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 sixth year of the Full Waveform Acoustic Logging Consortium in the Earth Resources Laboratory at M.I.T. Over the last six years, our work have evolved from simply modelling an open borehole in an isotropy, elastic formation to the study of logging under more complicated, realistic conditions, especially those that may be encounted in production and development environments.

In the past year, we have modelled elastic wave propagation in a transversely isotropic formation, in a formation where the borehole is irregular in radius, across an open fracture, and in a transversely isotropic porous formation, where the horizontal and vertical permeabilities are different. All of these situations are rather common in the field. It is important for us to understand how these complications may or may not affected our interpretation of the full waveform acoustic logs, and how large an error we are likely to make if our interpretation is based on a isotropy, elastic model of the formation. Just as importantly, we need to learn to identify these situations in the field, so that we can make the appropriate corrections to our interpretation.

In data analysis, we have refined the Extended Prony's Method to calculate the dispersion and attenuation of the guided waves in the borehole, and have applied the technique to both laboratory and field data with success. We have also studied the sensistivity of the guided waves to a transversely anisotropic formation. These sensistivities are critical in the inversion of the dispersion and attenuation obtained by the Extended Prony's Method for the actual elastic and anelastic properties of the formation.

In a continuation of last year's work, we have studied the attenuation of solid particles in a viscous fluid, applicable to the study of both drilling muds and unconsolidated sands.

We have studied the diffraction of a cylindrical transducer and its effect on the measurement of attenuation in laboratory experiments using the spectral ratio technique. We are also continuing in our effort of scale model experiments to mimic field situations which are not readily modelled by analytic or numerical methods.

A field study and comparison of velocities from core measurement, borehole compensated sonic log, full waveform acoustic log, and VSP in the Salton Sea Scientific Drilling Program is included in this report. Also included is an extended abstract on an effort to map fractures in the Canadian Shield using borehole geophysical techniques.

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

THEORETICAL DEVELOPMENTS

Anisotropy

Wave propagation in a borehole in an anisotropic formation was the focus of most of our theoretical efforts in the past year. There have been very few papers that address this subject in the literature. In this report, we have a paper by Ellefsen and Cheng (Paper 4) in which they derived, by Rayleigh's Principle, the analytic expressions for the sensistivity of the guided waves to different formation elastic constants in a transversely isotropic formation. The numerical evaluation of these sensistivities using measured elastic constants is presented in Ellefsen et al. (Paper 5). One of the more important observations is that the shear wave velocity measured from the refracted shear head wave or directly from the shear wave tool is the vertical shear wave velocity, while that measured indirectly by the inversion of Stoneley wave velocity is the horizontal shear wave velocity. It is important to distinguish the two in the application of the mechanical properties derivated from the shear wave log to various production and development problems.

Denis Schmitt contributed two papers (Papers 12 and 13) to this reort. The first is the theoretical formulation of wave propagation in a transversely isotropic porous formation, and the second the numerical examples. These two papers together represents an enormous effort in the theory of logging in porous media, and will be extremely useful as reference material. They, however, also have a practical side. One of the most surprising result of the theory is that although the refracted shear/pseudo-Rayleigh/flexual wave and the Stoneley wave measure the vertical and horizontal shear wave velocities, respectively, they are all sensistive ONLY to the horizontal permeability, not the vertical one. This is a result of the polarization of the particle motion of the various wave types. It turns out that all of the above waves have particule motion predominantly in the horizontal direction, and thus are sensistive only to the horizontal permeability of the formation. This has a large implication in the use of log data as input to reservoir simulation models.

Stoneley Wave Attenuation Across Fractures

Back in 1984, Mathieu had developed a kinamatic, low frequency model for the attenuation of a Stoneley wave across a fracture. In this report, Tang and Cheng (Paper 6) developed a dynamic model for the same problem. The model takes into the account the energy lost as wave propagation along the fracture away from the borehole, as well as the inertial effect and the compressibility of the fluid. It is shown that at high frequencies the fracture acts as a wave guide, and at low frequencies the wave travelling along it becomes diffusive. This model reduces to that of Mathieu at the low frequency and high viscosity limit and that of Hornby et al. (1987 *SEG Expanded Abstracts*) at the high frequency and low viscosity limit. The model fits the laboratory measurements of Poeter in the October 1987 issue of *The Log Analyst.* It now awaits further tests with both laboratory and field data.

Irregular Borehole

Irregular borehole radius significantly affects the amplitudes of guided waves and their interpretation. This is especially important in the case of Stoneley waves, since their amplitudes are used to estimate formation permeabilities as well as the hydraulic conductivity (or equivalant parallel plate thickness) of fractures. Thus we need to know how variations in borehole radius affect the amplitudes of the Stoneley waves so that appropriate corrections can be made by using the caliper log. In this report, Bouchon and Schmitt (Paper 3) generated synthetic microseismograms in boreholes of varying radii. They used the boundary integral method together with discrete wavenumber summation to obtain the microseismograms. With this method, we can now study the effects of borehole radius on Stoneley wave amplitudes in detail, and correction factors can be generated.

Viscous Attenuation

Gibson and Toksöz (Paper 9) presented a model for the velocity and attenuation of a composite of solids suspended in a viscous fluid. They fitted their model to experimental data with success. This model is applicable to the study of the properties of drilling mud, as well as those of unconsolidated and semi-consolidated sands. This model allows one to estimate the velocity and attenuation of an unconsolidated sand using the porosity only; or those of a drilling mud using the volume fraction of the solid particles in the mud. Conversely, one can use the velocity and attenuation obtained from the full waveform logs for a better estimate of formation porosity than just the velocity alone.

DATA ANALYSIS

Dispersion and Attenuation

In order to study the more complicated formations and to take full advantage of the full waveform acoustic logs, we have continued our work on refining the Extended Prony's Method for the determination of the dispersion and attenuation of guided waves from an array of receivers (Paper 2). We have applied the method to analyze the P leaky mode and Stoneley wave from laboratory data collected in lucite. We are able to obtain the dispersions of the first five modes of the P leaky wave, as well as that of the Stoneley wave. The dispersions and attenuations agree well with theory. We have also applied the method to field data in a porous formation. We obtain excellent dispersion and attenuation for the Stoneley wave. However, as in the studies we performed last year, when the data is compared to the prediction of tbe Biot-Rosenbaum theory, we found that the theory underpredicts the velocity dispersion and overpredicts the attenuation of the Stoneley wave. We intend to continue to persue this issue further.

Laboratory Measurements

Tang et al. (Paper 10) developed expressions for the diffraction of elastic waves generated by a cylindrical source. This is an extension of the work done last year for an acoustic source. Just as in the acoustic case, the diffraction effect is significant and is frequency dependent. Thus all laboratory measurements of attenuation using the spectral ratio method have to take this into account. Specifically, those measurements using samples of different sizes will underestimate the attenuation, while those using a standard (e.g. aluminum) of the same size as the sample will overestimate the attenuation. One has to keep this in mind when using uncorrected laboratory attenuation data.

We have also continued our efforts in laboratory scale experiments (Toksöz and Güler, Paper 7). We have analyzed our experimental data on Stoneley wave attenuation as a function of frequency and fracture aperture. We found that there are diffraction effects to be taken into account in the interpretation of scale experimental data. Toksöz and Güler also discussed the state of our knowledge in the detection and characterization of fractures in the field.

Field Examples

In this report we have included two field studies. One is from the Salton Sea Scientific Drilling Project (Tarif et al., Paper 11), where core measured velocities are compared with regular borehole compensated sonic log, full waveform acoustic log, and VSP velocities. In an environment where the in situ attenuation is high and the Poisson's ratio is low, the P wave amplitudes are very low, especially when compared to the rest of the waveform. In this case, this results in severe problems in velocity picking in the regular sonic log, and abnormally low velocities. As a matter of fact, most of the time the regular sonic log ended up picking the shear wave velocity instead. We were able to record the P wave on the full waveform log using a higher gain. The results from the analysis of the full waveform log agree well with the core measurements as well as those from VSPs.

We have also included an extended abstract by Paillet (Paper 8) on the characterization and mapping of subsurface fractures using borehole geophysical methods over an extended area in the Canadian Shield. Although the fractures are in igneous rocks, the techniques used and the experience gained can be transferred to the identification and characterization of fractures in hard sedimentary rocks such as the Austin Chalk.

FUTURE WORK

- **Fracture Characterization:**

  We have made substantial improvements in our model of Stoneley wave attenuation across a fracture. We intend to extend this model to include non-horizontal fractures. The model also needs further testing with laboratory and field data.

- **Formation Permeability:**

  We have pushed the Biot-Rosenbaum type of theory of wave propagation in a porous medium to its limits. We now need to test thoroughly the applicability of the theory in the field. We will do this by analyzing more field data and by comparing the theory with data collected in our ultrasonic modelling laboratory. We will also continue our effort in modelling porous formations with vertically varying permeability using the finite difference method.

- **Anisotropy:**

  We have begun to study the effect of transverse isotropy on full waveform logging. However, we have so far been restricted to situations where the axis of symmetry of the anisotropy coincides with the axis of the borehole. We will extend the theoretical development to a more general case to model tilted beds and vertically oriented transverse isotropy.

- **Borehole Correction:**

  We intend to study different effects of borehole washouts and other radius changes on the velocity and amplitdues of the guided waves (especially the Stoneley wave) using the boundary integral formulation developed this year. We will quantify these effects so that appropriate borehole corrections can be taken for the observed variations in velocity and attenuation due to variations in borehole radius.

- **Inversion:**

  With the ability to determine the velocity and attenuation dispersion accurately over a wide frequency range by using the Extended Prony's Method, we are now in a very good position to formally invert these dispersion curves for formation parameters. We will compare the results of inverting the dispersion obtained using the Extended Prony's Methods and those using the traditional spectral ratio method. We also intend to estimate the velocity dispersion of the P leaky mode and invert for formation shear wave velocity and P wave attenuation.

- **Data Processing:**

  Array processing has been shown to be a powerful method for the determinatin of formation properties from full waveform logs. However, there exists an abundance of older data where there were simply too few receivers available for proper array processing. We intend to look into the possibility of obtained group velocity dispersion of the guided waves from these data. Group velocity, together with phase velocity from the spectral ratio method, will help to better constrain the formation parameters obtained from these older data.

- **Ultrasonic Laboratory Models:**

  Ultrasonic borehole models have provided important data to test new theory and processing techniques. In this report, model data helped us test our new theory of Stoneley wave attenuatin across a fracture, as well as the accuracy of the Extended Prony's Method. We will continue in collecting full waveform data from laboratory models.