A practical approach to compensate for diodic effects of PS converted waves
Hengchang Dai* and Xiang-Yang Li, British Geological Survey

Summary
We propose a practical approach to compensate for the diodic moveout of PS converted waves using a velocity perturbation method. In this approach, the diodic moveout can be decoupled into two parts. One part is related to a base velocity and the other part is related to a velocity perturbation. The base velocity is used to correct the curved feature of the diodic moveout and the velocity perturbation is used to correct the dipping feature of the diodic moveout.

We have developed GUI tools to perform the diodic velocity analysis for stacking procedure and prestack time migration, and command line tools to perform the diodic moveout correction and prestack time migration with diodic moveout compensation. We have applied these tools to a real dataset and obtained improved images.

Introduction
In inhomogeneous media, PS converted waves often suffer from severe diodic effects. The traveltime and amplitude of PS converted waves may be different in the forward and reverse shooting directions, giving rise to different stacking velocities of PS converted waves and velocity ratios (Thomsen, 1999, Li, Dai and Mueller, 2001). These effects, compounded with the asymmetric raypath of PS converted waves will further increase the difficulties and costs in processing PS converted wave data. One common method to solve this problem is to separate a dataset into two volumes with different shooting directions (e.g. negative or positive offset directions). Different values of the PS converted wave velocities are used to process the two datasets separately and the two results are combined in the final stage. The problem in this method is that sometimes it is difficult to correlate the datasets and the final combined result may be degraded. In this paper, we propose a method to overcome this problem and apply this method to a 2D dataset for improving the PS converted wave imaging.

The diodic moveout of PS converted waves
In homogeneous media the moveout of PS converted waves is written as (Li and Yuan 2003, Dai and Li, 2005),
\[
t^2_{ps} = t^2_{ps0} + \frac{(2h)^2}{V^2_{ps}} - \frac{2k_{eff}(2h)^4}{V^2_{ps}[t_0^2 V^2_{ps} + m^2_4 (2h)^2]}, \quad (1)
\]
\[
k_{eff} = \frac{(\gamma_0 \gamma_{eff} - 1)^2 + 8\gamma_{eff}(1 + \gamma_0)}{8\gamma_0(1 + \gamma_{eff})^2}, \quad (2)
\]
where \(V_{ps}\) is the velocity of PS converted waves which is a combination of P- and S-wave velocities, \(\gamma_0\) and \(\gamma_{eff}\) vertical and effective \(V_p/V_s\) ratios, and \(\chi_{eff}\) the anisotropic parameter for PS converted waves. For homogeneous media, the PS converted wave moveout is invariant when source and receiver positions are interchanged. However, in lateral inhomogeneous media, PS converted wave moveout and velocity are not invariant under an interchange of source and receiver positions. This phenomenon is called diodic velocity, a term referring to the electronic diode, which operates differently in forward and reverse directions (Thomson 1999). This phenomenon is caused by the asymmetric ray-path of PS converted waves. Figure 1 schematically shows this phenomenon in which the media is uniform except for a zone of anomalous P and S velocities. For a given conversion point associated with the same offset length, the PS converted wave has different ray-paths when the source and receiver positions are interchanged and hence the velocities along the ray-paths are different. The two ray-paths involve different P- and S-wave velocities. Hence the converted wave velocity and velocity ratio are different for the two ray-paths, and so, the moveouts for the two ray-paths are different. The different moveouts increase difficulty on processing PS converted wave data.

Figure 1. PS converted wave ray-paths in inhomogeneous medium

In PS converted wave data processing, the events should be flattened using Equation (1). However, due to the diodic effect, using one velocity model cannot flatten the events for the two datasets with opposite offset directions.

The diodic effect also exists in prestack time migration processing. In prestack time migration, the travel time is
the summation of the traveltimes of the down-going P-wave and up-going S-wave:

\[ t_{ps} = t_p + t_s \]  

(4)

where \( t_p \) and \( t_s \) are approximated as:

\[ t_p = \frac{1}{1 + \gamma_0} \sqrt{t_{ps0}^2 + \frac{w_p^2}{V_p^2} - \frac{2\eta_{eff}w_p^4}{V_p^2[V_p^2(1 + \gamma_0)^2 + x_s^2]}} \]  

(5)

\[ t_s = \frac{\gamma_0}{1 + \gamma_0} \sqrt{t_{ps0}^2 + \frac{w_s^2}{V_s^2} - \frac{2\xi_{eff}w_s^4}{V_s^2[V_p^2(1 + \gamma_0)^2 + x_s^2]}} \]  

(6)

where

\[ \eta_{eff} = \frac{z}{(\gamma_0 - 1)^2} \text{ and } \xi_{eff} = -\frac{z}{\gamma_0 - 1}. \]

Due to the diodic effect, for a common image point, when the positions of source and receiver are changed, the ray paths are different and involve different velocities. The events in the common image point (CIP) gather cannot be flattened using one velocity model for two datasets with opposite offset directions.

To overcome this problem, two velocity models should be used. One model is used for the positive offset data and the other is used for the negative offset data. Conventionally, the dataset is separated into two volumes according to the offset direction. Each volume is processed using its own velocity model. However, there are some drawbacks which prevent this method being applied to real datasets. One of the drawbacks is that it is difficult to align the events when the two datasets are separately processed, especially when the signal-to-noise ratio is low or many events need to be aligned. Therefore, when the two poorly aligned datasets are combined, the final results are degraded. It is necessary to overcome this drawback. One solution is to process the two datasets in one interface, but using two velocity models for the opposite offset directions.

The perturbation of the velocity of PS converted waves

The velocity model of PS converted waves has four parameters. If each parameter has different values in the two models, eight parameters will need to be estimated. This is not practical because the uncertainty and workload are very large. Fortunately, the parameters in converted wave velocity model have different sensitivities to moveout. The error in the moveout is mainly determined by the PS converted wave velocity. Other parameters have less effect on the moveout. This means, we may need two velocities, but other parameters can be unchanged for the opposite offset data. We also find that in practice, because the difference between the two velocities is small, we can express the two velocities as a base velocity and a perturbation.

\[ V_{ps\text{offset}} = V_{ps}(1 \pm \Delta) \]  

(7)

where \( V_{ps} \) is the base velocity defined as the velocity without diodic effects, \( \Delta \) is the velocity perturbation (in percentage). The two velocities \( V_{ps\text{offset}} = V_{ps}(1 \pm \Delta) \) are used in Equation (1) for two opposite offset directions.

Figure 2 schematically shows how to apply two velocities to correct a diodic moveout. If only the base velocity is used to correct the event, the corrected event becomes a dipping straight line and the resulting stacked event will smear. When we add the velocity perturbation, the corrected event becomes a horizontal line and the resulting stacked event will be better resolved. The advantage of this perturbation method is that it can decouple the diodic moveout into two parts. One part is related to the base velocity and one part is related to the perturbation. The base velocity is used to correct the curved part of the events and the perturbation is used to correct the dipping part of the events. Following the above analysis, we developed tools to perform the diodic velocity analysis and apply the diodic velocity to correct the diodic moveout.

In prestack time migration, we use a similar perturbation method to deal with the diodic travel-times. The two velocities for opposite offset directions are also expressed as Equations (7). The two velocities are then used in Equation (5) and (6) for the two opposite offset directions in prestack time migration.

Note that in prestack time migration, an asymmetric travel time may be caused by incorrect values of the effective velocity ratio. However, if we assume that the values of the effective velocity ratio in prestack time migration equal to the values in the moveout, and also that the effect of the effective velocity ratio and anisotropy on travel time is smaller than the velocity, we do not need to add a perturbation to the effective velocity ratio and anisotropy.
Approach to compensate for diodic effects of PS-waves

We developed a GUI tool for migration velocity analysis, and a prestack time migration tool to compensate for the diodic moveout in prestack time migration.

Data example

The dataset is a 2D/4C marine acquisition from a filed located approximately 60km offshore North Africa (courtesy BG plc). A gas chimney causes heavy distortion. The gas attenuates the P-wave energy and reduces the P-wave velocity. However, it has a small effect on shear wave velocity. This inhomogeneity caused by the gas chimney results in diodic moveout. Without a suitable method to compensate for the diodic effect, the image obtained from this dataset will be degraded. Here we apply our tools to this dataset to deal with the diodic moveout.

This perturbation approach is applied to both NMO+stacking procedure and prestack Kirchhoff time migration. Figure 3 and 4 show the snapshots of the migration velocity analysis tool to perform the diodic effect analysis. In both figures, the first left panel shows the PS converted wave migration velocity, the second shows the velocity ratio, the third shows the anisotropy and the fourth shows the velocity perturbation. The furthest right is the common image point (CIP) gather panel. Without applying the velocity perturbation, the events below 2s in the CIP gather are dipping (Fig 3). With the velocity perturbation considered, the events became horizontal (Fig 4). For example, three events which marked with dipping lines in Figure 3 became horizontal in Figure 4, although on the far offset part, the events are not perfectly flattened. Stacking the horizontal events yield a more focused imaging than stacking the dipping events.

Figure 3. Snapshot of migration diodic velocity analysis tool. Without applying the velocity perturbation, \(\Delta = 0.0\), the events are dipping after NMO correction.

Figure 4. Snapshot of diodic velocity analysis tool. With the velocity perturbation applied, the events become horizontal after NMO correction.

Figure 5 shows a part of the migrated image which is obtained without the velocity perturbation. Figure 6 shows similar part of the image which is obtained with the velocity perturbation applied. Here we mark three rectangles on each image for comparison. Although the two images look similar, the details of the structures of the two images are different. The differences are obvious in the three marked rectangles. For example, in the up marked rectangle of Figure 6, the events have stronger energy and are more coherence. In the middle marked rectangle, horizons can be clearly identified from the image in Figure 6. However, in Figure 5, the lowest horizon despaired. In the low marked rectangle, the features of the structure in Figure 6 are quite different from Figure 5. We may identify a fault in Figure 6, not in Figure 5 (see the curve marked in this rectangle). This is due to that the velocity perturbation in prestack time migration does change the location of scatter point of PS converted waves and hence affects the appearance of the structure. The structure in Figure 6 looks shaper than that in Figure 5.

Figure 7 shows the profiles of the velocity perturbation and the base velocity of the PS-waves for the images corresponding to Figures 5 and 6. The velocity perturbation indicates the difference in PS wave velocity between the two opposite offset data which is related to the inhomogeneity of the media. In this case, the velocity difference between the two opposite offset direction is about 20 percent at the location of CIP 700.

Conclusions

We have proposed a practical approach to compensate for the diodic moveout of PS converted waves using a velocity perturbation method. In this approach, the diodic moveout is decoupled into two parts. One part is related to a base velocity and the other part is related to a velocity
Approach to compensate for diodic effects of PS-waves

perturbation, which indicates the difference of PS converted wave velocity between the two opposite offset data which is related to the inhomogeneity of the media. The base velocity is used to correct the curved feature of the diodic moveout and the velocity perturbation is used to correct the dipping feature of the diodic moveout. GUI tools have been developed to perform the diodic velocity analysis for stacking procedure and prestack time migration, and command line tools to perform the diodic moveout correction and prestack time migration with diodic moveout compensation. Application of these tools to a real dataset shows that we can easily estimate the base velocity and the velocity perturbation. The events in negative and positive offset data can be easily aligned. The results show that the quality of the migrated image improved when the velocity perturbation is applied. More features can be identified from the migrated image with the velocity perturbation applied than that from other images.

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Figure 5. Migrated image without velocity perturbation applied.

Figure 6. Migrated image with velocity perturbation applied

Figure 7. (a) Profile of the base velocity and (b) profile of the velocity perturbation.
Approach to compensate for diodic effects of PS-waves

References


Thomsen L., 1999, Converted wave reflection seismology over inhomogeneous, anisotropic media: Geophysics 64, 678-690.