Hydrocarbon identification by evaluating anisotropy parameters estimated from crosswell seismic data

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Abstract. This study aims to identify hydrocarbon by evaluating anisotropy parameters estimated from crosswell seismic data. Several approaches were performed in this study included shear wave splitting (SWS) and angle-based velocity variation (VVA) methods. Anisotropy coefficient K was estimated by SWS method and anisotropy parameters ε, δ, and γ were estimated using modified Thomsen’s equations in Vertically Transverse Isotropy (VTI) medium applied to Crosswell seismic geometry. The velocity variation was observed when pressure (P) wave propagated through a layered media containing hydrocarbon. The P-wave velocity was decreasing along with the increasing of the incidence angle and the calculated values of anisotropy (ε, δ, γ, and K) on the target zone within interval 1390 m to 1820 m depth were relatively high compared to the zone does not contain hydrocarbon. The evaluation was verified with Poisson’s, pressure wave velocity (VP) and shear wave velocity (VS) ratio analyses and validated to the existing petrophysics data. In conclusion, anisotropy values (ε, δ, γ and K) and velocity variation with angle of incidence have a positive relationship with hydrocarbon and applicable as a tool for identifying the presence of hydrocarbon in layered media.

1. Introduction
Anisotropy has been widely used in the scale of global [1] and in reservoir scale for seismic for modeling, data processing and inversion, hence the anisotropy parameter estimation becomes very important. There is a relationship between hydrocarbon and anisotropy [2]. Thomsen’s anisotropy parameters are the product of velocity variation with offset or angle (VVO or VVA) method that can be used as hydrocarbon indicator estimated using surface seismic [3]. Surface seismic is a normal seismic that is commonly used in petroleum exploration where the sources and the receivers are deployed relatively on the earth surface. Surface seismic has limited vertical resolution, so higher resolution data are required to identify hydrocarbon in thin layered media. Crosswell seismic data has much higher resolution than surface seismic.

The main data used in this study was a set of crosswell seismic data recorded using three orthogonal sensors (3-component). Crosswell seismic is a method of recording seismic data between two boreholes (wells). One borehole is assigned as source-well and another borehole is assigned as receiver-well. The multi-component receivers will record seismic waves in horizontal (X- and Y-component) and vertical (Z-component) directions. Seismic data from these different directions can be used to evaluate the presence of anisotropy by observing the travel time to each component. The traveltimes are then inverted to velocity. The high resolution velocity can be obtained by inverting the travel times using tomography
method. In this study, the pressure (P) -wave, shear horizontal (SH) -wave and shear vertical (SV) -wave traveltimes were inverted to produce pressure wave velocity ($V_P$), shear horizontal wave velocity ($V_{SH}$) and shear vertical wave velocity ($V_{SV}$), respectively. The anisotropy can be analyzed by these three different velocities.

The purpose of this study is to evaluate anisotropy parameters ($\varepsilon$, $\delta$, $\gamma$, and $K$) in delineating reservoirs containing hydrocarbon using a set of crosswell seismic data. The velocity differences and or gradients in each direction is an seismic anisotropy phenomenon. Degree of the anisotropy is proporsional to the velocity differences and/or gradients.

2. Data and Methods

The data used in this study is a set of crosswell seismic data employed a 3-C receiver array and Z-track tool as borehole source producing pressure (P) and shear (S) wave fields 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. The receiver components were designed in Z, X and Y directions which is perpendicular each other (orthogonal). Each component recorded P- and S-waves, including the PS-converted waves. The P- and S-waves were mixed up on each component. Therefore The P- and S-wavefields need to be separated.

This study utilized the seismic source only the P-wave. To complete the evaluation in identifying hydrocarbon, it was conducted in five main steps [4]:

Step-1: Wavefield separation into P-, SH-, and SV-waves. Some direction corrections including azimuth and inclination were applied to all receivers prior to waves separation [5].

Step-2: Delay time tomography of the P-, SH- and SV-waves to obtain P-velocity ($V_P$), SH-velocity ($V_{SH}$) and SV-velocity ($V_{SV}$) [6, 7]. The traveltimes were picked on the first arrival events of P-, SH- and SV-waves seismic gathers. The results of $V_P$, $V_{SH}$ and $V_{SV}$ sections are shown in figure 2.

Step-3: Shear wave splitting (SWS) to calculate anisotropy parameter $K$ [8, 9, 10] by means of inverting traveltimes of SH- and SV-waves representing $V_{fast}$ and $V_{slow}$ waves respectively using equation 1.

Step-4: Calculating anisotropy parameters $\varepsilon$, $\delta$ and $\gamma$ using Thomsen equation in VTI medium [11] by redefining the angle of incidence of crosswell seismic geometry as seen on figure 1. The new definition of $\varepsilon$, $\gamma$ and $\delta$ are stated in equation 2 to 5. And the sections are shown in figure 4.

Step-5: Hydrocarbon detection utilizing all the result from step-2 to step-4. Angle-based velocity variation (VVA) method was conducted in this step. Poisson’s ratio is calculated based on $V_P$ and $V_S$. A crossplot of $V_P/V_S$ – Poisson’s ratio was used to predict the hydrocarbon phase on the observation target. Validation was conducted by petrophysics data such as lithological log, water saturation ($S_W$) and porosity data.

Shear wave splitting (SWS) is a phenomenon that occurs when S-wave travel through an anisotropic medium. The S-wave undergoes polarization so that it separates into two wave components. One component of the S-wave propagates parallel to the fractured plane and the other propagates perpendicular to the fractured plane. The S-wave component propagating parallel to the fractured plane has higher velocity than the S-wave component that propagates perpendicular to the fractured plane [8, 9, 10]. SWS anisotropy coefficient $K$ was calculated using the equation 1 below [10], with $V_{fast}$ is the higher velocity, $V_{slow}$ is the slower velocity and $V$ is the isotropic velocity.

$$K \approx \frac{(V_{fast} - V_{slow})}{V}$$ (1)
Figure 1. Redefined the angle of incidence of crosswell seismic geometry.

For normal surface seismic, the Thomsen’s anisotropy parameters are $\varepsilon$ (epsilon), $\gamma$ (gamma) and $\delta$ (delta) [12]. Epsilon and Delta are correlated to the long offset and short wave, respectively, of P-wave and $\gamma$ is correlated to S-wave effect. For crosswell seismic geometry, these Thomsen’s parameters need to be redefined based on modified incidence angle schematic on figure 1. Then the redefined Thomsen’s parameters for crosswell geometry were calculated using the equations below:

$$
\varepsilon \approx \frac{V_P(0^\circ) - V_P(90^\circ)}{V_P(90^\circ)}
$$

$$(2)$$

$$
\gamma \approx \frac{V_{SH}(0^\circ) - V_{SV}(0^\circ)}{V_{SV}(0^\circ)}
$$

$$(3)$$

$$
\gamma \approx \frac{V_{SH}(0^\circ) - V_{SH}(90^\circ)}{V_{SH}(90^\circ)}
$$

$$(4)$$

$$
\delta = 4 \left\{ \frac{V_P(45^\circ)}{V_P(90^\circ)} - 1 \right\} - \left\{ \frac{V_P(0^\circ)}{V_P(90^\circ)} - 1 \right\}
$$

$$(5)$$

3. Results and discussion

Pressure velocity ($V_P$), shear horizontal velocity ($V_{SH}$) and shear vertical velocity ($V_{SV}$), as seen on figure 2, were obtained by delay time tomography method utilizing traveltime picks from P-, SH- and SV-waves seismic gathers. There were velocity anomalies between interval 1390 m and 1820 m depth. These anomalies were closely related to the reflection image on the tomograms either P- or S-waves.
Figure 2. (a) $V_P$ section overlaid on top of P-wave tomogram; (b) $V_{SH}$ section overlaid on top of S-wave tomo-gram; and (c) $V_{SV}$ section overlaid on top of S-wave tomogram. The velocity anomalies marked by white arrows, were indicating the interest zone.

In calculation of anisotropy coefficient $K$, $V_{SH}$ and $V_{SV}$ were representing $V_{fast}$ and $V_{slow}$, respectively. Figure 3 is shown the calculated $K$ values. High $K$ values in the interval of 1390 m and 1820 m depth were indicating the interesting zone to be evaluated. These anomalies are similar to $V_P$-, $V_{SH}$-, and $V_{SV}$-anomalies. By using equations 2 to 5, the calculated anisotropy parameters can be seen on figure 4. Some high anomaly values of $\epsilon$, $\delta$ and $\gamma$ were also observed in the interest zone between 1390 m and 1820 m depth. Higher values are indicating higher anisotropic media.

This study selected two main observed points, those are on-borehole (B) and off-borehole or tested (T) locations. Within each vertical location, it was selected two conditions, low anomaly and high anomaly. So in total, this study evaluated four observed points, B1, B2, T1 and T2 (figure 5). The on-borehole location points were selected based on water saturation ($S_W$) curve plotted in petrophysics data (figure 6). Observation point B1 at depth 950 m is on a layer with high $S_W$ and porosity 12% and showing low anomaly on the anisotropy sections. And observation point B2 at depth 1484 m is on a layer with $S_W$ 50% and porosity 30% and showing high anomaly on the anisotropy sections (figure 5).

Figure 3. Anisotropy coefficient $K$ section that was calculated by SWS method. High $K$ values in the interval of 1390 m and 1820 m depth were indicating the interest zone.
Figure 4. Anisotropy sections were calculated by equation 2 to 5. (a) $\varepsilon$-section; (b) $\gamma$-section and (c) $\delta$-section. The high anomalies value of $\varepsilon$, $\delta$ and $\gamma$ were observed in the interval 1390 m to 1820 m depth.

Figure 5. Observed location points. B1 and B2 were located on-borehole, and T1 and T2 were tested points located off-borehole. (a) observation points plotted on $\varepsilon$-section; (b) observation points plotted on $\gamma$-section; and (c) observation points plotted on $\delta$-section.
Figure 6. The petrophysics data that is showing porosities and $S_W$ on observed points. (a) Point B1 at 950 m depth has porosity 12% and (b) point B2 at 1484 m depth has porosity 30% with $S_W$ 50%.

The off-borehole points were picked based on crossplot of Poisson’s ratio and $V_p/V_s$ (figure 7). Gas case was indicated at depth of 1508 m (T2) and wet case was indicated at depth of 1289 (T1). T1 with $V_p/V_s = 1.66$ and Poisson’s ratio = 0.2 can be defined as wet case. T2 with $V_p/V_s = 1.7$ and Poisson’s ratio = 0.1 can be defined as gas case.

Figure 7. Crossplot of Poisson’s ratio and $V_p/V_s$. Point T1 at 1289 m depth and T2 at 1508 m depth were representing wet case and and gas case, respectively.
Angle-based velocity variation (VVA) method conducted in this step has shown a positive relationship with hydrocarbon and applicable as a tool for identifying the presence of hydrocarbon in layered media. In this study, P-wave velocity (VP) at observed points have been plotted along the incident angle. On-borehole observation has shown that at B1 there was relatively no velocity variation as a function of incident angle (figure 8.a), whereas at B2 there was velocity variation as a function of incident angle (figure 8.b). On the other side, the off-borehole observation has shown that at T1 there was relatively no velocity variation as a function of incident angle (figure 9.a), whereas at T2 there was velocity variation as a function of incident angle (figure 9.b).

The four observation points were plotted on anisotropy sections to verify the relationship between anisotropy value and the presence of hydrocarbon (figure 5). It was verified that the anisotropy anomaly consistently indicated the gas case layers. The presence of hydrocarbon was validated with petrophysics data such as water saturation and porosity (figure 6).

**Figure 8.** Crossplot of \( V_P \) as function of incident angle observed on-borehole location; a) Point B1 at 950 m depth there was relatively no velocity variation, and b) Point B2 at 1484 m depth there was velocity variation.

**Figure 9.** Crossplot of \( V_P \) as function of incident angle observed off-borehole location; a) Point T1 at 1289 m depth there was relatively no velocity variation, and b) Point T2 at 1508 m depth there was velocity variation.
4. Conclusion

Hydrocarbon identification was successfully carried out by evaluating anisotropy parameters estimated from crosswell seismic data. The anisotropy parameters $\varepsilon$, $\delta$ and $\gamma$ can be calculated using Thomsen equation in VTI medium with redefinition the incident angle applied to data with crosswell seismic geometry. The anisotropy values ($\varepsilon$, $\delta$, $\gamma$ and $K$) and VVA value have a positive relationship with hydrocarbon so it can be used as a tool for identifying the presence of hydrocarbon in the layered media verified with Poisson's ratio, $V_P/V_S$ and validated with petrophysics data such as water saturation ($S_W$) and porosity.

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