A practical approach to update the migration velocity model for PS converted waves
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Summary
A practical approach is developed to update the migration velocity model of the PS converted wave for improved imaging. It is achieved by analyzing the hyperbolic velocity of the inverse-NMO common imaging gathers produced from the prestack Kirchhoff time migration procedure. The correct migration velocity can be estimated from this velocity using a simple empirically derived formula. Applying this approach to the Alba data shows that the estimated migration velocity reliably converges to the correct velocity. The effect of velocity ratio on this estimation is small and may be neglected.

Introduction
Prestack Kirchhoff time migration (PKTM) is an efficient imaging method for processing 2-D and 3-D seismic data because of its potential for I/O flexibility and target-orientation (Bevc, 1997). It has been successfully applied to PS converted waves (C-waves) for imaging beneath gas clouds in the Valhall field as well as in other areas (Dai et al, 2000; Granli et al, 1999). However, applying the PKTM to C-waves is more complex than to single model waves (PP or SS) because two velocities ($V_p$ and $V_s$) are required. It is more difficult to update two velocities of C-waves than to update one velocity for PP or SS wave during PKTM processing. A recent study in C-wave processing shows that the advantage using C-wave velocity ($V_c$), the effective velocity ratio ($\gamma_{eff}$) and vertical velocity ratio ($\gamma_0$) during PKTM processing is that the moveout is not sensitive to the velocity ratios ($\gamma_{eff}$ and $\gamma_0$) (Dai and Li, 2002). It provides a possibility to simplify the updating procedure. In this paper, using the Alba dataset as an example, we show a practical procedure for updating $V_c$.

Prestack Kirchhoff Time Migration
Applying PKTM to C-waves requires migration P-wave and S-wave velocities ($V_p$ and $V_s$). However, it is difficult to measure $V_p$ and $V_s$ from field data directly. Instead, stacking C-wave velocity ($V_c$), the effective velocity ratio ($\gamma_{eff}$) and vertical velocity ratio ($\gamma_0$) can be measured using a data driven approach. Then stacking $V_p$ and $V_s$ can be transformed from $V_c$, $\gamma_{eff}$ and $\gamma_0$ (Thomsen, 1999). However, these stacking velocities are different from the migration velocities. They can only be used as the initial migration velocities in the PKTM and an updating procedure is needed to adjust their values and improve the migration images.

In PKTM processing, the common image point (CIP) gather which is produced before the final Kirchhoff summation is useful for analyzing the effects of the velocities and their ratio on the image quality. The events in a CIP gather produced with correct migration velocities are flattened like the events in a NMO corrected CDP gather. By checking the CIP gather we can update the migration velocity to improve the image quality. For C-waves, two parameters, $V_c$ and $\gamma_{eff}$ need to be adjusted ($\gamma_0$ is fixed since it is obtained by correlating PP and PS stack sections). However, adjusting two parameters simultaneously is a difficult task. Figure 1 shows an example in which the events are not flattened due to $V_c$ error in (a) and $\gamma_{eff}$ error in (b). It is difficult to distinguish the effects of the $V_c$ error from the effect of the $\gamma_{eff}$ error and it is also difficult to decide the required updating values.

![Figure 1. Part of a CIP gather. (a) $V_c$ is 95% of the correct value. (b) $\gamma_{eff}$ is 80% of the correct value.](image-url)
Updating the migration velocity model for PS waves

migration velocity need to be changed again. This method is subjective and time consuming. There is a need to find a simple and objective method.

Inverse-NMO CIP gather and Velocity analysis

For a CIP gather produced with correct velocity, the events should be flattened. The flattened events can be inverted using hyperbolic moveout with the same velocity. The inverse-NMO CIP is like a CDP gather without moveout correction. Hyperbolic moveout velocity analysis can be performed to this gather. If the velocities are correct, the velocity picked from the velocity analysis should be the same as the correct velocity. If the migrated velocity is not correct, the picked velocity may be different from the used migration velocity. Numerical analysis shows that the picked value is closer to the correct migration velocity (Figure 2) than the used migrated velocity. If the picked velocity is used to migrate the dataset again, the picked velocity from the resultant inverse-NMO CIP gather will be even closer than the previous one. Repeating this procedure, the picked velocity will converge to the correct velocity.

Figure 2. The events in a CIP gather (offset panel, upper three lines) and its corresponding inverse-NMO CIP gather (lower three lines) with different migration velocities. Three vertical bars in the \( V_c \) panel are the migration velocities corresponding to the events in the CIP gather. Three horizontal bars in the \( cV \) panel are picked velocities from the velocity analysis based on events in the inverse NMO CIP. Note that for the flattened event, the picked velocity is the same as the migration velocity as expected.

Testing on Alba OBC dataset

To validate this approach, we apply this approach to the Alba Field 3D-4C OBC data acquired in block 16/26 in the UK sector of the North Sea (MacLeod, et al, 1999). The data used were recorded from a sail line extracted from the 5th swath of the survey and the receiver cable is below the sail line. The CIP gather obtained from the PKTM is used to analyse the effect of velocity error. Figure 3a shows such a CIP gather. The events in this gather are flattened so that we can assume the velocities used are correct. Using the velocities, we can invert this CIP gather back so that the events in this CIP gather become the hyperbolic curves (Figure 3b). Then a hyperbolic velocity analysis is performed on this inverse-NMO CIP gather. Figure 4 shows the velocity spectrum. A velocity profile can be picked from this velocity spectrum. The picked velocity profile is the same as the migrated velocity (the middle curve in Figure 4).

Figure 3. (a) A CIP gather of Alba data obtained by using the correct migration velocities. All events are flattened except the events between 4s and 5s at far offsets affected by anisotropy. (b) is the corresponding inverse NMO CIP gather.

Figure 4. \( V_c \) spectrum obtained from Figure 3(b) using the hyperbolic moveout velocity analysis. The middle curve among the five velocity profiles is the correct migration velocity. The other four curves correspond to 80%, 90%, 110% and 120% of correct velocity.

To check the effect of \( V_c \) and \( \gamma_{eff} \) errors, different variations of velocities are used in this procedure. Figure 5 shows results with varied \( V_c \) and correct velocity ratio and Figure 6 shows results with varied velocity ratio and correct velocity.
The results in Figure 5 are very encouraging for updating \( V_c \). For example, Figure 5(a) is obtained using 80% of the correct velocity and the picked velocity converges to near 90% of correct velocity. Figure 5(b) is obtained using 90% of the correct velocity and the picked velocity converges to 95% of the correct velocity. From the other side, Figure 5(d) is obtained using 120% of the correct velocity, and the picked velocity converges to nearly 105% of the correct velocity. Finally if the correct velocity is used to migrate the data, the picked velocity equals the correct velocity (Figure 4). The correct value of the migration velocity can be approximately written as:

\[
V_c = 2 \ast V_{c\text{-pick}} - V_{c\text{-ini}}
\]  

(1)

This empirical equation shows that the correct value of the migration velocity can be estimated using the initial velocity and picked velocity.

In the above cases, the velocity ratio is correct. However, the effects of the velocity ratio need to be examined. Figure 6 shows the effects of the variation of \( \gamma_{eff} \). The peak positions in the \( V_c \) spectra are not changed in Figure 6(a) and 6(b) and changed little in Figure 6(c) and 6(d). However, the spectra are not well focused compared with Figure 4. It means that \( \gamma_{eff} \) mainly affects the focus of the spectra, while the peak positions in the spectra are less affected, although a large velocity ratio move the \( V_c \) peak position a little bit. The focus of the \( V_c \) spectra can be used to check the \( \gamma_{eff} \) error.

For the cases where both \( V_c \) and \( \gamma_{eff} \) error exist, the similar results are obtained. Figure 7 shows the similar spectra with both \( V_c \) and \( \gamma_{eff} \) errors. The peak position of \( V_c \) in Figure 7(a) is similar to that in Figure 5(a). However the \( \gamma_{eff} \) error in Figure 7(b) moves the peak position a little bit. Also the peak position in Figure 7(c) is similar to that in Figure 5(d) and the peak position in Figure 7(d) are changed a little bit due to the larger \( \gamma_{eff} \) error. In spite of \( \gamma_{eff} \) error, all of these spectra show that the picked velocity profiles are always closer to the correct migration velocity than the initial migration velocity. The updating procedure converges. Our experience shows that when updating \( V_c \), using a small value of \( \gamma_{eff} \) is better. Updating \( \gamma_{eff} \) still need to visually check the CIP gather. However, as \( V_c \) is already corrected, it should be easy to adjust \( \gamma_{eff} \) only.

**Conclusions**

In this work, we developed an approach to update the migration velocity and their ratio for C-waves. Updating migration velocity is achieved by applying a hyperbolic moveout velocity analysis to an inverse-NMO CIP gather, which is produced by PKTM. The correct \( V_c \) values can be estimated using the picked values from the \( V_c \) spectrum and the initial value of the migration velocity. The picked value is mainly affected by the velocity error. The velocity ratio has little effect on the picked values. However, the velocity ratio does affect focusing of the velocity spectrum. Updating \( \gamma_{eff} \) can be performed by checking the CIP gather and the inverse-NMO CIP gather produced with the correct migration \( V_c \).

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Updating the migration velocity model for PS waves

Figure 5. The velocity spectra obtained from inverse-NMO CIP gather with different velocity variations. The velocity used for (a), (b), (c), and (d) are 80%, 90%, 110% and 120% of the correct velocity respectively. The five curves indicate the velocity values as in Figure 4. In these cases, the velocity ratio $\gamma$ is fixed at the correct values.

Figure 6. Velocity spectra obtained from inverse-NMO CIP gather with different velocity ratio variations. The velocity ratio used for (a), (b), (c), and (d) are 80%, 90%, 110% and 120% of the correct velocity ratio respectively. The five curves indicate the velocity values as in Figure 4. In these cases, the velocity is fixed at the correct values.

Figure 7. Velocity spectra obtained from inverse-NMO CIP gather with different velocity and velocity ratio variations (a) 80% of $V_c$ and 80% of $\gamma_{eff}$, (b) 80% of $V_c$ and 120% of $\gamma_{eff}$, (c) 120% of $V_c$ and 80% of $\gamma_{eff}$, and (d) 120% of $V_c$ and 120% of $\gamma_{eff}$. The five curves indicate the velocity values as in Figure 4.