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Reducing Residual Moveout Seismic Anisotropy Model Using Three-Ray GMA (General Moveout Approximation)

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ABSTRACT - A "hockey stick" phenomenon is one of anisotropic effects that should be eliminated in marine seismic data. It can increase residual moveout at the far offsets and impact to the distortion of reflection event amplitude, eventually, reduce the seismic imaging quality. Conventional hyperbolic moveout approximation, an algorithm isotropic model commonly used for seismic processing, has a drawback in supressing such phenomenon. It is also not reliable for medium anisotropy model and long offset data. Many researchers formulated non-hyperbolic moveout approimations but it has limitation analysis for inteval offset-depth ratio (ODR) more than four. We present three-ray generalized moveout approximation (three-ray GMA) for transversely isotropic medium with vertical axis of symmetry (VTI), which is a modified non-hyperbolic moveout approximation from original GMA, to cover up of the weakness of the hyperbolic approximation. The objective of this study is to eliminate "hockey stick" effect and minimize the residual moveout much smaller at once at the far offsets (offset-depth ratio > 4). In this study, we used synthetic data for single layer model in VTI medium to calculate relative traveltime error for each recent method over a range of offsets ($0 \leq ODR \leq 6$) and anisotropic parameters ($0 \leq \eta \leq 0.5$). We also make comparative method for multi layer and implement it in a velocity analysis and residual moveout calculation. The three-ray GMA shows a better capability than comparative method to reduce residual moveout for larger offset. This result is important for enhancing seismic imaging.

Keywords: three-ray GMA moveout approximation, residual moveout, hockey stick, anisotropy

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INTRODUCTION

In exploration activity, long offset seismic data is indispensable to image deeper target of subsurface geology. However, a number of issues arise when the rock layers are very heterogeneous (strong anisotropy). A "hockey stick" phenomenon appears at the far offsets so that it will increase residual moveout value, then impact to the distortion of reflection event amplitude in seismic processing phase. The two-terms of hyperbolic traveltime, an isotropic moveout approximation in seismic data processing, cannot eliminate such phenomenon and has a drawback in handling long offset. Practically, the "hockey stick" usually is removed by muting process, consequently, we lose a lot of rock properties information and the seismic image quality will decrease. Thus, the isotropic moveout approximation is not reliable for medium anisotropy model and long offset data. Here, long offset means that the ratio of the offset (x) value to depth (z) is greater than one or offset-depth ratio (ODR) > 1 at one horizon.

Recent studies have developed anisotropy moveout approximation to improve the capability of isotropy model for larger offset. Tsvankin and Thomsen (1994, 1995) generalized the three-terms equation by including the fourth-order Taylor coefficient for long offset in transversely isotropic medium with vertical axis of symmetry (VTI). Alkhalifah and Tsvankin (1995) rewrited the generalized three-term equation in terms of and the anisotropy parameter η. Alkhalifah (1997) generalized the Dix (1955) equation by introducing effective anisotropy parameter η_{eff} to multilayered VTI media. Fomel and Stovas (2010) proposed generalized moveout approximation (GMA) of the nonhyperbolic approximation that can be applied to any kind of media. Song, *et al.* (2016) used Padé method to transform Taylor series approximation into rational approximation and involved a large number of coefficients. Song, *et al.* (2018) optimized the constant coefficients (up to nine coefficients) of GMA using simulated annealing to improve the accuracy of the original GMA. Those selected approximations have limitation analysis when offset-depth ratio > 4.

In this paper, we employed three-ray GMA method, a modified non-hyperbolic moveout approximation from original GMA. The goals are to minimize residual moveout much smaller and "hockey stick" effect at once; and preserve seismic data at larger offset (ODR > 4). Theoretical analysis and applications in single and multi-layers show that this method is excellent to many existing approximations within a wide range of anisotropy parameter, especially for a large offset-depth ratio.

METHODOLOGY

Moveout approximations for isotropic model

The two-terms or hyperbolic approximation for isotropic model (Taner and Koehler 1969) in use throughout the industry today is:

$$t^2(x) = t_0^2 + \frac{x^2}{V_{NMO}} \quad (1)$$

where is the traveltime as a function of offset , is the traveltime at zero offset, and is the velocity normal moveout. In conventional velocity analysis, the normal moveout (NMO) velocity is denoted as the root-mean square velocity (V_{RMS}). A more realistic representation of the traveltime equation implies knowledge of the anisotropic medium. The standard normal moveout (Equation 1) only considers the first two-terms of Taylor' series expansion and it is suitable for small offset.

Moveout approximations for anisotropic model (VTI medium)

Several moveout approximations or methods deal with VTI model (anisotropic) that we recast in such following:

Alkhalifah and Tsvankin approximation

The three parameters t_o , V_{NMO}, and η suggested by Tsvankin and Thomsen (1994) and modified by Alkhalifah and Tsvankin (1995) given by

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

where η is anisotropic parameter (anellipticity parameter)

Generalized moveout approximation (GMA)

The generalized moveout approximation or GMA was proposed by Fomel and Stovas (2010) with the functional form

$$t^2(x) = t_0^2 + \frac{x^2}{V_{NMO}} - \frac{Ax^4}{t_0^2\, V_{NMO}^4 + Bx^2 + V_{NMO}^4\sqrt{t_0^4 + 2Bt_0^2\frac{x^2}{V_{NMO}} + C\frac{x^4}{V_{NMO}^4}}} \quad (3)$$

where $A = 4\eta$, $B = \frac{1+8\eta+8\eta^2}{1+2\eta}$, and $C = \frac{1}{(1+2\eta)^2}$ for the accoustic VTI medium.

Three ray VTI GMA approximation

Abedi and Stovas (2019) introduced three-ray GMA method by modifying original GMA (Equation 3) and substituting parameters A, B, and C with

$$A = 4\eta\frac{(\eta + \sqrt{1+2\eta})^2}{(1+2\eta)^2}$$

$$B = \frac{1 + 2\eta(2 + \eta + 2\sqrt{1+2\eta})}{1+2\eta}$$

$$C = \frac{1}{(1+2\eta)^2} \quad (4)$$

Such moveout approximation is uniquely defined by three independent parameters of t_o, V_{NMO}, and η without raytracing and adequate for velocity analysis.

Moveout approximation test

For accuracy test of the moveout approximation, we use single layer for synthetic model with input common mid-point gather (CMP gather) for anisotropy parameters. The layer thickness is 1000 m and the vertical velocity is 2000 m/s. The 2D profile has a maximum offset of 6000 m, adopting mostly offshore seismic acquisition parameters (see Figure 1). This implies that the maximum offset-depth ratio is six. Here, we set anisotropic parameter (η) value is 0.5, considered as strong anisotropic.

The relative error (Δt) of moveout approximation can be computed by Equation 5 and the exact traveltime uses the eikonal raytracing anisotropy (Daley, *et al.*, 2010).

$$\Delta t = \frac{|t_{exact} - t_{approx}|}{t_{exact}} \quad (5)$$

In multi layer model, velocity analysis is conducted to obtain velocity and anisotropic parameter (η), which these parameters become input for flatenning process. In terms of velocity analysis, we carried out semblance scans for estimating V_{NMO} and the η parameter. As a proven semblance anisotropy approach, we use AB semblance algorithm (S_{AB}), which was developed by Sarkar, *et al.* (*2001, 2002*) and Fomel (*2009*), and defined as

$$S_{AB}(c) = \frac{\sum_{i=c-M}^{c+M}\left(\sum_{j=0}^{N-1} W(i,j)\ F(i,j)\right)^2}{\sum_{i=c-M}^{c+M}\left(\sum_{j=0}^{N-1} W^2(i,j)\sum_{j=0}^{N-1} F^2(i,j)\right)} \quad (6)$$

$$W(i,j) = A(i,j) + B(i,j)\ \varphi(i,j)$$

where (i,j) is a weighting function, c is the center of the time window, $2M+1$ is the length of the time window, N is the number of traces in one CMP gather, is the i-th sample amplitude of the j-th trace in the NMO-corrected CMP gather. Both and η values are picked from the maximum semblance coherency and used for flattening the reflection events.

After flatenning, we stack the traces from near-to-far offsets and provide amplitude spectra analysis to show the capability of the moveout approximation in enhancing the quality of stacked-trace seismic. By a simple mathematical operation, the residual moveout can be calculated as the difference between the exact traveltimes of reflection event and zero offset event (t_o). Besides, the best result of residual moveout of an approximation can be also indicated by wider bandwidth spectrum.

RESULTS AND DISCUSSION

Figure 2 depicts the traveltime (two-way time) vs offset curve from selected moveout approximations in a single layer VTI medium. The two-way time of 1000 ms comes from (see Figure 2), which is the traveltime at zero offset. Due to anisotropic effect, the hyperbolic moveout (Δt) approximation curve starts to deviates from offset 1000 metres and significantly increases at the far offsets. We can see that the three-ray GMA moveout approximation shows the best fitting with exact model (raytracing anisotropy) in whole data plot. Figure 3 shows the relative error of moveout approximation (in percentage) vs offset-depth ratio curve. The three ray GMA moveout approximation has much smaller error than other approximations for η = 0.5, indicating this approxination has better capability to reduce the residual moveout as well. For further analysis, we present 3D plots of relative traveltime errors (Δt) for anisotropy parameters in interval 0 ≤ η ≤ 0.5 and offset-depth ratios (x/z) over the range 0 ≤ ODR ≤ 6, as shown in Figure 3. Again, the three ray GMA moveout approximation show higher performance and superiority over the entire range.

In this section, we implement the moveout approximation to a synthetic model for multi layer in VTI medium with the far offsets of 6000 meters. The elastic and anisotropic parameters of each layer are summarized in Table 1. In Figure 5, we shows a few representative rays traced in a CMP pattern (Figure 5a) and a synthetic seismogram of the reflection events (Figure 5b), which are designated as VTI-anisotropic layers. The synthetic seismogram was generated at a 1-millisecond sampling rate using a Ricker wavelet as the source with a dominant frequency of 25 Hz.

In velocity analysis and flatenning (or normal moveout correction) step, by using hypercbolic moveout approximatiton, "hockey stick" strongly appears at the far offsets and the gaps or reflector deviation exhibits the residual moveout that caused by anisotropic effect (Figure 6). This condition should be avoided becasue it can smear the amplitude event in stacking traces step.

We make comparative velocity analysis (semblance) between the generalized moveout approximation (GMA) and the three ray VTI. Figure 7 displays the semblance scan over and η calculated from the reflection events in Figure 6 using the GMA approximation (Figure 7a) and the three ray VTI approximations (Figure 7b). The best-fit value with

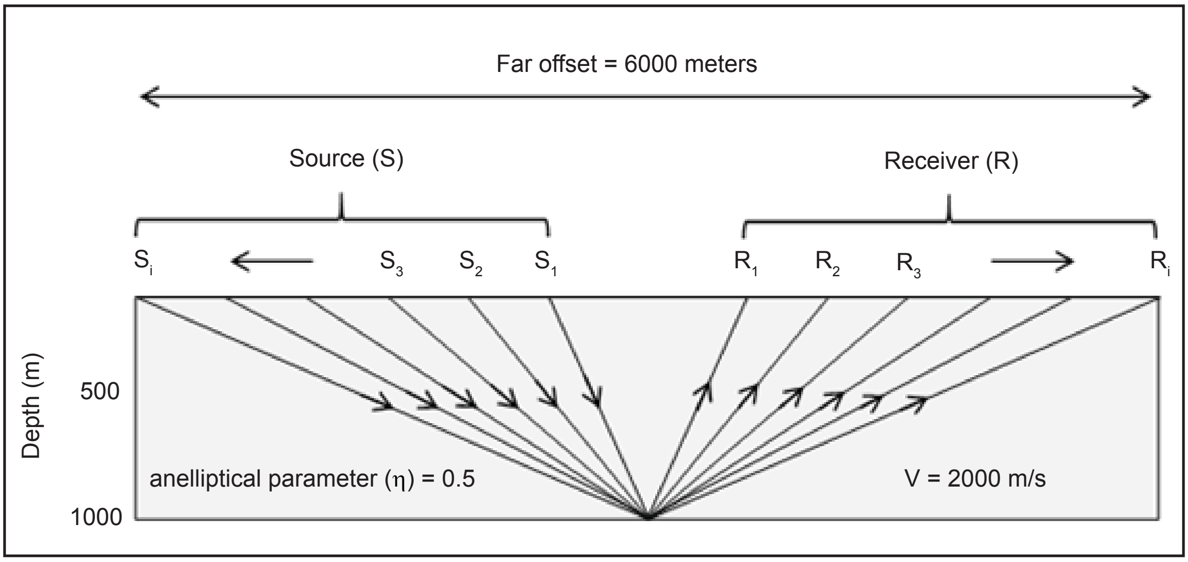

Figure 1
Single layer for synthetic model with offset-depth ratio of six.

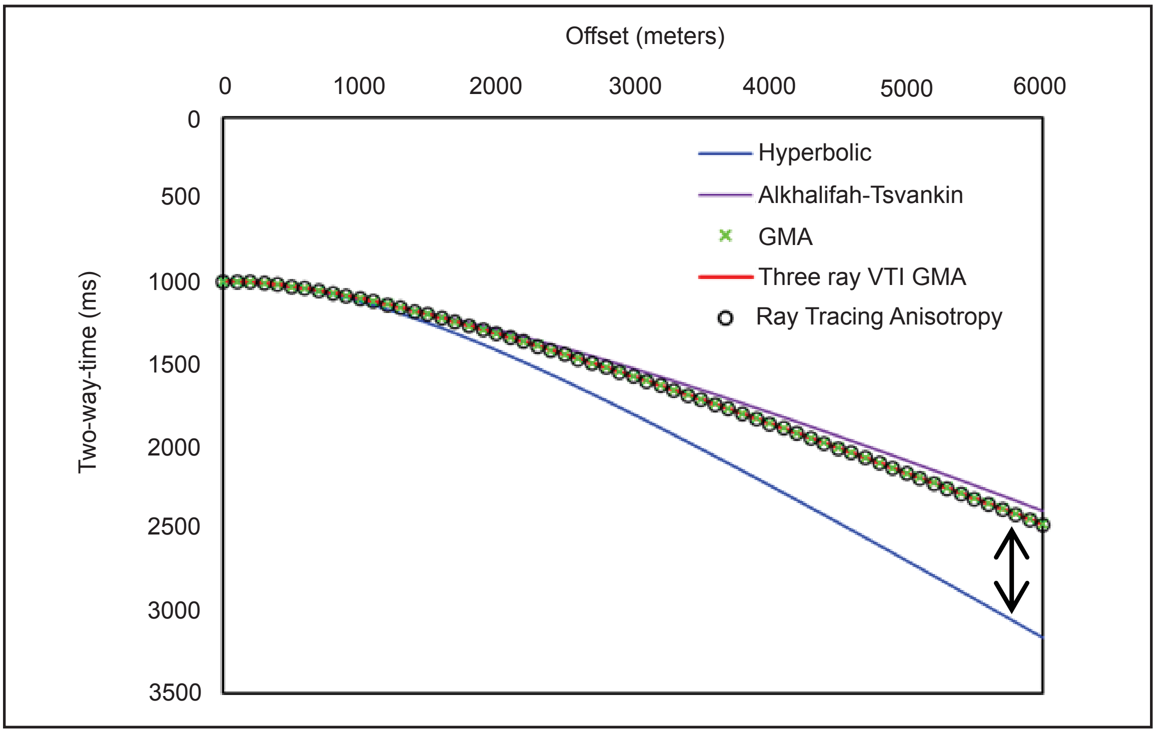

Figure 2
Two-way time vs offset curve of selected moveout approximation.
The hyperbolic approximation deviates due to anisotropic effect
and the three ray GMA has the best fitting to the exact model (raytracing anisotopy).

maximum semblance from each approximation is indicated by a white cross. These and η values are considered as velocity and anisotropic parameter stacking, then used for flatenning or NMO correction.

Comparative approximation is able to mitigate the "hockey stick" effect and supress the residual moveout much more than hyperbolic approximation (as shown Figure 8). The residual moveout values can be computed by substracting the exact traveltimes of reflection event and two-way time at = 998 ms, 1424 ms, 1790 ms, and 2130 ms (shown by magenta dased-line), respectively. Figure 8a (left side) shows

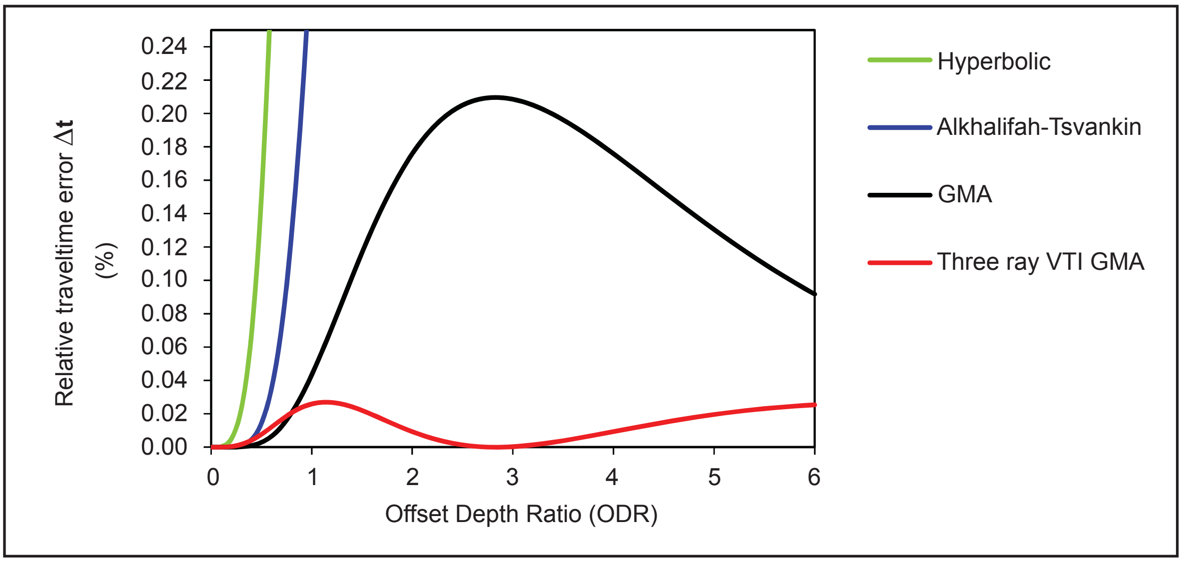

Figure 3
Curves of traveltime error vs offset-depth ratio for anisotropic parameter (η) = 0.5.
The three ray GMA has much smaller error than existing approximations.

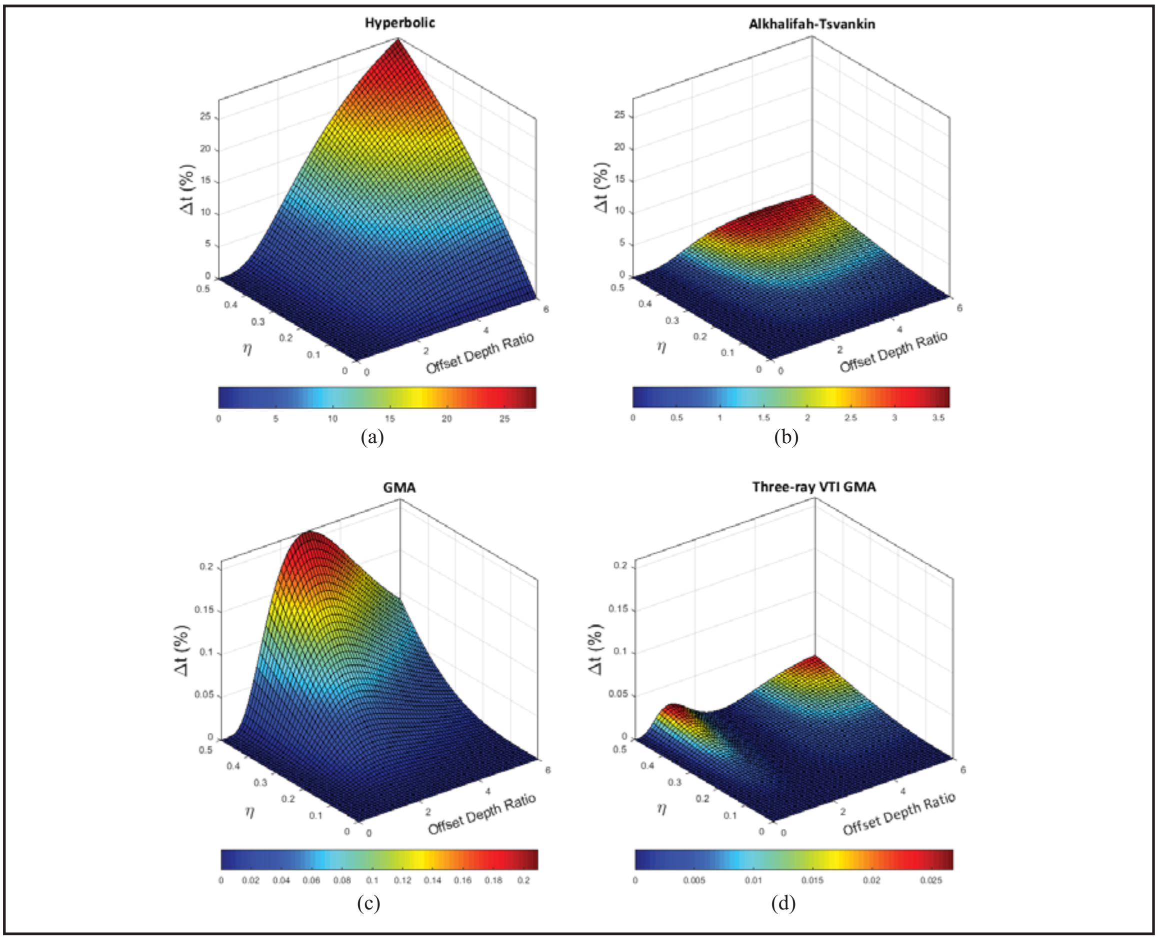

Figure 4
3D plots of relative traveltime errors (Δt in percentage) vs anisotropic parameter (Δ) vs offset-depth ratio (x/h) from selected approximations. The three ray VTI GMA has much smaller relative errors over the entire range.

the flatenned reflector and detail view of residual moveout plot from each trace (right side). The GMA approximation generates maximum residual is 4 miliseconds at the 2nd reflector, while the three ray GMA is 2 miliseconds at 1st- and 2nd reflectors. At the far offsets, the errors are always larger than at the near or mid offsets, where the anisotropic strongly interferes the seismic data. For many layers, one should keep in mind that despite it has small errors in the case of a few layers, the errors would be accumulated in deeper layers. Hence, we should have a robust approximation to minimize the such residual as much as possible.

When we obtain the best result of residual moveout from previous step, in stacking analysis, definitely, we would obtain better summation of traces and higher frequency content, in spite it is not discussed in this session. This is very important for enhancing the seismic image in deeper structure and reservoir characterisation.

CONCLUSION

The hyperbolic approximation, which is used for isotropic model, is not suitable for anisotropic model. An anisotropic effect (“e.g hockey stick” phenomenon) disturbs the seismic data at the far offsets and this impacts to the increasing of residual moveout when conducting NMO correction in seismic processing phase. We presented a robust moveout approximation, the three ray GMA, to eliminate such phenomenon. From numerical experiment results using synthetic data for a single layer, the relative traveltime errors can be reduced to much smaller values than existing methods with a large anisotropic parameter ($\eta = 0.5$)

Table 1
Elastic and anisotropic parameters of ***i***-th layer

Layer	Depth interval (m)	Vp (m/s)	Anisotropic parameter (*h*)
1	0 – 1270	2550	0.0254
2	1270 – 1800	2490	0.1388
3	1800 – 2300	2698	0.0537
4	2300 – 2700	2509	0.2067

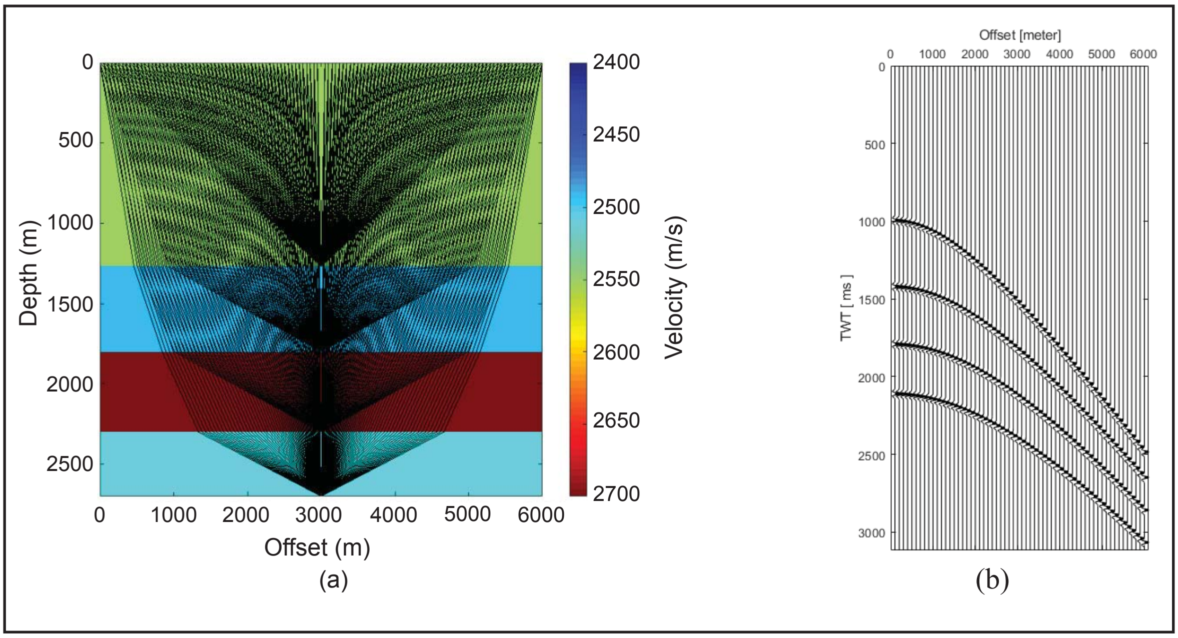

Figure 5
(a) The multilayer of VTI anisotropic model showing reflected rays.
(b) Synthetic seismogram of the reflection events.

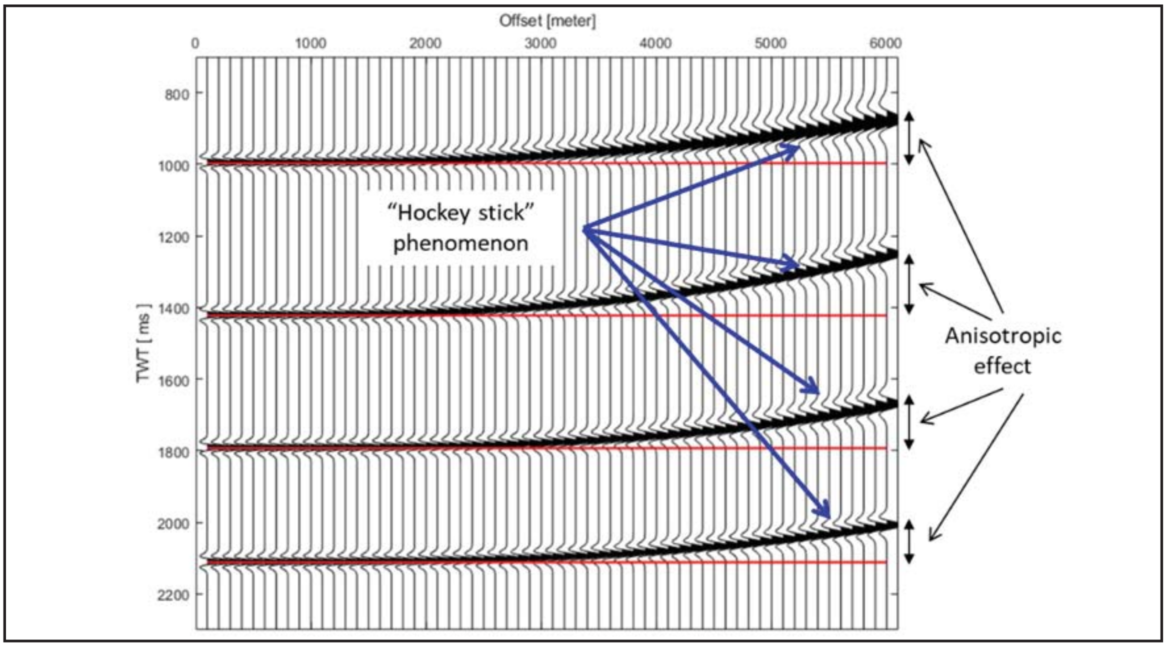

Figure 6
Flatenning reflection events using hyperbolic moveout approximation. A “hockey stick” phenomenon appears at the far offsets. Residual moveout also becomes larger at that position.

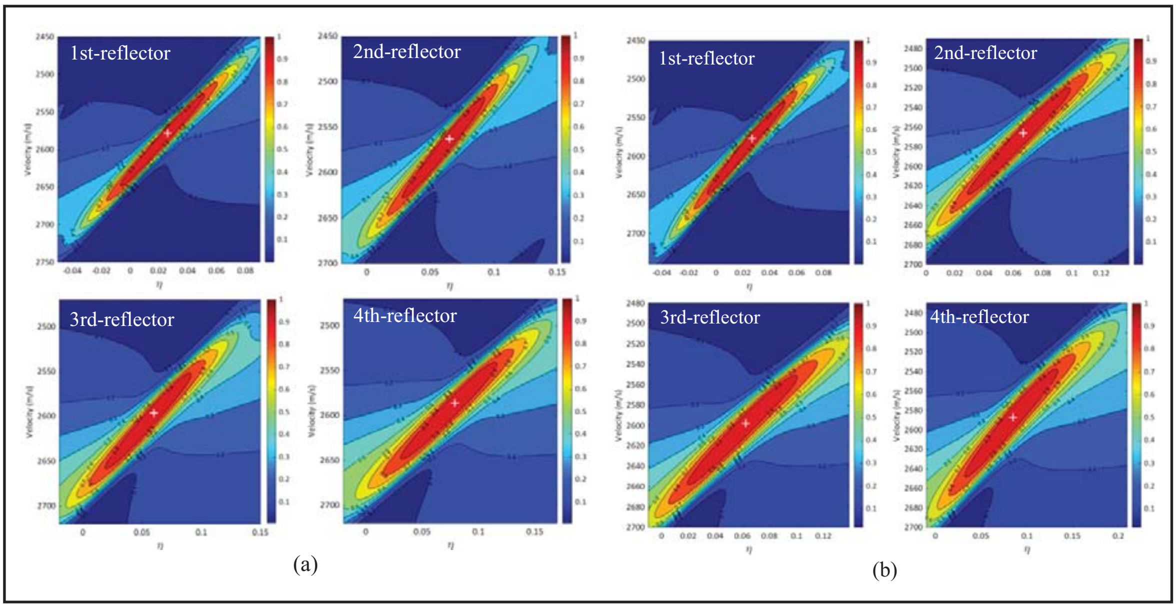

Figure 7
Semblances search over and η showing velocity and η value picks resulting from (a) the GMA approximation and (b) the three ray GMA for the 1^{st}, 2^{nd}, 3^{rd}, and 4^{th} layers, respectively. The white cross indicates the pick or maximum semblance value.

and over a wide range of anisotropy parameters ($0 \leq \eta \leq 0.5$) and offset-to-depth ratios ($0 \leq ODR \leq 6$). For multilayer case, the three ray GMA technique has better capability to reduce residual moveout than comparative GMA method at the far offsets. This is a key to succes in enhancing seismic imaging, especially deeper structures.

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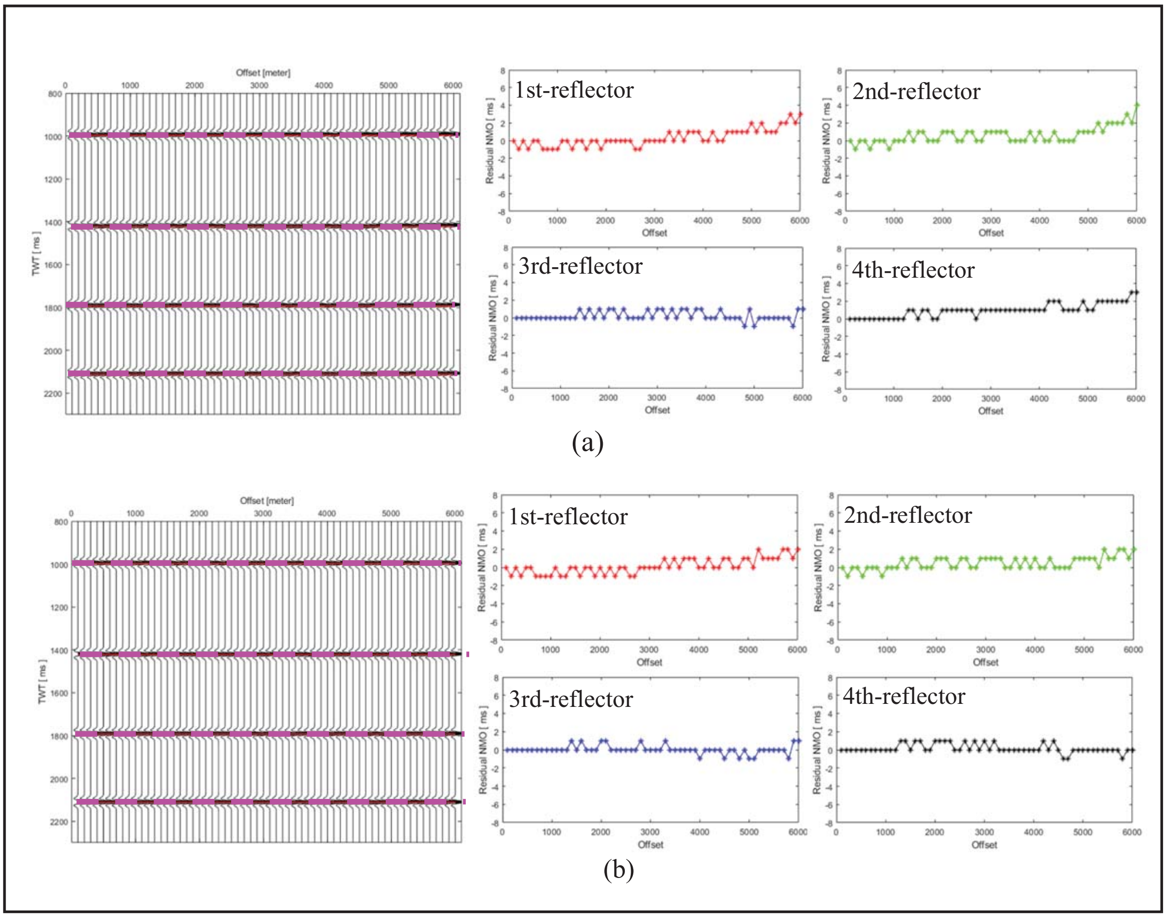

Figure 8
Seismic reflection and residual moveout
result using the GMA approximation and (b) using the three-ray GMA.

GLOSSARY OF TERMS

Symbol	Definition	Unit
CMP Gather	Common Mid-Point Gather	
NMO	Normal Moveout	
ODR	Offset-Depth Ratio	
Three-ray GMA	Three-ray Generalized Moveout Approximation	
VTI	Transversely Isotropic Medium with Vertical Axis of Symmetry	(%)
Δt	Relative Error	

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