GEOPHYSICAL WELL LOG ANALYSIS OF FRACTURED GRANITIC ROCKS AT ATIKOKAN, ONTARIO, CANADA

By F. L. Paillet and A. E. Hess

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CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

Multiply SI units	By	To obtain inch-pound units
meter (m)	3.281	foot (ft)
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
kilometer (km)	0.6214	mile (mi)
Liter (L)	0.2641	gallon (gal)
Liter per minute (L/min)		
Liter per second (L/s)	15.85	gallon per minute

The following units are listed to define abbreviations:

kilohertz (kHz
microsecond (μs)

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ABSTRACT

Two boreholes, drilled to approximate depths of 750 and 1,260 meters in a granitic intrusion located near Atikokan, Ontario, were studied by obtaining a full suite of conventional borehole geophysical logs. In addition, selected intervals in these boreholes were logged with a borehole acoustic televiewer that produces a high-resolution image of the borehole wall, an acoustic waveform-logging system using 34-kiloHertz magnetostrictive and 5-kiloHertz sparker sources, and a highly sensitive heat-pulse flowmeter. Emphasis in this study was on identifying and characterizing fracture zones that represent ground-water conduits in deeper portions of the granite, and on characterizing the properties of the largest intervals of unfractured granite. Major fracture zones were indicated by correlating geophysical-log anomalies detected on the suite of conventional logs (unpublished data from Atomic Energy of Canada). However, several other anomalies, were identified as mafic intrusions of approximately the same thickness as major fracture zones. Geophysical-log anomalies are compared for all major fracture zones that could serve as significant ground-water conduits, and fracture-zone permeability is estimated on the basis of acoustic tube-wave attenuation in these intervals. Acoustic televiewer logs obtained at depths below 1,000 meters in the deeper well indicate that most of the few fractures identified on core at these depths do not remain open enough under in situ conditions to produce detectable anomalies in acoustic refraction. Flowmeter data indicate that some ground-water circulation occurs in the upper portion of both boreholes. Water in the shallower of the two holes was observed to flow at 2.0 liters per minute; most of this flow entered the borehole at a depth less than 25 meters, and no flow occurred below a depth of 100 meters. Downflow at rates less than 0.5 liters per minute was determined to enter the deeper borehole within 20 meters of the surface, and to exit at various fractures down to a depth of 250 meters.

INTRODUCTION

Recent efforts to identify large rock bodies that might be suitable for the storage of radioactive wastes has increased interest in characterizing permeable fractures in otherwise impermeable crystalline rocks. The geologic factors that control the development and evolution of fracture networks in crystalline rocks is not well understood. Permeable fractures commonly consist of fine-scale features that are difficult to detect from the surface; yet, potential waste-storage sites cannot be drilled full of holes if the rock mass being investigated is to function as an effective barrier to the migration of radioisotopes. The problem is compounded because nondestructive surface geophysical measurements require relatively long seismic and electromagnetic wavelengths to achieve penetration to large depths, even within an undisturbed rock mass. The mechanical and hydraulic properties of crystalline rocks are known to be sensitive to the local state of stress, so that geophysical measurements need to be made under conditions as close to in-situ as possible, if the results of those measurements are to be used to predict rock-mass performance. With these considerations in mind, borehole geophysics is a logical means for investigating the properties of rocks within a large, sparsely-fractured rock mass.

Deep boreholes provide access to in situ conditions with relatively minor disturbance in the immediate vicinity of the borehole wall. Most geophysical logging devices provide sampling volumes that extend beyond the zone of drilling damage and stress concentration, giving scales of investigation consistent with the dimensions of individual fractures. A major task in the design of geophysical logging studies is to optimize the compromise between the need for high resolution of primary geological features, and the need for measurement beyond the annulus of alteration and stress concentration.

This report describes the geophysical investigation of a moderately-sized granitic intrusion located on the Canadian Shield in northwestern Ontario (fig. 1). This investigation is the most recent in a series of such investigations being conducted by the U.S. Geological Survey to improve techniques for the characterization of fractured crystalline rocks. One of the primary purposes of the program is to extend the methods previously tested in rocks of various lithologies to a new site; this enlarges the geophysical data base. Another objective was the field testing of two relatively new geophysical devices: a highly sensitive flowmeter, and a low-frequency acoustic-waveform logging system. One especially important objective is the identification of significant fracture features by means of various geophysical measurements having different volumes of investigation. In this case, one of the boreholes logged for this study deliberately was drilled at approximately 20° from the vertical in order to encounter a nearby suspected near-vertical fault or fracture zone identified from lineations on aerial photographs (Brown and others, 1980). Additional information about fracture properties also was obtained by comparing geophysical logs obtained in the borehole penetrating the observed fault or fracture zone with logs obtained in another borehole located away from major surface lineaments.

Previous studies (Keys, 1984; Davison and others, 1982) emphasized the identification of fractures in boreholes, and the comparison of those fracture indicators with results from borehole television surveys and core data. These studies have resulted in many modifications and improvements in fracture identification techniques applied to borehole geophysics; this report takes the analysis one step further. Rather than surveying entire boreholes with the full suite of geophysical logs, generalized fracture indicators were used to identify specific fracture intervals. Additional effort was concentrated on the two approaches to fracture characterization where results were most likely to have the greatest relevance to the siting of radioactive waste repositories: (1) Characterization of identified fracture zones that may serve as significant ground-water conduits; and (2) Characterization of major unfractured intervals that may correspond to locations suitable for repository construction.

DESCRIPTION OF THE STUDY SITE

The two boreholes logged during this study are located on the Canadian Shield approximately 30 km northwest of the town of Atikokan, Ontario (fig. 1). Both boreholes penetrate a moderately-sized granitic intrusion dated at 2658 +67 million years old (Brown and others, 1984) in Precambrian gneiss of the Superior Province. Surface reconnaissance, general appearance of fractures exposed in outcrops, and lithological trends in this intrusion and the surrounding gneiss are described by Brown and others (1980). Examples of the appearance of fractures and small intrusions in hydraulically exposed outcrops in the vicinity of the Atikokan boreholes are given in figure 2. The boreholes were drilled towards the margins of this intrusion, where surface exposures are described as massive, coarse-grained granite that is relatively homogeneous in character, with only locally weak indications of foliation (Brown and others, 1980). This massive granite was intruded by mafic dikes 1121 +27 million years before present (Brown and others, 1984), with orientation and character of the intrusions indicating a tensional stress regime completely different from the regime indicated by older, sealed fractures in the granite (West, 1984) and possibly related to Lake Superior rifting. More information on the lithology and distribution of fractures in surface outcrops in the vicinity of the Atikokan boreholes is given by Brown and others (1984).

The location of the two Atikokan boreholes, with respect to the surface exposure of granitic rocks and the location of major surface lineations is given in figure 1. Borehole ATK8 is located just west of one of these major surface lineations identified on aerial photographs, geophysical anomalies, and outcrop fracture data. This borehole was drilled towards the east at approximately 20° from the vertical, to encounter the subsurface extension of this surface feature. Borehole ATK8 extends a linear distance of 750 m to a depth of approximately 680 m. Borehole ATK5 is located approximately 5 km to the east of borehole ATK8 in an area without major surface lineations, although there are several short lineations in the area which have been interpreted as minor faults (Brown and others, 1984) (fig. 1). Borehole ATK5 was drilled to a linear distance of 1260 m, dipping to the west at an angle of approximately 20° to the vertical. Geophysical surveys indicate that borehole ATK5 may be deviated significantly from this orientation at depth; the vertical depth of the hole bottom may be somewhat less than approximately 1200 m indicated by the projection the observed dip of surface casing.

GEOPHYSICAL LOGGING EQUIPMENT

Many of the geophysical logs obtained as part of this study, or provided for this study by AECL, were obtained with conventional logging equipment such as that described by Keys and MacCary (1971), Keys (1979), and Hillary and Hayles (1985). A summary of the logs obtained by the U.S. Geological Survey in September, 1985 is given in table 1. All conventional geophysical logs were recorded simultaneously on an analog chart and in digital format on magnetic tape. A 0.15 m (0.5 ft) sampling interval was used.

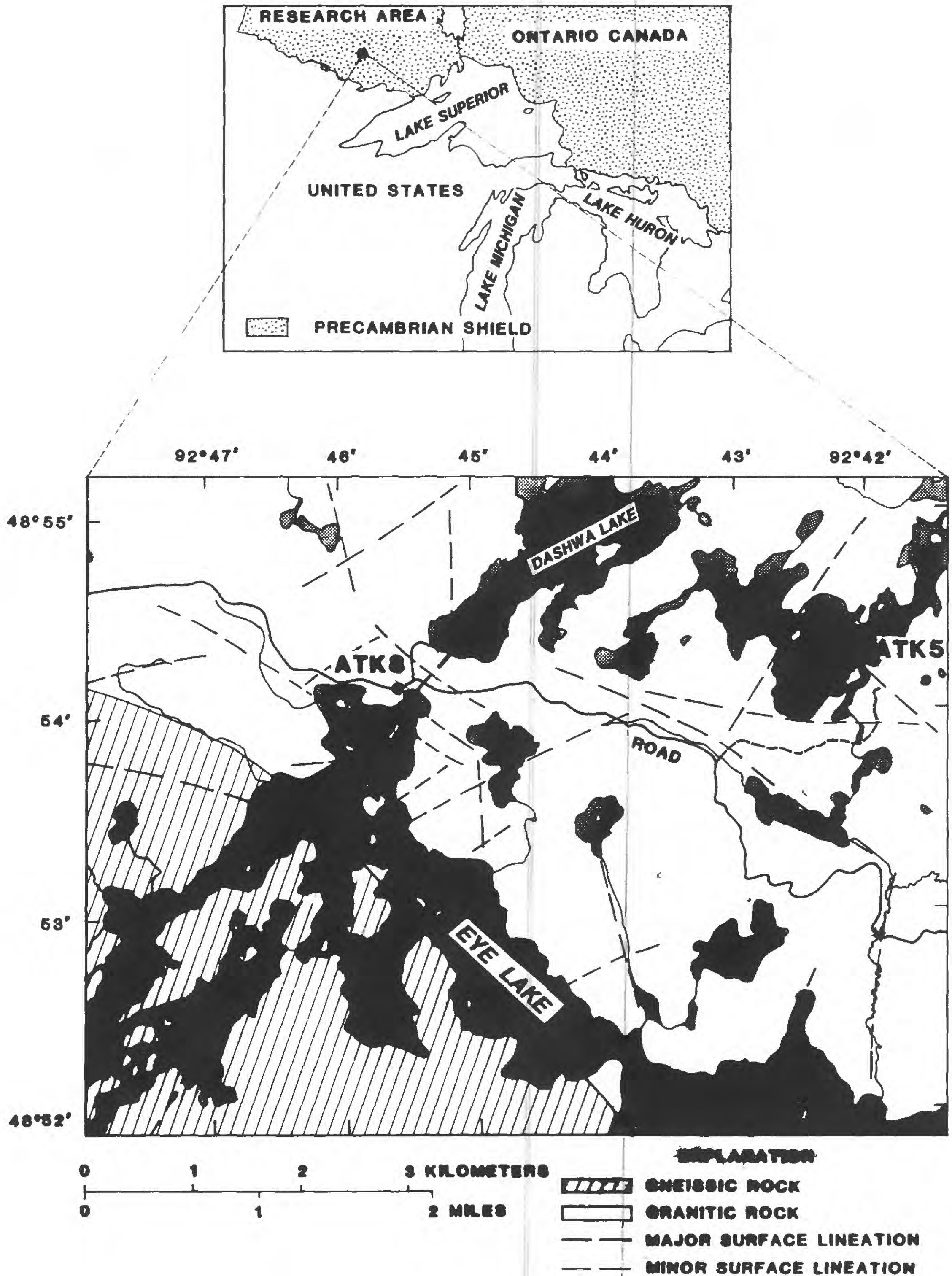


Figure 1.--Location of the Atikokan boreholes, surface exposure of contact of grantic rocks with gneiss, and location of surface lineations.

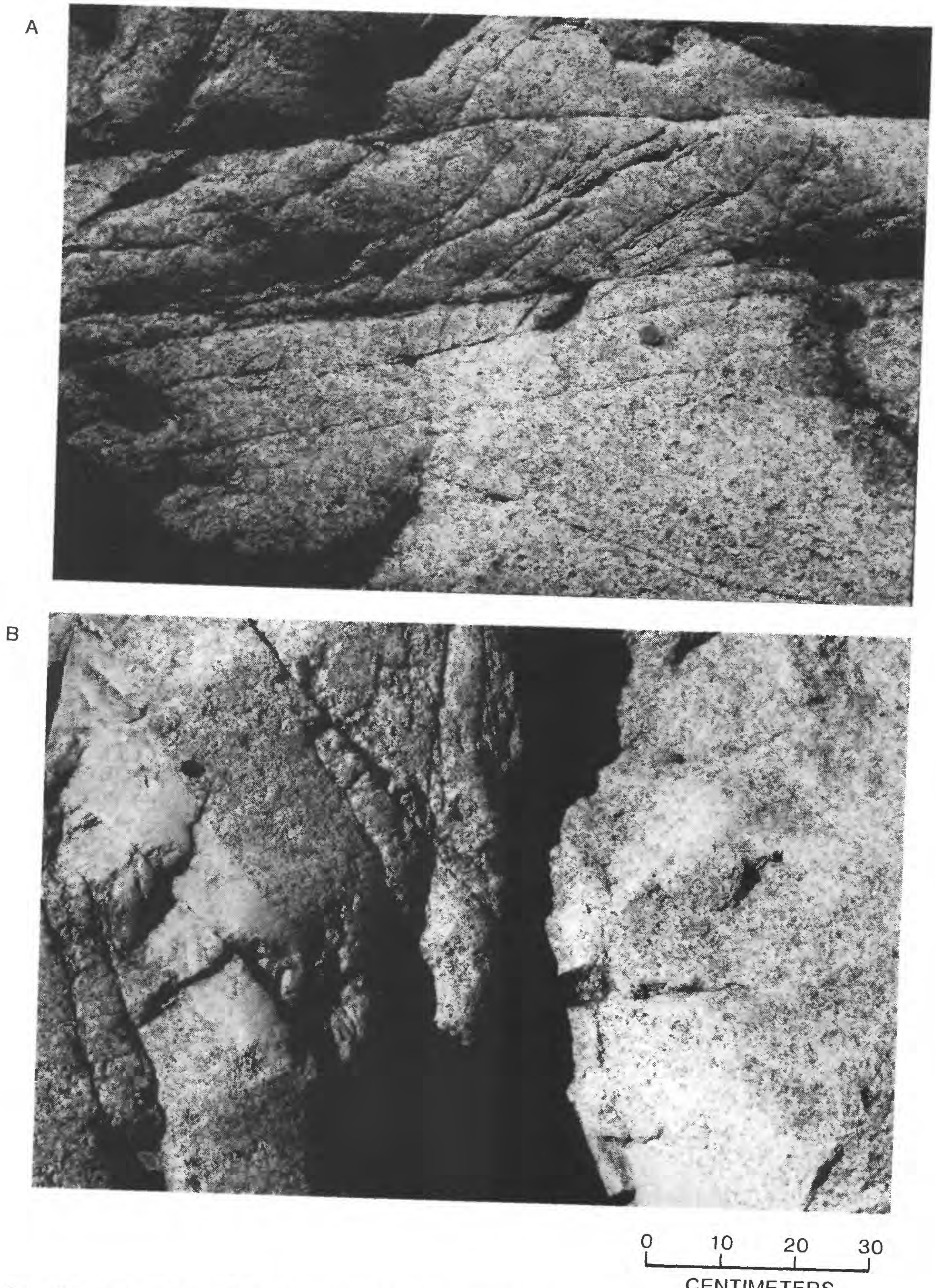


Figure 2.--Photographs of hydraulically exposed outcrop adjacent to borehole ATK5 showing: A) discontinuous fractures connected by fracture zone of multiply splaying fractures; B) one of many small pegmatitic intrusions (Canadian quarter gives scale in both photographs).

Table 1.--Geophysical borehole logs from ATK5 and ATK8 obtained by the U.S. Geological Survey, September 9-18, 1986

TYPE OF LOG	DEPTH INTERVAL (meters)	MAGNETIC TAPE Number	COMMENTS
	ATK8		
Temperature	725 m to surface	BGF581, file 1	Well flowing at surface.
Caliper	725 m to surface	BGF581, file 2	
Natural Gamma	725 m to surface	BGF581, file 3	
Single-Point Resistance and Self Potential Combination	725 m to casing	BGF581, file 4	
Acoustic Transit-Time Velocity	725 m to casing	BGF581, file 5	
Epithermal Neutron	725 m to surface	BGF581, file 6	
Acoustic Televiewer	All major fracture zones		
1/Acoustic Waveform	725 m to casing	BGF583	34 kHz source; skip some unfractured zones.
1/Acoustic Waveform	1200 m to casing	BGF584	5kHz Sparker source; selected zones.
	ATK5		
Caliper	1260 m to surface	BGF586, file 1	
Single-Point Resistance and Self Potential Combination	1260 m to casing	BGF586, file 2	
Acoustic Transit-Time Velocity	1260 m to casing	BGF586, file 3	
Acoustic Televiewer	All major fracture zones		
1/Acoustic Waveform	1260 m to casing	BGF587	34 kHz source; Discontinuous zones with some repeats.

1/ Digitized waveform logs contain considerable noise due to broken wire in magnetic tape deck; see discussion of data processing in text.

In addition to the suite of conventional geophysical logs obtained by the U.S. Geological Survey, two logs not routinely available were obtained in the Atikokan boreholes. These were acoustic waveform logs, and heat-pulse flowmeter measurements at discrete stations along the borehole. The acoustic-waveform logging system records the complete pressure waveform at two receivers located a fixed distance uphole from an acoustic-energy source. The recording system used by the U.S. Geological Survey consisted of a single tool and receiver string with two alternate energy sources. The high-frequency source operates at approximately 35 kHz, and waveforms are recorded at either 1 or 2 microsecond digitizing intervals. Other details on the use of this system are given by Paillet (1980, 1983a). An experimental low-frequency source also can be used with the same logging system and gives an effective source frequency of approximately 5 kHz in a 7.5-cm-diameter borehole. This source operates by means of a conventional automobile spark plug immersed in a saline fluid, and periodically fired by the discharge of a capacitor bank located in the electronics section of the logging tool. Sparker source performance depends much more on the borehole environment than does the high-frequency magnetostrictive source. Initial field tests of the sparker source have been described by Paillet (1984), and applications of the sparker source to fracture characterization are described by Paillet and Hess (1986).

The heat-pulse flowmeter was adapted from a British design described by Dudgeon (1975). The flowmeter provides accurate measurements of vertical flow in boreholes as small as 0.05 L/min. Measurements are made by recording the time required for the heating produced by a short current pulse at a grid centralized in the cylindrical measurement section of the tool to travel a few cm either uphole or downhole. Other details on flowmeter construction, and examples of flowmeter calibration are given by Hess (1982). Examples of heat-pulse flowmeter applications to fracture flow characterization at other AECL crystalline rock research sites are given by Keys (1984), Hess (1985), and Paillet and Hess (1986).

Although AECL researchers identified fractures on the basis of observed natural fractures in core, the primary means of fracture identification used in this study was the borehole acoustic televiewer. The acoustic televiewer is an ultrasonic acoustic device that produces a photographic image of the pattern of acoustic reflectivity on the borehole wall. Previous studies have shown that the acoustic televiewer provides indications of open fractures in crystalline rocks in the absence of unusual hole conditions that restrict acoustic televiewer operation (Keys 1979, 1984; Davison and others, 1982). Data on the character and distribution of fractures in core were made available by AECL at the time of logging for corroboration of fracture distributions made by means of acoustic televiewer logs.

CHARACTERIZATION OF FRACTURE PERMEABILITY

The geophysical logs for the two Atikokan boreholes are given in figures 3 and 4. Several of the conventional geophysical logs run in borehole ATK8 provided indications of the depths at which apparently permeable fractures intersected the borehole; some of these measurements including acoustic waveform and acoustic televiewer logs appeared to give anomalies that might be related quantitatively to fracture permeability. The major fracture zones in the

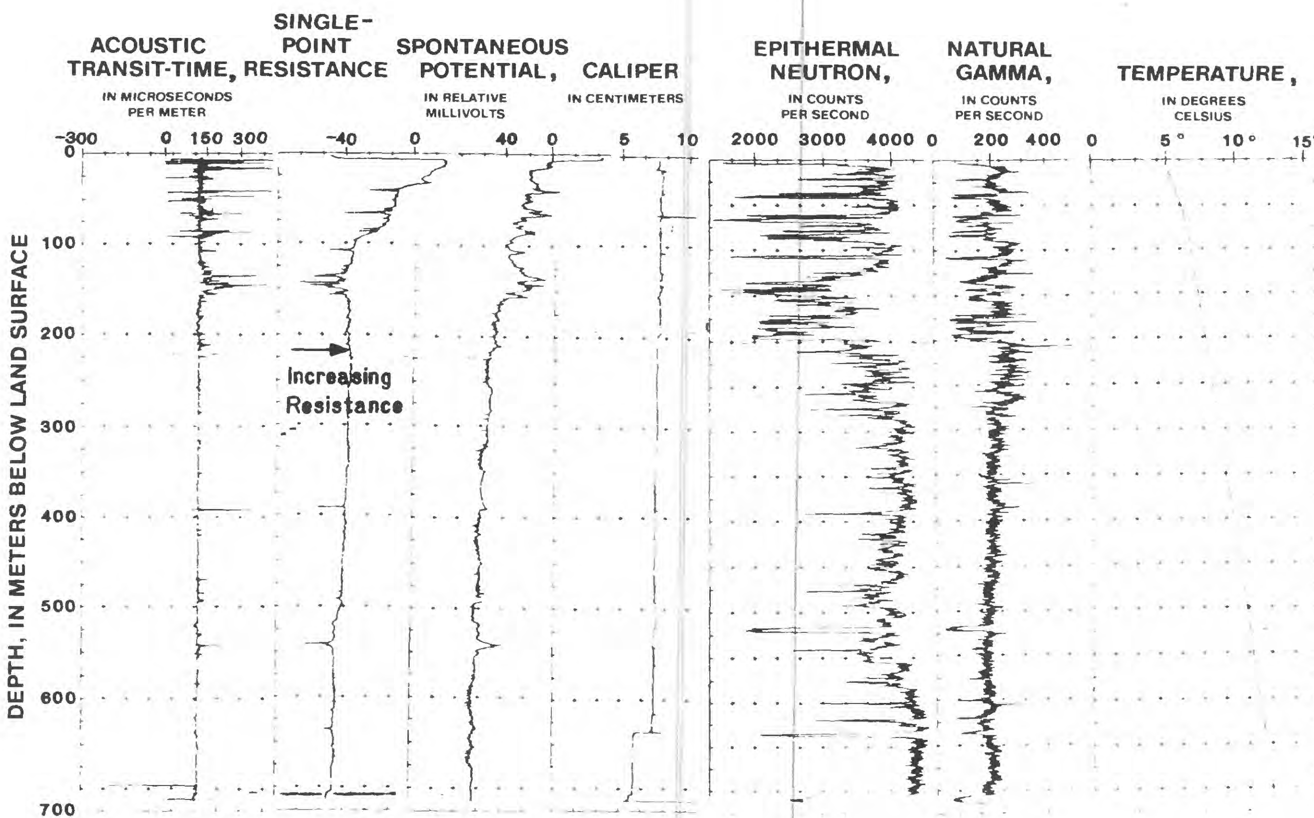


Figure 3.--Depth-correlated borehole logs for ATK8 showing acoustic-transit-time, single-point resistance, spontaneous potential, caliper, epithermal neutron, natural-gamma, and temperature profiles on logs collected by the U.S. Geological Survey.

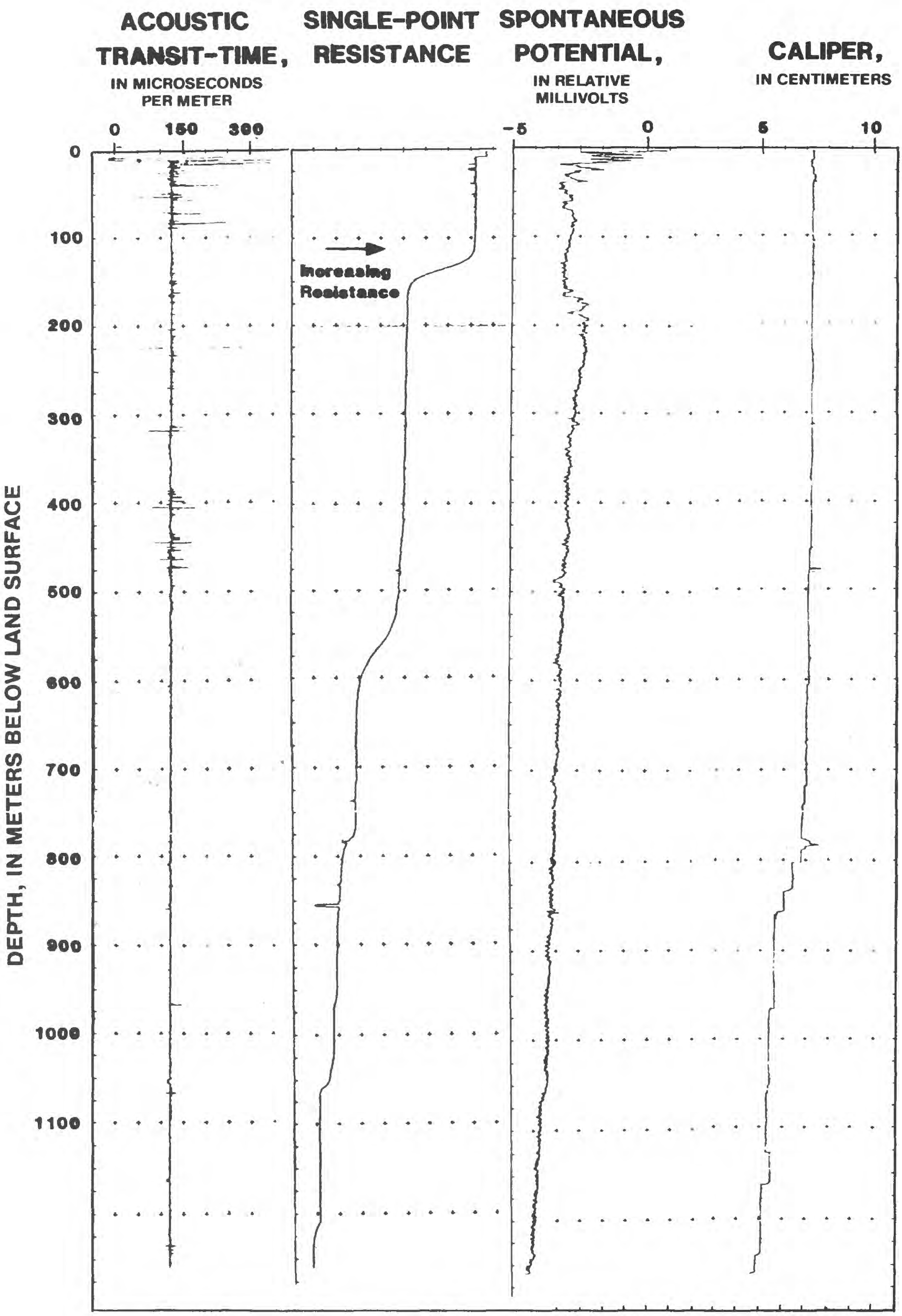
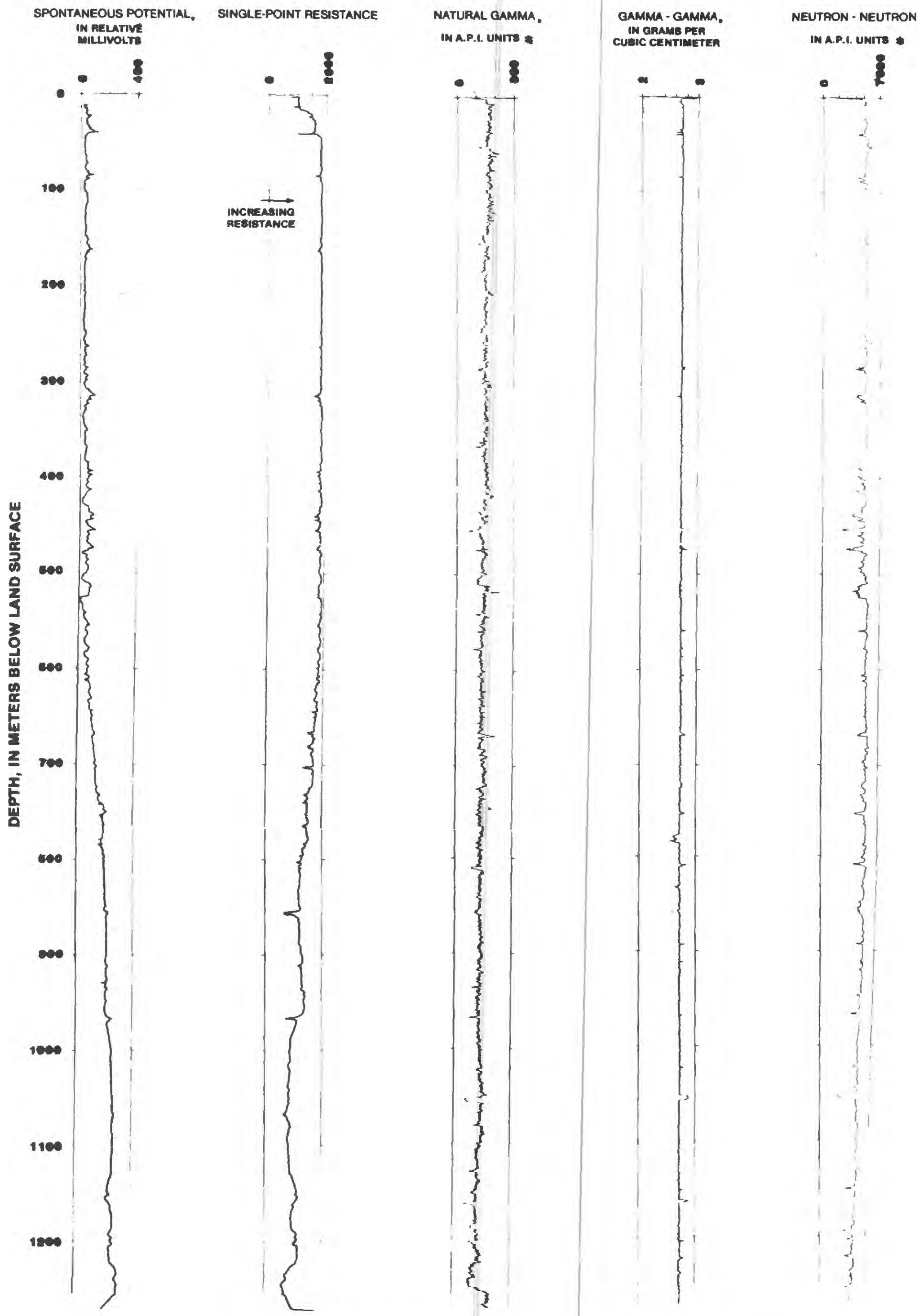


Figure 4a.--Depth-correlated borehole logs for ATK5 showing acoustic-transit-time, single-point resistance, spontaneous potential, and caliper profiles on logs collected by the U.S. Geological Survey.



* A.P.I units refer to the standarded response of gamma logging systems in the calibration facilities developed by The American Petroleum Institute in Houston, Texas.

Figure 4b.--Spontaneous potential, single-point resistance, natural-gamma gamma-gamma, and epitermal-neutron profiles on logs collected by Atomic Energy of Canada Limited.

portion of borehole ATK8 below 200 m are indicated by almost all of the geophysical logs that are known to be sensitive to fractures (including epithermal neutron, single-point resistance, acoustic transit-time and acoustic televiewer logs). The possibility that conventional geophysical logs alone might be used to identify fractures was tested by plotting the depths of possible fracture responses from each of the logs in figure 5 for borehole ATK8 and figure 6 for borehole ATK5. The single-point resistance log was found to provide the most unambiguous fracture indicator for the Atikokan lithology by the comparison of the log in figure 5 with core data and acoustic televiewer logs.

The differences between the U.S. Geological Survey and AECL spontaneous potential logs (fig. 4) probably result from the differences in hole conditions and the flushing of drilling mud from fracture openings during the time since drilling. The differences between the U.S. Geological Survey and AECL single-point logs resistance (figs. 4 and 6) are related to both the differences in tool characteristics and the effects of water quality stratification in the borehole caused by the flow regime in the upper part of the borehole and settling of suspended minerals in the time since drilling. The configuration of the U.S. Geological Survey single-point resistance tool renders the U.S. Geological Survey single-point log more sensitive to such variations in water quality. The fracture response of the U.S. Geological Survey log has been suppressed by lower gain settings to keep log deflections related to water-quality changes on scale. The U.S. Geological Survey single-point resistance logs in figure 4a were compared with the Atomic Energy of Canada Limited single-point resistance log in figure 4b to assess the effects of this gain suppression. The epithermal neutron log contains anomalies at all major fracture zones, but other epithermal neutron anomalies that resemble fracture responses apparently were related to mafic intrusions. The acoustic log was not sensitive to such variations in lithology, but the acoustic transit-time log did not indicate the deep fracture zone near the 640-m depth in borehole ATK8 because of the steep dip of the fracture with respect to the borehole.

Comparison of the logs in figures 5 and 6, with the core fracture and acoustic televiewer log data indicate that the locations of all major fracture zones intersecting boreholes ATK8 and ATK5 at depths below the intensely fractured portions of the boreholes above 300-400 m can be determined from the conventional geophysical logs. However, note that only an estimate of the relative permeabilities of the fracture zones can be determined from the relative size (amplitude and vertical extent) of the geophysical log anomalies. Distinguishing the sharp anomalies produced on some of the logs from the local lithology changes associated with intrusions from fracture effects would be difficult. Further, this qualitative estimation of fracture permeability is based on the assumption that observed geophysical anomalies are related to fracture permeability and alteration of rock adjacent to fractures. In general, we know of no simple way in which to separate the direct effects of fracture porosity and permeability from the log anomalies induced by alteration around fractures, and the properties of infilling minerals deposited in fracture openings.

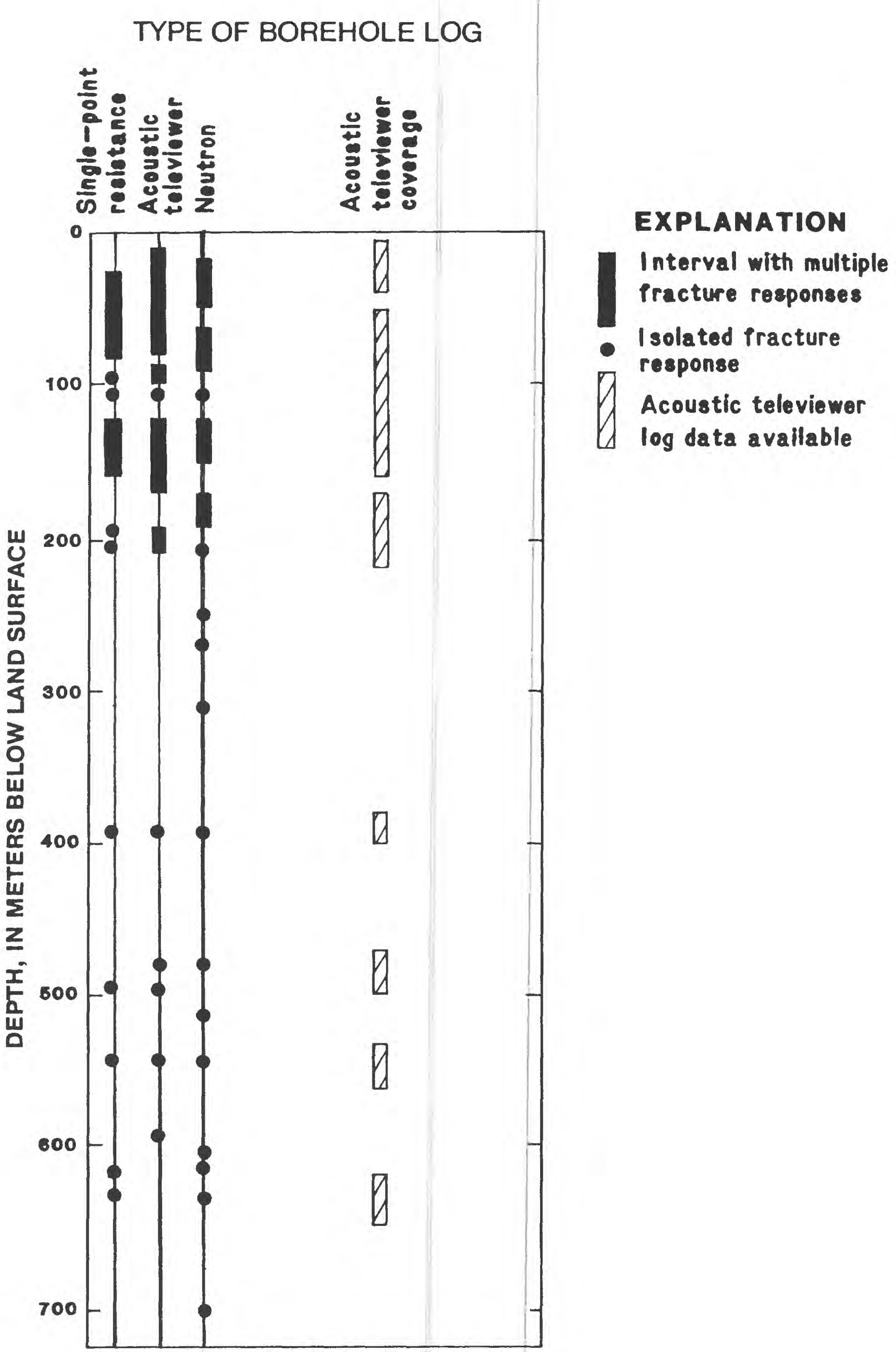


Figure 5.--Distribution of geophysical-log anomalies indicative of fracturing in borehole ATK8 based on borehole logs collected by the U.S. Geological Survey.

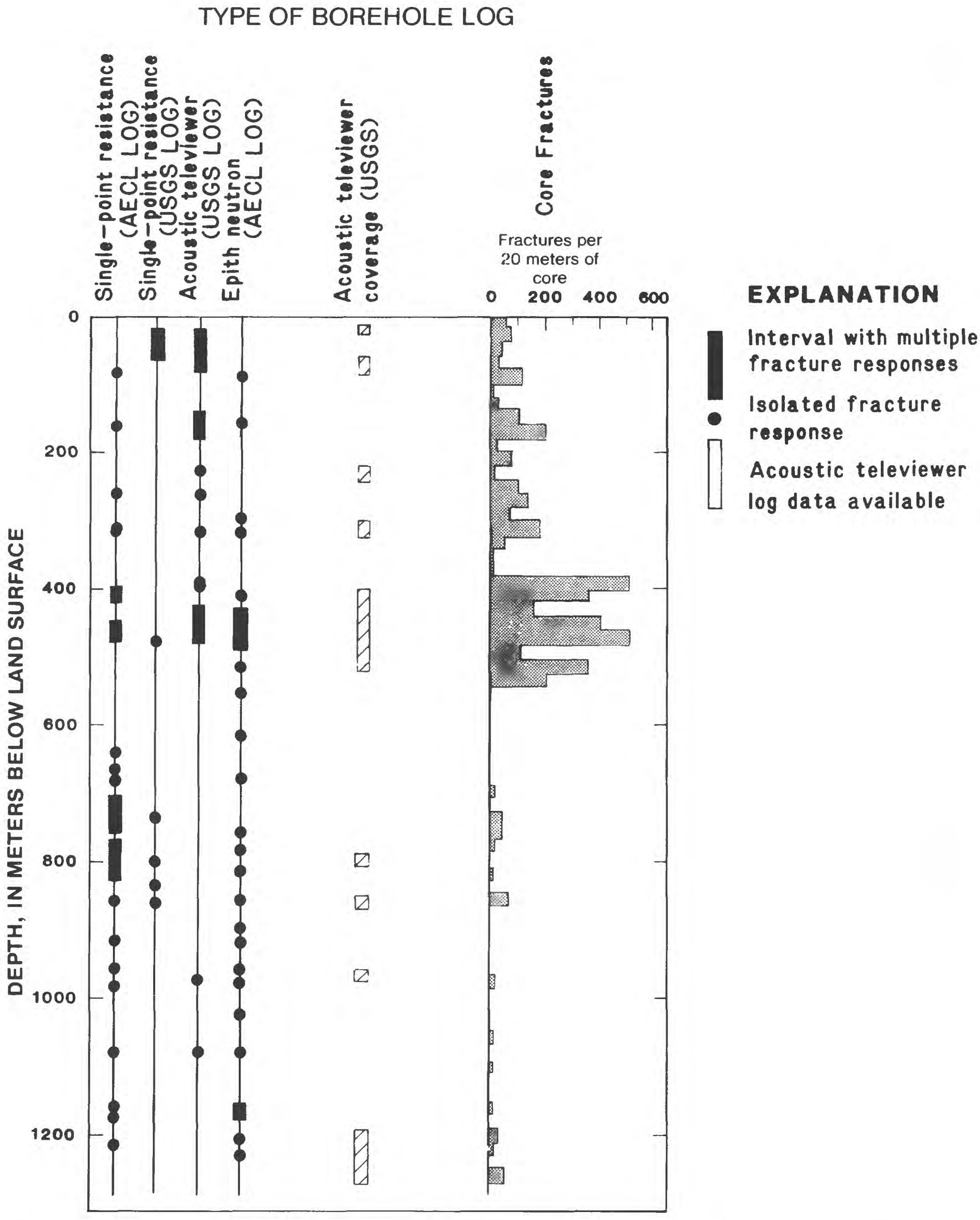


Figure 6.--Distribution of geophysical log anomalies indicative of fracturing compared to the distribution of core fractures in borehole ATK5 based on borehole logs collected by the U.S. Geological Survey and Atomic Energy of Canada Limited; core fracture data given for comparison.

No quantitative correlation between amplitude or vertical extent of epithermal of neutron, single-point resistance, and acoustic log anomalies could be identified (figs. 7, 9, 11, and 13). Two measures of relative fracture permeability are plotted in figures 8, 10, 12, and 14. One is the acoustic tube-wave amplitude log described by Paillet (1980, 1983a), and by Paillet and Hess (1986). However, even in the case of the acoustic tube-wave amplitude log, difficulties arise in partitioning acoustic tube-wave attenuation related to borehole wall permeability, and acoustic tube-wave attenuation related to variations in intrinsic permeability in the vicinity of fractures. In the cases where considerable weathering and alteration occur in the vicinity of fractures, the acoustic tube-wave method may overestimate fracture permeability by not accounting for the unknown amount of attenuation related to the intrinsic properties of the altered rock (Paillet, 1983a; Cheng and others, 1986).

Alteration did not appear extensive in the vicinity of most deeper fractures identified by means of televiewer logs in the lower portions of borehole ATK8, so fracture zone permeabilities were calculated by means of the acoustic tube-wave attenuation theory given by Mathieu (1984) and Mathieu and Toksoz (1985). All three deeper fracture sets indicated in figures 9 through 14 are calculated to have permeabilities expressed as equivalent single fracture apertures in the range from 0.4 to 0.5 mm. These equivalent single fracture apertures are derived from acoustic tube-wave amplitude attenuation of values ranging from 70 percent to 90 percent in the three major fracture zones in borehole ATK8 illustrated in figure 7 through 14. It is hoped that these calibrated permeability calculations will be corroborated by future packer tests in this borehole.

An alternate method for characterizing relative fracture permeability is illustrated in figures 8, 10, 12, and 14: the integration of apparent fracture opening in each 30 cm of the acoustic televiewer log. The relationship between apparent width of fracture opening on the televiewer log and permeability is based upon the known dependence of fracture permeability on facture aperture (Witherspoon and others, 1981). The integration was carried out by estimating the percentage of total area in each 30 linear cm of acoustic televiewer log representing apparent acoustic scattering by fracture openings. This requires additional intepretation to disregard other dark areas in acoustic televiewer logs caused by factors other than fractures intersecting the borehole wall. This calculation only can be semiquantitative at best, because the dark fracture trace on the acoustic televiewer log represents the convolution of a thin fracture opening with an ultrasonic beam nearly 1 cm wide. In spite of this fact, the acoustic televiewer fracture density log for the three major deep fractures (figures 8, 10, and 12) appears to be approximately the same, and therefore consistent with the acoustic tube-wave amplitude log. This similarity may be fortuitous; however, a properly filtered and averaged interpretation of acoustic televiewer logs possibly could be related to similarly averaged distributions of fracture permeability, expressed as the total effective aperture of an equilvalent single, isolated fracture (Snow, 1968).

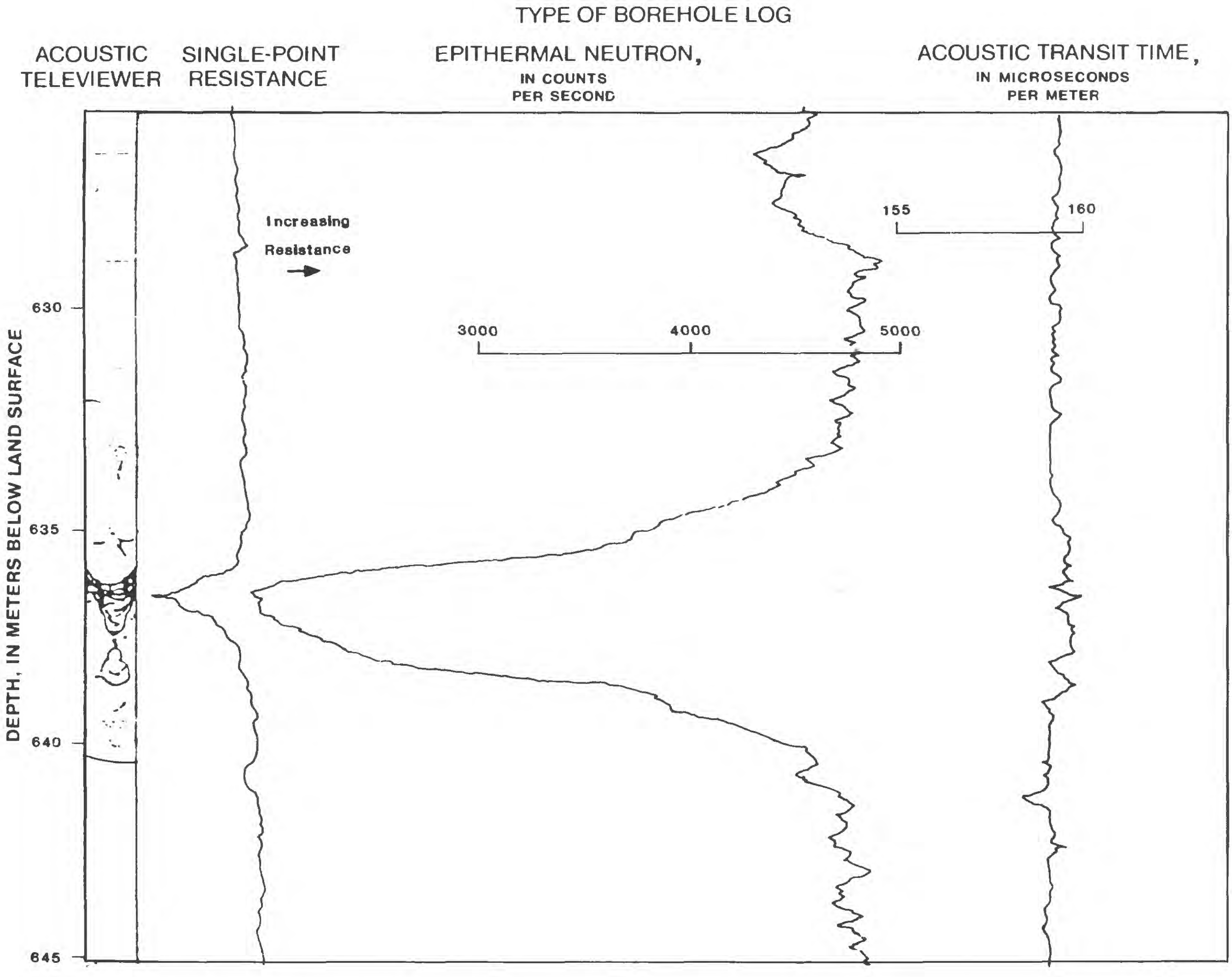


Figure 7.--Geophysical-log anomalies compared to acoustic-televiewer log for fracture zone near 640-meters in depth in borehole ATK8.

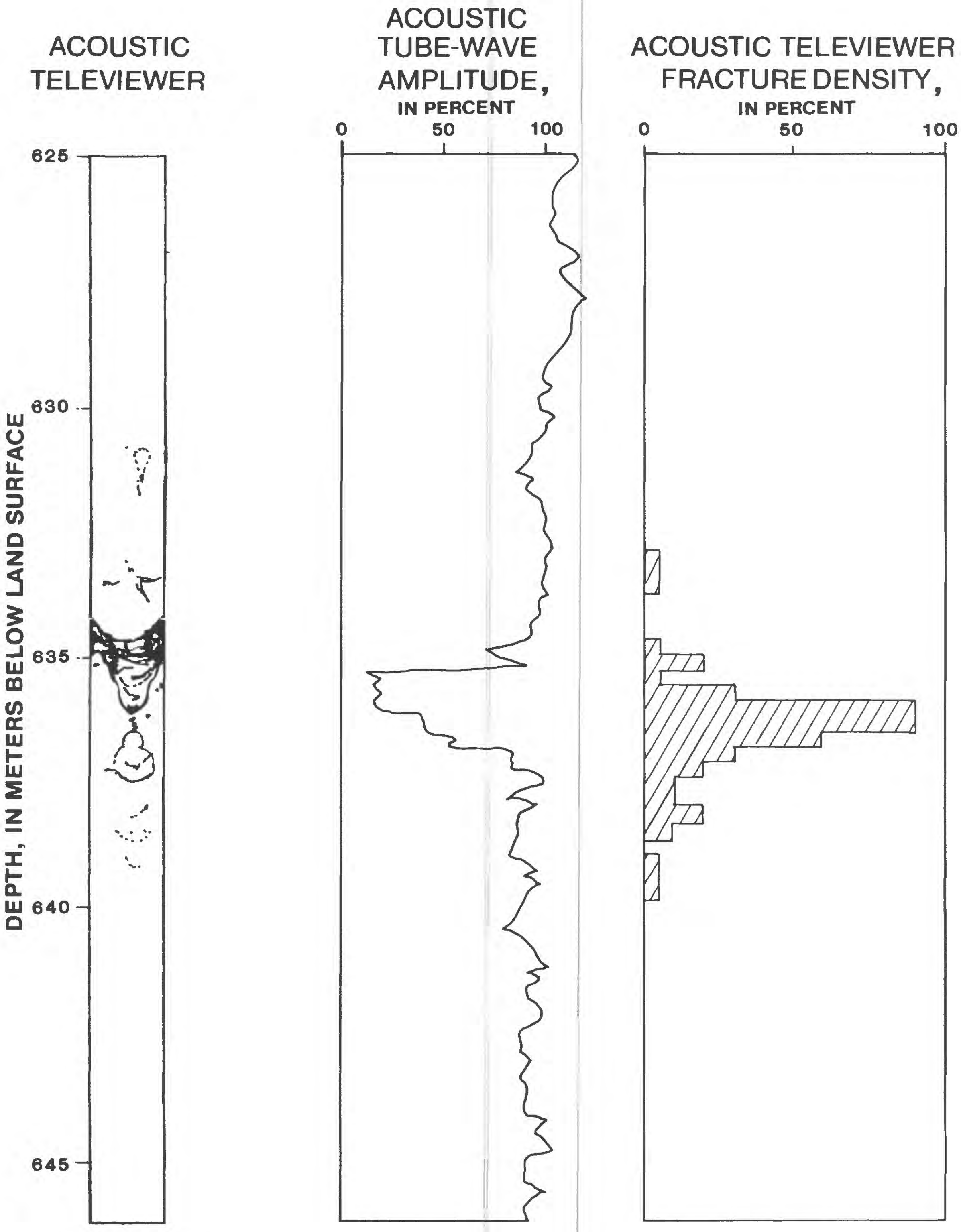


Figure 8.--Acoustic tube-wave amplitude log, and acoustic televiewer fracture-density log for fracture zone near 640-meter depth in borehole ATK8; acoustic televiewer log shown for comparison.

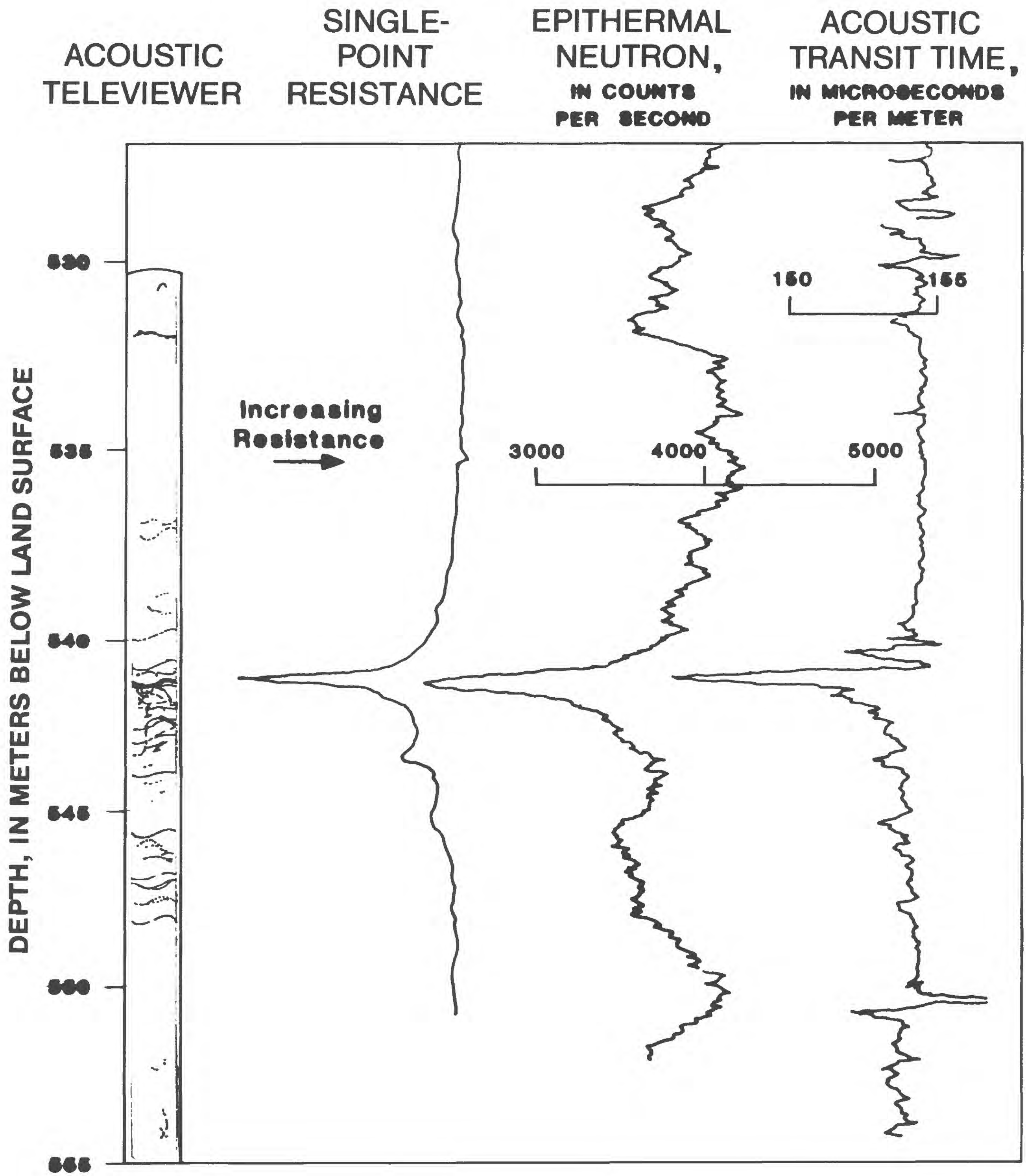


Figure 9.--Geophysical-log anomalies compared to acoustic televiewer log for fracture zone near 540-meter depth in borehole ATK8.

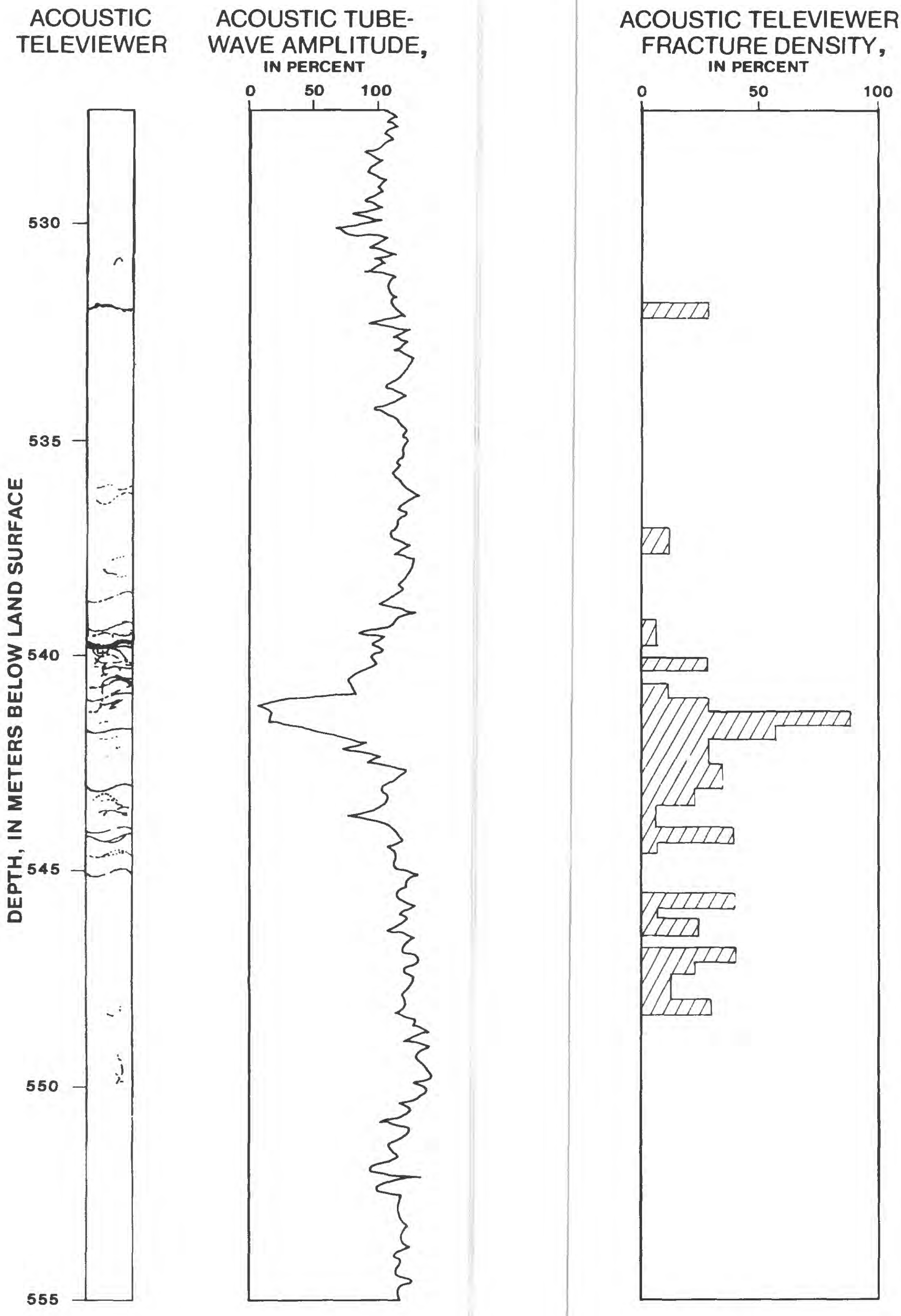


Figure 10.--Acoustic tube-wave amplitude log, and acoustic televiewer fracture-density log, for fracture zone near 540-meter depth in borehole ATK8; acoustic televiewer shown for comparison.

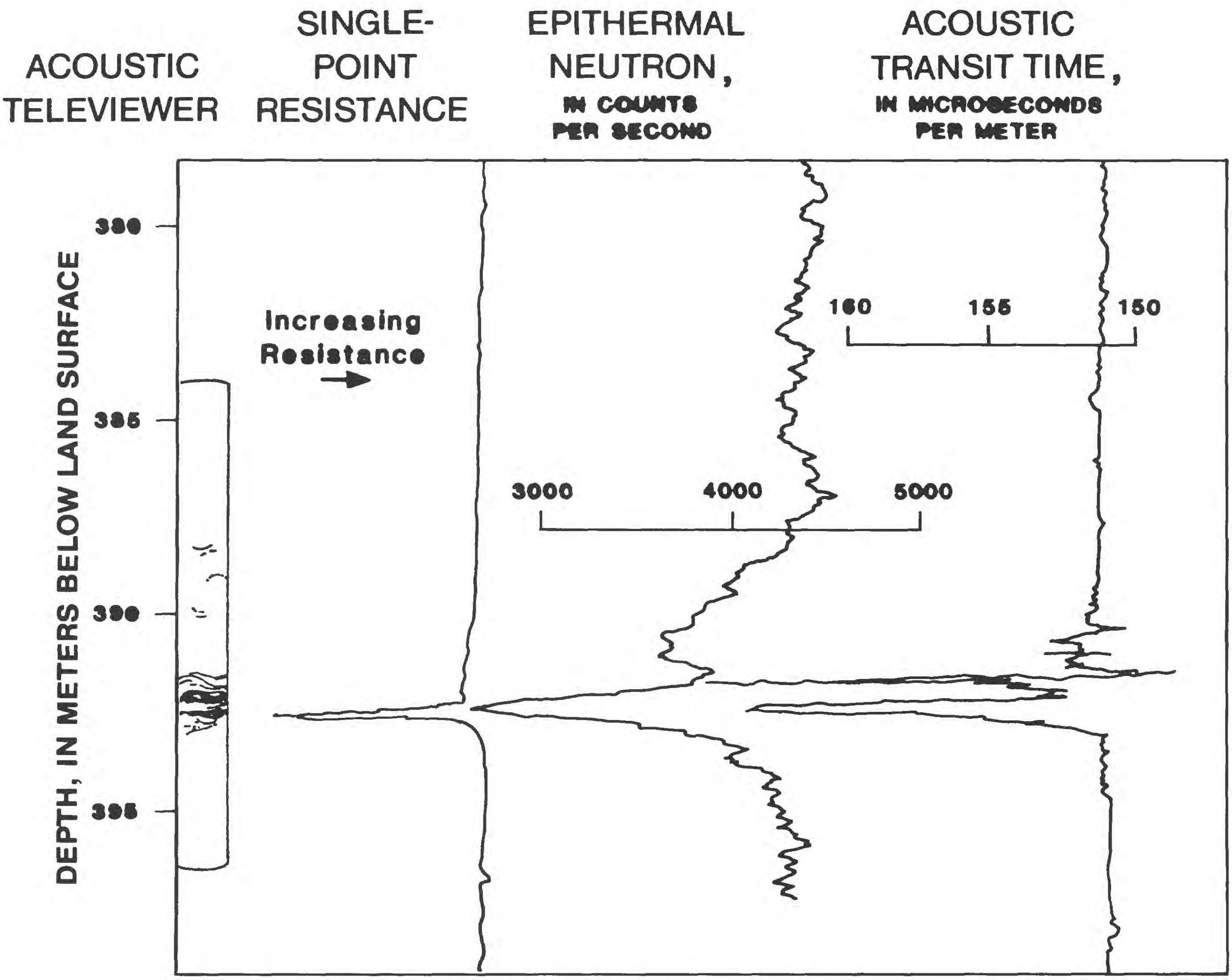


Figure 11.--Geophysical-log anomalies compared to acoustic televiewer log for fracture zone near 390-meter depth in borehole ATK8.

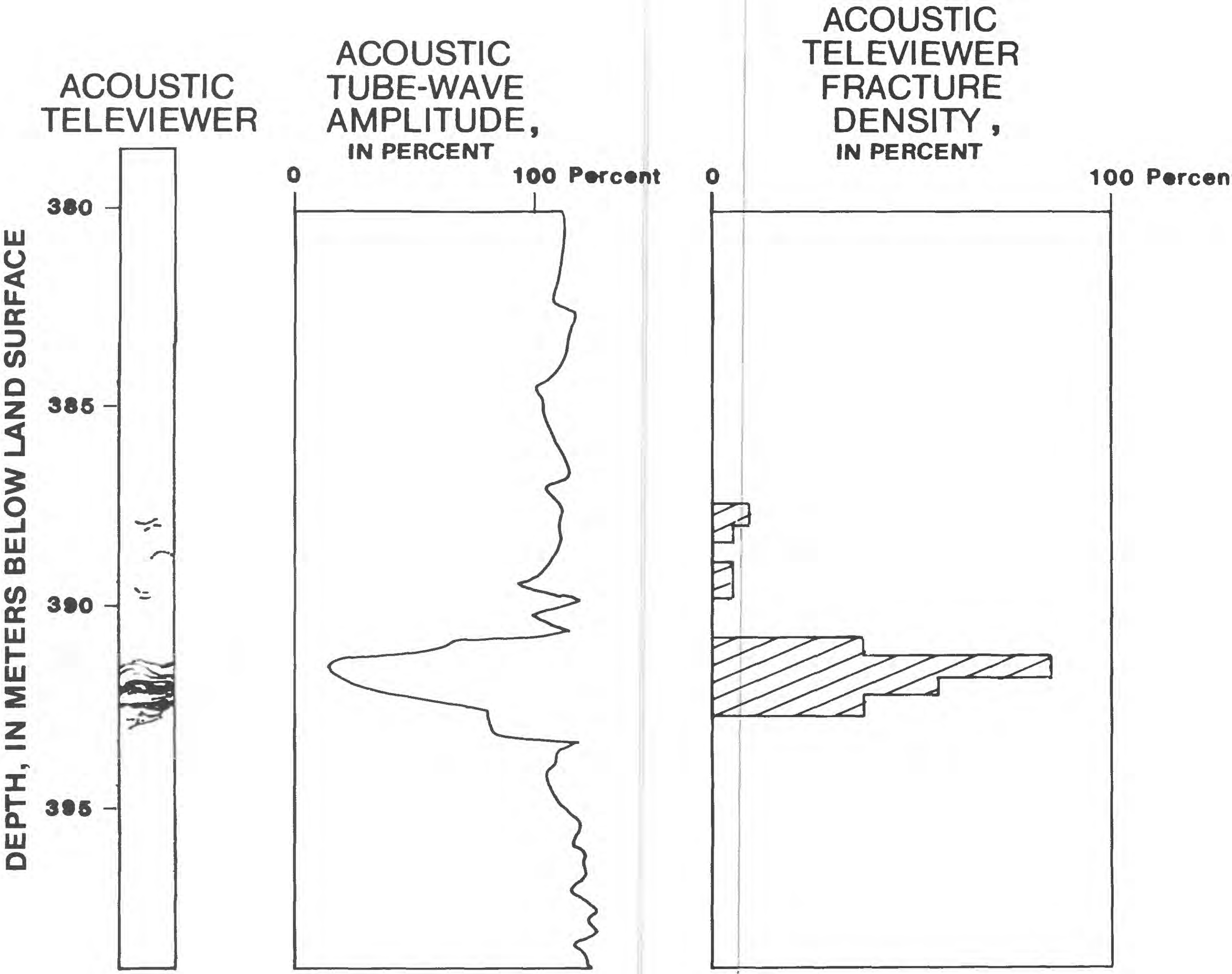


Figure 12.--Acoustic tube-wave amplitude log, and acoustic televiewer fracture-density log, for fracture zone near 390-meter depth in borehole ATK8; acoustic televiewer log shown for comparison.

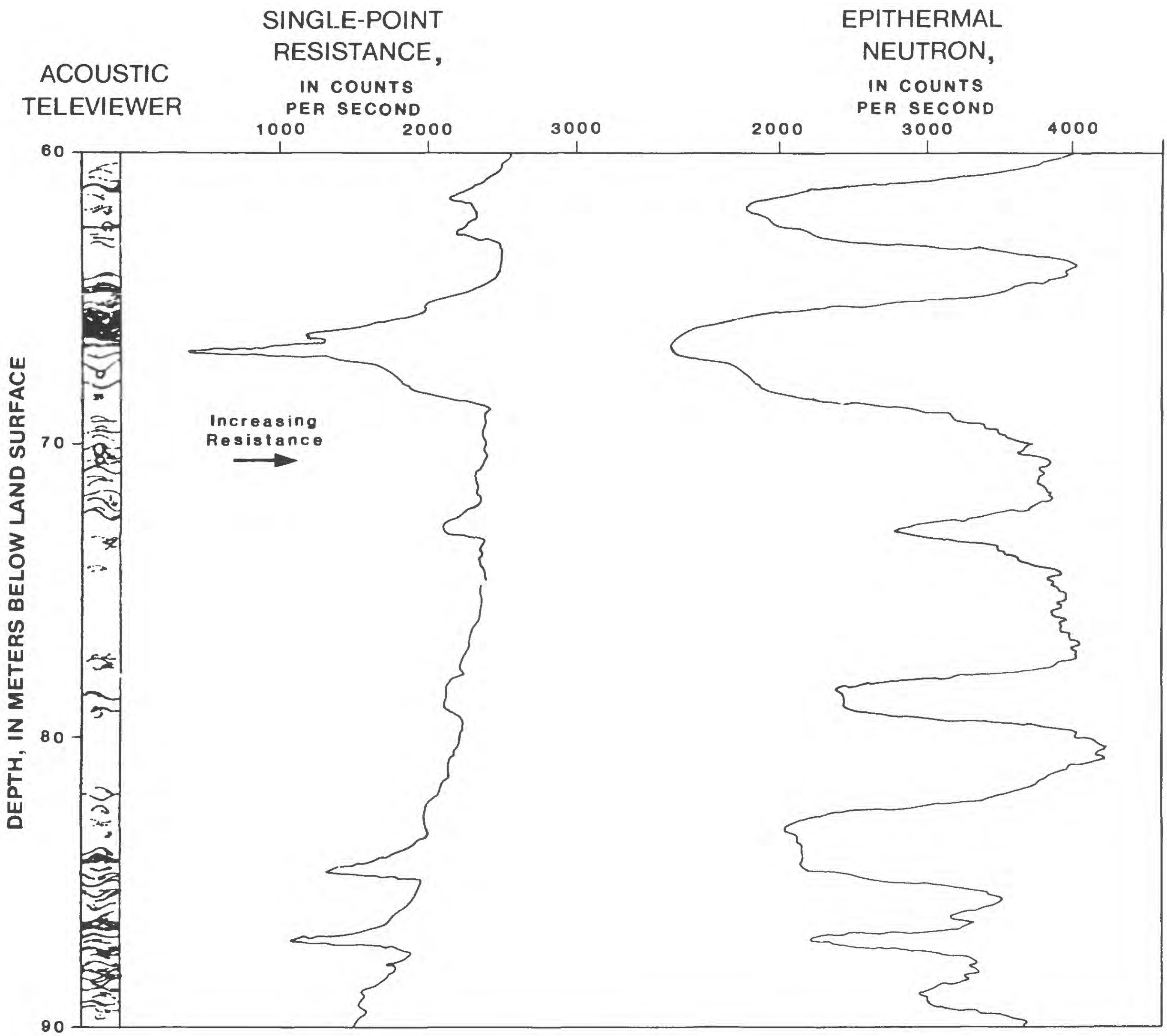


Figure 13.--Geophysical-log anomalies compared to acoustic televiewer log for fracture zone extending from 60- to 90-meters in depth in borehole ATK8.

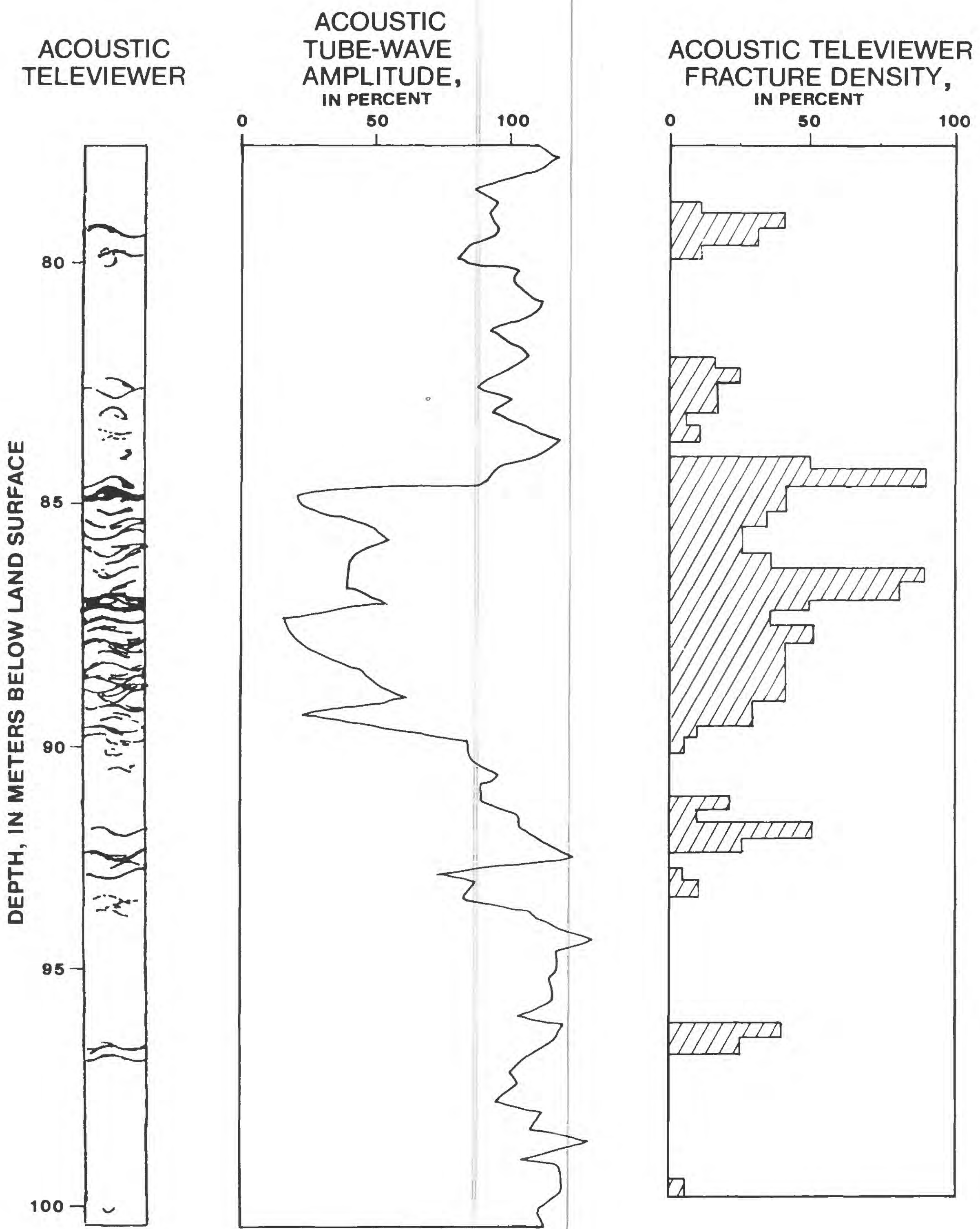


Figure 14.--Acoustic tube-wave amplitude log, and acoustic televiewer fracture-density logs, for fracture zone extending from 75- to 100-meters in depth in ATK8; acoustic televiewer log shown for comparison.

The acoustic waveform data obtained at Atikokan offered an opportunity to perform several other tests on the acoustic characterization of fractures including one test performed strictly by accident. This was a check on the redundancy of the acoustic waveform data. At the time the boreholes were logged, one of the wires connecting the waveform digitizer to the tape recorder was broken. As a result, 30 to 50 percent of the data points being fed to the recorder were not received, and these points were recorded as zeros. Fortunately, a great deal of redundancy had been built into the system by digitizing with approximately 10 points per period at the source frequency of 34 kHz, for a sample rate of 2 μs. As indicated in figures 7 through 14, this large loss of data did not severely degrade the quality of amplitude logs constructed from the waveforms. Useful and repeatable acoustic tube-wave amplitude logs were generated from these data, even with the irregular loss of up to half the recorded points.

The repeatability and effect of a greater density of sampling points is illustrated in figure 15. Two acoustic tube-wave amplitude logs are compared, each generated from waveforms recorded over the same interval of borehole on separate logging runs. The second run was recorded at twice the sampling rate, resulting in a smoother acoustic tube-wave amplitude log, even after discarding many bad data points introduced by the recorder malfunction. Comparison of the two acoustic tube-wave amplitude logs shows that the data collected with a lower sampling frequency gives an attenuation of 78 percent; whereas the high-frequency sampling data gives an attenuation of 81 percent. These are wave energy attenuations, so that the square root must be taken before permeabilities can be estimated from the curves given for high-frequency tube waves (Mathieu, 1984). The two attenuation percentages agree, giving effective single-fracture apertures for the fracture near 390 m in borehole ATK8 as approximately 0.4 mm, expressed as equivalent single-fracture aperture.

The upper portions of borehole ATK8 also were logged with the low-frequency sparker source. The theory given by Paillet (1983b, 1984) indicates that both the high-frequency waveforms (35 kHz) and the low-frequency sparker waveforms (5 kHz) ought to be dominated by tube wave energy. The curves relating fracture permeability to acoustic tube-wave attenuation given by Mathieu (1984) also show that little difference should occur in the percent tube-wave amplitude (or tube-wave energy) between these two waveforms for fractures in the 0.1 through 0.5 mm range of equivalent single-fracture aperture. Acoustic tube-wave amplitude logs generated from sparker-derived waveforms confirmed this theory by giving approximately the the same attenuations at individual fractures as those obtained with the high-frequency sources. An example is given in figure 16, where high-frequency acoustic tube-wave amplitude log data are compared to sparker acoustic tube-wave amplitude log data. The major difference in the two logs is the slightly larger attenuation associated with the major fracture zone between 85 and 92 m in depth, and the generally lower resolution of individual fractures within the fracture zone obtained with the low-frequency sparker source. This difference is the direct result of the longer source-to-receiver separation used to give a comparable number of wavelengths between source and receiver for both high-frequency and low-frequency logging systems. Both sets of acoustic tube wave of amplitude logs give an amplitude attenuation averaging about 70 percent over the fracture zone. Note that a somewhat smaller amplitude anomaly occurs for the sparker source at the set of minor fractures near 94 m in depth; this anomaly may be related to the greater depth of

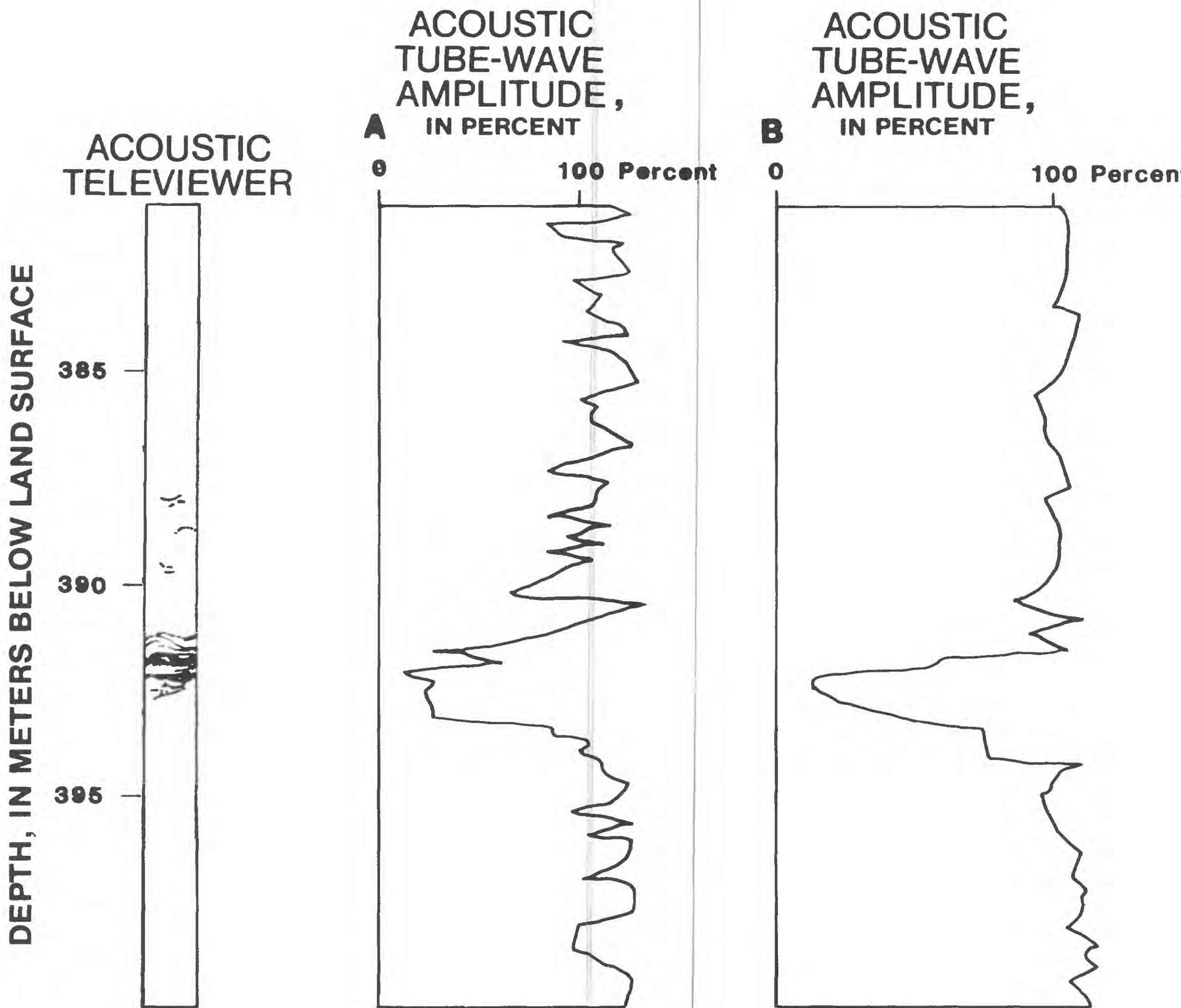


Figure 15.--Comparison of acoustic tube-wave amplitude logs constructed from separate logging runs using A) 2 microsecond sampling; and B) 1 microsecond sampling; fracture zone in borehole ATK8.

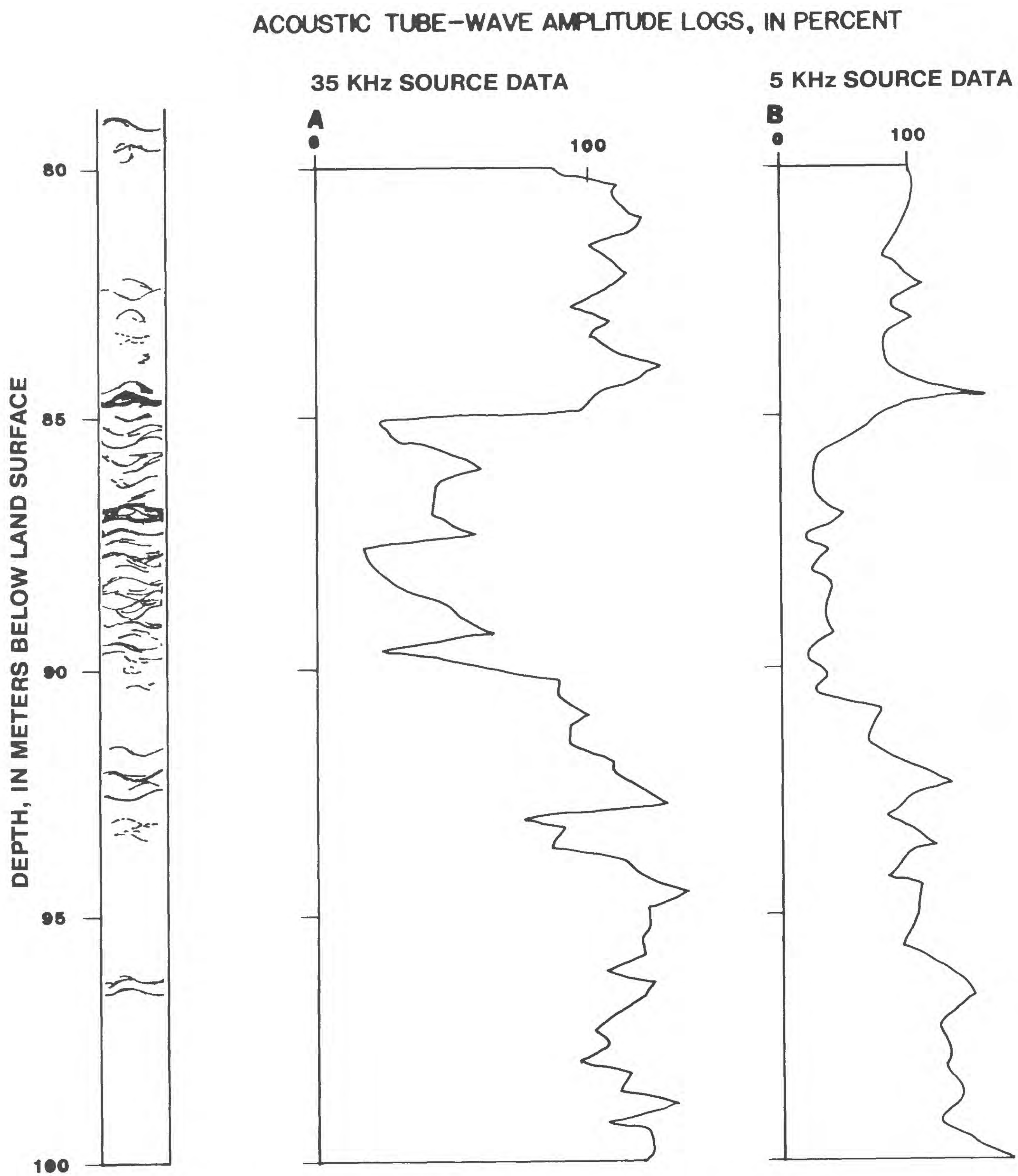


Figure 16.--Comparison of acoustic tube-wave amplitude logs for fracture zone in borehole ATK8, extending from 80 to 100 meter in depth, constructed by using waveforms obtained with: A) 35-kiloHertz (high-frequency) magnetrostrictive source, and B) 5 kiloHertz (low-frequency) sparker source.

penetration associated with the lower frequency data, indicating that the minor fractures have been opened slightly near the borehole. The two sets of data otherwise agree surprisingly well in view of the noisy character of both waveform records.

CHARACTERIZATION OF SPARSELY FRACTURED INTERVALS

The verification of the extremely low permeability and uniform mechanical properties (elastic moduli and Poisson ratio) of nearly fracture-free volumes of rock consitutes an important part of repository siting. The data given in figures 4 indicate that the lower portion of borehole ATK5 below 500 m in depth may be entirely free of major fracture conduits for ground water and contains a very low density of minor fractures. Considerable effort was expended in identifying and characterizing the few fractures intersecting lower part of borehole ATK5.

The distribution of fracture indicators on the conventional geophysical logs for borehole ATK5 is compared to the observed distribution of core-derived fractures (fig. 6). A number of large-amplitude anomalies are shown on the epithermal neutron log that could correspond to fractures; however, comparison of the neutron log with the gamma-gamma log indicates that many of these neutron anomalies correspond to local high-density anomalies. They apparently are mafic dikes or inclusions and not fractures. A much higher frequency of anomalies also occur on the AECL single-point resistance log than on the Survey single-point resistance log (fig. 4). The difference apparently relates to a difference in logging tools. The AECL log was generated with a conventional single-point probe measuring the potential drop between down-hole and surface electrodes. The U.S. Geological Survey log was generated with a differential single-point probe measuring the potential drop between two electrodes spaced approximately 2 cm apart in the borehole. This differential configuration apparently renders the response more sensitive to hole diameter changes, and less sensitive to lithology.

Two examples of acoustic televiewer, acoustic transit-time and acoustic tube-wave amplitude logs for the deeper portion of borehole ATK5 are given in figures 17 and 18. The two intervals were chosen for study because they correspond to the two deepest possible fracture anomalies and local concentrations of core fractures shown in figure 6. The acoustic televiewer logs for these intervals were poor quality because of the centralization problems associated with logging in a deviated hole. Very faint, discontinuous indications of fractures were identified on the acoustic televiewer logs. Experience in acoustic televiewer log interpretation indicates that these fractures may be completely closed and many may have been slightly opened in the vicinity of the borehole. Several minor anomalies appear associated with these fractures on the acoustic transit-time log; these anomalies may indicate that the fractures are slightly open around the borehole. The acoustic tube-wave amplitude logs for these intervals do not show that any significant fracture permeability occur here. However, the noisy nature of the data creates an irregular amplitude log, so minor indications of acoustic tube-wave attenuation may not be recognizable. In the examples given in figures 17 and 18, the malfunction of the recorder was very unfortunate; relogging this interval with an acoustic waveform system should be considered to verify the low permeability of these apparently closed fractures.

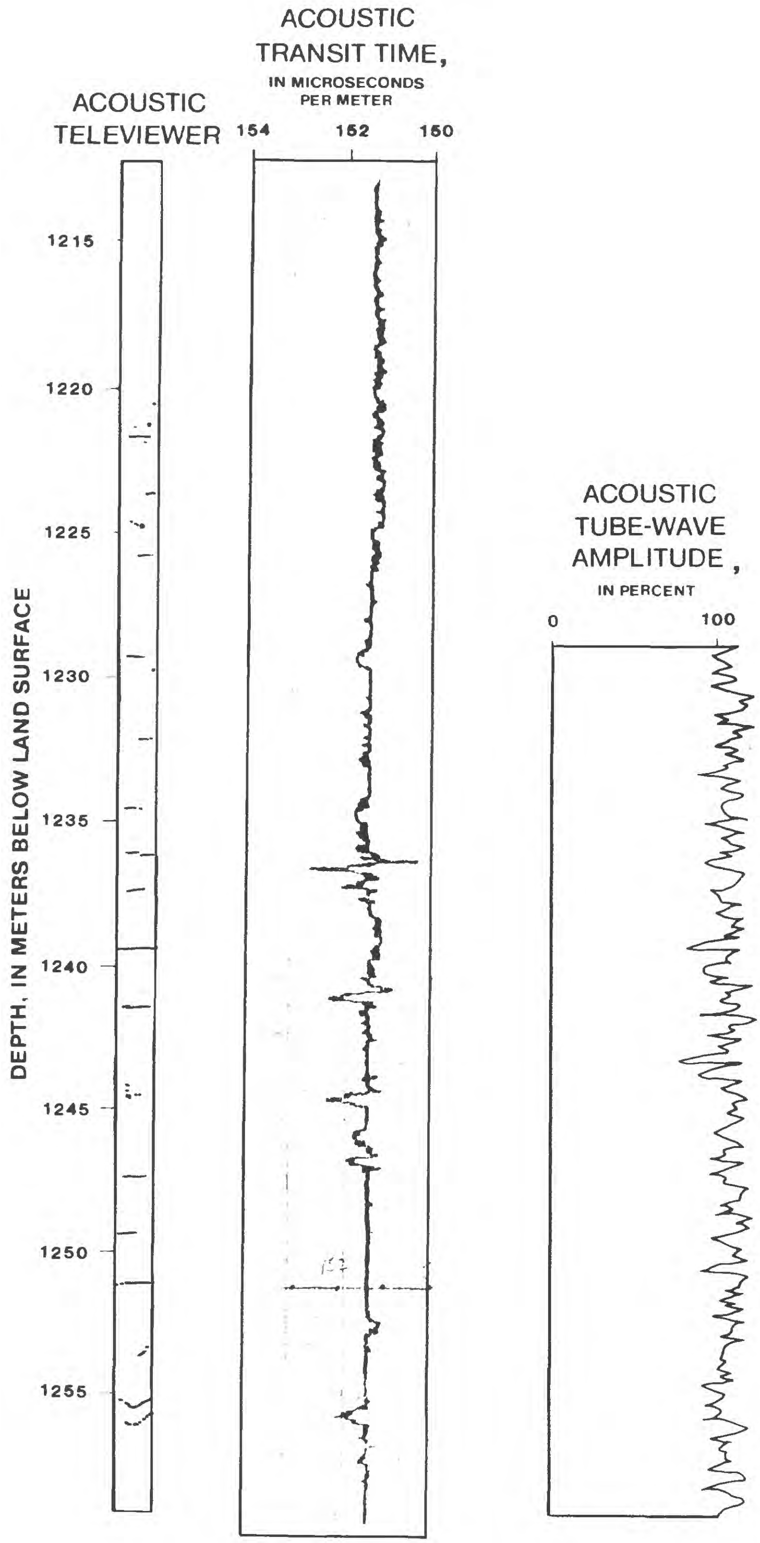


Figure 17.--Acoustic televiewer, acoustic transit-time, and acoustic tube-wave amplitude logs for core-defined fracture zone in borehole ATK5 near 1250-meter depth.

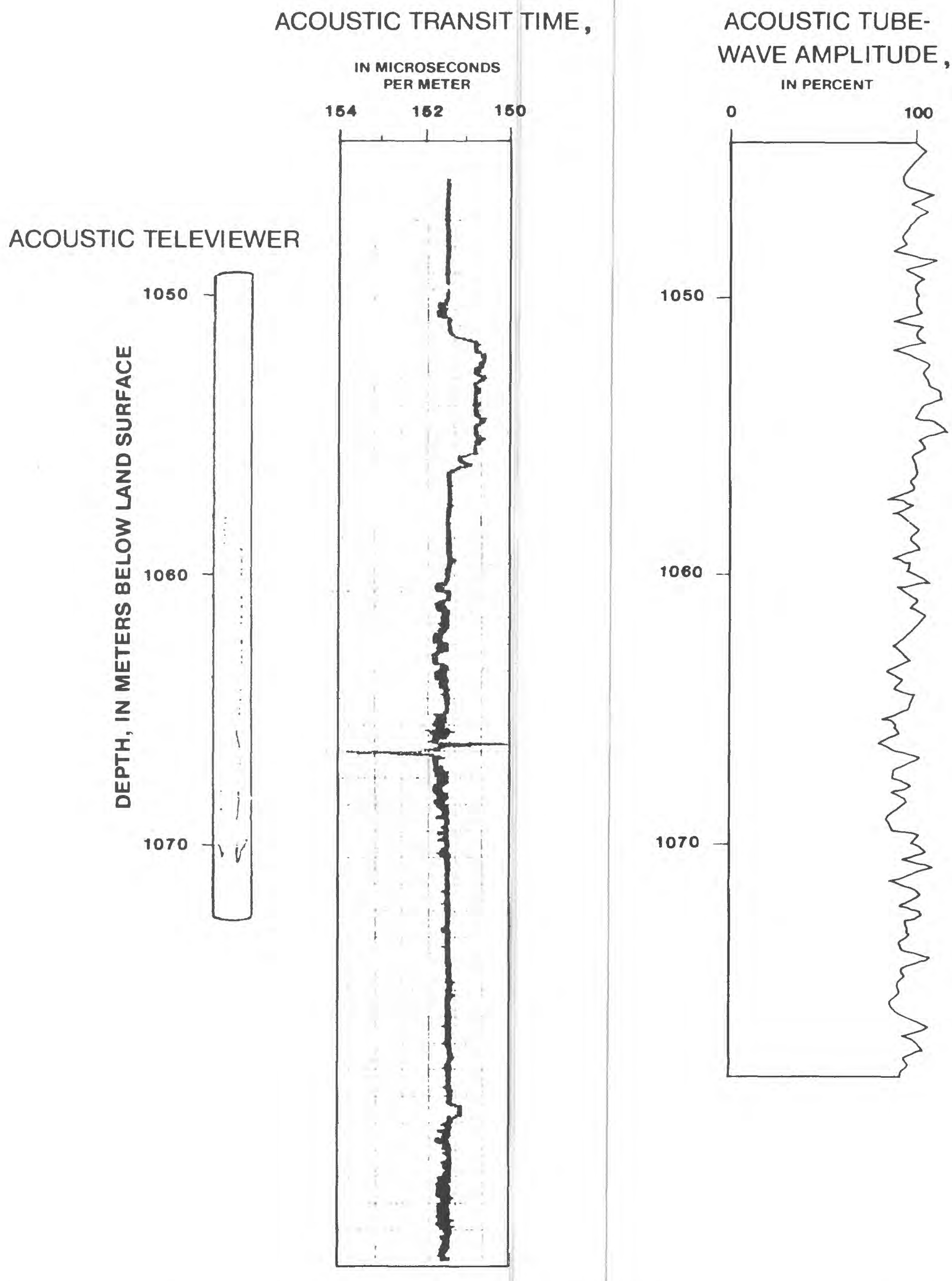


Figure 18.--Acoustic televiewer, acoustic transit-time, and acoustic tube-wave amplitude logs for core-defined fracture zone in borehole ATK5 near 1070-meter depth.

HEAT-PULSE FLOWMETER LOGGING

Previous investigations of fracture permeability systems have indicated that deep fracture zones form discrete ground-water conduits at depth in otherwise effectively impermeable crystalline rocks (Davison, 1984). Deep boreholes short-circuit head differences between these isolated systems, resulting in flow distributions along boreholes that can be related to head differences in different fracture sets. In previous studies, the high-sensitivity heat-pulse flowmeter has been used to clarify these natural head differences and the way in which different fracture systems are interconnected (Keys, 1984; Paillet and Hess, 1986). This flowmeter was used in both Atikokan boreholes to identify the fractures from which water was entering and exiting the boreholes under natural head differences.

Groundwater was flowing naturally out of the top of the casing of borehole ATK8 at the time of logging in September, 1985. The rate of flow was measured by recording the time required to fill a water sample bottle was estimated to be about 2 L/min; results of the flowmeter logging are given in figure 21. Note that the measured flow out of the top of the casing agrees with the flowmeter measurement made a couple of meters below the bottom of casing. The flowmeter data indicate that the greatest proportion of the water flowing out of the borehole enters from a set of fractures about 15 m below the surface (fig. 19). Another major entry point is from a set of fractures about 33 m below the surface. A much smaller upflow (about 0.3 L/min) arises from the major fractures near 84 m in depth. The flow near the entry point at 84 m is complex. The flowmeter indicates that a short interval of down flow occurs from the upper portion of the fracture zone to the lower portion. This unusual result was verified by several repeat measurements.

Clarification of the fracture flow system in the vicinity of borehole ATK8 can be obtained by plotting the fractures observed on acoustic televiewer logs in an east-west plane containing the borehole, and superimposing the flowmeter data (figure 20). Most of the ground-water flow enters near 15 m in depth from a westward-dipping fracture. This westward dipping fracture appears to intersect another eastward-dipping fracture at about 33 m in depth that also provides a major ground-water inflow to the borehole.

The flowmeter results obtained in borehole ATK5 are illustrated in figure 21, which indicates that a small rate of ground-water inflow from shallow fractures travels down the borehole and exits at fractures near 70 m and 240 m in depth. In both borehole ATK8 and ATK5, no indication of any ground-water flow was found below the upper few hundred meters. Several repeat measurements were made with the heat-pulse flowmeter located in these deep zones, and no ground-water flows were detected. The measurements made below 1000 m in depth in borehole ATK5 were the deepest yet for the heat-pulse flowmeter, demonstrating the ruggedness of the tool construction at relatively large hydrostatic pressures.

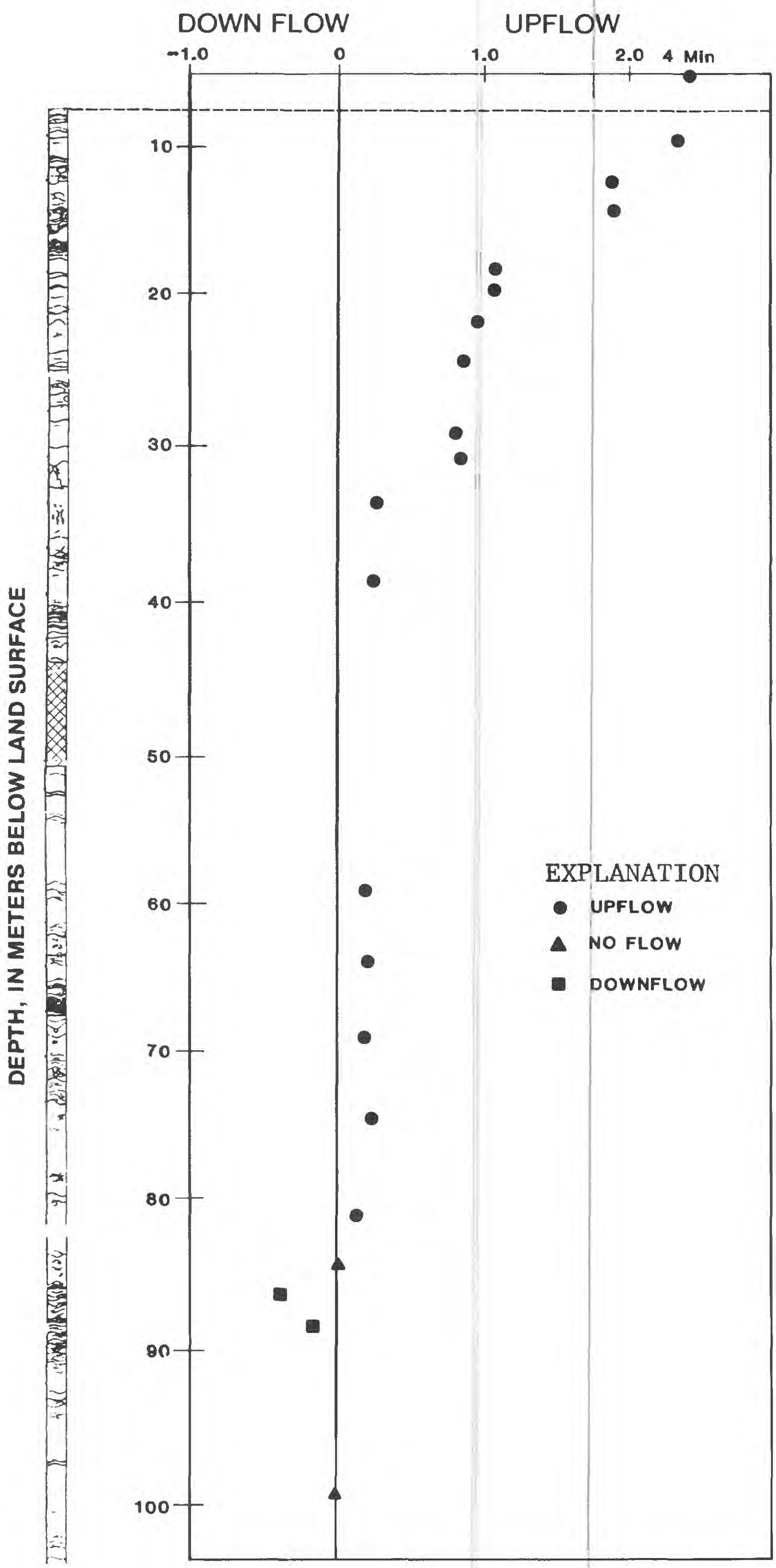


Figure 19.--Heat-pulse flowmeter measurements showing distribution of artesian flow in the upper portions of borehole ATK8.

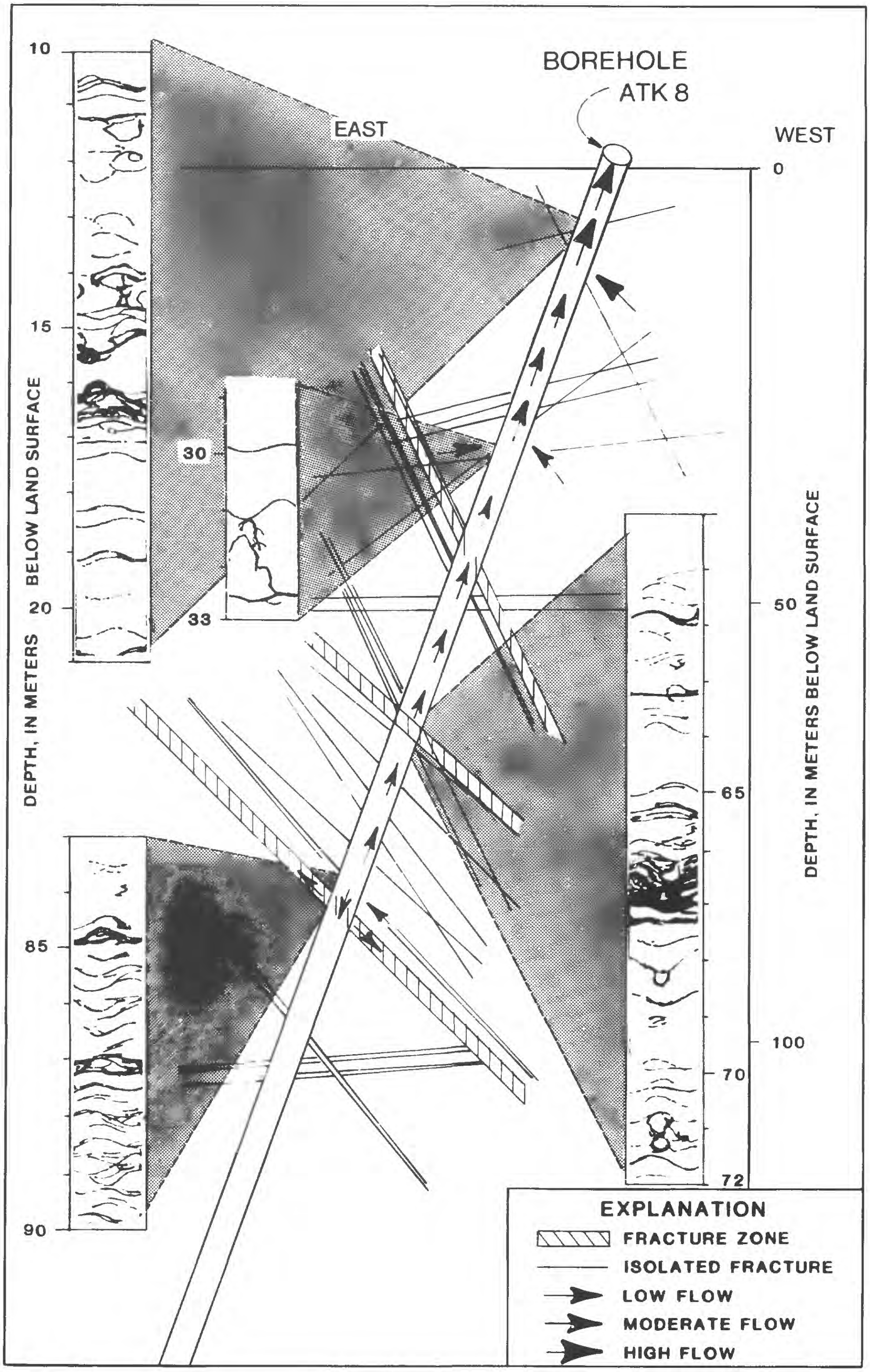


Figure 20.--East-west section through borehole ATK8 showing projection of fractures based on acoustic televiewer-log data, with probable flow path for water entering the borehole.

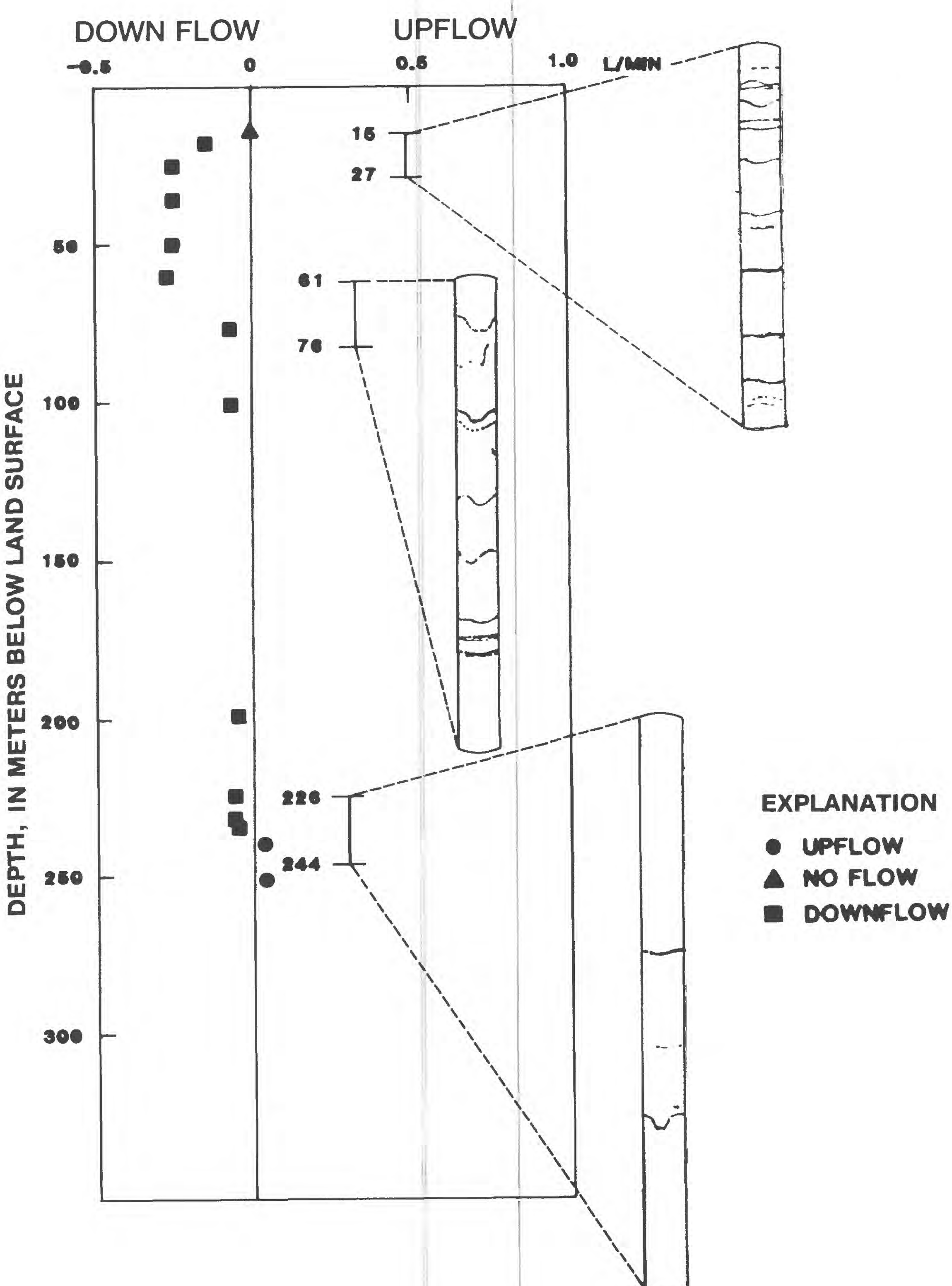


Figure 21.--Heat-pulse flowmeter measurements showing distribution of downward flow in the upper portions of borehole ATK5.

CONCLUSIONS

The borehole geophysical measurements made by the U.S. Geological Survey and Atomic Energy of Canada Limited researchers at the Atikokan research site have demonstrated the successful use of borehole geophysics in the characterization of fracture permeability in otherwise nearly impermeable crystalline rocks. Conventional geophysical borehole logs were used to identify major fracture zones at depth, and to indicate intervals of especially low fracture frequency. Comparison of various geophysical methods indicates that acoustic tube-wave amplitude attenuation appear to be the most consistent means for estimating fracture zone permeability. Many of the other measurements contain scale effects related to the size of the sample volumes investigated and responses to alteration that greatly complicate the resolution of fracture permeability. Even in the case of acoustic tube-wave amplitude logging, alteration in the vicinity of fractures may introduce variations of intrinsic acoustic attenuation that can lead to overestimation of fracture permeability. An unintentional partial malfunction of the waveform recording system demonstrated the robustness of this procedure (in the formal mathematical sense of low sensitivity to small perturbations) when at least ten points per wave cycle are recorded. Repeat runs at different sampling frequencies and comparison of high-frequency data with low frequency sparker-source data confirmed predictions on the frequency-dependence of acoustic tube-wave attenuation given by Mathieu (1984).

Investigation of a low fracture frequency interval in the deeper portion of borehole ATK5 indicated that this interval is characterized by especially small fracture-permeability. Even though some fractures were identified in the core, and some weak fracture-like responses were identified on single-point resistance and acoustic transit-time logs, the data indicate that these fractures may have been closed fractures that were opened near the borehole during drilling. This tentative conclusion is supported by the lack of acoustic tube-wave attenuation, but the poor quality of the data somewhat weakens that conclusion.

The heat-pulse flowmeter was successfully used to identify very low velocity ground-water flows in the shallow portions of both Atikokan boreholes. The entry points for water flowing out of the surface casing of borehole ATK8 were identified as fractures occurring at depths of about 15 m, 32 m, and 84 m below land surface. A downward ground-water flow regime was identified in borehole ATK5. Here ground-water enters from fractures near the bottom of casing, flows down the borehole at a rate of about 0.3 L/min, and exits at fractures about 70 and 240 m below land surface. In all cases, the flowmeter data could be used to identify the specific sets of fractures producing the ground-water inflow or outflow. As in several previous studies, the flowmeter data are notable for the large number of apparently permeable fractures that do not take part in the natural flow regime. However, no measurable ground-water flow was detected at depths below 250 m in either of the boreholes. These results once again demonstrate the useful results that can be obtained through the application of a sensitive flowmeter in fracture characterization.

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