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Prestack migration velocity analysis based on simplified two-parameter moveout equation*

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Abstract: Stacking velocity V_{C2}, vertical velocity ratio γ_0, effective velocity ratio γ_{eff}, and anisotropic parameter χ_{eff} are correlated in the PS-converted-wave (PS-wave) anisotropic prestack Kirchhoff time migration (PKTM) velocity model and are thus difficult to independently determine. We extended the simplified two-parameter (stacking velocity V_{C2} and anisotropic parameter k_{eff}) moveout equation from stacking velocity analysis to PKTM velocity model updating and formed a new four-parameter (stacking velocity V_{C2}, vertical velocity ratio γ_0, effective velocity ratio γ_{eff}, and anisotropic parameter k_{eff}) PS-wave anisotropic PKTM velocity model updating and process flow based on the simplified two-parameter moveout equation. In the proposed method, first, the PS-wave two-parameter stacking velocity is analyzed to obtain the anisotropic PKTM initial velocity and anisotropic parameters; then, the velocity and anisotropic parameters are corrected by analyzing the residual moveout on common imaging point gathers after prestack time migration. The vertical velocity ratio γ_0 of the prestack time migration velocity model is obtained with an appropriate method utilizing the P- and PS-wave stacked sections after level calibration. The initial effective velocity ratio γ_{eff} is calculated using the Thomsen (1999) equation in combination with the P-wave velocity analysis; ultimately, the final velocity model of the effective velocity ratio γ_{eff} is obtained by percentage scanning migration. This method simplifies the PS-wave parameter estimation in high-quality imaging, reduces the uncertainty of multiparameter estimations, and obtains good imaging results in practice.
Keywords: PS-converted-wave, PKTM velocity updating, two-parameter moveout equation, migration imaging

Introduction

In recent years, converted seismic waves (P-to-S on reflection) have been successfully used in gas cloud imaging, crack detection, heterogeneous reservoir prediction, and reservoir dynamic monitoring (Davis et al., 2012; Kendall, 2012; Calderon et al., 2013; Akalin et al., 2014; Donati et al., 2014; Zhang et al., 2015, etc). High-quality imaging processing of PS-wave data

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is critical to successful PS-wave seismic exploration, and PS-wave velocity analysis methods directly affect the accuracy of PS-wave data imaging. Compared with P-wave imaging, the PS-wave imaging more strongly depends on the velocity model. Because the PS-wave path is asymmetric and the traveling time formula is complex owing to several factors, such as the changes in P-wave and S-wave velocity, underground anisotropy, and the complexity of the common conversion point. With the development of PS-wave imaging, several methods for PS-wave velocity analysis have been studied and the PS-wave NMO equation was transformed from lower order to higher order and from a simple single-parameter to a high-precision multi-parameter form. Tessmer and Behle (1988) derived a velocity approximation formula for converted shear waves in homogeneous isotropic media according to Snell's law. Slotboom et al. (1990) presented a time-shifted hyperbolic form of the PS-wave time distance equation. Thomsen (1999) derived a high-order traveling time approximation equation of PS waves in layered media. According to the parameter definition of Thomsen (1999), by introducing a factor χ_{eff} that represents the anisotropic effect of PS-wave in VTI media, Li and Yuan (2001) derived a four-parameter (stacking velocity V_{C2}, vertical velocity ratio γ_0, effective velocity ratio γ_{eff}, and anisotropic parameter χ_{eff}) time–distance curve equation for simplified multilayered VTI media; furthermore, they extended the PS-wave prestack time migration double square root scattering wave equation from a single layer to multiple layers in VTI media and presented the relation between the initial velocity model of the PS-wave prestack time migration and the four-parameter stacking velocity model. Li and Yuan (2003, 2005a, 2005b) further studied the conversion point calculation and traveling time four-parameter model, developed a PS-wave PKTM imaging approach based on the asymptotic conversion point four-parameter velocity model, and provided a scheme and examples of the four-parameter velocity analysis. To improve the anisotropic parameters' reliability of the four-parameter velocity analysis, Miao and Zuk (2006) presented the simultaneous estimation of P-wave and PS-wave anisotropic parameters. Dai and Li (2007a, 2007b) theoretically proved that migration velocity updating is convergent based on the four-parameter iterative stacking velocity analysis in inverse normal-moveout common imaging point (CIP) gathers and further improved the velocity updating. Dai and Li (2006, 2008) further investigated the influence of velocity model error on the imaging accuracy of the PS-wave anisotropic prestack Kirchhoff time migration (PKTM). In summary, the four-parameter velocity analysis has been developed as the primary PS-wave time domain high-accuracy imaging method with good results in the PS-converted-wave seismic data processing (Yang et al., 2014; Yang et al., 2015, etc).

The PS-wave anisotropic PKTM imaging method based on the four-parameter velocity model can avoid the difficulties in the extraction of the time varying common conversion point and improve the imaging effect. This method takes a four-parameter stacking velocity model as the initial velocity model of PKTM and uses these parameters to carry out PKTM and obtain the CIP gathers; then, it corrects the velocity model by analyzing the residual moveout on the CIP gathers until all seismic events are flattened. This process requires several iterations, it is complex, and the interaction between the three parameters is not easy to determine accurately. It is worth looking into high-precision and high-efficiency imaging velocity parameter analysis technologies for improving the PS-wave seismic data processing. Based on the four-parameter time–distance curve equation, simplified equations have been proposed to improve the practicability and stability of the imaging velocity analysis (Dai and Li, 2005, 2010; Li, et al., 2013). Dai and Li (2005) combined and simplified the four-parameter time–distance curve equation that is based on the stacking velocity V_{C2}, the anisotropic parameter k_{eff}, and empirical parameter m and obtained a simplified equation with precision equivalent to the original four-parameter equation. Dai and Li (2010) further expanded the model analysis by relating m and k_{eff} with an approximately linear relation and simplified the equation to a two-parameter moveout equation, which can be used to carry out high-precision two-parameter stacking velocity analysis of PS waves. However, the high-precision PS-wave anisotropic PKTM typically requires four parameters (V_{C2}, γ_0, γ_{eff}, and χ_{eff}). Hence, the PS-wave PKTM velocity analysis is still complex and requires sequentially determining the difficult-to-handle stacking velocity V_{C2}, vertical velocity ratio γ_0, effective velocity ratio γ_{eff}, and anisotropic parameter χ_{eff}, which may produce multiple solutions in the iterative velocity analysis.

To overcome this problem, we extended the simplified two-parameter moveout equation from stacking velocity analysis to anisotropic PKTM velocity model updating and developed a new four-parameter (V_{C2}, γ_0, γ_{eff}, and k_{eff}) PS-wave anisotropic PKTM velocity updating method based on the simplified two-parameter moveout equation.

PS-wave anisotropic velocity analysis

Simplified two-parameter NMO equation

In multilayered VTI media, the simplified form (Dai and Li, 2005) of the four-parameter time-distance curve equation is

$$t_{\mathrm{C}}^2 = t_{\mathrm{C0}}^2 + \frac{x^2}{V_{\mathrm{C2}}^2} - 2k_{\mathrm{eff}} \frac{x^4}{V_{\mathrm{C2}}^2\left[t_{\mathrm{C0}}^2 V_{\mathrm{C2}}^2 + m \cdot x^2\right]}, \tag{1}$$

$$k_{\mathrm{eff}} = \frac{\left(\gamma_0\gamma_{\mathrm{eff}} - 1\right)^2 + 8\chi_{\mathrm{eff}}\left(1+\gamma_0\right)}{8\gamma_0\left(1+\gamma_{\mathrm{eff}}\right)^2}, \tag{2}$$

$$m = 2k_{\mathrm{eff}} \frac{\left(1+\gamma_0\right)\left[\left(\gamma_0 - 1\right)\gamma_{\mathrm{eff}}^2 + 2\chi_{\mathrm{eff}}\right]}{\left(\gamma_0 - 1\right)\gamma_{\mathrm{eff}}\left(\gamma_0\gamma_{\mathrm{eff}} - 1\right) + 2\left(1+\gamma_0\right)\chi_{\mathrm{eff}}}, \tag{3}$$

where x is the offset, V_{C2} is the PS-wave stacking velocity, and k_{eff} and m are functions of γ_0, γ_{eff}, and χ_{eff}. For maintaining the same precision as the original four-parameter equation, m can take empirical values.

Dai and Li (2010) further tested the simplified model and obtained the approximate linear relation between m and k_{eff}

$$m \approx 0.1 + 2.7k_{\mathrm{eff}}. \tag{4}$$

Thus, in multilayered VTI media, the PS-wave anisotropic NMO equation reduces to two parameters and is similar to the P-wave anisotropic NMO equation. This equation reduces the complexity of the PS-wave anisotropic stacking velocity analysis and the uncertainty of the solution of the four-parameter equation.

PS-wave anisotropic scattering equation and prestack time migration

In multilayered VTI media, the PS-wave scattering equation (Li and Yuan, 2001) is

$$t_{\mathrm{C}} = \sqrt{t_{\mathrm{P0}}^2 + \frac{x_{\mathrm{P}}^2}{V_{\mathrm{P2}}^2} - \frac{2\eta_{\mathrm{eff}} x_{\mathrm{P}}^4}{V_{\mathrm{P2}}^2\left[t_{\mathrm{P0}}^2 V_{\mathrm{P2}}^2 + (1+2\eta_{\mathrm{eff}})x_{\mathrm{P}}^2\right]}} + \sqrt{t_{\mathrm{S0}}^2 + \frac{x_{\mathrm{S}}^2}{V_{\mathrm{S2}}^2} - \frac{2\zeta_{\mathrm{eff}} x_{\mathrm{S}}^4}{V_{\mathrm{S2}}^2\left[t_{\mathrm{S0}}^2 V_{\mathrm{S2}}^2 + x_{\mathrm{S}}^2\right]}}, \tag{5}$$

where,

$$t_{\mathrm{P0}} = \frac{t_{\mathrm{C0}}}{1+\gamma_0}, \tag{6}$$

$$t_{\mathrm{S0}} = \frac{\gamma_0 t_{\mathrm{C0}}}{1+\gamma_0}. \tag{7}$$

In equation (5), t_{C} is the PS-wave traveling time, t_{C0} is the PS-wave equivalent vertical two-way traveling time, t_{P0} and t_{S0} correspond to the downward P-wave traveling time and upward S-wave traveling time, x_{P} and x_{S} are respectively the scattering point to the shot point and the receiver point of the horizontal distance, V_{P2} and V_{S2} are respectively the P-wave and S-wave RMS velocity, and η_{eff} and ζ_{eff} correspond to P-wave and S-wave anisotropic parameters.

There are also five parameters (γ_0, V_{P2}, V_{S2}, η_{eff}, and ζ_{eff}) in the anisotropic scattering equation conversion that control the process of PS-wave anisotropic PKTM, where V_{P2}, V_{S2}, η_{eff}, and ζ_{eff} are known as the PS-wave prestack time migration velocity parameters, and they are typically obtained through the relation equation calculation from V_{C2}, γ_0, γ_{eff}, and χ_{eff} that can be obtained by stacking velocity analysis.

Relation equations

The anisotropic prestack time migration velocity and stacking velocity parameters (Li and Yuan, 2001) are related as follows:

$$V_{\mathrm{P2}}^2 = \frac{\gamma_{\mathrm{eff}}(1+\gamma_0)}{1+\gamma_{\mathrm{eff}}} V_{\mathrm{C2}}^2, \tag{8}$$

$$V_{\mathrm{S2}}^2 = \frac{1+\gamma_0}{\gamma_0(1+\gamma_{\mathrm{eff}})} V_{\mathrm{C2}}^2, \tag{9}$$

$$\eta_{\mathrm{eff}} = \frac{\chi_{\mathrm{eff}}}{\left(\gamma_0 - 1\right)\gamma_{\mathrm{eff}}^2}, \tag{10}$$

$$\zeta_{\mathrm{eff}} = \frac{\chi_{\mathrm{eff}}}{1-\gamma_0}. \tag{11}$$

Therefore, from the stacking velocity analysis, we can obtain the initial velocity model (V_{C2}, γ_0, γ_{eff}, and χ_{eff}) to realize the PS-wave prestack time migration.

From the simplified two-parameter stacking velocity analysis, we can only obtain V_{C2} and k_{eff}, and γ_0, γ_{eff}, and χ_{eff} are unknown. However, the vertical velocity ratio γ_0 can be obtained through the vertical travel-time equation that is obtained by the superposition of the matched P and PS waves

$$\gamma_0 = \frac{2t_{\mathrm{C0}}}{t_{\mathrm{PP0}}}, \tag{12}$$

where t_{PP0} is the P-wave vertical two-way traveling time.

The effective velocity ratio γ_{eff} is more stable under weakly anisotropic media conditions. Combined with the P-wave stacking velocity, the initial γ_{eff} can be calculated according to Thomsen (1999)

$$\gamma_{eff} = \frac{V_{P2}^2}{(1+\gamma_0)V_{C2}^2 - V_{P2}^2}. \quad (13)$$

Finally, χ_{eff} is

$$\chi_{eff} = \frac{8k_{eff}\gamma_0(1+\gamma_{eff})^2 - (\gamma_0\gamma_{eff}-1)^2}{8(1+\gamma_0)}. \quad (14)$$

Equations (10) and (11) can be rewritten as

$$\eta_{eff} = \frac{1}{(\gamma_0-1)\gamma_{eff}^2}\frac{8k_{eff}\gamma_0(1+\gamma_{eff})^2 - (\gamma_0\gamma_{eff}-1)^2}{8(1+\gamma_0)}, \quad (15)$$

$$\zeta_{eff} = \frac{1}{1-\gamma_0}\frac{8k_{eff}\gamma_0(1+\gamma_{eff})^2 - (\gamma_0\gamma_{eff}-1)^2}{8(1+\gamma_0)}. \quad (16)$$

Thus, the relation of the parameters of equation (5) η_{eff}, ζ_{eff}, and k_{eff} is established. Equations (15) and (16) are more complex than equations (10) and (11).

Method application

By using the relation between the stacking and prestack time migration velocity, the migration velocity can be directly corrected with V_{C2} and γ_{eff}, and the migration anisotropic parameters η_{eff} and ζ_{eff} can be estimated using k_{eff} and γ_{eff}. Therefore, based on the analysis of V_{C2}, k_{eff}, and γ_{eff}, it is adequate to modify the prestack time migration velocity model (V_{P2}, V_{S2}, η_{eff}, and ζ_{eff}). The implementation of the new method process is as follows (Figure 1):

1. First, the P waves are processed by using hyperbolic velocity analysis to obtain the final stacking velocity V_{P2} and stacked section. On the asymptotic- or specified-layer common converted point gathers, the PS-wave velocity analysis using equations (1), (2), and (4) yields V_{C2} and k_{eff}. In the velocity analysis, V_{C2} controls events with near offsets and k_{eff} controls events with intermediate and far offsets. In the conversion point gathers, the near- and far-offset events are flattened. If the events are not flattened, the two parameters must be modified until the final stacking velocity V_{C2}, k_{eff}, and stacked sections are obtained.

2. The vertical velocity ratio γ_0 is estimated by correlating events in the P-wave and PS-wave stacked sections or migrated images after horizon calibration. The initial γ_{eff} is calculated by using equation (13) (Thomsen, 1999). From equations (15) and (16) and by using γ_0, γ_{eff}, and k_{eff}, η_{eff} and ζ_{eff} can be obtained without calculating χ_{eff}. Thus, from the new V_{C2}, γ_0, γ_{eff}, and k_{eff}, the initial velocity parameters of the prestack time migration can be determined.

3. According to equations (6) and (7), (8) and (9), and (15) and (16), the prestack time migration initial velocity model is calculated from the new four parameters, and the first run of PKTM is carried out to obtain the CIP gathers. Two-parameter velocity analysis is carried out on the CIP gathers, and the residual time difference is used to revise the parameters V_{C2} and k_{eff}. If the near- and far-offset events on the CIP gathers are uneven, V_{C2} and k_{eff} are modified till all events are flattened.

4. Finally, according to the tilt degree of events on the positive and negative offset of the CIP gathers or imaging profile quality, the scanning range and scanning interval of γ_{eff} are set to carry out the scanning PKTM and to determine the best γ_{eff} by comparing the imaging section.

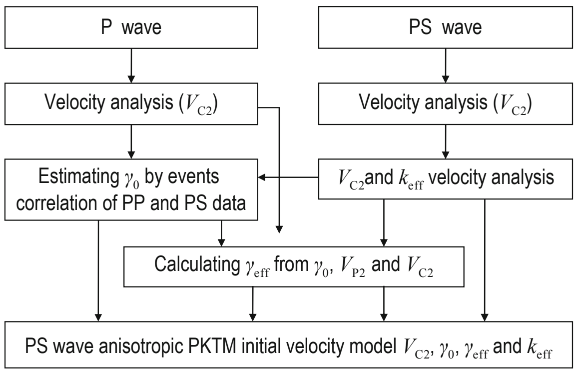

Fig.1 Initial velocity model of PS-wave prestack time migration.

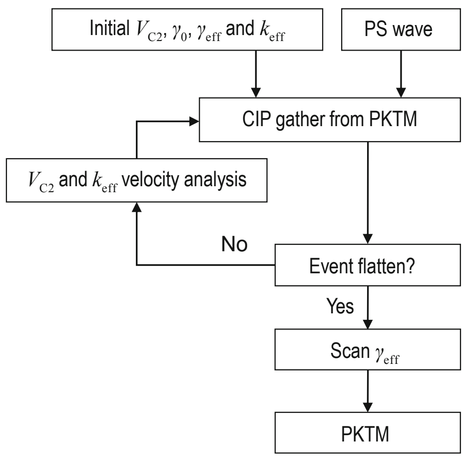

Fig.2 Anisotropic velocity updating of PS-wave prestack time migration.

In implementing this method, we first obtain V_{C2} and k_{eff} by using two-parameter stacking velocity analysis and derive the initial velocity model for migration imaging. The sparse vertical velocity ratio γ_0 is then calculated by matching the events of the P- and PS-wave stacking profiles, and the initial γ_{eff} is calculated with the Thomsen equation from the P-wave stacking velocity V_{P2}, the PS-wave stacking velocity V_{C2}, and vertical velocity ratio γ_0. Next, the velocity correction (Figure 2) is carried out by using the PS-wave PKTM and the two-parameter velocity analysis —first, the V_{C2} is accurately determined and then k_{eff} by analyzing the residual moveout—till the CIP gather events are completely flattened. Finally, using the PS-wave PKTM percentage scanning, the best γ_{eff} is determined by comparing the image quality. In this manner, the PS-wave anisotropic PKTM velocity analysis can be simplified, and V_{C2}, k_{eff}, γ_{eff}, and γ_0 can be determined clearly.

Sensitivity analysis of the simplified NMO equation

To analyze the sensitivity of the effect of the various parameters in equation (1) on the traveling time, the equation is rewritten as

$$t_C^2 = t_{C0}^2 + \frac{x^2}{V_{C2}^2} - \frac{2k_{eff}x^4}{V_{C2}^2\left[t_{C0}^2V_{C2}^2 + \left(0.1 + a\cdot k_{eff}\right)x^2\right]}. \quad (17)$$

The traveling time error can be quantitatively expressed as

$$\Delta t_C = E_{V_{C2}}\Delta V_{C2} + E_{k_{eff}}\Delta k_{eff} + E_a\Delta a, \quad (18)$$

where

$$E_{V_{C2}} = -\frac{x^2}{V_{C2}^3} + \frac{2k_{eff}t_{C0}^2x^4}{V_{C2}\left[t_{C0}^2V_{C2}^2 + \left(0.1 + a\cdot k_{eff}\right)x^2\right]^2} + \frac{2k_{eff}x^4}{V_{C2}^3\left[t_{C0}^2V_{C2}^2 + \left(0.1 + a\cdot k_{eff}\right)x^2\right]}, \quad (19)$$

$$E_{k_{eff}} = \frac{a\cdot k_{eff}x^6}{V_{C2}^2\left[t_{C0}^2V_{C2}^2 + \left(0.1 + a\cdot k_{eff}\right)x^2\right]^2} - \frac{x^4}{V_{C2}^2\left[t_{C0}^2V_{C2}^2 + \left(0.1 + a\cdot k_{eff}\right)x^2\right]}, \quad (20)$$

$$E_a = \frac{k_{eff}^2x^6}{V_{C2}^2\left[t_{C0}^2V_{C2}^2 + \left(0.1 + a\cdot k_{eff}\right)x^2\right]^2}. \quad (21)$$

To quantitatively analyze the traveling time t_C error of the two-parameter PS-wave moveout equation, the three-layer VTI medium model (Table 1) is used to analyze the relation between the traveling time t_C error and V_{C2}, k_{eff}, and m. For precise values of m, equation (1) is equivalent to the four-parameter time–distance curve equation. For approximate values of m, equation (1) is reduced to the two-parameter equation with the same precision as the original four-parameter equation. Considering the approximate relation between m and k_{eff}, we set $m = 0.1 + a\cdot k_{eff}$ and the effect of the approximate value m on the precision of equation (1) is analyzed by changing a. In Table 1, a = 2.7, and the error of the

Table 1 Three-layer VTI medium model

Layer	z_i (m)	v_{p0} (m/s)	v_{s0} (m/s)	ε	δ	t_{c0}	v_{c2}	k_{eff}	m	m_{dhc}
1	500	1875	826	0.225	0.100	0.872	1541	0.088	0.330	0.337
2	500	3306	1819	0.134	0.000	1.298	2047	0.127	0.467	0.442
3	500	3368	1829	0.110	-0.035	1.720	2264	0.108	0.390	0.391

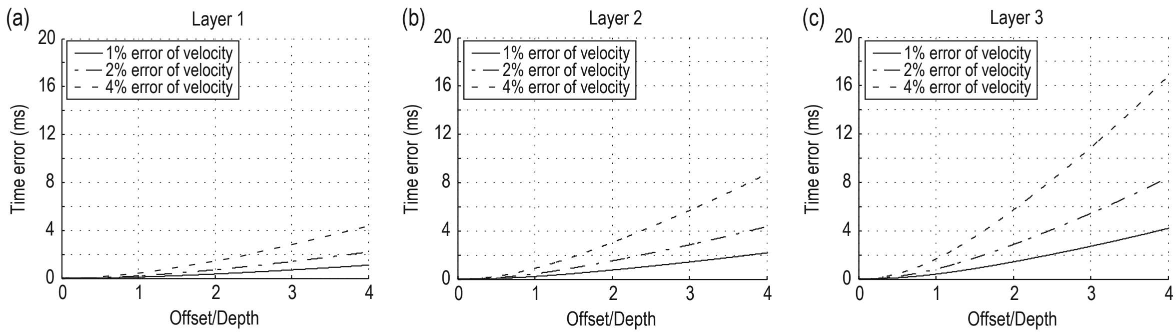

Fig.3 Traveling time error for variable velocity vs offset/depth for (a) layer 1, (b) layer 2, and (c) layer 3.

approximate m relative to the precise m is only 2%, 5%, and 0.3%, suggesting that the error owing to m is very small. In addition, and from equation (1), we can see that the effect of varying a on the traveling time error is very small. Figures 3–5 show the relation between the traveling time t_C error and V_{C2}, k_{eff}, and a in the model. As it can be seen from Figures 3–5, the PS-wave traveling time is severely affected by V_{C2}, and k_{eff} is approximately one-tenth of the effect when the x/z (Offset/Depth) is greater than 1, whereas the effect of a can be neglected when x/z is smaller than 2. Apparently, equation (1) is not sensitive to a and using $m \approx 0.1 + 2.7k_{eff}$ (Dai and Li, 2010) in the velocity analysis does not affect the two-parameter equation in the analysis of V_{C2} and k_{eff}.

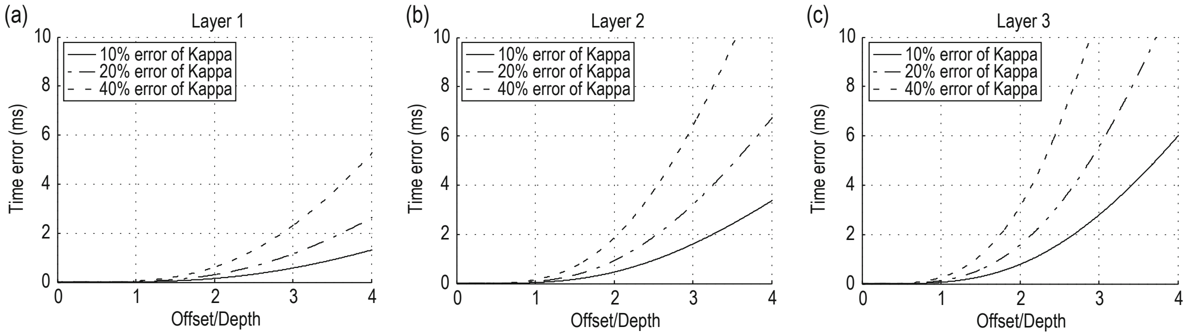

Fig.4 Traveling time error for variable Kappa error vs offset/depth for (a) layer 1, (b) layer 2, and (c) layer 3.

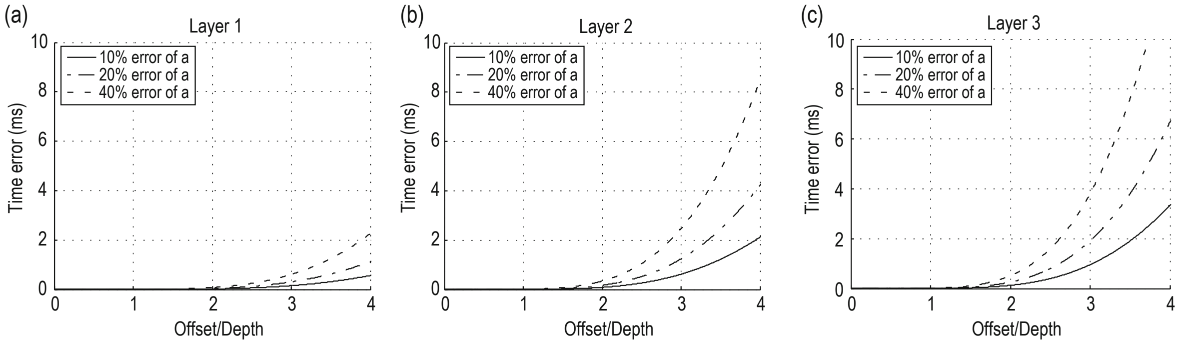

Fig.5 Traveling time error at different constant a values vs offset/depth for (a) layer 1, (b) layer 2, and (c) layer 3.

Model data test

The convex model is shown in Figure 6 and the parameters of the model are given in Table 2. We use the imaging of position A to verify the feasibility and effectiveness of the new PS-wave anisotropic PKTM velocity updating method based on the simplified two-parameter equation. First, the PS-wave initial velocity model parameters of PKTM are determined according to the flow chart in Figure 1. Then, the velocity parameters are corrected according to the migration velocity updating the flow chart in Figure 2. Figure 7 shows the CIP gather of position A after migration using the initial velocity parameters and before the migration velocity correction. Figure 8 shows the velocity correction. After V_{C2} and k_{eff} are corrected, all the events in the CIP gather are flattened. Figure 9 shows the effect on the CIP gather after the PS-wave PKTM velocity analysis with the new velocity correction method. Figure 9a shows the PKTM result with the stacking velocity as the initial velocity and Figure 9b shows the PKTM result after the velocity correction based on the two-parameter equation, which suggests that the near- and far-offset events are almost flattened but the third layer of the positive and negative offset events is uneven with apparent tilt owing to the significant imaging error in the effective velocity ratio γ_{eff}. Nevertheless, after the PKTM percentage scanning γ_{eff}, all events are completely flattened with good continuity in amplitude in the final PKTM result corresponding to the final velocity model, as shown in Figure 9c. The above demonstrate that the new velocity correction method based on the two-parameter equation satisfies the requirement of high-precision PS-wave anisotropic PKTM.

Table 2 Parameters of the convex model.

Layer	v_{P0} (m/s)	v_{S0} (m/s)	ε	δ	ρ (gm/cc)
1	2500	1500	0.140	-0.012	2.20
2	3000	1800	0.170	0.000	2.30
3	3500	2100	0.128	0.078	2.37
4	4000	2400	0.120	0.100	2.44
5	4500	3000	0.100	0.080	2.50

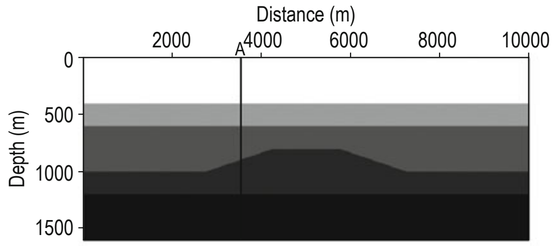

Fig.6 Convex model.

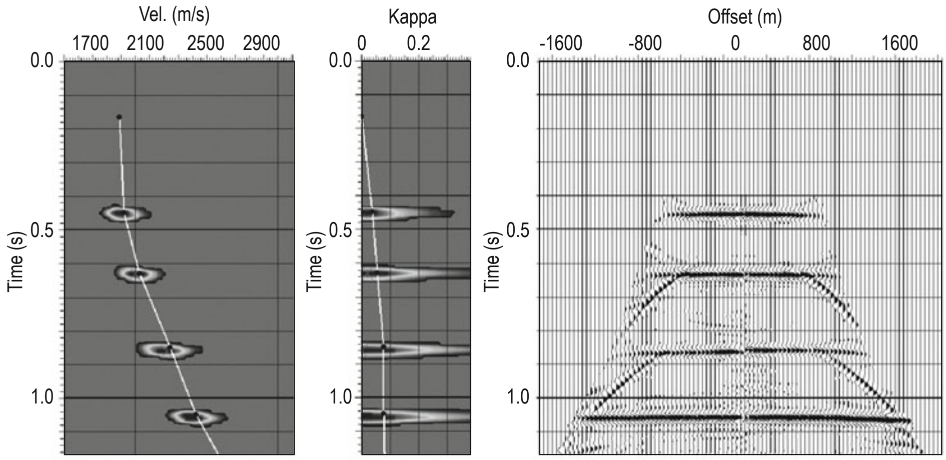

Fig.7 Prestack time migration velocity updating before migration.

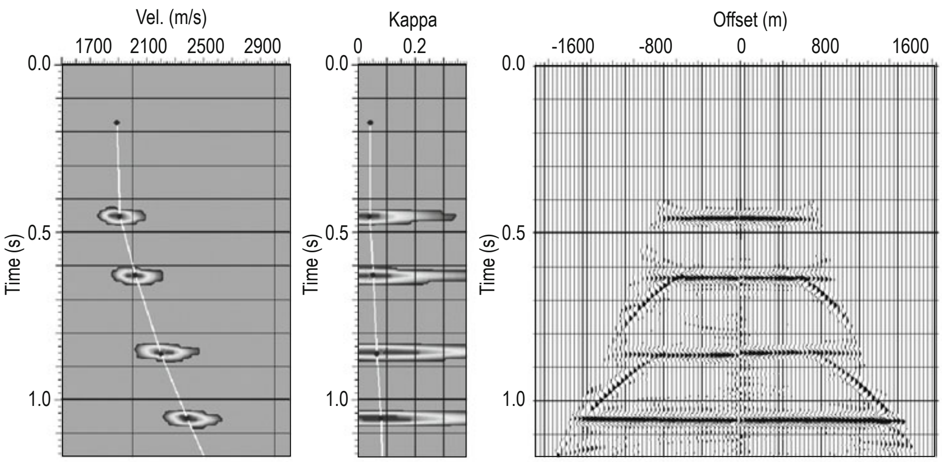

Fig.8 Prestack time migration velocity updating after migration.

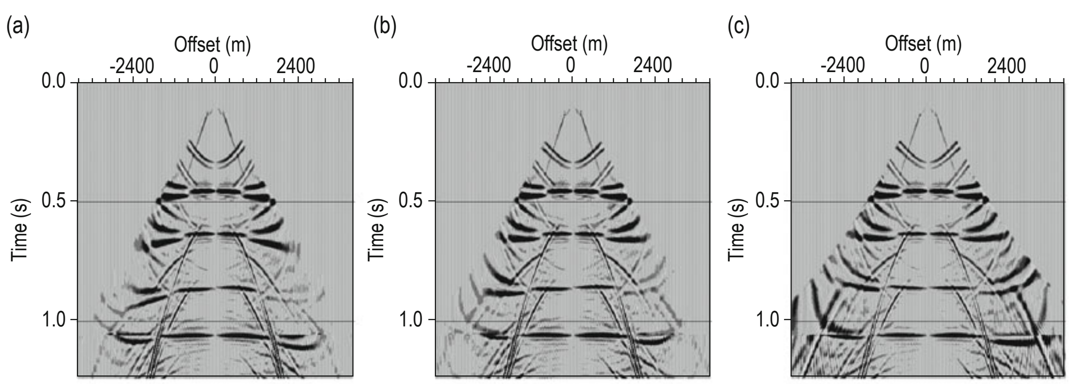

Fig.9 The CIP gather effect of the prestack time migration velocity analysis: initial velocity (a), based on the two-parameter equation of velocity updating (b), and the final velocity model after the percentage of scanning (c).

Application

Real PS-wave seismic data from an area in Western China are processed with the proposed method. First, common conversion point gathers are extracted from PS-wave data at specified target layers, and static correction and prestack noise elimination are completed. Then, high-precision two-parameter velocity analysis is performed to obtain the stacking velocity V_{C2}, k_{eff}, and the final stacked section. γ_0 is estimated from the correlation events between the P-wave and PS-wave stacked sections. Moreover, using the stacking velocity of the P waves, γ_{eff} is calculated. In this manner, an initial PS-wave PKTM velocity model involving V_{C2}, γ_0, γ_{eff}, and k_{eff} is obtained. From the initial velocity model, PKTM is performed to obtain the CIP gathers. Two-parameter velocity analysis is carried out on the CIP gathers and the iterations continue until all events are flattened. Finally, we use different percentages of γ_{eff} to perform PKTM and determine the best value by comparing the imaging section.

Figure 10 shows the PKTM moveout-corrected velocity and anisotropic semblance spectra, and the CIP gather before and after the moveout correction. As it can be seen, there is residual moveout on the CIP gather produced by PKTM using the initial velocity model and all events are flattened after velocity picking. Figure 11 shows the migration imaging results of different percentages of γ_{eff} scanning. From the different imaging results, we can determine the best γ_{eff} based on the flattening of all the events in the CIP gathers. Figure 12 shows the initial and final PKTM stacked sections. It can be clearly seen that in the final imaging results, the PS-wave imaging has significantly improved as well as the continuity of the reflection events, whereas the amplitude variation is typical.

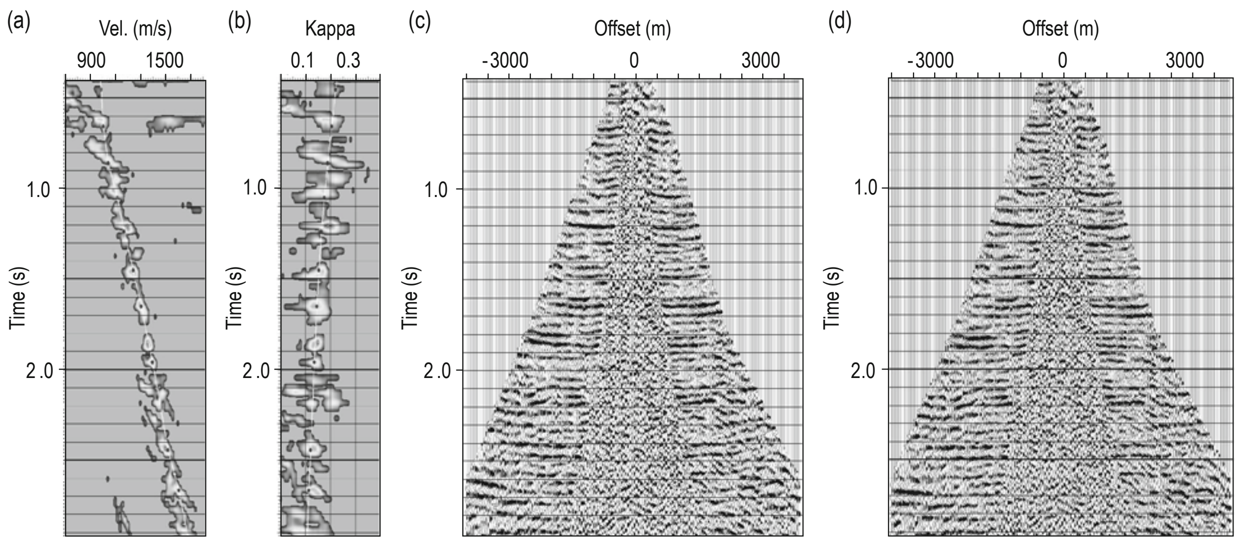

Fig.10 Prestack time migration velocity updating: velocity (a) and Kappa (b) semblance spectra, CIP gather before (c) and after (d) velocity picking.

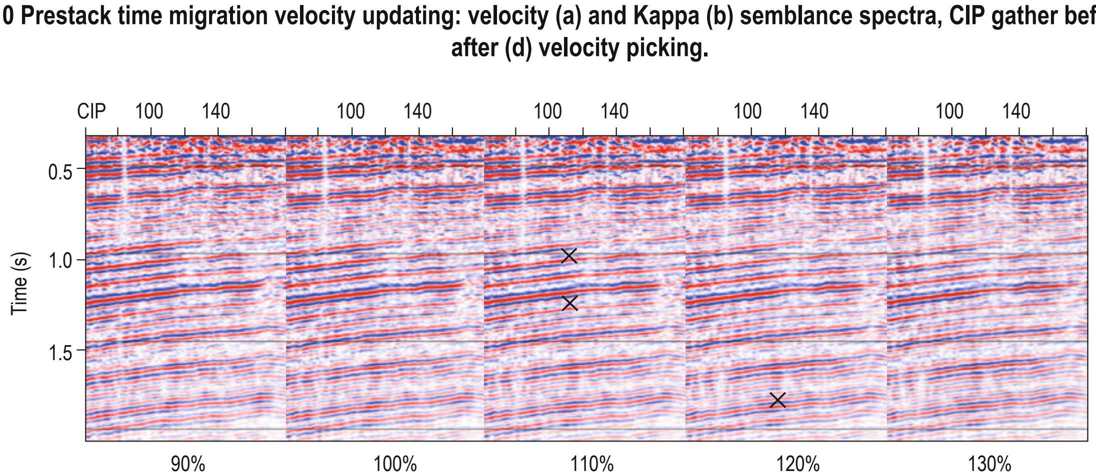

Fig.11 Percentage of scanning γ_{eff} PKTM; the cross marks represent the selection points of γ_{eff}.

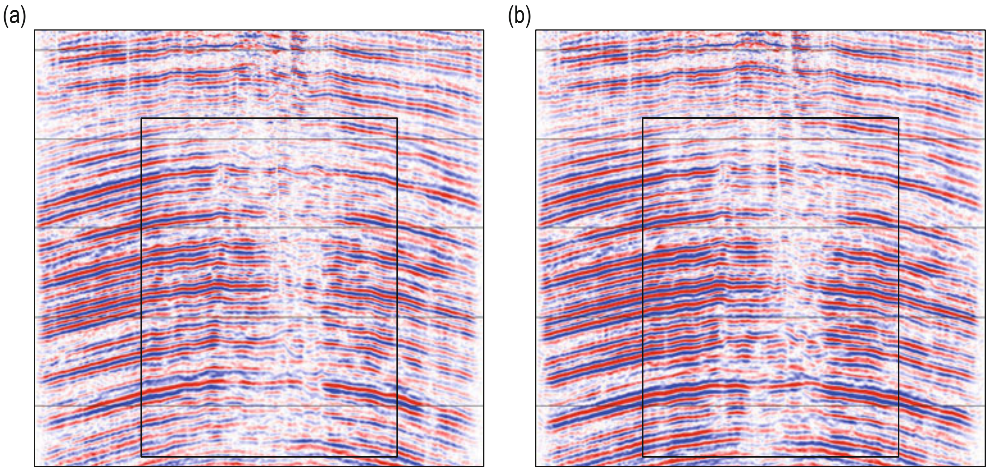

Fig.12 Prestack time migration stack section comparison of the initial (a) and final (b) velocity model.

Conclusions

Theoretical analysis, and model and real data processing prove the applicability of the proposed four-parameter PS-wave velocity analysis method. In summary, we infer the following.

(1) The simplified two-parameter moveout equation can be used not only in the PS-wave stacking velocity analysis but also in the prestack time migration velocity model updating.

(2) The use of the simplified two-parameter moveout equation to the velocity analysis simplifies to some extent the four-parameter velocity estimation method in high-precision PS-wave imaging and improves the processing efficiency, and the use of the velocity model to the prestack time migration produces robust results.

(3) The vertical velocity ratio is obtained by correlating the P-wave and PS-wave stacked sections or imaging after level calibration.

(4) Unlike the case of the four-parameter velocity analysis method, the effective velocity ratio cannot be directly obtained with intermediate offset from the PS-wave CIP gather when the simplified two-parameter moveout equation is used in the velocity analysis, instead, the initial effective velocity ratio is calculated using the Thomsen (1999) equation in combination with the P-wave velocity analysis, and the final velocity model of the effective velocity ratio is obtained by percentage scanning migration. Thus, the obtained effective velocity ratio model is more reliable and yields more high-precision anisotropic prestack time migration results.

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