REPORT SUMMARY

by

C.H. Cheng

Earth Resources Laboratory
Department of Earth, Atmospheric, and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139

INTRODUCTION

This report contains the results of work completed during the eighth year of the Full Waveform Acoustic Logging Consortium in the Earth Resources Laboratory at M.I.T. During the past year, we were able to accomplish many of the goals we had set out to do. We have concentrated our efforts in understanding logging in fractured and anisotropic media, so as to enable us to infer for the properties of the media from full waveform acoustic logs.

For logging in fractured media, we have developed the theory of scattering of Stoneley wave by a horizontal fracture, as well as transmissions through the fracture and attenuation by the fracture. We have also developed the theory for the case when the fractures are small compared to the wavelength of the rock and we have an effective anisotropic medium. In the case of a horizontally layered medium such as a shale, we can invert for the degree of shear wave anisotropy using the Stoneley wave velocity.

In the area of logging in permeable formations, we have developed a much simplified theory that gives similar results as the Biot-Rosenbaum theory. We have also coded the latter for finite-difference modelling. We have developed an inversion algorithm which gives formation permeability from Stoneley wave phase velocity and attenuation. The algorithm gives good results when compared with core permeability measurements.

On other related topics, in petrophysics we have a report on the estimation of formation permeability from velocity anisotropy measurements. We have also extended our research away from the borehole to a crosshole situation. We have calculated the near and far field radiation pattern in the formation from a point source inside the borehole. This knowledge is critical in the application of diffraction tomography to crosshole measurements.

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

THEORETICAL DEVELOPMENTS

Anisotropy

In the past year, we have continued our work on full waveform acoustic logging in an anisotropic formation. Two papers by Ellefsen et al. address this problem. The first one (Paper 2) deals with the determination of the degree of shear wave anisotropy from the inversion of the Stoneley wave velocity. The second paper (Paper 3) studies the forward problem of the effect of various types of anisotropy on the propagation of guided wave modes (Stoneley, psuedo-Rayleigh, flexural, and screw) in the borehole. Two different techniques are used: Perturbation theory using Hamilton's Principle and the Finite Element method. Both methods give good results for small degrees of anisotropy, but the Finite Element method is not restricted to such conditions whereas the Perturbation method is.

Fractures

In last year's report, we presented the theory of dynamic conductivity of a fracture and how it fits observed data. It was remarked at that point that one effect not taken into account is the backscattering of the incoming wave energy by the fracture. This year Tang et al. (Paper 5) addressed the scattering problem by a mode summation technique. The problem of the incoming Stoneley wave scattering into a reflected Stoneley wave and being converted into other modes such as the psuedo-Rayleigh or the leaky P mode is solved. The results agree well with ultrasonic modelling data. In the case where the backscattering is weak, the result from this analysis agrees with that from the simple analysis of dynamic fracture conductivity from last year.

Permeability

A breakthrough we have this past year is to apply the concept of dynamic conductivity to a porous medium. The result is a model of Stoneley wave propagation in a porous formation that is much simpler than the Biot-Rosenbaum model (Tang et al., Paper 4). This model gives almost identical results as the Biot-Rosenbaum model in the critical low frequency range. Moreover, the physics of the attenuation and dispersion of the Stoneley wave is clearly illustrated in this model, which is based on the perturbation of the elastic Stoneley wave propagation. The use of dynamic conductivity allows us to extend the validity of the method to much higher frequencies than previous results.

Finite Difference Modelling of a Biot Solid

For the past few years we have been working on modelling the problem of full waveform logging in a porous formation using the finite difference method, the idea being that we can easily model vertically heterogeneous formations and changing borehole radius and their effects on Stoneley wave velocity and attenuation. The past year we have had some success with our finite difference model, and we have much deeper understanding of this difficult problem, especially modelling the interaction between the borehole fluid and the Biot solid (Stephen et al., Paper 6).

DATA ANALYSIS

Anisotropy Inversion

Ellefsen et al. (Paper 2) deals with the problem of determination of the degree of shear wave anisotropy from the inversion of the Stoneley wave velocity. The method assumes the knowledge of the vertical compressional and shear wave velocities, along with other borehole parameters. The inversion is tested with full waveform array sonic data collected in a shaly sand section and the results show a shear wave anisotropy of about 20%.

Permeability

In previous years we have attempted to invert for formation permeability using Stoneley wave dispersion and attenuation. Our results were mixed because of the large error involved (mainly in attenuation measurements) in using just two receivers. This year we invert for formation permeability using data from an array full waveform sonic log (Cheng et al., Paper 7). We determine the Stoneley wave dispersion and attenuation using the Extended Prony's method and then invert the results to obtain formation permeability and shear wave velocity. The results agree very well with core data. This is a very promising technique for the determination of formation permeability and needs to be tested using data collected in a variety of formations with different permeabilities.

Log Interpretation

One of the major uses of array full waveform sonic logs is the improved resolution and accuracy. We have applied multi-shot processing to array sonic data collected from the Ocean Drilling Program (Burns et al., Paper 9). In conjunction with other logs such as the resistivity log and a measure of Stoneley wave attenuation based on the energy of the full waveform trace, we are able to make a detailed interpretation about the structure of the oceanic crust that would not be possible with just conventional logs.

PETROPHYSICS AND BOREHOLE ACOUSTICS

In addition to studying the modelling and processing of full waveform acoustic logs, we are also working in related areas that are critical to the characterization and development of a reservoir. Two of these topics are petrophysics and crosshole imaging.

Anisotropy

In petrophysics we present a method to invert in situ velocity anisotropy to infer for the permeability of the formation (Gibson and Toksöz, Paper 8). This is a more refined and complete work than the one presented in the Annual Report last year. This paper gives a quantitative model for the relationship between pore geometry, permeability, and velocity, and should be very useful in aiding the interpretation of logging data.

Borehole Radiation

One important tool in the characterization and development of reservoirs is crosshole seismic tomography. Up to the present, only travel time information has been used. However, in order to truly take advantage of the crosshole geometry, we need amplitude information as well. In the two papers by Meredith et al. (Papers 10 and 11) we present a review of existing work related to the radiation pattern of a point source in a borehole as observed inside the formation, and we generate complete waveforms using the discrete wavenumber method. Our results are exact and can be used to quantify the limitations of previous works which used far field approximations.

FUTURE WORK

- **Anisotropy:**

  We have successfully quantified the degree of shear wave anisotropy by inverting the Stoneley wave velocity. We have also studied the velocity dispersion of the normal modes in a vertically anisotropic formation. We are planning to study the dispersion of the leaky modes and generate synthetic microseismograms in these formations.

- **Fracture Characterization:**

  We have completed our study on the scattering of Stoneley wave energy from the horizontal fracture. We need to continue to make improvements to our fracture model. These include introducing models other than the parallel plate model of a fracture and to reconcile the in situ fracture attenuation data with theory.

- **Inversion:**

  We have presented results of inversion of array full waveform data for the elastic parameters in an anisotropic formation as well as the permeability of a porous formation. Both methods work well in the data set we have. We need to apply these algorithms to data sets from a variety of formations to thoroughly test their applicability in the field.

- **Data Processing:**

  Improved processing of array sonic data allows us to get a better estimate of in situ permeability and shear wave anisotropy from the inversion. Multi-shot processing allows us to get a better depth resolution from the array data without sacrificing accuracy. We will continue to incorporate up-to-date signal processing techniques into our analysis of full waveform data.

- **Ultrasonic Laboratory Models:**

  We have performed ultrasonic laboratory model experiments on back scattering from horizontal fractures which allowed us to test our theory. This has been an important part of our research effort. We will continue our efforts in this area in the coming year.

- **Permeability:**

  In this report we present a simplified model of wave propagation in a porous medium which gives essentially the same results as the much more complicated Biot-Rosenbaum model. We have applied it to the Stoneley wave propagation, but the same concept can be applied to any of the other wave modes. We will continue our studies in this area.

- **Borehole Acoustics:** An important element in reservoir characterization and description is seismic crosshole tomography. To do tomography properly we need to understand the coupling of the seismic waves generated by a source in a borehole into the formation and then back into the second borehole. We would like to take advantage of our experience in full waveform logging and apply it in this area. We have started this past year with a study on the radiation pattern in the formation due to a point source in a borehole, and we will continue our efforts in the coming year.