An Improvement of Velocity Variation with Offset (VVO) Method in Estimating Anisotropic Parameters

Ida Herawati, Sonny Winardhi, Wahyu Triyoso, and Awali Priyono

***Abstract*— Seismic anisotropy causes deviation of traveltime reflection from hyperbolic moveout. The deviation can be seen at far offset and its deviation depends on anisotropic parameter and offset. This paper discuss velocity variation with offset (VVO) method as a tool for estimating anisotropic parameters; ε and δ. Anisotropic parameter is one of important aspect in seismic anisotropy analysis. While other methods use non-hyperbolic moveout for estimating anisotropic parameter, VVO method uses hyperbolic assumption for moveout correction and leave reflector unflat at far offset because anisotropy. The method calculates residual traveltime and then changes it into anisotropy velocity to obtain anisotropic parameter using linear inversion method. This paper provides an improvement and limitation of VVO method in estimating anisotropic parameter. Comparison between VVO method and other established method is discussed theoretically in this paper. To test the method, synthetic model is built and the result show promising outcome in predicting ε. Meanwhile accuracy for δ estimation depends on accuracy of moveout velocity. Advantage of VVO method is that ε and δ can be estimated separately using P-wave gather data without well information.**

Keywords- anisotropic parameter; velocity versus offset; velocity dependent offset

I. INTRODUCTION

Seismic anisotropy is defined as velocity dependent on angle or offset. In recent years, many researchers have acknowledged of anisotropy effect on seismic data processing and interpretation. Analysis of anisotropy must be considered in doing normal moveout (NMO) correction, velocity analysis, time-depth conversion and amplitude versus offset (AVO) analysis [1]. Factors causing anisotropy are intrinsic anisotropy, crack, and thin bed laminated. Reference [2] measured seismic velocities from core plug and show that intrinsic anisotropy is present in shale and coal rock because micro lamination of their formed mineral. Sand and carbonate are isotropic unless they are fractured or thin laminated. Lamination of isotropy layer will give anisotropy effect if its thickness is smaller compared to seismic wavelet [3]. Pressure on rock affect anisotropy velocity which varied azimuthally depends on crack direction [4].

One of important things in anisotropy analysis is parameter estimation. Other than for seismic imaging purposes, knowing of anisotropic parameter also helps us in understanding the reservoir. Besides from core plug measurement, some researchers attempt to obtain anisotropic parameter from well data or seismic data. Anisotropy analysis from seismic data involves gather data and common methods used for parameter estimation are mostly based on traveltime reflection/moveout velocity such as suggested by [5] and [6].

This paper will discuss alternative method in estimating anisotropic parameter using P-wave seismic data suggested by [7] called velocity variation with offset (VVO). The method is based on calculation of velocity variation along offset caused by anisotropy and it allows us to predict anisotropic parameter in the absence of velocity information from well/checkshot data. In this paper we will review VVO method and discuss improvement of the method from current research point of view. There are some established methods in estimating anisotropic parameter that have been widely used in processing software. This paper will briefly discuss one of those methods called Alkhalifah's inversion method and compared it with VVO method. A technique of estimating ε and δ simultaneously using velocity versus offset information with the help of linear

DOI: 10.5176/2335-6774_2.1.20

inversion method will be discussed here with synthetic model example.

II. Velocity Anisotropy

There are some models in anisotropy which are vertical transverse Isotropy (VTI), horizontal transverse isotropy (HTI) and tilted transverse isotropy (TTI). Rock physics and seismic data show that VTI model is often seen in sediment rock such as thin bed layering and shale anisotropy [1]. Reference [8] derives an equation of plane wave for weak polar anisotropy and gives three anisotropic parameters known as Thomsen's parameters. In VTI medium, velocity depends on the angle between the vertical symmetry axis and direction of travel and Thomsen's parameters are defined as follows:

$$\varepsilon = \frac{Vp_{90} - Vp_0}{Vp_0}. \quad (1)$$

$$\delta = 4\left(\frac{Vp_{45}}{Vp_0} - 1\right) - \left(\frac{Vp_{90}}{Vp_0} - 1\right) \quad (2)$$

Parameter ε shows difference between P-wave vertical velocity (Vp_0) and horizontal velocity (Vp_{90}). δ is a measurement of near vertical velocity for P-wave where Vp_{45} is velocity at 45°. Other parameter is γ which measures difference between vertical and horizontal for S-wave velocity.

For transverse isotropic media, phase velocity for P-wave or $Vp(\theta)$ is defined as:

$$Vp(\theta) = Vp_0(1 + \delta \sin^2\theta \cos^2\theta + \varepsilon \sin^4\theta). \quad (3)$$

Weak anisotropy assumes the magnitudes of ε and δ are less than 0.2. Even though, δ and ε were originally introduced to simplify velocity equation for weakly anisotropy media, [6] have identify that they also assist moveout analysis for transversely isotropic models with arbitrary strengths of anisotropy.

For VTI medium, [7] derived an equation to obtain velocity anisotropy or $Vp(\theta)$ based on hyperbolic moveout and simplify weak anisotropy equation by assuming that for small θ, the third term of (3) which contains ε is neglected. So (3) becomes:

$$Vp(\theta) = Vp_0(1 + \delta \sin^2\theta). \quad (4)$$

By plotting $Vp(\theta)$ and $\sin^2(\theta)$ for near offset, intercept and horizontal gradient velocity ($Vp_0{*}\delta$) can be obtained in similar way with obtaining gradient in AVO method. Meanwhile ε parameter is obtained by assuming that velocity anisotropy follows ellipse curve [7]. Reference [9] show that gradient velocity obtained from VVO method can be used as an alternative tool to indicate hydrocarbon present especially in gas reservoir in addition to common direct hydrocarbon indicator method such as AVO analysis. Sand filled with gas will have higher δ and ε compared to water saturated sand. The advantage of this method over AVO analysis is that VVO does not require a preserved amplitude data.

In this study, velocity information until far offset will be used as an input for (3) to obtain δ and ε simultaneously using linear inversion method. A technique on obtaining velocity along angle of propagation, $Vp(\theta)$, will be discussed in this paper.

III. Comparison of VVO with Alkhalifah's Inversion Method in Estimating anisotropic Parameter

Reflection traveltime for isotropic medium is based on hyperbolic moveout defined as:

$$t^2 = t_0^2 + \frac{x^2}{V_{NMO}^2} \quad (5)$$

where t is travel time at x in two way time (TWT), t_0 is travel time at zero offset (x = 0), x is offset and V_{NMO} is normal moveout (NMO) velocity.

Anisotropy presence disturbs this reflection moveout and cause deviation of traveltime at far offset. Reference [7] defines relationship between those deviations with offset dependent velocity, Vh_j. In VVO method, gather data is corrected using initial stacking velocity ($V_{NMO} = V_{stack}$) based on hyperbolic moveout and then calculate time deviation (residual moveout) of each offset, Δt_j. The residual moveout for each offset (Δt_j) is calculated as time difference between correct moveout (moveout with Vh_j) with moveout with V_{NMO} and can be approximated as:

$$\Delta t_j = \Delta T - \Delta T_{stack} \approx \frac{x_j^2}{2Vh_j^2 T_0} - \frac{x_j^2}{2V_{stack}^2 T_0}. \quad (6)$$

Velocity dependent offset (Vh_j) is then calculated independently for each offset:

$$\frac{1}{Vh_j^2} = \frac{(\Delta T_{stack} + \Delta t_j)2t_0}{x_j^2} \quad (7)$$

Where ΔT_{stack} is travel time difference to zero time (t_0) after V_{stack} or V_{NMO} as in (6) and V_{NMO} is obtained during velocity analysis. Meanwhile Δt_j will be calculated using cross correlation method as explained in the next section.

There are several methods which estimate anisotropic parameter using moveout velocity analysis such as shifted-hyperbolic moveout [10], modified three term Taylor series [6], and Alkhalifah's traveltime inversion methods [11]. Those methods are based on non-hyperbolic reflection traveltime, in which the third term is related to anisotropic parameter. Reference [11] derives quadratic term equation for P- and S-wave in transversely isotropic media becomes:

$$t^2 = t_0^2 + \frac{x^2}{V_{NMO}^2} - \frac{2\eta x^4}{V_{NMO}^2\left[t_0^2 V_{NMO}^4 + (1+2\eta)x^4\right]} \quad (8)$$

So moveout for P-wave can be explained with vertical travel time and two effective parameters V_{NMO} and η where η is called as ellapticity parameter defined as $(\varepsilon-\delta)/(1+2\delta)$. In Alkhalifah's inversion method, 2D scan semblance of V_{NMO} and η is used to flat the reflector event and to reduce ambiguity in estimating anisotropic parameter. δ is estimated with the help of well velocity (Vp_0) based on (9) and ε is then calculated based on η value. This method needs long offset and also the extracted values of η are sensitive to error in V_{NMO} [5]. Meanwhile in VVO method, moveout correction still uses hyperbolic assumption and leave the reflector unflat at far offset so that residual moveout (Δt) can be calculated to get velocity data of each offset.

The VVO method involves calculation of interval velocity and transformation of offset to angle. In isotropic medium, moveout velocity (V_{NMO}) is equal to RMS vertical velocity (V_{RMS}) then interval velocity can be obtained by applying Dix's equation. However, that simple approach is not valid for anisotropy medium where moveout shortspread (V_{NMO}) is not equal to V_{RMS} even for horizontal reflector [8]. In anisotropic media, if Dix formula is used to derive interval velocity such as in this study then obtained velocity is apparent interval velocity (Vp') that contains anisotropic parameter δ and defined as:

$$V_{NMO} = Vp' = Vp_0(1+\delta). \quad (9)$$

This relationship must be taken into account when Vp_0 is estimated using (3) which become:

$$Vp'(\theta) = Vp_0'(1+\delta\sin^2\theta\cos^2\theta + \varepsilon\sin^4\theta). \quad (10)$$

Current transformation offset to angle is mostly for isotropic medium such as in [12] in which offset information convert to group angle. However for anisotropic media, group angle is different with phase angle. Meanwhile for reservoir property interpretation, such as in weak anisotropy equation, angle and velocity that is used is phase angle and phase velocity. Therefore group angle is needed to be changed to phase angle. However calculation between phase and group angle is depend on parameter anisotropy itself, so mathematical calculation that relates phase and group velocity is complex. However, for weak anisotropy, group velocity can be approximated by phase velocity [8]. Reference [13] study new ray-traced approach that is more accurate in offset-angle transformation by taking into account the difference between group and phase angle. They find that an accuracy of conventional transformation which assumed group angle = phase angle in anisotropic media is getting less with an increasing of angle and anisotropy degree. In VVO method, transformation of offset to angle assumed that group angle is the same as phase angle. Therefore when dealing with strong anisotropy case, VVO method will lose its accuracy in defining anisotropic parameter.

IV. Application of VVO Method in Synthetic Model

In this paper the VVO method is tested on simple synthetic model. Gather is built using available software based on finite difference algorithm with parameter shown in Fig. 1. The maximum offset is set to 5000 m with dominant frequency 30 Hz and sampling rate 2 msec. Second layer is anisotropic media with ε=0.12 and δ=0.06. The gather is then corrected by hyperbolic moveout with V_{NMO} based on the model. Gather after moveout correction shows flat event for first reflector at 1000 msec (Fig. 2a). Meanwhile for bottom of anisotropic layer (around 1300 msec), reflector is flat for offset < 1800 m and gets deviated as offset increasing. Fig. 2b shows gather after non–hyperbolic moveout correction based on Alkhalifah's inversion method with the same V_{NMO} and η for second layer is picked around 0.061 to get flat reflector. In VVO method, we will calculate residual travetime after moveout shown in Fig 2a to obtain velocity information of each offset.

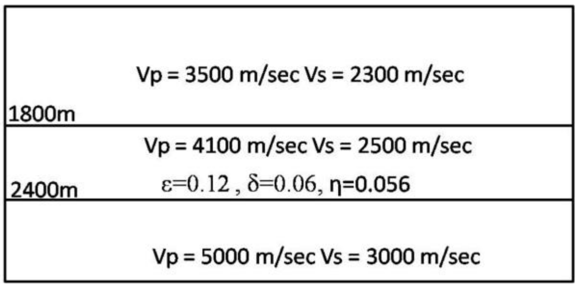


Figure 1. Simple horizontal model with second layer is anisotropic media

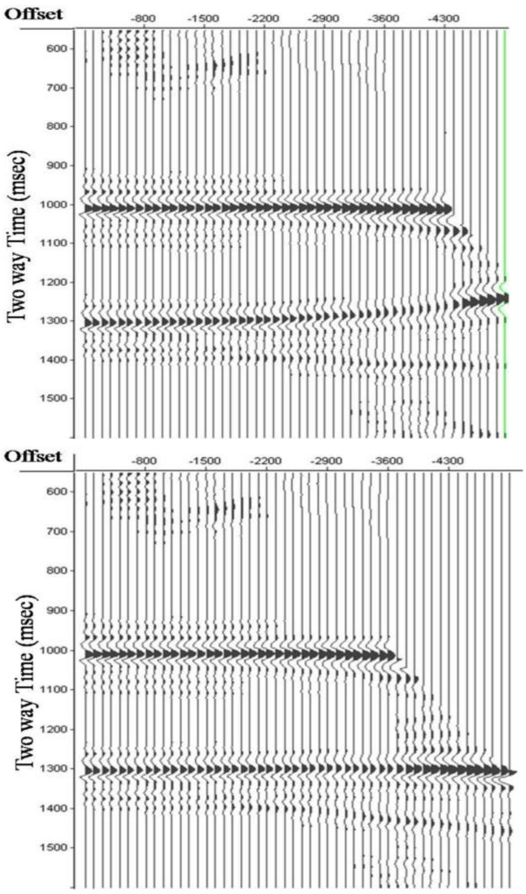


Figure 2. Gather after normal moveout with hyperbolic equation showing hockey stick effect on the bottom of second layer. (b) Gather after normal moveout with non-hyperbolic assumption based on Alkhalifah's traveltime inversion.

Residual moveout (Δt) can be calculated either in time domain or frequency domain and it is obtained by calculating time shift of particular reflector event of two closest traces. In this paper, Δt is calculated in frequency domain with the help of S-transform [14]. Frequency analysis is expected to give more detail result since it allows delay time that smaller than sampling rate especially since we work with weak anisotropy. Reference [15] show with synthetic example that Δt calculation in frequency domain gave result closer to the Δt model compared to its calculation in time domain. Each trace is transformed to S-transform and two nearest traces are cross-correlated resulted in amplitude and phase spectrum as shown in Fig. 3. Delay time is then calculated from gradient of phase spectrum. However as seen in Fig. 3 the phase is varied with frequency and the filter based on signal to noise ratio is applied to pick the frequency range. Firstly, amplitude spectrum is converted into amplitude in unit dB (Fig. 4a). Then -10 dB cut off is used considering that amplitude above -10 dB have signal to noise ratio around 0.7 (Fig. 4b). Secondly, gradient phase is calculated over resulted frequency range which is around 22 – 55 Hz. The process is repeated until last offset with a nearest-offset trace is used as reference for measuring Δt for the next trace.

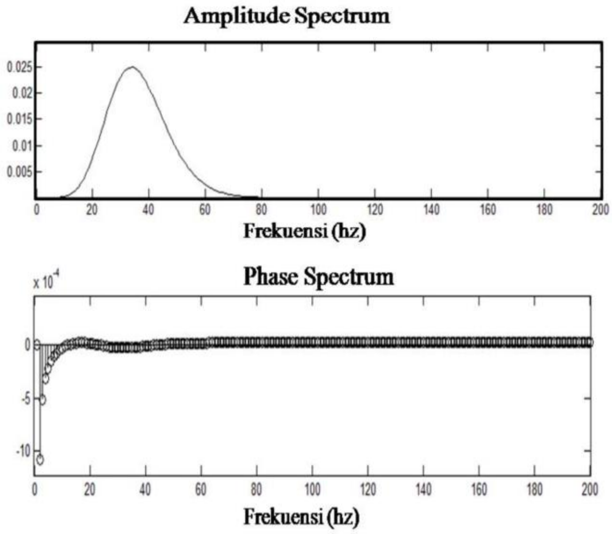
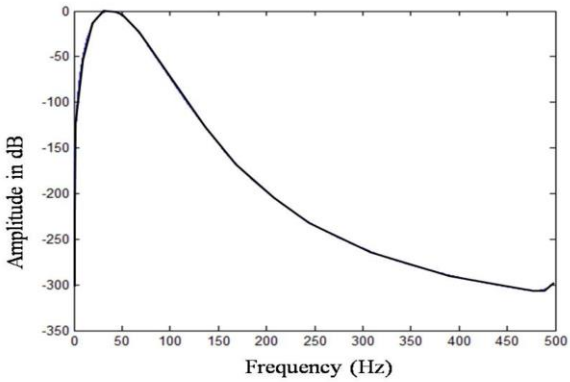
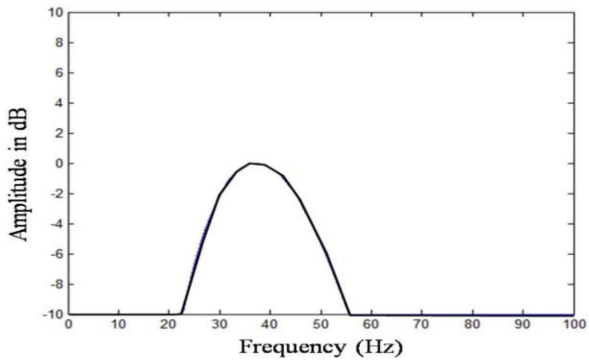


Figure 3. Example of cross-correlation result between two traces in amplitude and phase spectrum.



(a)



(b)

Figure 4. Amplitude spectrum in dB (a) and amplitude spectrum that has been cut above -10 dB (b).

Since Δt is calculated after velocity analysis, then its value will depend on V_{NMO}. Fig. 5 shows Δt at bottom of anisotropy layer (reflector two) for different V_{NMO}. For modeled V_{NMO} = 3695 m/sec, residual moveout start to deviate from 0 m from offset 1800 m and time shifts get larger up to -30 msec showing that faster velocity is needed to flat the reflector event. Meanwhile if picked velocity is too high such as 3800 m/sec, then data is overcorrected and Δt has positive value.

After obtaining Δt of each offset then velocity information is calculated using (7) and apparent interval velocity per offset, *Vp'*, are calculated using Dix's equation. The next step is to transform it to velocity of angle using offset-angle transformation in [12] or other available transformation. Obtained velocity for each angle will be used as an input data for (10) and will be solved by linear inversion method. Solution for linear problem is defined as:

$$m = \left[G^T G\right]^{-1} G^T d. \qquad (11)$$

Where d is known data ($Vp'(\theta)$ and θ), G is kernel matrix, and m is model parameter that we need to estimate ($Vp0'$, ε, and δ). With two known and three unknown parameter then (10) has underdetermined problem and there will be ambiguity in solving the problem. One of ambiguity is the angle range of input data. Reference [5] states that for X/D < 1 (X=offset, D=depth), hyperbolic assumption is still valid and [2] mentions that anisotropy effect is significant for angle >20°. Obtained residual moveout for X/D < 1 is closed to 0, so velocity and angle data that we input for inversion method started from X/D > 1 (around 1800 m) or around 20°.

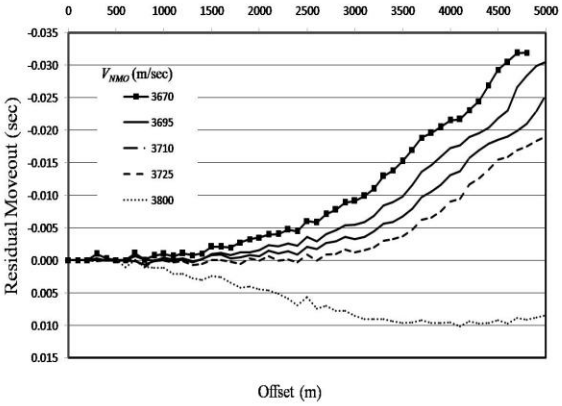


Figure 5. Residual moveout caluclation for different V_{NMO}.

As shown in Fig. 5 that different picked velocity resulted in different residual moveout, then it will result in different value of ε and δ. Fig. 6 shows inversion result of anisotropic parameter estimation for different V_{NMO}. Estimation of ε is quite stable in variation of picked V_{NMO} with error 10% compared to model value. Meanwhile δ value is more varied due variation of V_{NMO} with deviation 25% from the model. This result shows that δ value is more affected by V_{NMO} due to their relationship as defined in (9). Accuracy of ε in this method gives advantage on reservoir interpretation because ε value is more related to rock property [16]. If right V_{NMO} is picked in this case 3695 m/sec, then anisotropy parameter can be estimated closed to the model as shown in Table 1. For vertical velocity, Vp_0, estimation from this method is accurate with an error of 0.5. For δ the inversion result is 0.056 so an error is around 6% and the result for ε is 0.11 with the model 0.12 so an error is around 8%.

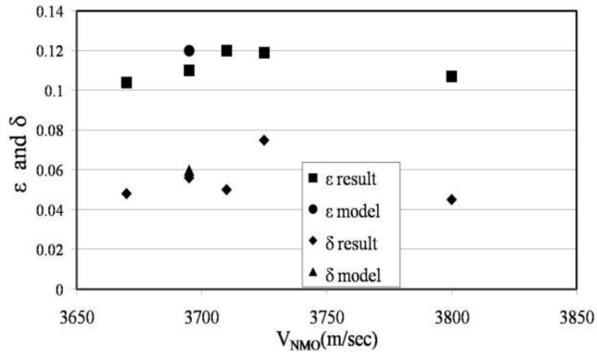


Figure 6. Anisotropic parameter from inversion result for different V_{NMO}

TABLE I. COMPARISON OF ANISOTROPIC PARAMETER BETWEEN MODEL AND INVERSION RESULT

Anisotropic parameter	Model	Inversion Result
$Vp0$ (m/sec)	4100	4127
δ	0.06	0.056
ε	0.12	0.11

V. CONCLUSIONS

VVO method provides alternative tool to predict anisotropic parameters for weak anisotropic case. The assumption of this method is still hyperbolic moveout and doesn't directly give anisotropic parameter during velocity analysis. However it gives advantage in providing separation value of ε and δ in the absence of well velocity. Estimation of ε and δ can help us in understanding reservoir such as lithology or fluid property. In VVO method, estimation of ε has better result compared to δ estimation which δ value is more affected by velocity picking. The method however depends on continuity of seismic event especially at far offset since it will affect residual moveout calculation. Therefore removal of random noise is needed to improve data quality. The ambiguity of inversion method also influences accuracy in anisotropic parameter value. Forward modeling using well information or rock physics study will help us to predict expected value of anisotropic parameters and range of error in our prediction.

REFERENCES

[1] I. Tsvankin, J. Gaiser, V. Grechka, M. Van Der Baan, and L. Thomsen, "Seismic anisotropy in exploration and reservoir characterization: An overview," Geophysics, vol. 75, pp. 75A15-75A29, September 2010.

[2] Z. Wang, "Seismic anisotropy in sedimentary rocks, part 2: Laboratory data," Geophysics, vol. 67, pp. 1423-1440, October 2002.

[3] G.E. Backus, "Long-wave elastic anisotropy produced by horizontal layering," Journal of Geophysical Research, vol. 67, pp. 4427-4440, October 1962.

[4] G. Mavko, T. Mukerji, and N. Godfrey, "Predicting stress induced velocity anisotropy in rocks," Geophysics, vol. 60, pp. 1081-1087, July 1995.

[5] T. Alkhalifah, "Velocity analysis using nonhyperbolic moveout in transversely isotropic media," Geophysics, Vol. 62, pp. 1839-1854, December 1997.

[6] I. Tsvankin and L. Thomsen, "Nonhyperbolic reflection moveout in anisotropic media," Geophysics, vol. 59, pp. 1290-1304, August 1994.

[7] Supriyono, "Velocity variation with angle or offset (VVO), A new tool for direct hydrocarbon indicator, case studies in low and high impedance clastic reservoirs," Doctoral Disertation, Institut Teknologi Bandung, 2011.

[8] L. Thomsen, "Weak elastic anisotropy," Geophysics, vol. 51, pp. 1954-1966, October 1986.

[9] Supriyono, A. Priyono, W. Triyoso, and L. Prasetya, "Velocity Versus Offset (VVO): A new tool for direct detection of gas in low-impedance sand reservoir," First Break, vol 30 , pp. 59-68, April 2012.

[10] R. J. Castle, "Theory of normal moveout," Geophysics, vol. 59, pp. 983-999, June 1994.

[11] T. Alkhalifah and I. Tsvankin, "Velocity analysis for transversely isotropic media," Geophysics, vol. 60, pp. 1550-1566, September 1995.

[12] J. R. Resnick, "Seismic data processing for AVO and AVA Analysis," in Offset dependent reflectivity: theory and practice of AVO analysis, J.P. Castagna and M. M. Backus, Eds., SEG Investigations in Geophysics No. 8, 1993, pp. 175-189.

[13] P. K. Mukhopadhay and S. Mallick, "An accurate ray-based offset-to-angle transform from normal moveout uncorrected multicomponent data in a transversely isotropic medium with vertical symmetry axis," Geophysics, vol. 76, pp. C41-C51, May 2011.

[14] R.G. Stockwell, L. Mansinha, and R.P. Lowe, "Localization of the complex spectrum: The S transform," IEEI Trans. Signal Processing, vol. 44, no 4, pp. 998-1001, April 1996.

[15] I. Herawati, S. Winardhi, W. Triyoso, and A. Priyono, "Estimation of seismic anisotropic parameter using velocity dependent offset analysis," Expanded Abstr., 3rd Ann. Internat. Conf on Geological and Earth Sciences, Singapore, September 2014.

[16] Y. Li, "An empirical method for estimation of anisotropic parameters in clastic rocks," The Leading Edge, vol. 25, pp. 706-711, June 2006.

AUTHORS' PROFILE

Ida Herawati is a doctoral student at Geophysical Engineering Department, Institut Teknologi Bandung (ITB), Indonesia. She got her M.Sc from Colorado School of Mines, USA in 2002. Before pursuing her doctoral degree, she has worked as development geophysicist in oil and gas company for 10 years. Her research interest is in the area of seismic reservoir characterization and anisotropy.

Dr. Sonny Winardhi is a senior lecturer at Geophysics Engineering Department of ITB. He earned his M.Sc and Ph.D from University of Western Ontario, Canada. He has spent more than 13 years on doing research mainly on AVO modelling, stratigraphic inversion study, and multi attribute analysis.

Dr. Wahyu Triyoso is a senior lecturer at Geophysics Engineering Department of ITB. He earned his M.Sc and Ph.D from Tokyo University. He has over 20 years of experience in the field of geophysics for most of oil and gas industry and also seismology for non exploration.

Dr. Awali Priyono is a Professor in Exploration Seismology at Geophysics Engineering of ITB. He got his Doctor in Geophysics from Kiel University-West Germany. He has almost 30 years experiences in seismic acquisition, processing and imaging.