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On the source-frequency dependence of fracture-orientation estimates from shear-wave transmission experiments

Leo K. Santos [a], J.J.S. de Figueiredo [a,b,*], Bode Omoboya [c], Jörg Schleicher [d,b], Robert R. Stewart [c], Nikolay Dyaur [c]

[a] UFPA, Faculty of Geophysics, Laboratory of Petrophysics and Rock Physics – Dr. Om Prakash Verma, Belém, PA, Brazil
[b] National Institute for Petroleum Geophysics (INCT-GP), Brazil
[c] Allied Geophysical Laboratories, University of Houston, Houston, TX, USA
[d] Department of Applied Mathematics (DMA), Institute of Mathematics, Statistics, and Scientific Computing (IMECC), University of Campinas (Unicamp), 13083-859 Campinas, SP, Brazil

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ABSTRACT

Shear-wave propagation through anisotropic fractured or cracked media can provide valuable information about these fracture swarms and their orientations. The main goal of this work is to recover information about fracture orientation based on the shear waveforms (S-waveforms). For this study, we carried out ultrasonic S-wave measurements in a synthetic physical model made of epoxy resin (isotropic matrix proxy), with small cylindrical rubber strips as inclusions (artificial cracks) inserted in it to simulate a homogeneous anisotropic medium. In these experiments, we used low, intermediate, and high frequency shear-wave sources, with frequencies 90, 431, and 840 kHz. We integrated and interpreted the resulting S-wave seismograms, cross-correlation panels and anisotropic parameter-analysis curves. We were able to estimate the crack orientation in single-orientation fracture zones. The high frequency peaks associated with scattered S-waves provided interpretable information about the fracture orientations when the propagation direction was parallel to the fracture plane. The analysis was possible utilizing results from frequency-versus-polarization-angle curves. Moreover, we applied a bandpass filtering process to the intermediate and high frequency seismograms in order to obtain low frequency seismograms. A spectral analysis using frequency–wavenumber (F–K) spectra supports this filtering process. The results obtained using an analysis of cross-correlograms and the Thomsen parameter γ extracted from filtered high-frequency data were quite similar to those obtained using a low-frequency source. This highlighted the possibility of using less expensive high-frequency sources to recover information about the fracture set.

1. Introduction

The Earth's subsurface has a very complex distribution of geological features such as fractures, faults and folds. Among all the features existing in the subsurface, fractures are of major importance, because in most unconventional reservoirs, the oil and gas production is controlled by fractures in the subsurface. Because the fractures act as conduits for fluids in most of these reservoirs, the location, orientation, and density of fractures are important parameters to be characterized in order to optimize the production of fluids. Also, their characteristics are important to be defined, for example, when hydraulic fracturing is required. This process is essential to increase the permeability of fractured reservoirs (particularly shale and carbonates), which usually have high secondary porosity, but low permeability (Lonergan, 2007; Nelson, 2001). Knowing the preferential orientation of the fractures before this process is crucial to enhance the fluid flow (Holditch et al., 1978).

Due to the importance of fracture characterization, several methods have been developed in order to obtain information about fracture parameters. Using a parameter called "scattering index" in the high-frequency domain, Willis et al. (2005) were able to estimate the preferential orientation of a set of fractures from the analysis of backscattered energy. They obtained a satisfactory result on a real field dataset. Zhang et al. (2006) estimated the fracture spacing using backscattered energy based on the Local-Wavefield-Decomposition (LWD) method proposed by Sacchi et al. (2004). Using a seismic section in the time-domain, generated from a shot gather normal to the fracture strike, they used LWD to identify the coherent energy reflected from fractures. They then generated a new seismic section showing only the contributions of fracture reflections. From this new seismic section, they extracted the highest wavenumber value by means of an F–K panel. This value allowed estimating the fracture spacing. Zhang et al. (2006) demonstrated the method to produce reasonable results in a real-data application.

However, testing such methods on real field data has the inherent drawback that the true result is unknown, leaving the quality of the method very hard to judge. One of the viable alternatives to overcome

* Corresponding author at: UFPA, Faculty of Geophysics, Belém, PA, Brazil.
E-mail addresses: lky96@mst.edu (L.K. Santos), jadsomjose@gmail.com (J.J.S. de Figueiredo), bodeomoboya@gmail.com (B. Omoboya), js@ime.unicamp.br (J. Schleicher), rrstewart@uh.edu (R.R. Stewart), nidyaur@gmail.com (N. Dyaur).

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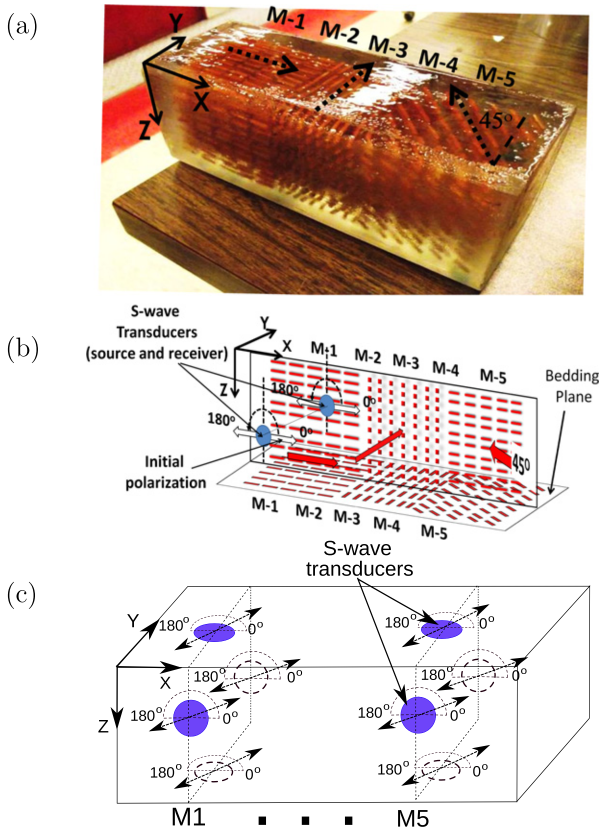

Fig. 1. (a) Photograph of the fractured model showing three regions with the same crack density but with three different set orientations. (b) Schematic diagram of crack placement in the fracture model (view from below). All cracks are oriented parallel to the YX plane (bedding plane), with their axes parallel to the X axis, Y axis and in the diagonal direction. (c) Schematic representation of the S-wave transducer placement at the centers of the regions at opposite sides of the model (blue: sources, white: receivers). This figure is a result of experiments performed by (de Figueiredo et al., 2012).

this issue is to use physical modeling experiments. Based on Hudson theory (Hudson, 1981), Tillotson et al. (2012) used a synthetic silica cemented sandstone to determine the relationship between shear-wave splitting and the fracture density of this synthetic rock. Their results showed that the magnitude of shear-wave splitting is of the same order as the fracture density, independently of the fluid type that is saturating the cracks. This relationship confirmed previous experiments performed by Assad et al. (1992) using a synthetic anisotropic medium made of epoxy resin with penny-shaped rubber inclusions.

In a similar epoxy-resin model with regions of different crack orientations, de Figueiredo et al. (2012) used an analysis of low-frequency P- and S-wave seismograms, cross-correlation panels, and curves of Thomsen's anisotropy parameter γ (Thomsen, 1986) to estimate the preferential fracture-set orientation of each region. This work complements their research on estimating fracture orientations. While de Figueiredo et al. (2012) used only low-frequency sources to obtain information about preferential fracture orientation in the model, we demonstrate the use of three different sources in the low (LF), intermediate (IF), and high-frequency (HF) domains, with 90, 431, and 840 kHz, respectively. The corresponding ratios between fracture size and dominant wavelength were 1.3 (LF), 0.6 (IF), and 0.3 (HF). In order to recover reliable information from these higher frequencies, we use a bandpass filter to obtain low-frequency information. Before the filtering process, the seismograms are converted into F–K spectra in order to visualize the signals' frequency distribution.

The methodology of de Figueiredo et al. (2012) allowed efficiently extracting fracture orientation information when the S-wave propagation was normal to the bedding planes. Here, we extend their analysis to the case of S-waves propagating parallelly to the bedding planes. Our objective is to make the determination of fracture orientation independent of the S-wave propagation direction relative to the fracture orientation.

We start with an interpretation of the S-wave seismograms, correlograms, and curves of the anisotropy parameter γ. We demonstrate that the low-pass filtering of the seismograms helps to make the contained information more easily accessible. From the Fourier-transformed seismograms, we then generate frequency-versus-polarization-angle curves, which allow estimating the fracture orientation. As in de Figueiredo et al. (2012), the interpretation considers the fracture orientation to be unknown. To simplify our procedure, we assumed that reasonable estimates of the other fracture parameters, such as the size of the inclusions and the crack density, are available. This is not a necessary requirement and can be dropped in practice.

It is important to emphasize that the cross-correlation method has already been applied successfully to real field data. It showed its feasibility when it was applied on a real field data in a VSP experiment (Ran Zhou et al., 2006) and for 2D-4C (Lou et al., 2001) and 3D-4C (Chichinina et al., 2012) marine OBS acquisition. Ran Zhou et al. (2006) applied the cross-correlation method in a circular VSP survey in order to estimate the fracture orientation at the reservoir level, in a carbonate reservoir located in the North East Caspian Sea. Ran Zhou et al. (2006) applied the cross-correlation method to estimate shear-wave splitting, fracture density, and fracture orientation for field data from the Valhall field, North Sea. Chichinina et al. (2012) applied the cross correlation function (CFC) to separate S1 and S2 waves in a multi-component data set from the Golf of Mexico. In the latter two cases, the authors performed the cross-correlation process between two measured orthogonal (radial and transverse) components. They repeated this process for a series of angles and lag times. The fracture orientation they found with the method was consistent with the known geology of the area.

2. Experimental procedure

We studied the effect of oriented fractures on elastic wave propagation in a synthetic epoxy-resin model with embedded cylindrical neoprene-rubber strips simulating cracks. The construction of the anisotropic cracked sample as well as the ultrasonic measurements were

Table 1
Geometrical parameters of the reference model (R) and the three regions (M-1, M-3, M-5) of the cracked model.

Model	Crack density (%)	Measuring length model (cm)		Number of layers	Cracks per layer	Crack length (cm)	Crack aper. (cm)
		L_Z	L_Y				
R	Isotropic	7.51	7.62	0	0	–	–
M-1	4.5	7.56	7.89	10	36	0.8	0.2
M-3	4.5	7.56	7.89	10	36	0.8	0.2
M-5	4.5	7.59	7.81	10	36	0.8	0.2