Several recent studies have demonstrated the ability to measure the effects of shear-wave (S-wave) birefringence using mode-converted (PS) waves. Standard PS-wave processing relies on the assumption that the subsurface is horizontally isotropic. The two horizontal components are typically rotated (about the vertical axis) to a direction that is oriented radial and transverse to the source receiver geometry. In the presence of azimuthal anisotropy in the subsurface geology, the upcoming S-wave will split into two—one polarized in the fast direction (S1) and the other in the slow direction (S2). If S-wave birefringence is ignored, then the radial component will be comprised of a mixture of both fast and slow shear-wave energy. This mixing will result in a degradation of resolution and S/N ratio by destructive interference between the fast and slow S-wave arrivals.

Recent developments in PS-wave processing have made it possible to resolve these fast and slow directions and the travelt ime lag between them. The measured travelt ime differences provide useful information regarding the magnitude of anisotropy, and the measured azimuth provides further insight into the orientation of stress fields and/or fracture directions.

In September 2002, a 2D/4C test line was acquired at Ekofisk Field in the southern North Sea. This test line consisted of 40 four-component (4C) receivers and a 3D grid of sources. Subsequent analysis of the PS-wave data, primarily in the near surface, indicated the presence of significant birefringence. The measured birefringence correlates well with the local seafloor subsidence that has been induced by compaction within the underlying chalk reservoir at a depth of approximately 3 km. These results provide new information useful for characterizing fracturing and stress fields attributed to seafloor subsidence at Ekofisk.

Additionally, the magnitude of the S-wave birefringence (time shift between S1 and S2) correlates very closely with the relative change in the S-wave static corrections that were derived during 2D processing of the radial component data —indicating that an important link exists between them at Ekofisk. This correlation suggests that the calculated PS receiver statics are related to both azimuthal anisotropy and near surface S-wave velocity variations. Such observations provide further evidence that the effects of S-wave birefringence should be considered when imaging shear-wave seismic data, and that corrections begin with statics.

Survey background. Ekofisk Field was discovered in 1969 and has been producing since 1971. The reservoir is trapped within a large anticline structure consisting of a high porosity chalk. Estimated initial oil in place is 6.7 billion STB of oil and approximately 1.9 billion STB of oil have already been produced. Approximately one third of the reservoir is seismically obscured on existing 2D seismic sections. This may be partly due to the destructive interference effects of S-wave birefringence.

Processing of both the P-wave and PS-wave data was limited to a 2D test line extracted from the center of the survey over the top of the cable (yellow outline in Figure 1). The processing sequence for the P-wave data included vector fidelity analysis and compensation, hydrophone/geophone (PZ) summation, deconvolution, residual statics, and prestack Kirchhoff time migration. The PS-wave data processing included vector fidelity analysis and compensation, horizontal geophone orientation analysis, rotation to radial and transverse components, long-period detector static corrections, deconvolution, CCP binning, PS-wave DMO, and common-offset time migration. The radial component is produced by mathematically rotating the horizontal geophones until the direction coincides with the source-to-detector azimuth. The transverse is then the component perpendicular to the source-to-detector azimuth in a clockwise direction.

The final PS-wave section was compressed to two-way P-wave sections. PS-wave data are compressed to two-way P-wave time. Note that the PS-wave data resolution is quite good shallow but degrades slightly with depth. This may be partly due to the destructive interference effects of S-wave birefringence.
Determination of principal S-wave directions. In order to determine the principal direction of the S-waves (S1 and S2), common-azimuth stacks were created for each detector location using the 3D blanket of sources. For a given detector, 100 azimuth bin stacks of both the radial and transverse components were created producing 72 different seismic traces. The data were NMO-corrected and offset-limited to 500 m before stacking.

Azimuth bin stacks for detector location 1 are shown in Figure 3. A key indication of the principal directions is the attenuation of the energy on the transverse component. This "null" trace occurs on the transverse component when the source-to-detector azimuth aligns with either S1 or S2. Once these directions are determined, the radial component was then evaluated to determine the direction with the shortest traveltime (i.e., the fast S1 direction). The orientation of S1 was determined for each of the 40 detector locations using the above method and is displayed in the graph in Figure 4. A consistent trend is seen changing from NW/SE orientation on the western end of the line to a more E/W orientation toward the east. Figure 4 also demonstrates how the S1 orientation changes by about 60° over a distance of 1 km, providing evidence that S-wave birefringence is rapidly varying over this part of Ekofisk.

S-wave birefringence magnitude measurements. While the method described in the previous section provides a very good estimate of the direction of S1, it does not give a very accurate measurement of the magnitude of the S-wave birefringence. To accurately measure the time delays between the fast and slow S-waves, a 2C × 2C Alford rotation and layer-stripping algorithm was applied to each common-azimuth stack. This method groups 36 radial and 36 transverse azimuth bin stacks into orthogonal azimuths to produce the necessary 4C data for Alford rotation. For example, radial and transverse receiver components from N10E are combined with the orthogonal pair of receivers from N100E. Repeating this procedure for all common-azimuths from 0 to 350° yields 36 four-component groups that were layer stripped using Alford rotations.

For this study, a shallow analysis window was used in order to isolate and investigate the effects of S-wave birefringence in the near-surface geology. The PS-wave time window included data between 0 and 550 ms. Two deeper windows were also analyzed after layer stripping of the overburden. The amount of observed birefringence was lower for these deeper layers but any conclusions about the anisotropy at this level must be tempered by the fact that the results are affected by significant reflection-point dispersion due to the analysis being performed on common-receiver gathers and not common conversion-point gathers.

In addition to providing the fast S1-wave direction and amount of splitting, the results before and after layer stripping to 550 ms show an improvement in timing and continuity of deeper events (Figure 5). The four panels shown in
Figure 5a are: (1) the radial component from 0 to 350°, (2) the transverse component from 0 to 350°, (3) the transverse component repeated and polarity reversed from 90 to 440°, and (4) the radial component repeated from 90 to 440°. The third and fourth data panels are essentially identical to the first and second panels but shifted 90° and the third is reversed in polarity. The two radial components are the diagonal terms and the transverse components are the off-diagonal terms of the 2C × 2C Alford data matrix. Clearly, correction for azimuthal anisotropy improves the deeper data. Note also that the off-diagonal energy has been minimized down to 550 ms but that some residual energy appears deeper. This is an indication of possible additional S-wave birefringence below the overburden.

The results of the overburden layer stripping also showed a very similar pattern of S1 orientation to the earlier hand picks but it also gave us an indication as to the magnitude of the birefringence occurring in the near surface (see the graph in Figure 6). Note the same S1 orientation trend from east to west with increasing birefringence to the west. This indicates that the velocity ratio between S1 and S2 is increasing away from the central part of the field.

**S-wave birefringence and seabed subsidence.** So what causes this S-wave birefringence? It is well known that differential stress fields can preferentially open fracture sets and pore spaces in the principal horizontal stress direction and cause S-waves to polarize and split. The amount of birefringence depends on the difference in the stress fields or the density of the fracturing, assuming a uniformly fractured medium. The chalk reservoir at Ekofisk has compacted as a result of rapid pressure depletion during the early years of production and water weakening effects caused by the injection of seawater. This compaction has caused the seabed to subside by over 8 m, leaving a large bowl-shaped depression on the seafloor (Hermansen et al., 1997 SPE). This subsidence can induce a stress field at the seafloor where the maximum horizontal stress would be parallel with contours of the depression and the magnitude of differential horizontal stress would be proportional to the slope. In a previous study over nearby Valhall Field by Olofsson et al., the connection between near-surface S-wave birefringence and sinking of the seabed was demonstrated.

Displaying the measured orientation and magnitude of anisotropy as vectors on top of the seabed subsidence map for Ekofisk shows a very strong correlation (Figure 7). It is believed that the increased magnitude of S-wave birefringence is associated with increased differential stress along the edges of the subsidence zone and the orientation of the stress field is subparallel to the contours. It also indicates that the magnitude of the birefringence is decreasing toward the center, possibly due to a smaller differential stress field in this area.

**S-wave birefringence and static correction.** During the processing and analysis of these test data, an interesting observation was made correlating the magnitude of the S-wave birefringence to the magnitude of the S-wave detector static correction (Figure 8). This static correction was determined by comparing common-detector stacks of the radial component to the equivalent stacks of the P-wave data. Using the P-wave data as the reference, the common-detector PS-wave data was time shifted to produce similar time structures (a-c in Figure 9). The subsequent shifts were then used as S-wave detector static corrections and applied to both horizontal components of the PS-wave data.

Static corrections are related to local variations in the near surface velocity, both on land and on the seafloor. This is true for both P-waves and S-waves. In this case, as a result of the previous anisotropy analysis, it is clear that two near surface S-wave velocities must be investigated—S1 and S2. To accomplish this, the horizontal components at each detector were individually rotated to the previously determined S1 and S2 directions. New PS1 and PS2 common-detector stacks were then created and displayed (d-e in Figure 9). The PS2 data on the eastern end of the line are very weak and noisy due to the
relatively small amount of birefringence observed and the alignment of the source-to-detector propagation direction azimuths with the fast S1 direction. Computing the time shifts required to match both the PS1 and PS2 data to the P-wave data (over the western end of the line) gives the graph in Figure 10. These results show that the correction computed using the radial component, while correcting the longer period trend, does not compensate for the differences between PS1 and PS2. The resulting PS1 and PS2 component data were then processed through stack. These stacks again show the timing differences between the fast and slow S-waves and the lack of PS2 data on the eastern end of the line related to the wave propagations directions (Figure 11). There is also improved imaging of the deeper structure on the western side of the PS2 section around 1700 ms.

Discussions/conclusions. Wide-azimuth 4C OBC seismic data can provide important information about near-surface stress fields in and around producing chalk reservoirs. These measurements can be obtained by evaluating the amount of energy present on the transverse component and the traveltime differences between the fast and slow directions. A 2C × 2C Alford rotation and layer stripping approach is a more accurate means of determining these orientations and timing differences. The resulting near-surface stress and fracture information may prove valuable for future engineering studies and subsequent decisions on drilling and pipeline locations.

The S-wave birefringence results from the Ekofisk test show a very good correlation to the measured seafloor subsidence due to production from the deeper reservoir. In addition, a strong correlation exists between the measured S-wave detector static correction and the magnitude of the anisotropy. It follows that, based on this observation, S-wave birefringence and S-wave statics must be evaluated together and azimuthal anisotropy analysis should be included in any wide-azimuth multicomponent survey. The measurement of and correction for the two orthogonal S-wave velocities (S1 and S2) are critical in efforts to better image wide-azimuth mode-converted shear-wave data and these corrections begin with quantifying lateral variations in S1 and S2 shear statics.


Acknowledgments: The authors thank ConocoPhillips Norway and its PL018 shareholders (Total Exploration Norge AS, Norsk Agip A/S, Norsk Hydro Produksjon a/s, Petoro AS, and Statoil ASA) for permission to publish the results of this study.

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