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Improved Seismic Imaging through Petrophysical Approach using Thomsen's Parameter Estimation in Anisotropic Prestack Depth Migration (PSDM)

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Abstract

Research has been carried out using the Prestack Depth Migration (PSDM) anisotropy method for 2D reflection seismic data. This research aims to estimate anisotropic parameter values with a petrophysical approach to the Prestack Depth Migration method to obtain better imaging results. The type of anisotropic medium used is Vertical Transverse Isotropy (VTI) because that can explain the effect of anisotropy in a simple form on the sediment layer. In theory, 2 parameters are needed to describe this parameter, namely ε and δ. δ is an anisotropic parameter that describes the velocity variation towards a nearly vertical direction and is the control depth of seismic. In contrast, ε describes the velocity variation towards the near horizontal direction. The stages of data processing are divided into two; the first is PSDM isotropy, which flattens gather at near offset (angle mute <30 degrees), and PSDM anisotropy to flatten-gather at far offset (mute angle> 30 degrees). The results of this study showed that the relation of ε and δ in shale formations was (δ = 0.4958ε - 0.0152) and sand formation (δ = 0.9082ε - 0.0203) and the range of anisotropic parameters δ and ε were -0.02 up to 0.13 and 0 up to 0.3. From all ranges of anisotropic parameter values, this study belongs to the "weak anisotropy" category Thomsen (0 to 0.5). The value of anisotropy parameters obtained can give the results of seismic images more accurately and clearly than PSDM isotropy. It can correct errors in the depth of seismic up to 51 m.

Introduction

Many researchers have been interested in seismic anisotropy in recent decades after Thomsen published a "Weak Elastic Anisotropic" paper in 1986[1]. Regardless of the earth's fundamental anisotropy structure, most seismic data processing algorithms are isotropy[2]. This erroneous assumption leads to false imaging and thus avoids errors in interpretation[3]. Thomsen introduced the measurement of anisotropy as more effective and scientific by submitting constants ε, δ, and γ as a parameter effective for the measurement of anisotropy, where ε and δ for determining the anisotropy of P-wave and parameter γ to control the parameters of the anisotropy of the S-wave[4].

Based on the above, this research attempts a depth migration concept that uses the principle of Kirchhoff integral migration by applying the anisotropy parameters obtained with a petrophysical approach to get the correct image seismic of the subsurface. The medium used in this study is assumed as Vertical Transverse Isotropy[5], [6]. The migration process was conducted by Prestack Depth Migration anisotropy for the depth of the region[7]. Then, the Prestack Depth Migration anisotropy results will be validated by reviewing the well data.

Theory and Calculation

Seismic waves are mechanical waves arising from an earthquake[8]. Generally, it can also be interpreted as a wave propagation phenomenon caused by interference with the surrounding medium[9]. Seismic waves can be generated by two methods, namely, active and passive methods. The active method is a method that deliberately causes interference created by humans, while the passive method is naturally occurring disorders[10]. **Figure 1** shows seismic waves composed of body waves and surface waves.

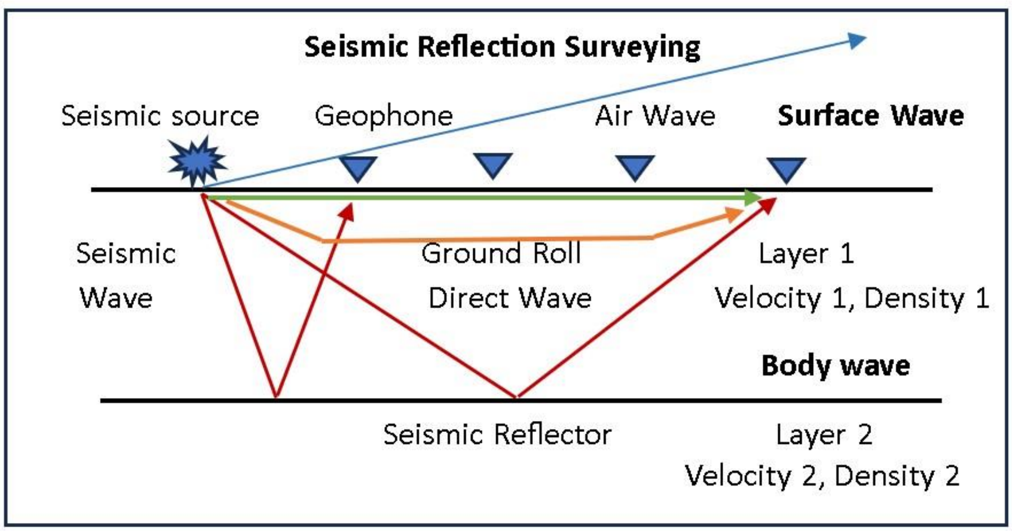

Figure 1. Sketch of a seismic survey[11].

Seismic data migration is a seismic data processing process that aims to map seismic events in the actual position[12]. Seismic data processing is generally divided into 4 main categories: enlarge the tilt angle, shorten the reflector, move the reflector towards up dip, and improve lateral resolution.

The migration process that produces a cross-section of migration in the time zone is called time migration. This migration is generally valid for small to medium lateral velocity variations [13]. If the lateral velocity variation is large, this time migration cannot produce a sub-surface image properly and correctly. To shortcoming this, migration techniques are carried out in-depth migration, where the migration results are displayed in the depth region shown in **Figure 2**, resulting in subsurface images following actual geological conditions[14].

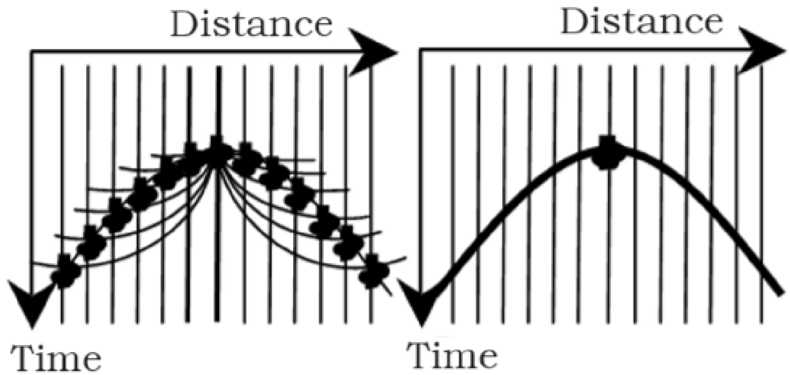

Figure 2. Illustration of the diffraction point[15].

According to Thomsen, seismic anisotropy is a dependence on seismic velocity on angles. This angle is the angle between the direction of deployment and polarized. These two angles are identical in the P wave but will differ in the anisotropic medium. Anisotropic events in seismic waves occur when there is a difference in group and phase velocity, causing the seismic wavefront to become elliptical and not spherical anymore[16]. With a wavefront like that, there will be a difference in the velocity of the wave that propagates in its direction. According to Thomsen[17], anisotropy in sedimentation caused by three main factors: stress, pressure, and sedimentation in rocks are common trigger factors, a thin layer of isotropic medium compared to a symmetrical wavelength (horizontal or sloping layer), and vertical or tilt fractures or microcracks

There are several types of anisotropy, one of which is used in this study is Vertical Transverse Isotropy. VTI occurs when the axis of symmetry with the vertical direction wavefront towards horizontal spreads faster and slower in the vertical direction[18]; an illustration of wave propagation can be seen in **Figure 3**.

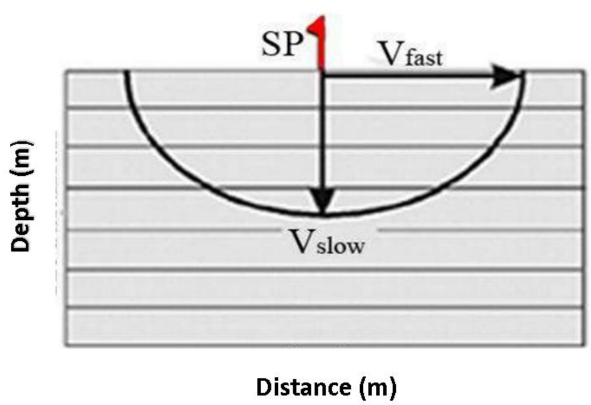

Figure 3. Vertical Transverse Isotropy[19].

Bancroft and Elapavuluri introduced the anisotropic parameters obtained from his experiments and explained or introduced them with Thomsen parameters, namely δ (delta), ε (epsilon), and η (eta)[20]. δ (delta) is a Thomsen parameter that affects the velocity around the vertical direction, and the greatest influence occurs vertically, so it is often called a depthing parameter; ε (epsilon) is a Thomsen parameter that affects velocity at far offset and is often called an elliptical parameter and η (eta) are parameters that explain the relationship between δ and ε. A VTI medium with a vertical symmetry axis has five constants that do not depend on the elasticity of the medium[21], that is, C11, C33, C13, C44, and C66. Thomsen describes the parameters with the following equation:

$$\varepsilon = \left(\frac{C_{11}-C_{33}}{2C_{33}}\right) = \left(\frac{V_{P\psi}-V_{P\tau}}{V_{P\tau}}\right) \tag{1}$$

$$\gamma = \left(\frac{C_{66}-C_{44}}{2C_{44}}\right) = \left(\frac{V_{S\psi}-V_{S\tau}}{V_{S\tau}}\right) \tag{2}$$

$$\delta = \left(\frac{(C_{13}-C_{44})^2-(C_{33}-C_{44})^2}{2C_{33}(C_{33}-C_{44})}\right) = \left(\frac{V_{P45^o}-V_{P\tau}}{V_{P\tau}}\right) - \varepsilon \tag{3}$$

$$\sigma = \left(\frac{C_{33}}{C_{44}}\right)(\varepsilon - \delta) \tag{4}$$

$$\eta = \left(\frac{\varepsilon-\delta}{1+2\delta}\right) \tag{5}$$

Equation (3) was revealed to be Alkhalifah's equation[22]:

$$\eta + 2\eta\delta = \delta\varepsilon - \delta \tag{6a}$$

$$\eta + \delta(2\eta + 1) = \varepsilon \tag{6b}$$

$$\delta = \frac{\varepsilon}{(2\eta+1)} - \frac{\eta}{(2\eta+1)} \tag{6c}$$

which means the equality relationship delta and epsilon are approximated by the eta parameter becomes linearly with $\delta = a\varepsilon - b$, whereas:

$$a = \frac{\varepsilon}{2\eta+1} \tag{7a}$$

$$b = \frac{\eta}{2\eta+1} \tag{7b}$$

The ψ symbol in the above equations shows a parallel direction perpendicular to the rock layer (fast velocity), Vp is P-wave velocity, and Vs is S-wave velocity. Then Thomsen connects the velocity and the parameter into the equation:

$$V_P(\theta) = V_{P0}[1 + \delta \sin(\theta) \cos^2(\theta) + \epsilon \sin^4(\theta)] \tag{8}$$

$$V_{S\perp}(\theta) = V_{S0}\left[1 + \left(\frac{V_{P0}}{V_{S0}}\right)^2 (\varepsilon - \delta) \sin^2(\theta) \cos^2(\theta)\right] \tag{9}$$

$$V_{S\parallel}(\theta) = V_{S0}[1 + \delta \sin^2(\theta)] \tag{10}$$

Vp (θ) is the P-wave velocity of an angle, then $Vs\perp$ (θ) is the S-wave velocity perpendicular to the vertical axis (vertical in the case of VTI), and $Vs\parallel$ (θ) is the S-wave velocity parallel to the vertical axis (Horizontal in the VTI case). The above velocity equation can be illustrated in **Figure 4**. From Equation 6c, Thomsen wrote again a simpler equation with Equation 8:

$$V_P(\theta) = V_{P0}[1 + \delta \sin^2(\theta) + (\varepsilon - \delta) \sin^4(\theta)] \tag{11}$$

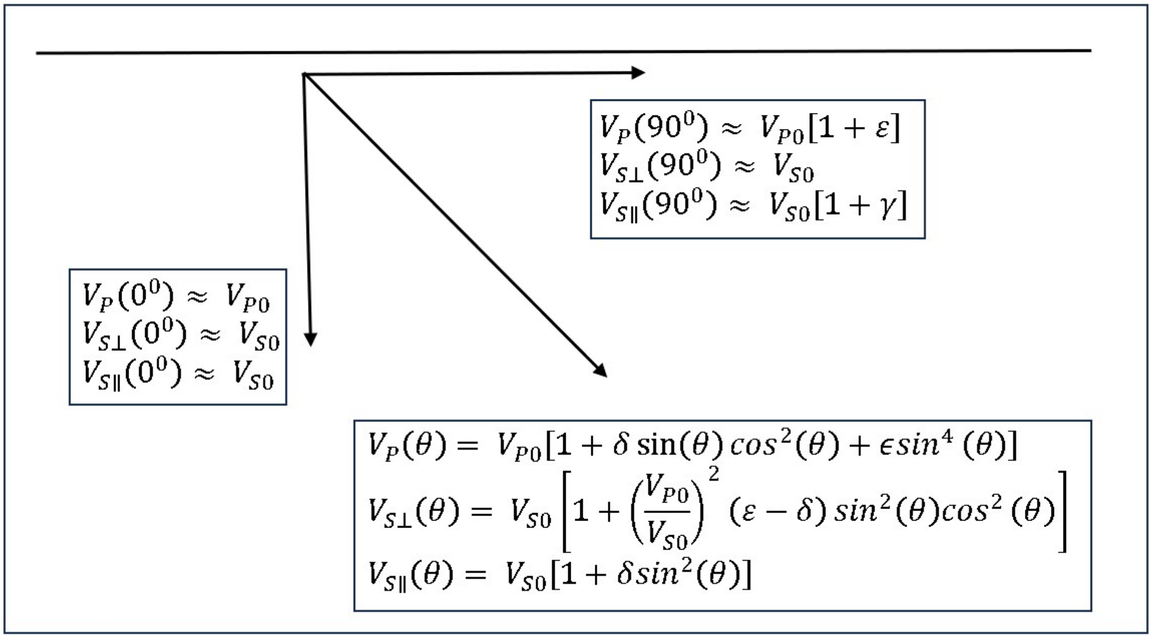

Figure 4. Calculation of Anisotropic Velocity.

Experimental Method

This study's type of seismic data is CDP Gather with coordinates laterally from 2092 -3202 (CDP number), which means the 2D seismic trajectory is 16,650 m with sample intervals every 15 m. Data time from 0-5000 milliseconds, with sampling every 2 milli second record. The steps in conducting this research are shown by a flowchart in **Figure 5**.

The data processing of this research will be divided into two parts, namely PSDM Isotropy to get Gather and Section PSDM Isotropy, then PSDM Anisotropy to get Gather Anisotropy and Anisotropy section.

a. Isotropic PSDM

First is the data processed using the Dixx Transformation method and Constrained Velocity Inversion to convert the velocity of V_{rms} to $V_{interval}$. Then, the migration process using the Kirchoff method with the aperture set at 4995 m at a depth of 1000 m. After the complete migration, muting is carried out for Isotropy 30°. After that, Picking Semblance Residual Moveout corrects the interval speed along the wave propagation path so it is not too fast or too slow from the actual velocity. The result of picking semblance will be a vertical function, which will later be made a section, which is then used to update the speed using the grid tomography method.

b. Anisotropic PSDM

The first study of literature to determine the relationship of anisotropic parameters ε and δ. Then do picking semblance Effective Eta every 450m or every 30 CDP. From the petrophysical research data (Wang, Z 2002) about Sedimentary Rocks, the values of ε and δ for each rock are plotted into a cartesian coordinate, then linear regression to get the relationship between them.

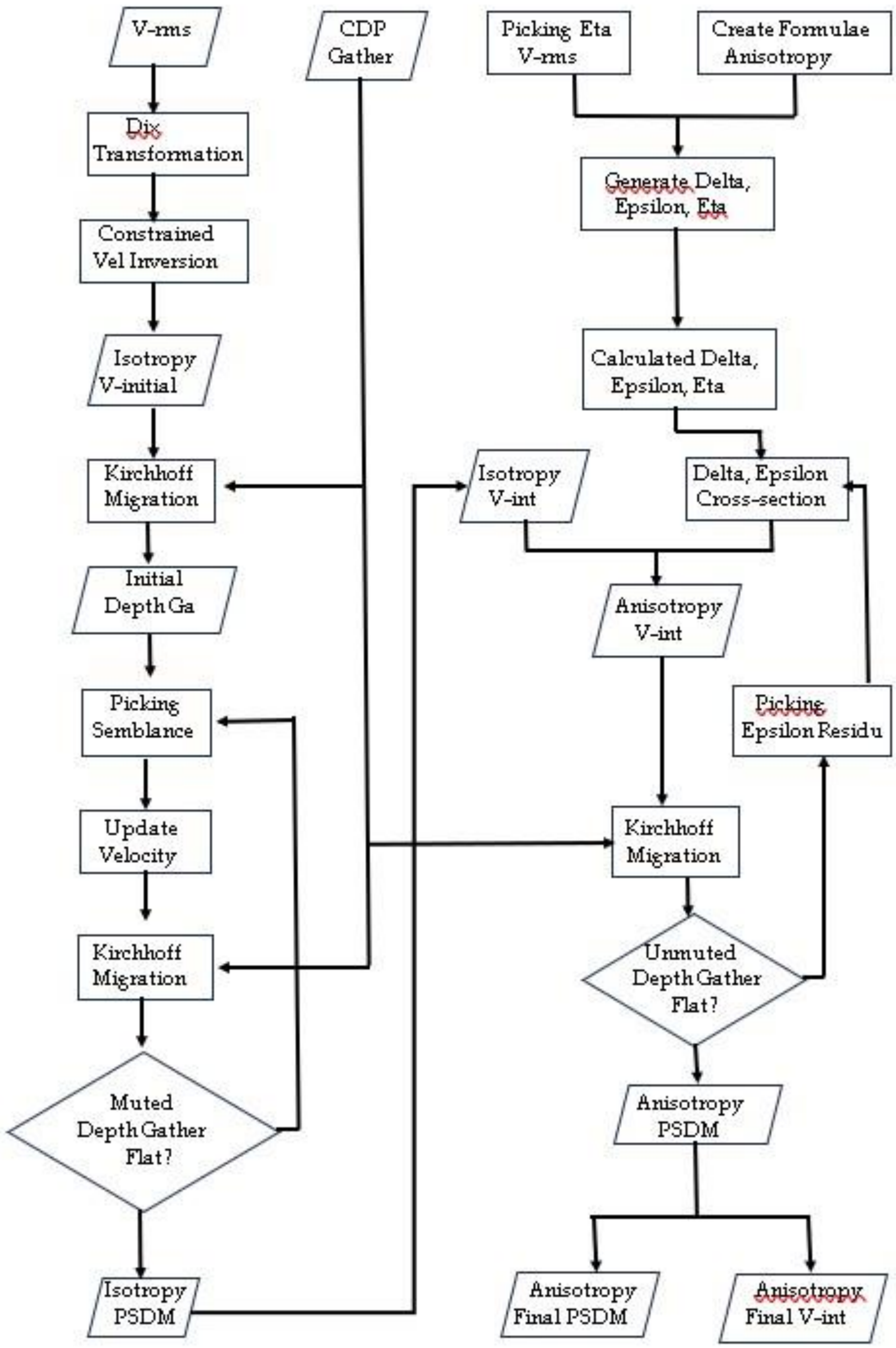

Figure 5. Flowchart of research.

After obtaining the value of ε and δ cross-sections, both are created manually in the builder window model by entering the value of ε and δ in each formation that looks for the value of ε δ. The values of ε and δ are obtained by sampling the eta values in the eta section and formula: ε. If the rock formation is sand, use the relationship δ and ε for sand, and so on. The final step is the process of anisotropic migration, including δ and ε section, CDP gather, and cross-section of the anisotropy interval velocity.

Result and Discussion

A. Analyses of PSDM Isotropic

The results of this study's final interval velocity model indicate lateral velocity variation and can represent formations in the area survey than velocity. V_{rms}. The model interval velocity can provide satisfactory results in the seismic migration process, indicated by the appearance of the depth gathered in the near offset area that has been flat.

One example of depth gathered before and after the updated velocity model can be seen in **Figure 6** and **Figure 7**. Depth gathers before the update speed appears to curve down, and semblance is positive (to the right of the zero line), which means the speed model is too high. After updating the speed iteratively, in **Figure 7,** the value of the residual moveout semblance becomes zero and flat in the near offset area at the gather depth. It indicates there is no error in this interval speed model.

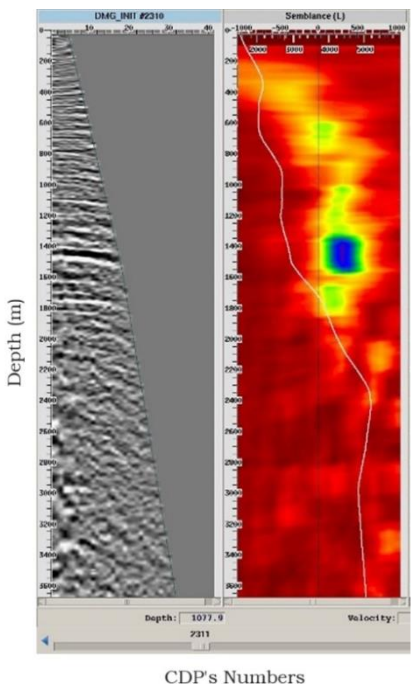

Figure 6. Gather and semblance display before velocity update.

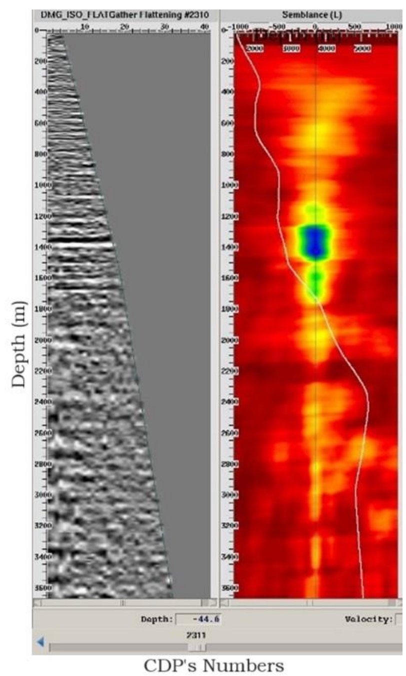

Figure 7. Gather and semblance display after velocity update.

The results of the seismic section also show that the results of processing Isotropic PSDM are better than PSTM. The bedding structure, fracture pattern, and clearer image quality show it. The red and black colors are brighter (tune) in the section of PSDM. Gather results of PSDM processing Isotropy cause Isotropy is flat in the near offset area (under mute 300). Flatter gathered seismic means that the seismic wave energy that crosses the same reflector (layer) can be stacked optimally and produce a good seismic section.

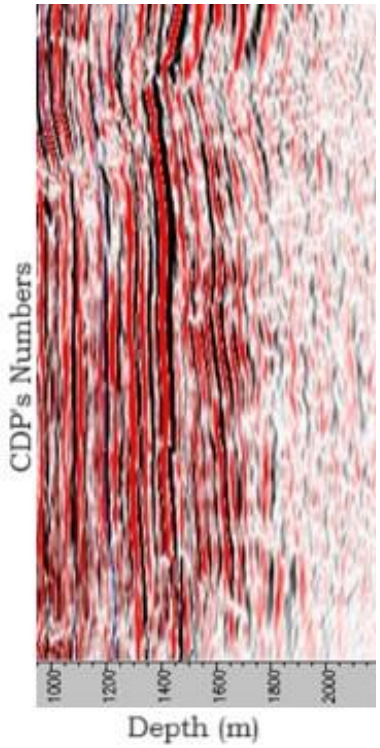

Figure 8. Enlargement of the PSTM seismic section with a PSDM seismic section isotropic before velocity update.

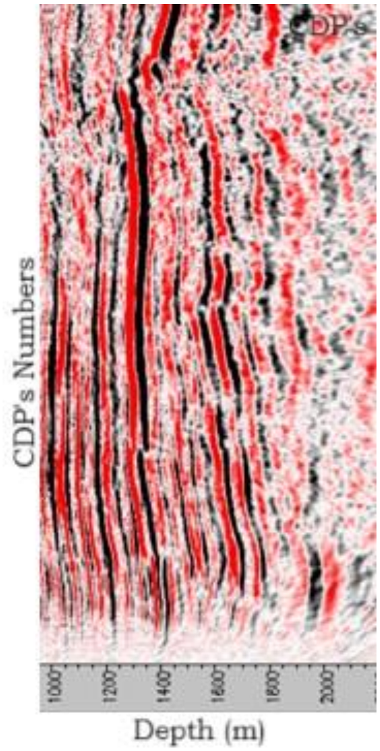

Figure 9. Enlargement of the PSTM seismic section with a PSDM seismic section isotropic after velocity update.

Figure 8 and **Figure 9** show a section-piece result of Isotropic PSDM. From the picture, it can be seen that apart from the more apparent structure layer, the structure of the layer also appears to be slightly lifted, and minor faults occur that are not visible in the PSTM seismic section. The model velocity causes that (V_{rms}) used for PSTM is slower than the model interval velocity ($V_{interval}$) used for Isotropic PSDM.

B. Analyses of PSDM Anisotropic

In this study, the value of anisotropic parameters can be estimated in the formation of Baturaja and Gumai. Both formations meet the criteria as an anisotropic medium because of the character of constituent rock formations and ODR at gathering depth in Baturaja and Gumai formations, which are less than 1. Gumai formation rocks are shale stones, and Baturaja formations are shale stones and little limestone.

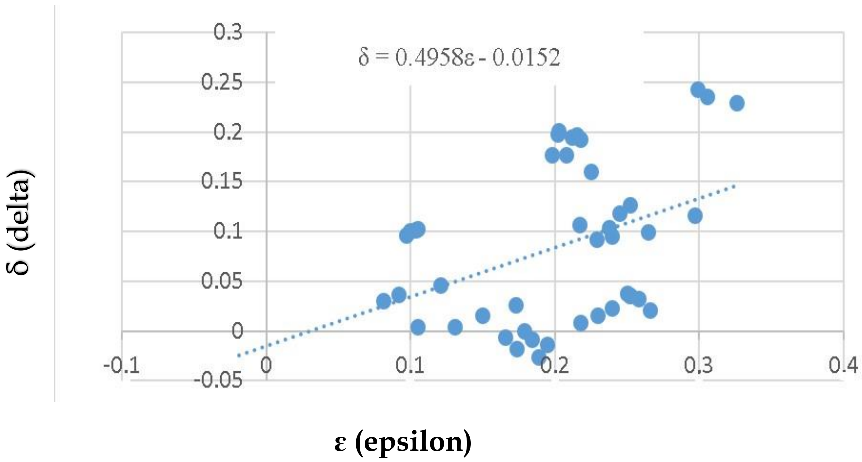

Figure 10. The relationship between δ and ε.

The graph results of the relationship between δ and ε indicate the value δ = 0.4958ε - 0.0152 for the formation composed of shale stones. The graph also shows that the value δ is not the same as ε (δ ≠ ε), commonly called an elliptic anisotropy. This approach follows the actual subsurface of the earth, an anisotropic medium. To obtain anisotropic parameter values in this study, combining the formula regarding the formulation of eta anisotropy parameters with formulas from the linear regression results of ε: δ relationship.

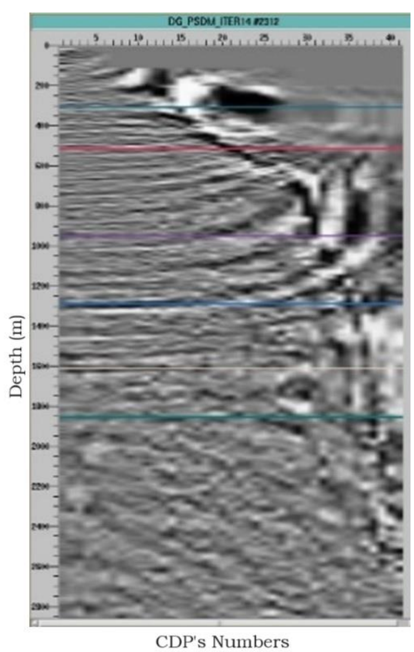

Figure 11. Gather the final Isotropy before the far offset is corrected.

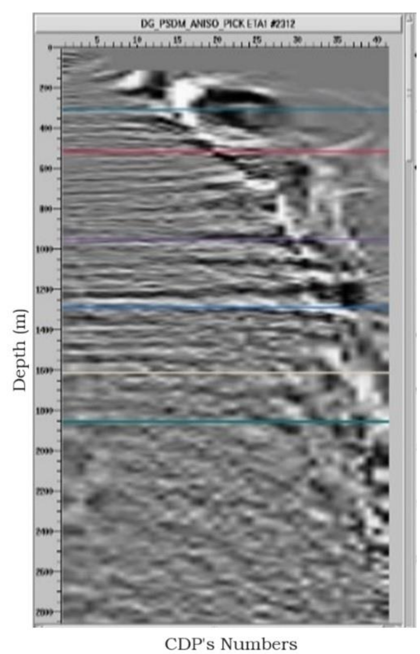

Figure 12. Gather final anisotropy after the far offset is corrected.

This research's section model of ε has successfully corrected the far offset data of depth gathered. **Figure 11** and **Figure 12** show the difference between the final gathered isotropic PSDM (before the far offset corrected) and the final depth gathered is anisotropic PSDM. The velocity of final Isotropy is too high, showing at depth gathered in the far offset area that curves upwards, generally called a hockey stick. It occurs because the near-horizontal seismic velocity is greater than the near-vertical velocity. After correction using an anisotropic parameter ε, the hockey stick effect has disappeared, and the gather becomes flat at far offset.

The corrected depth gathered at far offset can provide more information. In PSDM isotropy, the seismic section can only provide information on the area near the offset because, at far offsets, a hockey stick makes the stacking process not accumulate all traces. Therefore, in PSDM Isotropy, the depth gathered is muted at 300 or not summed at all in the stacking process. While on PSDM Anisotropy, seismic has been corrected until far offset, so the depth-stacking process gathers maximally until far offset. It is an advantage of the PSDM Anisotropy method, which can provide more information to improve the seismic image than PSDM isotropy. **Figure 12** shows a seismic cross-section of the PSDM anisotropic method with mute at 400.

If the seismic section is enlarged in the selected area, then compared with the seismic isotropic section, it can be seen in the seismic anisotropy section, the layer structure is lifted, and the seismic image quality is better. The anisotropy parameter δ corrects layer structure and causes lift. While seismic image quality results from a correction of the addition of anisotropic parameter ε.

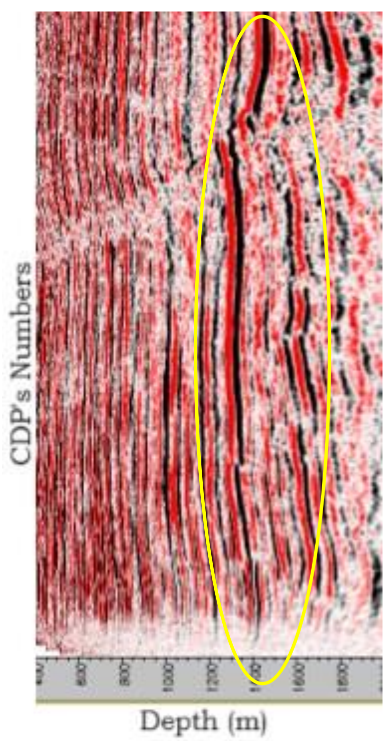

Figure 13. Section of PSDM isotropic.

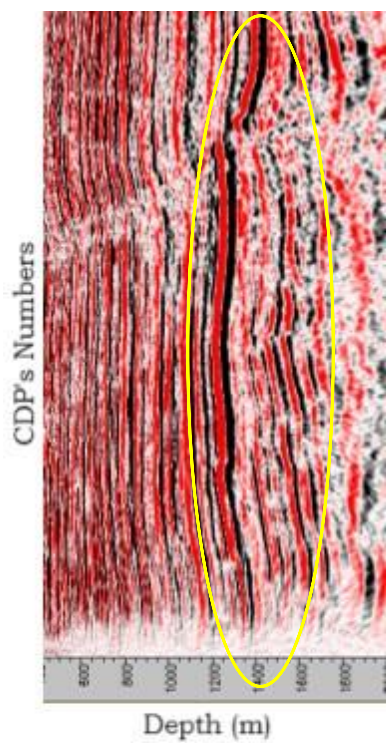

Figure 14. Section of PSDM anisotropic.

In **Figure 13** and **Figure 14**, the seismic section of anisotropy shows a stronger amplitude and a clearer continuity of the layering structure. The advantage of the PSDM anisotropic method is that it can make it easier for interpreters to read.

C. Quality Control Anisotropic Parameters

Quality control is needed to find out whether the results of processing PSDM anisotropy are correct, especially in the anisotropic parameter δ. Anisotropic parameter δ quality control is done by calculating the depth error of horizon seismic from PSDM Isotropy and anisotropy with markers from good data (sonic speed). The well position is in CDP number 2311. Whereas for the anisotropy parameter ε, quality control is done by comparing the parameter value ε from picking residue ε with the value ε obtained from the eta parameter.

Table 1. Comparison of seismic depth errors with wells.

No	Name of Formation	Depth of Seismic Isotropic (m)	Depth of Well Marker (m)	Error (m)	Depth of Seismic Anisotropic (m)	Depth of Well Marker (m)	Error (m)
1	Gumai	1,017	978	39	989	978	11
2	Baturaja	1,286	1,225	61	1,235	1,225	10

Table 1 shows that in the Gumai formation, the PSDM anisotropy method can correct seismic depth with an error depth of 11 meters compared to isotropic PSDM with a depth error of 39 m. The error depth is 10 meters in PSDM anisotropy compared to PSDM Isotropy with an error depth of 61 m in the Baturaja formation. The result of overlaying isotropic and anisotropic PSDM seismic data with well marker data can be seen in **Figure 15** and **Figure 16**.

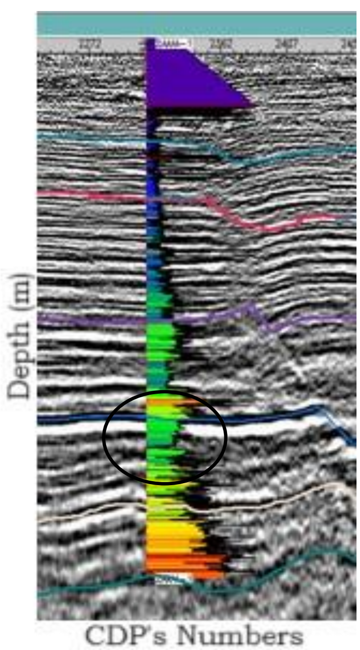

Figure 15. Results of overlaying isotropic seismic horizons with well markers.

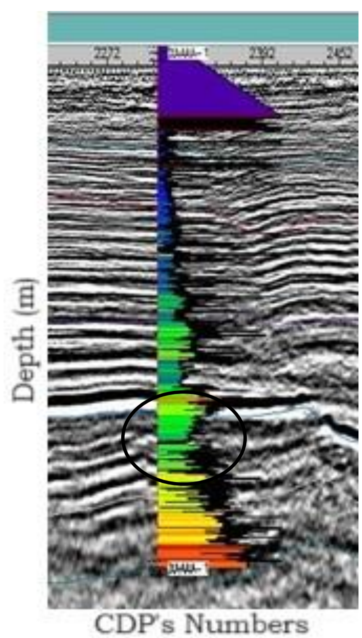

Figure 16. Results of overlaying anisotropic seismic horizons with well markers.

The results of picking residues ε every 100 CDP with parameter values ε in this study did not differ significantly and had a relatively similar pattern. The Gumai formation shows the maximum difference between the study results with picking residue ε is 0.1. At the same time, the comparison of the anisotropic parameter values in the Baturaja formation shows a maximum value of 0.13.

Conclusion

Estimation of anisotropy parameters is an essential aspect of seismic analysis. The PSDM anisotropy method gives a more accurate and precise image than PSDM isotropy because of the correction of anisotropic parameters δ for near-vertical velocity and ε for near-horizontal velocity. The Anisotropic PSDM method can eliminate the Hockey Stick effect on the depth gathered so it becomes flat until far offset. It is indicated by a strong reflector display and the continuity of structure more consistent in the seismic section. The relationship between ε and δ in shale rock formations is ($\delta = 0.4958\varepsilon - 0.0152$) and in sandstone formations ($\delta = 0.9082\varepsilon - 0.0203$). It shows that in shale rock formations, the value of δ is ~ 1/2 ε, and for sandstone values δ ~ ε. The value range of the anisotropy parameter δ for the Gumai formation is -0.01 to 0.12, and for the Baturaja formation is -0.02 to 0.13. While the range of values for the anisotropic parameter ε in the Gumai formation is 0 to 0.28, the Baturaja formation is 0 to 0.3. This study belongs to the "weak anisotropy" from all fields of anisotropic parameter values. Thomsen's anisotropic parameter δ affects the depth calculations. Error depth corrected by anisotropic parameter δ for the Gumai formation is 28 m, and for the Baturaja formation is 51 m. While the error parameter ε in the Gumai formation is 0.1, and the Baturaja formation shows a maximum difference of 0.13.

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