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Using Seismic Tomography to Characterize Fracture Systems Induced by Hydraulic Fracturing.

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Abstract

Microearthquakes induced by hydraulic fracturing have been studied by many investigators to characterize fracture systems created by the fracturing process and to better understand the locations of energy resources in the earth's subsurface. The pattern of the locations often contains a great deal of information about the fracture system stimulated during the hydraulic fracturing.

Seismic tomography has found applications in many areas for characterizing the subsurface of the earth. It is well known that fractures in rock influence both the P and S velocities of the rock. The influence of the fractures is a function of the geometry of the fractures, the apertures and number of fractures, and the presence of fluids in the fractures. In addition, the temporal evolution of the created fracture system can be inferred from the temporal changes in seismic velocity and the pattern of microearthquake locations. Seismic tomography has been used to infer the spatial location of a fracture system in a reservoir that was created by hydraulic fracturing.

Introduction

Microearthquakes induced by human activities have been studied to reveal information about the earth for many years. The largest areas of study have been in microearthquakes induced by construction of surface water reservoirs and by mining. More recently, there has been interest in studying the seismic activity induced by hydraulic injections to obtain information about the subsurface fracture system created by the injections (Jones and Stewart, 1993; Roff et al, 1995, Moriya and Niitsuma, 1995).

In many regions, it has been found that the injection of water into the earth under pressure has resulted in microearthquake activity (Fehler, 1989; Wallroth et al, 1995). These microearthquakes are associated with the presence of fluids and increased fluid pressures. At this time, it is not entirely clear if the microearthquakes occur in the same regions where the injected fluid is present. The injected fluid may cause changes in pore pressure away from the injection zone which may induce microearthquakes. Alternatively, increased strains in the region where the fluid is injected may induce stress changes and cause microearthquakes away from locations where fluid is present. The direct result of a fluid injection may be a pore pressure increase causing a decrease in the effective stress and a resulting increased probability of seismicity. In addition, the fluids may reduce friction along pre-existing fractures increasing their chances of sliding.

Induced microearthquakes are also associated with fluid extraction from reservoirs. Poroelastic theory indicates that shear stresses accumulate both within and outside of drained volumes (Segall, 1989). In a recent field study, Rutledge et al. (1994) mapped reservoir fractures using microearthquakes induced by oil production. Figure 1 shows distinct planes delineated by microearthquakes occurring over a 6-month monitoring period in a fractured, carbonate-rock, oil reservoir. Only fluid extraction was taking place prior to and during the monitoring period. The planes along which movement was induced are peripheral to the two active production wells, FS2 and FS1. The production history in this area suggests that the seismically active fractures are not hydraulically connected to current production and that movement is being induced along previously drained fractures peripheral to those being currently drained.

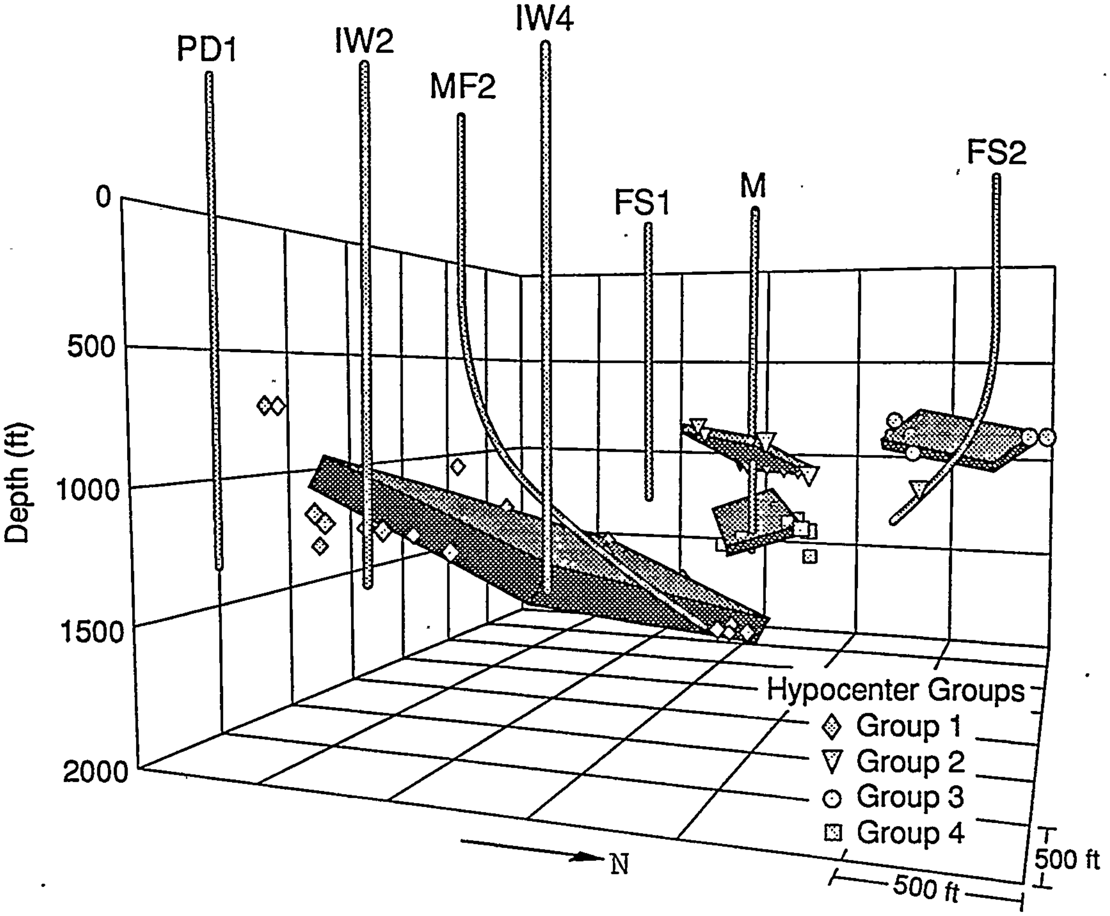

Figure 1. Locations of microearthquakes and wells in producing oil field in Kentucky, USA.

When microearthquakes occur, the seismic energy radiated may be recorded and used to infer properties of a region where they occurred. For example, spectral content of waveforms may be used to infer source characteristics (Fehler and Phillips, 1991) as well as scattering from heterogeneities and anelastic properties of a region (Feustel, et al, 1995). Microearthquake locations may be determined and used to infer the size and location of the region that was altered by the injection (Fehler, 1989; Rieven et al, 1995; Phillips et al., 1995). In addition, clustering of microearthquakes gives indications of fluid flow paths. More recently, seismic tomography has been implemented to infer spatial variations in mechanical properties of the stimulated region that may be used to characterize more directly the effects of the fluid injections (Block et al, 1994).

Travel time tomography

Traveltime tomography using microearthquakes induced by fluid injections can provide important information about the velocity structure of a hydraulically fractured reservoir. Determination of the volumes of rock where velocity changes occur provides indirect evidence for the location of the injected fluid and the nature of the changes caused by the fluid. Therefore, we would like to determine spatial variations in the velocity structure from the earthquake data. In addition to spatial variations, temporal variations are likely to occur during the fluid injection. Thus, a complete travel-time tomographic treatment of data from a reservoir undergoing hydraulic fracturing should include a determination of both spatial and temporal variations in the velocity structure.

Tomography Using Earthquakes as Sources

Many authors have discussed how to use earthquakes as sources for traveltime tomography (Michelini and McEvilly, 1991). Block et al (1994) implemented a method for using microearthquakes induced by hydraulic fracturing as sources to determine the three dimensional structure of a region stimulated by the injection. They used data from only 4 stations but had high-quality P and S wave arrival times. Their method used separation of parameters to numerically decouple locating the microearthquakes from the velocity determination problem while maintaining the mathematical coupling of the two problems (Pavlis and Booker, 1980). This allowed the use of a large number of microearthquakes in the inversion. A second-difference spatial regularization scheme was needed to make the inversion problem numerically stable. Block et al (1994) found that the S-wave velocity structure was better resolved than the P-wave structure due to the larger relative change in S-wave velocity, compared to P-wave velocity, caused by the introduction of fluid-filled fractures. Figure 2 shows a horizontal slice through the S-wave velocity structure obtained for an inversion.

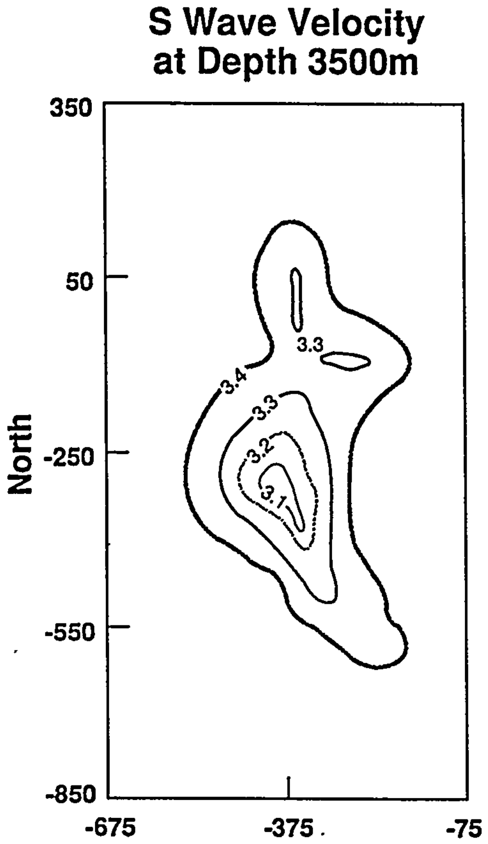

Figure 2. S-wave velocity fracture found by inversion of arrival times from microearthquakes recorded during a hydraulic fracturing experiment.

Temporal Variation in Velocity Structure

For cases where observations of injections are conducted using boreholes, we have few observation stations resulting in an insufficient amount of data to resolve both spatial and temporal variations in velocity structure. We thus choose a parameterization where velocities in a block are considered to be different from a background value only after a threshold number of earthquakes have occurred in the block. Once a block has the required number of earthquakes, its velocity is considered to be perturbed and that velocity can be found. We regularize by requiring that all perturbed blocks have a similar velocity unless the travel times provide strong evidence to the contrary. This parameterization was chosen based on the observed change in the volume of the reservoir in which seismicity occurs during the injection. Figure 3 shows that during the injection, the volume of the reservoir containing microearthquakes increases linearly with the injected fluid volume. Since the size of the seismically active portion of the reservoir increases linearly with the volume of the injected fluid, we assume that each sub-volume of the reservoir receives the same amount of fluid during the time-scale over which the injection occurs. Thus, the effect of the fluid on the velocity of each sub-region of the reservoir should be the same.

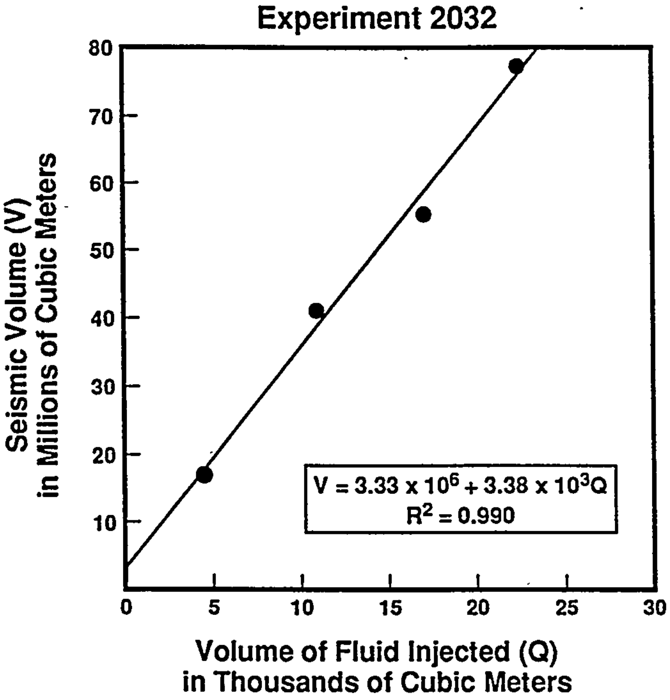

Figure 3. Volume of seismically active region vs. injected fluid volume.

We find that this model parameterization provides a more consistent way of dealing with the three-dimensional P- and S- wave tomography problem when temporal changes in the velocity structure are important. When using seismicity that occurred throughout the injection, we found that the spatial second-difference regularization yielded an unreasonable image when no temporal variations were allowed. Using a time-varying scheme, we were able to obtain a superior temporal and spatial image of the velocity structure of the reservoir.

Using the results of the tomograms with hydraulic information obtained during the injection allows reservoir engineers to infer properties of the fracture system created during the hydraulic stimulation.

Conclusions

Use of reservoir microearthquakes induced by stimulation or normal production operations can provide information on reservoir fracture systems with greater spatial resolution than is possible from surface imaging techniques, and at far greater distances from boreholes than other borehole imaging/detection methods. In addition to determining the location, orientation, and size of stimulated zones, measurements of velocity changes may provide direct information about the characteristics of the fracture system that was produced. Production-induced microseismicity can be used to map natural reservoir fracture systems in reservoirs, and could provide information on the mechanical response of reservoirs to production-induced stress changes. Such information could improve the understanding of temporal changes in fracture permeability and provide better solutions to problems associated with reservoir compaction and subsidence.

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