Characterization of In-Situ Stress and Permeability in Fractured Reservoirs

DE-FC26-02NT15346

Goal
The purpose of this project is to develop and implement large-scale numerical models (running on parallel Linux clusters) to quantify the effects of fracture parameter variations on seismic reflection signals and in-situ stress variations on flexural modes in boreholes. These forward-modeling efforts will be used to develop data analysis and inversion routines for estimating the heterogeneous fracture distribution in fractured reservoirs from seismic and borehole field data.

Performer
Massachusetts Institute of Technology
Cambridge, MA

Results
Fracture orientation and spacing are important parameters in reservoir development. This project resulted in the development and testing of a new method for estimating fracture orientation and two new methods for estimating fracture spacing from seismic data. The methods developed were successfully applied to field data from fractured carbonate reservoirs.

Researchers have:

- Developed a new method for estimating fracture orientation from scattered energy in seismic data.
- Developed two new methods for estimating fracture spacing from scattered energy in seismic data.
- Tested these methods on numerical model data and field data from two fractured carbonate reservoirs.
- Validated fracture orientation results with borehole data from the two fields.

Benefits
This work provides a method to estimate fracture property distributions from seismic data. This information can be used in reservoir simulators to predict oil recovery and identify areas most promising for drilling.

Background
Fractured reservoirs historically have been difficult to produce because of the inability to predict fracture location, orientation, and permeability. This project addresses these problems by developing new methods to image and characterize fractures from seismic data.

Summary
Researchers developed a new method for determining the reflection and scattering characteristics of seismic energy from subsurface fractured formations. The method is

based upon observations made from 3D finite difference modeling of the reflected and scattered seismic energy over discrete systems of vertical fractures. Regularly spaced, discrete vertical fractures impart a ringing coda type signature to seismic energy that is transmitted through or reflected off of them. This signature varies in amplitude and coherence as a function of several parameters including: 1) the difference in angle between the orientation of the fractures and the acquisition direction, 2) the fracture spacing, 3) the wavelength of the illuminating seismic energy, and 4) the compliance, or stiffness, of the fractures. This coda energy is the most coherent when the acquisition direction is parallel to the strike of the fractures. It has the largest amplitude when the seismic wavelengths are tuned to the fracture spacing, and when the fractures have low stiffness. The method uses surface seismic reflection traces to derive a transfer function that quantifies the change in the apparent source wavelet before and after propagating through a fractured interval. When a 3D seismic survey is acquired with a full range of azimuths, the variation in the derived transfer functions allows identification of subsurface areas with high fracturing and determine the strike of those fractures. The method was calibrated with model data and then applied it to data from two fractured carbonate reservoirs giving results that agree with well data and fracture orientations derived from other measurements.

In addition, two approaches for estimating fracture spacing from scattered seismic energy were developed. The first method relates notches in the amplitude spectra of the scattered wavefield to the dominant fracture spacing that caused the scattering. The second uses conventional frequency-wavenumber (FK) filtering to isolate the backscattered signals and then recovers an estimate of the fracture spacing from the dominant wavelength of those signals. Both methods were tested on synthetic data and then applied to the Emilio field data with similar results. Emilio field is a fractured carbonate reservoir in the Adriatic Sea.

The first method is based on the observation that discrete, vertically aligned fracture systems impart one or more notches in the spectral ratios of stacked reflected seismic traces. This apparent attenuation is due to the azimuth-dependent scattering introduced by the fractures. The most prominent notch is located at the frequency where the P wavelength is about twice the fracture spacing. The frequency location of the notches can be used to determine the fracture spacings. The method was applied to Emilio field data, resulting in the fracture spacing estimates of about 30-40 meters.

In the second method, the seismic data in the FK domain was analyzed. In studies on the scattering effects of discrete fractures on synthetic seismic data, the presence of both forward and backscattered signals were observed. In particular, the backscattered signals (the energy that is propagating back towards the source) appear to be at a maximum when the acquisition direction is normal to the fractures and at a minimum where the direction is parallel to the fractures. In the FK domain, the backscattered energy can be separated to determine the fracture spacing from its dominant wave-length. The technique was tested on synthetic model data and then applied to the data from Emilio field, resulting in a fracture spacing estimate of about 48-53 meters.

Current Status (June 2006)
The project has been completed. Methods for estimating fracture orientation, fracture spacing, and fracture density from the seismic scattering signals have been tested with numerical modeling data and field data from two different oil fields. The results have been validated against well log measurements, other seismic analysis methods, and existing geologic models of the fields. Based on these comparisons, the methods appear to be robust and accurate. The next step is to use these seismically derived fracture parameters as the basis for improving input into flow models. This phase will be conducted in collaboration with industry partners after this project has been completed.

Funding
This project was selected in response to DOE's Oil Exploration and Production solicitation DE-PS26-01NT41048, focus area Critical Upstream Advanced Diagnostics and Imaging Technology.

Publications
Burns, D.R., Willis, M.E., Minsley, B.J., and Toksoz, M.N., Characterizing subsurface fractures from reflected and scattered seismic energy, 7th Annual SEG Japan International Symposium on Imaging Technology, 2004.

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Pearce, F., Seismic scattering attributes to estimate reservoir fracture density: a numerical modeling study, M.S. Thesis, Massachusetts Institute of Technology, Cambridge, MA, 2003.

Rao, R., Willis, M., Burns, D., Toksoz, M.N., and Vetri, L, Fracture spacing and orientation estimation from spectral analyses of azimuth stacks, expanded abstract, 75th SEG Annual Meeting, 2005.

Willis, M. E., Burns, D. R., Rao, R., Minsley, B. J., Toksoz, M. N., and Vetri, L., Spatial orientation and distribution of reservoir fractures from scattered seismic energy, Geophysics, in press, 2006.

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Willis, M., Rao, R., Burns, D., Byun, J., and Vetri, L., Spatial Orientation and Distribution of Reservoir Fractures from Scattered Seismic Energy, expanded abstract, 74th SEG Annual Meeting, 2004.

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Performer Contribution: $550,000 (37% of total)

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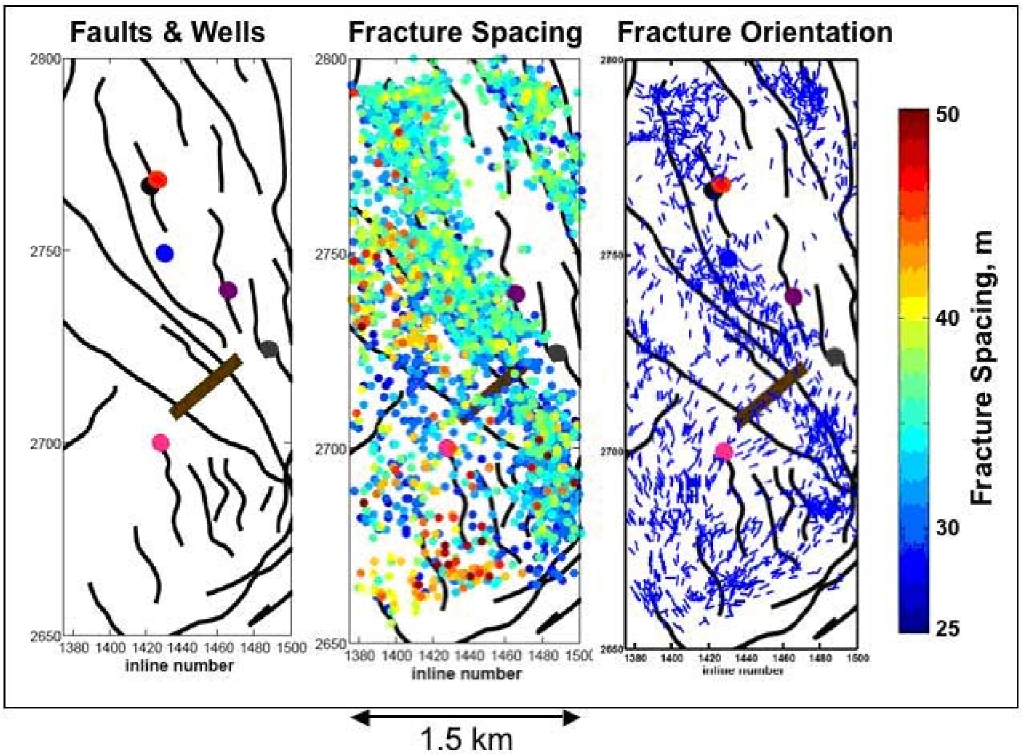

Scattered wavefield analysis of 3-D seismic data volume in a fractured carbonate reservoir (Emilio field). The left panel shows the seismic faults and well locations. The right panel shows the spatial distribution of fracture density and orientation (the direction of each line segment gives the orientation estimate). The center panel shows the estimated spacing of fracture corridors, with the spacing values given by the color bar on the far right.