FIELD TEST OF A LOW-FREQUENCY SPARKER SOURCE FOR ACOUSTIC WAVEFORM LOGGING

by

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ABSTRACT

Low-frequency acoustic-energy sources for waveform logging have important applications in: 1) Verifying theoretical calculations; 2) generating tube waves in large-diameter boreholes; and 3) providing larger sample volumes in cases where borehole effects are important. A new low-frequency source was fabricated by modifying an existing acoustic-waveform logging system to discharge multiple capacitors in series with an automobile spark plug. The sparker source was tested in boreholes of 15- and 8-centimeter diameter in homogeneous granite containing isolated fractures. The sparker source produced repeatable waveforms with frequencies centered on 5 kilohertz in the 8-centimeter-diameter borehole, and 7 kilohertz in the 15-centimeter-diameter borehole, compared to frequencies near 15 kilohertz for the same system using a low-frequency magnetostrictive source. The lower-frequency sparker source excited consistently measurable tube waves, in agreement with theory. Test results also confirmed that lower-source frequencies greatly decreased sensitivity to borehole effects. Observed differences in frequency content and extent of shear-mode excitation in the two different diameter boreholes are probably related to differences in mode-excitation functions. The data confirm theoretical predictions that optimum shear-mode excitation occurs for source frequencies near normal-mode cutoff. Reflection of low-frequency tube waves appears to be an effective means for distinguishing between isolated open fractures and intervals containing extensive alteration around nearly impermeable fractures.

INTRODUCTION

Acoustic well logging has been an accepted method for measuring the primary porosity of sedimentary rocks in the petroleum industry for many years (Pickett, 1960). Compressional velocities determined from acoustic well logs also have become important in verifying velocity distributions used in processing seismic-reflection data (Narvarte, 1949). Recent acoustic well-log research has focused on attaining greater spatial resolution through sophisticated processing of acoustic-log data (Willis and Toksöz, 1983), and through the use of logging proves with as many as 12 receivers at variable offsets from the source (Arditty and others, 1982). However, other important applications for acoustic well-log data do not demand such a precise degree of resolution, but do require effective compressional velocities averaged throughout larger columns of rock. For example, the interpretation of seismic-reflection coefficients depends on the recognition of relatively large contrasts in acoustic impedance. The major source of uncertainty introduced here is the extrapolation of velocity contrasts at high frequencies used in well logging to large-scale contrasts at low-frequencies (Lindseth, 1979). This contrast in scales is indicated by comparing acoustic-logging wavelengths of tens of centimeters with seismic wavelengths of tens of meters.

Applications of longer wavelength acoustic data especially are important in hydrogeology and engineering geology. Ground-water modelers are interested in the properties of geologic formations averaged throughout a representative elementary volume for input into predictive models of ground-water flow and contaminant migration. In a recent attempt to interpret fracture permeability on the basis of acoustic waveform logs, Paillet (1980, 1983a) observed that tube-wave attenuation could be correlated with permeability in some cases. However, it was noted that tube-wave amplitude only could be measured in those cases where the tube-wave mode was excited significantly. Calculations indicate that excitation of measurable tube waves requires source excitation at frequencies much less than those used in conventional acoustic-logging probes for boreholes more than a few centimeters in diameter (Paillet, 1981). At the same time, other considerations indicate that the properties of fractured rocks need to be measured throughout a relatively large sample volume. Openings serving as permeable conduits in fractured rock tend to be much larger than pore spaces in granular rocks, so that representative elementary volumes in fractured-rock aquifers tend to be several orders of magnitude larger than representative volumes in sedimentary aquifers. Mechanical properties of fractured rocks also tend to be scale-dependent (Goodman, 1976), so that larger sample volumes can provide more realistic estimates of rock properties for many engineering applications.

Another motive for investigating longer acoustic wavelengths in well-logging applications is the fact that the frequency range between acoustic well-logging [10 kHz (kilohertz)] and seismic prospecting [100 Hz (hertz)] remains largely unexplored. Beydoun and others (1983) demonstrated that tube waves generated by the interaction of seismic waves and permeable fractures near fluid-filled boreholes could be used to estimate fracture permeability. These authors indicated that the physical mechanism relating fracture permeability to borehole waves is the transformation of wave modes from compressional body waves in rock to guided tube waves along the borehole. The relationship between fracture permeability and tube-wave attenuation at the logging frequencies treated by Paillet (1980) is apparently based on the viscous-dissipation mechanism investigated by Rosenbaum (1974). The frequency range between these two extremes may contain even more information about fracture properties, or intermediate frequencies may be most effective for characterizing fractures of intermediate size. Characteristic frequency for maximum dissipation of wave energy has been shown to depend upon both permeability and effective size of fluid conduits (White, 1983; Biot, 1956). The use of widely varying frequencies to characterize fracture permeability could provide an excellent test of the theoretical relationships between fracture permeability and acoustic-wave attenuation given in the literature.

The few cases where acoustic frequencies in the range from 100 Hz to 10 kHz were used in borehole geophysics have been in the context of borehole-to-borehole seismic surveys, rather than well logging (Wong and others, 1983; Scott, 1981). These methods sometimes could resolve the largest natural fractures that might provide ground-water flow paths, but they could not measure tube-wave attenuation. For this reason, a new low-frequency acoustic-logging source was designed to produce frequencies between 1 and 10 kHz. The objective of this initial test was to provide an acoustic-energy source that could be attached to the receiver section of a conventional acoustic-waveform logging probe. Waveform data then could be acquired with the low-frequency source for direct comparison with conventional waveform logs obtained with the same receiver system. Another objective of the initial experiment was to test the new source with very little modification or special adaptation of existing equipment. In this case, the intent was to provide an initial set of data for the unexplored frequency range, under the assumption that design of a practical low-frequency acoustic-waveform logging probe should wait until sound experimental verification of the scaling rules given by theory is available.

EQUIPMENT AND TEST SITE

The acoustic-energy source used in this study is similar to the sparker source designed by Scott (1981) for borehole-to-borehole seismic exploration. The one major difference in the sparker source described here is the lesser power requirements associated with the shorter source-to-receiver spacing. The sparker source described here was designed to fire a conventional automobile spark plug by discharge of multiple capacitors in series. Firing frequency of the original logging system was decreased to once every 5 seconds to accommodate capacitor recharge. Spark-plug gap and electrolyte content in the flexible housing around the spark plug were varied, until the sparker produced a repeatable, relatively noise-free signal in a fluid bath in the laboratory. Additional checks on source repeatability and overall signal character were conducted in a shallow test well to verify system performance in the borehole environment.

Acoustic logging and waveform digitizing systems used for this study are the same as those described by Paillet (1983b, 1980), with the source section replaced by the new sparker source. The new configuration is compared to the pre-modification logging tool in figure 1. The capacitor bank in the new source required a significantly longer electronics section than that in the original logging tool. This additional length of tool was incorporated into the source-receiver spacing to provide approximately the same number of acoustic wavelengths between sparker source and receiver at an anticipated frequency of 5 kHz, as were provided by the unmodified tool at 15 kHz. The source-to-receiver spacing (fig. 1) was designed to provide the same number of wavelengths between source and R1 and R3 for the sparker source as between source and R1 and R2 for the magnetostrictive source of the unmodified tool. This requirement was considered important because wavelength and period wold be the natural length and time scales for measurements made in the same borehole with the same logging system.

The only other modification made to the logging system was a removal of low-frequency cutoff filters from the receiver electronics to insure good response at anticipated frequencies. A comparison of waveforms obtained with the original high-frequency source before and after removal of this filtering indicated that the only change to waveform records was addition of low-frequency noise. This noise appeared to affect operation of the logging system in the transit-time mode, making the compressional-wave arrival algorithm in the logging system unstable. The additional noise did not seem to affect tube-wave amplitude logs (such as those described for very small diameter boreholes by Paillet, 1980), and this noise easily could be removed from recorded waveforms by application of a digital filter.

The sparker-based logging system was tested in a borehole at the Underground Research Laboratory (URL) located on the southern edge of the Canadian shield in southeastern Manitoba, Canada. The URL is a research site established by Atomic Energy Canada Limited (AECL) to study the geology, hydrology, and geomechanical aspects of fractured plutonic rock as part of Canada's Nuclear Fuel Waste Management Program. The choice of this study site was motivated by the availability of multiple boreholes intersecting isolated fractures in otherwise nearly homogeneous intervals of granitic rock. Although their gneissic zones and xenoliths occur within the granitic batholith that underlies the URL site, core data and previous work by the author indicate that velocities in unfractured rock vary with lithostatic stress according to a trend that is nearly identical to velocity variations of a single sample of granite from eastern Massachusetts at various confining pressures (Nur and Simmons, 1969).

The section of borehole used in this study, URL-M11, was selected because it contained isolated open fractures, a major fracture interval, an interval of unfractured rock, and an interval containing only a few small, closed fractures (fig. 2). This borehole had a diameter of 15 cm (centimeters), considered typical of boreholes where acoustic-waveform logs might be applied. The geophysical logs in the interval illustrated in figure 2 also were typical of the logs obtained elsewhere at the URL site, in that a major fracture zone was associated with many apparently large fractures on the televiewer log, and with major anomalies on other geophysical logs; however, most of the natural flow along the borehole bypasses the major fracture zone and entered the isolated set of fractures towards the bottom of the figure. This isolated feature appeared as a single subhorizontal band on the televiewer log, but additional high-resolution televiewer logs indicated that this one feature was actually composed of at least four subparallel fractures within a few centimeters of each other. The temperature log indicated the flow of relatively cool water down to this set of fractures, whereas the resistivity logs indicated that water in the borehole below this depth was significantly more saline than water flowing down into the fracture.

The very slow firing rate of the sparker-source appeared as a major obstacle to the logging of many sections of borehole. The firing rate of once per 5 seconds was quite slow compared to 15 per second for the tool in the conventional mode. The much greater offset between source and receiver compensated for this, however, in that vertical recording stations could be spaced further apart. Wavelength scaling described previously indicated that waveforms only needed to be digitized every 1 m (meter) along the borehole rather than ever 0.15 m, for high-frequency waveform logs. Even at the apparently unrealistic firing rate of only once per 5 seconds, the need for fewer recordings per depth interval resulted in a logging speed of approximately one-fourth of that used in waveform logging with the high-frequency source.

LOW-FREQUENCY WAVEFORMS IN UNFRACTURED ROCK

The sparker-based acoustic-logging system produced waveforms in the unfractured interval of borehole URL-M11, that clearly were dominated by the tube-wave mode. A representative set of waveforms for the unfractured interval is illustrated in figure 3. Representative amplitude spectra for complete sparker-source waveforms are illustrated in figure 4. These spectra indicated that the low-frequency source produced almost all its energy at frequencies less than 10 kHz, with a peak near 7 kHz. Identity of the highest-amplitude part of the waveforms in figure 3 as the tube wave was confirmed by the mode-excitation functions given by Paillet (1983b) and reproduced in figure 5. This figure indicated that the tube wave was the only guided wave mode excited at the center band frequency of 7 kHz.

A second important aspect of the waveforms in figure 3 is the well-defined character of the shear arrival. The identification of the shear picks in figure 3 was confirmed by the move out of the arrivals between near and far receivers, which corresponds to a velocity very close to the known shear velocity of 3.35 km/s (kilometers per second). A typical sparker waveform recorded at greater resolution is illustrated in figure 6a. Mode-excitation functions in figure 5 indicated that the well-defined shear arrivals obtained with the sparker source in the 15-cm-diameter borehole were closely equivalent to the waveforms obtained at higher frequencies in a 8-cm-diameter borehole by Paillet (1980). The smaller hole diameter effectively stretched out the mode-excitation functions, so that both cases corresponded to borehole forcing at frequencies similar to the low-frequency cutoff for the first normal mode. An amplitude, power spectrum generated from a Hanning window centered on the shear arrival in figure 6a is illustrated in figure 6b. Even though the dominant frequency of the entire waveform was centered on 7 kHz, the shear arrival had a frequency very similar to cutoff for the first normal mode (about 10 kHz). This is an important consideration for shear-wave excitation, because pronounced contributions to shear-head wave spectra have occurred for frequencies in the vicinity of normal-mode cutoff (Paillet and White, 1982; Paillet, 1981).

Predictions of mode-excitation functions also were checked by examining waveforms obtained with the sparker source in smaller diameter boreholes adjacent to URL-M11. Representative waveforms obtained in an 8-cm-diameter borehole penetrating unfractured granite are illustrated in figure 7. The power spectrum for the near receiver is given in figure 8. Waveforms produced by the same logging system in rocks of identical properties in different diameter boreholes can be quite different as noted by Paillet and White (1982). In this case, waveforms obtained in the smaller diameter borehole were characterized by a lower frequency centered at about 5 kHz, and had no recognizable compressional or shear arrivals. The moveout between near and far receivers for the predominant arrivals in waveforms obtained in the small diameter borehole were consistently close to 1.45 km/s , or indistinguishable from tube-wave velocity. Mode-excitation functions for this borehole can explain the lack of head waves because the small annulus width between logging tool and borehole wall shifted both compressional and shear normal modes to high frequencies (Paillet, 1981). If most of the energy was contributed to the compressional and shear head waves at frequencies in the vicinity of compressional and shear normal-mode cutoff, then head waves would not be excited if forcing were confined to frequencies significantly less than cutoff for the fundamental modes.

This explanation for the lack of head waves in figure 7 is supported by the high-resolution recordings of waveforms illustrated in figure 9. Many waveforms and high-frequency energy, starting at the expected compressional and shear head-wave arrival time. This high-frequency arrival probably represented a very small contribution from the source at high frequencies corresponding to cutoff for the first normal mode. Estimates of the frequency of these low-amplitude arrivals were about 25 to 30 kHz, corresponding to cutoff for the first normal mode in 8-cm boreholes at URL as calculated by Paillet (1980).

Lower frequency content of the sparker-source waveforms in the smaller diameter borehole also can be explained by reference to mode-excitation diagrams. The source spectrum of the sparker probably can be modeled as an explosive-point source using a spectrum similar to that given by Peterson (1974). The small annulus in the case of the small diameter borehole effectively stretched out the mode-excitation functions so that the increase in tube-wave amplitude with frequency became almost linear. In that case, the much smaller increase in tube-wave amplitude with increasing frequency could produce tube waves with somewhat lower frequencies for a given source excitation.

FRACTURE CHARACTERIZATION WITH THE SPARKER SOURCE

The primary objective of the sparker-source field test was to verify that larger wavelengths provided by a relatively low-frequency source would provide a larger column of investigation, and would excite tube waves in large diameter boreholes. The most important result from field testing of the sparker source in borehole URL-M11 was, therefore, verification that the lower-frequency source excites tube waves in larger diameter boreholes that are sensitive to fracture permeability to the same extent as indicated for high-frequency tube waves in small diameter boreholes. Performance of the sparker source in the lower part of the test interval in URL-M11 was compared to waveform logs obtained with a relatively low-frequency magnetostrictive source in the same interval (fig. 10). Sparker waveforms are more widely spaced in the figure because of the proportionately larger sample volume associated with the larger source-to-receiver spacing. That is, if waveforms are digitized once every meter along the borehole, there will always be at least two stations where a given fracture lies between source and receiver. The waveforms in figure 10 indicate that the sparker source produced data that were sensitive only to the large open fracture near 187 m, whereas higher frequency data were significantly distorted by relatively minor fracturing between major fracture zones in figure 2. Relative insensitivity to apparently closed fractures on the part of the sparker-source system probably was associated with the domination of the low-frequency data by the tube-wave mode. Pressure oscillations and displacements in this mode were effectively confined to the fluid column according to the calculations given by Cheng and Toksöz (1981), so that tube-wave attenuation occurred through energy dissipation when fluid could oscillate within permeable fractures. The limited field tests of the sparker source thus confirm that lower source frequencies did excite tube waves in larger diameter boreholes, and lower frequency tube waves apparently were sensitive to fracture permeability. The lack of distortion in compressional and shear arrivals in the sparker-source waveforms in figure 11 likewise indicates that lower frequency source produced head waves that penetrated beyond the small annulus where drilling effects artificially have opened otherwise closed fractures.

In previous studies of tube-wave attenuation described by Paillet and White (1982) and Paillet (1980), tube-wave attenuation never was found associated with tube-wave reflections, even when dip or f-k filtering was applied to sets of waveforms in the vicinity of isolated fractures in a deliberate search for such reflections, even though tube waves are commonly seen at lithology contacts (White, 1983). These results differed significantly with finite-element models of wave propagation along boreholes that intersected permeable fractures (Bhasavanija and others, 1982). This discrepancy has been attributed to the contrast between the planar layer of fluid used as a fracture model in the finite-difference study, and the interconnected openings between locked asperities that probably represent real fractures. The irregular nature of natural-fracture faces may not have been very good reflecting surfaces for short-wavelength vibrations. It also was clear that the locked faces of natural fractures could not represent nearly as abrupt an impediment to acoustic propagation as the continuous layer of fluid. In spite of all these qualifications, high-density waveform logging of the lower fracture zone in URL-M11 with the sparker source indicated that tube waves were being reflected off the top of the fracture (fig. 11). The slope of the line drawn through the apparent reflection in figure 11 was estimated from the waveform plots, and was found to be approximately 1400 microseconds per meter. This value was almost exactly twice tube-wave velocity, confirming the identity of these arrivals as reflected tube waves. The slope of the line in figure 11 appeared as twice tube-wave velocity, because the reflected tube waves represented energy making a complete round trip to the fracture and back for each increment in depth as the tool was pulled past the fracture. This reflected tube wave was consistently observed during repeated logging of the interval illustrated in figure 2. Note that reflected tube waves were not observed below the lower fracture zone, or from either side of the major fracture zone near the top of figure 2.

The recognizable tube-wave reflection observed at the top of the lower-fracture zone appeared to result from both the uniformity of the upper surface of the fracture zone, and significant permeability of the fracture itself. In previous work at the URL site, Davison and others (1982) noted that a limited number of isolated open fractures appeared to account for the greatest degree of permeability in most of the boreholes. The lower fracture zone in figure 2 was originally selected for study as a typical example of such very permeable fractures located in the vicinity of a major fracture zone, which apparently provided much more effective permeability than many apparently large fractures indicated on the televiewer log in the top of figure 2. Large fractures at the top of figure 2 produced major anomalies on all acoustic logs, including those obtained with the sparker source. The presence of reflected tube waves may have provided the most effective means for discriminating between lithology changes associated with altered rock in the vicinity of fracture zones, and the few open fractures in relatively unaltered rock, that appeared to account for a major part of the permeability at the URL site.

CONCLUSIONS

An experimental sparker source for acoustic-waveform logging has been shown to provide waveforms with acoustic energy concentrated at frequencies between 1 and 10 kHz in boreholes of 8- and 15-cm-diameter. According to the calculations given by Paillet (1981), these source frequencies should produce measurable tube waves in boreholes in most rock types with diameters to as much as 30 cm. Therefore, the sparker source should be applicable to tube-wave logging in a large percentage of cases where the permeability of fractured crystalline rocks is of interest.

Comparison of waveforms obtained in two adjacent boreholes penetrating unfractured granite verified the frequency-scaling rules for waveform logging derived by Paillet and White (1982) and Cheng and Toksöz (1981). Mode-excitation functions appear to account for the difference in tube-wave frequencies between the two boreholes. An especially important result was the absence of compressional and shear-head waves in the waveforms obtained in the small diameter borehole. Theoretical calculations (Paillet and White, 1982) indicated that dominant contributions to head-wave spectra were associated with frequencies near normal-mode cutoff. Experimental results presented here confirmed the importance of providing source frequencies near normal-mode cutoff if shear-wave velocities and amplitudes were measured.

Limited acoustic-waveform logs obtained in the study interval of borehole URL-M11 confirmed that larger sample volumes provided by the lower frequencies of the sparker source improved the ability to distinguish between major permeable fractures and minor closed fractures that may have been slightly opened during drilling. The significant tube-wave reflection from the top of an isolated permeable fracture in URL-M11 had not previously been observed for well-logging frequencies, although Huang and Hunter (1981) reported such reflections at seismic frequencies in data obtained from surface-to-borehole measurements. The example presented here indicated that coherent reflections of tube waves from the surfaces of isolated open fractures may provide a means whereby these permeable fractures may be distinguished from other intervals of fractured and very altered rock with relatively little permeability.

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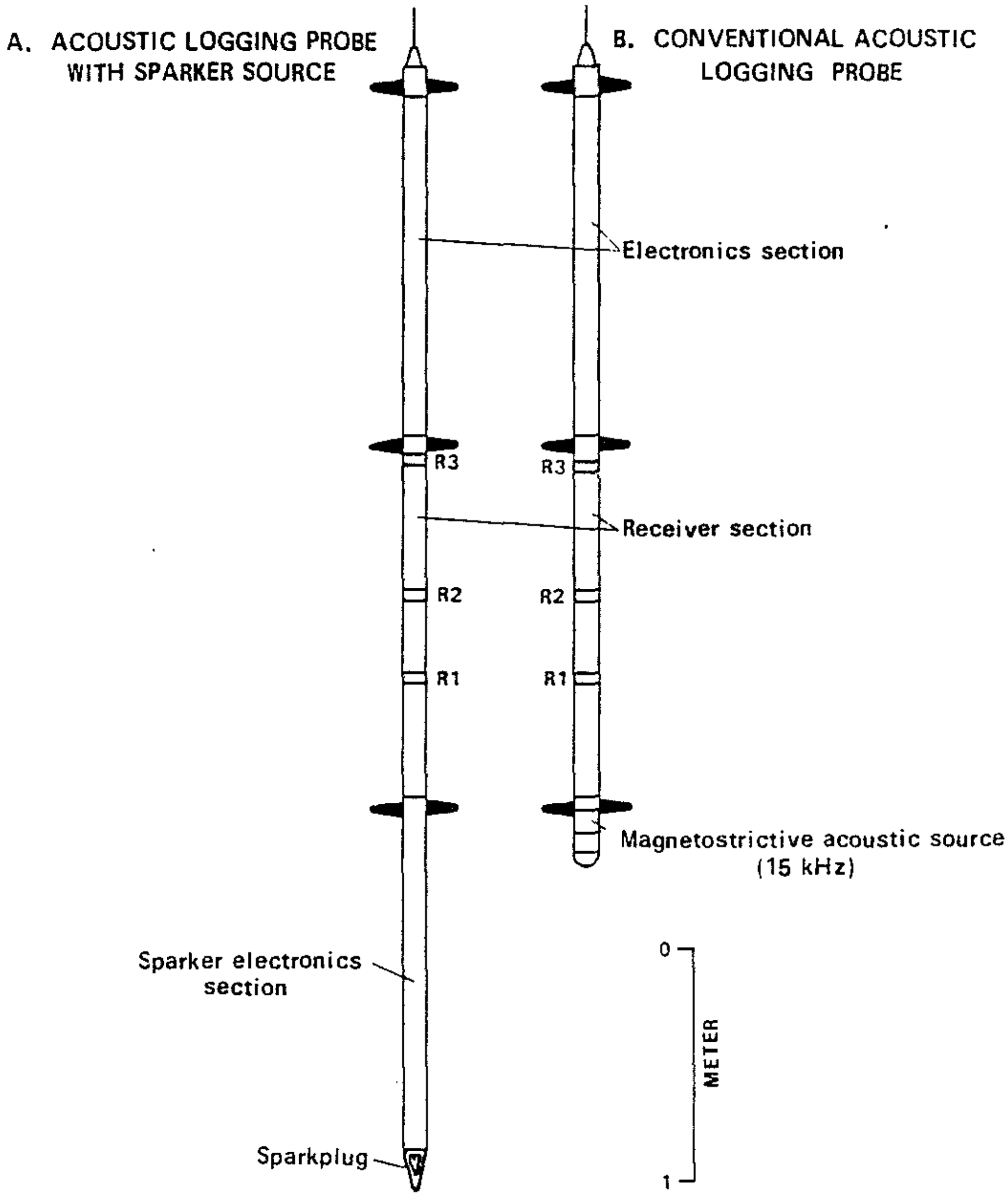


Figure 1. Comparison of acoustic logging probe with sparker source and conventional acoustic logging probe with magnetostrictive source.

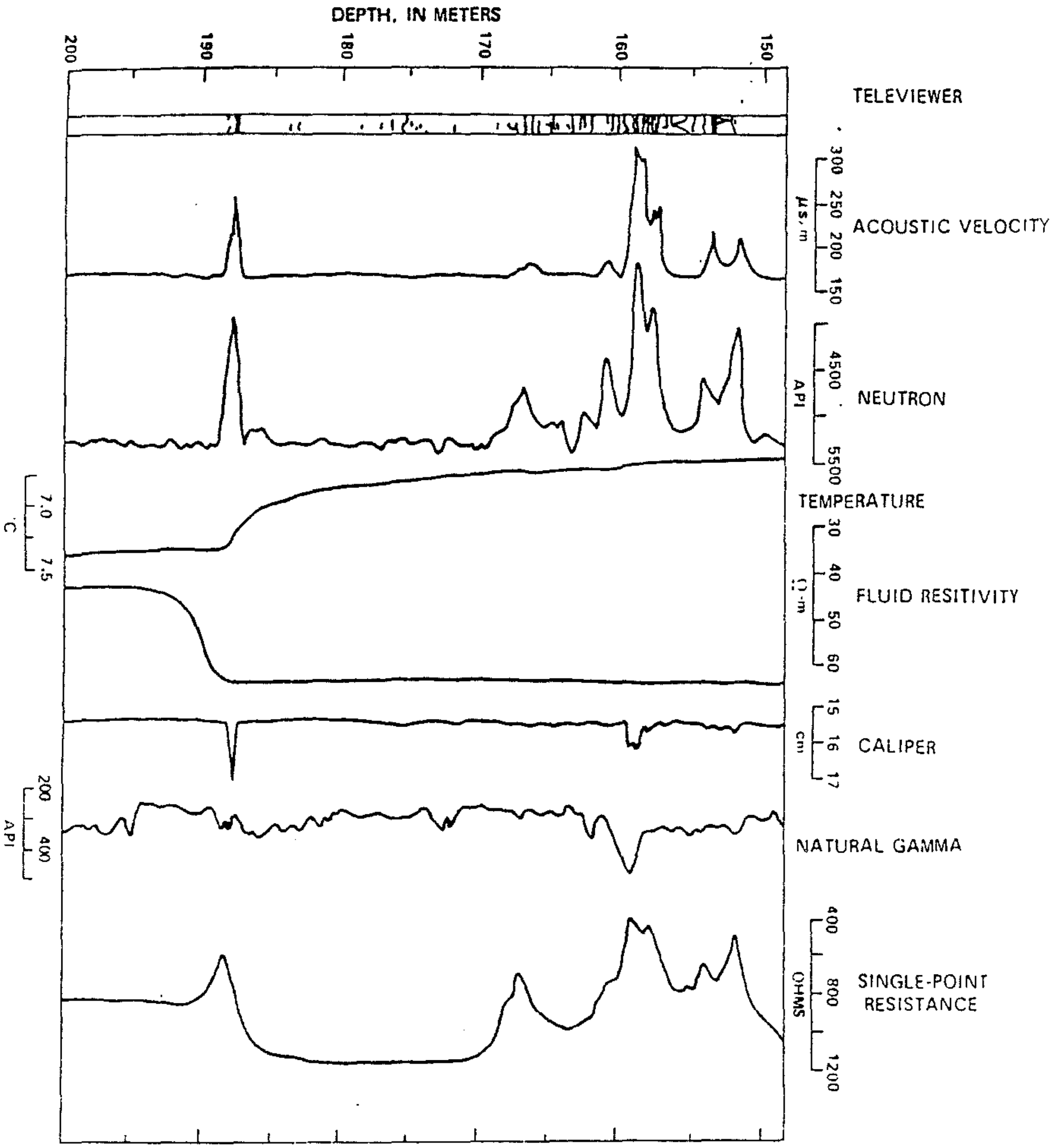


Figure 2. Commercial well logs obtained by Atomic Energy Canada Limited compared to U.S. Geological Survey televiewer log for selected study interval in borehole URL-M11.

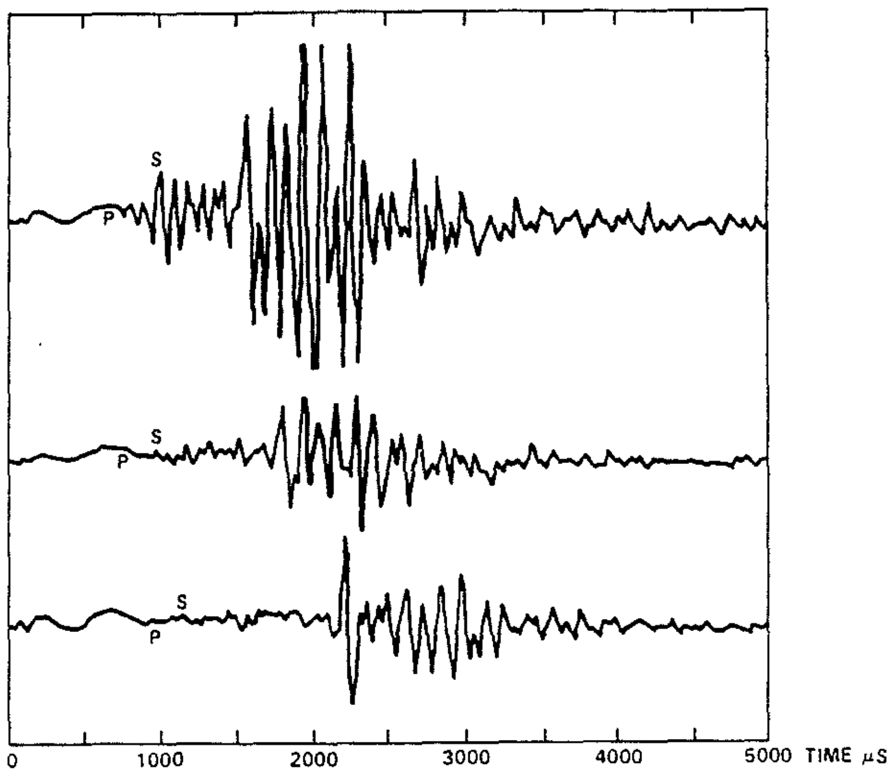


Figure 3. Acoustic waveforms obtained with sparker source at three different source-to-receiver spacings in unfractured granite; borehole diameter is 15 centimeters, and P and S denote compressional and shear arrivals.

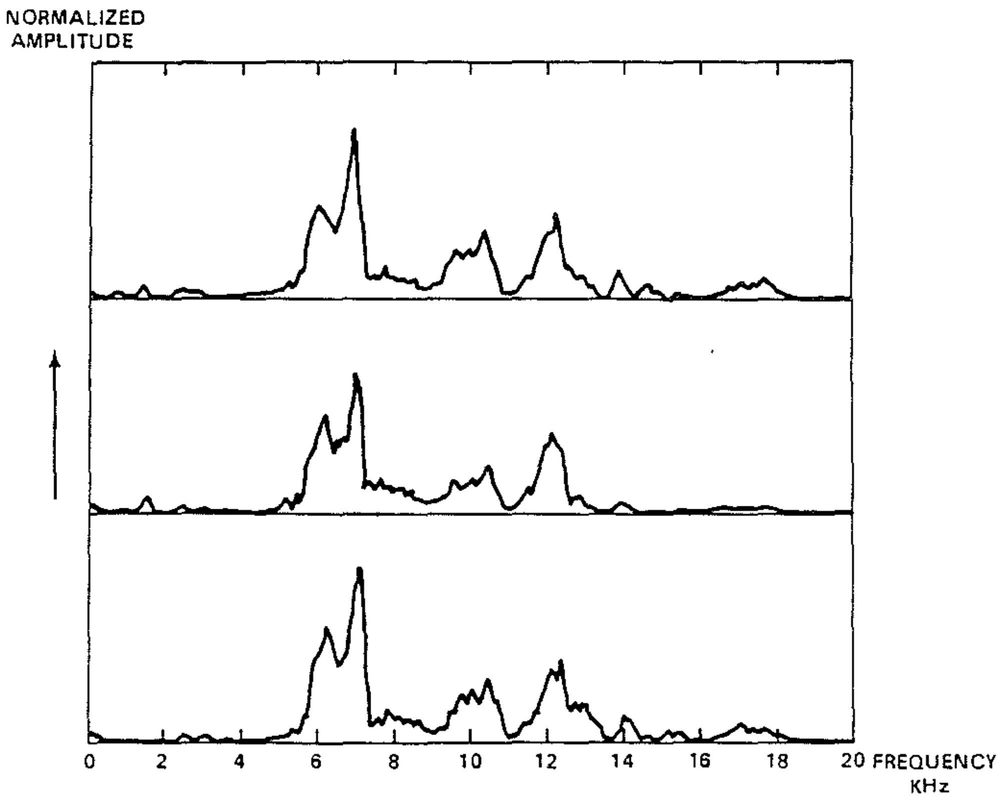


Figure 4. Three amplitude-power spectra from three different waveform records in unfractured granite, indicating source-frequency distribution and repeatability; borehole diameter is 15 centimeters.

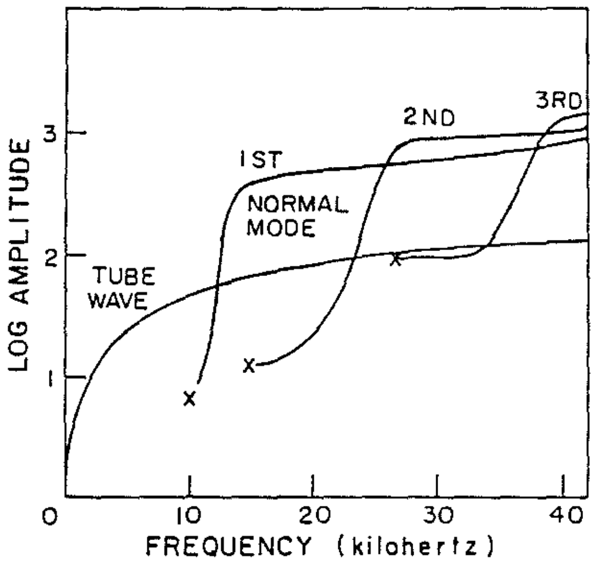


Figure 5. Mode excitation functions calculated for a 15-centimeter diameter borehole in granite (modified from Paillet, 1983).

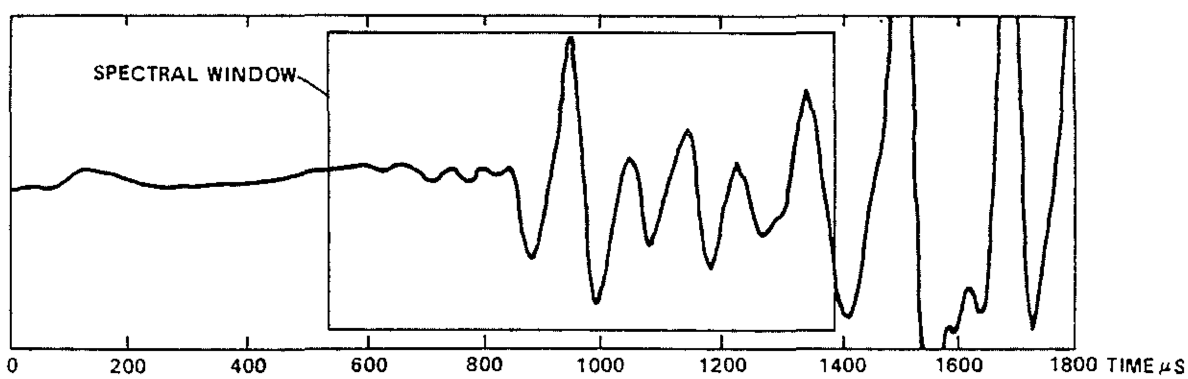


Figure 6a. High-resolution recording of shear arrival in unfractured granite; borehole diameter is 15 centimeters.

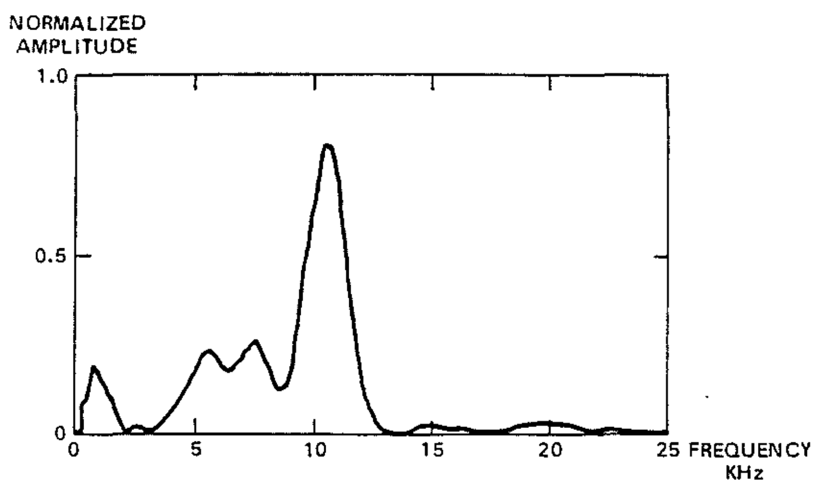


Figure 6b. Amplitude power spectrum for shear arrival in figure 6a.

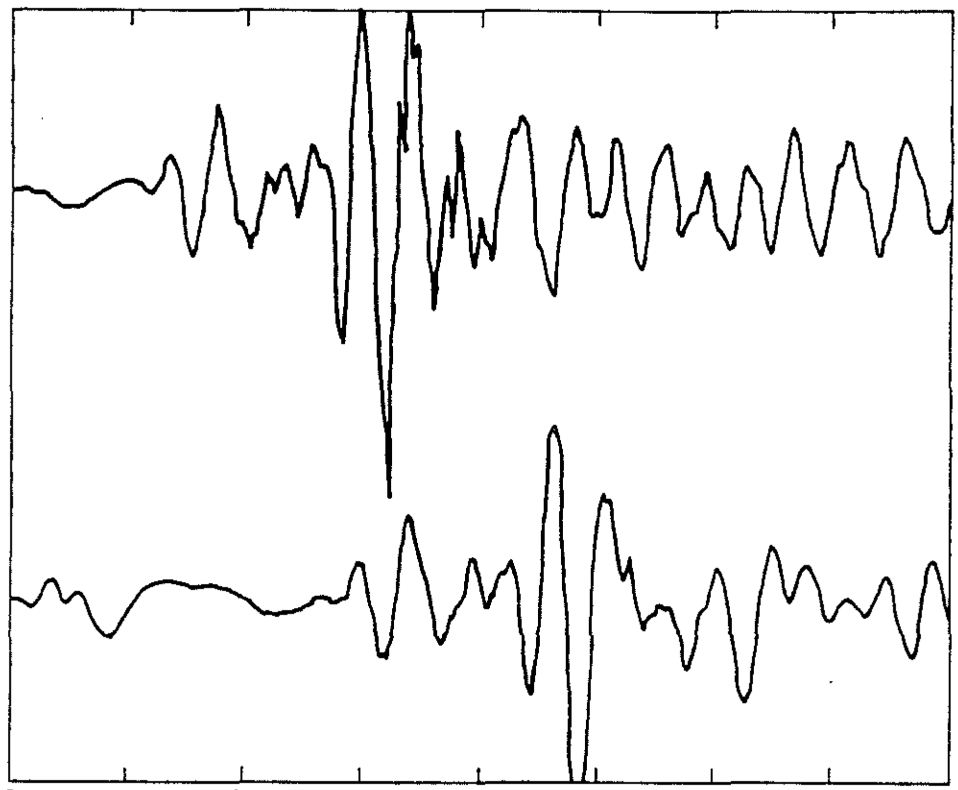


Figure 7. Acoustic waveforms obtained with sparker source at two different source-to-receiver spacings in unfractured granite; borehole diameter is 8 centimeters.

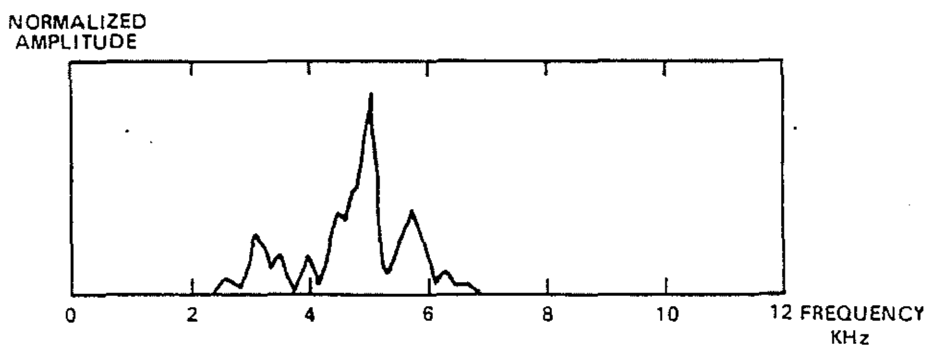


Figure 8. Amplitude power spectrum for sparker source in unfractured granite; borehole diameter is 8 centimeters.

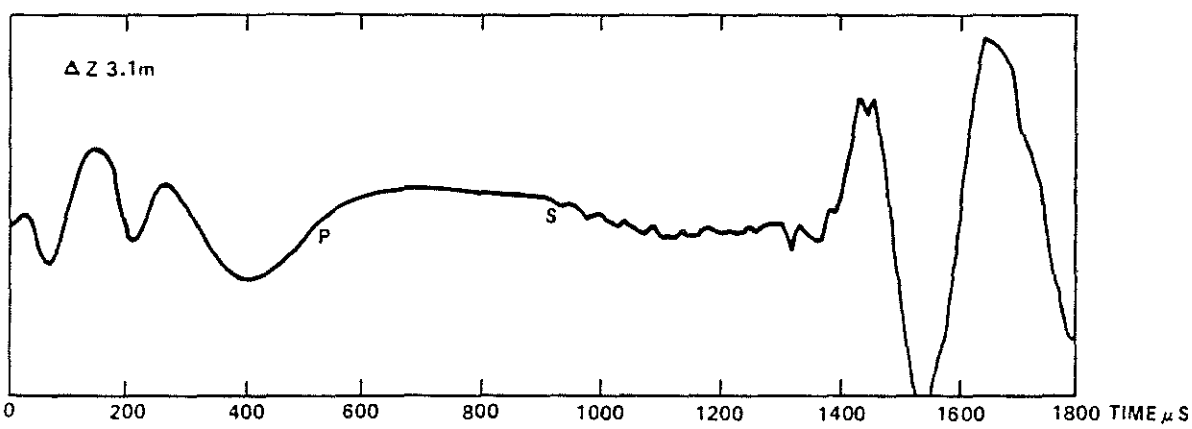
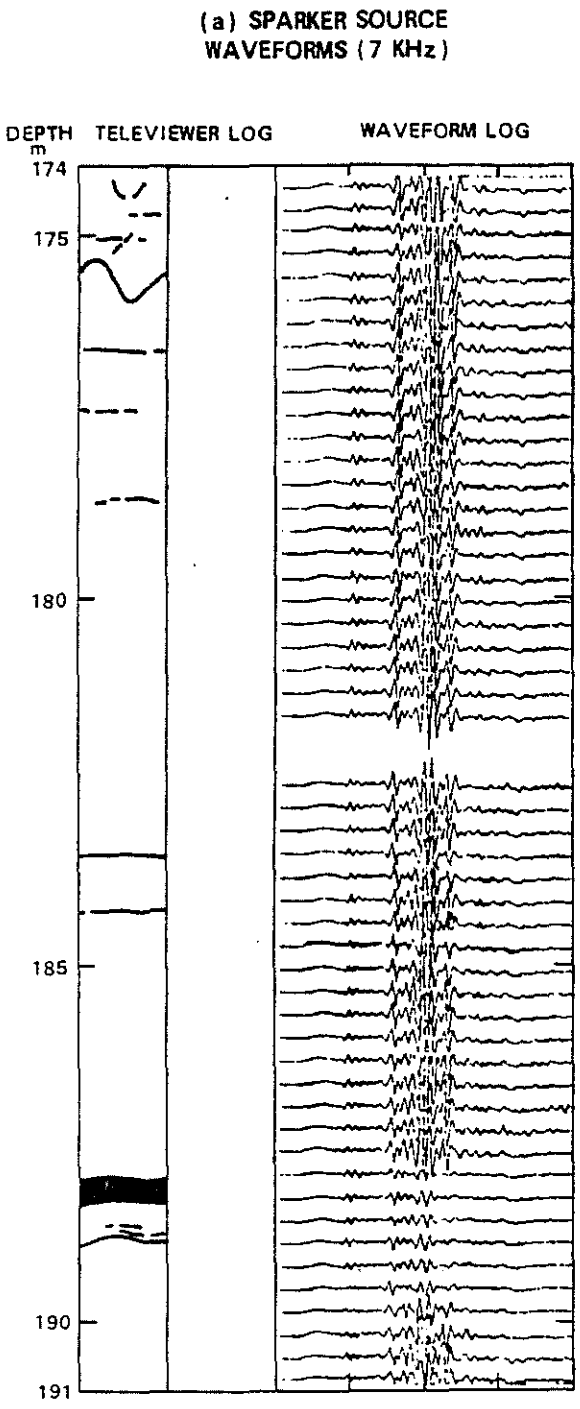


Figure 9. High-resolution recording of waveform from sparker source in 8-centimeter diameter borehole; P and S denote calculated arrival times for compressional and shear head waves.



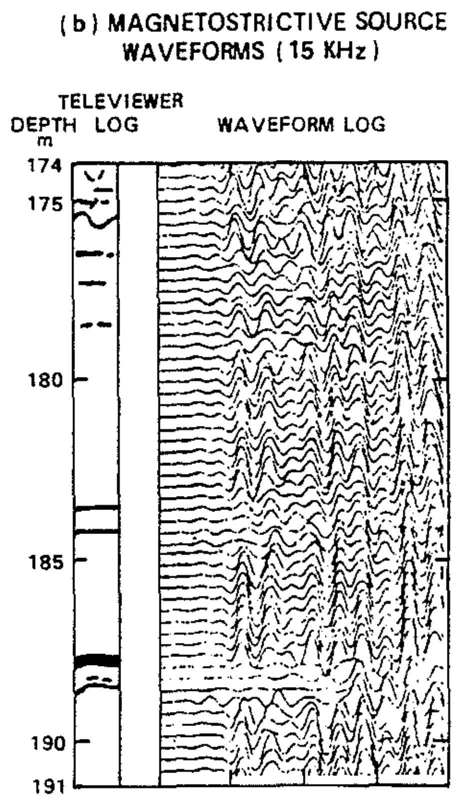


Figure 10. Acoustic waveform logs obtained with sparker source compared to those obtained with a conventional magnetostrictive source of 25 kHz using the same receiver section for an interval containing several minor fractures.

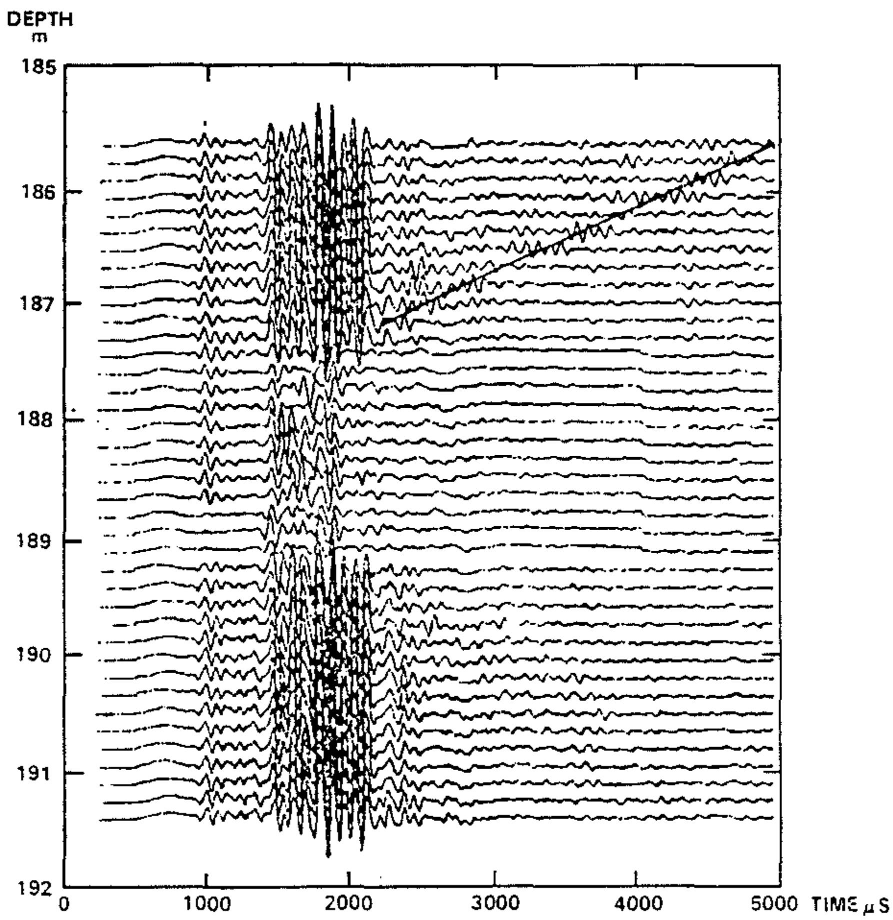


Figure 11. Waveform log obtained with sparker source for interval in borehole URL-M11 containing an isolated fracture that is relatively permeable; diagonal line indicates reflected tube wave from upper fracture surface.