Approaches for investigation of oriented cracks of reservoirs using multicomponent VSP

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Abstract. The paper analyses the VSP data inversion in order to determine elastic constants of a transversely isotropic medium with a horizontal axis of symmetry of an infinite order (HTI), simulating an oriented fractured reservoir. Acquisition system of VSP is characterized by the absence of sub-horizontal directions of propagation of seismic waves. In this regard, it was necessary to determine the accuracy with which the elastic constants of the anisotropic layer are restored. The seismograms of the full wave field were selected as the initial data, calculated synthetically for the model of the medium containing azimuthally anisotropic layers. A complex of compressional and shear waves propagating from a source and recorded in the well. In such layers, the shear wave incident on the roof of the HTI layer splits into two waves that propagate at different velocities and have a mutually orthogonal displacement vectors. The processing task was to select waves $S_1$ and $S_2$ and build their arrival time curves. These arrival time curves were used in the inversion. The inversion was solved in the form of minimizing the functional of the mean square residual. Elastic constants, determined by inversion, almost exactly coincided with the model ones. The results obtained show the validity of the chosen approach for solving the inverse problem.

1. Introduction
One of important objects for seismic prospecting is investigating fractured reservoirs in order to discover the cracks orientation controlling the direction of maximum reservoir permeability, and vertical seismic profiling (VSP) is a valuable technology providing deep knowledge of the sub-surface [1]. Aligned fracturing results in anisotropy of the medium. The aim of this paper is to test the approaches to VSP data processing in order to evaluate the accuracy of the reservoir properties revealed, including the cracks orientation and elastic moduli in the anisotropic layers.

2. Synthetic data computation and processing
The 3D model was created in the to test the capability of seismic methods in solving this problem since evaluation of the inversion accuracy requires using synthetic data with known parameters. The model was based on the horizontally layered model with transversely isotropic layers with horizontal axis of symmetry (HTI). These layers simulate the fractured beds with cracks orientated orthogonally to the infinite-fold symmetry axis. The model parameters are presented in Figure 1. These includes the depths of layers, seismic waves velocities and Thomsen parameters in anisotropic layers as well as direction of horizontal symmetry axis [2].
| Layer | Top, m | $V_p$, km/s | $V_s$, km/s | $\rho$, g/sm$^3$ | $\varepsilon$ | $\delta$ | $\gamma$ | Axis Azimuth |
|-------|-------|-------------|-------------|----------------|-------------|---------|---------|-------------|
| 1     | 0     | 2.791       | 1.669       | 1.800          | 0           | 0       | 0       | 0           |
| 2     | 220.0 | 5.238       | 2.756       | 2.400          | 0           | 0       | 0       | 0           |
| 3     | 507.5 | 4.803       | 2.740       | 2.060          | 0           | 0       | 0       | 0           |
| 4     | 630.0 | 6.000       | 3.177       | 2.710          | 0           | 0       | 0       | 0           |
| 5     | 797.5 | 4.880       | 2.729       | 2.690          | 0           | 0       | 0       | 0           |
| 6     | 940.0 | 5.683       | 3.019       | 2.650          | 0           | 0       | 0       | 0           |
| 7     | 1207.5| 4.786       | 2.651       | 2.060          | 0           | 0       | 0       | 0           |
| 8     | 1450.0| 5.805       | 3.204       | 2.727          | 0.042       | -0.144 | 0.253   | 35°         |
| 9     | 1600.0| 5.703       | 3.080       | 2.788          | 0.040       | -0.144 | 0.265   | 35°         |
| 10    | 1690.0| 5.630       | 3.079       | 2.765          | 0.040       | -0.147 | 0.262   | 35°         |
| 11    | 1750.0| 3.000       | 1.800       | 2.350          | 0           | 0       | 0       | 0           |
| 12    | 1767.5| 4.253       | 2.654       | 2.561          | 0.024       | -0.187 | 0.240   | 35°         |

Figure 1: Parameters of the model

Figure 2: Location of the well and shot points
Figure 3: Full wavefield seismograms for the shot point 2. The vertical Z-component is shown in blue, radial R-component in green and tangential T-component in brown
Figure 2 displays the relative location of the well and shot points. The green dashes indicate the horizontal infinite-fold symmetry axis direction. Lebedev finite difference scheme on staggered grids [3] was applied to model the wavefield with vertical force sources. Figure 3 shows the 3-component full wavefield seismograms computed for the shot point 2. The horizontal R-component exhibits an intensive field of downgoing shear and converted PS waves. In the upper isotropic part of the model, these waves have zero amplitude on the T-component. Substantial amplitude of these waves on T-component emerges in reflection from the anisotropic layer top, and within the anisotropic part of the model. This indicates azimuthal anisotropy present in the interval.

In an anisotropic layer, the shear (as well as converted) waves split into two quasi-shear (qS) ones, which propagate with different velocities and have mutually orthogonal displacement vectors. This effect is referred to as birefringence, or shear-wave splitting. In the case of HTI medium, the displacement vector of the fast wave $S_1$ is perpendicular to the infinite-fold symmetry axis, i.e. parallel to the cracks. The recorded horizontal components of the seismograms demonstrate an interferential wavelet of the two quasi-shear waves. The processing aims to resolve the displacement vectors of the two quasi-shear waves generated, which allows predicting the cracks orientation, and to determine travel times of these waves. In 1986 Obolentseva I.R. and Gorshkalev S.B. [4] have proposed the approach to separation of the interfering quasi-shear waves based on cross-correlation function (CCF) calculation. Primary criterion of waves separation is maximal similarity of $S_1$ and $S_2$ wavelet shapes. At the beginning of the analysis the components covariance matrix $A$ is composed within the time interval of the shear waves and its eigenvalues and eigenvectors are computed.

$$A = \begin{pmatrix}
\sum x_i x_i & \sum x_i y_i & \sum x_i z_i \\
\sum y_i x_i & \sum y_i y_i & \sum y_i z_i \\
\sum z_i x_i & \sum z_i y_i & \sum z_i z_i
\end{pmatrix}$$

The ancillary coordinate system $x', y', z'$ is established coinciding with the matrix eigenvectors in decreasing order of eigenvalues. This makes the $z'$ direction orthogonal to the plain formed by the qS-waves displacement vectors. Rotation within the x'y' plane can determine the orthogonal directions where the two quasi-shear waves have maximum of cross-correlation implying that they are recorded free of interfering. This produces $x''$ and $y''$ components recording the $S_1$ and $S_2$ waves in the anisotropic part of the section. Figure 4 demonstrates the examples of polarization analysis of the downgoing direct shear wave being the most prominent in the downgoing shear wavefield for two different shot points. Intensive field of compressional waves on z-component impedes the analysis substantially, thus the analysis was performed using the horizontal components only.

The seismic gathers for shot point 2, the amplitudes of interfering $S_1$ and $S_2$ waves are nearly equal, so the maximum CCF criterion performs correctly. The shot point 5 is located in the direction close to the anisotropic medium vertical symmetry plane, so the amplitudes of the interfering $S_1$ and $S_2$ waves differ significantly. In this case, the other criterion is to be applied, i.e. zeroing the energy proportional to the $S_1$ wavelet on the orthogonal component. Figure 5 presents the results of shear waves polarization analysis in the anisotropic part of the section. Panel A shows initial horizontal components after parametric wavefield separation isolating the downgoing S-waves; panel B shows the resulting separated quasi-shear waves and obtaining their traveltimes by phase picking. Panel C shows time delay $\Delta t$ between the $S_1$ and $S_2$ waves increasing regularly with depth and remaining constant in the intermediate isotropic layer. The azimuth of $S_1$-wave displacement vector shown in panel D is close to the value 145° specified in the model. This processing procedure was carried out for all shot points and applying phase correction produced correct travel times of these waves to be used in inversion.
Figure 4: Examples of shear waves polarization analysis within the anisotropic part of the section

Figure 5: Shot point 2. Results of shear waves polarization analysis in the anisotropic part of the section. A — input horizontal components; B — resulting separated quasi-shear waves and phase picking producing their travel times; C — time delay between the $S_1$ and $S_2$ waves; D — azimuth of $S_1$-wave displacement vector.
Figure 6: Ray paths of $S_1$ and $S_2$ waves for the shot point 10 located at $X = 1000$ m, $Y = 0$ m.

Figure 6 shows the ray paths of the two quasi-shear waves arriving at the same receiver point as projections of rays to both horizontal and vertical planes illustrating that the rays trajectories are different not only in the anisotropic part of the section, but in the whole overburden as well. Thus, azimuthal anisotropy makes the waves propagation trajectories three-dimensional even in a horizontally layered section, and time delay $\Delta t$ between these waves is determined by difference in their travel times along the whole path from the source to the receiver. This implies the requirement to take the whole overburden properties into account for correct inversion in the anisotropic depth interval. Travel times of P, $S_1$ and $S_2$ waves obtained from all shot points were used as the data times $t_{data}$ for the inversion procedure. The inversion was performed as minimization of the mean-square error between the $t_{data}$ and the synthetic $t_{syn}$:

$$\sum (t_{data} - t_{syn})^2 \rightarrow \text{min}.$$  

The synthetic times $t_{syn}$ were computed for a certain current model realization, and the model parameters were automatically varied in order to find the minimum of the misfit function, more detailed description of the algorithm is presented in the paper [5].

The inversion was performed in two stages. At first the values of compressional and shear velocities in the isotropic part of the section were obtained ($t_{data}$ for this part were used). 3.0 km/s and 2.0 km/s were specified as the initial estimate of compressional and shear velocities respectively. This inversion results in the error values of order of $10^{-5}$ ms, and practically correct values of waves velocities. Then the inversion was performed for the remaining $t_{data}$ observed in the anisotropic 8-th layer of the model. Initial estimate of this layer parameter was as: $VP0 =$
4.5 km/s, $V S_0 = 2.6 km/s$, $\varepsilon = 0.1$, $\delta = 0.1$, $\gamma = 0.1$, azimuth 0°. The parameters resulting from the inversion were: $V P_0 = 5.57 km/s$, $V S_0 = 2.62 km/s$, $\varepsilon = 0.045$, $\delta = -0.14$, $\gamma = 0.26$, azimuth 35° and practically exactly agree with the model parameters, the minimization error obtained were $10^{-2}$ ms. It is worth to note that the symmetry axis direction obtained as the solution of the kinematic problem agrees with the results of polarization analysis.

3. Conclusions
Processing of synthetic wavefields resulted in successful separation of interfering $S_1$ and $S_2$ waves and obtaining their travel times. Two-stage inversion using the $P$, $S_1$ and $S_2$ waves travel times resulted in estimation of the model parameters including the cracks orientation and elastic constants in the anisotropic layer with good accuracy. This accuracy was achieved in spite of relatively narrow range of waves propagation angles in the anisotropic layer determined by VSP acquisition geometry lacking sub-horizontal propagation direction of waves in the anisotropic part of the section. The results obtained demonstrate feasibility of the approach selected to solve the inverse problem. Nonetheless, the processing revealed that time delay between the $S_1$ and $S_2$ waves is determined not by time of propagation of these waves in the anisotropic layer only, but by difference of ray paths in the isotropic overburden. This indicates that successful inversion requires information on the section as the whole, and all inaccuracies in the model of overburden will affect the accuracy of the anisotropic layer parameters obtained in inversion.

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