

F-K Characteristics of the Seismic Response to a Set of Parallel Discrete Fractures

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Abstract

We model seismic wave propagation in a reservoir with discrete fracture zones using a finite difference scheme, which implements the Coates-Schoenberg formulation for fractured media. We study the variation of scattered energy in the direction perpendicular and parallel to the fracture strike. In the modeled data, we observe variations in the coherence of seismic energy and interference between backward and forward scattered energy. We then sorted data from the Emilio field in Italy in azimuthal gathers. These panels show a striking qualitative resemblance to the modeled data. We conclude that, in this case, a discrete representation of the fractures in the reservoir predicts the observation in the field data well. This supports the idea that fractures can cluster into fracture zones that scatter seismic energy.

We then analyze the seismic energy on a profile in the direction perpendicular to the fracture strike. First we use estimated scattered energy in a window around the target zone to estimate the spacing between large fracture zones. The scattered energy in a later time window is shown to consist of mainly P to S scattered energy. For the estimation of smaller spacings, we rely on the smaller wavelength of these converted waves to illuminate finer structure. The result of spacing estimation is not very sensitive to the time window from which we estimate the scattered energy, because, in f-k domain, the wavenumber values of the dominant backscattered energy within successive time windows are almost the same, but frequency content drops gradually. Finally we apply this analysis to field data from Emilio Oil Field, and estimate a fracture spacing of about 40 m.

1. Introduction

Fractures impact the mechanical properties of a solid, affect seismic wave propagation and control the fluid flow and production of oil and gas in reservoir. Knowledge of their distribution, orientation and physical properties are therefore of great importance for developing production and stimulation programs.

Several studies explain fracture-induced anisotropy using effective-media theory (e.g., Schoenberg and Sayers, 1995), which assume that fractures or cracks, with scales much smaller than seismic wavelength, are isolated and sparsely distributed in media. Such fractured media imparts a particular signature to 3D seismic data, an AVOaz – amplitude variation with offset in azimuth. Vetri, et al. (2003) analyzed the AVOaz of the PP and PS reflected energy to obtain information about fracture orientation, density and other properties. PS (converted) energy can be used as a tool for fractured reservoir characterization by analyzing shear wave splitting (Gaiser, et al., 2002; etc.).

However, the magnitude of seismic anisotropy in field data cannot always be well explained by effective media theory (Lynn, 2004; Zhang, et al., 2005). In some geological situations, small cracks cluster into large-scale fracture corridors or fault zones (Liu, et al., 2000), thereby causing a different seismic signature than do individual small cracks. In such cases, discrete fracture models need to be considered in order to better explain field data observation. Scattering is characteristic on the seismic response of media with large discrete fractures.

In this paper, we analyze data obtained by modeling seismic wave propagation through a medium with discrete fractures. We compare the results from receiver lines perpendicular and parallel to the fracture strike to field data acquired over a fractured reservoir, sorted in the same way. Similar experiments were done by Willis et al. (2004) and Willis et al. (2006), to validate a method that estimates dominant fracture orientation at the reservoir level from scattered energy. Given the fracture strike, fracture spacing can be estimated from the scattered field. In this paper, we describe a method to extract coherent backscattered energy and estimate fracture spacing from its frequency-wavenumber spectrum, especially how to use scattered P to S energy to illuminate finer structure. Then we will discuss the sensitivity of estimated results to the choice of the time window. At the end, a field case from Emilio Oil Field will be shown and compared to the analysis of numerical data.

2. Modeling Method

A system of aligned cracks, or fractures, can be described as an effective anisotropic medium when the dominant wavelength is long compared to the fractures scales (like width and spacing). Schoenberg and Muir (1989) derive the effective properties of a finely layered medium based on this long-wavelength equivalent medium theory. In order to accurately model wave propagation through boundaries in an elastic solid with a Finite-Difference (FD) scheme, Muir et al. (1992) extended Schoenberg and Muir’s derivation to represent a stiffness coefficient in a grid cell traversed by a boundary. Coates and Schoenberg (1995) developed this idea further to represent fractures with linear slip behavior in a FD scheme. We use this method to represent discrete fractures in our model. Our finite difference code has 2nd order accuracy in both space and time and uses a rotated-staggered-grid scheme.

3. Description of the Model

We implement fractures as a compliant zone with a thickness equal to a single cell in the finite difference grid, while we represent its properties by assigning anisotropic elastic constants to this grid cell. The lateral extent of the fractures is large compared to the wavelength. We consider a 3-layered model; the fractured layer is sandwiched between two homogeneous, isotropic layers. The source and receiver arrays are located at the surface. Figure 1 shows the schematic of the model. Detailed model parameters are listed in Table 1.

Table 1: Model Parameters

	Vp (m/s)	Vs (m/s)	Density (kg/m ³)	Nominal Wavelength (m)	
				P	S
Top Layer	2460	1230	2300	60	30
Fractured Layer*	3300	1800	2200	80	45
Bottom Layer	2460	1230	2300	60	30
Fracture Compliance	$Z_N = Z_T = 2 \times 10^{-10}$ (m/Pa)				
Source	Point Source, Ricker Wavelet, center frequency $f_0 = 40$ (Hz)				
Fracture spacing	30m				

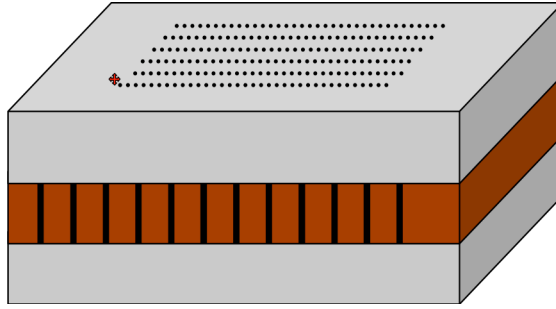


Figure 1: A fractured reservoir embedded in a three-layered model.

4. Scattering Characteristics in Time-Spatial Domain

4.1 Numerical Modeled Data

Because of the scale of the fractures, waves traveling through the fractured reservoir can be scattered strongly. Figure 2 shows the vertical velocity acquired over the 3-layered model without and with fractures in the middle layer. In each of the panels, the direct wave has been muted. As a reference, we show the result for the layered model without fractures in Figure 2a. We have identified reflection and converted energy from the top and bottom of the reservoir. Between 0.55 and 0.6 s, we observe a P wave that is reflected as an S wave at the bottom of the reservoir and transmitted at the top as a P wave.

Figure 2b shows a line collected over the fractured reservoir perpendicular to the fracture strike. Scattered energy from the fracture zones contaminates the events arriving in later time, especially for PS energy converted at the top and bottom of the reservoir. Strong scattered waves are the dominant energy in this case. Frequency-wavenumber spectra of these data show both forward and backward scattered energy and further analysis reveals that most of this energy is composed of S-waves. It is likely that interference between these forward and backward scattered waves causes the coda to appear incoherent. Figure 2c shows a line collected parallel to the fractures. This figure shows that the scattered coda is much more coherent when the line is parallel to the fractures. This suggests that energy is scattered out-of-plane from fractures parallel to the acquisition line. Even though this energy is coherent it obscures the S -reflection from the bottom of the reservoir.

4.2 Emilio Field Data

The Emilio Field is located in the Adriatic Sea, Italy and has a carbonate reservoir at a depth of 2850 m with two orthogonal sets of fractures oriented ENE and NNW (Vetri, et al., 2003). The lithology varies from clastics to evaporites above the target limestones. The data records shown in Figure 3 are from an area with NNW oriented fractures.

Figure 3 shows data sorted in the perpendicular and parallel directions to the fracture strike. Both panels show a strong reflection from the evaporites around 1.9 s. Most fractures are below the evaporites in this field. Comparing the data in Figure 3a and b with those in Figure 2b and c, we observe similar variation of coherence of (scattered) energy from the direction perpendicular to parallel to the fracture strike. In Figure 3, the profile perpendicular to fracture strike, energy within 2.0-2.4 s is so incoherent that almost no event can be identified. In contrast, in the profile parallel to fracture strike (Figure 3b), the energy is much more coherent. In particular, the top of the reservoir around 2.1 s can be identified in this figure, while in the perpendicular direction, the scattered coda is so strong that it obscures this reflection.

However, other events are visible (indicated with the red arrows) and they may be erroneously attributed to reflections. This is consistent with the observations made from the synthetic data.

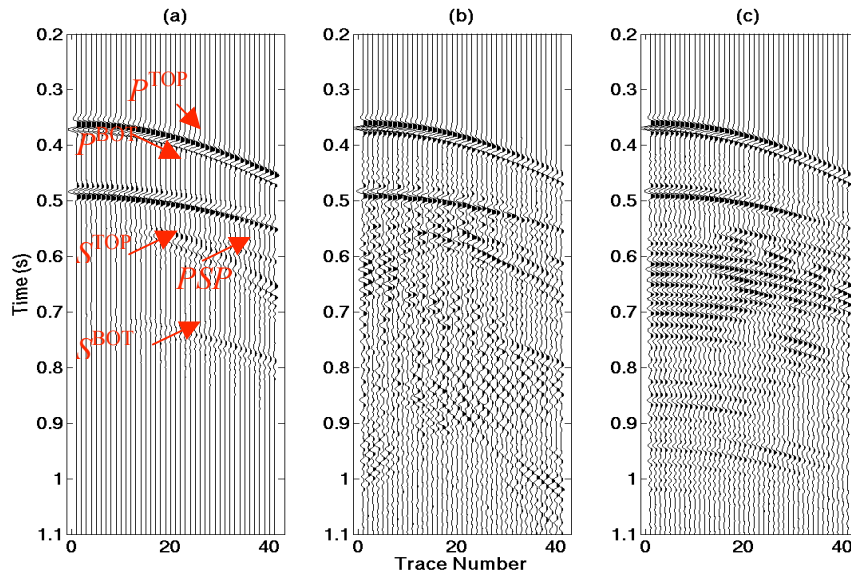


Figure 2: (a) Vertical velocity recorded in a line over the medium without fractures. (b) Vertical velocity measured in a line over the medium with fractures, perpendicular to the fractures. (c) as (b), but parallel to the fractures.

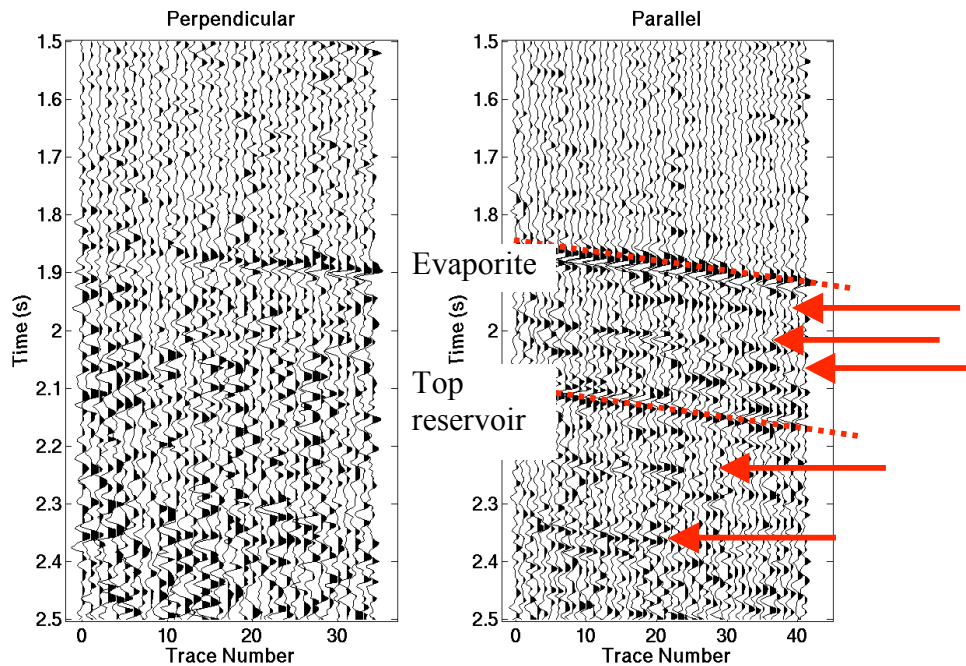


Figure 3: Example from Emilio field data. (a) Vertical velocity sorted in a gather perpendicular to the fracture strike. (b) Same, but parallel to the fracture strike.

5. Spacing Estimation in Wavenumber-Frequency Domain

In the previous section, we investigated the characteristics of scattering off discrete fractures in the time-spatial domain. We observed that there is a characteristic difference in the appearance of the scattered energy in data section sorted into different directions with respect to the fracture strike. Willis et al. (2006) use this characteristic feature of the scattered energy to determine fracture strike. In addition to knowing the orientation of fractures, the spacing between fracture corridors is also an important parameter impacting fluid mobility.

The frequency-dependent seismic responses should contain this information. Grandi et al. (2005) analyzed backscattered energy at near offset of shot-gathers acquired in the direction perpendicular to fracture strike to estimate fracture spacing in the f-k domain. Figure 4 shows the results of using the same method on the numerical modeling data generated with 30 m spacing. In this case the method has been improved by using the Local Wavefield Decomposition (LWD) method (Sacchi, 2004). Figure 4a shows a near offset shot gather perpendicular to fracture strike. Data is windowed between the PP reflected energy from the top and bottom interfaces of the reservoir to focus on estimating the scattered energy in this window (shown in Figure 4b). LWD is then applied to capture the local coherent scattered energy. Figure 4c shows the normalized energy distribution of the decomposed seismic data at each dip value p . The two main parts of the scattered energy correspond to backscattered (negative dip values) and forward scattered (positive dip values) energy. Energy above 80% at negative values of p is used to reconstruct a new seismic section as shown in Figure 4d. This new section represents the coherent backscattered energy from the fractures (thus only traveling in directions with negative p values).

The f-k content of this backscattered energy may be used to estimate fracture spacing using the following relation:

$$d = \frac{\lambda_a}{2} = \frac{v_a}{2f} = \frac{1}{2|k_a|} \quad (1)$$

where d is the estimated fracture spacing, k_a and f are the wave number and frequency of the dominant back scattered energy, v_a is an apparent velocity and λ_a is an apparent wavelength. The idea of this formulation is that the repeat pattern observed in the backscattered energy has wavenumber information that is related to fracture spacing. Inspection of snapshots of the wave field gathered during modeling reveals that seismic waves bouncing between fractures leads to resonance and modes propagation. The repeat pattern of backscattered waves received at surface referred to in this paper, might be different from the modes in the fracture zone.

As indicated in Figure 4e, the (k, f) values of the maximum energy in the spectrum are $(-0.0157$ 1/m, 78 Hz), hence the estimated fracture spacing with our equation is 31.8 m. The actual spacing between fractures zones in this model is 30 m. We have repeated this for various (larger) fracture spacings and each time the spacing estimated with our methodology was very close to the actual spacing.

We also applied the same process to data from a model with smaller -- 20 m -- fracture spacing. In this case there is almost no backscattered energy in the window within the reservoir P reflectors because the frequency content of the seismic source is too low to effectively discriminate fractures. Most energy locates at positive values of p . To overcome this limitation in resolution, we move the window to later times to capture scattering containing PS converted energy from the fractured zone. Shear waves have shorter wavelengths and therefore, a higher resolving power than P waves. Figures 5b-e compare the divergence and curl energy computed in two windows, the shallow (PP) window and a deeper (PS) window. We can see that in the shallow (red) window there is strong divergent energy (Figure 5b) but almost no curl energy (Figure 5c). In the deeper (blue) window, both divergent (Figure 5d) and curl (Figure 5e) energies are strong, the curl energy is especially large at these later times. In addition, the coherent backscattered energy in the deeper (blue) window is higher than that in the shallow (red) window. Strong PS converted waves can be generated at interfaces with high contrast (Toksöz et al., 2005), such as fracture zones, and it may therefore be more advantageous to choose scattered energy arriving later in time. By doing so, we may be

able to resolve the finer structure of the reservoir. For the case with 20 m spacing, as shown in Figure 6, a time window at later time (blue) is picked. Going through the same process as above but for new time window, spacing of 19.8 m can be estimated.

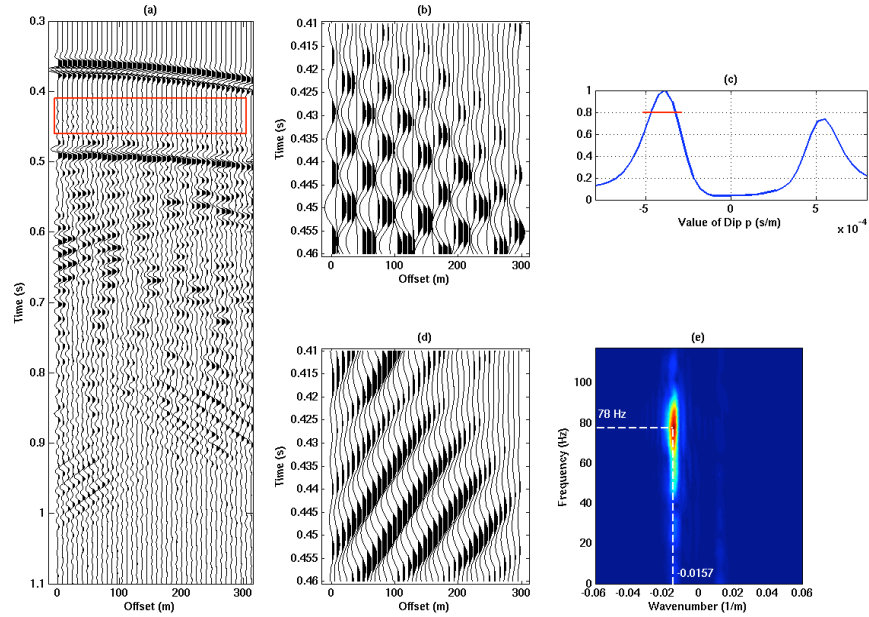


Figure 4: Determination of fracture spacing in f-k domain for model with 30 m spacing.

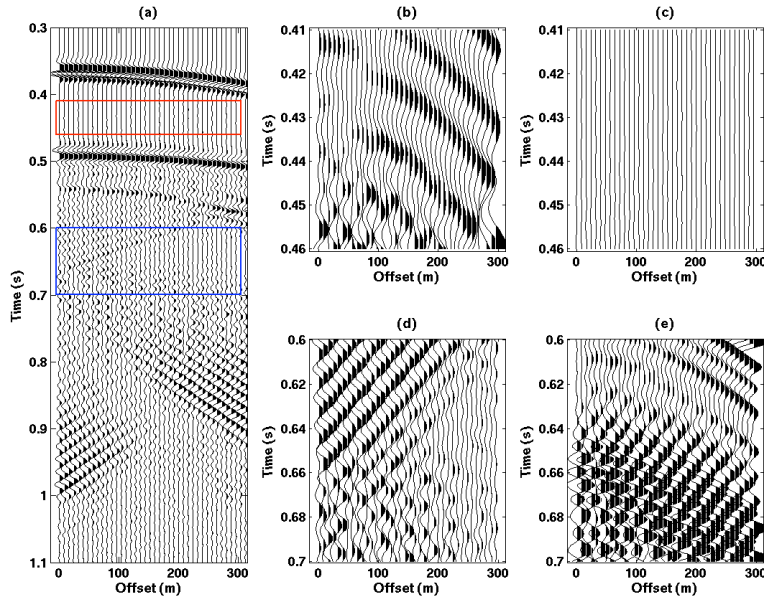


Figure 5: Divergent and curl energy in two successive time windows for model with 20 m fracture spacing. (b) and (d) are divergent energy for red and blue windows respectively; (c) and (e) are curl energy for these two windows. Data in the same time window are shown in the same scale.

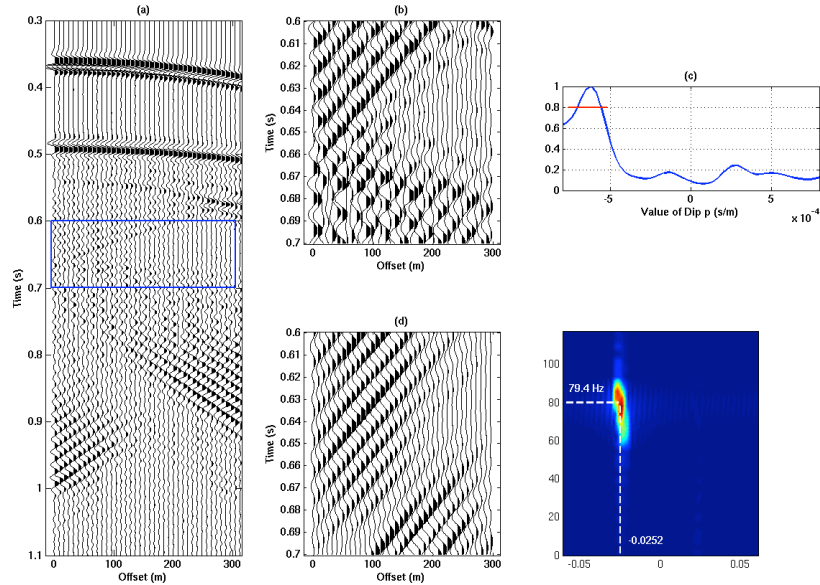


Figure 6: Determination of fracture space in f-k domain for model with 20 m spacing.

6. Sensitivity of Estimated Spacing to the Choice of the Time Window

The analysis of the previous section shows that where the window is located is a factor that might affect the results of fracture spacing estimates. Since in real data analysis it is hard to know in advance where the window should be located to capture the PP or PS scattered energy, it is important to understand the sensitivity of the results to the time windows we choose.

To test the sensitivity four windows are chosen to cover the full time series of the model data with fracture spacing of 30 and 40 m. The time windows are: 0.41-0.46s, 0.5-0.6 s, 0.6-0.7 s and 0.7-0.8 s. Figure 7 shows that distributions of backscattered energy in the f-k domain after being processed with the LWD method and f-k transformation as was done previously. For the 30 m fracture spacing case, when the window is moved from earlier to later time the location of the backscattered energy in the f-k domain migrates to lower frequencies but with almost the same wavenumber value. For the 40 m fracture spacing case, however, when the window is moved to later time the backscattered energy in the f-k domain splits into two maxima. Because the data were filtered with the LWD operators at certain dips, there two peaks are almost collinear on a line passing through the origin of f-k plot. The peaks with lower and higher frequency content correspond to the fundamental and the higher modes of the scattered energy. The fundamental mode in this case follows the same trend seen for the case with 30 m spacing. The higher mode generated might be a resonance effect of the PS energy between fractures. It should be noted that when the time window is moved down from the earliest (0.41-0.46 s, which contains only PP energy) to the latest (0.7-0.8 s, where PS energy dominates), the seismic wavelengths that are analyzed become shorter because of the PS converted energy. Therefore, PS converted energy bouncing back and forth within discrete fracture zones will generate higher modes than PP energy does. Once these different modes propagate out of the fractured layers they will interfere with each other, which contributes to the repeat pattern received at the surface.

For a given discrete fracture zone, the fracture spacing estimation should therefore not be too sensitive to the time window chosen because the wavenumber value of the backscattered energy is quite stable compared to the frequency values.

This feature of distribution of backscattered energy in f-k domain provides us a robust tool for picking wavenumber value, which tell us that if we are not sure which energy to pick in f-k domain, we could look at the energy in windows above or below to find the energy with almost the same wavenumber values, which might be the best choice for spacing estimation.

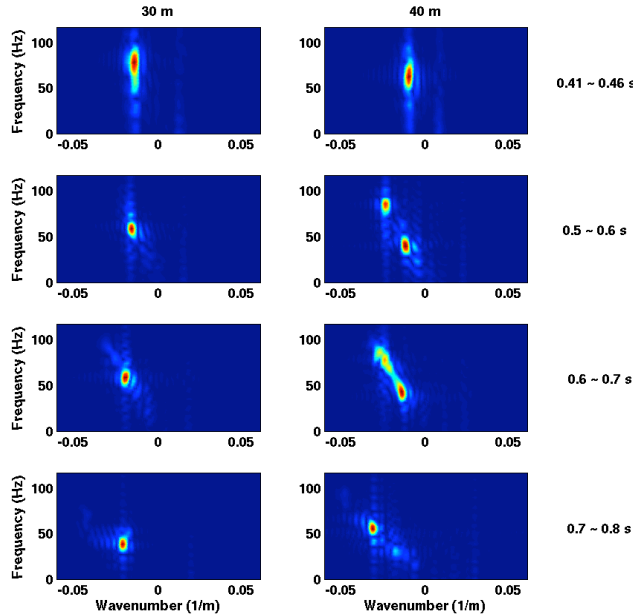


Figure 7: Distribution of backscattered energy in f-k domain with moving windows for cases with fracture spacing 30 m and 40 m.

7. Emilio Field Data Analysis

In the previous section we showed data from the Emilio Oil Field in the time-spatial domain for characterizing the azimuthal variation of scattered energy. In this section we estimate the fracture spacing from a seismic section in the direction normal to fracture strike. In practice, we would first estimate the fracture strike using a method such as developed by Willis et al. (2006), and then only consider the direction normal to the strike to estimate the spacing.

Because of the irregular spacing between receivers due to acquisition issues and sorting into azimuthal gathers, we first used the LWD method to interpolate the actual seismic profile into a regularly spaced section. We then chose four successive time windows with duration of 0.25 s (as shown in Figure 8). This decomposes the section into four windows so we can focus on different parts of the data. The first window contains reflections from above the evaporites (1.5-1.75 s), the second around the evaporites (1.75-2.0 s), the third from the reservoir (2.0-2.25 s) and the fourth window contains reflections from below the reservoir (2.25-2.5 s).

Comparing the frequency-wavenumber domain representation of the different windows, we observe that scattered energy becomes strong in the windows with energy from below evaporites. Other studies have pointed out that this is where vertical fractures come into existence. The strongest energy peaks in the window located around the reservoir.

We also note that the wavenumber values of the dominant backscattered energy in the window below the reservoir are almost the same as those in windows around reservoir and the evaporites. This again indicates that the robustness of this method with respect to the wavenumber. The spacing estimated

from the frequency-wavenumber spectrum of the backscattered energy in window between 2.0-2.25 s for Emilio Field is about 40 m.

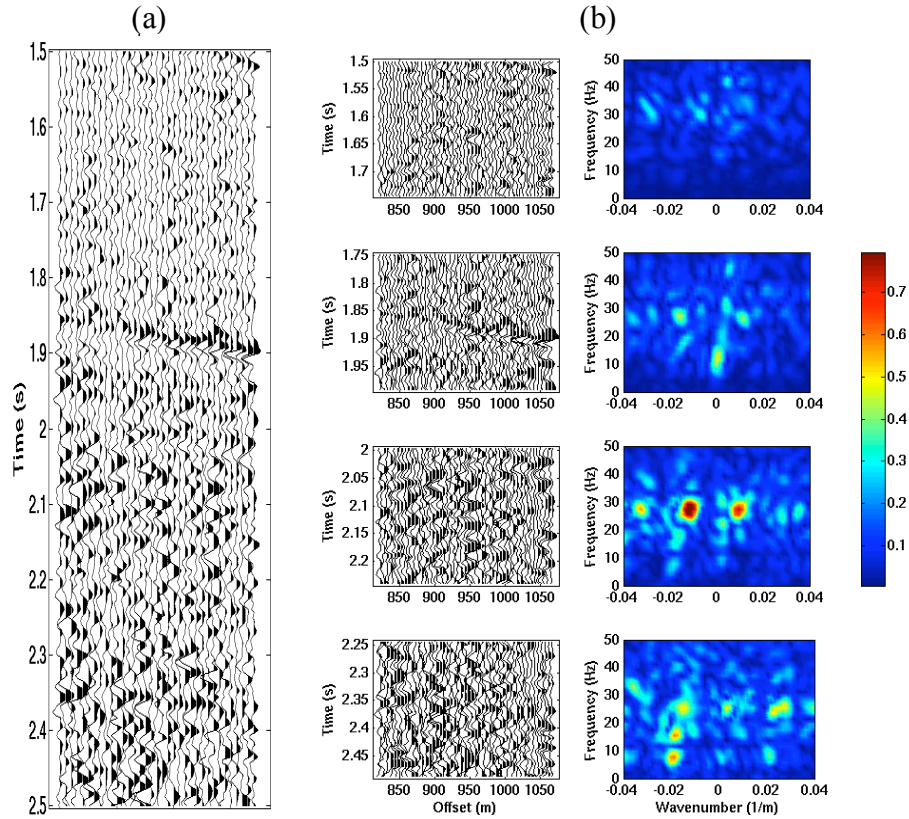


Figure 8: Energy distribution in f-k domain at different time windows for Emilio Field Data. Four successive time windows with time duration 0.25s are used. (a) Seismic section normal to fracture strike before interpolation; (b) f-k analysis of seismic data within four successive time windows after interpolation by the LWD.

8. Conclusions

We have modeled seismic-wave propagation in a medium with discrete vertical fractures, in order to explain observations made in field data. The wave field is scattered by such fractures. We observe, however, that the scattering appears differently in different directions. In the direction perpendicular to the fractures, scattered waves in the forward and backward direction interfere, causing the scattered wave field to appear incoherent. In the parallel direction the scattered wave field is more coherent. We then sorted field data acquired over a fractured carbonate reservoir in the same way. A comparison shows remarkably similar scattering patterns in directions both perpendicular and parallel to the fracture strike in the reservoir.

By considering the backscattered energy from parallel discrete large fracture zones, we can estimate the fracture spacing in the f-k domain. Strong P to S scattered energy with higher SNR can be used to illuminate finer structure of the fractured reservoir due to the shorter wavelength. We estimate the fracture spacing from the frequency-wavenumber spectrum of the scattered energy in particular time windows selected from a data section normal to the fracture strike. We show that the estimated values are quite robust as the wavenumber of the dominant energy in each time window remains stable. When the

fracture spacing is on the order of a seismic wavelength, the backscattered energy splits, which we believe is due to higher modes. This needs further investigation.

In the field data analysis, backscattered energy in successive time windows almost have the same wavenumber values in f-k domain, which is similar with what we found in numerical data analysis. This characteristic of backscattered energy in f-k domain may thus provide a robust way to estimate fracture spacing. For the Emilio data this approach yields a fracture spacing value of about 40 m.

Acknowledgements

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