**IN-SITU PERMEABILITY DETERMINATION
USING BOREHOLE AND SEISMIC LOGGING DATA**

FINAL REPORT

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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 results using this method are consistent with the results obtained by other existing modeling methods such as the finite difference method and the boundary integral method, but the calculation speed is much faster than those of the other methods.

Using this technique, we can account for the effect of borehole irregularities on Stoneley wave reflections. Figure 1 shows the iso-offset Stoneley wave reflections from field data compared to the synthetic reflections generated from borehole irregularities using the method of Tezuka *et al.*, (1994). By comparing the field data to the synthetics, the Stoneley wave reflections caused by fractures and permeable zones can be distinguished from those caused by borehole irregularities.

We have applied this technique to laboratory scale-model experimental data to test the validity of the approaches (Zhu *et al.*, 1992). More recently, Cheng and Cheng (1996) and Tang and Cheng (1996) applied these techniques to field data with good success. The use of Stoneley waves for fracture characterization appears to work best with fractures that are roughly normal to the axis of the borehole. Reprints of Cheng and Cheng (1996) and Tang and Cheng (1996) are included as Appendices A and B, respectively.

We have also investigated the sensitivity of Stoneley wave velocity and attenuation to a gas-saturated formation. Figure 2 shows the Stoneley wave reflection coefficients through a gas-saturated formation with varying permeabilities. Because of the low viscosity and

density of gas, the Stoneley wave is sensitive to gas-saturated permeable formations with permeability on the order of millidarcies.

Shear Wave Logging

During the past three years much of our effort in the characterization of fractures from acoustic logging has been focused on shear wave logging using dipole sonic logging tools. This technique is more applicable to situations where the fractures are sub-parallel to the axis of the borehole, resulting in the formation appearing to be azimuthally anisotropic.

We have found that the commonly used four-component rotation of cross-dipole logging data gives a robust and accurate estimate of the directions of the principal axes of the formation shear wave anisotropy. We applied several rotation algorithms to a cross-dipole shear-wave logging data set from the Powder River Basin in Wyoming and found that independently rotated source-receiver sets are very consistent with each other in anisotropic sections. Figure 3 shows the rotated angles from seven different source-receiver pairs in an anisotropic section of this data. The repeatability of these angles demonstrates the robustness of the approach.

Because of cross-coupling in non-ideal situations in the field, and the dispersive nature of the flexural waves, determining the amount of shear wave velocity anisotropy can be unstable and processing dependent. After the rotation we compare two methods for estimating the phase velocities of fast and slow waves—a semblance method and homomorphic processing

(Ellefsen *et al.*, 1993). We find homomorphic processing to be more reliable due to the dispersive nature of flexural waves. The dispersion of the flexural waves can be seen clearly in Figure 4 where rotated fast and slow flexural waves for all seven source-receiver pairs are plotted. Although there is significant separation in the two components in the first arrivals, the differences vanish in about three cycles, corresponding to the arrival of the Airy phase of the flexural modes. Since the Airy phase tends to have larger amplitudes, it has a big influence on velocity determination methods based on semblance cross-correlation. In particular, the size of the correlation window must be chosen carefully. A more stable and robust velocity estimation scheme needs to be developed.

Laboratory Modeling

In addition to field data, laboratory scaled-model experiments have provided a good testing ground for our theoretical developments. Laboratory measured dipole data obtained with a scaled tool and a scaled borehole drilled in an anisotropic material (phenolite) were used to simulate the flexural modes propagating in a transversely isotropic (TI) formation whose symmetry axis is perpendicular to the borehole (Zhu *et al.*, 1995). A variety of rotation methods were used to analyze the data. Two flexural modes were generated in this lab experiment. Their velocities are related to those of the fast and slow shear waves in the model material. The experimental results show that the particle motion of the fast flexural wave is linear and in the same direction as that of the fast shear wave in the formation. The

polarization direction of the fast flexural wave coincides with that of the fast shear wave and is independent of the direction of the dipole source. The particle motion of the slow flexural wave is nonlinear and elliptic. Its polarization direction and variation are dependent on the anisotropic material and the source direction. This means that the slow flexural wave is a more complicated wave mode rather than the simple mode where the particle motion generated by a dipole source is in the direction of the slow shear wave. The polarization characteristics of the fast flexural wave can be used to determine the principal axis of an anisotropic formation by in-line and cross-line logging data.

Numerical Modeling

In support of our efforts, we have also developed a three-dimensional elastic anisotropic finite difference wave propagation algorithm to help us understand the different wave modes we observe in the full waveform acoustic and shear wave logs (Cheng *et al.*, 1995). The code runs on our 512-node nCUBE massively parallel super computer, and an MPI-based version is portable to other parallel computing platforms. This codes allows us to visualize the flexural wave propagation in an azimuthally anisotropic formation, and to study the interaction of the two flexural modes.

Fluid Flow in Heterogeneous Formations

Zhao *et al.* (1992) modeled fluid flow through a single fracture with rough surfaces. The results of that study indicate that the flow exhibits strong frequency dependence, even for small fractures with contacting surfaces. The amount of flow through the fracture is also reduced by the surface roughness. These results, along with some other early modeling of heterogeneous permeability effects, led to some new results during the past few years (Zhao, 1994). Zhao *et al.* (1994) modeled the effects of permeability heterogeneity on the Stoneley wave attenuation in full waveform acoustic logs using the finite difference technique. When the Stoneley wavelength is large compared to the scale of the heterogeneities, the wave is sensitive to the overall fluid transmissivity. If the scales are comparable, however, the effect of heterogeneous permeability variations can be significant. The models were applied to two data sets, one from a laboratory scale model, and the other from a fractured zone in the field. Figures 5 and 6 show the results of using a homogeneous permeability model to match the Stoneley wave data compared to using a more realistic heterogeneous model.

PASSIVE MONITORING OF HYDRAULIC FRACTURES

The flow of fluid through a reservoir, be it petroleum, steam, gas or water, is influenced not only by the matrix permeability but by the occurrence of "large-scale" discontinuities such as fractures, joints and faults. In many cases, the existence of these structures can produce orders of magnitude variations in the permeability such that the parameter becomes

virtually lithology-independent (Bourbié *et al.*, 1987). This usually limits the accessibility of a large portion of the reserves, and subsequently, the production volume. It is this fact that motivates research in the characterization of in-situ and induced fractures at the reservoir scale.

Reservoir stimulation, or hydraulic fracturing, has long been used to increase the permeability of both petroleum and geothermal reservoirs, but in most cases the procedure must be applied carefully in order to avoid introducing fractures in unwanted locations, thus altering the reservoir permeability in an undesirable way. During hydraulic fracturing, fluids are pumped into the reservoir where they flow away from the injection point and into the media. This forced injection can cause dislocations within the rock by several mechanisms. First, a true hydraulic fracture causes rupture of the low permeability matrix. This mechanism is thought to be governed by tensile opening of the rock matrix plus some rotation of the rock blocks on either side of the crack. The second type of dislocation is produced by slippage of the walls on pre-existing cracks and joints. In either case, the dislocations usually produce microseismic events (also referred to as acoustic emissions) which generate seismic waves that propagate away from the dislocation. In the last ten years, there has been increased interest in using this phenomenon to improve reservoir management by delineating the created fracture and characterizing the altered permeability.

Seismic monitoring during injection has been implemented in a variety of reservoir types, including many Hot Dry Rock (HDR) geothermal fields such as Los Alamos National Labora-

tory's experimental site in Fenton Hill, New Mexico, Soultz-sous-Floret, in the Rhinegraben, France, and Ogachi and Hijiori, Japan, and at the steam field at the Geysers, California. Recently, several petroleum companies have conducted seismic monitoring experiments for both production field management and waste disposal. These surveys have produced very high quality seismic data, which allows detailed analysis of the fracture geometry, and the rupture processes itself.

We have participated in several recent experiments, focusing on data processing, analysis and interpretation. Our primary goal has been to gain a better understanding of the hydraulic fracture process by using seismic methods to locate and characterize the acoustic emission, and to improve the resolution of the methods that currently exist. Our efforts have focused on several aspects of the seismic monitoring method. Specifically, we have improved the microearthquake hypocenter location determination through the use of joint velocity-hypocenter inversion and multiple relative event hypocenter location using differential traveltimes. We have also made use of the occurrence of doublet events (two events which are almost identical in waveform) to estimate the empirical Green's function and determine the relative source time function of the larger of the two events. This technique provides insight into the rupture process itself which, in view of the large number of events that occur in the context of hydraulic fracturing, gives us a valuable tool in tracking variations in rupture mechanisms over the course of the injection. Combining the multiple relative event locations with the empirical Green's function method has allowed us to extract important

information about the rupture directivity and velocity.

Historically, work on microseismicity monitoring supported under this grant began with the development of the method of joint velocity-hypocenter inversion (Block, 1991). This work, conducted in cooperation with Drs. Mike Fehler, Leigh House, and Scott Phillips of Los Alamos National Laboratory, showed that microearthquake hypocenter locations could be improved by inverting for the seismic P and S velocities simultaneous with the location coordinates and the origin time of the hypocenter. Additionally, the method successfully delineated areas of decreased shear wave velocities (up to 13 percent) and demonstrated that these anomalies correlated well with the locations of the most intensely fractured portions of the reservoir, as determined from the hypocenters of the induced microseismicity.

In 1993, we developed a method of reducing the errors in hypocenter location by reducing the impact of errors in the estimated velocity model for the reservoir. This method, referred to as Multiple Relative Event Location (MEL), bases its success on the fact that doublet events occur very close together. The similarity of the waveforms of the two events waveforms guarantees that the seismic rays have traveled along almost identical paths and that any error in the model would subsequently apply equally to both. This effect allows us to determine the hypocenter location of these two events relative to each other with very small error. The process of hydraulic fracture produces large numbers of seismic events that have been shown to include many similar events (referred to as multiplets). This fact allows us to delineate the three-dimensional distribution of seismicity associated with the fracture. The MEL method

inverts the P and S arrival times for all of the target events plus the differential arrival times between multiplet events. The differential arrival times are determined using cross correlation of the P and S arrival between a master event in a multiplet set and another event from the same set. The non-linear traveltimes inversion is accomplished using a conjugate gradient algorithm that produces rapid and stable results (Rodi *et al.*, 1993).

We applied the MEL technique to 157 events from the Los Alamos National Laboratory HDR hydraulic injection experiment. The hypocenters, as determined using MEL, defined a planar surface of approximately 30 meters across. The relative results were twice as accurate as the results obtained by inverting only the P and S arrivals without the differential times (Rodi *et al.*, 1993; Li *et al.*, 1995). An analysis of the effectiveness of the method indicated that MEL can improve the accuracy of the results as described, but will still be affected by the geometry of the receiver array, a problem that can only be remedied during the survey design stage.

Recently, several petroleum companies have undertaken seismic monitoring of hydraulic fracture experiments and have improved the survey design by increasing the receiver coverage. In 1993, ARCO Oil and Gas Company conducted a Deep Well Treatment and Injection (DWTI) project that demonstrated that hydraulic injection could be used to facilitate solid waste disposal (ARCO, 1994). The experiment was designed with a dense array of receivers and excellent receiver coupling in the wellbore. The data quality is excellent. ARCO supported the M.I.T. Earth Resources Laboratory's (ERL) efforts by contributing this data and

software and supported our determination of hypocenters for 200 of the 2400 events recorded during the injection. This data allowed us to examine the effects of a well instrumented, downhole receiver array on hypocenter determination. The 90 percent confidence regions for hypocenters determined using this array were found to vary from a minimum of 8 ft in the semi-major axis and 3 ft in the semi-minor axis to regions in excess of 100 ft near the far end of the fracture (at a range of approximately 1200 ft). Due to the orientation of the fracture to the two wells, the semi-major axis is oriented roughly perpendicular to the trend of the fracture. Where the confidence region is small, near the center of the array, the lateral fracture geometry will be well defined, but near the end of the fracture, the lateral distribution of hypocenters will not resolve small fracture detail (Rieven and Rodi, 1995). This analysis shows that data recorded for events near the center of the array can be used for a detailed investigation of the rupture mechanics in this vicinity.

Li *et al.* (1995) demonstrated that high quality seismic records from acoustic emissions offer significantly more information about the rupture processes than just the hypocenter locations. Building on the works of Mueller (1985), Frankel *et al.* (1986) and Li and Thurber (1988), Li *et al.* (1995) identified 16 events from the Los Alamos, Fenton Hill HDR injection, for which Relative Source Time Functions (RSTFs) could be determined. To do this, they identified a doublet event of small relative amplitude which they used as the Empirical Green's function (EGF). The EGF represents an approximation to the true earth response induced by a perfect impulsive source at the EGF event's hypocenter location. The RSTFs

of 16 events were then determined by deconvolving the EGF signal from each of the 16 seismic signals (Li *et al.*, 1995).

A comparison of the 16 RSTFs suggest that the Fenton Hill events exhibit a predominance of simple, single pulse source functions but that this is not necessarily true for all events. Several RSTFs exhibited complex rupture characteristics, specifically multiple source pulses (Li *et al.*, 1995). They also estimated the individual rupture dimensions and the seismic stress drop of each of these events. The results indicate that the rupture dimensions range from 3.5 m to 12 m in radius and the stress drop varies from 1.4 bars to 19.2 bars. They suggest that the variation in stress drop reflects the stress heterogeneity within the fractured zone. Additionally, they examined the RSTFs to assess the azimuthal variation in RSTF amplitudes. They observed that the RSTF amplitudes were high in the direction of rupture propagation, but lower in the direction away from the rupture propagation. They compared this direction with the direction determined from the distribution of 157 hypocenters and found that the two were in excellent agreement.

Finally, a temporal analysis of the relative hypocenters (using a grid search algorithm for matching the observed P and S and differential arrival times) was used to estimate the rupture growth rate and fracture height. They estimated that the rupture front propagated at a velocity of 0.1 meter per minute and the centroid of the 157 events propagated at a velocity of 0.22 meters per minute (Li *et al.*, 1995). Future study of this characteristic may include comparison with the expected rupture speed for various physical source mechanisms.

The work supported under this grant and completed in cooperation with both the geothermal and petroleum industry has allowed us to make significant progress in understanding hydraulic fracturing which contributes directly to an improved understanding of in-situ permeability. It has provided the means by which we have increased the accuracy of hypocenter location algorithms, as well as confirming that RSTFs can be used effectively to characterize variations in the rupture process. These new tools, coupled with the improved data acquisition recently accomplished, open a new avenue toward understanding not only the hydraulic fracturing process, but a host of other associated concepts including fracture mechanics in heterogeneous media, the effects of water in rock rupture, the influence of in-situ fractures on hydraulic injection, and the variation in stress in various geologic environments.

CONCLUSIONS

Over the past few years, under this grant and the Borehole Acoustics and Logging Consortium at MIT, we have developed a deep understanding of the interaction of acoustic waves, especially Stoneley waves in a borehole, with fractures and permeable zones intersecting a borehole. In particular, we found that the Stoneley wave is sensitive to the permeability of the fracture or permeable zone. Furthermore, the Stoneley wave is both reflected from and attenuated by the fracture or permeable zone. By using the reflected and transmitted Stoneley wave amplitude, we can estimate the permeability of the fracture or permeable zone. This approach is best suited for fractures that are approximately normal to the axis