Seismic anisotropy estimation in TTI media using walkaway VSP data

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Abstract

Walkaway VSP data are commonly used to estimate *P*-wave anisotropic parameters for subsurface formations that exhibit transverse isotropy (TI). When vertical transverse isotropy (VTI) is assumed for dipping formations where the anisotropic symmetry axis is normal to the bedding, errors can occur in the estimated anisotropic parameters. Using a simple layered model, we examine the errors in estimated Thomsen parameters ε and δ as a function of dip angle and anisotropic magnitude. The results show that errors in ε in general are smaller than those measured for δ. When formation dips are greater than 5° and the anisotropic parameters are greater than 0.05, the use of a tilted TI assumption is necessary to correctly recover the anisotropic parameters from the traveltime data. We then investigate the discrepancies between *P*-wave velocity in the symmetry direction, V_0, and vertical interval velocities, V_v, from check-shot surveys using a tilted TI model. We find that if V_v is used as V_0 without proper adjustments, significant errors can result in the estimated anisotropic parameters. Finally using numerical simulations we demonstrate a new method that simultaneously estimates Thomsen parameters and updates the velocity V_0 for general TI formations from walkaway VSP traveltime data. Our results show that the anisotropic parameters are well resolved for the test models using this inversion method.

Introduction

VSP surveys provide the best way to measure anisotropic parameters for media with transverse isotropy (TI) (Thomsen, 2002). The results may be used to constrain depth models in seismic or high-resolution 2D/3D VSP imaging or to constrain sediment velocities in a salt proximity survey. When local dip angles of the geological structures are sufficiently high, the anisotropic symmetry axis often cannot be approximated by the local vertical direction. This assumption of vertical transverse isotropy (VTI) may lead to substantial errors in anisotropic parameter estimation which may subsequently cause lateral positioning errors of subsurface events in seismic imaging. In these cases, a tilted transverse isotropy (TTI) assumption (with the axis of symmetry normal to bedding) becomes necessary for accurate extraction of anisotropic parameters from VSP data.

There are three parameters used to describe weak *P*-wave anisotropy in TTI media, the *P*-wave velocity in the direction of the symmetry axis, V_0, and Thomsen parameters ε and δ (Thomsen, 1986). In TTI media vertical interval velocities V_v determined from VSP check-shot or zero-offset surveys may not approximate V_0 well; therefore, analysts should also solve for the unknown TTI normal velocity, V_0.

It has been reported that extracting anisotropic parameters for special TTI media using offset VSP surveys can help improve seismic depth imaging (Grech et al., 2002). In these cases, raypaths parallel and perpendicular to the bedding were used to extract velocities in these directions. For general TTI cases, however, there is no systematic method to estimate the anisotropic parameters using walkaway VSP data. Jackson (1995) and Zhou et al. (2003) utilized a tomographic inversion scheme to extract the TTI anisotropic parameters from walkaway traveltime data. The questions that need to be answered are; how do we build an adequate anisotropic starting model from VSP interval velocities and how do we determine the three anisotropic parameters simultaneously.

To answer these questions, we assess the effects of TTI symmetry direction and normal velocity V_0 on the estimated Thomsen parameters ε and δ. Using numerical modeling and simulations we examine the errors in our estimated ε and δ for dipping beds in which the anisotropic symmetry axis is perpendicular to the bedding. We investigate the two assumptions that: 1) the symmetry axis is normal to the titled beds, 2) the symmetry axis is normal to the bedding but V_v is used as V_0. This quantitative study will give guidance for the use and applicability of these assumptions. Finally, we present a quantitative approach to determine Thomsen parameters with a simultaneous update of V_0 for TTI media using walkaway VSP data. This method is an expansion of the tomographic inversion methodology mentioned above. We further show significantly improved results with the simultaneous update.

Errors in anisotropy estimation by VTI assumption

Our initial task was to examine the errors in the estimated Thomsen parameters manifested by assuming VTI symmetry for TTI data. *P*-wave traveltimes for a single-receiver walkaway line were numerically simulated using the simple 3-layer TTI velocity model shown in Figure 1. In this model the dipping layer is anisotropic, and the symmetry axis (z_1) of anisotropy is perpendicular to the bedding. To investigate how the errors vary with the dip angle and the magnitude of the given anisotropy, we rotated the anisotropic layer from horizontal to a maximum dip of 30° using increments of 5°. For simplicity we assume that the two Thomsen parameters ε and δ are equal (i.e., elliptical anisotropy) and vary from 0.05 to 0.2, incrementing by 0.05. The velocity, V_0, in the symmetry direction remains constant in all tests. For each dip angle and anisotropic parameter pair, *P*-wave traveltimes were computed for the walkaway line using a ray-bending algorithm in (x_1, z_1) coordinates (Fig.1).

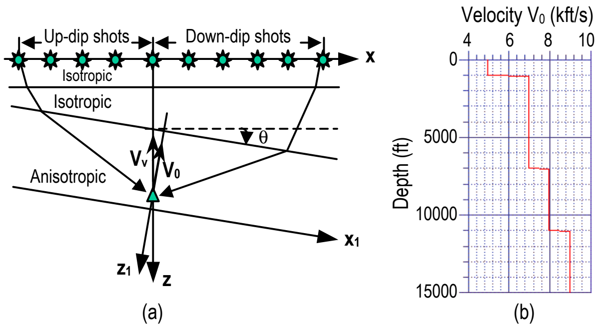

Figure 1 – A simple 3-layer TTI model. (a) 2D depth model, where z_1 is the symmetry axis of the anisotropic layer. (b) P velocity V_0 in the symmetry direction at the well location.

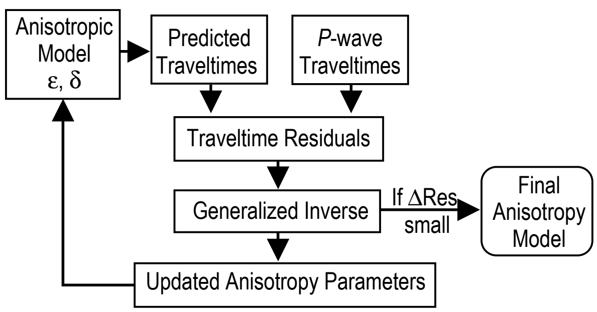

Figure 2 – Flow chart of the traveltime inversion scheme.

We next assumed the anisotropy symmetry axis to be vertical and extracted ε and δ from the simulated travel-time data using the inversion method illustrated in Figure 2. Before inversion, the vertical velocity of the dipping anisotropic layer was updated using the traveltimes at the zero-offset trace to build an isotropic starting model, as is normally done for walkaway data. The initial Thomsen parameters were set to zero. During the inversion process, the Thomsen parameters are updated iteratively to minimize the traveltime residuals in a least-square sense. To avoid errors in estimated anisotropic parameters caused by insufficient coverage of incidence angles or uneven ranges of incidence angles on the two sides of the walkaway line, traces were selected to cover up to 75° of incidence angles on both sides. Such an angle range provides sufficient data to recover the Thomsen parameters assuming TTI symmetry.

Figure 3 shows the absolute and relative errors in the recovered values of ε for a range of ε and layer dip angles. These figures indicate that ε was underestimated, and the relative error increases almost linearly with the layer dip. For layer dips below 5°, the relative error is less than 5% for this model. For a layer dips above 10°, the error is greater than 12%. Figure 4 shows similar error distributions for δ. Unlike ε, δ was overestimated. The largest errors occur at the mid range of the layer dips and high anisotropy values. Even at dips less than 5°, the relative error exceeds 20% of the input anisotropy value.

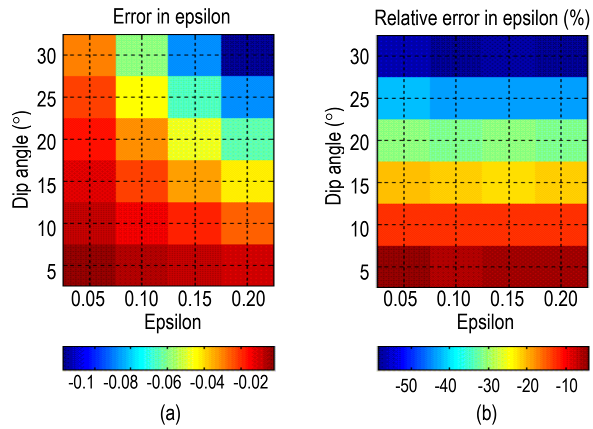

Figure 3 – (a) Absolute and (b) relative errors in estimated anisotropic parameter ε due to VTI assumption. All walkaway data were used in the inversion.

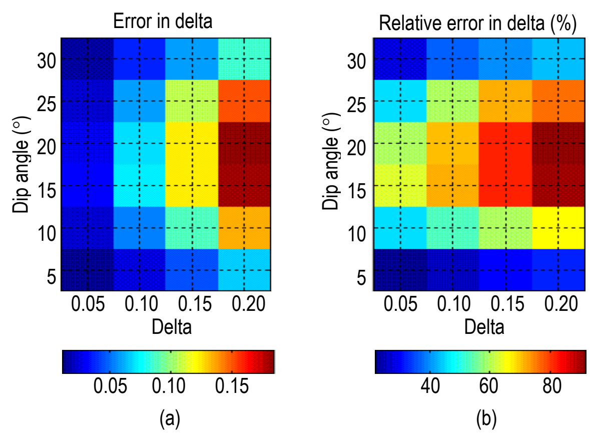

Figure 4 – (a) Absolute and (b) relative errors in anisotropic parameter δ due to VTI assumption. All walkaway data were used.

When a one-sided (all shots recorded on one side of the well) walkaway line is acquired due to unique area constraints, the data will likely contain mostly up-dip or down-dip shots. Consequently, we need to investigate how the anisotropy estimation will be affected by having only one-sided walkaway data. Figures 5 and 6 show errors estimated for ε using only up-dip and down-dip shots, respectively. While both results look similar to the full walkaway result (Fig.3), the up-dip results are better at small layer dips (< 10°); the relative error is below 5%. At a dip angle of 20°, the error is approximately 10%. For larger dip angles (>20°), the down-dip shots give slightly better results, as the errors are below 50%. Our tests also show that the values of recovered ε vary slightly with the choices of the trace range used in the inversion.

Figures 7 and 8 show the error estimated for δ using up-dip and down-dip shots, respectively. Similar to the full walkaway result (Fig.4), the up-dip shots give over-estimated values of δ, but the errors are much higher. The relative error, for example, exceeds 30% even at the small dip angle of 5°. Unlike the results obtained for the full walkaway and the up-dip shots, down-dip shots give under-estimated, negative values. The relative error at the smallest dip angle exceeds -40%. Our tests show that the values of recovered δ vary significantly with the trace ranges used in the inversion.

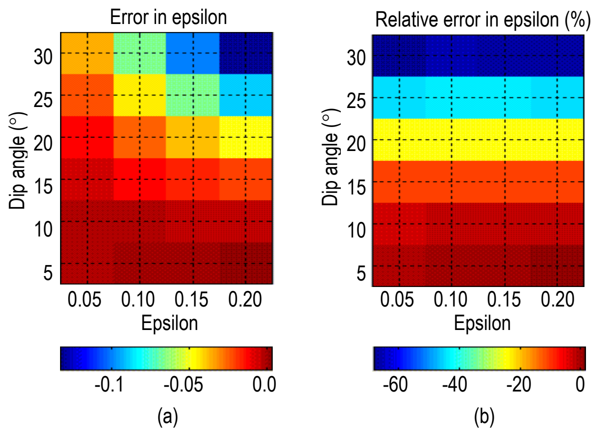

Figure 5 – (a) Absolute and (b) relative errors in ε due to VTI assumption using up-dip shots.

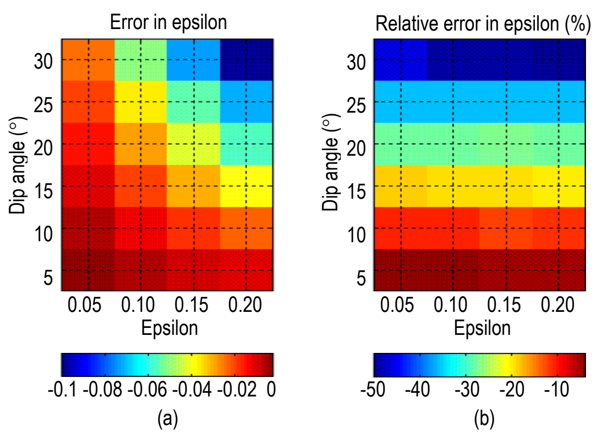

Figure 6 – (a) Absolute and (b) relative errors in ε due to VTI assumption using down-dip shots.

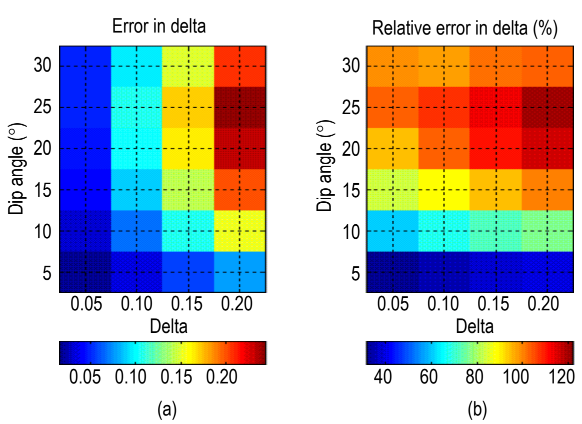

Figure 7 – (a) Absolute and (b) relative errors in δ due to VTI assumption using up-dip shots.

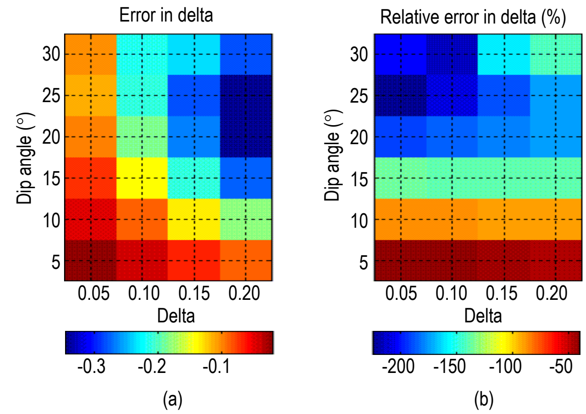

Figure 8 – (a) Absolute and (b) relative errors in δ due to VTI assumption using down-dip shots.

For this test case, in general, ε can be more accurately recovered than δ. For dips less than 5°, the relative errors are below 5% for the recovered ε and around 30% for δ. These results suggest that assuming a VTI symmetry axis in certain geologic and source configuration conditions will not correctly recover the anisotropy parameters.

Interval velocity induced errors in anisotropy estimation

One of the advantages obtained from a VSP anisotropy study is the interval velocity information acquired from a check-shot or zero-offset VSP. This information provides the apparent velocities along the well trajectory. If the formations are horizontal and exhibit VTI anisotropy, the vertical interval velocity function V_v is a good approximation of the velocity in the symmetry direction, V_0. In this case, the only unknowns are the Thomsen parameters ε and δ. In the case of TTI symmetry however, the interval velocity function may not be a good approximation since both formation dip and anisotropy can affect the raypaths in the check-shot survey. Direct use of the interval velocities may lead to errors in the estimated Thomsen parameters even if the TTI assumption is used. It is necessary to examine the effects of the velocity V_0 on the inversion results.

We initially investigated the discrepancies between the two velocity functions V_v and V_0 in the presence of formation dips and TTI anisotropy. We numerically modeled a check-shot survey using a TTI model and examined how the interval velocities vary with formation dips. Figure 9 illustrates a 2D TTI model and the survey geometry of a two-line walkaway survey. The formations between 15000 ft and 25000 ft at the well location are anisotropic and contain a velocity gradient zone L_1, represented by a group of thin layers, and a uniform velocity zone L_2, represented by a constant velocity layer. Traveltime data were simulated for a shot at zero offset, using 11 receivers placed in these two zones over an interval of 1000 ft. The interval velocities along the well were computed from these simulated check-shot data for layer dips of 10°, 20° and 30°. They are shown in Figure 10 as solid red, blue and green lines, respectively. The black line in the figure is the true velocity function in the symmetry direction (also shown in Fig. 9b). At these dip angles, the apparent interval velocities are higher than the true value, by about 0.4%, 1.3% and 3.6%, respectively. The interval velocities for the constant velocity layer in effect behave as if it were a number of thin layers having slightly different velocities. In addition, experiments with isotropic models indicate that the layer dip alone does not significantly affect the interval velocity measurements.

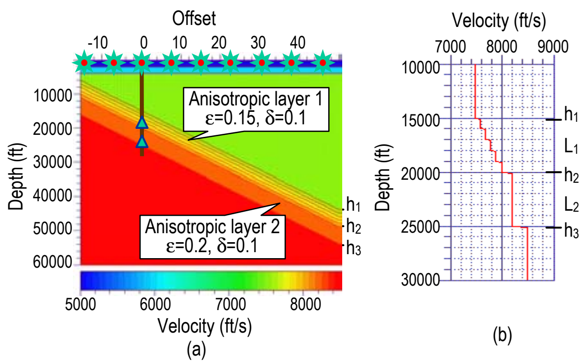

Figure 9 – (a) A 2D TTI model and (b) P-wave velocity V_0 in the symmetry direction.

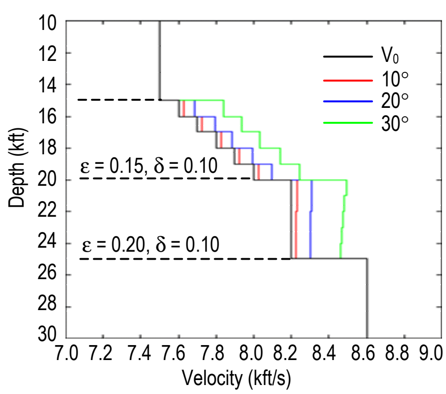

Figure 10 – Apparent vertical interval velocities V_v for the test TTI model.

Next we investigated how the estimated anisotropic parameters are affected by the use of an improper velocity function V_0 in the model. The synthetic traveltime data used in the single-dipping-layer VTI tests were used to invert for Thomsen parameters assuming TTI symmetry. The velocity V_0 (Fig. 1) in the symmetry axis was modified using the apparent interval velocity modeled from the zero-offset trace.

Figure 11 shows the absolute and relative errors in the recovered values of ε for the input values of ε and dip angle. These two figures exhibit similar patterns as in the VTI symmetry tests, but the errors for large dip angles are substantially lower than the VTI results. For layer dips less than 5°, the relative error is below 5%. Figure 12 shows the error distribution for δ. The error distribution is similar to the error shown by ε. For layer dips less than 5°, the relative error is below 5%. For large dips, however, the errors range from -50 to -120%.

These simulated results indicate that the apparent interval velocities V_v obtained from a check-shot survey in a VTI medium can be different from the velocity measured in the symmetry axis, V_0, in the presence of TTI anisotropy. Although the deviation is less than 5% for this particular model, errors in the extracted anisotropic parameters can be significant at high dip angles if V_v is used directly as V_0 without proper adjustments.

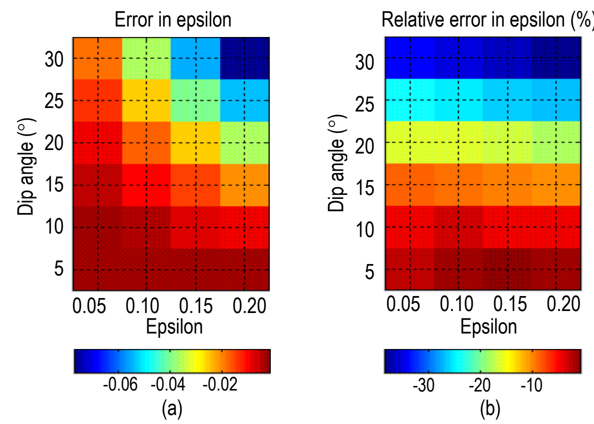

Figure 11 – (a) Absolute and (b) relative errors in estimated ε due to improper values of velocity V_0 using full walkaway data in the inversion.

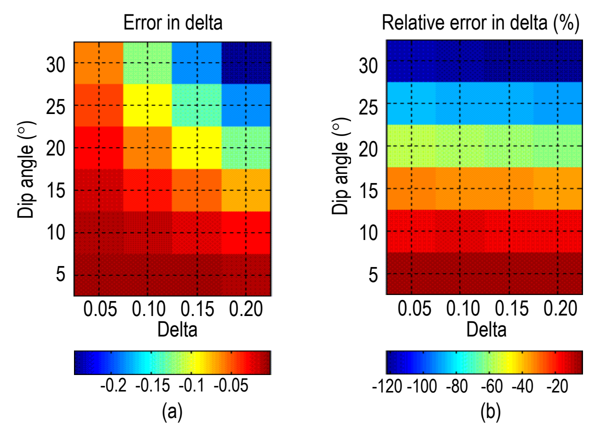

Figure 12 – (a) Absolute and (b) relative errors in estimated δ due to improper values of velocity V_0 full walkaway data were used in the inversion.

Inversion for Thomsen parameters in TTI media

To improve the estimation of the anisotropic parameters for TTI media, we must adjust the apparent interval velocity function used to approximate the velocity V_0 in the symmetry direction. Previous simulation results indicate the difference between the two velocity functions is less than 5%, and the discrepancy varies almost linearly with depth in uniform formations. This suggests that we can use the interval velocity function V_v as a starting value of V_0. By including V_0 in the traveltime inversion, we can simultaneously estimate Thomsen parameters and update the velocity. As the inversion will change the velocities V_0, affecting all receivers in or below the layer, we must start the inversion from the top layer and invert each layer successively downward using a layer stripping technique. Figure 13 illustrates the inversion process.

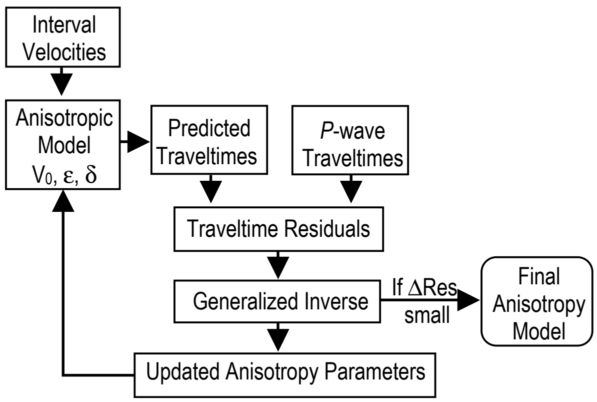

Figure 13 – Flow chart of the traveltime inversion scheme for three anisotropy parameters.

This method was applied to the synthetic walkaway survey illustrated in Fig. 9. The model layer dip was set to 30°. The first break times for the two single-receiver walkaway lines were simulated using the true velocity function V_0 and the anisotropic parameters in Fig.9. The blue crosses in figures 14 and 15 show the simulated traveltime data. The apparent interval velocities along the well computed using 30° dip (solid green line in Fig.10) were used to build the starting model.

We began the inversion with the upper anisotropic zone. The traveltimes predicted by the starting model before the inversion are shown as blue crosses in the upper diagram of Fig. 14. The difference between the simulated first break times and the predicted times (traveltime residuals) are shown as blue stars in the lower diagram. Although both traveltime and residual data exhibit an asymmetric pattern around zero offset, the true first break times are faster than the predicted times at large offsets. This phenomenon is often a signature of *P*-wave TI anisotropy.

Inversion was performed for the five thin layers in the upper zone. The layers were grouped, in effect treated as having identical anisotropic characteristics. The recovered anisotropic parameters are listed in Table 1, and the updated V_0 is also shown in Figure 16. The anisotropic parameters coincide very well with the test values of ε=0.15 and δ=0.1. The final traveltime residuals after the inversion (red stars in the lower diagram of Fig.14) are negligible (< 0.3 ms). The updated velocity function V_0 also coincides well with the true values. The maximum relative error in V_0 is less than 0.1%. The results of inversion without updating V_0 are also shown in Fig. 14 and Table 1 as a comparison.

We then used the Thomsen parameters and velocity function V_0 estimated from the inversion to define the upper anisotropic zone. Apparent interval velocities (the green line in Fig. 10) were again used to build a starting model for the lower anisotropic layer. Simultaneous inversion for δ and ε was performed. Fig. 15 shows the traveltimes and residuals, which are similar to the results obtained from the upper layer case. The recovered δ, ε, and V_0 velocities are shown in Table 1 and Fig. 16. The test values of δ and ε (ε=0.2 and δ=0.1) were successfully recovered. The estimated values of V_0 are consistent with the true value, having a maximum error below 0.2%.

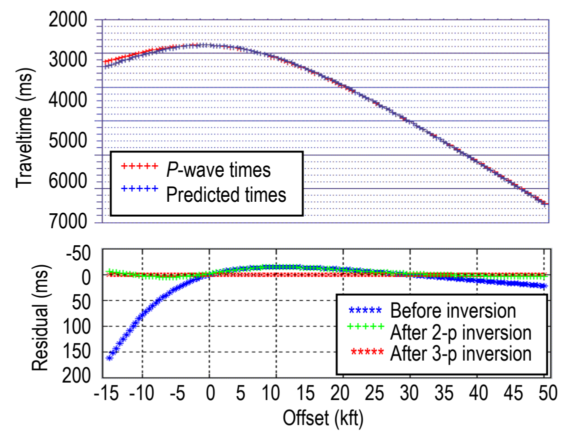

Figure 14 – Traveltime and residual data for the upper anisotropic zone. The predicted times were computed from the isotropic starting model before inversion. The residuals are the difference between the *P*-wave times and predicted times.

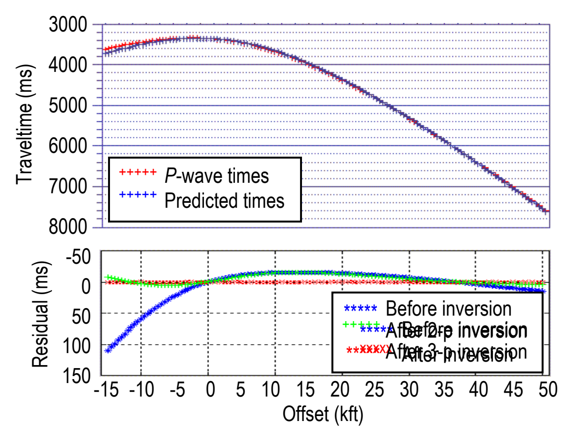

Figure 15 – Traveltime and residual data for the lower anisotropic layer.

Table 1. Inversion results.

Layer#	ε	δ	$\Delta V_0/V_0$(%)	Parameters
1	0.15	0.10	< 0.1	V_0, ε, δ
2	0.20	0.10	< 0.2	V_0, ε, δ
1	0.12	-0.03	NA	ε, δ
2	0.18	-0.06	NA	ε, δ

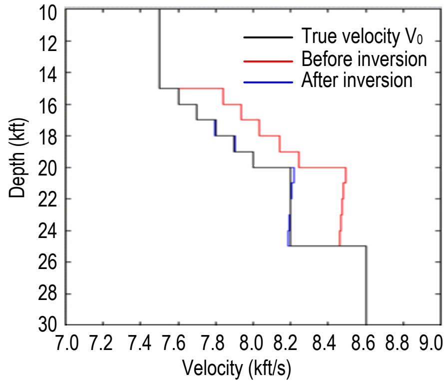

Figure 16 – Velocity function V_0 before and after inversion.

Discussion

Our first simulation study which examined the errors inherent in assuming VTI, demonstrates that Thomsen parameters ε and δ can have large errors when a VTI assumption is used for TTI formations. Parameter δ in particular is very unstable, as its values depend on the trace range used in the inversion. The second simulation study which investigated the effects of the vertical velocity V_0 suggests that erroneous values of V_0 can be a significant source of error when estimating anisotropic parameters. An incorrect value of V_0 will produce a constant bias in the total traveltime residuals. Using this uncorrected velocity for anisotropy estimation will produce erroneous values of δ and ε . This is an intrinsic problem to model-based inversion. Since δ is sensitive to near vertical rays, δ will be more sensitive to improper values of V_0 than will be ε. Without adequately updating V_0, the anisotropic parameters cannot be properly extracted even if the proper symmetry axis is used.

A common practice when computing anisotropy parameters is to average up-dip and down-dip shot gathers to minimize the effects of local structural dips or velocity heterogeneity. This practice is based on the general observation that using up-dip shots alone may overestimate the anisotropic parameters, while using down-dip shots alone may underestimate the parameters. Our results show that ε is mostly underestimated in a TTI medium when up-dip or down-dip shots alone are modeled under the assumption of VTI. As a result, averaging the two groups of shots does not improve the estimate of ε. Although δ is overestimated using up-dip shots and underestimated using down-dip shots, the values of δ are highly dependent on the choices of trace range in the inversion. There is no clear correlation between the two groups of results. When the structural dip is greater than a few degrees, the rays from shots with similar offsets can have very different incident angles at the receiver. Consequently it is difficult to identify the traces having identical incidence angles and find an objective way to average the shot gathers for improving the inversion results.

This work can be expanded to handle general TI cases. In this study a ray-bending algorithm was used to compute traveltimes for simple TTI models. For more realistic models, finite-difference based methods (i.e., Zhang et al., 2002) can be used to handle irregular layer interfaces that exhibit a local TI symmetry axis, and to handle velocity heterogeneity in the model as well. We studied a simple 2D TTI case where the symmetry axis is normal to the bedding, and the formation dip is in the source-receiver plane. There are of course instances where the symmetry axis is at an arbitrary angle to the bedding plane, or the formation dip is out of the source-receiver plane. In the latter case, a 3D modeling program is required to correctly predict the traveltimes.

Conclusions

This study demonstrates that anisotropy estimates can be severely biased by the assumption of VTI symmetry for data recorded from TTI media. Although the difference between the velocity in the symmetry direction V_0 in TTI formations, and the apparent interval velocity measured from a check-shot survey is small, large errors can be introduced by the direct use of the interval velocity function. By updating the vertical velocity V_0 and performing simultaneous estimation of the Thomsen parameters δ and ε, we can minimize errors in δ and ε using walkaway VSP data. Further research should be initiated to investigate how to determine anisotropic parameters from walkaway data when the formation dips are out of the source-receiver plane.

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