Tying PS to PP depth section: Two examples of anisotropic prestack depth imaging of 4C data

Side Jin*, CGG Americas, Inc.

Summary

Neglecting anisotropy in seismic imaging, PP and PS images may not be consistent, even if prestack depth migrations are used. The difference in the two images can be used to estimate pertained anisotropic parameters which can be fed back to the migration to produce more consistent images. I show two 2D-4C real data examples with two different anisotropic complexities. The PS reflectors produced from isotropic processing of the first example are systematically deeper than the corresponding PP events. Nevertheless, an anisotropic depth migration based on the simplest VTI model can make the PS image consistent with the PP image. For the second example, the isotropic prestack depth migration can produce consistent PP and PS images, which suggests that the anisotropy is elliptical.

Introduction

Subsurface materials are generally anisotropic to seismic wave propagations. Yet, most seismic imaging techniques are based on isotropic assumptions because of difficulties to estimate the anisotropy parameters required for the imaging. Recent advance of the imaging techniques shows that the image quality can be improved if the anisotropic effect is taken into account in the migration processes. For simple structures, some parameters related to anisotropy can be derived from time processing (Alkhalifah and Tsvankin, 1995). In depth domain, the estimation of anisotropy parameters is, in general, more difficult and unreliable from surface seismic data, because the heterogeneity of the media often mimics the anisotropy. Without sufficient constraints on the model, the ambiguity between the heterogeneity and the anisotropy make it possible that the anisotropic effect can be easily explained by a heterogeneous isotropic model. The anisotropy just goes away unnoticed in this case. While the anisotropy can be hidden in mono-component data imaging such as marine streamer data depth imaging, it is often evident in multi-component data imaging. Recent developments in ocean-bottom multi-component recording technology can provide high quality P- and mode-converted S-wave data. More than one subsurface image can thus be obtained, e.g., PP and PS sections. P- and S-waves respond differently to the anisotropy and give more information to reduce heterogeneity/anisotropy ambiguity. If the anisotropy is neglected or wrong anisotropy parameters are used, the images from the different types of waves will not be consistent (Nolte et al., 1999). Taking advantage of this additional information provided by the multi-component data, it is possible to estimate more reliably some of the anisotropy parameters by matching different sections. In this paper, I show two case examples of P-wave and converted wave (PS) prestack depth migrations. One of the examples demonstrates that the best focused PP and PS will not be depth-consistent if anisotropy is not taken care of.

Anisotropic model building

Mathematical description of general anisotropy involves a large number of parameters that can not be solved from surface seismic data. A simplified anisotropic model, commonly used in exploration seismology, is the VTI model, i.e., transverse isotropy with a vertical axis of symmetry. Only five parameters are needed to describe the VTI model (Thomsen 1986). In Thomsen’s notation, the first four parameters are vertical velocities of P- and S-waves (Vp0 and Vs0) and the anisotropic parameters denoted as ε and δ. The fifth parameter, γ, determines the SH-wave velocity which is not used in this paper. I adopt also the VTI model here.

Vp0 determination

Three parameters (Vp0, ε and δ) govern the P-wave propagation. In order to make the VTI model building practicable, I make the further assumption that the anisotropy is weak. I will show that the following two examples both exhibit weak anisotropy, so it is a valid assumption here. In general, P-waves are less sensitive to anisotropy than S-waves. Not shown in this paper, my numerical tests showed that the best focused P-wave isotropic image is very similar to the P-wave anisotropic image, if the anisotropy is weak (ε≤0.1 and δ ≤0.1). I therefore can derive a P-wave velocity model using any velocity building technique neglecting the anisotropy. For the examples shown in this paper, I use the automated velocity inversion developed by Jin and Beydoun (2000). The obtained velocity will be used as Thomsen’s vertical velocity Vp0, although they are not strictly the same.

Vp0 and ε - δ determination

Since the P-wave anisotropy is neglected, the difference between PP and PS images is due to S-wave anisotropy only. In a VTI medium, the traveltimes of S-waves depend on the vertical velocities Vp0 and Vs0, and on the difference ε - δ. The P-wave velocity Vp0 is determined previously. The other parameters are determined in the following way: choosing several values of the difference ε - δ, for example, ε - δ = 0, 0.02, 0.04, 0.06, 0.08 and 0.1, for each of the values, find the model Vp0 that focuses best the PS image. The correct values of Vs0 and ε - δ are those that match the PS image to PP image. For a given ε - δ, the process of
Tying PS to PP depth section

determining $V_{io}$ is similar to that of determining $V_{p0}$, except that the ray tracing from source points to reflectors is performed in the pre-determined $V_{p0}$ model.

Example 1

In the first example, I use a 2D-4C OBC line. The total number of receiver positions is 360 with a spacing of 25 meters. The depth of sea bottom is around 25 meters.

First, isotropic prestack depth velocity building and migration are performed for both PP and PS data. Figure 1a and 1b depict the PP image and the isotropic PS image ($\varepsilon - \delta = 0$), respectively. The P- and S- velocity models are obtained by the velocity inversion (Jin and Beydoun, 2000) which focuses best the images. Kirchhoff migration is used to produce the final images. We can observe a depth difference of 200 meters between the two images. This discrepancy announces the anisotropy of the subsurface media.

To evaluate the anisotropy revealed by the isotropic imaging, the S-wave velocity inversion was run for each of the five $\varepsilon - \delta$ values: 0.02, 0.04, 0.06, 0.08 and 0.1. Anisotropic PS wave prestack depth migration is then performed for the five obtained S-wave velocity models with the corresponding $\varepsilon - \delta$ values. The PS image that best matches the PP image was found with the value $\varepsilon - \delta = 0.06$ (Figure 1e). This could be the best average value to measure the anisotropy of the rocks under the area where the data were acquired, in the sense that it makes the PP and PS images consistent. This implies that the media are elliptically anisotropic. Nevertheless, this conclusion therefore indirectly supports the conclusion that the media are elliptically anisotropic. Nevertheless, this conclusion has to be subjected to further investigation, because it was drawn from the 2D data. Neglecting 3D propagation may have a bias effect on the 2D processing.

Example 2

The second example is structurally more complex, but, surprisingly, it does not show any apparent anisotropy as the first example. The dataset is a 2D-4C OBC line from the Mahogany field in the Gulf of Mexico. The cable was 1.5km long, with 60 4C receivers spaced by 25 meters. The source interval was 25 meters. For each move of the cable, the source vessel traveled 21.5km, allowing for a minimum far offset of 10km for each receiver position. The cable was moved 7 times and thus a 4C line of approximately 10 km length was acquired. The depth of sea bottom is about 120 meters. The complexity of the Mahogany dataset has challenged seismic imaging techniques and has been studied by many researchers (Alerini et al., 2001 and references therein).

For the Mahogany data, I did the model building and imaging in the same way as the first example. However, the PP and PS images match each other with $\varepsilon - \delta = 0$. The salt structure is unlikely isotropic, so this only suggests that the subsurface rocks exhibit elliptical anisotropy. The isotropic methods are generally valid to image this kind of data. Figure 2 shows the depth migrated PP and PS images.

The ratio $V_{p0}/V_{io}$ is found to be greater than 10 in shallow depth from the velocity inversions. S-wave propagation is very sensitive to anellipticity ($\varepsilon - \delta \neq 0$), when $V_{p0}/V_{io}$ is large. In fact, Thomsen (1986) derived the equation for the S-wave moveout velocity in a weak VTI medium:

$$V_{nmo}^{s} = V_{s0}[1 + (V_{p0}/V_{s0})^2(\varepsilon - \delta)]$$

We can see that the difference $\varepsilon - \delta$ is amplified by the squares of $V_{p0}/V_{s0}$ (more than 100 in this example). However, the imaging results of PS waves do not show any sign of anisotropy comparing to those of PP waves. The large $V_{p0}/V_{s0}$ therefore indirectly supports the conclusion that the media are elliptically anisotropic.

Discussion and conclusions

The two examples have shown that isotropic heterogeneous velocity models can flatten quite well the reflections on the image gathers of complex structures, and thus give well focused images. This heterogeneity/anisotropy ambiguity often gives the impression that the anisotropy does not exist, if the true depths of the reflectors are unknown. It makes the estimation of anisotropy difficult and unreliable from mono-mode seismic data alone.

Multi-component data offer the opportunity to produce more than one depth sections from different types of waves. These waves have different sensitivities to the anisotropic properties of media. Comparison of the sections can easily
Tying PS to PP depth section

reveal small amount of anisotropy. The discrepancy between sections can be used to derive relevant anisotropic parameters. Combination of PP and PS data is still limited for the resolution of the full set of anisotropic parameters, even for the simplistic VTI model. We can only get an estimate of the difference $\varepsilon - \delta$, not $\varepsilon$ and $\delta$ individually. Often a constant difference $\varepsilon - \delta$ is enough to make up the discrepancy between images, so a more detailed resolution seems to be difficult to achieve without additional constraints. Notwithstanding, the first case example has show that a significant improvement of the consistency and quality of PS image can be obtained with the partial resolution of the anisotropic parameters.

Figure 1: PP-wave and PS-wave Prestack Depth Migration(PSDM). (a) PP PSDM; (b) Isotropic PS PSDM; (c) Isotropic PS common image gather; (d) PP PSDM (same as (a)); (e) Anisotropic PS PSDM; (f) Anisotropic PS common image gather. The image gathers (c) and (f) correspond to the rightmost traces of the images (b) and (e). Note the depth difference of 200 meters between (a) and (b).

References


Tying PS to PP depth section


(a) PP-wave PSDM

(b) PS-wave PSDM

Figure 2: PP-wave (a) and PS-wave (b) PSDM. Although the two images are produced by isotropic method, they are very consistent. This suggests that the anisotropy is elliptical.