

VTI anisotropy parameter estimation in the tau-p domain: An example from the North Sea

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Summary

Seismic anisotropy parameter estimation can be performed in the τ - p domain. Here we present a methodology for extracting anisotropy parameters that employs traveltime picking in the t - x domain and inversion in the τ - p domain. The sensitivity of the technique to the magnitude of anisotropy and offset-to-depth ratio is investigated. Offset-to-depth ratios of greater than 1.5 are a minimum requirement for any estimation method based on non-hyperbolic moveout. We apply the technique to ocean-bottom data from the Valhall field in the North Sea. The results show a moderate amount of anisotropy with effective η values of 0.05 to 0.08 on average. Parameter estimation, however, is affected by the presence of a gas cloud near the crest of the field.

Introduction

Stratification or horizontal alignment can produce VTI anisotropy. Knowledge of the presence of anisotropy is important for accurate seismic imaging, time-to-depth conversion, and offers information on lithologic properties. A diagnostic of anisotropy is non-hyperbolic moveout in reflections from layered media.

We use a τ - p domain method to estimate VTI anisotropy parameters (Van der Baan et al., 2001; Van der Baan and Kendall, 2002). It can be shown that this approach is more accurate for both traveltime prediction and parameter estimation than more conventional approaches based on Taylor-series expansions (Tsvankin and Thomsen, 1994, Alkhalifah, 1997). In addition, layer stripping is a linear process. This means that both effective and local parameters can be recovered by removing the effects of anisotropy in the overburden.

Here we also present a sensitivity analysis of this relatively new tool and an application to real data from the Valhall field in the Norwegian sector of the North Sea.

Description of τ - p method

Conventionally anisotropy parameters are estimated in the t - x domain using a modified Taylor series expansion (Tsvankin and Thomsen, 1994; Alkhalifah, 1997). However, Van der Baan et al. (2001) and Van der Baan and Kendall (2002) showed that it is possible to invert for these

parameters in the τ - p domain with a greater degree of accuracy.

The traveltimes and $\Delta\tau_i(p_x)$ curves for each individual layer i are related by the τ - p transform (Hake, 1986)

$$t = p_x x + \sum_i \Delta\tau_i \quad (1)$$

In this equation the individual $\Delta\tau_i(p_x)$ curves depend on the horizontal slowness p_x and are given by

$$\Delta\tau_i/\Delta\tau_{0,i} = (v_{0,i}^d v_{0,i}^u) [(v_{ph,i}^d)^2 - p_x^2]^{1/2} + (v_{ph,i}^u)^2 - p_x^2]^{1/2} / (v_{0,i}^d + v_{0,i}^u) \quad (2)$$

with $\Delta\tau_{0,i}$ the zero-offset intercept time and $v_{0,i}$ its associated phase velocity. The symbols ^d and ^u denote down- and up-going waves, respectively.

Although it is possible to compute exact expressions for the phase velocity and thus exact traveltimes and $\Delta\tau_i(p_x)$ curves, a strong non-uniqueness exists in the inversion results. Therefore, reduced-parameter expressions were developed using

$$v_p^2(p_x) \approx \alpha_n^2 (1.25 - 2\eta p_x^2 \alpha_n^2 + S_n^{1/2}) / (2 - 4\eta p_x^2 \alpha_n^2 - 3\eta p_x^4 \alpha_n^4) \quad (3)$$

$$v_{sv}^2(p_x) \approx \{-1 + 2\sigma p_x^2 \beta_0^2 + [(1 - 2\sigma p_x^2 \beta_0^2)^2 + 8\sigma p_x^4 \beta_0^4]^{1/2}\} / (4\sigma p_x^4 \beta_0^2) \quad (4)$$

$$\begin{aligned} \text{where } S_n &= 9/16 - 3\eta p_x^4 \alpha_n^4 + \eta(1.5 + 4\eta)p_x^4 \alpha_n^4 \\ \alpha_n &= \alpha_0(1 + 2\delta)^{1/2} \\ \eta &= (\varepsilon - \delta)/(1 + 2\delta) \\ \sigma &= (\varepsilon - \delta)\alpha_0^2/\beta_0^2 \end{aligned} \quad (5)$$

At this point expressions (1) and (2) can be used in two different ways to estimate VTI anisotropy parameters. Firstly, it is possible to transform the data to the τ - p domain and pick the $\tau(p_x)$ curves of each target horizon directly. We opt for a different approach following Wookey et al. (2002) by picking the horizons in the t - x domain. The picked $t(x)$ curves can be transformed into the required $\tau(p_x)$ curves by computing the differential moveout ($p_x = \partial t / \partial x$) and using equation (1). However, to better constrain the resulting $\tau(p_x)$ curves, we smooth the picks by first fitting a modified Taylor series expansion. This improves the quality of the obtained $\tau(p_x)$ curves since the sensitivity to small picking errors is reduced.

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Sensitivity analysis

Naturally the inversion results depend on the offset-to-depth ratio (x/z) used, the actual values of the anisotropy and the accuracy of the time picks. To quantify the uncertainty in the estimates, a sensitivity analysis was implemented. Two measures are used to reflect the amount of confidence that can be attached to the inversion results.

The first measure is the *misfit* (i.e., the discrepancy between the observed and predicted $\tau(p_x)$ curves). Unfortunately, the misfit does not reflect the possible spread in the determined parameters. We therefore implement a second measure to compute the range of allowable values. This is done by perturbing the best-fit parameters until some specified level of error is exceeded. The error used is directly related to the accuracy of the time picks. Hence, the second measure essentially gives the range of values that produce moveout curves within the envelope defined by the best-fit model and the data resolution.

The sensitivity tool can also be used to assess the uncertainty in the estimation of anisotropy parameters in general. For instance, Figure 1a displays the maximum error in η for different x/z ratios (for an actual η of 0.16)

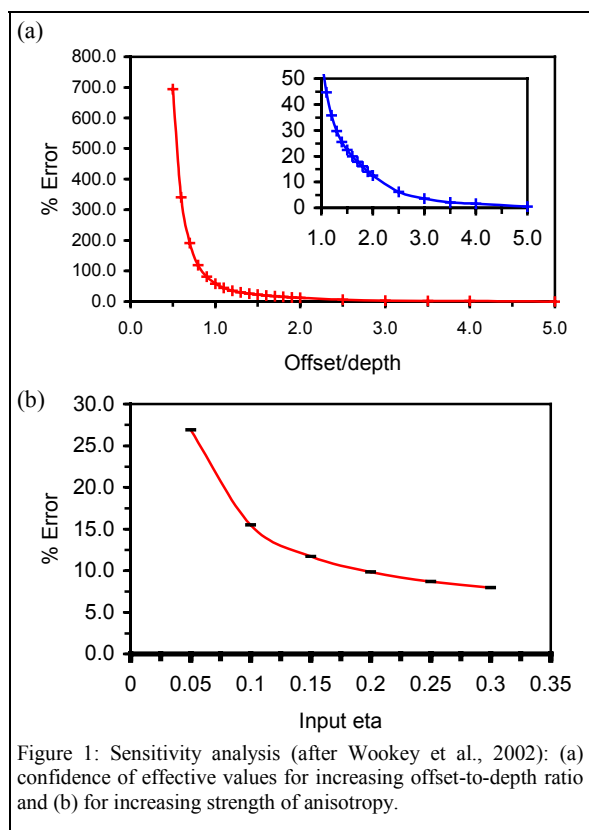


Figure 1: Sensitivity analysis (after Wookey et al., 2002): (a) confidence of effective values for increasing offset-to-depth ratio and (b) for increasing strength of anisotropy.

and Figure 1b displays the maximum error for a fixed ratio ($x/z = 2.0$) and varying strength of anisotropy η (in both cases using P-wave data only). Figure 1 shows that with sufficient offset, anisotropy parameters are recovered with a high degree of confidence. In addition, the strength of anisotropy determines the amount of non-hyperbolic moveout observed and thus the level of confidence in the results.

Case study: Valhall – North Sea

We have applied the τ - p inversion method to a 2D line in the Valhall area, North Sea. Although it is 3-C dataset, at present only the P-wave data is used (Vertical component + Hydrophone). The converted wave data (x-component) will be analyzed in the near future.

The structure in Valhall is characterized by a shallow anticline. However, over the range of offsets covered by a single CMP the structure is relatively flat. The chalk reservoirs are located in the Tor (2200 m. depth) and Lower Hod (2440 m depth) formations, with average thicknesses of 24 to 30 meters. The overburden is primarily siltstone / shale.

Data processing

Processing of seismic data for anisotropy parameter estimation is a challenge since there is a precarious balance between improvements to the signal-to-noise ratio and distortion of the curvature of the reflection traveltimes curves.

Ideally processing should improve the continuity and resolution of events to facilitate horizon identification and allow traveltimes picks to the largest offset range possible (non-hyperbolic moveout is only evident in the far offset). On the other hand we have to make sure that the curvature of the events is not affected by the processing. Fortunately, we are only interested in traveltimes moveout information; conservation of frequency content and amplitudes is less important.

Hence, the employed processing sequence starts with a mute, AGC and bandpass filter. Two FK filters are then applied in cascade to reduce the linear noise in the far offset such that the picks can be extended to larger offsets. Then a predictive deconvolution filter is designed to further reduce the linear noise and improve the lateral continuity of reflectors. A second bandpass filter is applied to remove high-frequency noise introduced by the predictive deconvolution filter. Finally, adjacent CMP's are combined and similar offsets stacked.

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The last step improves the continuity of reflections significantly (see Figure 2). An extensive series of tests has been done to guarantee that the signal-to-noise ratio was improved and that events could be picked to large offsets without affecting the curvature of the reflections.

Optimum input data for the application of this method is raw data with static corrections applied, but before top mutes are applied to remove any linear noise as in Figure 2.

Picking

We selected five different horizons (Figure 2c) for analysis, choosing those where $t-x$ picks could be made with confidence. Conventional velocity analysis was carried out along the line before the horizons were selected in order to avoid picking multiples and as a quality control of inversion results. The picking was done on CMPs with 4 kilometers offset to each side. 20 CMP's were selected on the basis of data quality and the largest possible offset-to-depth ratio available.

The picking was difficult in the region of the gas cloud due to deterioration in the data quality. The gas cloud is also marked by an abrupt change in velocities.

Results

Estimated values of stack velocities and effective values of the anisotropy parameter η are shown in Figure 3. There is good agreement between the velocity field estimated from semblance analysis and the velocities estimated from the τ - p analysis. In addition, use of the estimated stacking velocities to flatten the CMP gathers reveals that residual moveout is clearly present, thus indicating the presence of anisotropy.

Effective values of η show that horizons 2 and 3 exhibit relatively high values of anisotropy. Layers 4 and 5 display lower values of anisotropy except at the left and right edges. The average value of η varies between 0.05 to 0.08.

Interval values of η and α exhibit a stronger variation due to the fact that these parameters are more susceptible to change than effective values and because of the influence of the gas clouds. Furthermore, some static problems are present and the continuity of reflectors, an important factor in the picking process, is also affected by the presence of gas clouds in the area.

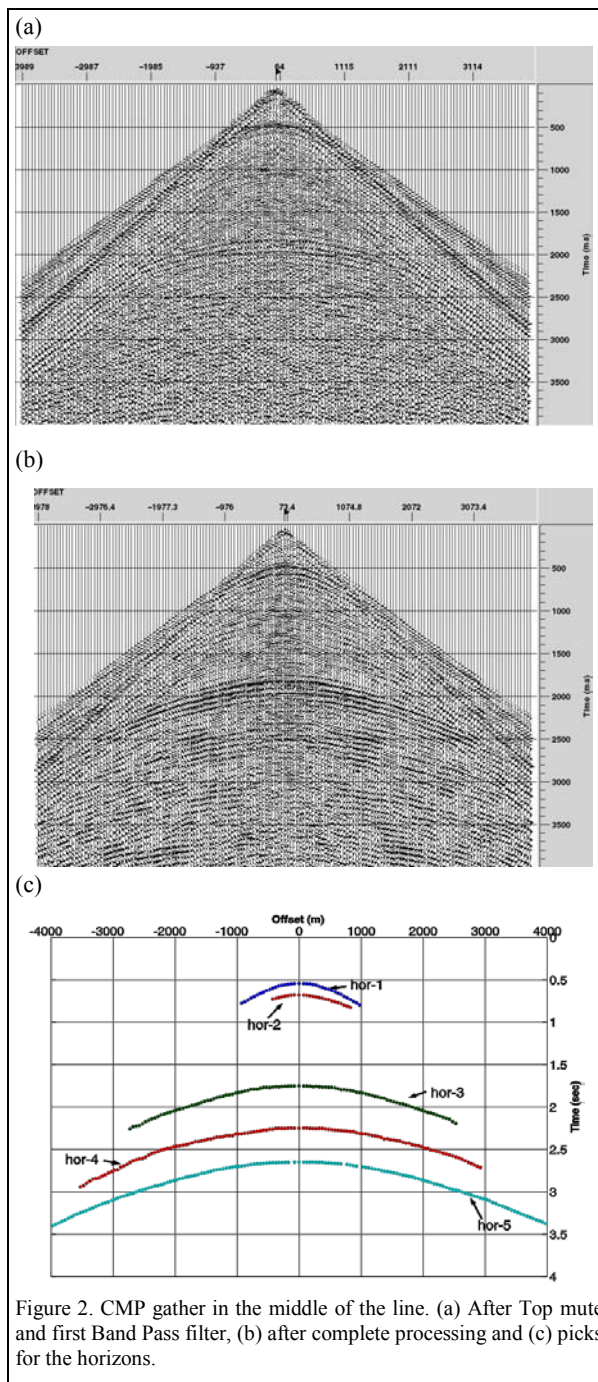


Figure 2. CMP gather in the middle of the line. (a) After Top mute and first Band Pass filter, (b) after complete processing and (c) picks for the horizons.

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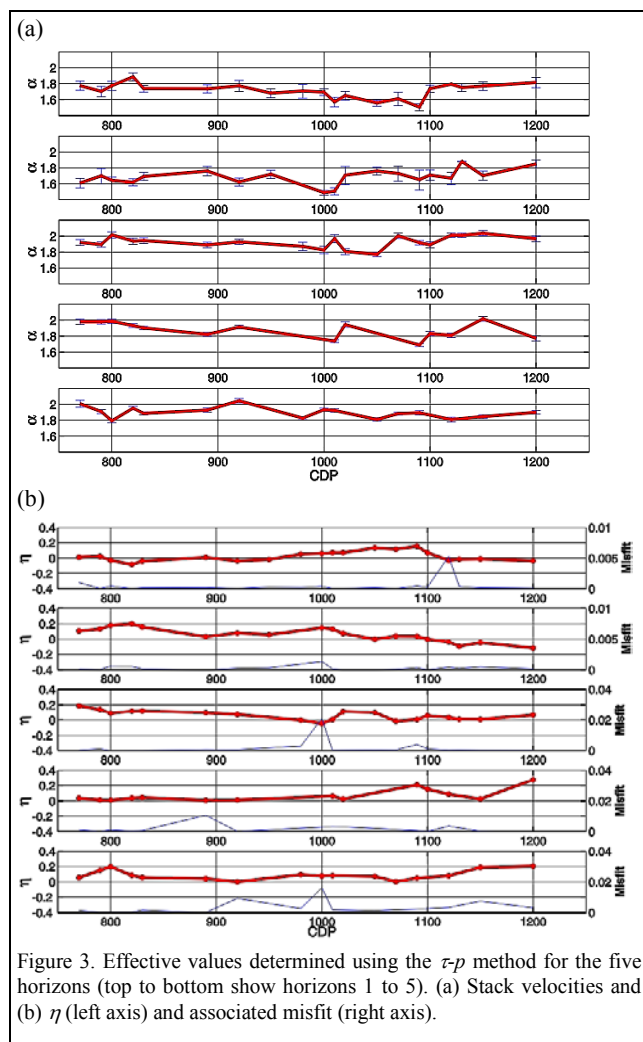


Figure 3. Effective values determined using the τ - p method for the five horizons (top to bottom show horizons 1 to 5). (a) Stack velocities and (b) η (left axis) and associated misfit (right axis).

Conclusions

Results show that it is possible to estimate anisotropy parameters from surface seismic reflection data in the τ - p domain for VTI media. The developed tool is highly sensitive, and the quality of the results depends on the offset-to-depth ratio, the strength of the anisotropy, and the quality of the picks. The latter requirement is strongly dependent on the quality of the seismic data. A sensitivity analysis has been implemented to determine the level of confidence that can be attached to the inversion results. Accurate seismic data processing is essential to allow for confident estimation of the anisotropy parameters. Quality control is essential during the picking stage.

For this particular case study, the values of α , τ and η are strongly affected by lateral velocity variations due to the presence of gas in the area. In order to understand how significant the effect of these velocity changes is, forward-modeling of traveltimes is required. Intended velocity models will exhibit both slow and abrupt lateral variations. Future work will also include analysis of the effect of dipping horizons.

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Acknowledgments

We thank Dirk Smit (Shell) and Olav Barkved (BP) for continued support and advice on this project. BP-Norge and PGS provided the data used in this study. A part of this work was done by James Wookey during an internship at Shell Aberdeen. Funding for parts of this research come from Shell International, Schlumberger Cambridge Limited, BP Norge and ABB Offshore systems. The Valhall partnership – BP Norge, Amerada Hess Norge, TotalFinaElf and Enterprise Norge – are thanked for permission to present these results. Carlos Guerrero would like to thank ECOPETROL for the funding of his research.