# REPORT SUMMARY

by

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## INTRODUCTION

This report contains the results of work completed during the seventh year of the Full Waveform Acoustic Logging Consortium in the Earth Resources Laboratory at M.I.T. During the past year, we have been concentrating on the problem of logging in fractured and anisotropic media. We have developed theories for wave propagation in boreholes in these media. One of the theories is for the propagation and attenuation of Stoneley waves across a horizontal fracture and along a vertical fracture. The theory has been checked against laboratory data obtained from scale models. The theoretical predictions and experimental results agree very well.

We have also developeda theory for calculating the phase and group velocities of guided wave modes, including non-axisymmetric modes such as the flexural and screw modes, in a borehole embedded in a general, weakly anisotropic medium. This addresses the effects of logging in holes drilled into tilted blocks, non-horizontally drilled into sedimentary sequences, and drilled into formations with vertical fractures. We used a perturbation method based on Hamilton's Principle to calculate these velocities.

We have generated techniques of inverting for the relevent parameters in these media such as the different elastic moduli and the degree of anisotropy from the full waveform logs.

This year we have begun applying some of the techniques we have developed over the past years to logs in the field. In one example, we compare the shear wave velocity obtained in soft sediments by our inversion technique to those based on the difference between measured P-wave velocity and that predicted using Wood's equation. The results give us some handle on the limitations and accuracies of our technique. In another example, we restacked array data in various combinations to obtain a better depth resolution for the velocities picked from array data without sacrificing the use of a larger number of receivers to enhance the signal to noise ratio. In a third paper, we apply a general inversion to a number of different logs to obtain the lithology in a marine environment. Another paper deals with the implications of the differences in hydraulic conductivity estimated from Stoneley wave attenuation and packer tests in the field.

Another focus of the past year's research is rock physics. Specifically, the relationship between permeability, velocity, including anisotropy, and pore geometry. The aim is to interpret measured velocities in terms of pore sizes and shapes, and then to use these pore geometries to model the flow properties of the rocks.

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

## THEORETICAL DEVELOPMENTS

### Anisotropy

Logging in anisotropic formations has remained one of our main focuses in the past year. Ellefsen and Cheng (Paper 2) studied the sensitivity of various guided waves from monopole, dipole, and quadrupole sources (namely, the pseudo-Rayleigh, Stoneley, flexural, and screw waves) to different formation parameters in transversely isotropic formations using the Hamilton's Principle. This is a more complete and updated version of a preliminary report in last year's report. In addition, the method was shown to be useful in calculating the group velocities of these guided waves as well as the effects of non-spherical boreholes on their propagation.

Also using Hamilton's Principle, Ellefsen and Cheng (Paper 3) developed a method to estimate the effect of a more general anisotropic formation on the guided waves. They showed two examples: one in a transversely isotropic formation with the axis of symmetry perpendicular to the axis of the borehole, and the other with the axis 10° apart. The first case may be representative of logging in a formation with vertically aligned fractures, or in a horizontal borehole through a transversely anisotropic formation. The second is representative of logging in a slightly deviated borehole in a transversely isotropic formation. In both cases, it was shown that the flexural wave is sensitive to the anisotropy, while the pseudo-Rayleigh, Stoneley, and screw waves tend to average the anisotropic properties. This suggests the need for future development of dipole logging tools with three or more different dipole components and means of downhole orientation determination.

Other papers dealing with this topic are included in the rock physics section.

## Fractures

We have continued to make progress in the study of acoustic logging in fractured media. Tang et al. (Paper 5) addressed the problem of logging along a vertical fracture. They used a boundary perturbation technique to modify the boundary conditions along which the borehole guided waves are propagating. They concentrated on the study of Stoneley wave attenuation along such a fracture. The results were checked against data obtained from laboratory scale model experiments and were shown to fit very well. Actually, the first order results are rather simple and can be easily inverted to get an estimate of the thickness of the fracture.

We have also studied theoretically and experimentally the guided waves propagating along a plane parallel fracture. The results were incorporated in our study of Stoneley wave attenuation across a fracture. Furthermore, these results have applications for the study of cross hole imaging and the waveguide effect of permeable zones. The results are summarized in Tang et al. (Paper 4)

Paillet et al. (Paper 11) tried to reconcile the differences in the estimated equivalent fracture width from pump test and Stoneley wave attenuation measurements in the field. They suggested that a network of interconnecting tube-like structures may be responsible. In any case, it is clear that in situ fractures do not behave like parallel planes over the frequency range covered from pump test to acoustic logging.

## Inversion

Last year we developed the formulation for calculating the sensitivity of the different guided waves to the elastic moduli of a transversely isotropic formation. In this year's report, Ellefsen and Cheng (Paper 6) addressed the inverse problem, namely, how to obtain the elastic parameters of a transversely isotropic formation from the full waveform logs. Ellefsen and Cheng used a constrained inversion technique based on *a priori* information of the general relationships between the different elastic parameters in a transversely isotropic formation based on studies made on core samples. The vertical compressional and shear moduli ($c_{33}$ and $c_{44}$) were assumed known from direct P and S/pseudo-Rayleigh measurements. Using pseudo-Rayleigh and Stoneley wave dispersions, the other elastic moduli were inverted for. It is shown that the horizontal shear wave modulus ($c_{66}$) is well resolved, while the two other P-wave moduli, $c_{11}$ and $c_{13}$, are not well resolved. This is consistent with the results from sensitivity analysis. These last two moduli are probably better estimated from empirical relationships derived from core studies than from the full waveform inversion. We are looking forward to applying this technique to data, both from laboratory scale model experiments and from the field.

# DATA ANALYSIS

Last year, we began applying some of the techniques we have developed over the past few years to analyze full waveform acoustic logging data from the field. In this report, we show three examples based on logging data obtained in the Ocean Drilling Program (ODP), as well as data provided to us by our sponsors.

## Shear Wave Velocity in Sediments

Meredith et al. (Paper 8) applied the inversion technique of Cheng (1987 Ann. Rept.) to full waveform logs from a hole drilled into unconsolidated and semi-consolidated sediments. The tool used was the old Schlumberger tool, thus the frequency content was too high to excite any Stoneley wave. By inverting the P wave and P leaky modes, Meredith et al. were able to obtain an estimate of the shear wave velocities. These velocities were compared with an upper bound calculated from the observed P-wave velocities and those calculated using Wood's equation. The inversion results fell within or close to the bounds for shear wave velocities above about 0.8 km/s. Below this value of shear wave velocities, the inversion results were too high compared to Wood's prediction. This was attributed to bad data, inadequate recording length, and numerical inaccuracies. This study will continue with other data from the ODP.

## Depth Resolution

A disadvantage of a longer receiver array is the decrease in depth resolution. In this report, Thompson and Burns (Paper 9) begin to investigate methods of improving the depth resolution by stacking the subarrays of a large receiver array, taking into account the logging speed. They were able to obtain resolution of half the array length. Further work will be done in this area in the coming year.

## General Log Analysis

Mendelson (Paper 10) presented inversion schemes based on least squares inversion and linear programming for estimating lithology from conventional logs. He found that linear programming in general worked better and depended less on the accuracy of the known lithological properties. He applied the inversion to data from the ODP, North Sea, and California with reasonable success.

# ROCK PHYSICS

## Anisotropy

In this report, we have two papers dealing with anisotropic velocity measurements from cores. In Gibson and Toksöz (Paper 7), an inversion technique was presented for the determination of permeability from velocity measurements covering a range of azimuths and varying uniaxial stress. First a crack distribution and orientation was obtained from the velocities. Then the permeability of the rock was modelled using this crack distribution and some assumptions about crack length. The results compared favorably with other estimates of permeability in fractured rocks. Although the rock sample used in this study was a crystalline rock, the technique has potential application in estimating permeability from fractured reservoirs.

In the other paper, Mendelson and Toksöz (Paper 13) addressed the problem of whether transverse isotropy is an adequate model in some rock samples. They used both the Scanning Electron Microscope (SEM) to view the pore and grain structure, and ultrasonic measurements of velocities along three perpendicular axes and at 45° between the axes. It is found that in one sample the transverse isotropy model is adequate, while in another sample, a core which had undergone various in situ stresses, a more general orthorhombic model with nine elastic constants is necessary.

## Permeability

Bernabé (Paper 12) proposed a model for the pore geometry in sandstones. Using this model, which consisted of spherical pores, tubes, and sheets or cracks, he was able to model sandstone permeability data from the literature. This model is primarily applicable to clean sandstones.

# FUTURE WORK

- **Anisotropy:**

  We have extended the theoretical development of logging in anisotropic formations from horizontal transverse isotropy to a more general case to model tilted beds and vertically oriented transverse isotropy. So far we are restricted to calculating velocity dispersion of the various guided waves. We hope to generate synthetic microseismograms using numerical techniques in the coming year.

- **Fracture Characterization:**

  We have extended our work from Stoneley wave attenuation across a horizontal fracture to that along a vertical fracture. We are currently concentrating on the scattering of Stoneley wave energy from the horizontal fracture, with possible future applications to non-horizontal fractures.

- **Inversion:**

  We have presented initial results of inversion of full waveform logs for the elastic parameters in an anisotropic formation. Further tests of the technique will be performed, hopefully with field data. The inversion for shear wave velocity in a slow formation will also be further studied and improved upon.

- **Data Processing:**

  We have initiated projects which have their emphasis on the processing of field data. These involve higher depth resolution from array data, as well as estimates of velocity dispersion using the Extended Prony's Method. The latter is to detect possible permeability/anisotropy in the formation.

- **Ultrasonic Laboratory Models:**

  Ultrasonic borehole models continue to provide tests for our theoretical forward and inverse modelling algorithms. This effort will continue in the coming year. Experiments planned include back scattering from horizontal fractures, transversely isotropic (both vertically and horizontally oriented) boreholes, and permeable formations.

- **Permeability:**

  We are continuing our study of permeability models. In this report we present two such models based on rock physics studies. Future efforts will include laboratory scale model experiments and finite difference modeling, as well as analysis of field data.