REPORT SUMMARY

by

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INTRODUCTION

This report contains the results of work completed during the fourth year of the Full Waveform Acoustic Logging Consortium in the Earth Resources Laboratory at M.I.T. This is the first year of the second phase of the Consortium, and the emphasis in our research has evolved from a primarily theoretical study of wave propagation in a borehole to a more balanced treatment of all aspects of the problem. As a result, theoretical models developed over the past years are now being applied to field data for the determination of the physical properties of formations in a variety of situations. The knowledge gained from these applications is in turn helping us to refine the theoretical models used.

One of the most important parameters in formation evaluation is the *in situ* permeability. In this report we have a number of papers dealing with the subject, from theoretical papers investigating the Biot-Rosenbaum model in detail, to the application of the model to field data, and a field comparison of *in situ* fracture permeability obtained from pump test, full waveform acoustic log, and hydrophone VSP studies. We also have synthetic microseismograms generated for formations with fractures of different thicknesses using the finite difference method.

We have continued our study of the use of full waveform acoustic logs in a poorly bonded cased hole. In this report we have one paper each on theory and on data analysis in this subject.

We have also made initial attempts in the inversion of real data. In this particular case, we made use of the P wave and PL mode to obtain formation S-wave velocity in soft sediments. The preliminary results are very encouraging. Last, but not least, we have included a preliminary report on the model experiment setup in the laboratory. Modelling allows us to study complicated boreholes under controlled conditions.

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

THEORETICAL DEVELOPMENTS

Formation Permeability

Formation permeability is an extremely important parameter which affects the propagation of seismic waves in a borehole. In the past year we have been investigating the effect of a Biot-type porous solid on borehole wave propagation, and in particular, Stoneley wave propagation. Denis Schmitt contributed three papers in this report based on his thesis work. The first is a very detailed review of Biot theory and the formulation for wave propagation in porous solids. Much has been said about using the Biot-Rosenbaum theory to model wave propagation in a porous borehole. Here Schmitt examines the theory in detail and points out all of the assumptions involved. He also modifies Biot's theory by the introduction of a unified definition of mass and viscous coupling coefficients, both of which are frequency dependent.

The effect of such a porous formation on wave propagation in a borehole is studied thoroughly in Schmitt's second paper. Synthetic full waveform acoustic logs in porous formations are generated using the discrete wavenumber summation technique. Effects of different saturating fluids, permeability, frequency and porosity are studied, as well as whether the formation is open to the borehole fluid. The results show that if the formation is closed to the borehole fluid, the porous formation behaves very much like an elastic one. However, if the borehole and pore fluid pressures are directly coupled, the guided waves, especially the Stoneley wave, are strongly affected. The Stoneley wave attenuation increases and its phase velocity decreases with increasing formation permeability. The pseudo-Rayleigh wave is less affected. The permeability effect on Stoneley wave propagation increases with decreasing frequency. Gas-saturated formations, because of the increased mobility of the saturant, have a greater effect on the Stoneley wave propagation than water- or oil-saturated formations. All this provides the theoretical basis for data interpretation in a later paper by Burns and Cheng.

Two of the parameters in the Biot formulation that have been ignored by Rosenbaum, as well as by other authors, are the pore shape and pore geometry. The effects of these on the mass and viscous coupling coefficients are studied in the third Schmitt paper. In a formation that is open to the borehole, the pore shape and geometry do not affect significantly the Stoneley wave propagation. However, they do affect the pseudo-Rayleigh wave propagation. Since, as we shall see later, the accurate determination of *in situ* permeability requires knowledge of the formation shear-wave velocity and attenuation, changes in pseudo-Rayleigh wave propagation must be taken into account.

Wave Propagation in Poorly Bonded Cased Holes

One of the potential uses of the full waveform acoustic log is the determination of formation velocities behind casing. In previous reports we have addressed this problem in some detail from both velocity dispersion and energy partition standpoints. In this report, we investigate the energy partitioning of the guided waves in a free pipe situation. Of particular interest is the second Stoneley mode propagating in the fluid annulus between the casing and the cement or formation. Our results show that this second Stoneley wave is controlled by the properties of the fluid annulus, cement and formation. The first or primary Stoneley mode, that is, the one propagating in the fluid column within the casing, is mostly decoupled from the formation. The pseudo-Rayleigh wave is more dispersive in a free pipe situation than in a well bonded case. This will assist us in the interpretation of the results of the data analysis presented in Block et al. in this report.

Finite Difference Modelling of Vertically Heterogeneous Media

The subject of wave propagation in a vertically heterogeneous medium has always been of considerable interest. However, the difficulty involved has resulted in limited work in this area. This year we have modelled vertically heterogeneous media using the finite difference technique. In particular, we investigate the effect of fractures, thin beds and bed boundaries on full waveform acoustic logs. Strong reflections of the body and guided waves are observed even in very thin fractures. Stoneley waves are attenuated crossing a fracture, and the attenuation increases with increasing fracture width. Bed boundaries and thin beds also cause reflections of body and guided waves, confirming the interpretation of field data by Paternoster and Larrère in last year's report. Overall, the finite difference method has been shown to be a reliable one for the study of wave propagation in more complicated borehole geometries.

DATA ANALYSIS

We have increased our efforts in this past year in the analysis of full waveform acoustic logging data. We have studied a number of different data sets, each unique in its own way, for the determination of such formation properties as *in situ* permeability, formation velocities behind poorly bonded casing, shear wave velocities in very soft marine sediments, and the hydraulic conductivity of fractures. We have had varying degrees of success in these efforts. More importantly, in each case we have learned more about the range of applicability of our theoretical models. This feedback from field data will allow us to develop better models in the coming years.

Formation Permeability

We have applied the Biot-Rosenbaum theory of wave propagation in a borehole in a porous formation, as detailed in the papers by Schmitt in this report, to published data relating Stoneley wave propagation and core measured permeability (Burns and Cheng, Paper 8). The data were published by the Mobil logging group. They reported strong correlations between Stoneley wave attenuation and phase velocity with core permeability. We try to model these correlations using the Biot-Rosenbaum theory. Because not all necessary parameters, such as formation shear wave velocity and density, were published together with the Stoneley wave data, assumptions had to be made. Even so, the results are very encouraging. It appears that Stoneley wave attenuation is more sensitive to permeability than Stoneley wave phase velocity. However, since it is much easier to measure formation P- and S-wave velocities accurately than to measure P- and S-wave attenuation, the variations in the Stoneley wave phase velocity resulting from permeability changes, rather than lithology changes, can be more readily measured than variations in Stoneley wave attenuation. Thus both Stoneley wave velocity and attenuation should be used to get the best estimates of *in situ* permeability.

This method of *in situ* permeability determination is most sensitive in the region of permeability of 10 millidarcies to a few darcies. Below 10 millidarcies, variations in Stoneley wave velocity and attenuation from non-lithologic sources are difficult to pick out. Above a few darcies, the large permeability frequently results in almost complete attenuation of the Stoneley wave signal.

Velocity Analysis of Array Data

The determination of P- and S-wave velocities in an openhole situation is more or less routine these days. Even in well bonded cased holes, the formation velocities are easily obtained. In poorly bonded cased holes, however, the ringing caused by the casing often obscures the formation signals. Recently, different investigators have begun using full waveform acoustic logging tools with large (8 or more) receiver arrays and applying velocity analysis techniques in the hope of obtaining formation velocity information in poorly bonded cased holes. In the March, 1986 issue of Geophysics, Hsu and Baggeroer presented results of velocity analysis in one poorly bonded cased hole example. In this report, Block et al. (Paper 4) look at this problem systematically by applying Average Semblance and Maximum Likelihood Spectral Analysis techniques in our velocity analyses of actual and synthetic array data. It is clear that formation arrivals can be detected behind casing. However, the casing and cement do have an influence on the formation velocities, especially the P-wave velocity. We are in the process of analyzing array data obtained before and after casing from the M.I.T. research borehole in Michigan.

Inversion of Data from Soft Sediments

Inversion of full waveform data has always been a long term goal of this Consortium. This year we have made a significant step towards our ultimate goal. Cheng et al. (Paper 9) present the results of formation shear-wave velocity and compressional-wave quality factor obtained from the inversion of full waveform acoustic logging data. The data were obtained in soft marine sediments during the Deep Sea Drilling Project Leg 95 cruise using a standard Schlumberger full waveform acoustic logging tool. The data from two receivers (8 and 10 ft) are Fourier-transformed into the frequency domain. The amplitude ratio of the two spectra is windowed between 7.5 and 15 kHz and the result then inverted for the formation shear-wave velocity and compressional-wave Q using a standard non-linear least-squares inversion algorithm. The forward model used in the inversion is the P wave train obtained from the branch-cut integration method. Since, in these soft sediments, there are no refracted shear waves or psuedo-Rayleigh waves, and at a center frequency of about 12 kHz the Stoneley wave is not well excited, the P wave train is a good approximation. Although there is no good method of directly checking them, the results obtained from the inversion agree very well with laboratory measured values obtained on core samples from similar lithologies.

A more qualitative approach to lithology identification from full waveform logs is proposed by Paillet et al. (Paper 2). It involves simple measurements of energy arrivals in different time windows corresponding to the P-wave, P-leaky-mode, pseudo-Rayleigh-wave and Stoneley-wave arrivals. Relative amplitudes of these modes, as well as formation velocities obtained using conventional methods, can be used for lithology identification.

Fracture Detection and Characterization

One use of the full waveform acoustic logs is for fracture identification and characterization. In our 1984 report, Mathieu and Toksöz presented a theoretical model for Stoneley wave attenuation on crossing fractures. Over the past years, we have also been studying the characterization of *in situ* fractures by using a hydrophone VSP. This past summer we had the opportunity to field test these methods at a site near Mirror Lake, New Hampshire, in cooperation with the Water Resources Division of the U.S.G.S. A set of fractures in granite was studied using the full waveform acoustic log, hydrophone VSP, televiewer, and a pump test. Results are rather surprising (Hardin et al., Paper 11). The model of Mathieu and Toksöz gives values of hydraulic conductivity of the same order of magnitude as the pump test. The hydrophone VSP model of Beydoun et al. (Paper 11, 1984 Annual Report) underestimates the fracture conductivity. This is because fracture stiffness was not taken into account in the model. After we introduce fracture stiffness on the order of that of a fluid layer, the results from the VSP model are then consistent with those from logging and pump testing.

Comparisons of the fracture orientations obtained from the VSP, pump test, and televiewer log reveal that both the VSP and pump test show a fracture orientation and dip different from that seen by the televiewer. Thus it is clear that the more regional flow pattern away from the borehole may be different from the orientations of individual fractures intersecting the borehole. Care must be taken in extrapolating fracture orientations seen in a borehole to a larger scale.

MODEL EXPERIMENTS

Over the past years, we have been trying to develop in our laboratory the capability of doing scaled model full waveform logging experiments. We are happy to report that we have achieved this goal. Some of our initial results are presented in the paper by Shortt in this report. We have chosen to use a sparker type source rather than a more conventional piezoelectric transducer. The former generates a signal with a much broader frequency band than the latter. This is evident in the lucite model presented in this report, where we are able to excite the low frequency Stoneley wave. With this scale modelling capability, we intend to study the effects of three-dimensional heterogeneities, such as fractures and bed boundaries intersecting the borehole at an angle, on the full waveform acoustic logs. These three-dimensional borehole models are too complicated to study numerically, even with the aid of a supercomputer. The scale models will also allow us to perform controlled experiments on the effect of *in situ* permeability on the propagation of Stoneley waves, as well as a large number of other problems one encounters in actual field operations.

FUTURE WORK

The application of previously developed theoretical models to field data has increased our understanding of the problem of wave propagation in a borehole. It also points out the strengths and inadequacies of our models. In the coming year, we plan to continue in the direction we have taken in this past year, that is, the further development of theoretical models guided by the analysis of field data. Specifically, we intend to continue our research in the following areas:

- **Wave Propagation in a Porous Formation:** In the past year, we have learned a great deal about wave propagation in a borehole in a porous formation, and the use of the phase velocity and attenuation of Stoneley waves to determine *in situ* permeability. However, much work remains ahead of us if we are to fully understand the problem. A complete set of field data will help us define the limits of the Biot-Rosenbaum model. We also plan to collect such data in our model laboratory. We intend to study further the effects of such parameters as pore shape and geometry, pore fluid compressibility and viscosity, as well as the presence and thickness of mudcakes, on the observed Stoneley and pseudo-Rayleigh wave propagation. Our goal is to reliably determine the absolute permeability of a porous formation.

- **Poorly Bonded Cased Holes:** We have demonstrated the ability to obtain formation velocities in a poorly bonded cased hole using array data. However, it appears that under certain situations the formation velocities, especially the P-wave velocity, are affected by the casing, cement, and the fluid annulus. We will investigate methods of decoupling the casing effects from the formation velocities. We will also study the effects of using arrays of different numbers of receivers and receiver separations on the accuracy of different methods of velocity analysis.

- **Full Waveform Inversion:** We had initial success in the inversion of the full waveform acoustic logging data. Much work lies ahead. We need to understand the stability and robustness of the method applied to field data collected in different lithologies, as well as different ways to decouple the borehole responses from the source effects. Confirmation of the velocities and especially the Q values obtained by comparison with core measurements is also necessary. We will pursue these questions in the coming year.

- **Fracture Characterization:** For the first time this past year, we were able to compare different methods of characterization of *in situ* fractures. Our model of wave propagation past a fracture in a borehole, while adequate, is far from perfect. It is a kinematic rather than a dynamic model. Work is already underway to develop a dynamic model, as a counterpart to the Biot-Rosenbaum model for a porous formation. We expect results in the coming year.

- **Finite Difference Modelling:** The finite difference method appears to be well suited for the study of wave propagation in a vertically heterogeneous borehole. We will continue to use our program to study different borehole conditions. We also intend to modify the program to handle a porous formation. When that is done, we can study the effect of porous zones of varying thicknesses, as well as vertical changes in formation permeability, porosity and saturation. It remains one of the most powerful methods currently available for the modelling of complicated boreholes.

- **Shear Wave Logging:** In the past year, because of manpower constraints, we have not made much progress in studying non-axisymmetric wave propagation. We have already begun to rectify this. Currently, we are studying shear-wave logging in a porous formation, and will investigate shear-wave logging in multi-layered boreholes.

- **Scaled Laboratory Models:** We believe scaled laboratory modelling of wave propagation in a borehole is an important component in the overall effort of understanding full waveform acoustic logs. Scale models provide checks for our numerical microseismogram synthesis programs. More importantly, three dimensional features such as inclined fractures and off-centered tools can be easily introduced in a laboratory model. Computer simulations of such 3-D problems are close to impossible, at least at ERL. We have developed the necessary equipment in this past year, and we intend to actively conduct scale experiments in the coming year.