3D Seismic Characterization of Irregularly Distributed Fractures in Unconventional Reservoirs

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Summary

Obtaining information of the spatial distribution of subsurface natural and induced fractures is critical in improving the production of geothermal or hydrocarbon fluids. Traditional seismic characterization methods for subsurface fractures are usually based on the effective anisotropy medium theory, which may not be true in reality where the fracture distribution is non-uniform. In this abstract, we propose to test the double-beam method to characterize non-uniformly distributed fractures that are commonly observed in the unconventional reservoirs. We built a 3D layered reservoir model and the reservoir layer is geometrically irregular and it contains a set of randomly spaced fractures with spatially varying fracture compliances. We used an elastic full-wave finite-difference method to model the wavefield where we treat the fractures as linear-slip boundaries and the recorded data include all elastic multiple scattering. Taking the surface seismic data as input, the double-beam method forms a focusing source beam and a focusing receiver beam toward the fracture target. The fracture information is derived from the interference pattern of these two beams, which gives fracture orientation, fracture spacing, and fracture compliance as a function of spatial location. The fracture orientation parameter is the most readily determined parameter. The beam interference amplitude depends on both fracture spacing and compliance in a local average sense for random fractures. The beam interference amplitude is large when there are dense fractures or the compliance value is large, which is important in the interpretation of the fluid transport properties of a reservoir.

Introduction

Knowledge about the geometry and mechanical properties of subsurface fractures can be used to probe the regional stress state and to control potential movement of fluids. This is critical to interpret the regional tectonic evolution history and guide the drilling and hydraulic fracturing to further improve the production of geothermal or hydrocarbon energy (Hubbert and Willis 1957, Olson 1989, Barton et al. 1995, Nelson 2001, Montgomery and Smith 2010). Fractures are common in geology and can be observed in multiple geological settings. We can directly observe fractures at exposed geological outcrops (e.g., Nelson 2001). For subsurface fractures, we can use seismic waves to detect their distribution and use this information to understand fluid flow (e.g., Vinegar et al. 1992, Schoenberg and Sayers 1995, Bakulin et al. 2000b, a, c, Petrovitch et al. 2013, Petrovitch et al. 2014, Kang et al. 2016).

The aligned fractures in the reservoir would produce anisotropy and result in the reflected/transmitted P and S wave amplitudes varying with azimuth angle. This feature can be utilized to detect subsurface fractures (e.g., Rüger and Tsvankin 1997, Lynn et al. 1999, Perez et al. 1999, Thomsen 1999, Stewart et al. 2002, 2003, Vasconcelos and Grechka 2007, Far et al. 2014). Shear-wave splitting (e.g., Crampin 1985, Tatham et al. 1992, Vetri et al. 2003, Long 2013, Verdon and Wustefeld 2013) is also widely used to characterize the anisotropy which is thought to be introduced by the existence of fractures. All these anisotropy-related methods are based on the effective medium theory (EMT), which assumes that the distribution of fractures is spatially uniform (e.g., David et al. 1990). However, in reality, natural fractures are usually observed to have multiple spatial scales and are distributed and embedded in reservoirs with various geometries (Gale et al. 2007). Fang et al. (2017) showed that fractures with a random spacing can form fracture clusters and the clusters can generate strong multiply-scattered seismic waves that could mislead the interpretation of reflected P-wave AVOAz results (amplitude variation with offset and azimuth for the reflected waves). On the other hand, waves that are diffracted from fractures can also be used to image fracture characteristics (e.g., Willis et al. 2006, Landa et al. 2008, Klokov and Fomel 2012, Fang et al. 2013, Schoepp et al. 2015, Protasov et al. 2016, Silvestrov et al. 2016). However, these imaging-based methods have limited capability in distinguishing multiple sets of fractures.

Different from the anisotropy-related and imaging-based methods, Zheng et al. (2013b) proposed to utilize the waves that are multiply scattered among fractures to characterize fractures. For the sake of brevity, we refer the method as the double-beam method (*db* for short). The *db* method can effectively invert for the fracture orientation, fracture spacing between neighboring fractures, and fracture compliance of the subsurface target in the fractured layer. This method is effective in producing information on multiple coexistent fracture networks with constant fracture spacing at a flat fractured layer. In the real world, fracture orientation may be consistent with in situ stress but the spacing between neighboring fractures could be randomly distributed in a fractured reservoir layer (e.g., Ramsay and Huber 1987, Narr and Suppe 1991, Nelson 2001). In this paper, we will evaluate the ability of the *db* method for characterizing random fractures. We will test this fracture characterization method by using a 3D synthetic dataset generated by an elastic finite-difference method (e.g., Schoenberg 1980, Coates and Schoenberg 1995, Fang et al. 2013, Zheng et al. 2013a, Zheng et al. 2013b, Zheng et al. 2016, Fang et al. 2017), in which fractures are modeled as linear slip boundaries (Schoenberg 1980)

Methodology

Fracture characterization by the *db* method

Zheng et al. (2013b) proposed the *db* method as a seismic fracture characterization tool by focusing a source-beam and a receiver-beam from the surface to a target zone in a fractured reservoir. The essence of the *db* method is based on multiple scattering of a local incident plane wave upon a set of fractures (Figure 1). The scattering wavenumber $\mathbf{k}^r$ and the incident wavenumber $\mathbf{k}^s$ are not independent but they are related by the local fracture network geometry around the target (Zheng et al. 2013b):

$$\mathbf{k}_T^r = \mathbf{k}_T^s + n\frac{2\pi}{a}\hat{\varphi}, \quad n = 0, \pm1, \pm2, ... \tag{1}$$

where $\mathbf{k}_T^r$ and $\mathbf{k}_T^s$ are the horizontal components of $\mathbf{k}^r$ and $\mathbf{k}^s$, respectively; $\hat{\varphi}$ is the fracture orientation defined as a unit vector perpendicular to the fracture plane and a is the fracture spacing (Figure 1).

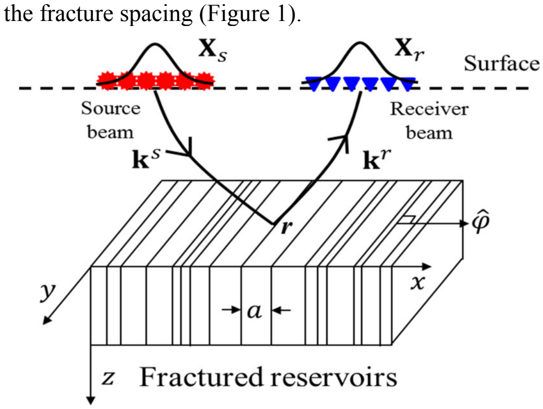


Figure 1. Schematic showing fracture characterization by using the db method. Stars and triangles represent sources and receivers, respectively. a is the local fracture spacing between two neighboring fractures around the target location r. The fracture planes are vertical and randomly distributed. $\hat{\varphi}$ denotes the normal direction to the fracture plane.

This formula links the wavenumbers of incident and scattered beams with the fracture orientation and spacing. For applying the db method on the surface seismic data, we choose n=-1 which is a special case in the multiple scattering. If the reservoir layer is dipping, we can adopt a local coordinate transformation (Hu and Zheng 2017).

Numerical examples

To test the *db* method for characterizing fractures with random spacing and spatially varying fracture compliance in a reservoir layer with lateral variations in its depth, we created a 3D velocity model with a non-flat fractured reservoir layer (Figure 2). A synthetic seismic dataset was generated using a 3D elastic staggered grid finite-difference method (Fang et al. 2013, Fang et al. 2017). We adopted the linear-slip boundary conditions to represent fractures (Schoenberg 1980, Schoenberg and Douma 1988). The 3D model contains 5 layers (Figure 2). The fracture network is embedded within a layer that is geometrically contorted in depth varying from 500 to 400 m (Figure 2b). There are 29 fractures with spacing varying randomly from 40 to 120 m parallel to the x-direction (). The fracture spacing follows a uniformly random distribution, which has been widely observed in the field (e.g., Bonnet et al. 2001). The histogram of the fracture spacing is shown in Figure 3b. The fracture compliance is set to be randomly distributed in space with values changing from 2.5×10^{-10} to 10^{-9} m/Pa. The normal and tangential fracture compliances are assumed to be the same.

We select six target locations on top of the reservoir layer along the y-direction to probe fractures (Figure 3). These *db* images with picked *bright spots* are shown in Figure 4. The fracture orientations are all correctly identified as 90° (Figure 4). Figure 5 illustrates the relation between the beam amplitude and the distribution of fractures for the six targets. In Figure 4a, 4b and 4d, we can observe one "bright spot" which indicates the inverted fracture spacing of the fracture set that is closest to the target center. In Figure 4c, 4e and 4f, we can distinguish two *bright spots,* which indicate two fracture spacing values near the center of the target. For randomly spaced fractures, the *db* method is still capable of resolving both fracture spacing and fracture orientation.

Figure 6a shows the local average of the compliance field around all 441 targets. To determine this field for each target, we use a Gaussian spatial window to window the model compliance field and then transforms the windowed field into the wavenumber spectral domain. The Gaussian window size corresponds to the Gaussian beam width (100 m) used in the *db* method. In the local fracture wavenumber spectrum, we picked the strongest amplitude as the approximate local averaged fracture compliance. Figure 6b shows the inverted compliance map using the *db* method. We see that the patterns of the model local compliance map (Figure 6a) and the *db* inverted compliance map (Figure 6b) are similar. Several key observations must be stressed here. First, these targets with dense fractures and large fracture compliance correspond to large amplitudes in the beam image, such as around (x=1400,y=1400) m. Second, the *db* method yields amplitude of σ which approximates the spectral amplitude of the windowed compliance field around the target. Our previous work (Zheng et al., 2013a) showed a one-to-one correspondence between the local fracture compliance and the *db* amplitude. But that is for regularly spaced fractures. Here we consider irregularly spaced fractures, as a result, discrepancies are expected. The amplitude of the peak in the *db* output should be roughly proportional to the fracture compliance. Overall, the *db*-inverted relative fracture compliance map (Figure 6b) recovers major spatial patterns of the subsurface fractures. The fracture orientation is the most robustly inverted parameter regardless of whether the fracture spacing is regular or not. The *db* amplitude depends on both the fracture density as well as the fracture compliance. A set of densely distributed fractures with small compliance values may yield the same *db* amplitude as a system containing fewer but more compliant fractures.

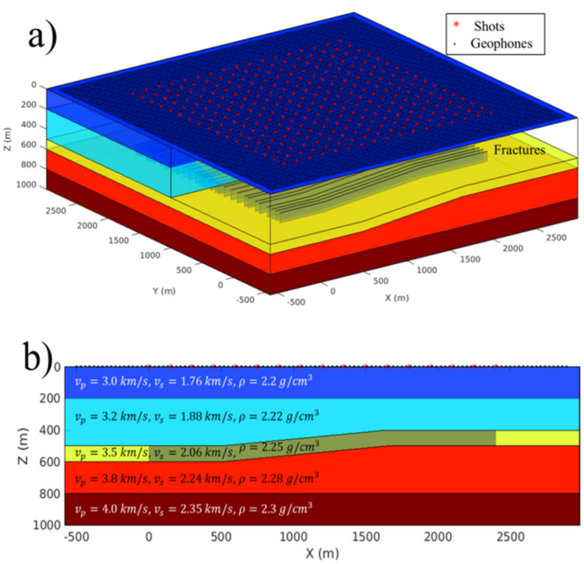


Figure 2. A 5-layered model with randomly spaced fractures in a non-flat reservoir layer. The fractured reservoir is the third (yellow) layer. The fracture planes (gray) are vertical and bounded within the third layer and they are trending along the x-axis. The fractured layer forms a ramp, having a 5° dipping along the x-direction from x=500 m to x=1643 m with depth of the upper surface ranging from 500 to 400 m. a) is the 3D view of the model. The black and red dots on the surface represent the location of receivers and sources, respectively. b) is a cross-sectional view of the model with elastic parameters: *P*-wave velocity (v_p), *S*-wave velocity (v_s) and density (ρ) shown in each layer.

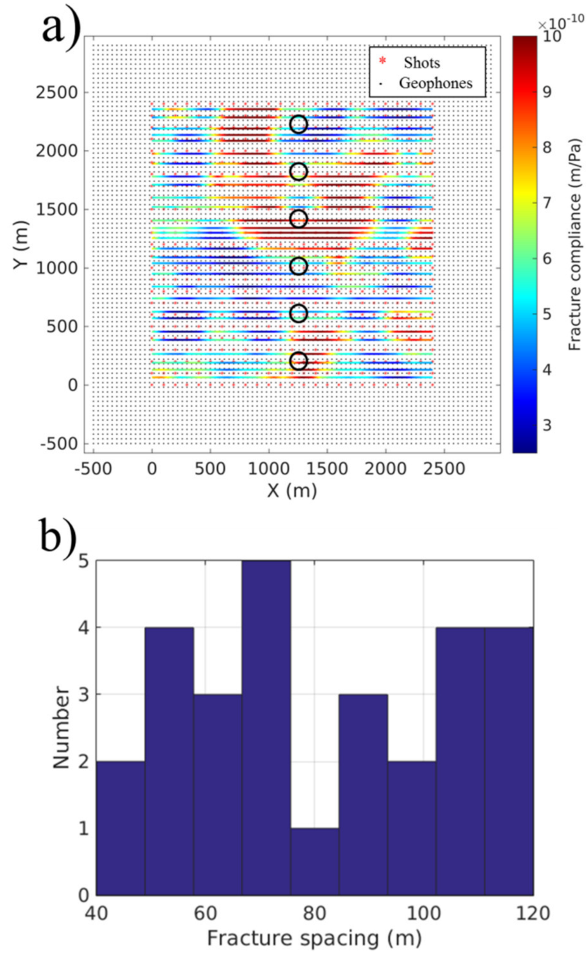


Figure 3. (a) Map view of the seismic acquisition geometry (black dots: receivers; red dots: sources) and the spatial distribution of 29 randomly spaced fractures with nonuniform fracture compliance. The fracture spacing varies randomly from 40 to 120 m while the fracture compliance varies from 2.5×10^{-10} to 10^{-9} m/Pa, indicated by color. The shot spacing is $dx_s = dy_s = 100$ m while the receiver spacing is $dx_g = dy_g = 40$ m. There are 625 shots and 7396 receivers. Six black circles indicate the spatial locations of six selected subsurface fracture targets from (1200 m, 200 m) to (1200 m, 2200 m). These subsurface targets are on the top surface of the reservoir layer. (b) Statistics of the random fracture spacing.

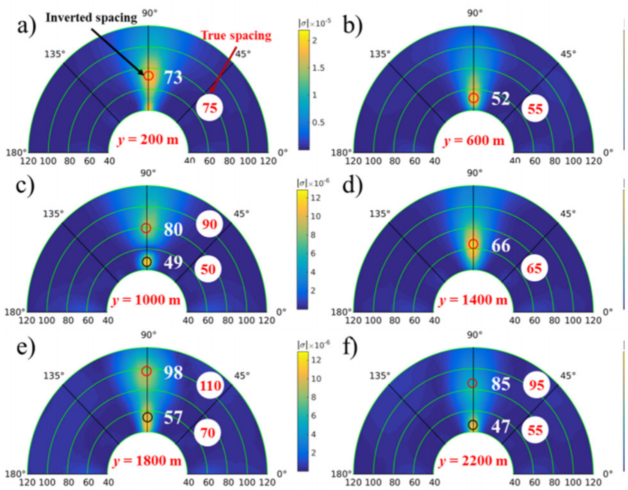


Figure 4. (a) to (f) are *db* images for different targets (marked as blue spots in Figure 3a) from (x=1200 m, y=200 m) to (x=1200 m, y=2200 m) with a beam width of 100 m at 45 Hz.

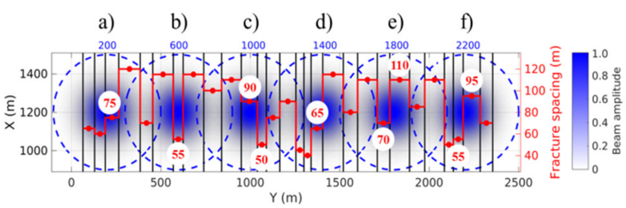
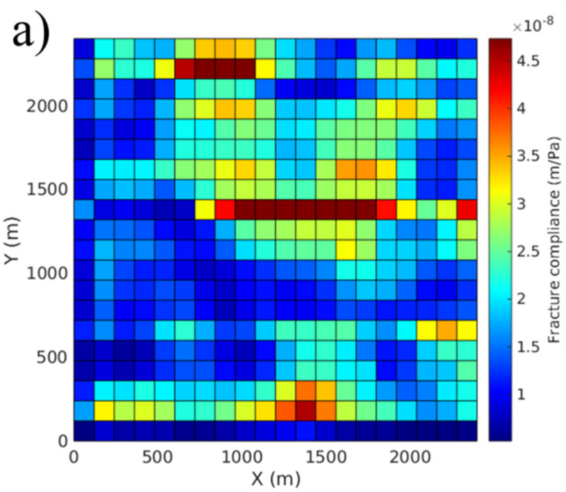


Figure 5. Map of the fracture distribution, fracture spacings in the model and *db* inverted fracture spacing found in Figure 4. For each fracture target, the solid red line indicates the fracture spacing in the model while the red numbers labeled around the target center are the fracture spacings of the model for each target.



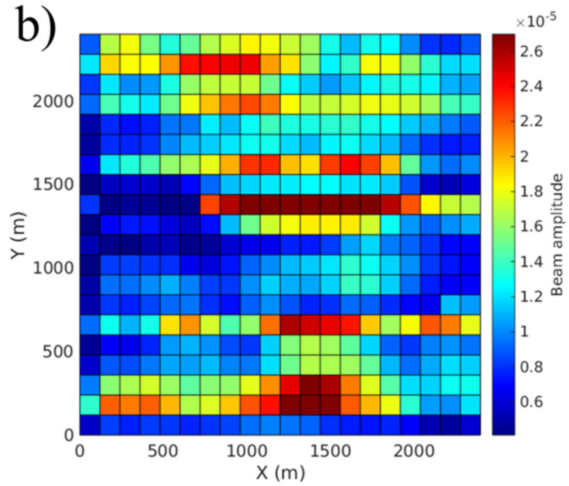


Figure 6. (a) The local compliance map for all 441 subsurface targets determined from wavenumber spectrum of windowed compliance field. (b) The inverted compliance map (related to the beam amplitude) for all targets using the *db* method at frequency of 45 Hz with beam width of 100 m.

Conclusions

We used full elastic modeling to investigate the ability of the *db* method for inferring fracture parameters in a unconventional reservoir model with a randomly spaced fracture network in a non-flat reservoir layer. All fractures trend in the same direction but their spacing and compliance follow random distributions. We use the *db* method based on the interference of two focusing Gaussian beams at the target to invert for the fracture parameters (orientation, spacing, and relative fracture compliance) around a selected target in the reservoir. In the *db* method, the fracture orientation parameter is the most readily determined parameter that is critical in horizontal drilling and production development. The second output of the *db* method is the fracture spacing within a target zone. If the fractures are not uniformly distributed around the target, the *db* method may give multiple spacings. The third output of the *db* method is the *db* image amplitude. In the *db* image, the high amplitude indicates large total compliance (combined effect of fracture density and individual fracture compliance) while low amplitude corresponds to small total compliance. As such, the *db* amplitude is useful in assessing the fluid transport properties of the field.