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Joint evaluation of fracture azimuth by electromagnetic wave and elastic wave

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ABSTRACT

With the multi-wave, multi-component seismic wave exploration, one can apply the anisotropy of fracture media to analyze the attributes of the fracture media, including the fracture azimuth. In the meantime, the techniques of full-polarimetric electromagnetic wave, including full-polarimetric borehole radar, can also be used to analyze the attributes of the fracture. However, the analysis precision of both the multi-component elastic wave exploration and full-polarimetric electromagnetic wave exploration is prone to the influence of noise and other factors. So far, some researchers have conducted studies on the joint inversion of electromagnetic waves and seismic waves. This paper develops evaluation techniques of fracture azimuth by electromagnetic wave, elastic wave, and joint analysis of coincident elastic reflection and electromagnetic data. Firstly, based on the shear wave splitting of elastic waves, this paper develops a statistical analysis technique which applies Pearson correlation coefficient to count and analyze the azimuth angle of fracture. Secondly, based on the information of electromagnetic polarization rotated by fracture, this paper develops a statistical analysis method of full-polarimetric electromagnetic waves which applies the maximum amplitude ratio between the co-polarization and cross-polarization to analyze the azimuth angle of fracture. Furthermore, based on the analysis result of the elastic wave and full-polarimetric electromagnetic wave, this paper develops a joint analysis technique which adopts the standard deviation. At last, authors in this study conduct joint detection experiments on the coincident fracture medium by using the ultrasonic and full-polarimetric ground penetrating radar. The experimental result indicates that both single geophysical methods are capable of analyzing the fracture azimuth angle, but the joint analysis is more accurate.

1. Introduction

Crampin (1981, 2005, 2008) showed the observations of anisotropy in the Earth's crust. The most diagnostic feature of azimuthally-aligned anisotropic wave propagation is shear-wave splitting, where shear-waves split into differently polarized phases which are azimuthally-aligned and travel at different velocities. Azimuthally-aligned shear-wave splitting was also positively recognized in seismic reflection surveys, and vertical seismic profiles in oil exploration surveys (Helbig and Thomsen, 2006; Mueller, 1991). Microfracture media can be approximated as an anisotropic medium, so microfracture geometry can be monitored by variations in shear-wave splitting. Thomsen (1988, 1999) discussed a derivation of the tensor rotation algorithm of shear-wave data into its principal time series, i.e., those two time series which each contain only one of the two split shear wave modes (fast and slow). Based on this kind of algorithm, it is possible to evaluate the fracture attributes by the shear-wave splitting.

In the meantime, exposed to the electromagnetic wave, the object responds not only in respect of amplitude, phase and frequency, but also of polarization effect. After the electromagnetic wave interacts with the surface of the object, the object would make the rotations of different degrees to the electromagnetic wave polarization. By analysis and processing of the polarization information, the attribute of the object can be recognized. With the advancement of applying polarization information, the full-polarimetric technology is developing rapidly (Lee et al., 2001). Zhou et al. (2004) introduce the polarimetric technology into the ground based system, applying the ground based polarimetric synthetic aperture radar (SAR) system to do the study in the environmental area. In recent years, the ground penetrating radar (GPR) has begun to absorb the full-polarimetric technology. As a result, the full-polarimetric GPR system and its signal analysis technology have been thus developed and have begun to be applied to the exploration test of subsurface objects (Chen et al., 2001). The borehole radar, with the upgraded full-polarimetric detecting instrument and corresponding

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full-polarimetric signal processing and analyzing technology, is applied to the analysis of subsurface fracture roughness and other attributes (Miwa et al., 1999, 2000; Sato and Takeshita, 2000; Zhao and Sato, 2006, 2007, 2008).

To achieve fracture attributes with high quality, it might be a good way to combine information provided by models obtained from different geophysical data. Recently, some researchers have begun to carry out joint analysis of electromagnetic and seismic wave. Linde et al. (2008) showed a joint inversion of crosshole radar and seismic traveltime data, and the joint inversion could improve the resulting models as indicators of geologic variability. Irving and Holliger (2010) showed an inversion of seismic and GPR reflection data for the geostatistical properties of the probed subsurface region. Tronicke et al. (2011) proposed a particle swarm optimization (PSO)-based inversion strategy to jointly invert GPR and P-wave seismic traveltimes from co-located crosshole experiments, and demonstrated that joint inversion is capable to solve rather complex geophysical inverse problems. Carpentier et al. (2012) showed a combined interpretation of coincident high-resolution seismic reflection and GPR data acquired across the northwest Canterbury Plains.

We try to improve the accuracy of fracture azimuth evaluation by a combined analysis of coincident elastic reflection and full-polarimetric electromagnetic data. Before this, we developed evaluation algorithms of fracture azimuth based on the shear-wave splitting and full-polarimetric electromagnetic data, respectively. Finally, these methods were applied to experimental data.

2. Methodology

2.1. Evaluation of fracture azimuth by elastic wave

When there is one or more fractures in the subsurface media, the shear wave goes through the fracture in an oblique crossing angle and is separated into the fast shear wave, $S_1(t)$, which is parallel with the direction of the fracture, and slow shear wave, $S_2(t)$, which is vertical to the fracture. Therefore, $S_x(t)$ and $S_y(t)$ received and recorded by the X-component of the detector, along the measuring line, and Y-component of the detector, vertical to the measuring line, would contain the components $S_1(t)$ and $S_2(t)$. Therefore, after the recorded X-component and Y-component are rotated in a certain angle, θ, in the coordinate system, we can get the following equation set,

$$\left.\begin{aligned} S_1{'}(t) &= S_x(t)\cos\theta + S_y(t)\sin\theta \\ S_2{'}(t) &= -S_x(t)\sin\theta + S_y(t)\cos\theta \end{aligned}\right\}. \tag{1}$$

Since the fast shear wave, $S_1(t)$, and slow shear wave, $S_2(t)$, are highly correlated to each other, we can judge whether they are well separated by identifying the similarity between $S_1{'}(t)$ and $S_2{'}(t)$ acquired by Eq. (1). When $S_1{'}(t)$ and $S_2{'}(t)$ are similar to each other to the maximum, we regard them as $S_1(t)$ and $S_2(t)$, respectively, and the angle θ is the included angle between X-direction and direction of $S_1(t)$, i.e. the azimuth of the fracture.

We introduce the Pearson correlation coefficient, i.e.

$$r = \frac{\sum V_1 V_2 - \frac{\sum V_1 \sum V_2}{N}}{\sqrt{\left(\sum V_1{}^2 - \frac{\left(\sum V_1\right)^2}{N}\right)\left(\sum V_2{}^2 - \frac{\left(\sum V_2\right)^2}{N}\right)}} \tag{2}$$

to measure the similarity between $S_1{'}(t)$ and $S_2{'}(t)$. In the Eq. (2), V_1 and V_2 are two vectors with the equal length and N is the number of vector elements. When the time difference between the fast and slow shear waves is $\Delta\tau$, let $V_1 = S_1{'}(t+\Delta\tau)$ and $V_2 = S_2{'}(t)$, then we can get the following equation,

$$\begin{aligned} r(\theta,\Delta\tau) = {} & \Bigg\{\sum\Big[S_x(t+\Delta\tau)\cos\theta + S_y(t+\Delta\tau)\sin\theta\Big]\Big[-S_x(t)\sin\theta + S_y(t)\cos\theta\Big] \\ & -\frac{\sum\Big[S_x(t+\Delta\tau)\cos\theta + S_y(t+\Delta\tau)\sin\theta\Big]\sum\Big[-S_x(t)\sin\theta + S_y(t)\cos\theta\Big]}{N}\Bigg\} \\ & /\Bigg\{\sum\Big[S_x(t+\Delta\tau)\cos\theta + S_y(t+\Delta\tau)\sin\theta\Big]^2 \\ & -\frac{\left(\sum\Big[S_x(t+\Delta\tau)\cos\theta + S_y(t+\Delta\tau)\sin\theta\Big]\right)^2}{N}\Bigg\}^{1/2}\Bigg\{\sum\Big[-S_x(t)\sin\theta + S_y(t)\cos\theta\Big]^2 \\ & -\frac{\left(\sum\Big[-S_x(t)\sin\theta + S_y(t)\cos\theta\Big]\right)^2}{N}\Bigg\}^{1/2}. \end{aligned} \tag{3}$$

In here, N stands for the time window length of the signals of $S_x(t)$ and $S_y(t)$. Given different angles, θ, and time differences, $\Delta\tau$, we can acquire different correlation coefficients through calculation by Eq. (3). Then we can search the value of θ corresponding to the maximum correlation coefficient, which is the azimuth of the fracture.

Each record can be used to work out an azimuth, which is projected onto the polar coordinates. In 0 ~ 2π, the polar coordinates are divided into small segments of equal sizes. Then, the number of angles falling into each segment is counted. With the number as the radius of the segment, the angle rose diagram can be obtained. In the diagram, the angle corresponding to the segment with the longest radius is the optimized azimuth in the statistics.

2.2. Evaluation of fracture azimuth by full-polarimetric electromagnetic wave

First of all, we apply the numerical simulation data to build a fracture azimuth identifying template. Then, we compare the actually measured data with the template to gain the fracture azimuth. The model, shown in Fig. 1, contains vertical fractures parallel to each other in the homogeneous medium. The 3D finite different time domain (FDTD) algorithm is applied to undertake the numerical simulation. The central frequency of the excitation source is the 1 GHz Ricker wavelet. The 360° full-azimuth co-polarimetric and cross-polarimetric measure is implemented, with the angle between the initial measuring line and the fracture being 0°.

The result of numerical simulation is shown in Fig. 2. In the figure, the horizontal ordinate is the included angle between the fracture

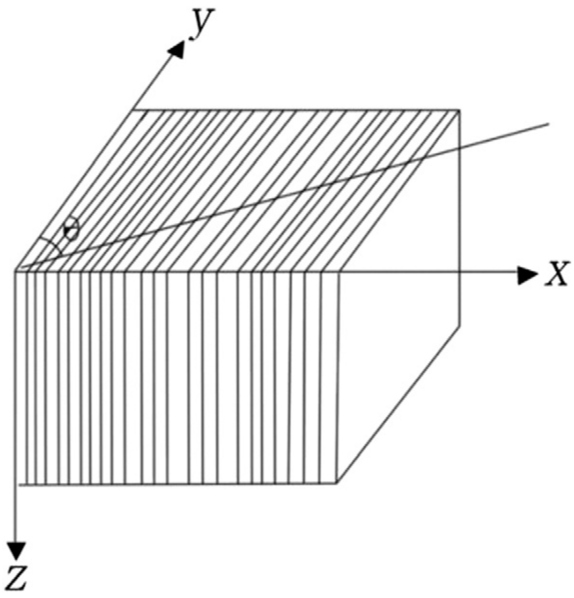

Fig. 1. Numerical model of fracture medium for the numerical simulation.