# Report Summary

by


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## INTRODUCTION

This report contains the results of work completed during the fifth year of the Full Waveform Acoustic Logging Consortium in the Earth Resources Laboratory at M.I.T. During this past year, the emphasis in our research has continued in the direction of a more balanced treatment of all aspects of the acosutic logging problem, namely, theory, data processing, and interpretation. The aim is faster and more accurate determination of formation properties from the full waveform acoustic logs under a variety of conditions one might encounter in the field.

In situ permeability, in both porous and fractured formations, remains the focus of our research efforts. In this report we have a number of papers dealing with the subject, from theoretical papers studying wave propagation in a radially layered porous formation and shear wave logging in a porous medium, to a progress report on finite-difference modelling of wave propagation in a porous material, and ultrasonic modelling of the effects of fractures on full waveform logs. We have also examined the correlation between permeabilities obtained from full waveform logs and those measured in core samples. A paper on the depth of investigation of different methods of in situ fracture permeability determination is also included in the report.

Data processing received more attention in the past year. We have continued to work on some of the projects we had started last year, namely, the inversion of the P wavetrain for $V_s$ and $Q_p$ in a slow formation, and the determination of formation velocities behind (poorly bonded) casing using velocity analysis. In addition, we have initiated efforts in array processing of full waveform logging data using the extended Prony's method.

This method is very promising for the accurate determination of formation guided (both pseudo-Rayleigh and Stoneley) wave dispersion and attenuation.

In an effort to further study how the borehole affects the determination of formation properties, we have studied the effect of the viscosity of the borehole fluid on full waveform logs. We have also made laboratory measurements of the quality factor of a drilling mud.

Lastly, but not least, we have initiated efforts of incorporating expert system approaches in the interpretation of full waveform logs. Two papers, one on the correlation of waveforms for better velocity determination, and the other on well-to-well log correlation, represent our initial efforts in this area.

The following is a summary of the papers in this report.

## THEORETICAL DEVELOPMENTS

### Formation Permeability

Formation permeability determination remains the major goal of full waveform acoustic logging. In the past year, we have continued our efforts in the theory of wave propagation in a porous, permeable medium. Denis Schmitt contributed two papers in this area. The first is an extension of his work from the previous year (Schmitt et al., Paper 3). This past year, he studied full waveform logging in a radially layered porous formation. The layers can have different permeabilities as well as other formation properties. This represents the varying borehole conditions due to invasion, drilling damage, or mud cake. The results show that the Stoneley wave is sensitive to the borehole condition immediately at the borehole-formation boundary. This will affect the determination of in situ permeability from Stoneley wave properties.

In a second paper, Schmitt et al. (Paper 9) studied the problem of non-axisymmetric, or shear wave, logging in a porous formation. It is shown that the fundamental modes of propagation, i.e., the flexural mode under dipole excitation and the screw mode under quadrupole excitation, behave very similarly to the Stoneley wave. However, at the low frequency end, both the flexural and the screw mode propagate and attenuate with the formation shear wave values, regardless of whether the borehole fluid is coupled to the pore fluid of the formation. Thus shear wave logs will provide us with an important baseline for the determination of in situ permeability from Stoneley wave properties.

In actual field conditions, the permeable zone may be relatively thin. In order to model such thin permeable layers imbedded in an otherwise impermeable formation, we have to use finite difference models. In this annual report, there is a paper by Ralph Stephen (Paper 4) on the progress made in the past year in the finite difference modelling of wave propagation in a Biot porous solid.

## Viscous Borehole Fluid

One ongoing concern in the past years has been the effect of viscosity of the borehole fluid on the amplitudes of the Stoneley and pseudo-Rayleigh waves. Dan Burns (Paper 2) studied this effect using boundary layer theory. It is determined that under normal logging frequencies and normal range of mud viscosities, the effects on Stoneley and pseudo-Rayleigh wave amplitudes will be insignificant.

## Shear Wave Logging

In addition to the study of shear wave logging in a porous, permeable formation as discussed above, Schmitt and Cheng (Paper 8) also studied shear wave logging in a radially layered elastic formation, such as in the case of a well-bonded cased hole. It is found that the flexural and screw modes propagate at the velocities of the outermost layer, i.e., the formation, under such conditions. Thus, it is possible to log shear wave velocities behind casing. This is important in cased slow formations where one cannot use the Stoneley wave velocity to estimate formation shear wave velocity.

## P-wave Inversion for $V_s$ and $Q_p$

In a large number of data sets collected in slow formations, the frequencies are too high to excite any Stoneley waves and alternative methods have to be found to obtain shear wave velocities from such data. Since the P wavetrain has been shown to be affected by formation Poisson's ratio, and hence shear wave velocity, we have decided to invert for formation shear wave velocity from the P wavetrain. A non-linear iterative inversion scheme was developed to simultaneously invert for $V_s$ and $Q_p$ (Cheng, Paper 10). The method uses the branch-cut integral representation for the P wavetrain and is quite fast. The algorithm was shown to be quite robust for the determination of $V_s$. However, $Q_p$ is more easily affected by noise and incorrect borehole parameters, such as density and borehole radius, in the input. This technique was successfully applied to full waveform data collected in soft sediments at the Deep Sea Drilling Project site 613 (Meredith et al., Paper 11).

# DATA ANALYSIS

## Formation Permeability

We have continued our efforts of quantitative determination of in situ permeability from Stoneley wave velocity and attenuation. We have approached this problem using a formal inversion algorithm applied to the data published by the Mobil logging group (Burns et al., Paper 6). We have found strong correlations between Stoneley wave attenuation and phase velocity with core permeability. It appears that Stoneley wave attenuation is more sensitive to permeability than Stoneley wave phase velocity; however, it is also sensitive to noise and uncertainties in formation shear attenuation and borehole fluid attenuation. The variation in Stoneley wave phase velocity with permeability appears to be larger in the data than predicted by theory. The departure of Stoneley wave phase velocity from its value in a purely elastic formation appears to correlate very well with in situ permeability. Thus, it is possible to obtain reliable estimates of relative permeability from Stoneley wave velocity and attenuation. However, estimates of absolute permeability await a better understanding of the correction factors involved.

Another type of in situ permeability is that of fracture permeability. A comparison of fracture permeability obtained from full waveform logs, flow test, packer test, and vertical seismic profiles was performed on the data obtained in a fractured granitic formation (Paillet et al., Paper 7). The fracture permeability estimate from Stoneley wave attenuation was from the work of Mathieu and Toksöz published in the 1984 Annual Report of the Consortium. Paillet et al. demonstrated that the results obtained from full waveform logs using Stoneley wave attenuation are consistent with those from flow tests and packer tests. This points to future applications of full waveform logs for the identification and characterization of fractured reservoirs.

## Processing of Array Data

The trend in data collection in full waveform acoustic logging is towards array data to improve signal to noise ratio in velocity analysis. Array data with eight or more source-receiver separations are commonly available. In the 1986 Annual Report we had initiated the study of velocity analyses of full waveform logging data in poorly cased holes by the use of the Maximum Likelihood Method and Average Semblance. In this report, Block et al. (Paper 12) present a detailed comparison of the relative merits of the two methods in a variety of different casing conditions. Maximum Likelihood appears to work better than Average Semblance under most conditions.

An alternate method of processing full waveform data from an array of eight or more receivers is presented in Ellefsen et al. (Paper 13). The method is known as the extended Prony's method, and is based on the assumption that the spectral content in successive receivers can be represented by a sum of exponentially decaying sinusoids. This model is especially appropriate in modelling Stoneley and psuedo-Rayleigh waves since these do behave as exponentially decaying sinusoids. Excellent estimates of the dispersion and attenuation of Stoneley and psuedo-Rayleigh waves in synthetic, laboratory model, and field data were obtained using this method.

### Formation Attenuation Determination

Burns and Cheng (Paper 5) have investigated the problem of determining formation shear wave attenuation from the pseudo-Rayleigh and Stoneley wave attenuation using partition coefficients and a linear inversion algorithm. It was shown that good estimates of formation shear wave attenuation can be obtained from pseudo-Rayleigh and Stoneley wave attenuation in open and well-bonded cased holes. However, properties of the borehole fluid do have significant influence on the attenuation determined.

## EXPERIMENTAL RESULTS

Last year we presented initial results of our effort in using ultrasonic models to study full waveform logging in situations where our numerical and analytic methods are limited. The continuation of this effort is reported in Guler and Toksöz (Paper 17). In this paper, wave propagation across a horizontal fracture and along a vertical fracture are studied, and the relative attenuation of different waves are analyzed. It appears that the S/pseudo-Rayleigh wave is more sensitive to horizontal fractures, while the Stoneley wave is more attenuated along vertical fractures. More complicated borehole conditions will be studied in the future using this modelling capability.

We have also measured the attenuation in a drilling mud (Tang et al., Paper 16). After correcting for the radiation pattern of the transducer, a Q of 30 was obtained for a sample of water-based drilling mud over a relatively large range of frequencies. More measurements will be made as different muds are made available to us.

## INTERPRETATION

We have initiated efforts to apply expert system approaches to well log interpretation in general and full waveform log interpretation in particular. Lineman et al. (Paper 14) discuss the use of Dynamic Depth Warping in the problem of well-to-well log correlation. Larrère (Paper 15) uses the same technique for P- and S-wave velocity determination. Both are based on the object-oriented programming environment of LISP, and are demonstrated to be successful.

## FUTURE WORK

In the past year, we have increased our emphasis on problems of analysis of full waveform acoustic logging data while maintaining our traditional attention to the theory of wave propagation in a borehole. We have also complemented our theoretical and field studies with controlled laboratory ultrasonic modelling experiments. In the coming year, we expect a similar mix of emphasis on the theory and application of full waveform logging. Some of the areas we intend to work on are as follows:

- **Wave Propagation in a Porous Formation:** This year we have developed the theory of shear wave logging in a porous formation. In the coming year, we intend to incorporate this into our effort toward the determination of formation permeability. We also intend to continue our detailed analysis of field data in order to further quantify the observed correlation of core permeability with Stoneley wave velocity and attenuation, and see if the correlation can be explained satifactorily using the Biot-Rosenbaum-Schmitt type of model.

- **Fracture Characterization:** Fracture identification is an important application of full waveform acoustic logs. Comparisons of fracture permeability determined from full wavefrom logs with other estimates such as packer and flow tests have shown that our current model of Stoneley wave attenuation across a fracture is reasonable but imperfect. It is a kinematic rather than a dynamic model. We hope to develop a dynamic model, as a counterpart to the Biot-Rosenbaum-Schmitt model for a porous formation. Ultrasonic modelling of fractures in the laboratory will add to our understanding of wave propagation across a fracture and will provide quantitative verification of any future fracture models developed.

- **Anisotropy:** Fractures and/or thin beds can be considered as equivalent anisotropic materials. Shales are known to be anisotropic. It is known that the shear wave velocity measured from the refracted shear wave or the low frequency first arrival of the pseudo-Rayleigh wave is different from that inferred from the Stoneley wave in an anisotropic medium. We intend to pursue this problem in detail and investigate the possibility of characterizing the degree of anisotropy, at least in a transversely isotropic material penetrated by a vertical borehole, by using the dispersion characteristics of the pseudo-Rayleigh and Stoneley waves. Other forms of anisotropy will also be investigated.

- **Processing of Array Data:** We have demonstrated the ability of the extended Prony's method to obtain very accurate and detailed dispersion and attenuation of pseudo-Rayleigh and Stoneley waves. This method will be applied to data from both open and cased boreholes to test the robustness of the technique under field conditions.

- **Inversion:** The dispersion and attenuation of the guided waves obtained from the extended Prony's method analysis of data will be ideally suited for the inversion of formation properties. Because only the dispersion and attenuation will be used, the source is no longer a problem, and since we do not need to model the whole waveform, and need only to find the complex root of the period equation, the algorithm should be much faster than full waveform inversion. Because of the detail and accuracy possible in the extended Prony's method, more detailed models can be used for the inversion. This will be a major focus of our efforts next year.

- **Finite Difference Modelling:** The finite difference method remains to be the one method suited for the study of wave propagation in a vertically heterogeneous borehole. We will incorporate a porous material into the finite difference algorithm, so that we can study the effect of porous zones of varying thicknesses, as well as vertical changes in formation permeability, porosity and saturation. It remains one of the most powerful methods currently available for the modelling of complicated boreholes.

- **Shear Wave Logging:** In the past year, we have studied shear wave logging in a porous formation, and investigated shear wave logging in multi-layered boreholes. We will incorporate these results into our efforts toward the determination of in situ permeability and formation properties behind casing.

- **Ultrasonic Laboratory Models:** Physical laboratory modelling is an important component in the overall effort of understanding full waveform acoustic logs. These models provide checks for our numerical microseismogram synthesis programs. In this past year, we have studied horizontal and vertical fractures using such models. In the coming year, we will continue this effort by modelling complicated borehole environments such as dipping beds using laboratory models.