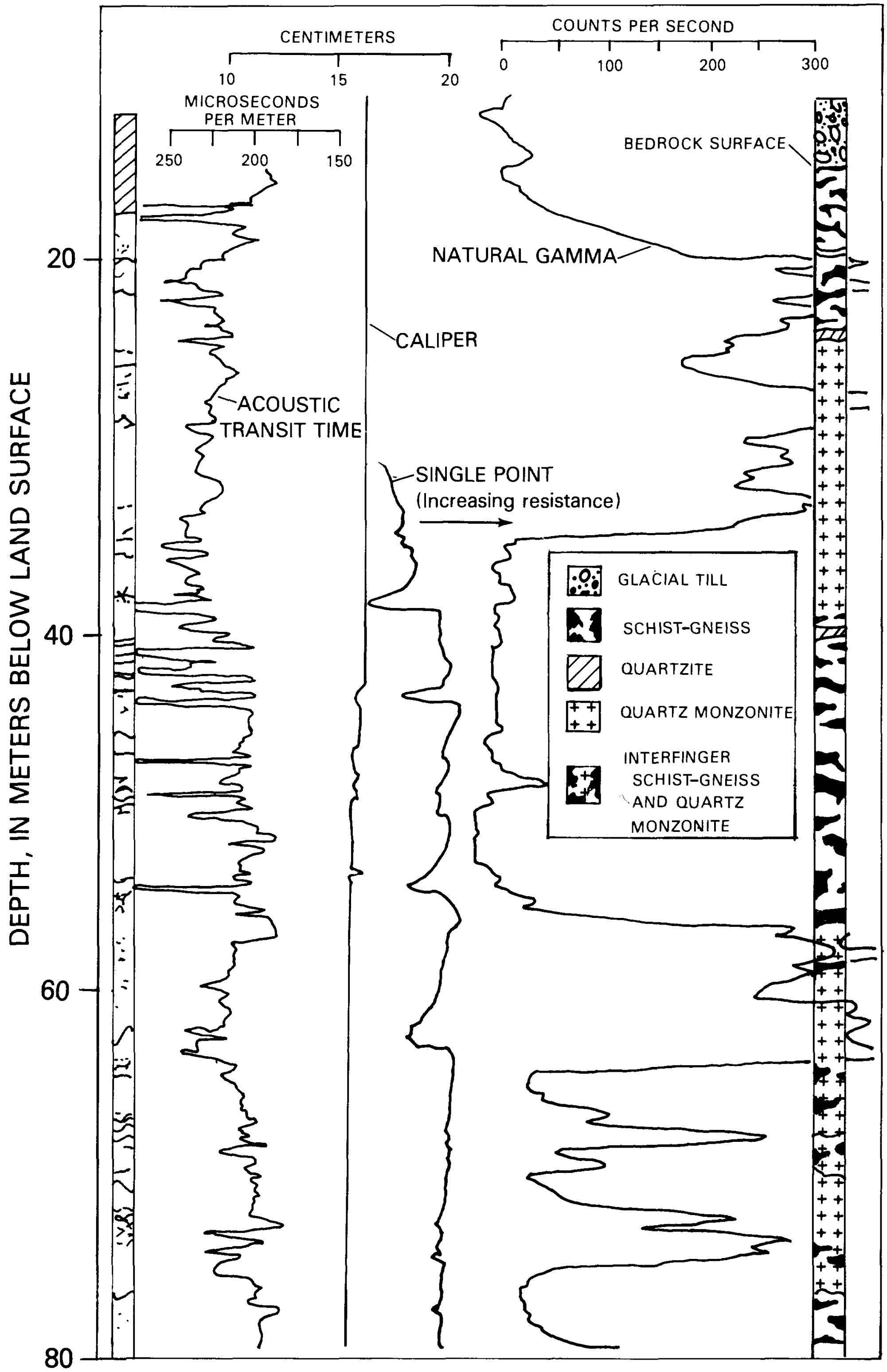

Figure 8.--Summary of geophysical logs and cuttings description for borehole EBR4.

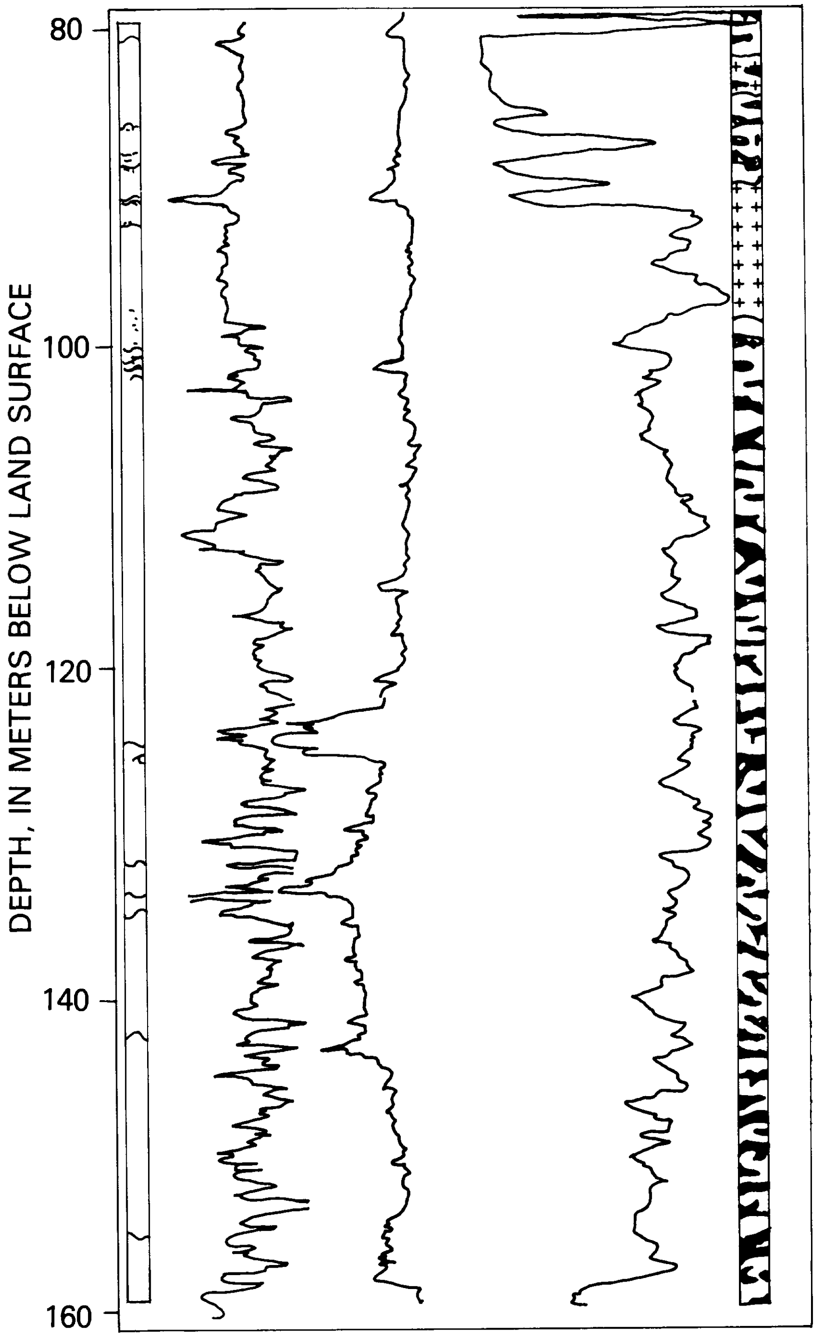

Figure 8.--continued.

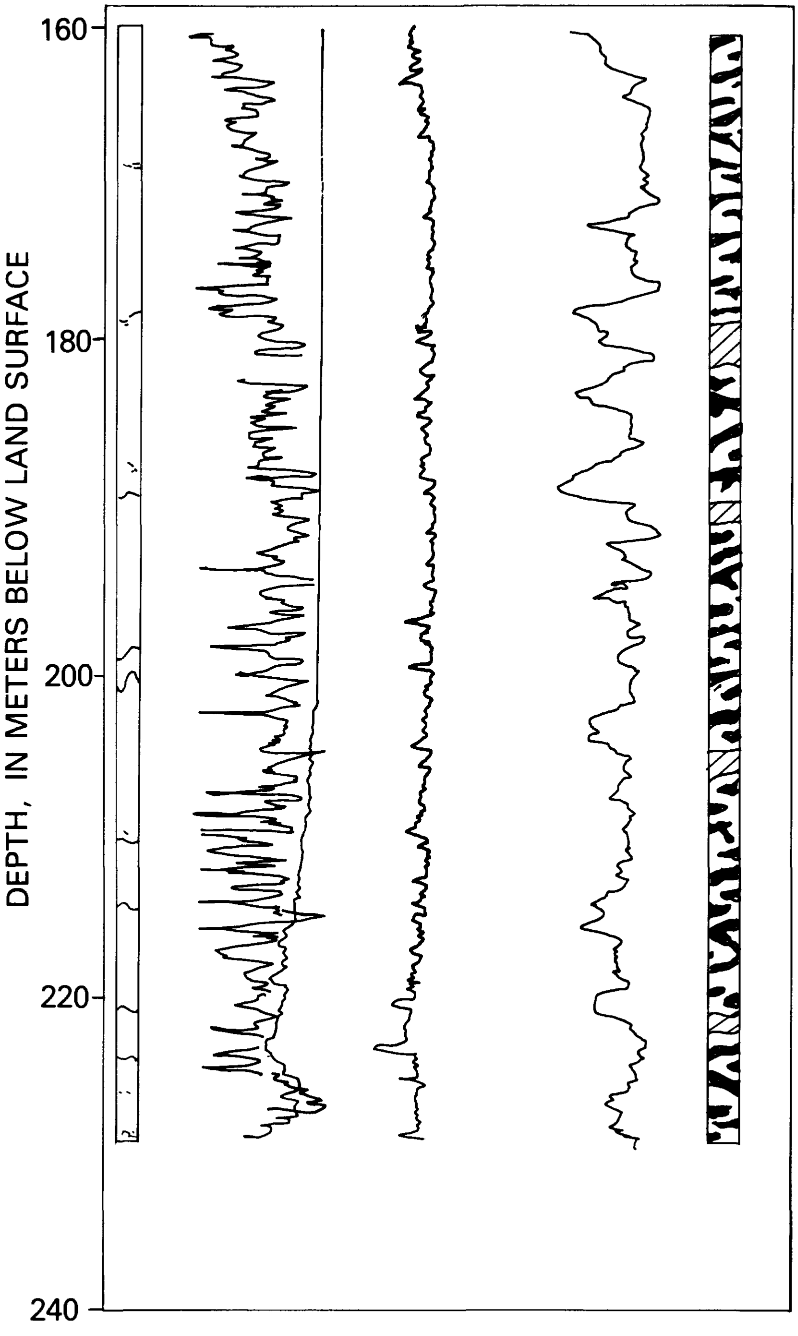

Figure 8.--continued.

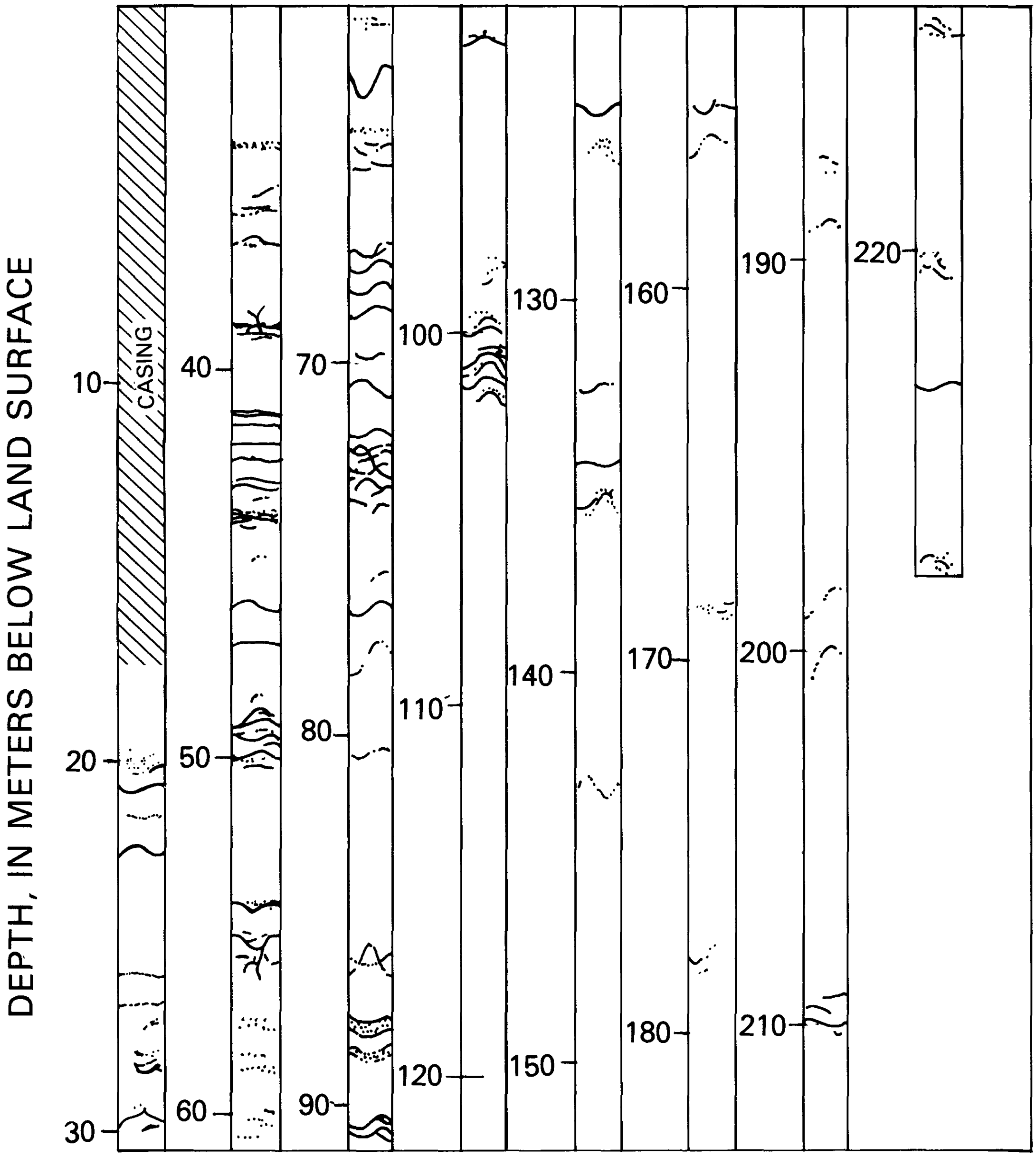

Figure 9.--Televiewer log data for boreholes EBR4.

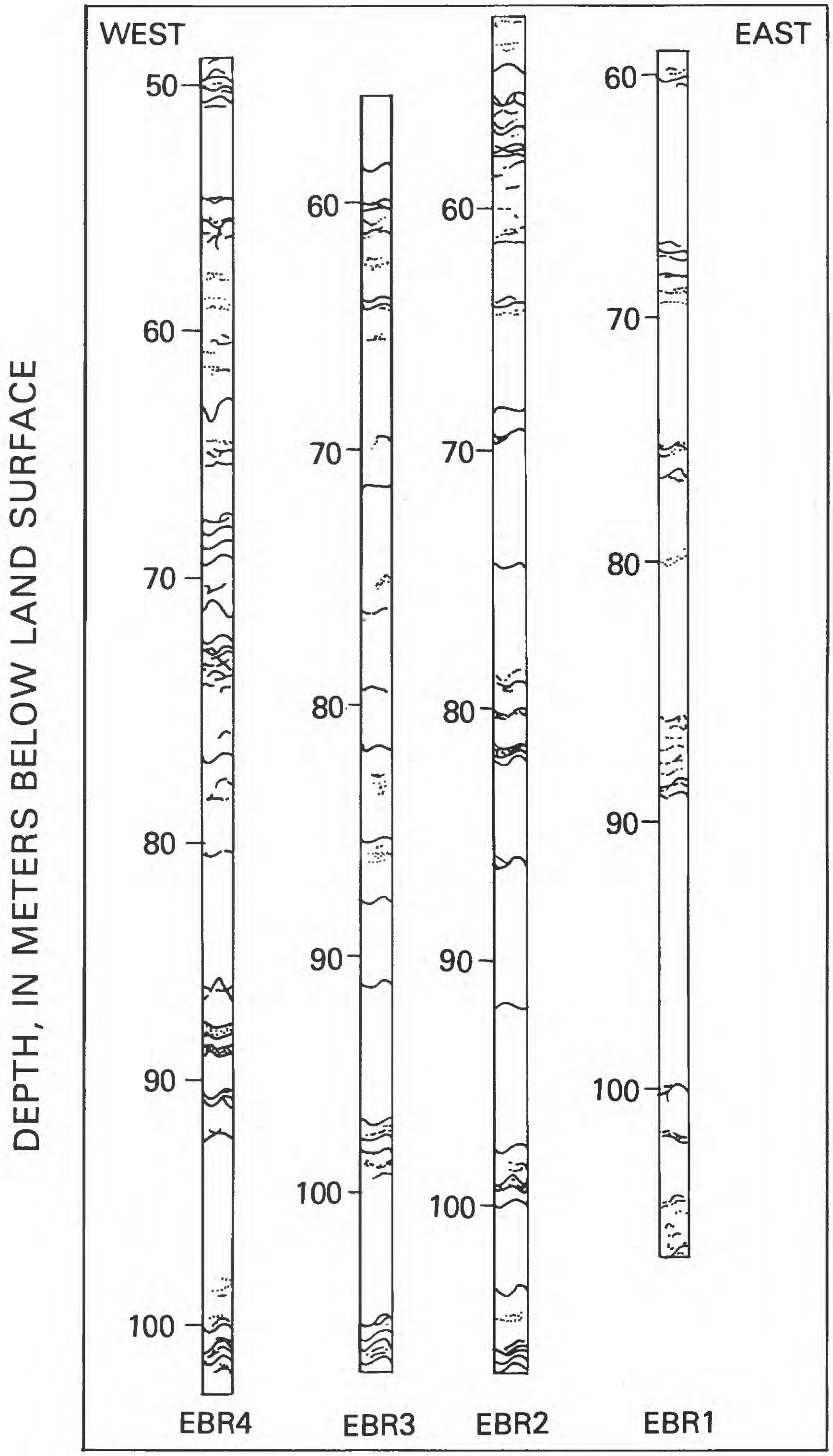

Figure 10.--Depth adjustment of the EBR boreholes to provide horizontal alignment of eastward-dipping fractures.

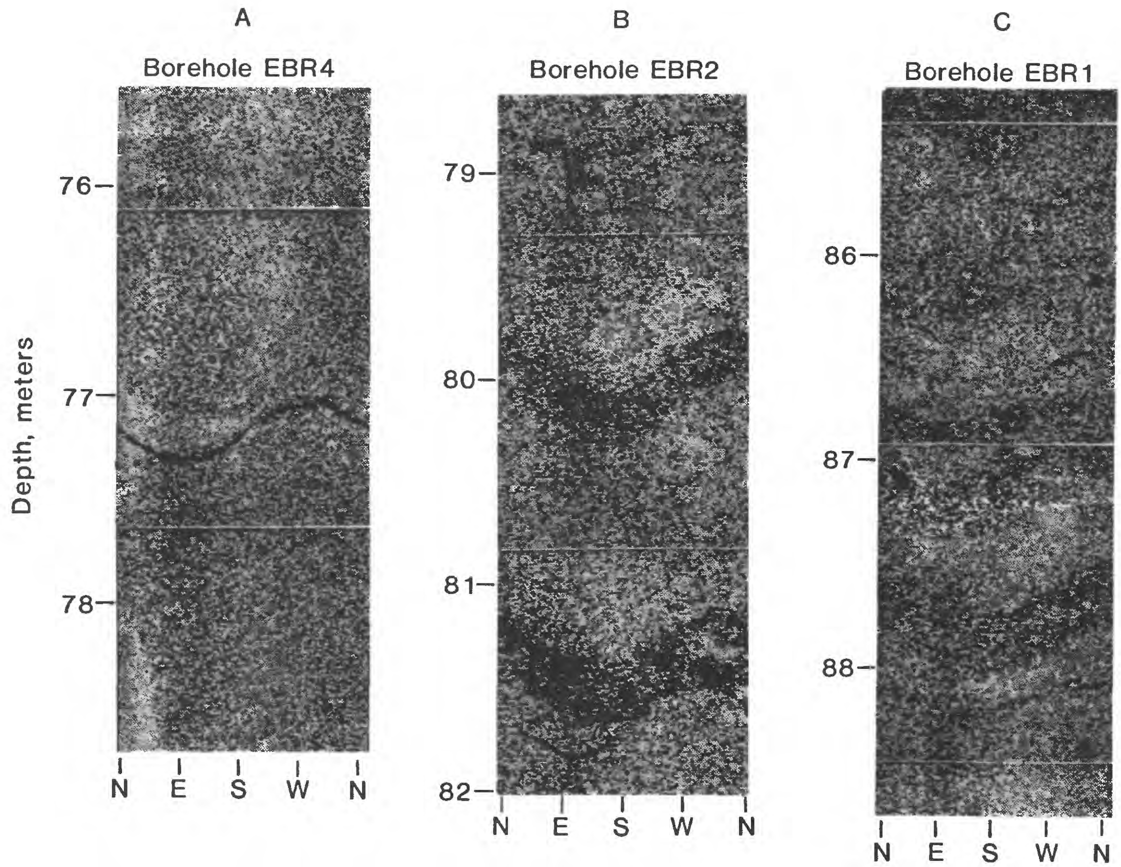

Figure 11.--Example of fracture correlation across the EBR boreholes; eastward-dipping fracture in : (A) borehole EBR4 compared to fractures at the projected intersection of this fracture with (B) borehole EBR2, and (C) borehole EBR1.

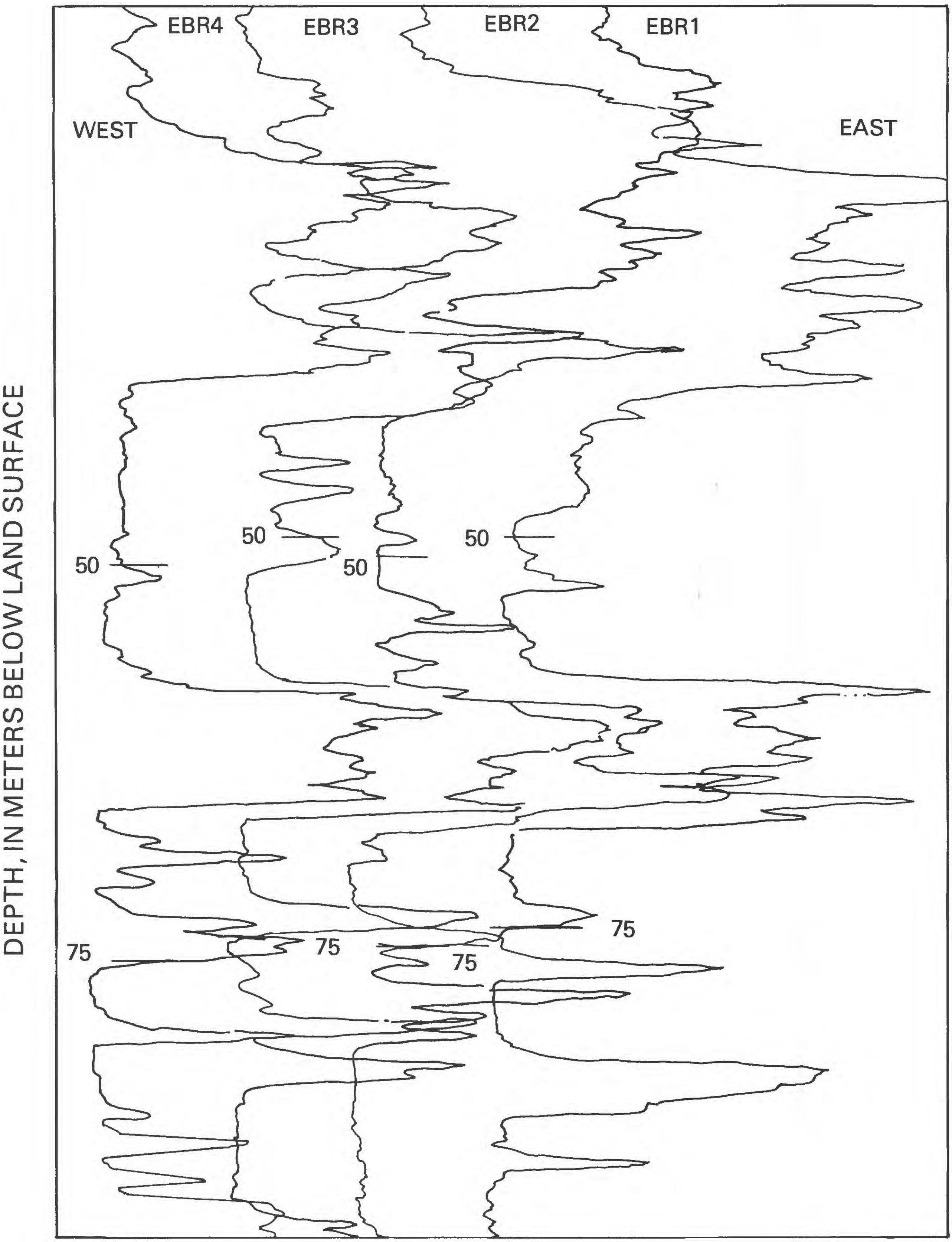

Figure 12.--Depth adjustment of natural gamma logs from EBR boreholes for illustrating correlation with minimal vertical alignement.

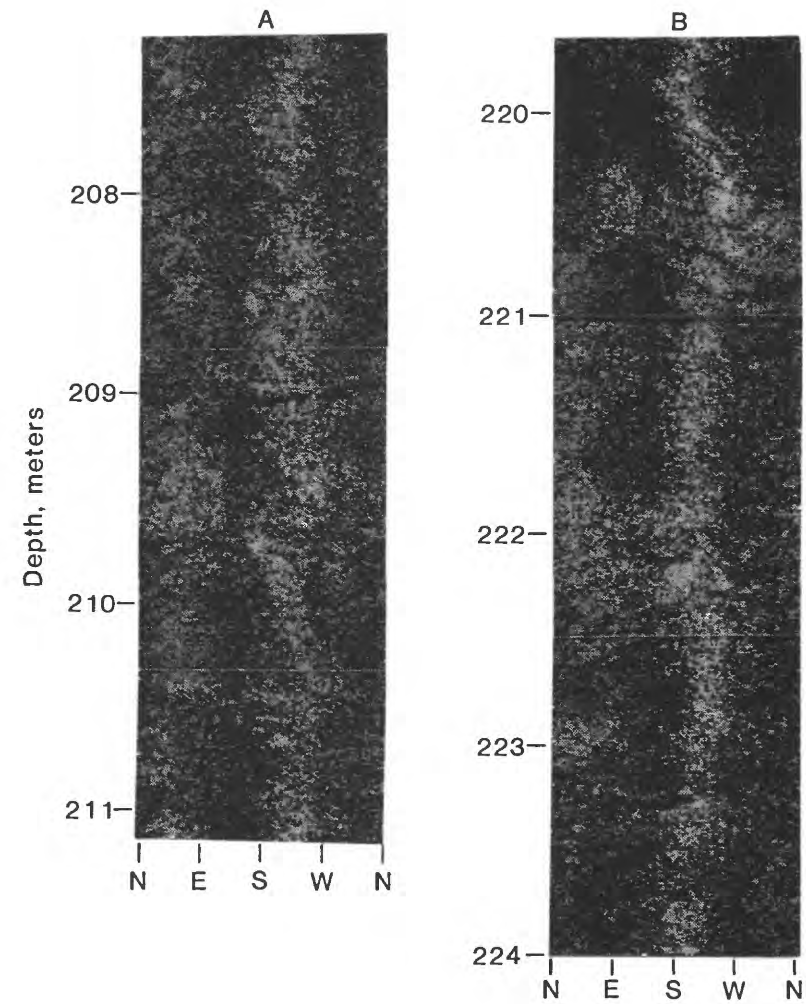

Figure 13.--Televiewer logs of major fractures near (A) 210 meters and (B) 223 meters in borehole EBR4.

DEEP FRACTURES IN BOREHOLE EBR4

Televiewer logs for the deeper part of borehole EBR4 are given in Figure 9. This borehole penetrated through more than 60 meters of apparently unfractured rock, but encountered prominent fractures at depths of about 210 and 222 meters. The original photographs of the televiewer logs showing these two fracture sets are given in figure 13.

SUMMARY

A set of four adjacent bedrock boreholes have been constructed at an easily accessible site on the Hubbard Brook Experimental Forest in West Thornton, New Hampshire. The boreholes are located within a few meters of a nested piezometer station providing data for input to a local ground-water model that can be related to fracture flow patterns in the crystalline basement at the site. Caliper, natural gamma, single-point-resistivity, acoustic televiewer, and acoustic waveform logs were obtained in all four boreholes. Single-point-resistivity logs indicate significant anomalies at some of the largest fractures indicated on the televiewer log. These anomalies may indicate that electrically conductive clay minerals are present in and adjacent to some fracture openings, indicating that some geochemical interaction between rock and ground-water in fractures may have occurred.

REFERENCES

Davison, C. C., 1984, Monitoring hydrological conditions in fractured rock at the site of Canada's underground research lab: Ground Water Monitoring Review, v. 4, no. p. 95-102.

Davison, C. C., Keys, W. S., and Paillet, F. L., 1982, Use of borehole-geophysical logs and hydrologic tests to characterize crystalline rock for nuclear-waste storage, Whiteshell Nuclear Research Establishment, Manitoba, and Chalk River Nuclear Laboratory, Ontario, Canada: U.S. Department of Energy Report ONWI-418, issued by the U.S. Department of Commerce, National Technical Information Service, 103 p.

Keys, W. S., and MacCary, L. M., 1971, Application of borehole geophysics to water-resources investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 2, Chapter El, 126 p.

Kierstein, R. A., 1983, True location and orientation of fractures logged with the acoustic televiewer (including programs to correct fracture orientation): U.S. Geological Survey Water-Resources Investigations Report 83-4275, 71 p.

Lau, J. S. O., 1983, The determination of true orientations of fractures in rock cores: Canadian Geotechnical Journal, v. 20, no. 3, p. 221-227.

Likens, Eugene, 1985, An ecosystem approach to aquatic ecology--Mirror Lake and its environment: New York, Springer-Verlag [in press].

Paillet, F. L., 1980, Acoustic propagation in the vicinity of fractures which interest a fluid-filled borehole: Society of Professional Well Log Analysts Annual Logging Symposium, 21st, Lafayette, La., 1980, Transactions, p. DD1-DD33.

_____ 1983, Acoustic character of hydraulic fractures in granite: Symposium on Rock Mechanics, 24th, American Institute of Mining, Metallurgical, and Petroleum Engineers, College Tex., 1983, Proceedings, p. 327-334.

Paillet, F. L., and Keys, W. S., 1984, Applications of borehole geophysics in characterizing the hydrology of fractured rocks: National Water Well Association and Environmental Protection Agency Conference on Surface and Borehole Geophysics in Ground Water Investigations, San Antonio, Tex., 1984, Proceedings, p. 743-762.

Paillet, F. L., and Turpening, Roger, 1984, Borehole and surface-to-borehole seismic applications in fracture characterization: Annual International Society of Exploration Geophysicists Meeting, 54th, Atlanta, Ga., 1984, Proceedings, p. 333-335.

Paillet, F. L., and White, J. E., 1982, Acoustic normal modes in the borehole and their relationship to rock properties: Geophysics, v. 47, no. 8, p. 1215-1228.

Stewart, R. R., and Huddleston, P. D., and Kan, T. K., 1984, Seismic versus sonic velocities--A vertical seismic profiling study: Geophysics, v. 49, no. 8, p. 1153-1168.

Winter, T. C., 1984, Geohydrologic setting of Mirror Lake, West Thornton, New Hampshire: U.S. Geological Survey Water-Resources Investigations Report 84-4266, 68 p.

Zemanek, Joseph, Caldwell, R. L., Glenn, E. E., Halcomb, S. V., Norton, L. J., and Strauss, A. J. D., 1969, The borehole televiewer--A new logging concept for fracture location and other types of borehole inspection: Journal of Petroleum Technology, v. 21, no. 6, p. 762-774.