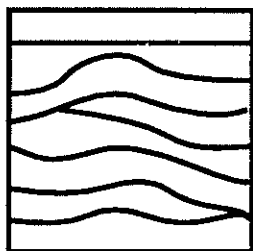


# Borehole Acoustics and Logging Consortium

Annual Report

1994



**EARTH  
RESOURCES  
LABORATORY**

Department of Earth, Atmospheric, and Planetary Sciences  
Massachusetts Institute of Technology  
Cambridge, Mass. 02139

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Sara Brydges, Naida Buckingham, Liz Henderson, Stephen Gildea, Jane Maloof and  
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# Borehole Acoustics and Logging Consortium

## Annual Report 1994

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# REPORT SUMMARY

by

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## INTRODUCTION

This report contains the results of work completed during the twelfth year of the Borehole Acoustics and Logging Consortium in the Earth Resources Laboratory at M.I.T. This year we have achieved one of our major goals in numerical modelling. We have completed a code for modelling elastic wave propagation in a borehole in a generally anisotropic and heterogeneous formation in three dimensions. This opens up a lot of possibilities in terms of modelling full waveform and shear wave logging.

Along the same trend, we have continued to develop our numerical modelling of permeable zones. We are able to simulate Stoneley wave propagation in zones with varying vertical permeability. This allows us to match the field observations better. Another application of numerical flow modelling is to model tracer transport in heterogeneous media. This has applications in environmental as well as enhanced oil recovery areas.

Another area we have addressed is the influence of borehole geometry on the full waveform and dipole wavefield. We have looked at the effects of a borehole with an irregular cross-section on the full waveform, and we have also effectively modelled a borehole with a vertically varying radius, such as in the case of washouts. We can model the scattered Stoneley waves from these washouts and the results compare well with data.

On the field data side, we have a paper dealing with the estimation of permeability from Stoneley waves. This case study was done in a water well. We have processed a number of other data sets during the past year, and some of the results will be discussed at the Annual Meeting.

On the more theoretical side, we have a paper on the radiation of a borehole source into a layered or transversely isotropic medium. This work is done using the Boundary Element method. We also have a paper addressing the possibility of using non-linear semblance to better process the full waveform array data. The idea is to estimate velocity changes (increases) away from the borehole.

In the laboratory we have examined the effects of fractures (vertical, horizontal, and inclined) on flexural wave propagation. We have also begun to investigate the electro-seismic coupling in porous rocks, with an eye on the possibility of coupling acoustic and electric logs to better delineate permeability/fluid changes in the field.

More detailed descriptions of the papers follow.

## THEORETICAL DEVELOPMENTS AND NUMERICAL SIMULATIONS

### Finite Difference Microseismograms

After many years' work, Cheng et al. (Papers 2, 3, and 4) succeeded in generating a three-dimensional, staggered-grid finite-difference elastic wave propagation algorithm. This algorithm is fourth-order accurate in space and second-order accurate in time, and runs on the nCUBE2 supercomputer at ERL. The best feature of this algorithm is that it is completely heterogeneous. The borehole is specified on the grid simply by setting the shear wave modulus to zero. The model can handle orthorhombic and lower orders of anisotropy. The first paper (Paper 2) introduces the algorithm and shows the tests to check for accuracy and stability. The second paper (Paper 3) shows the applications to effects of geometry such as an elliptic borehole, a horizontal borehole, and a borehole in a formation with dipping layers. The third paper (Paper 4) addresses the problem of logging in an anisotropic formation. The finite difference algorithm is successfully used to model the results from our ultrasonic model laboratory, as well to explain features seen in field data.

### Borehole with Irregular Cross Section

Peng et al. (Paper 6) consider the coupling of an incident elastic wave into a borehole of irregular cross-section and investigate the cross-mode coupling phenomenon in sonic well logging in the presence of borehole irregularity. The mode-matching method is used. Different from its original formulation, Peng et al. employ the Reichel et al. algorithm to obtain the discrete least square approximation by trigonometric polynomials, a technique closely related to the fast Fourier transform (FFT). This method not only yields great accuracy but also gains computational speed. This study shows that the pressure in the borehole fluid is sensitive to the irregularity of the borehole cross-section, it is larger if the incident wave is along the effective minor axis and smaller if the incident wave is along the effective major axis.

### Borehole Radiation

An algorithm based on the boundary element method is established by Dong et al. (Paper 13) for modeling seismic source radiation from open or cased boreholes in layered transversely isotropic (TI) media. The axis of symmetry of TI layers is assumed to be parallel to the borehole axis. Under this assumption, the problem is significantly simplified because the element discretization of the borehole remains one dimensional. For fluid-filled open boreholes, three equivalent sources on each element are required to represent the boundary effects on the inner fluid and the outer solid. The three

boundary conditions for a fluid-solid interface set up a system of equations for the equivalent sources on all elements. Once the sources are known, displacements in the solid and pressure in the fluid are obtained. For fluid-filled and cased boreholes, the method treats borehole fluid, casing, and cement as a cylindrically layered isotropic medium. This method has applications in the modeling of single well imaging as well as cross-hole tomography and reverse VSP.

### Stoneley Wave Propagation in Heterogeneous Permeable Media

To further study the problem of acoustic logging in heterogeneous porous formations, Zhao et al. (Paper 9) study the case where the formation permeability varies in the borehole axial and radial directions. Using the finite difference approach, such heterogeneities as random heterogeneous permeability variations, multiple fracture zones, and permeable (sand) – non-permeable (shale) sequences can be readily modeled. Our numerical simulation results show that the continuous permeability variations in the formation have only minimal effects on the Stoneley wave propagation. Whereas the discontinuous variation (e.g., permeable sand and non-permeable shale sequences) can have significant effects on the Stoneley wave propagation. However, when the Stoneley wavelength is considerably large compared to the scale of heterogeneity variations, the Stoneley wave is sensitive only to the overall fluid transmissivity of the formation heterogeneity. This technique has been applied to interpret the acoustic logging data across a heterogeneous fracture zone. This modeling technique, in conjunction with a variable permeability model, successfully explains the non-symmetric patterns of the Stoneley wave attenuation and reflection at the top and bottom of the fracture zone, while it is difficult to explain these patterns using a homogeneous permeable zone model. This technique can be used as an effective means for characterizing permeability heterogeneities using borehole Stoneley waves.

The analysis of solute transport is an effective means for studying medium heterogeneities. Zhao and Toksöz (Paper 12) discuss the effects of heterogeneity on the tracer transport. Tracer transport in various permeability heterogeneities is simulated, assuming steady fluid flow. The results show that the tracer distribution is very closely correlated with the medium heterogeneity, and anisotropy in tracer transport exists when there is permeability lineation and large permeability contrast between low- and high-permeability regions. An important feature by which the tracer transport differs from the fluid flow field is that the tracer transport tends to smear the effects of a thin non-permeable layer (or small permeability barriers) through diffusion into the low-permeability layer, while the fluid flow cannot penetrate the low-permeability layer. In addition, the modeling results also show that the tracer transport strongly depends on the tracer source dimension, as well as the flow source dimension.

### Non-Linear Semblance Processing

Tezuka (Paper 10) describes a simple method to evaluate an acoustic altered zone around the borehole using an array of sonic waveforms. The method is based on a semblance

velocity analysis and a nonlinear travel time window is introduced. On the assumption that a velocity gradient of the altered zone may be linear, the nonlinear travel time window is calculated as a function of averaged velocity and a normalized velocity gradient. The method is applied to the synthetic acoustic data calculated by finite difference modeling. Case studies with several altered formation models confirmed that this method is a good estimator of the velocity gradients around the borehole.

## DATA PROCESSING

### Effects of Radius Changes on Stoneley Waves

Tezuka et al. (Paper 5) describe a propagator matrix formulation for the problem of the Stoneley wave propagation in an irregular borehole. This is based on a simple one-dimensional theory we had proposed in previous years. The borehole and the surrounding formation are modeled by multi-layers discretized along the borehole axis, then the propagator matrices at each boundary are calculated. The mass balance boundary condition is introduced to express an interaction of the Stoneley wave at the interfaces which include radius changes.

The method is used to investigate the reflection and the transmission characteristics of the Stoneley wave with several models. The results are consistent with the results obtained by other existing modeling methods such as the finite difference method and the boundary integral method. The calculation speed is much faster than those of the other methods.

The method is applied to the field data to simulate the synthetic iso-offset records and the results have been compared with the actual field records. The results show a good agreement in the major reflections due to the washout zones and an important disagreement in the reflections related to the fractures. This result suggests the possibility of distinguishing the fracture induced reflections from others.

### Permeability Estimates

Tang and Cheng (Paper 8) describes a fast algorithm for estimating formation permeability from Stoneley wave logs. The procedure uses a simplified Biot-Rosenbaum model formulation. The input to the inversion is the Stoneley wave spectral amplitudes at each depth and receiver, the borehole fluid properties (velocity and density), the borehole caliper log, the formation density and porosity (from log data), and the compressional and shear velocities for the interval of interest. The model uses the borehole caliper and elastic properties to compute the Stoneley wave excitation as a function of frequency, and the porosity and permeability to compute the fluid flow amplitude reduction. This method also uses a reference depth of known permeability and compares amplitude variations at other depths relative to the reference depth. The permeability value obtained from the inversion represents the best fit over all receivers and all relevant frequencies. A processing example in a water well is used to demonstrate the ability of this technique

to extract formation permeability from Stoneley wave logs.

## LABORATORY STUDIES

### Ultrasonic Shear Wave Logging Models

Ultrasonic model logging is performed with dipole transducers in aluminum and lucite borehole models by Zhu et al. (Paper 7) to study the propagation of the flexural waves in a fractured or cased borehole. The experimental results show that the flexural wave is much more sensitive to a horizontal fracture than to a vertical one. The propagation of flexural waves in a borehole with an inclined fracture is related to both the polarization of the flexural wave and the direction of the fracture. The experimental results show that a very strong low-frequency flexural wave can be generated by a dipole source in a cased borehole and it propagates with the shear wave velocity of the formation. High-frequency waves generated by a dipole source propagate with the compressional wave and flexural wave velocities of the casing. These laboratory experiments show that dipole logging can be an effective means for determining horizontal and declined fractures and for measuring the formation shear wave velocity in a cased borehole.

### Electro-Seismic Experiments

The conversion between seismic and electromagnetic energies (or electro-seismic effect) in a fluid-saturated porous rock is well known in theory. When seismic waves propagate through a fluid-saturated porous formation, relative motion between the pore fluid and the solid matrix is generated and cation motion in the fluid is formed. The streaming electric current induces electromagnetic waves in the formation. There is a complementary phenomenon, i.e., the conversion of electric energy into acoustic energy in the porous formation. Zhu and Toksoöz (Paper 11) examine this electro-seismic effect in the laboratory. A compressional or a shear transducer excites an acoustic wave in the water-saturated sample and the electric signals generated on the surface are measured by an electrode. The relationship between the electric potential and acoustic wave or the conductivity of water-saturated rocks is studied. The electro-seismic conversion in rock samples is also investigated. Electro-seismics could provide an effective means for estimating the fluid-saturated porous formation, and may lead to the design of a combination acoustic-electric logging tool.

## FUTURE WORK

- **Dipole Logging and Shear Wave Anisotropy:**

Estimating shear wave velocity from dipole logging data is not as straight forward as it appears, mainly because dipole logging is directional, and thus is affected by azimuthal anisotropy, as well as borehole effects such as borehole breakout and borehole ellipticity. It also makes it difficult to compare to shear wave velocity

measured or derived from monopole or omnidirectional full waveform logs. We now have a numerical model which allows us to simulate logging in an anisotropic formation. We will be running more different models to try to fully understand the effect of anisotropy on full waveform and shear wave logs. The model will also be used to generate the data necessary to test our processing algorithms.

- **Fracture Characterization:**

We have begun to investigate the use of dipole logs in fracture characterization. We have performed some laboratory model experiments. We are hoping to develop a more theoretical analysis to fracture characterization using flexural waves. The ability of shear wave logging to detect fractures behind casing will also be investigated.

- **Data Processing:**

This year we have started to do more processing of data, especially dipole logging data. There are several data sets which we are currently working on, their results should be available during the coming year. It is especially important to process the dipole data in order to understand the capabilities and limitations of current logging tools to estimate formation anisotropy.

- **Petrophysics:**

Petrophysics is an integral part of log interpretation. We had expected to have a bigger contribution from petrophysics in this year's report. However, the petrophysics laboratory of Prof. Dale Morgan has taken a little more time than anticipated to set up. We did investigate the electro-seismic effect in core samples in the past year. Currently we are working on (with John Schatz) the relationship of shear wave velocity and quasi-static shear modulus. The latter is useful in predicting sanding and for hydrofrac design. We anticipate more petrophysics work in the coming year.

- **Ultrasonic Laboratory Models:**

The ultrasonic model laboratory will continue to be a major part of our efforts. We have improved the performance of our dipole transducers in the laboratory. We are in the middle of a major equipment upgrade which we hope will allow us to shape our source waveforms better and thus have a better representation of the actual field logs in the laboratory.

