Estimating anisotropy parameter by shear wave splitting of crosswell seismic data: a case study on inter-bedded sand-shale layers

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Abstract. This paper describes a method to determine anisotropy parameter by shear wave splitting of crosswell seismic data. The purpose of this work is to present a section of anisotropy to be used in detecting hydrocarbon. Splitted S-waves were detected by picking the traveltimes of S-fast and S-slow on SH and SV components, respectively. Polarization method was done on the 3-C crosswell data using hodogram analysis, so that from these three components we can observe P-, SH- and SV-waves. Tomography of SH- and SV-wave of crosswell seismic were run to produce SH and SV tomograms. Due to the azimuth randomness of the 3-C receivers, an azimuth and inclination correction were implemented on the data, and some preconditioning were applied to enhance the quality of the firstbreaks including deconvolution, bandpass filtering and fx-decon. The traveltimes were picked on SH and SV components, furthermore to be inversed using traveltime tomography algorithm. In this work, a case study was carried out to the seismic data collected on inter-bedded sand-shale layers. The results of this work are SH- and SV-wave tomograms and the anisotropy section. We conclude that this method is effectively presenting an anisotropy section to be used for reservoir recognition.

1. Introduction

Anisotropy has been widely used in seismic seismic exploration work for imaging, fracture detection, lithology discrimination and reservoir characterization [1,2,3]. Anisotropy has been successfully improved seismic image, such as subsalt exploration targets in Gulf of Mexico, even it was considered as mild anisotropy [4]. Anisotropy parameter $\eta$ estimated from surface seismic whereas in a relatively low resolution [5]. There is relationship between apparent anisotropy with lithology [6] and there is a correlation between hydrocarbon and anisotropy [7]. It was obviously observed the effect of "hockey-stick" at the CMP gather of surface seismic dataset in sand reservoirs containing gas (gas sand), while CMP gather in the same layer that does not contain gas (wet sand) did not show any symptoms of anisotropy [7]. One method in estimating anisotropy parameter is Shear Wave Splitting (SWS) [8,9,10,11]. When passing through fractures, S-wave is splitted into perpendicular components. One component is parallely polarized to the fracture plane propagating as faster velocity, and the other component is perpendicularly polarized to the fracture plane as slower velocity. This phenomenon is shear wave splitting (SWS).
Although anisotropy can be estimated from surface seismic data, however it can be estimated in higher resolution utilizing crosswell seismic data. Crosswell seismic survey is technically conducted to obtain detailed interwell profiles. Crosswell seismic provides higher resolution inter-well images compared to surface seismic. In our study area, some geological challenges are present in high undulating topography, unconsolidated weathering layer, shallow coal streaks, complex structure and inter-bedded sand-shale layers. Field evaluation using conventional surface seismic survey is very challenging due to the limitation of data quality. Therefore, crosswell seismic survey was conducted in this area to overcome those geological challenges and data limitation.

The main data used in this study was a set of crosswell seismic data recorded using three orthogonal sensors (3-C) and Z-track tool as borehole source producing P- and S-wavefields with the source sweep frequency was defined at 30 – 200 Hz. One profile of crosswell data involved two boreholes; one borehole was assigned as source-well and another borehole was assigned as receiver-well. Each receiver component recorded P- and S-waves, including the converted waves. The P- and S-waves are mixed up on each component. A wavefield separation technique was applied to separate the P- and S-waves from the gather. The separation method used in this work was two passes rotations to produce the P-, SH- and SV-waves. In this work, we utilized the traveltimes differences of SH- and SV-waves to estimate the anisotropy parameter. A Tomographic inversion of SH- and SV-waves were implemented to produce SH and SV velocities.

![Figure 1](image-url)

**Figure 1.** The illustration of S-wave passing through fractures. S-wave is splitted into perpendicular components. One component is parallely polarized to the fracture plane propagating as faster velocity, and the other component is perpendiculary polarized to the fracture plane as slower velocity [8].

The goal of this work is to present a section of anisotropy estimated by SWS method to be used in detecting hydrocarbon. A petrophysical data (composite logs) was used to validate and evaluate the presence of hydrocarbon.

2. Methodology
The methodology used to achieve the objectives was as follows; 1) Tomography parameterization using synthetic data; 2) Wave separation on the 3-C gather using a rotational technique with hodogram analysis to obtain SH- and SV-waves; 3) Travelettes measurement by picking the direct wave at each gather dominated by SH- and SV-waves; 4) Traveltime inversion by non-linear traveltime tomography
to obtain SH and SV velocities; 5) Calculating anisotropy parameter by SWS; 6) Quick evaluation on layers indicating hydrocarbon presence.

A set of synthetic data was produced to evaluate tomography parameters to be implemented on real data. A wedge shape was used as true model in forward modeling. The geometry of the synthetic data was set exactly the same as the geometry of the real data (table 1).

| Parameter                     | Profile  |
|-------------------------------|----------|
| Receiver well                 | left     |
| Source well                   | right    |
| Inter well distance (m)        | 686.2    |
| Receiver interval (m)         | 7.5      |
| Source interval (m)           | 7.5      |
| Sample rate (ms)              | 0.5      |
| Sweep frequency (Hz)          | 30-200   |
| Listening time (s)            | 1.6      |
| Receiver depth start (m)      | 1917.5   |
| Receiver depth end (m)        | 125.0    |
| Source depth start (m)        | 2028.0   |
| Source depth end (m)          | 220.5    |
| Total number of shot          | 242      |
| Total number of receiver      | 240      |

Wave separation was performed by rotation based on hodogram analysis. Two passes rotational were implemented to correct the azimuth and the inclination of each receiver component, followed by traveltimes picking on SH- and SV-waves. Some preconditioning were applied to enhance the quality of the firstbreaks including deconvolution, bandpass filtering and fx-decon. The traveltimes measured then inverted with tomography parameters tested on the synthetic data. The output were velocity of SH- and SV-waves ($V_{SH}$ and $V_{SV}$). Assuming the medium is VTI, the SH-wave is roled as faster S-wave and the SV-wave is roled as slower S-wave. These two types of velocities were used to calculate the anisotropy parameter ($K$) by SWS method with equation (1), where $V_{fast}$ is $V_{SH}$, $V_{slow}$ is $V_{SV}$ and $V$ is the average velocity of $V_{SH}$ and $V_{SV}$.

$$ K \approx \frac{(V_{fast} - V_{slow})}{V} $$  

Well data was needed to evaluate the correlation between anisotropy and the presence of hydrocarbon. The well data were mud log and composite log.

3. Results and discussion

Real field data was inverted using tomography parameters tested on synthetic data. A wedge model was used to evaluate the resolution. The true model and the tomography results are shown in figure 2. The inversion result using the best tomography parameters was closely similar to the true model, either the structures shape or the velocities. The best parameters was used in tomography is shown in tabel 2. This parameter was then implemented on the real field data with changing in number of iteration. Number of iteration used in tomography of the real field data was 30. The tomography results of the real field data, i.e. $V_{SH}$ and $V_{SV}$ were used to estimate anisotropy parameter ($K$).
Table 2. Tomography parameters.

| Inversion Parameters |  |
|----------------------|--|
| Grid size            | 7.5 m |
| Smoothing control    | 10    |
| X/Z smoothing ratio  | 40    |
| Minimum velocity     | 1900 m/s |
| Maximum velocity     | 4000 m/s |
| Number of iteration  | 20    |

Seismic anisotropy is the variation of velocity in the direction of wave propagation, either P- or S-waves, or the velocity difference in accordance with the direction of polarization of the S-wave [12]. In other words, anisotropy is the ratio between the maximum and minimum velocity in different directions. Quick detection of anisotropy was observed by analyzing the traveltime differences between maximum and minimum traveltime. Figure 3 shows the delay time of SH- and SV-waves. Zone with the depth below 1000 m showed the larger delays than the shallower zone. It indicates that below 1000 m potentially has stronger anisotropy.

Tomography was implemented to invert the traveltime of SH- and SV-waves producing tomogram SH ($V_{SH}$) and tomogram SV ($V_{SV}$). The tomography parameters suitably worked on the real field data. The tomograms were verified using the seismic reflection images. The seismic images were depth migrated crosswell seismic (figure 4). Verification was done by overlying the velocities on top the reflection seismic image of the S-wave. The velocity anomalies were conformable with the S-wave reflections image. High contrast on the tomograms were correlable with the high magnitude reflection on the seismic image. The tomograms provided resolution inter-well velocities as high as the crosswell seismic reflection image.

**Figure 2.** Depth velocity model. (a) true model and (b) tomography result of the synthetic data. The tomography result is similar to the true model, either in structures shape or the velocities.
Figure 3. Delay time of SH- and SV-waves. Zone with the depth below 1000 m shows the larger delays than the shallower zone.

The velocities were used to calculate anisotropy parameter ($K$) with equation (1), where $V_{\text{fast}}$ is $V_{SH}$, $V_{\text{slow}}$ is $V_{SV}$ and $V$ is the average velocity of $V_{SH}$ and $V_{SV}$. Figure 5 shows the tomogram SH and SV and the calculated anisotropy parameter ($K$). The quick indication by time delays of SH and SV (figure 2) was conformable with anisotropy calculated by SWS (figure 5.c). Anomalies were observed on the zone below 1000 m.

Well data were used to evaluate the estimated anisotropy parameter $K$. Well data were used to investigate any correlation between the parameter $K$ with the presence of hydrocarbon. From mud log data, it can be observed that the gas is started read by the depth of 1000 m. And from composite log, the water saturation ($S_W$) is start showing low percentage by 1000 m. In this work, the presence of hydrocarbon indicated from well data correlate with the anisotropy anomaly $K$.
Figure 5. Tomographic inversion result and parameter anisotropy $K$ calculated by SWS. (a) $V_{SH}$; (b) $V_{SV}$ and (c) $K$.

Figure 6. Validation with well data. (a) mud log; (b) composite log. The two well data indicate the presence of hydrocarbon start at around 1000 m and it is correlable with the anisotropy anomaly $K$. 
4. Conclusions
Anisotropy parameter $K$ calculated by SWS shows anomalies below 1000 m with the resolution is as high as the reflection image. In this work, the anisotropy anomaly $K$ is correlable to the presence of hydrocarbon indicated from well data.

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