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 eleventh year of the Borehole Acoustics and Logging Consortium in the Earth Resources Laboratory at M.I.T. We continued our trend toward more general borehole acoustics instead of just full waveform logging. In this report we have papers related to borehole radiation as well as reception patterns, as well as more theoretical work on the Green's function of an anisotropic medium. The borehole reception pattern paper is the continuation of the work from last year, where we dealt with the receiver pattern in an open borehole. This year the work is extended to include cased boreholes.

On the subject of borehole radiation, this year we have two papers dealing with the radiated seismic wavefield away from a borehole. The interest is in the areas of downhole sources as applied to single hole imaging, measurement while drilling, reverse vertical seismic profiling, as well as cross borehole tomography. In all these areas how the source energy is coupled into the borehole under different situations is of tremendous interest.

On the more traditional full waveform acoustic logging side, we have a paper dealing with logging in a randomly heterogeneous formation, and one on the effect of permeability heterogeneity on the measured Stoneley wave velocity and attenuation. We also have a paper on the ultrasonic modeling of shear wave logging in an azimuthally anisotropic formation.

On the numerical side, we have one paper on a fourth-order staggered-grid finite difference formulation of full waveform logging in a transversely isotropic formation with vertically varying properties, and one on the formulation of an optimal absorbing boundary condition for finite difference elastic wave propagation algorithms.

Finally, as a continuation of previous work, we are working to improve our algorithm to location microearthquakes generated by hydraulic fracturing and thus provide a better location of the fracture in a three-dimensional space. A more detailed summary of the papers follows.

THEORETICAL DEVELOPMENTS

Cased Hole Coupling

Last year Peng et al. (1992 Annual Report) showed the importance of the borehole effect on downhole three component measurements and how the borehole can distort the amplitude and direction of an incoming wave, especially for an incoming shear wave in a soft formation. This year we carried the analysis to that of a cased hole (Peng et al., Paper 6). It is found that because the casing increases the Stoneley wave velocity in soft formations, the borehole coupling effect is even more important in a cased hole. It is clear that in order to get proper amplitude and azimuth, borehole coupling effects must be taken into account. This is of extreme importance in single well imaging experiments where the location of the reflector is often determined by back projecting the incoming wave along its azimuth. If the observed azimuth is not the true azimuth, the location of the reflector will be wrong.

Borehole Radiation

We are also continuing our work with radiation from a downhole source. Meredith et al. (1991 Annual Report) first addressed the problem of Mach wave radiation from tube wave sources in a borehole in a soft formation. Gibson (Paper 7) modeled this effect by considering the tube wave to be a moving secondary point source generated by the primary source of acoustic energy. A discretization of the source well allows a numerical solution of the integral equation which yields the displacement field by a general source distributed in space and time. The time at which each point source in the discretization emits energy is determined by the group velocity of the tube wave, while the radiation of the individual sources is characterized by the stress field induced by the tube wave at the borehole wall. An integration along the borehole of these point sources then yields the observed Mach wave arrivals. Because of the use of ray tracing, this approach has the advantage over the discrete wavenumber approach in that it can be used in a heterogeneous formation.

In a related development, Burridge et al. (Paper 9) use a simple asymptotic analysis, based on the smallness of the ratio of the borehole radius to the wavelength, to reveal the interaction between tube waves and seismic waves. The pressure field in a tube wave acts as a secondary source of seismic waves and conversely an incoming seismic wave excites a tube wave. The asymptotic analysis leads to a characterization of these sources in terms of the solution to two-dimensional elastostatic problems. These may be solved exactly when the borehole has an elliptical cross-section even in an anisotropic formation, provided we stay in the long wavelength limit.

Wave Propagation in Anisotropic Media

For a number of numerical modeling techniques such as the boundary element method and the discrete wavenumber method, we need to numerically calculate the Green's function of the formation. In this year's report, Dong and Schmitt (Paper 8) obtain concise and numerically feasible dynamic and static Green's functions in dyadic form by solving the wave equation and the equilibrium equation with general source distribution in transversely isotropic (TI) media. The wave and equilibrium equations are solved by using an extended version of the Kupradze method originally developed for isotropic media. The dynamic Green's function is expressed through three scalar quantities characterizing the propagation of SH and P-SV waves in a transversely isotropic medium. The 2-D inverse Laplacian operator contained in previous Green's function expressions is eliminated without limiting to special cases and geometries. The final dyadic form is similar to that of the isotropic dyadic Green's function, and therefore lends itself to easy analytical and numerical manipulations. The static Green's function has the same dyadic form as the dynamic function except that the three scalars must be redefined. With this development, we are now in position to model a number of borehole propagation problems in anisotropic media.

NUMERICAL SIMULATION

Stoneley Wave Propagation in Heterogeneous Permeable Media

Previous studies on Stoneley wave propagation in permeable media primarily focused on the situation where the permeability is homogeneously distributed in the formation. In many in-situ situations, however, the permeability distribution of the formation is heterogeneous, due to effects such as a damaged zone around the borehole, random variation of the formation permeability, and layering, etc. In this report Zhao et al. (Paper 3) investigate the effects of formation permeability heterogeneity on Stoneley wave propagation using the theory of dynamic permeability and a finite difference technique in cylindrical coordinates to model the dynamic pore fluid flow in an arbitrarily heterogeneous porous medium surrounding the borehole. For a formation having random permeability variation with various heterogeneity scale lengths (smaller than the scale of the borehole), the Stoneley wave attenuation and dispersion are nearly the same as those calculated with a constant permeability, as is the case for a formation with permeability linearly increasing or decreasing away from the borehole. For a damaged zone case where the zone has much higher permeability than the virgin formation, the attenuation exhibits a peak and the Stoneley wave velocity is significantly decreased in the frequency range from 0 to 3 kHz. These features, if measured from the data, can be used as a diagnostic of the borehole condition.

Acoustic Logging in Random Media

Since most formations are heterogeneous, it is important to study their effects on borehole wave propagation. Tang et al. (Paper 5) investigate the propagation of borehole acoustic waves in the presence of various types of heterogeneous formations by modeling them as stratified media with varying velocity-depth distributions using finite-difference techniques. The wavefield modeling results show that the scattering due to heterogeneity can cause significant amplitude attenuation and travel time delay for the transmitted waves. The effects of the random formation heterogeneity on the borehole acoustic waves are controlled by the degree of heterogeneity variation and the heterogeneity scale length relative to the wavelength.

Finite Difference Microseismograms

One of the most effective way to model logging in complex formations is through the use of the finite difference technique. This year we have two papers addressing this topic. In Cheng et al. (Paper 2) we present a finite difference scheme for seismic wave propagation in a fluid-filled borehole in a transversely isotropic formation. The first-order hyperbolic differential equations are approximated explicitly on a staggered grid using an algorithm that is fourth-order accurate in space and second-order accurate in time. The grid dispersion and grid anisotropy are analyzed and are shown to be less than the corresponding second-order algorithm. Vertically heterogeneous borehole models can be studied using this method.

An effective absorbing boundary condition is necessary for any efficient finite difference algorithm since it will minimize the grid size and thus speed up the computation. Peng and Toksöz (Paper 10) design an optimal absorbing boundary condition by expressing the extrapolation on the artificial boundaries of a finite difference domain as a linear combination of wave fields at previous time steps and/or interior grids. The optimal absorbing boundary condition designed in this paper yields about 10–20 dB smaller in magnitude of reflection coefficients than previously published methods.

FIELD AND LABORATORY STUDIES

Imaging a Hydrofrac

Rodi et al. (Paper 11) examine the problem of locating microearthquakes induced by hydraulic fracturing using seismic arrival time data. In addition to the use of absolute arrival times measured for individual events (as done in Block et al., 1991 Annual Report), we consider the use of differential arrival times amongst a set of two or more

seismic events as a means of constraining their locations relative to one another. Differential arrival times can be measured very accurately using cross-correlation techniques and are less sensitive than absolute arrival times to subsurface velocity structure. Rodi et al. (Paper 11) applied it to a set of 19 microearthquakes recorded during a hydraulic fracturing experiment conducted as part of the Los Alamos Hot Dry Rock project. We find that the events, except for a few outliers, delineate a planar zone 30 meters in dimension, presumably a fracture plane. This example shows that the use of differential arrival times improves the accuracy of locating microearthquake clusters and thus provides a better hydrofrac image.

Ultrasonic Shear Wave Logging Models

Zhu et al. (Paper 4) use a mono/dipole transducer made of a PZT piezoelectric tube for laboratory experiments in borehole models. The radiation pattern of the dipole source is measured in a water tank. Measurements are performed with the transducers in an azimuthally anisotropic borehole model made of Phenolite XX-324. Both fast and slow flexural waves with different velocities are generated by a dipole source in the model. The flexural waves are related to the fast or slow shear waves in the anisotropic material. Experimental results show that the flexural wave splits into a fast and a slow component in an azimuthally anisotropic borehole; therefore, dipole acoustic well logging could be an effective means for estimating a formation's anisotropy.

FUTURE WORK

- **Borehole Acoustics**

  We will continue to study both the borehole source radiation and borehole coupling problems, with the aim of properly correcting the downhole measured wavefield, especially in imaging structures away from the borehole.

- **Anisotropy:**

  Acoustic logging, especially dipole logging, in an azimuthally anisotropic formation is of extreme importance to us. We are currently developing numerical modelling techniques for this situation, as well as starting a number of collaborations with our sponsors to analyse the latest cross-dipole data.

- **Fracture Characterization and Imaging:**

  In addition to fracture characterization using full waveform and shear wave logging data, we will be continuing our efforts in the imaging of hydrofracs using passive microearthquake data. With the latest field equipment and data processing techniques, we hope to be able to image the hydrofrac well beyond the borehole. We

will also look at the use of the shear wave log to estimate fracture height behind casing.

- **Petrophysics:**

Although we do not have a paper on petrophysics in this year's report, we are continuing and expanding our efforts in understanding how microstructures such as pore shapes and volumes affect the macroscopic rock properties that we can measure downhole such as velocity, resistivity and permeability. The electroseismic effect coupling through the Biot model is currently under theoretical and experimental study.

- **Data Processing:**

More and more data sets are available to us from a number of sponsors. These data are collected using different contractor's tools. We will increase our efforts in the analysis of these data.

- **Ultrasonic Laboratory Models:**

We will continue to use ultrasonic laboratory models to test and confirm our theoretical predictions. This year we have ultrasonic models of the dipole tool in an azimuthally anisotropic formation. We will be continuing our work in this area.