Converted Wave Velocity Analysis from Isotropy to Anisotropy - Accuracy and Limitation

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Introduction

In recent years, converted wave seismic exploration has attracted growing attention due to the fact that it can provide additional information to complement ***P*** wave data. A variety of examples can be cited, from imaging through gas clouds (Granli et al, 1999) to imaging subsalt structures (Kendall, et al 2000), and so on. However, due to its asymmetric ray path, converted wave propagation in anisotropic and/or inhomogeneous media is much more complicated than single mode wave propagation. In this paper, we investigate two different anisotropic analysis approaches and compare their accuracy and limitations, then develop a methodology to handle converted wave anisotropic velocity analysis and imaging for isotropic and polar anisotropic media.

Anisotropic velocity analysis methods

Three-term Taylor approximation:

For polar anisotropy or VTI (Vertical transversely isotropic) media, Tsvankin and Thomsen (1994, 1999) derived a three-term Taylor expansion formula which describes converted wave travel time as a 4th order non-hyperbolic equation approximation.

$$t_{ps}^2 = t_{ps0}^2 + \frac{x^2}{v_{c2}^2} + \frac{A_4 x^4}{1 + A_5 x^2} \qquad \text{eq. (1)}$$

where

$$A_4 = \frac{-1}{(1+\gamma_e)^2}\left[2\eta\frac{(\gamma_0^{2-1})}{\gamma_0}\gamma_e^2 + \frac{(\gamma_2^2-1)^2}{4(\gamma_0+1)}\right] \Big/ v_{c2}^4 t_{ps0}^2 ,$$

$$A_5 = \frac{-A_4 x^2}{1 - v_{c2}^2 \big/ v_{p2}^2(1+2\eta)} .$$

The truncation of the Taylor series assumes that the offset to depth ratio ***x/z*** is small. Determining travel time t_{ps} involves four parameters: the vertical ***P*** to ***S*** velocity ratio γ_0, the effective ***P*** to ***S*** velocity ratio γ_e, converted wave velocity v_{c2} and the anisotropy parameter η. The advantage of this formulation is that there is no need to know the ***P*** wave velocity or to compute the converted point location.

Double square root equation (DSRT):

Li and Yuan (1998) proposed a non-hyperbolic double square root equation for converted wave anisotropy parameter analysis, formulated below as:

$$t_{ps} = \sqrt{\frac{t_{ps0}^2}{(1+\gamma_0)^2} + \frac{x_p^2}{v_{p2}^2} - \Delta t_p^2} + \sqrt{\frac{\gamma_0^2 t_{ps0}^2}{(1+\gamma_0)^2} + \frac{(x-x_p)^2}{v_{s2}^2} + \Delta t_s^2} \qquad \text{eq. (2)}$$

where

$$x_p \approx x\left[c_0 + c_2\frac{(x/z)^2}{1+c_3(x/z)^2}\right],$$

Coefficients c_0, c_2 and c_3 are functions of γ_e and γ_0, defined in Thomsen (1999). Δt_p and Δt_s are the higher order P and S travel time deviations respectively. They are functions of γ_0, γ_e, v_{p2} and the anisotropy parameter σ.

This equation is accurate enough for long spread and strong anisotropy. However, it assumes that v_{p2} can be obtained from ***P*** wave processing and γ_0 from an initial PP-PS stack correlation. It is also computationally more expensive than the three-term method.

Problems arise when there is no reliable ***P*** wave velocity information, for instance, in the case of a gas chimney. Li (2000) also proposed a method for short spread data by removing the last term in equation (1). It turns out that v_{c2} can be determined since γ_0 is insensitive to v_{c2} scanning. Then γ_e and/or σ can be derived according to Thomsen formulas (1999) in some special case (such as δ=0).

Our approaches:

Inspired by Li's method, instead of deriving γ_e, which may accumulate computation error, we developed an approach for converted wave velocity analysis. We start from the isotropic case by dropping Δt_p and Δt_s from equation (2) and then use our recently developed 3D semblance-picking tool for interactive analysis. This permits simultaneously scanning over v_{c2} and γ_e, which are related to v_{p2} and v_{s2} by

$$v_{p2}^2 = \frac{(1+\gamma_0)\gamma_e}{(1+\gamma_e)} v_{c2}^2 \text{ and } v_{s2}^2 = \frac{(1+\gamma_0)}{(1+\gamma_e)\gamma_e} v_{c2}^2 .$$

This is referred to as the short spread double square root method (SSDSRT). For VTI media, the method is still valid for short spreads. For converted wave travel times, γ_e is not only affected by vertical inhomogeneity (i.e. the multi-layering effect) but also by anisotropy. Thus we can perform anisotropic velocity analysis using isotropic code for short spread data without any change. This is more efficient than using the double square root method for all the cases and does not require ***P*** wave velocity information. Compared with the three-term method, it provides a smooth and practical transition from isotropy to anisotropy. For long spread data or at shallow depth, the double square root method still needs to be used to preserve accuracy. With our 3D semblance picking tool and prior velocity knowledge from ***P*** wave processing, γ_e and σ can be also independently determined according to equation (2). Therefore, by combining the SSDSRT and DSRT methods, we can handle all cases of VTI anisotropy more accurately and efficiently.

For the case where γ_0 is not available or is questionable, a 4D graphics picking tool has also been developed, which permits scanning over a suite of 3D semblance cubes, each assuming a different γ_0 values to determine γ_0, γ_e and σ simultaneously. Semblance picking in 4D is potentially complicated by having to select amongst multiple semblance maxima but it does provide an alternative tool.

Data examples

A synthetic data is used to test the various methods. The model consists of four reflection events (see Figure1a) with anisotropy parameters listed in table 1. The first event has stronger anisotropy. At the maximum offset of 2500m the first event at 358ms corresponds to $x/z \cong 4.5$, the second event at 638ms is at $x/z \cong 2.5$, the third event at 1170ms is at x/z of 1.4, and the last event at 1686 ms is approximately at x/z of 0.9. Three methods are applied to these events. For the last two events, which correspond to $x/z <\cong 1.4$, all the methods have worked well and flattened events (see Figure 1). However, at $x/z \cong 2.5$ and 4.5, only the double square root method performs well, flattening the two shallow events at all offsets (see Figure 1d). As expected, both the three-term and SSDSRT methods fail to flatten the events (see Figure 1b and 1c).

To investigate the capability for anisotropy parameter analysis with the SSDSRT method, 3D semblance slices have been examined. The results show that v_{c2} has good resolution, is stable and is not sensitive to the x/z ratio, since the main effect on v_{c2} is due to the x^2 term. In contrast, γ_e is sensitive to the x/z ratio. Taking event 2 as an example, a semblance comparison is made for two offset ranges, one analysis performed with offsets to 2500m ($x/z \cong 2.5$), and the other with offsets only to 900 m ($x/z \cong 1.0$). Semblance slices are shown in Figure 2. The semblance maximums from both slices clearly and identically indicate v_{c2} = 1499 m/s, which is closest to the true value of 1483m/s (see table 1) using a 50 m/s v_{c2} increment for the semblance scan. For the long spread case ($x/z \cong 2.5$), while there is good semblance focusing at γ_e = 2.1, it deviates to the high side from the true value of 1.959. (The γ_e increment is 0.05 in the semblance scan). Only for the short spread case ($x/z \cong 1.0$) does the semblance maximum correspond to the correct value of γ_e at 1.95 (see Figure 2b). Therefore, for long spread data, even though γ_e picked from semblance analysis may flatten the events, it is not reliable for interpretation purposes. We also applied our approach to real data, and results will be shown in the presentation.

Table 1. Parameters used in modeling.

Reflection Number	1	2	3	4
γ_0	2.271	2.271	2.094	2.055
σ	0.644	0.171	0.226	0.294
v_{c2}	1.541	1.483	1.928	2.083
γ_e	1.190	1.959	1.442	1.255

Conclusions

From comparison of different anisotropic analysis methods, we observed that the three-term and SSDSRT methods are accurate enough for short spread data with *x/z* ratio approximately 1.4. For long spread data, only the DSRT method, which can handle large offset and strong anisotropy, performs well. By combining SSDSRT and DSRT methods and 3D graphics tools, short spread as well as long spread converted wave data for isotropic and polar anisotropic media can be analyzed efficiently and accurately.

References

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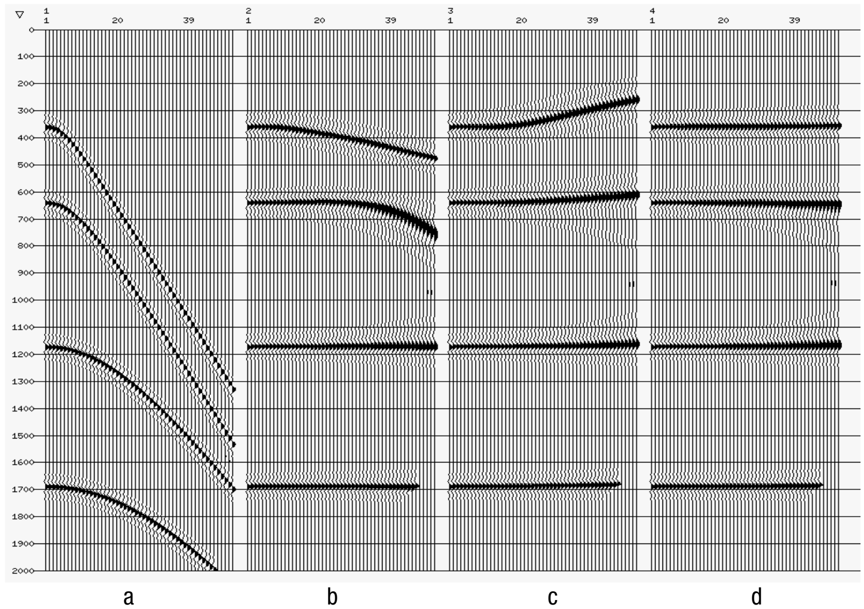

Figure 1. a) Synthetic data with four anisotropic events, b) NMO correction using three-term method, c) NMO correction using SSDSRT method, d) NMO correction using DSRT method.

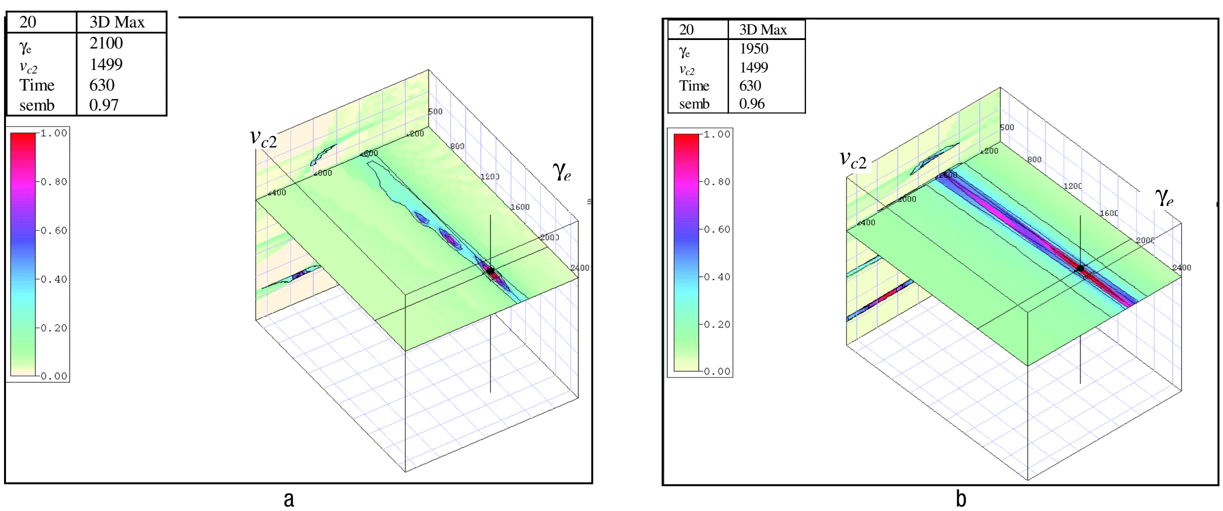

Figure 2. 3D semblance analysis. a) semblance slice from long spread data shows good resolution but $\boldsymbol{\gamma_e}$ deviates to a higher value than the model, b) semblance slice from short spread data shows correct $\boldsymbol{\gamma_e}$ at 1.95 but lower resolution. The values for $\boldsymbol{\gamma_e}$ are multiplied by 1000 in the displays.