Anisotropic inversion and imaging of PP and PS reflection data in the North Sea

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The technology of ocean bottom surveys has put mode-converted waves at the forefront of seismic exploration and reservoir characterization. For example, PS-waves proved effective in imaging offshore reservoirs screened by gas clouds that cause high attenuation/scattering of compressional energy (e.g., Thomsen, 1999). Also, information about shear-wave velocities contained in converted modes can be used to separate the effects of saturation and pressure, as well as reduce the uncertainty in predicting lithology and fluid saturation. The high sensitivity of PS-wave reflection coefficients to shear-wave velocity and density makes converted-wave AVO analysis a potentially powerful tool in detecting hydrocarbon-saturated rocks.

Conventional (isotropic) processing of mode conversions, however, often turns out to be inadequate because the influence of anisotropy on PS-wave moveout and amplitude is much more substantial than that on P-wave signatures. In particular, mis-ties between PP and PS sections (such as different depths of reflectors) are difficult to remove without taking anisotropy into account. Assuming a purely isotropic overburden often causes smearing of the conversion point, which leads to errors in building common-conversion-point (CCP) gathers and poor focusing of PS images. Also, shear-wave splitting in anisotropic media makes it necessary to rotate PS-wave displacement components prior to imaging or AVO analysis.

The difficulties in applying isotropic processing techniques to mode conversions underscore the importance of anisotropic velocity analysis of PS data. In the presence of anisotropy, it is especially beneficial to combine PP- and PS-waves in model-building algorithms because a certain subset of the medium parameters influences both P- and S-wave propagation. For transverse isotropy with a vertical symmetry axis (VTI media), signatures of P- and SV-waves depend on the P-wave vertical velocity \(V_p\) and Thomsen parameters \(\epsilon\) and \(\delta\); additionally, SV-wave kinematics is a function of the shear-wave vertical velocity \(V_{S0}\). It should be emphasized that reflection traveltimes of PP-waves alone typically are insufficient for resolving the individual values of \(V_p, \epsilon\) and \(\delta\).

Anisotropic velocity analysis of PP and PS data

It is well known that velocity analysis and inversion of PS-waves is complicated by such features as conversion-point dispersal, polarity reversal, and moveout asymmetry with respect to zero offset (i.e., the traveltime of PS-waves generally does not remain the same if the source and receiver are interchanged). The last problem, called the “diodic velocity” by Thomsen (1999), is the most serious because it precludes application of the conventional hyperbolic moveout equation to converted waves. To overcome the inherent difficulties in dealing with PS-waves, Grechka and Tsvankin (2001) suggested a model-independent procedure to reconstruct the traveltimes of pure SS-wave reflections from PP and PS data. Their algorithm for computing SS traveltimes is exact and entirely data-driven, so knowledge of the velocity field is not required. The reconstructed SS moveout is symmetric with respect to zero offset and can be processed by velocity-analysis methods developed for pure modes.

An efficient approach to the joint inversion of PP and SS traveltimes is stacking-velocity tomography, which operates with stacking [or normal-moveout (NMO)] velocities on 2-D lines and NMO ellipses in wide-azimuth 3-D surveys. For anisotropic models composed of homogeneous layers or blocks separated by smooth interfaces, the NMO ellipse of any pure-mode reflection at a given common-midpoint (CMP) location can be computed by tracing only one (zero-offset) ray, which makes iterative inversion computationally feasible. Grechka, Pech and Tsvankin (2001) developed stacking-velocity tomography for multicomponent (PP and SS) data in TI media with arbitrary tilt of the symmetry axis.

These two new methods provide the basis for the
following processing flow devised for anisotropic velocity analysis of multicomponent data:

(i) Prestack horizon-consistent picking of PP and PS traveltimes on 2-D or 3-D data volumes and identifying the events reflected from the same interface.


(iii) Tomographic inversion of the NMO velocities (in 2-D) or NMO ellipses (in 3-D), zero-offset traveltimes, and reflection slopes for the interval anisotropic parameters (Grechka, Pech and Tsvankin, 2001).

Here we apply this proposed methodology to estimate the interval VTI parameters and improve imaging of PS-wave data for the Lower Tertiary Siri reservoir in the North Sea.

**Reconstruction of SS traveltimes above the Siri reservoir**

The Siri survey includes three 4-C (multicomponent) seabed seismic lines and an 8.7 km x 17.6 km 3-D towed-streamer data set that crosses the Norwegian-Danish North Sea border. This work is limited to the 2-D processing of the north-south 4-C line. A detailed description of the acquisition, model-based (isotropic) processing and interpretation, and the subsurface geology can be found in Signer et al. (2000). The deepest interpreted horizon (top Balder) is right above the top of the thin (~30 m) reservoir (Figure 1), and the structure of the overburden is close to horizontally layered.

Prestack PP and PS (PSV) reflection traveltimes

![Figure 1. Depth section above the Siri reservoir built by Signer et al. (2000).](image)

**Figure 2.** Raw picked traveltimes (in s) of the PP (a) and PS (b) reflections from the top overpressure interface (see Figure 1). (c) SS-traveltimes reconstructed from the PP and PS data. Offset h (h = r - s) is either positive or negative depending on the sign of the difference between the receiver (r) and source (s) coordinates.
for all interpreted horizons in Figure 1 were obtained using a semi-automatic Schlumberger picker. The travel-time picks were made on common-receiver gathers with the receiver increment $\Delta r = 200$ m; the source increment within each gather was $\Delta s = 25$ m. Figures 2a,b show typical raw PP and PS traveltime picks for one of the interfaces in the overburden. Clearly, PSmoveout is asymmetric with respect to zero offset, which is partly caused by picking errors and the fact that the sources are located at the ocean surface, whereas the receivers are placed on the sea bottom. This moveout asymmetry, however, is a typical feature of mode conversions for laterally heterogeneous isotropic media or any anisotropic model without a horizontal symmetry plane. The most pronounced asymmetry is observed in the area of increased lateral variation in the traveltimes (indicative of lateral heterogeneity) near CMP location $x_{CMP} = 8$ km (Figure 1).

In reconstructing the SS traveltimes (Figure 2c) from those of the PP and PS (PSV) reflections, we followed the general methodology of Grechka and Tsvankin (2001). Their algorithm, illustrated in 2-D by Figure 3, is designed to identify the receiver coordinates of the PP and PS rays that are excited at the same location and have the same reflection point. Then the SS traveltime between the obtained shear-wave receiver positions $\rho_1$ and $\rho_2$ is given by

$$t_{SS} (\rho_1, \rho_2) = t_{PS}(s, \rho_1) + t_{PS}(r, \rho_2) - t_{PP}(s, r) \quad (1)$$

To enforce the symmetry of the SS traveltimes and reduce picking errors, $t_{PP}(s, r)$ was replaced with the average of the reciprocal PP times.

The processing of this particular data set required some adjustments because the sources and receivers are located at different levels. The processing flow used to obtain the SS-wave reflection traveltimes from each interface included estimation of the reflection slopes (ray parameters) for both PP- and PS-waves at the source locations, downwarp kinematic continuation (mapping) of the sources onto the ocean bottom, interpolation of the source locations, building common-shot gatherers, and matching the reflection slopes of the PP- and PS-waves at each source location. Therefore, the computation of the SS traveltimes is entirely based on the recorded reflection data and does not require any information about the subsurface velocity or structure. It is assumed, however, that the event-correlation procedure yields PP- and PS-waves reflected from the same interface.

The reconstructed SS-wave traveltimes for the top overpressure interface are shown in Figure 2c. The times in Figures 2a,b were picked for a wide range of offsets limited by $h_{max, PP} \approx h_{max, PS} \approx 4$ km, which yields the maximum offset-to-depth ratio for the top overpressure interface of about 2.5. The offsets of the reconstructed SS reflections are smaller than those for the original PP and PS data ($h_{max, PP}$ has to be divided by the $V_P/V_S$ ratio to estimate the maximum offset for the SS-waves) but still sufficient for the purposes of moveout velocity analysis.

**Velocity analysis of PP and SS data**

The traveltimes of PP-waves and reconstructed SS-waves can be used to compute their associated zero-offset times ($t_{t0}$ and $t_{t0}$) and stacking (moveout) velocities ($V_{t0, PP}$ and $V_{t0, PS}$) to increase the fold of SS data, we formed composite CMP gathers that include offset-traveltime pairs from all CMP locations within a certain interval $w_{CMP}$. We found that $w_{CMP} = 0.5$ km provides
both sufficient stability and acceptable lateral resolution in estimating stacking velocities.

Figure 4 shows the obtained zero-offset traveltimes and stacking (NMO) velocities for the top of the Baldor formation (i.e., the top of the Siri reservoir). The SS traveltimes are missing near the beginning of the line where the needed PP and PS traveltimes were not available. The error bars in Figure 4 correspond to the 95% confidence intervals calculated assuming random (Gaussian) distribution of the traveltimes. Only the best-fit hyperbolas. Only the most reliable portion of the data for CMP locations 7–10 km was used for the parameter estimation.

Before describing the parameter-estimation results, we briefly discuss the properties of the estimated move-out velocities and traveltimes indicative of the presence of anisotropy. The velocity analysis for the top Baldor horizon (Figure 4) and other interfaces yields the ratio of the NMO velocities \( \gamma_{nm} \equiv V_{nm,S}/V_{nm,P} \) that can be compared with the ratio \( g_0 \) of the vertical velocities of the SS-waves (\( V_{S0} \)) and PP-waves (\( V_{P0} \)) \( (g_0 \equiv V_{S0}/V_{P0}) \). Since such a large difference cannot be caused by vertical heterogeneity in isotropic media, anisotropy is the only plausible explanation for the deviation of \( \gamma_{nm} \) from \( g_0 \).

Assuming for simplicity that the medium above each reflector consists of a single homogeneous VTI layer, we can explain the difference between the ratios \( g_0 \) and \( \gamma_{nm} \) in terms of the anisotropic coefficients \( \epsilon \) and \( \delta \)

\[
\gamma_{nm} = \frac{V_{nm,S}}{V_{nm,P}} = \frac{V_{S0}}{V_{P0}} \frac{\sqrt{1 + 2\sigma}}{\sqrt{1 + 2\delta}} = g_0 \frac{\sqrt{1 + 2\sigma}}{\sqrt{1 + 2\delta}}
\]

where \( \sigma \equiv (V_{P0}/V_{S0})^2 (\epsilon - \delta) \). Substituting our estimates of \( \gamma_{nm} = 0.45 \) and \( g_0 = 0.3 \) into equation (2) and linearizing it in \( \epsilon \) and \( \delta \) leads to the relationship \( \epsilon \approx 0.06 + 1.25 \delta \). Clearly, at least one of the anisotropic coefficients \( \epsilon \) or \( \delta \) does not vanish, and matching of both PP and SS data requires the subsurface model to be effectively anisotropic.

**Estimation of the anisotropic parameters**

An important prerequisite for successful inversion is identification of the medium parameters constrained by the available data. The low energy recorded on the trans-
verse displacement component (not analyzed here) and the predominantly horizontal layering above the reservoir (Figure 1) suggests that the medium is azimuthally isotropic (i.e., VTI). Since the structure is subhorizontal and is assumed to be composed of VTI layers, $PP$ and $PS$ reflection data can be inverted for the NMO velocities and anellipticity parameter $\eta$ but not for the vertical velocities $V_{p0}$ and $V_{s0}$ and the coefficients $\epsilon$ and $\delta$ (Tsankin and Grechka, 2000). In general, $PP$ and $PS$ reflection traveltimes in horizontally layered VTI media do not constrain reflector depth, even if the model parameters are selected in such a way that both $PP$ and $PS$ common-image gathers are flat and located at the same depth. Therefore, in the moveout-inversion procedure described below, the parameter $\delta$ is set to a certain predetermined value.

The input data included the $PP$ traveltine picks and reconstructed $SS$ traveltimes in the range $7 \text{ km} \leq x_{\text{CMP}} \leq 10 \text{ km}$ from the mid Miocene, intra Oligocene, base Oligocene, h8, and top Bakler horizons. The VTI model in Figure 6 was produced by stacking-velocity tomography for a fixed value of $\delta = 0$ under the assumption that all interfaces are planar and have arbitrary unknown dips. The error bars for the interval parameters, corresponding to the 95% confidence intervals, were inferred from the errors in the zero-offset traveltimes and NMO (stacking) velocities, such as those in Figure 4. Setting $\delta = 0.1$ (another plausible value) yields a completely different anisotropic model that fits both $PP$ and $PS$ data equally well.

With the reflector dips (Figure 6e) found to be so small, it is possible to assume that all interfaces are horizontal and apply the conventional Dix formula to obtain the interval NMO velocities. Then those velocities can be combined with the ratios of the interval vertical velocities of $P$- and $S$-waves to estimate the interval VTI parameters. After smoothing the effective NMO velocities, we performed this inversion for CMP locations between

\[ a \]

\[ b \]

\[ c \]

\[ d \]

\[ e \]

\[ f \]

Figure 5. The ratios $g_0$ (circles) and $g_{\text{aniso}}$ (triangles) for the following horizons marked in Figure 1: (a) mid Miocene, (b) intra Oligocene, (c) base Oligocene, (d) top overpressure, (e) h8, and (f) top Bakler.
7 km to 10 km; as before, the anisotropic parameter $\delta$ was fixed to ensure a unique result. The coefficients $\epsilon$ of several equivalent anisotropic models obtained at four different CMP locations for a range of $\delta$ values are plotted in Figure 7. All the models fit the picked $PP$ and $PS$ traveltimes equally well; the standard deviation between the measured and computed traveltimes does not exceed 0.3% for the top Balder reflection. However, it is impossible to find a layered isotropic model that provides a good fit to both $PP$ and $PS$ data. Although the estimated values of $\epsilon$ in each layer do change somewhat along the line, no statistically meaningful lateral variation of $\epsilon$ is observed (the standard deviation of $\epsilon$ for a given $\delta$ is about 0.03).

To overcome the inherent nonuniqueness of the inversion process, it is necessary to have an independent estimate of at least one model parameter ($V_{p0}$, $V_{s0}$, $\epsilon$, $\delta$ or reflector depth). Here, we combine reflection data with $P$-wave traveltimes measured using check shots along well Siri-1 located close to $x_{CMP} = 10$ km (data courtesy of Statoil). The check shots helped to build the time-to-depth conversion curve and estimate the depths of the reflectors used in the moveout-inversion algorithm. Then the NMO velocities and zero-offset traveltimes of $PP$- and $SS$-waves were inverted for the VTI parameters $V_{p0}$, $V_{s0}$, $\epsilon$ and $\delta$. The results displayed in Figure 8 were obtained from the interval NMO velocities (estimated using the Dix equation) and zero-offset traveltimes at CMP location $x_{CMP} = 10$ km. The standard deviations in the interval values of $\epsilon$ and $\delta$ do not exceed 0.03.

The largest interval values of $\epsilon$ and $\delta$ are observed in the middle part of the section, with $\epsilon$ reaching almost 0.25 in the Oligocene layer. Clearly, the anisotropy is quite significant for both $P$-waves and, particularly, $PS$-waves (the interval $\sigma$ above the reservoir is about 0.5). Also, throughout the section $\epsilon > \delta$, so the parameters $\eta > 0$ and $\sigma > 0$, which is consistent with predominantly positive values of $\eta$ obtained in other case studies for VTI media.

### Processing of $PS$ data

Because of its model-independent nature, the algorithm of Grechka and Tsvankin (2001) used to reconstruct the $SS$ traveltimes is purely kinematic and cannot produce correct reflection amplitudes. Therefore, we processed the original converted-wave data and compared the results obtained for isotropic and VTI models of the overburden.

Anisotropic CCP stacks were generated using the
inverted VTI model for $\delta = 0$ from Figure 6 (the check shots became available after the processing had been completed). The anisotropic travelt ime curves and CCP trajectories were computed for each model layer and used in the CCP stacking. The isotropic model was obtained from the VTI model by setting $\epsilon = \delta = 0$. Comparison of the isotropic (Figure 9a) and VTI (Figure 9b) stacked sections reveals significant improvements achieved by accounting for anisotropy. First, application of accurate NMO velocities in the VTI model substantially boosted higher frequencies in the stacked reflections and, therefore, increased the temporal resolution. Second, the anisotropic processing provided a crisp picture of faulting in the shallow part of the section and significantly improved the image of the top of the reservoir. Note that although the anisotropic parameter estimation was performed only for the left part of the line, the improvements are observed for the whole range of CMP locations in Figure 9.

Figures 9c,d,e,f help to better understand the main reasons for the superior quality of the anisotropic result. As illustrated by Figures 9d and 9e, the correct NMO velocities computed for the VTI model have a much stronger influence on the temporal resolution than they do on the lateral resolution. To enhance fault imaging, it is necessary to account for anisotropy in computing CCP trajectories (Figures 9d and 9f). Poor focusing and positioning of the fault-plane reflections on the isotropic
section is explained by the smearing of the conversion point that occurs because of anisotropy and layering. We estimated that this smearing at the target level (top Balder) exceeds 500 m for the largest offsets in the data (Figure 10) and is about 340 m for the maximum offset (2600 m) used to produce the stacks in Figure 9.

Such a significant shift of the conversion point not only reduces the lateral resolution but also biases the isotropic AVO response for PS-waves because each CCP gather includes reflections from a wide range of subsurface points. In addition, neglecting anisotropy in AVO analysis introduces an error in the offset-to-angle transformation that reaches 8° for an offset of 3 km; the corresponding error for PP-waves is only about 2.5° (Figure 10).

Note that the distortions in isotropic processing are particularly severe if PS data are imaged using model-based methods (e.g., Figure 9), including prestack depth migration. Some alternative approaches rely on semblance picking in combination with CCP scanning to find the optimal sorting and image PS data. Flattening of PS events is often achieved by using a moveout equation with the effective parameters which are not derived from the actual subsurface model. To choose the best way of sorting the data, it is possible to analyze imaging results obtained by varying the stacking trajectory and processing positive and negative offsets separately. This method works best if the model has a certain degree of structural complexity, where the final trajectory is the one that aligns the structure laterally between the two stacks. Another way of searching for the optimal sorting is based on maximizing semblance in CCP gathers for several key reflectors.

Although these methods can somewhat improve the quality of the isotropic images in Figure 9, they cannot fully correct for the influence of anisotropy. Note that the algorithm outlined in this paper operates on common-receiver gathers and does not depend on the presence of structure, which makes it especially effective for reservoirs in stratigraphic traps. Also, with the advent of prestack depth migration it becomes necessary to build an accurate physical model of the subsurface that explains all measured signatures simultaneously.

Figure 11 shows time-migrated images of PS-waves (a) and PP-waves (b) obtained using the VTI velocity model. Although the general appearance of the two sections is similar, there are some noticeable differences in the images of the shallow faults and the subhorizontal events at the reservoir level. Since the amplitudes of PP- and PS-waves depend on different combinations of the medium parameters, PP and PS images can provide complementary information about the subsurface.

Conclusions

Ignoring seismic anisotropy may cause serious errors in processing and interpretation of multicomponent seismic data, especially if mode-converted PS-waves are used for reservoir-characterization purposes. This case study shows that overburden anisotropy significantly changes
Figure 9. Model-based PS-wave common-conversion-point time stacks: (a) isotropic (i.e., corresponding to $\epsilon = \delta = 0$); (b) VTI. The area marked by the dashed line on plots (a) and (b) obtained with separate moveout computation and CCP sorting; (c) isotropic moveout and isotropic CCP sorting; (d) anisotropic moveout and anisotropic CCP sorting; (e) isotropic moveout and anisotropic CCP sorting; (f) anisotropic moveout and isotropic CCP sorting.
the lateral position of the conversion point, ray trajectories and NMO velocities in CCP gathers, and offset-to-angle mapping. Therefore, assuming isotropy in the overburden severely reduces both the spatial and temporal resolution of PS-wave images and can make them unsuitable for detailed interpretation.

We presented a successful application of a methodology designed for anisotropic processing of multicomponent data. The 2-D version of the model-independent algorithm of Grechka and Tsvankin (2001) was used to reconstruct the pure SS-wave reflection traveltimes from PP and PS data. The interval parameters of the assumed VTI model were obtained from joint stacking-velocity tomography of PP- and SS-waves (Grechka, Pech and Tsvankin, 2001). For horizontally layered VTI media, however, the combination of PP and PS reflection traveltimes does not constrain the four relevant parameters of VTI media — the P- and S-wave vertical velocities $V_p$ and $V_s$, and the anisotropic coefficients $\varepsilon$ and $\delta$. Independent information about the reflector depths obtained from P-wave check shots was used to remove the ambiguity in parameter estimation and build a VTI model suitable for depth imaging.

Common-conversion-point stacks of PS-waves generated for the estimated VTI model have a much higher quality than do the conventional isotropic sections. Most notably, significant improvements were achieved in fault imaging and in the definition of the top of the reservoir. Accounting for anisotropy was also essential for obtaining an accurate AVO response for the PS reflections.

A more technical version of the parameter-estimation section of this paper was published in the CWP Project Review Volume last year (Grechka, Tsvankin, Bakulin and Hansen, 2001).

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**References**


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**Figure 11.** Comparison of time-migrated sections of (a) PS-waves and (b) PP-waves. The time scale of the PS section is compressed by a factor of two. Both sections were computed for the VTI model with δ = 0. The PS-wave image is obtained from the CCP stack, the PP-wave image from the CRP (common-reflection-point) stack.

**Note**

This research was performed while Vladimir Grechka was with the Center for Wave Phenomena and Andrey Bakulin was with Schlumberger Cambridge Research. Jan Ove Hansen was previously with Schlumberger Stavanger Research.

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