# THEORETICAL MODELS RELATING ACOUSTIC TUBE-WAVE ATTENUATION TO FRACTURE PERMEABILITY — RECONCILING MODEL RESULTS WITH FIELD DATA

by

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## ABSTRACT

Several recent investigations indicate that tube-wave amplitude attenuation in acoustic full-waveform logs is correlated with permeability in fractured rocks. However, there are significant differences between predictions based on theoretical models for tube-wave propagation and experimental waveform amplitude data. This investigation reviews the results of existing theoretical models for tube-wave attenuation in fractured rock and compares model predictions with acoustic full-waveform data where extensive independent fracture-permeability data are available from straddle-packer permeability tests. None of the tube-wave models presented in the literature predicts attenuation at fracture apertures as small as those producing attenuation in the field; and most models predict tube-wave reflections, which are rarely measured at frequencies greater then 5 kHz. Even the unrealistic assumption that all of the tube-wave energy loss is caused by viscous dissipation in fracture openings does not result in predicted apertures being as small as those indicated by packer permeability measurements in most situations.

On the basis of these results, it is concluded that plane-fracture models cannot account for the measured tube-wave attenuation where natural fractures intersect fluid-filled boreholes. However, natural fractures are fundamentally different from plane parallel passages. This difference appears to explain the small equivalent flow apertures and lack of reflections associated with fractures in waveform-log data. Permeable fracture openings modeled as irregular tubes embedded between asperities along the

fracture face are predicted to produce significant tube-wave attenuation when tube diameters exceed 1.0 cm, but arrays of such tubes conduct fluid flow equivalent to that through plane fractures less than 2 mm in effective flow aperture. Although the theory predicts some reflection from simple cylindrical passages, scattering from irregular distributions of natural fracture openings probably accounts for the infrequency with which coherent tube-wave reflections occur in field data.

## INTRODUCTION

Several recent investigations conclude that tube-wave attenuation measured in fluid-filled boreholes is correlated with borehole-wall permeability. For example, Rosenbaum (1974) used the porous-media formulation of Biot (1956a,b) to calculate tube-wave amplitude attenuation produced by borehole-wall permeability in sandstone aquifers. This result is supported by experimental data (Cheng et al.;, 1987, Burns et al.; 1988, Winkler et al., 1989). However, the effect of filtercake on borehole-wall permeability in many sedimentary formations appears to limit the practical application of this method in exploratory boreholes (Rosenbaum, 1974). Tube-wave methods have proven more useful in the interpretation of fracture permeability in core holes where drilling mud is not used, in air-percussion drilled boreholes for geotechnical applications, and in situations where large fracture openings are not blocked by mud filtrate (Paillet, 1980, 1983). A typical example of the correlation between tube-wave amplitude determined from acoustic-waveform logs and independent information on the size and location of fractures given by the televiewer log is illustrated in Figure 1. Similar results have convinced some investigators that the size of the tube-wave amplitude anomaly, expressed as the integrated deficit of tube-wave energy or mean-square amplitude with respect to the average energy in unfractured intervals, can be taken as a semi-quantitative indication of fracture permeability (Paillet, 1980; Brie et al., 1988).

Early applications of tube-wave attenuation in predicting fracture permeability were based on establishing a direct correlation between independent measurements of fracture permeability and tube-wave attenuation (Paillet, 1983; Brie et al., 1988). The method subsequently was expanded to include interpretation of tube-wave attenuation by means of theoretical models relating tube-wave energy loss to the aperture of a plane parallel-fracture flow model (Mathieu, 1984; Algan and Toksöz, 1986). Results based on these theoretical models appeared to agree with independent permeability measurements, if allowances were made for the different scales over which tube-wave amplitude and conventional straddle-packer permeability tests are made (Paillet et al., 1987; Hardin et al., 1987).

More recent improvements in theoretical fracture models and comparison of straddle-packer permeability tests with interpretation of tube-wave amplitudes based on those models indicate that there are significant differences between model predictions and tube-wave data. This report reviews existing models for tube-wave attenuation in fractured rocks, and compares model predictions with tube-wave amplitude data for carefully selected borehole intervals where independent permeability measurements have been made for isolated sets of fractures. The comparison demonstrates that there are substantial qualitative differences between model predictions and tube-wave data. New models for tube-wave attenuation in fractures may be required in order to account for the characteristics of tube-wave attenuation in boreholes. One possible model is presented in this report. This revised tube-wave attenuation model accounts for the tube-wave attenuation produced by fractures with small equivalent plane fracture apertures and appears to explain the absence of coherent tube-wave reflections from permeable fractures at frequencies greater than 5 kHz.

## MODELS FOR TUBE-WAVE ATTENUATION IN FRACTURED ROCK

There have been several recent efforts to model acoustic propagation along fluid-filled boreholes intersected by permeable fractures. The earliest of these was based on the direct calculation of waveform time series using finite-difference models of rocks containing boreholes and fractures. The mathematical difficulties and number of nodal points required to perform these calculations limit the resolution of the results. In particular, finite-difference calculations require large fracture-flow apertures to produce attenuation of the transmitted waveforms; and almost all of the attenuation is accounted for by a large, coherent reflected tube-wave (Stephen et al., 1985; Bhashvanija, 1983). Finite-difference models are otherwise assumed not to provide the resolution required to model tube-wave propagation across the small apertures of natural fractures in boreholes.

The observation that tube-wave attenuation in fractured formations was almost never associated with measurable reflections (Paillet, 1980, 1984) induced Mathieu (1984) to model tube-wave attenuation by means of a balance between pressure oscillations driven by the tube wave and viscous dissipation in the fracture. This apparently arbitrary assumption cannot be derived from the equations of fluid motion but can be taken as a practical means for weighting tube-wave attenuation in units related to fracture aperture (Figure 2). This method estimates the flow aperture of the plane parallel fracture required to produce the observed attenuation. Because the method is based on the assumption of no energy-loss mechanism other than viscous dissipation and is based on the highest order terms in the fluid equations, it predicts the smallest possible aperture required to produce the attenuation. If used in this manner, the method yields a conservative estimate of fracture aperture. That is, the analysis yields the smallest equivalent flow aperture that could account for the tube-wave attenuation. The same approach also can be used to estimate the depth of penetration of the tube-wave oscillations into the surrounding formation (Algan and Toksöz, 1986).

Rigorously developed models for tube-wave attenuation in fractures have become available since 1986. The complexity of the full set of wave equations required to model tube-wave attenuation in fractures is indicated by the presence of four different length scales: acoustic wavelength, borehole diameter, fracture aperture, and viscous boundary-layer thickness. The last of these, the viscous boundary layer thickness for motion within the fracture, is a function of frequency:

$$\text{Boundary layer thickness } d = 2(\eta/\omega)^{1/2},$$

where $\omega$ is the acoustic frequency and $\eta$ is the dynamic viscosity of water. Some of these scales can be considered fixed for all models. For example, all models are based on the assumption that fracture aperture is much smaller than the acoustic wavelength and larger than the boundary-layer thickness for fluid motion within the fracture. Significant changes in the proportion of reflected and absorbed energy occur as the ratio of fracture aperture to boundary-layer thickness decreases from very large to finite values. For very large fracture apertures, almost all energy loss occurs by reflection, in agreement with finite-difference models. When fracture apertures become one or two orders of magnitude larger than the boundary-layer thickness, there is a significant loss of energy to fluid motion within the fracture. As the fracture-aperture size approaches the boundary-layer thickness, almost all wave energy is transmitted across the fracture opening. These results do not appear to be sensitive to the exact shape or orientation of the fracture opening (Hornby et al., 1989; Brie et al., 1988) but are sensitive to the borehole radius.

Typical model results for tube-wave propagation across a plane, fluid-filled fracture are given in Figure 3 (Tang and Cheng, 1989), illustrating transmitted tube-wave amplitude as a fraction of incident tube-wave amplitude for frequencies ranging from 0.01 to 10 kHz. In general, the transmitted amplitude decreases as fracture aperture increases. Transmitted energy increases with increasing frequency for a given fracture aperture. The results in Figure 3 were obtained for a fracture perpendicular to the borehole axis and were based on the assumption that acoustic wavelengths are much larger than fracture aperture. The latter assumption is always satisfied for fracture apertures less than 1 cm and frequencies less than 20 kHz. However, this assumption precludes extrapolation of model results to complete reflection in the small wavelength limit.

Hornby et al. (1989) and Brie et al. (1988) considered tube-wave attenuation for fractures aligned at an arbitrary angle to the borehole axis. In general, the results indicate that the estimated acoustic energy losses are increased in approximate proportion to the cross sectional area of intersection between fracture and borehole. For non-perpendicular intersections, the increase in area of intersection introduces an effective increase in energy loss in proportion to 1/cos(90-J), where J is the angle of intersection between the borehole axis and fracture plane. In the limit of fracture plane parallel to the borehole axis (J = 0), the percentage energy lost by a propagating tube-wave increases continuously with source-to-receiver distance (Tang and Cheng, 1989). These results have been confirmed in laboratory models where the attenuation of tube waves propagating across plane-parallel fractures of known aperture has agreed closely with predictions (Tang and Cheng, 1989; Brie et al., 1988; Poeter, 1987; Zlatev et al., 1988).

## TUBE-WAVE ATTENUATION AND PERMEABILITY IN NATURAL FRACTURES

Obtaining accurate fracture permeability measurements for comparison with tube-wave data for natural fractures intersecting fluid-filled boreholes is difficult. Independent information on fracture permeability in situ is expensive and time consuming to obtain. Moreover, data must be obtained for isolated fractures that can be identified both on the acoustic waveform logs and in the permeability measurements. Permeability usually is measured by means of packer isolation and injection tests, where the measured decrease in pressure within an interval of borehole is compared to model predictions or "type curves" in an infinite plane fracture of given aperture. The permeability determined in this way often is represented in terms of the flow aperture (in millimeters) of an equivalent plane fracture (Hsieh et al., 1983; Ziegler, 1976). One of the major problems in comparing tube-wave amplitude data with such permeability measurements is finding isolated fractures where permeability in the packed-off interval is associated with a single fracture set.

Comparison of the scales associated with permeability measurements by means of packer isolation tests, tube-wave amplitude attenuation, and core inspection indicate that these measurements sample fracture-flow properties through substantially different volumes of rock. Packer tests measure the effective permeability associated with quasi-steady flow into the formation for 10 m or more around the borehole (Hsieh et al., 1983). Tube-wave oscillations are sensitive to the permeability of fractures a few wavelengths into the formation, or from 1 to 3 m at logging frequencies near 10 kHz on the basis of calculations given by Algan and Toksöz (1986). Direct measurement of fracture aperture is sometimes possible if fracture faces can be recovered intact and the width of fracture openings can be estimated from the size of mineral crystals that have grown within the fracture. Intervals of fracture contained in core samples are subject to stress release and mechanical damage during drilling, and core-fracture measurements apply to fracture segments no more than 0.05 m long. All three of these approaches to fracture-permeability estimation involve the averaging of permeability for different volumes of fractured rock. Scale effects impact fracture flow directly through variation of fracture apertures, and indirectly through the statistics of fracture interconnections. Because of the inherent variability in fracture aperture, the volume-averaged values are not expected to agree even when measurements are made at the same nominal depth in boreholes. Agreement and consistency of different methods for in situ fracture-permeability estimation only is possible when a number of measurements have been correlated and all sources of error and ambiguity about the responses of individual fracture sets have been removed from the data.

Initial results in a long-term effort to compare tube-wave attenuation with other permeability measurements appeared to indicate that the interpretation of tube-wave attenuation using the method of Mathieu (1984) was consistent with other data (Paillet et al., 1987). The apertures of individual fractures estimated from tube-wave attenuation at Mirror Lake, New Hampshire, appeared to agree with the flow aperture of fractures estimated from packer tests, and inferred from cross-hole pumping tests. This original experiment was restricted to a single fracture zone because numerous other fractures interpreted to have apertures ranging from 0.1 to 0.5 mm did not conduct flow. Only the results from the permeability zone were considered relevant. The apparently poor agreement at those depths where little or no permeability was inferred from the results of packer tests was taken as evidence for lack of connections between fractures.

Since the publication of the limited packer test results from Mirror Lake in 1987 (Paillet et al., 1987), additional packer-test data have been made available for a series of boreholes in a granite batholith at Lac du Bonnet, Manitoba. Hydrologic investigations at the latter site also indicate that large-scale permeability is associated with fracture or fault zones. At least two of the zones were intersected by three boreholes in which tube-wave attenuation measurements were made (Davison, 1984; Paillet, 1988). Comparison of tube-wave interpretations made using the Mathieu (1984) and Tang and Cheng (1989) method and the packer-isolation and -injection test data are presented in Table 1. Data for fracture zones at Mirror Lake, New Hampshire (Paillet et al., 1987), and Chalk River, Ontario (Paillet, 1983), are given for comparison. In these data sets, packer tests were made for intervals ranging from 3 to 20 m; therefore, direct comparison cannot be made between the flow aperture associated with individual fractures using the tube-wave method and the packer-test data. However, the Mirror Lake data are the only example in which the effective flow aperture of the entire fracture zone measured in the packer tests is as large as the flow aperture of the largest individual fracture interpreted from the tube-wave amplitude data. These results indicate that the consistency between packer tests and tube-wave attenuation interpretation at Mirror Lake is the exception rather than the rule.

Fracture-permeability distribution in one of the Manitoba boreholes measured by packer-isolation tests for 20-m intervals is compared to the fracture-permeability distribution inferred from tube-wave amplitude data in Figure 4. Fracture apertures estimated from tube-wave attenuation are given as the apertures of individual fractures and as 20-m interval sums where the total permeability in each interval has been expressed as the aperture of a single equivalent plane fracture as described by Paillet et al., (1987). Results from a vertical-seismic-profile (VSP) tube-wave analysis (Huang and Hunter, 1981; Hardin et al., 1987) using much lower frequency surface seismic-energy sources also are given for comparison. The length scale associated with VSP analysis is considered intermediate between that of the tube-wave attenuation measurements and the packer tests. The packer-test data, tube-wave interpretation, and VSP results indicate a similar distribution of permeability. Some differences among the permeability distributions given in Figure 4 would be expected because of the different scales of investigation associated with each method. However, the Mathieu (1984) analysis of tube-wave amplitude-attenuation data yields fracture apertures that are consistently much greater than those given by the packer tests. If the results of this analysis are assumed to be the lower bound on fracture apertures that can be inferred from tube-wave attenuation, it may not be possible to use plane fracture flow models to interpret tube-wave data.

The several-meter isolation intervals used in packer tests make comparison between measured permeability and tube-wave attenuation difficult for individual fractures. However, the fracture-flow apertures estimated from tube-wave data can be compared to apertures measured from sections of fractures identified in core. Two examples are given in Figure 5. In these examples, fracture aperture is inferred from core samples by taking the maximum size of mineral crystals that have grown within the fracture opening. Such measurements provide an upper bound on fracture aperture, because the maximum crystal size represents crystals in the widest part of the fracture and does not account for the effect of infilling minerals on hydraulic conductivity. This factor is an important consequence of the fracture-asperity model (Tsang and Witherspoon, 1981), where mineral deposits fill the largest openings between asperities, compared to the plane-fracture model, where crystals are constrained by the uniform fracture aperture. In Figure 5A, the measured fracture apertures are larger than the apertures estimated from the tube-wave data, in agreement with the plane-fracture models. In Figure 5B, fracture apertures are estimated to be about 0.3 mm from the tube-wave data; but individual fractures have apertures of 0.2 mm or less in the upper of the two fracture sets, and possibly much less. In this example, tube-wave interpretations appear to overestimate fracture aperture. This overestimation may be serious if asperities and infilling minerals act to reduce the hydraulic conductivity of these fractures.

The results presented in Table 1 and Figure 4 appear to indicate that application of the Mathieu (1984) method of tube-wave attenuation often over-predicts fracture aperture. Rigorously derived models for oscillatory flow in fractures (Figure 3) indicate that application of more sophisticated fracture models makes the discrepancy much worse. For example, Figure 3 indicates that a plane fracture at least several millimeters in width is required to produce a measurable decrease in transmission of tube-wave energy at logging frequencies. The data in Figure 4 indicate that fractures which conduct water as if they were less than 1 mm in aperture produce tube-wave attenuation that would require a fracture more than 10 mm wide if the rigorously derived Tang and Cheng (1989) model is applied to the interpretation. These results apply to a comparison where there is a significant difference in the scale of investigation. However, the tube-wave method appears consistently to overestimate fracture aperture, for all of the data given in Figure 4.

The characteristics of tube-wave data for propagation across natural fractures contain two other inconsistencies in addition to aperture interpretation in comparison with fracture models: (1) lack of tube-wave reflections at large fractures, and (2) absence of frequency dependence in measured tube-wave amplitudes. All plane-fracture models predict that reflected tube waves account for a substantial part of transmission losses in tube-waves propagating across fractures. However, no reflections were ever detected in data obtained with logging sources using frequencies greater than 10 kHz in Manitoba, and only a few, weak reflections were detected in these same boreholes using an experimental 5-kHz sparker source (Paillet, 1984). One of the few examples in which tube-wave reflections were detected is illustrated in Figure 6. Comparison of tube-wave amplitude data obtained in the same fractured interval using 34 and 5 kHz acoustic logging sources also did not indicate any significant effect of frequency on measured attenuation (Figure 7), even though such frequency dependence is predicted in Figure 3.

All of these results indicate substantial differences between the predictions of tube-wave attenuation associated with fluid-filled plane fractures and measurements of tube-wave attenuation in propagation across natural fractures. The tube-wave attenuation data appear to indicate significant attenuation (consistently greater than 50 percent) at fractures with independently measured hydraulic apertures that seem too small to produce such attenuation. At the same time, the data from natural fractures does not contain the large-amplitude tube-wave reflections or frequency dependence predicted from the fracture models. This lack of even qualitative agreement between model predictions and data from natural fractures is unexpected, given that data from experiments using artificial fractures in laboratory scale models appear to agree very well with the theoretical models.

## RECONCILING MODEL PREDICTIONS AND FRACTURE DATA

The large discrepancies between model predictions and tube wave measurements in boreholes intersected by natural fractures can be reconciled if natural fractures are assumed to have properties very different from those of plane parallel openings used in theoretical models and in laboratory scale models. Natural fractures intersecting boreholes at depth are expected to be different from plane parallel openings or "fluid slabs" in that contacts at asperities located on the fracture face are capable of supporting lithostatic and tectonic stresses. In natural fractures, fluid motion occurs along irregular openings embedded in the fracture face. A few large "flow tubes" may produce significant tube-wave attenuation, and yet the amount of water carried by these tubes might be equivalent to that carried by a very small planar opening. This argument may be used to explain the apparent inconsistency between tube-wave attenuation measurements and effective fracture aperture measured in packer-isolation tests. The irregularities of the flow tubes embedded in the fracture plane also might explain both the lack of coherent reflections except at frequencies above 5 kHz and the lack of frequency dependence in the measured attenuation. The distribution of sizes and shapes of flow tubes could scatter tube waves unless wavelengths are long enough so that irregularities in the fracture plane are averaged over a coherent surface of reflection. Even then, tube-wave reflections might occur with lower amplitudes than those predicted for a single cylindrical flow tube (Hornby et al., 1989).

The fracture-permeability model used to describe natural fractures is illustrated in Figure 8A. The fracture openings are described as an irregular set of interconnected passages between asperities. The flow-tube model proposed here (Figure 8B) is one of several alternative models used in the literature to describe flow in the passages between asperities within fractures (Tsang and Witherspoon, 1981; Witherspoon et al., 1981; Brown, 1987). The irregular passages in Figure 8A are assumed to be composed of a spectrum of flow tubes of different sizes such as those illustrated in Figure 8B. When packer tests are conducted, the flow moves outward from the borehole as if along a regular network of tubes. Even though the flow is not planar within the fracture, the outflow appears to match type curves for flow along plane fractures because the fracture acts as if it were a thin layer of porous media. The aperture of an equivalent plane fracture depends upon the spacing of flow tubes in addition to their average size. The transmissivity, $T_0$, of a single cylindrical flow tube is defined as the discharge of the tube under uniform pressure of hydraulic-head gradient:

$$T_0 = \frac{\rho g a^4}{8\gamma},$$

where $g$ is the acceleration of gravity, $a$ is the radius of the flow tube, and $\gamma$ is the dynamic viscosity of water. The transmissivity, $T$, of the array of flow tubes given in Figure 8B is the total discharge per unit head gradient per unit cross section of the fracture zone:

$$T = T_0/D,$$

where $D$ is the average spacing between flow tubes in Figure 8B.

Tube-wave attenuation associated with flow tubes is given by modifying the model of Tang and Cheng (1989) to include a cylindrical opening of diameter, $2a$, intersecting a borehole of diameter $2R$ (Figure 8C). The tube-wave attenuation produced by isolated flow tubes of various radii at frequencies of 1 Hz and 10 kHz in a 7.62-cm-diameter borehole is illustrated in Figure 9. These results indicate that individual flow tubes as small as 1 cm in diameter can produce measurable tube-wave attenuation.

Tube-wave attenuation can be related to effective fracture aperture by relating the transmissivity of an array of flow tubes such as that in Figure 8B to the transmissivity of a plane parallel fracture. The calculation of such apertures requires a value for the average separation of flow tubes, which cannot be determined from borehole data. This result is an indication of the significant difference in scale of investigation between packer-isolation tests and acoustic-waveform logs. The cylindrical openings required to produce tube-wave attenuation in Figure 9 still appear relatively large in comparison with the fracture apertures inferred from packer testing. Comparison of the equations for flow in rectangular openings and cyclindrical tubes indicates that the ratio of the aperture of a plane opening ($b$) to the diameter of a flow tube ($a$) carrying the same flow is given by:

$$b/a = (0.29/e)^{1/3},$$

where $e$ is the ratio of tube spacing to tube diameter, $D/a$. Assuming that e varies from 10 to more than 100, then the ratio $b/a$ varies from 0.1 to 0.3. The calculations given in Figure 9 indicate that measurable tube wave attenuation would be produced by a flow tube more than one centimeter in diameter. The flow carried by an array of such tubes would then correspond to the flow carried by a single, equivalent plane fracture with an aperture ranging from 1 to 3 mm. These equivalent fracture apertures are still somewhat larger than the the flow apertures measured for fractures producing measurable tube-wave attenuation in Figure 4, but are significantly smaller than the apertures given in Figure 3. It is assumed that the additional tube wave energy losses observed in the field are attributed to scattering produced by flow tube irregularities not accounted for in Figures 8B and 8C.

One of the most important results of the the flow tube model is the indication that fracture permeability cannot be related directly to the aperture of a plane parallel fracture. Comparison of Figures 8B and 8C indicates that additional information is required before local tube-wave attenuation can be related to fracture permeability by means of the flow-tube model given in this report. The flow tube model in Figure 8B is related readily to an equivalent plane fracture, because the geometry of flow is similar to flow in a plane passage when averaged over scales larger than that of the flow-tube spacing. The difficulty in relating local tube-wave attenuation to fracture aperture is caused by the small sample size of the flow-tube population in the vicinity of the borehole. For this reason, it appears more consistent to relate tube-wave attenuation to fracture transmissivity. However, even when transmissivity values are used instead of equivalent fracture apertures, differences are expected between the results of tube-wave interpretations and packer tests for individual fractures because of the difference in volume of fracture being sampled. Estimates of fracture transmissivity based on tube-wave interpretations might agree with packer-test results only when a number of measurements are averaged for several different fracture zones. Even then, the consistent difference in scale between tube-wave interpretations and packer-tests results may produce a consistent difference in permeability estimates that is a fundamental property of the fracture network unrelated to measurement error and interpretation.

## CONCLUSIONS

Careful comparison of tube-wave-attenuation data and permeability measured by means of packer-isolation and -injection tests indicates that there is a consistent correlation between tube-wave amplitude and fracture permeability. However, fracture-aperture interpretations based on plane-fracture flow models for tube-wave attenuation consistently appear to overestimate the aperture of fractures associated with more than 50 percent energy loss in transmission across fracture openings. Plane fracture models also predict that transmission losses are accompanied by coherent tube-wave reflections and that transmission coefficients increase with increasing tube-wave frequency. Coherent reflections rarely, if ever, are observed in data sets obtained using conventional acoustic sources in fractured igneous and metamorphic rocks; and only a few weak reflections have been observed using an experimental 5-kHz logging source. Comparison of data sets obtained with 34 kHz and 5 kHz logging sources demonstrates a lack of frequency dependence in attenuation for this frequency range. All of these results indicate that tube-wave attenuation in natural fractures cannot be predicted using plane-fracture flow models.

The apparently small hydraulic aperture of natural fractures associated with large tube-wave attenuation can be explained if fractures are modeled as networks of flow tubes embedded in the fracture plane rather than as simple planar openings. Calculations demonstrate that individual flow tubes greater than 1 cm in diameter can produce measurable tube-wave attenuation, yet transmit as little water as plane fractures less than 2 mm in aperture. The irregular shape and distribution of flow tubes could account for the lack of coherent tube-wave reflections except when wavelengths become long enough to average out local irregularities in the reflecting surface. Even then, scattering from flow tubes would significantly reduce the amplitude of those reflections that are recorded.

The flow-tube model (Figure 8B) also emphasizes the difference in scale of investigation of tube-wave and packer-test data. It seems unlikely that the fracture plane will contain a fully representative population of flow tubes over the small fracture segment affecting tube waves adjacent to the borehole. For this reason, tube-wave attenuation may correlate better with fracture transmissivity than with apparent hydraulic aperture estimated for much larger volumes of rock. By correlating with transmissivity, the effects of fracture orientation automatically are removed from the interpretation. The transmissivity interpretation is assumed to apply to the interval over which the fracture intersects the borehole. In those situations where televiewer logs, core photographs, or other information indicate fracture orientation, the strike and dip of the fracture plane may be taken into account when relating local fracture transmissivity to fracture permeability over a larger scale. This approach appears consistent with the numerical calculations of Hornby et al. (1989) and Brie et al. (1988), in which the effect of fracture orientation is to increase attenuation in proportion to the elliptical distance over which the fracture plane intersects the borehole wall. In the limiting case of fractures parallel to the borehole axis, fracture transmissivity would increase linearly with source to receive separation, in agreement with the theory given by Tang and Cheng (1989) and consistent with laboratory model experiments with vertical fractures.

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| Site | Lithology | Freq. (kHz) | Tube-wave amplitude deficit (percent) | Aperture of largest fracture (mm) Mathieu (1984) method | Aperture of largest fracture (mm) Tang and Cheng (1989) method | Permeabilty from packer test (mm) |
|---|---|---|---|---|---|---|
| Mirror Lake, New Hampshire | Schist | 12 kHz | > 90 | 0.4 | > 10 | 0.5 |
| Lac du Bonnet Batholith, Manitoba* | Granite | 34 | > 95 | 0.5 | > 10 | 0.3* |
| Chalk River, Ontario | Gabbro | 34 | > 95 | 0.5 | > 10 | 0.2 |

*Data from fracture zone and borehole with largest equivalent single fracture aperture in packer test data.

Table 1. Comparison of fracture apertures interpreted from tube-wave amplitude data for fractures using the Mathieu (1984), and Tang and Cheng (1989) methods with equivalent fracture aperture for the entire interval containing that fracture; data given for most permeable interval at each site.

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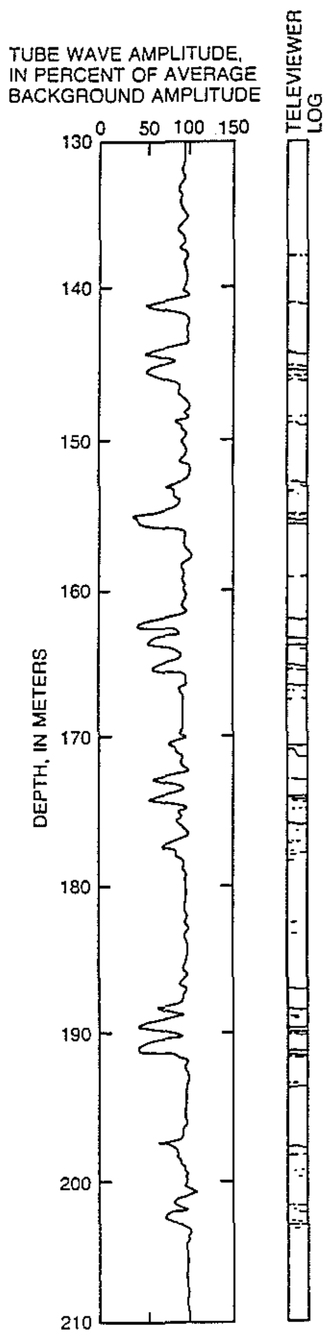


Figure 1: Tube-wave amplitude log representing mean tube-wave energy transmitted from source to receiver compared to televiewer log illustrating the consistency with which tube-wave amplitude attenuation correlates with fractures; data from the Lac du Bonnet Batholith, Manitoba.

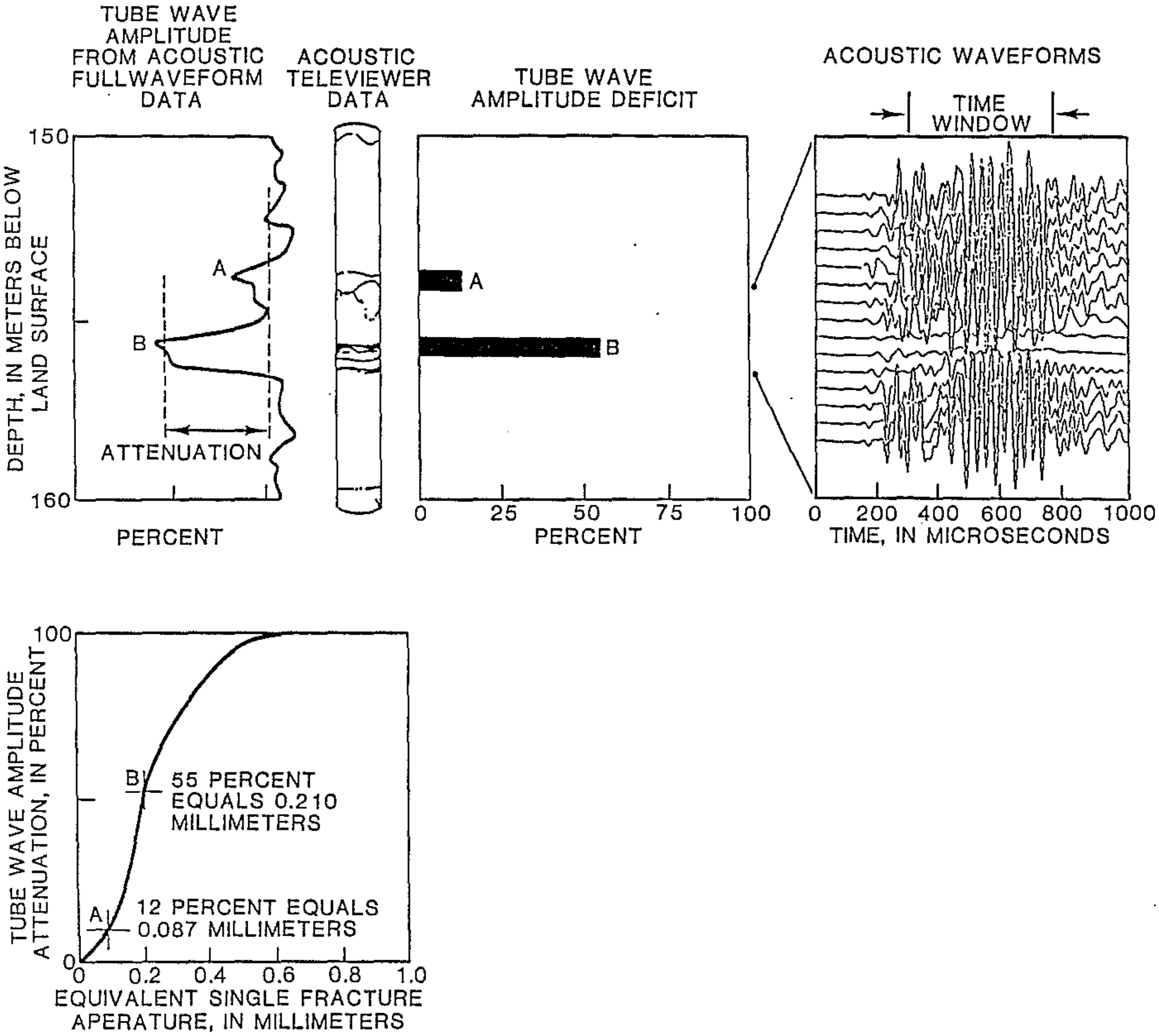


Figure 2: Mathieu (1984) method of interpreting tube-wave amplitude attenuation applied to data from Lac du Bonnet Batholith, Manitoba.

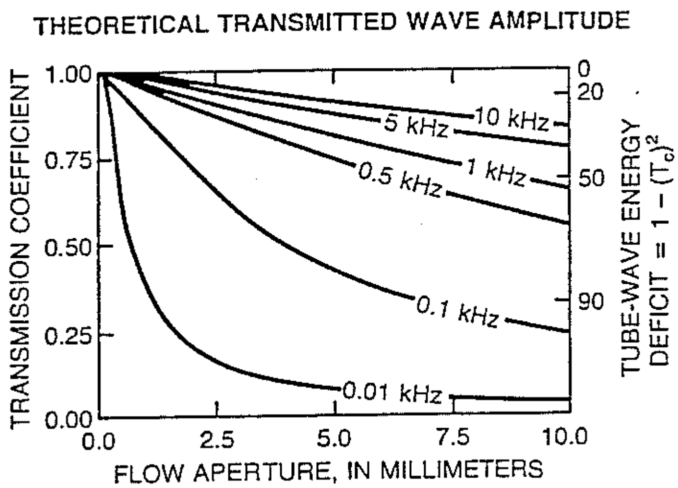


Figure 3: Theoretical transmitted tube-wave amplitude and associated tube-wave energy deficit calculated as a function of fracture aperture and tube-wave frequency using the plane-fracture model of Tang and Cheng (1989); calculations based on water, granite and a borehole diameter of 7.5 cm.

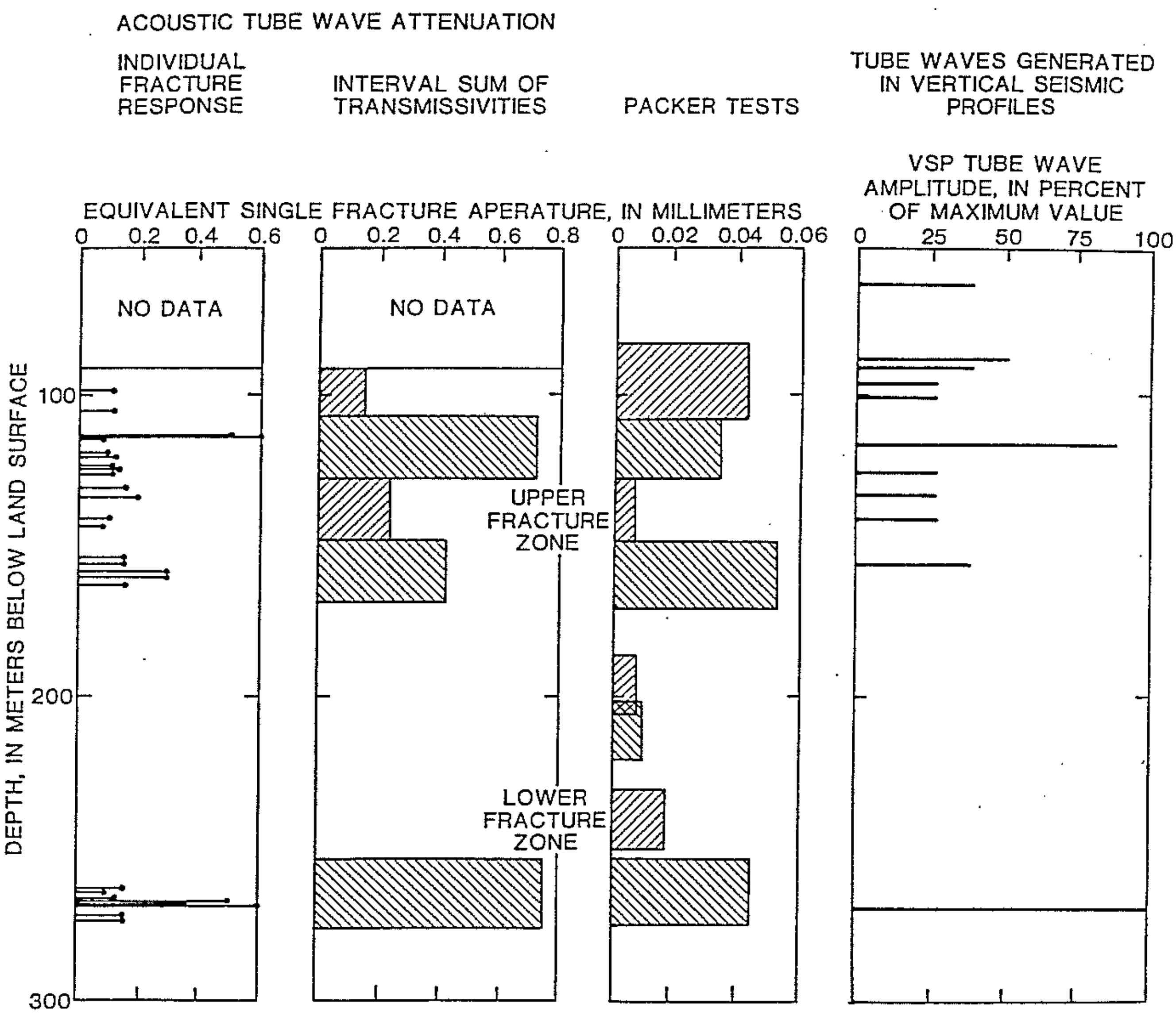


Figure 4: Comparison of fracture permeability estimates based on tube-wave attenuation using the Mathieu (1984) method with permeability measured by means of packer-isolation and -injection tests; data from low-frequency vertical-seismic-profile tube-wave analysis given for comparison.

CORE FRACTURE DESCRIPTION

A — Set of 2 subparallel fractures, each 0.8 mm wide.

B — Set of 2 subparallel fractures, 2.0 and 3.0 mm wide.

C — Set of 2 subparallel fractures, 0.5 and 0.2 mm wide.

D — Set of 4 steeply dipping fractures, one is 0.2 mm wide, others 0.1 mm.

E — Single steeply dipping fracture, 0.5 mm wide.

F — Core intact; tube waves suppressed by borehole wall breakouts.

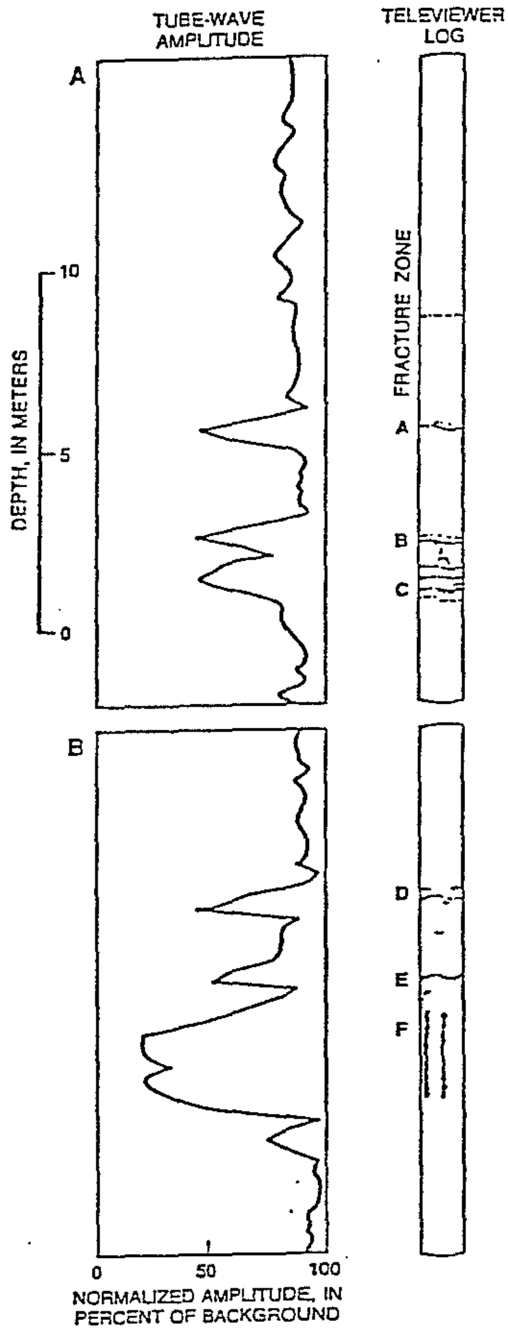


Figure 5: Examples of fracture aperture estimated from core-fracture measurements for: (A) fracture set where thicknesses of partially filled fractures are greater than those estimated from tube-wave attenuation; and (B) fracture set where thicknesses of partially filled fractures are equal to or less than those estimated from tube-wave interpretation.

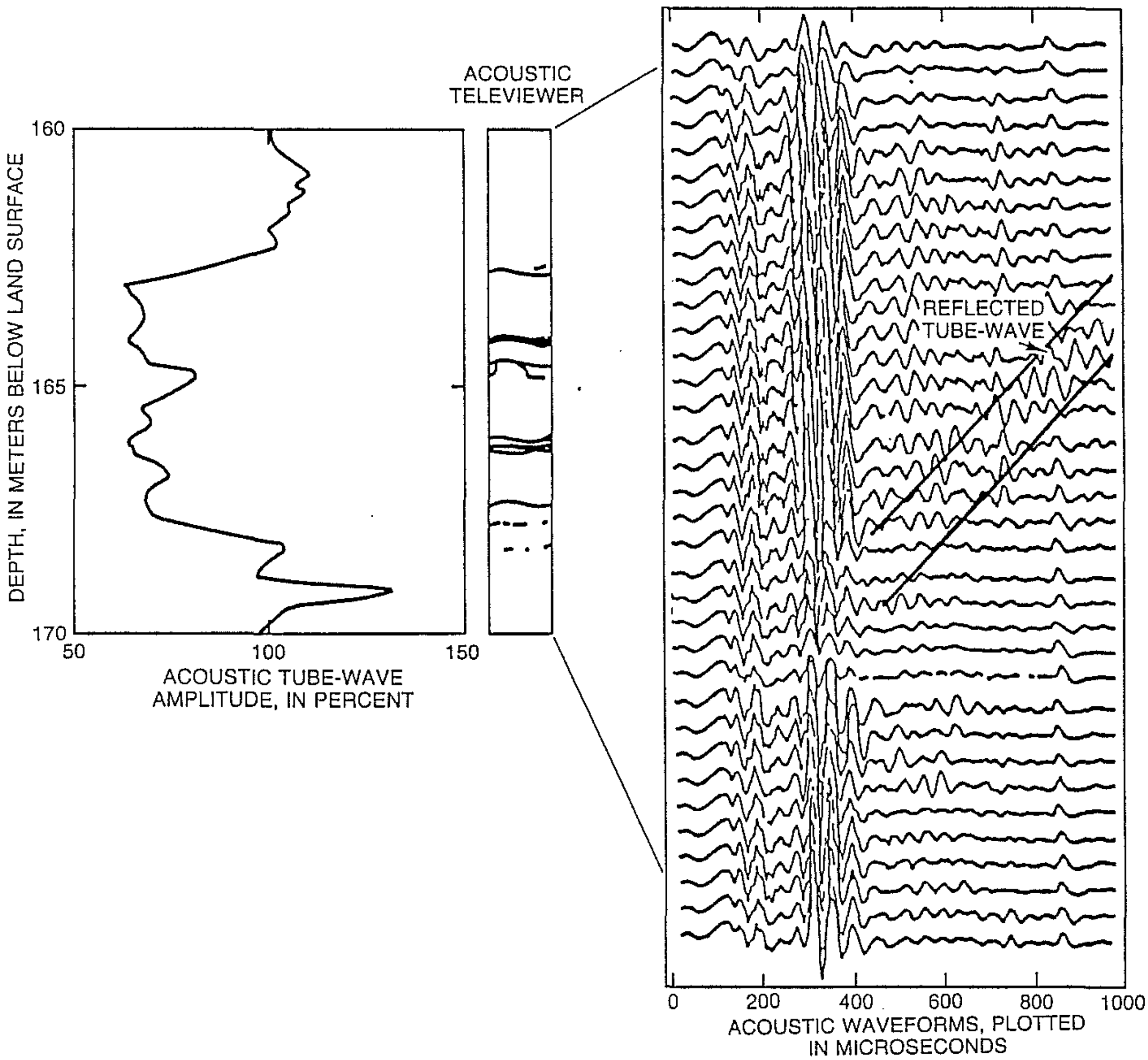


Figure 6: Example of coherent 5 kHz tube-wave reflection associated with a permeable fracture oriented nearly transverse to the borehole, illustrating the small amplitude of such reflections.

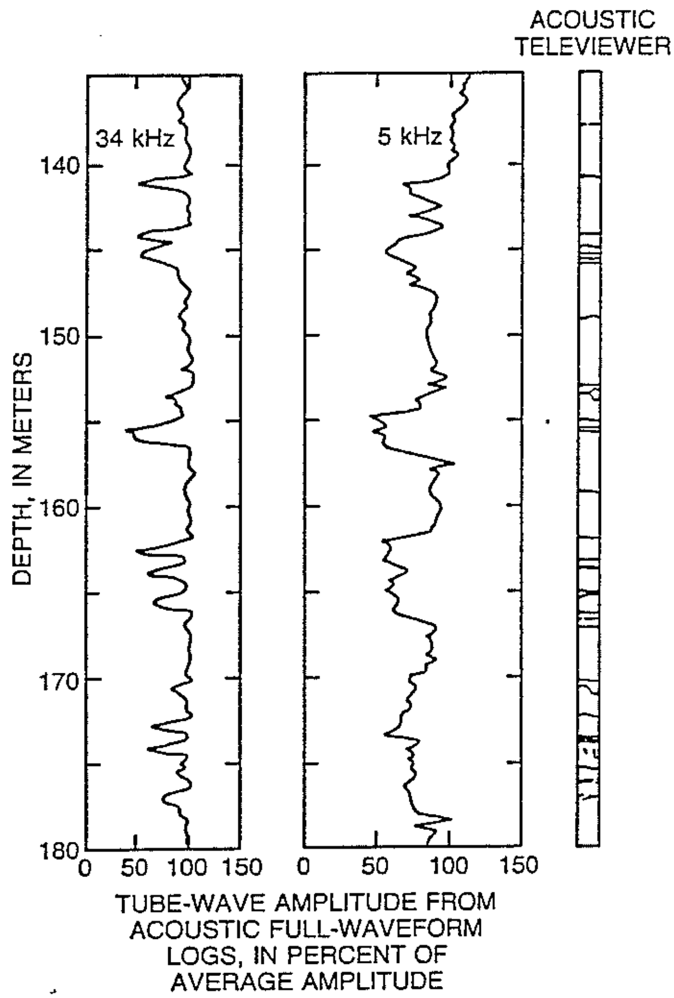


Figure 7: Comparison of tube-wave amplitude logs obtained using (A) 34 kHz and (B) 5 kHz tube-wave energy sources.

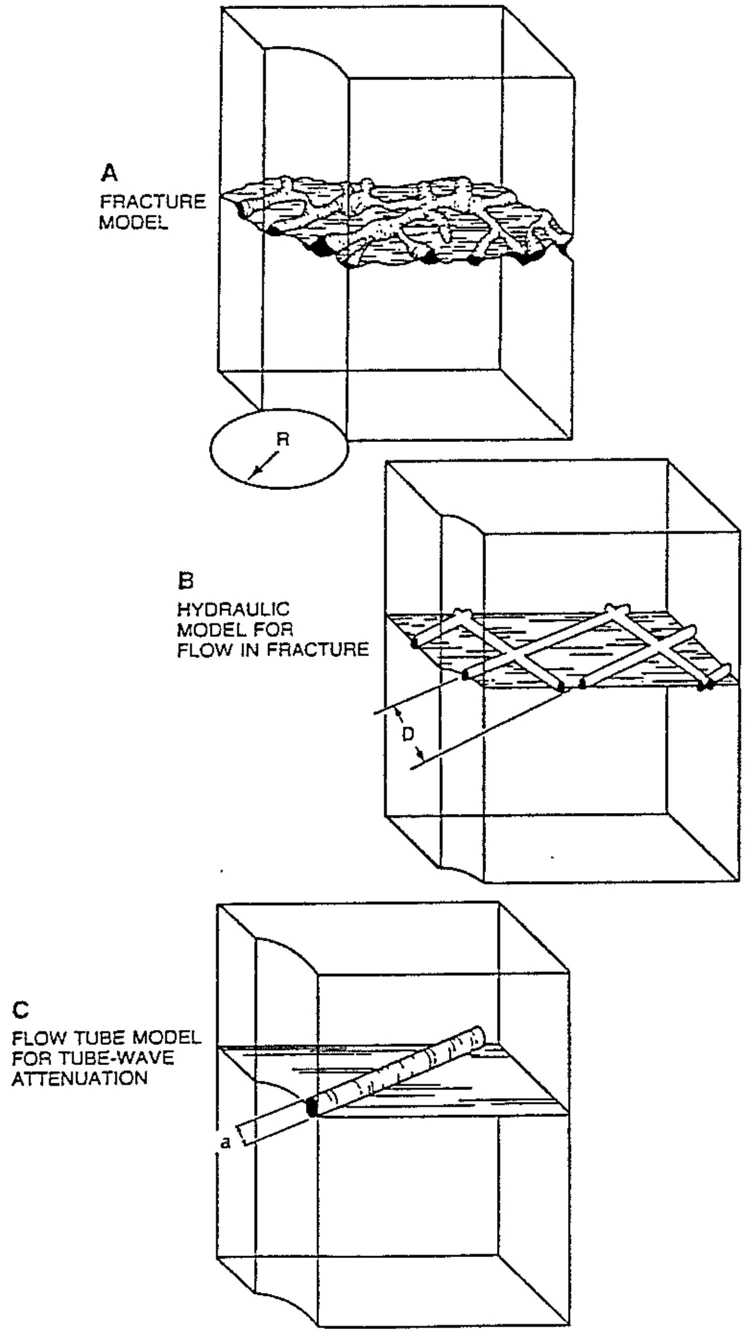


Figure 8: Revised model for natural fractures illustrating: (A) irregular flow-tube model for natural fractures; (B) flow-tube array-model for analysis of hydraulic properties of fractures; and (C) isolated flow-tube model for analysis of tube-wave amplitude attenuation.

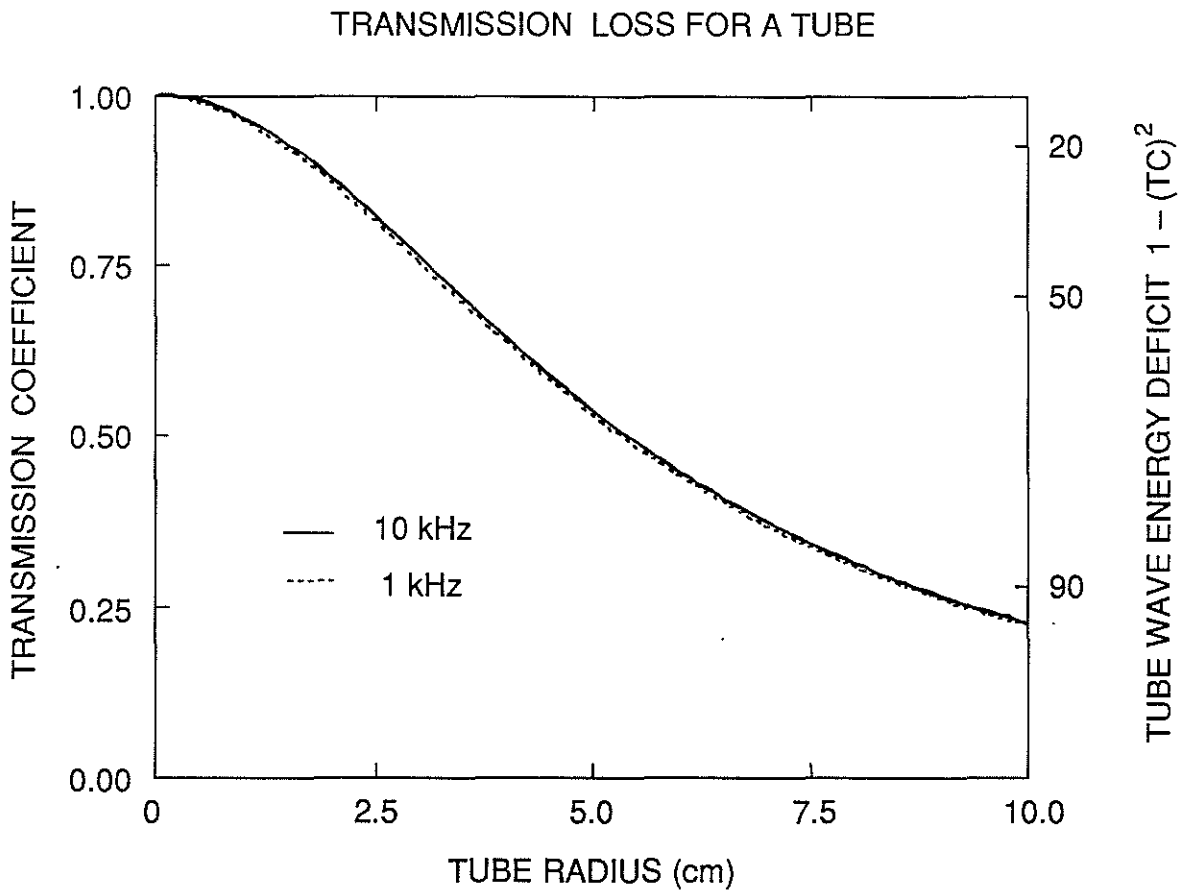


Figure 9: Tube-wave attenuation and associated tube-wave energy deficit as a function of flow-tube radius and tube-wave frequency using the revised flow-tube model for tube-wave attenuation; calculations based on water, granite and a borehole diameter of 7.5 cm.