

Seismic characterization of fractured reservoirs using 3D double beams

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Summary

We propose an efficient target-oriented method to characterize seismic properties of fractured reservoirs: the spacing between fractures and the fracture orientation. We use both singly scattered and multiply scattered seismic waves by fractures. Based on the diffraction theory, the scattered wave vector is related to the incident wave vector computed from the source to the target using a background velocity model. Two Gaussian beams, a source beam constructed along the incident direction and a receiver beam along the scattered direction, interfere with each other. We then scan all possible fracture spacing and orientation and output an interference pattern as a function of the spacing and orientation. If multiple targets are used, the interference pattern is spatially varying and the most likely fracture spacing and orientation can be inferred. Our method is adaptive for a variety of seismic acquisition geometries. If seismic sources (or receivers) are sparse spatially, we can shrink the source (or receiver) beam-width to zero and in this case, we achieve point-source-to-beam interference. We validated our algorithm using a synthetic dataset created by a finite difference scheme with the linear-slip boundary condition, which describes the wave-fracture interaction.

Introduction

Naturally fractured reservoirs are documented almost everywhere and most of the world's oil is from fractured reservoirs (Nelson, 2001). Exploring new reservoirs and enhancing the recovery factor for existing reservoirs are the main themes in the current fossil energy landscape. A key element is to obtain an accurate permeability field. Current reservoir simulators have evolved to a state that has already outpaced our ability to supplying a reliable and detailed permeability field. It has been shown that by incorporating a detailed permeability map the predicted well production matches better than using the up-scaled permeability field. For fractured reservoirs, fractures, voids and vugs are ubiquitous features, although small in volume but when interconnected or aligned with each other due to local tectonic stress, they may provide preferable fluid flow paths and therefore they can be more important than the matrix permeability. Reliable assessment of properties of fractures is critical for oil recovery.

The type of information we are interested in includes fracture orientation, fracture density or spacing and fracture compliance. Widely used seismic methods to

characterize fractured reservoirs include shear wave splitting (Vetri *et al.*, 2003) and the amplitude-versus-angle-and-azimuths (AVAz) for *P* waves (Ruger and Tsvankin, 1997). These methods regard the vertically fractured medium as an equivalent anisotropic medium (HTI) with a horizontal symmetry axis. This is essentially a long-wavelength approximation, which requires that there are many fractures per wavelength. Tatham *et al.* (1992) showed that at least 10 fractures per wavelength are needed for the fractured medium to be viewed as an equivalent anisotropic one. However, complex overlying geological structures will make the CDP-based method less accurate and the uneven illumination can also cause bias in the *P* wave AVAz analysis. So we need a method, which can account for complex wave phenomenon in the overlying structures. The method should also be able to extract spatially varying fracture information as well as account for the uneven seismic illumination. If the fracture spacing is close to the wavelength, one needs scattering theory to characterize the fractures (Willis *et al.*, 2006; Zhang *et al.*, 2006; Burns *et al.*, 2007; Zheng *et al.*, 2011; Chen *et al.*, 2012).

Here we develop a double-beam stacking method. The method is a phase-space method and it can provide spatially varying fracture properties for a wide range of scales. Therefore, it is localized in the spatial as well as in the angular domains, necessary for balancing the uneven illumination. Before we go into the inverse problem of finding fracture orientation and spacing, let us take a look on how fractures scatter seismic waves. For simplicity, we consider plane wave scattering by periodic structures. Scattering by non-periodic structures is a straightforward extension by windowing.

Theory and Method

Here we aim at developing a new scheme, which we call the double-beam stacking method. The method is a phase-space method and it can provide spatially varying fracture properties for a wide range of scales. Therefore, it is localized in the spatial as well as in the angular domains (Figure 1), necessary for balancing the uneven illumination. Fracture information within the interference zone (pink area in Figure 1) is extracted. The 5-dimensional seismic data can be represented as $p(\mathbf{x}_s, \mathbf{x}_g, t)$ where symbols \mathbf{x}_s , \mathbf{x}_g and t are source location, receiver location and time, respectively. The double-beam stacking is an f - k analysis for the localized data, resulting in a 10-dimensional dataset (Figure 1):

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$$B(\mathbf{x}_s^0, \mathbf{x}_g^0, t_0; \mathbf{k}_s, \mathbf{k}_g, \omega) = \int p_w(\mathbf{x}_s, \mathbf{x}_g, t) e^{i\omega t - i\mathbf{k}_s \cdot \mathbf{x}_s - i\mathbf{k}_g \cdot \mathbf{x}_g} d^2 \mathbf{x}_s d^2 \mathbf{x}_g dt \quad (1)$$

where $p_w(\mathbf{x}_s, \mathbf{x}_g, t)$ is the windowed data

$$p_w(\mathbf{x}_s, \mathbf{x}_g, t) = p(\mathbf{x}_s, \mathbf{x}_g, t) \times w_s(\mathbf{x}_s - \mathbf{x}_s^0) w_g(\mathbf{x}_g - \mathbf{x}_g^0) w_t(t - t_0) \quad (2)$$

where W_s , W_g and W_t are windowing functions for sources, receivers and time, respectively. If the source window width W_s is zero, then we have the common source gather case. Likewise, if $W_g \neq 0$, we have the common receiver gather. If $W_s \neq 0$ and $W_g \neq 0$, we get beams. t_0 is the center of the time window and it is determined as the traveltim for waves from the source beam center \mathbf{x}_s^0 to the target then reflected back to the receiver beam center \mathbf{x}_g^0 .

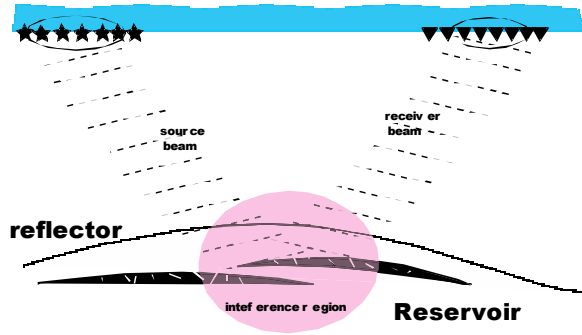


Figure 1. Interference geometry for double beams. Stars are sources and triangles are receivers. The pink ellipse indicates the interference zone within which the fracture properties can be inferred.

The form of the beams can be taken as Gaussian beams (e.g., Cerveny, 1982; Hill, 1990; Hale, 1992; Hill, 2001; Nowack, 2003; Gray and Bleistein, 2009). If the beam widths are infinite, then we have plane wave extrapolation such as the double-square-root operator, plane wave migration, offset plane waves etc. The local angle information for waves is essential to perform the illumination correction. The double-beam stacking is a phase-space method and it simultaneously possesses both space and wavenumber properties of the wavefield.

We first detect fracture spacing and orientation, which only depend on symmetry of the fractures. A good starting point is to understand wave propagation in periodic structures. Assume we have a set of vertical fractures that

are equally spaced along the x direction and let a plane wave be incident upon the fractures from above (Figure 2). The incident field upon the fractures is $\exp[i\mathbf{k}_s \cdot (\mathbf{r} - \mathbf{r}_s)]$ and the scattered field at wavenumber \mathbf{k}_g is

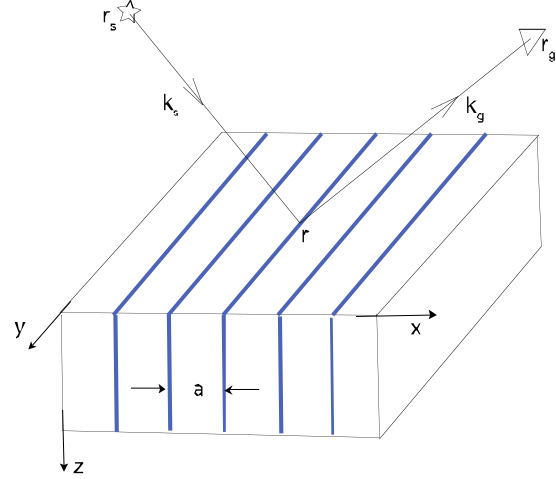


Figure 2. Schematic showing scattering by a set of parallel fracture. Fracture planes are vertical and parallel to the y direction.

Assuming the fracture system is periodic along x and the spacing between two adjacent fractures is a . By Floquet theorem (Ishimaru, 1978), the scattered wavenumbers \mathbf{k}_g are necessarily discrete and they are related to the incident wavenumber \mathbf{k}_s by

$$\mathbf{k}_g = \mathbf{k}_s + n \frac{2\pi}{a} \mathbf{e}_x, \quad n = 0, \pm 1, \pm 2, \dots \quad (3)$$

where \mathbf{e}_x is the unit direction along the x axis. Relation (3) is exact for a periodic structure and it includes both singly scattered and multiply scattered waves. For thin fractured reservoirs, singly scattered waves by fractures may not have enough energy and often they are too close in timing to the primary reflection. However, multiply scattered waves among fractures may develop large amplitudes and they often are isolated from primary reflection off the top of the reservoir. This has been observed in our numerical simulation. When $n=0$, it is the specular reflection which corresponds to the common-mid-point (CMP) stacking. Many seismic studies use CMP stacking to distinguish fracture orientation (e.g. Willis *et al.*, 2006). Since the fracture spacing a and its orientation \mathbf{e}_x are completely eliminated when $n=0$, inference of fracture spacing using CMP stacking is challenging using scattering relation (3), i.e., the fracture spacing is comparable to the wavelength

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for plane wave incidence. $n = \pm 1$ corresponds to the forward or backward scattering. For typical seismic exploration applications, $|n| \geq 2$ is less interesting because the scattered wavenumber is likely to be in the evanescent regime. It has been observed by f-k analysis that the backscattered energy is the strongest (Zhang *et al.*, 2006). So in the following numerical example, we only consider backscattering (e.g. $n = -1$). This does not exclude the utility of $n = +1$ quantum number, as it can be important when we consider P-S scattered waves. By varying the fracture spacing a and its orientation ϕ , we effectively stack the seismic data along different moveout curves using equation (1).

We propose the following efficient fracture characterization steps:

1. Pick a target at depth and a frequency;
2. From the seismic source beam center, we trace a seismic ray to the target and compute the incident slowness vector;
3. Pick a fracture spacing a and orientation ϕ ;
4. Based on the incident slowness vector, the local velocity, and a , we can compute the outgoing slowness vector and trace the ray from the target point all the way up to the recording depth and the emergent point is the receiver beam center; the traveltime from the source to the target and then to the receiver is also computed;
5. Now we perform double-beam stacking for a time window around the central ray arrival time and obtain a stacking amplitude for this pair (a, ϕ) ;
6. Pick another (a, ϕ) , and repeat from step 3 until all the values (a, ϕ) are scanned;
7. We can also pick a different source beam center and repeat from step 2 until we exhaust all the available source beams.

Example

To validate our idea of using our double-beam stacking to infer fracture spacing and orientation, we test our methodology on a synthetic dataset. The 3D model (Figure 3) contains a reflecting interface, which separates the upper and lower media. In the upper medium, $V_p = 2500$ m/s, $V_p/V_s = 1.6$ and $\rho = 2000$ kg/m³; and in the lower medium $V_p = 4000$ m/s, $V_p/V_s = 1.6$ and $\rho = 2300$ kg/m³. The source time function is a Ricker wavelet with a central frequency of 40 Hz. The receivers are in a rectangular domain on the surface and they range from $x = 200$ m to $x = 2300$ m with 20m spacing and from $y = 200$ m to

$y = 3500$ m with 20m spacing. Six sets of vertical fractures are placed in the lower medium in the depth interval between 1300m to 1380m. The six fracture sets have varying fracture spacings and orientations.

To model seismic wave propagation through fractured media, we adopt the linear-slip boundary condition proposed by Schoenberg (1980): the traction is continuous across the fracture surface but the displacement is discontinuous. The normal (or tangential) displacement discontinuity is related to the normal (or tangential) traction by a normal (or tangential) compliance. This validity of this boundary condition to model wave-fracture interaction has been supported by a series of laboratory experiments (Pyrak-Nolte and Cook, 1987). In the numerical simulation, we use Coates and Schoenberg's (1995) finite-difference effective medium method to simulate fractures with linear-slip boundaries. In this model, the thickness of fractures is assumed to be infinitely small and their elastic properties are determined by the fracture compliance. In our simulation, the fracture tangential and normal compliances are equal to 10^{-9} m/Pa, which represents gas-filled fractures. As a proof of concept, we pick two targets at depth 1320m. The target A is at $(x, y) = (1750\text{m}, 1700\text{m})$ and the target B is at $(1750\text{m}, 750\text{m})$. The receiver beam width is 150m and the source beam width is also 150m. The source beam center is at $(1200\text{m}, 800\text{m})$. In the double beam stacking, we use frequency of 60 Hz. The fracture spacing is the same ($a=50\text{m}$) for both localities. The orientation of the fracture symmetry axis at the target A is 20 degrees and at target B it is 0 (or 180) degrees with respect to the x -axis. Our double-beam method is able to recover the fracture spacing and orientation for target A (Figure 4a) and target B (Figure 4b).

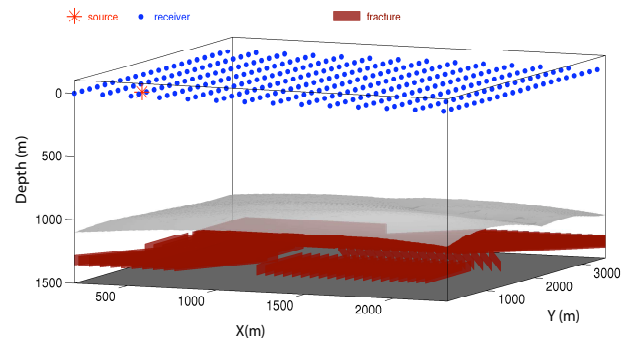


Figure 3. Fracture model in the numerical example.

Conclusions

We have introduced an efficient 3D *double-beam stacking* method, in which the interference of two beams produces a

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characteristic pattern that depends on fracture spacing and orientation. The method is a phase-space method where point-source field and the plane-wave field are special cases. The method is adaptive for all kinds of acquisition geometries. We calculate the incident wave vector from the source to the target and then compute the backscattered wave vector based on the scattering theory and then stack the backscattered seismic data. Our method includes multiply scattered seismic waves and it works best when the wavelength and the fracture spacing are comparable. For typical seismic frequency bandwidths (10s Hz) and velocities (1000s of m/s), our method should be able to infer fracture spacing information when spacing is on the order of 10s of meters for P-to-P scattering. However, if we use P-to-S scattering, much smaller spacing can be recovered and the stacking technique is same as for the P-P case.

Acknowledgments

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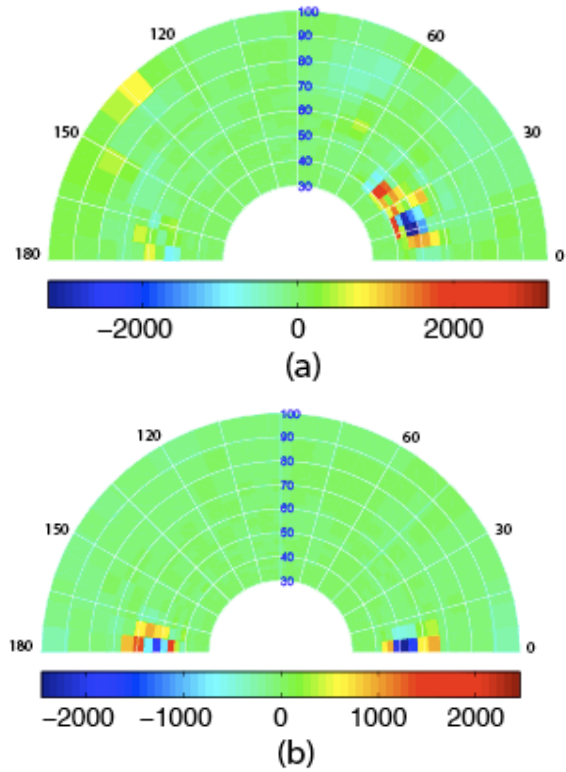


Figure 4. Double-beam stacking results at target A (a) and B (b) as a function of fracture spacing (radius; blue numbers in meters) and orientation. The orientation is for the symmetry axis of the fractures measured counter-clockwise with respect to the x-axis.

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