Modelling and analysis of anisotropy in the reservoir and overburden

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Analysis and understanding of seismic anisotropy has proven to be a valuable tool in many exploration and reservoir management studies. Seismic anisotropy should not be viewed as a problem that must be dealt with but instead regarded as an additional attribute to understand the rocks within the reservoir and overburden. Recent developments in borehole and seismic methods coupled with the latest rock physics modelling techniques have generated new work flows capable of predicting and interpreting the anisotropic signature within seismic data.

Benefits of understanding the anisotropy include:

- Improved seismic imaging for well placement
- Resolve seismic-to-well tie problems that prevent the use of powerful rock physics and inversion tools
- Ability to study sub-seismic resolution fractures that can control permeability within the reservoir
- Optimised survey design

This article presents a series of work flows that have been designed to exploit seismic anisotropy as an attribute. These work flows have been developed and applied to borehole seismic (VSP), borehole log and seismic reflection datasets. The intention is to provide the reader with an insight as to how the problem of anisotropy can be solved with benefit to the geological understanding of the reservoir. All the workflows described have been applied using the RokDoc® toolbox.

Background

Rock outcrops can be observed to contain heterogeneities at any scale. The seismic method is not able to individually detect each of these scales of heterogeneity. Instead, a seismic wave samples average properties over a volume of rock. Fine-scale laminated layering, mineral alignment, cracks and fractures all represent examples of heterogeneities that are believed to exist in many rocks but are below the scale of resolution of a seismic wave. Although these features cannot be individually resolved they do have an effect on the up-scaled seismic properties. If the small scale heterogeneities exhibit a preferential alignment, then the up-scaled seismic properties will be directional dependent. This directional dependence is known as seismic anisotropy.

The simplest form of anisotropy is to assume a single plane of symmetry; this is known as transverse isotropy (TI). The TI system has been demonstrated to have a wide application within exploration seismology (Thomsen, 1986). Two cases of TI are commonly used:

(a) VTI – transverse isotropy with a vertical axis of symmetry; this case describes the directional dependence that is generated by the preferential mineral alignment commonly observed in shales (Figure 1a).
(b) HTI – transverse isotropy with a horizontal axis of symmetry; this case describes the directional dependence that is generated by vertically aligned features, such as preferentially orientated cracks or fractures in sandstone and carbonate reservoirs (Figure 1b).

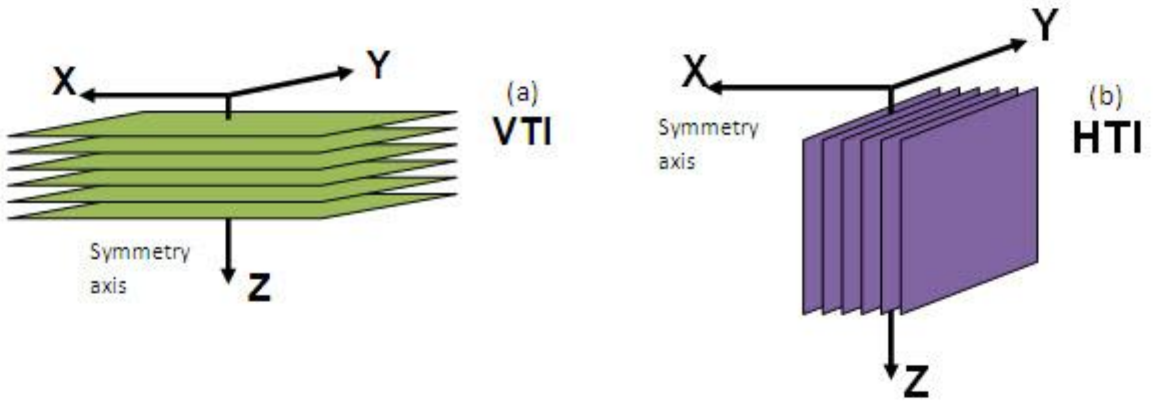


Figure 1: Schematic representation of (*a*) VTI anisotropy and (*b*) HTI anisotropy.

Case Study 1: Quantifying anisotropy - Offset VSP analysis

The offset vertical seismic profile (VSP) technique provides the most direct observations of the in-situ seismic anisotropy. A set of multi-component sensors is lowered down a well while a series of events are generated from shot locations with a range of offsets and azimuths at the surface (Figure 2). Correct interpretation and processing of VSP data should be undertaken in conjunction with borehole log data (Figure 3).

An offset VSP provides a dataset from which the velocity (and its inverse, known as slowness) for a particular depth interval can be calculated. Theoretically calculated curves can then be optimised to fit the data and used to quantify the interval's anisotropy (MacBeth, 2002). An example is shown in Figure 4.

Shear-wave energy propagates as vibrations of particles in the plane orthogonal to the direction of travel. The presence of anisotropy with TI symmetry causes shear-wave energy to split into two components with particle motion polarized parallel and orthogonal to the medium's symmetry. The two shear-wave components continue to propagate through the medium with different velocities, controlled by the magnitude and direction of the anisotropy. Analysis of the particle motion of shear-wave arrivals is an important indicator of anisotropy (Figure 5). Particle motion plots that display a characteristic cross shape can be interpreted to indicate the presence of anisotropy.

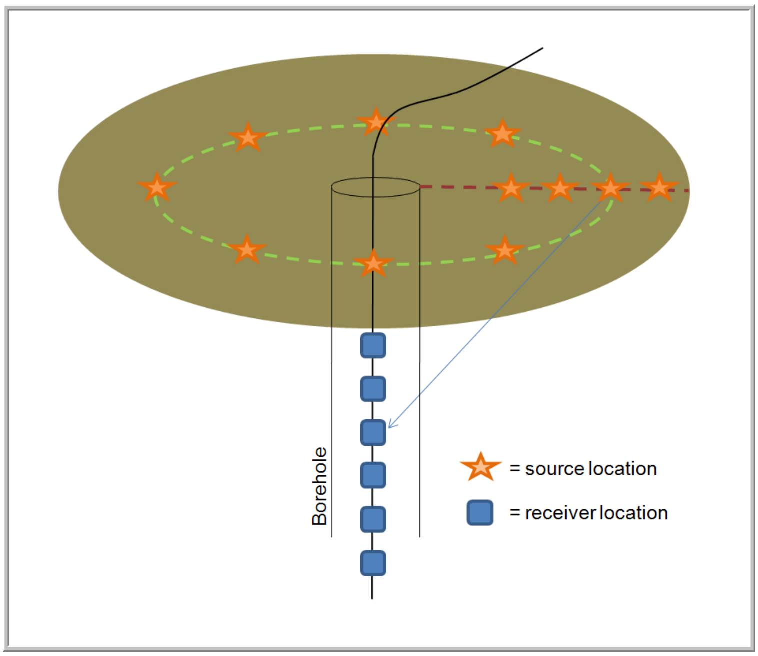
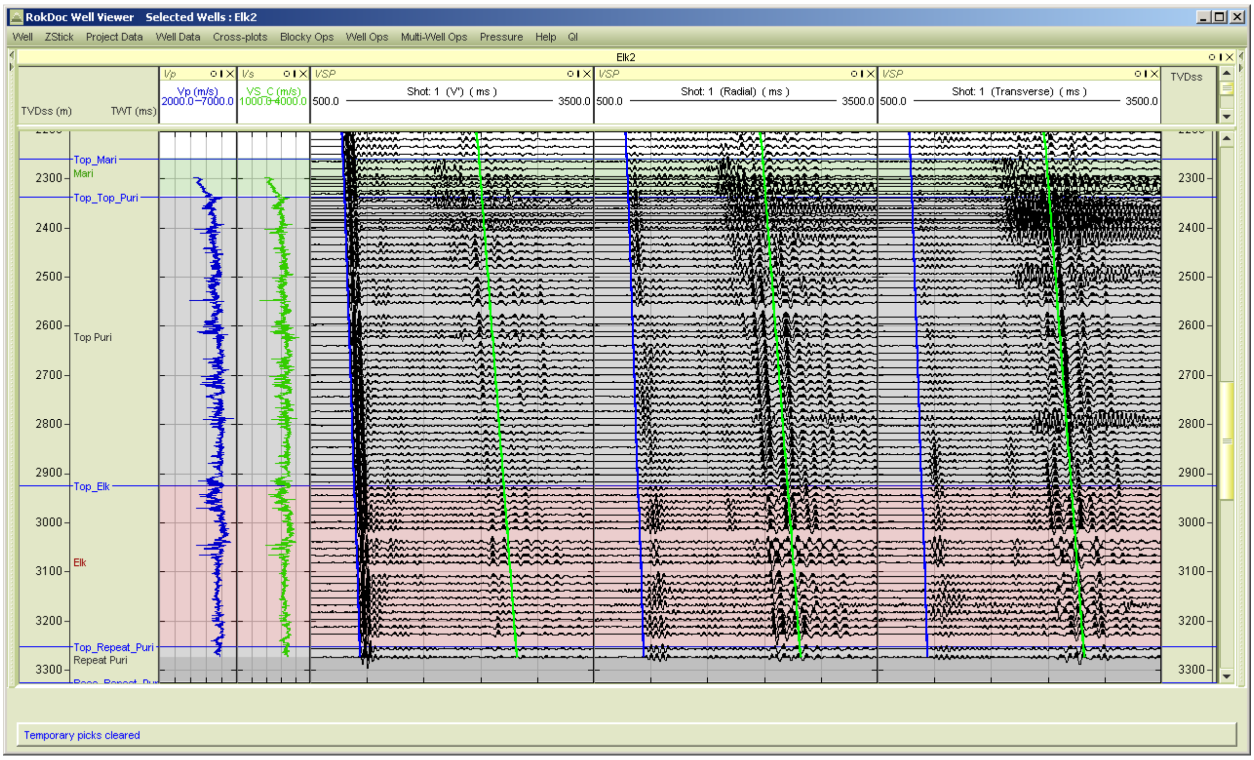


Figure 2: Schematic illustration of an offset VSP survey. Data are collected by recording the signal generated by a series of shots (*orange stars*) located at the surface on a string of multi-component sensors (*blue squares*) that have been lowered down a borehole. Data are collected for a range of offsets (*dashed red line*) and azimuths (*dashed green line*).



Temporary picks cleared

Figure 3: Multi-component VSP data (Vertical, Radial and Transverse components shown *left* to *right*). Sonic velocity (*blue*) and shear sonic velocity *(green*) log data are shown for comparison. The interpreted P and S arrivals (*blue* and *green lines*) provide an estimate of the interval velocities that should be compared with the sonic log data.

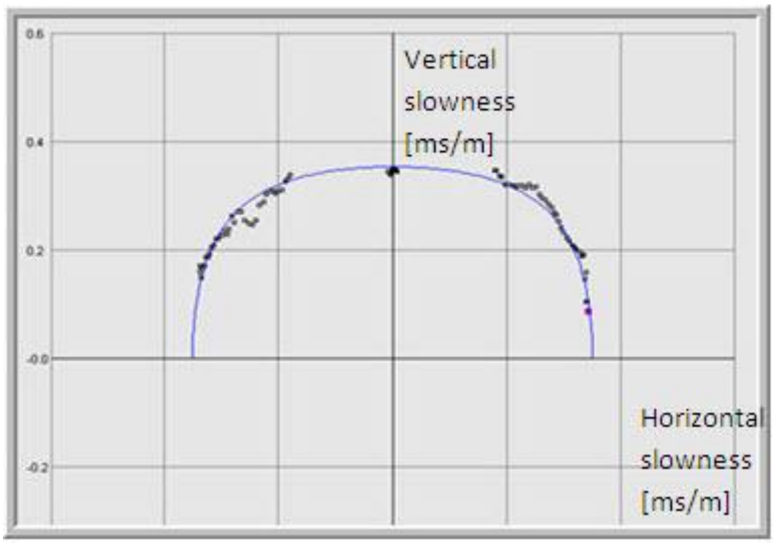
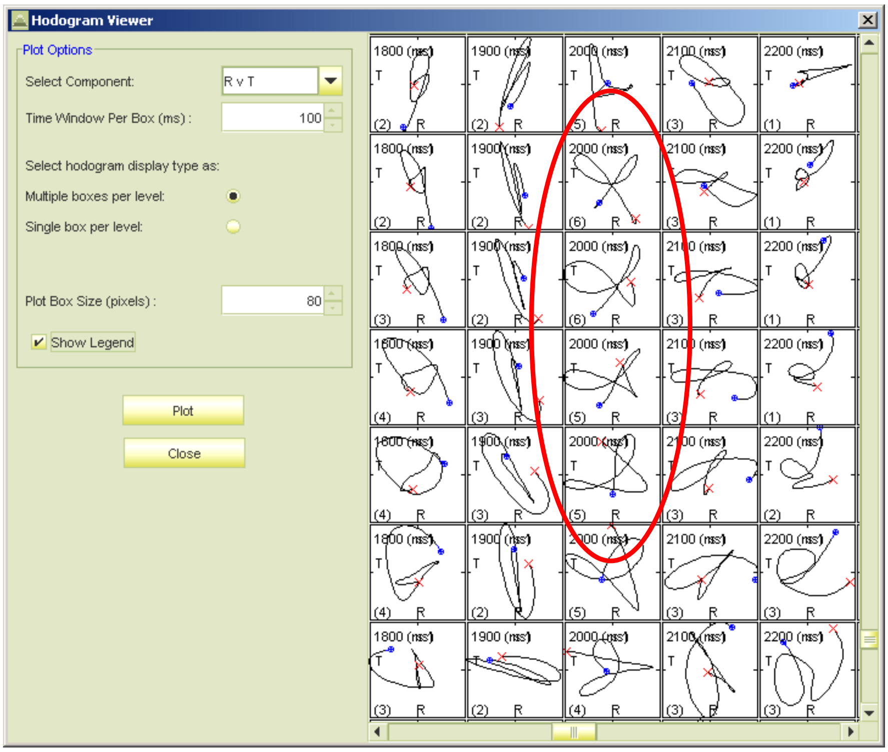


Figure 4: Plot of horizontal and vertical slowness as calculated from an offset VSP dataset. Anisotropy generates a deviation of the data points from a perfectly circular pattern. The *blue* curve is a theoretical curve that has been optimised to provide an estimate of the anisotropic parameters.


Hodogram Viewer

Plot Options

Select Component: R v T

Time Window Per Box (ms) : 100

Select hodogram display type as:

Multiple boxes per level: ●

Single box per level: ○

Plot Box Size (pixels) : 80

☑ Show Legend

Figure 5: Particle motion plots (hodograms) generated using a 100ms time window of data encapsulating the shear wave arrival. Anisotropy is interpreted by the splitting of the shear wave energy into two perpendicular planes – observed by the characteristic cross shapes in the highlighted plots.

Case Study 2: Improving the tie - Deviated well corrections

Technical developments in drilling have led to an increase in the number of deviated wells drilled in the exploration and development of hydrocarbon reservoirs. Poor well-to-seismic ties have frequently been observed in rock physics projects that use the log data from deviated wells. Well-to-seismic ties are crucial for seismic inversion and the interpretation of reservoir properties. Modelling of the anisotropy within the target interval can provide a solution (Wild *et al.*, 2008).

The seismic reflection method is sensitive to the near vertical velocity. Meanwhile, borehole logging tools measure the sonic velocity along the sidewall of a well. Thus, sonic measurements in a vertical well will measure the vertical velocity but sonic measurements in a deviated well will measure the velocity in an arbitrary direction defined by the well's deviation. This problem can be observed by comparing sonic log data for the same interval measured in four vertical and deviated wells (Figure 6).

Theoretical and empirical models have been published that permit the calculation of anisotropic parameters for a variety of geological units, e.g. shales/fractured sandstones. Geological knowledge can be used to calibrate these models for an anomalous interval. A correction for the deviated well path can then be calculated and applied to the deviated well data. The improvement in velocity correlation between the four vertical and deviated wells can be observed by comparing Figures 6 & 7. Synthetic traces generated using the verticalised log data exhibit an improved correlation to the seismic traces (Figure 8). Importantly, the observed seismic AVO behaviour is erroneously modelled when the initial log data are used. The correct Class IIp AVO response is predicted when the synthetic gather is generated with the verticalised log data. Without the anisotropy correction, the seismic AVO response would not have been understood and interpretations such as variations in fluid saturation would not be possible.

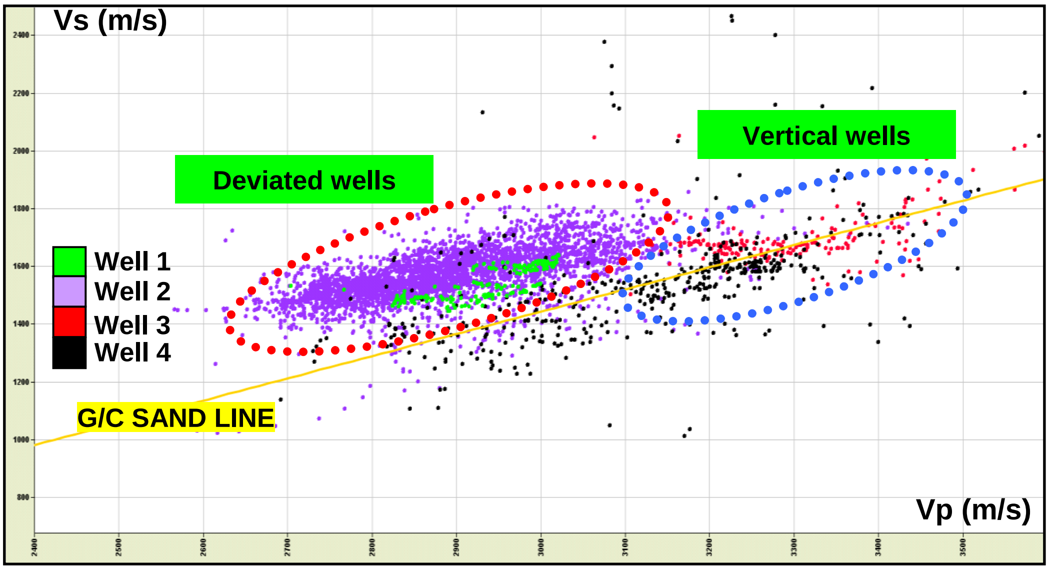


Figure 6: Comparison of P- and S-wave sonic velocities, measured in the same sandstone interval encountered by four different wells. Wells 3 and 4 (*red* and *black*) are vertical. Wells 1 & 2 (*green* and *purple*) are deviated. The yellow line represents the Greenberg-Castagna trend line for sandstones.

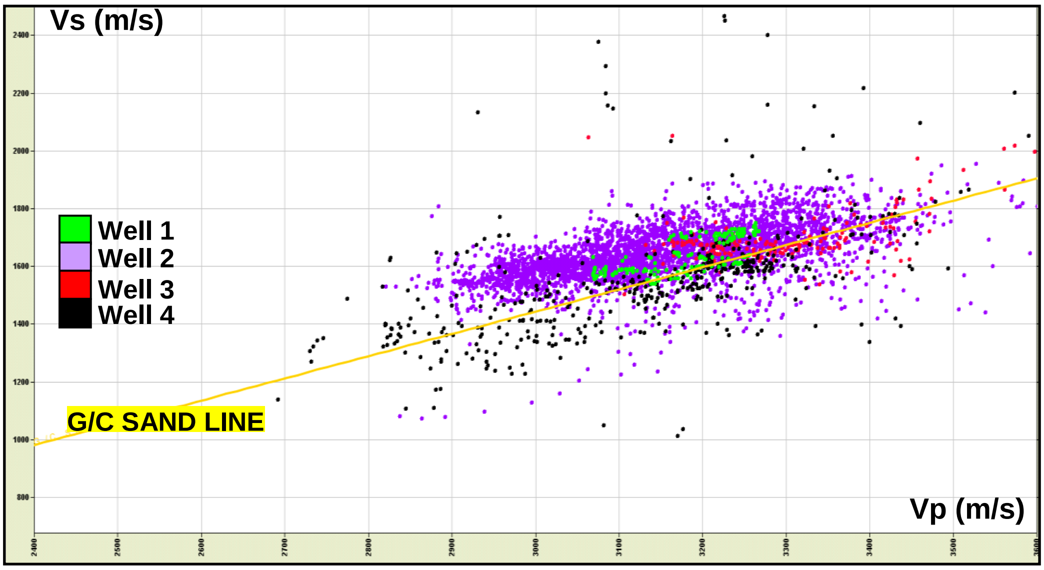


Figure 7: Comparison of P- and S-wave sonic velocities, measured in the same sandstone interval encountered by four different wells. An anisotropy correction has been applied to the deviated well data (*green* and *purple*). The improved correlation in velocities can be observed by comparing this plot with Figure 6.

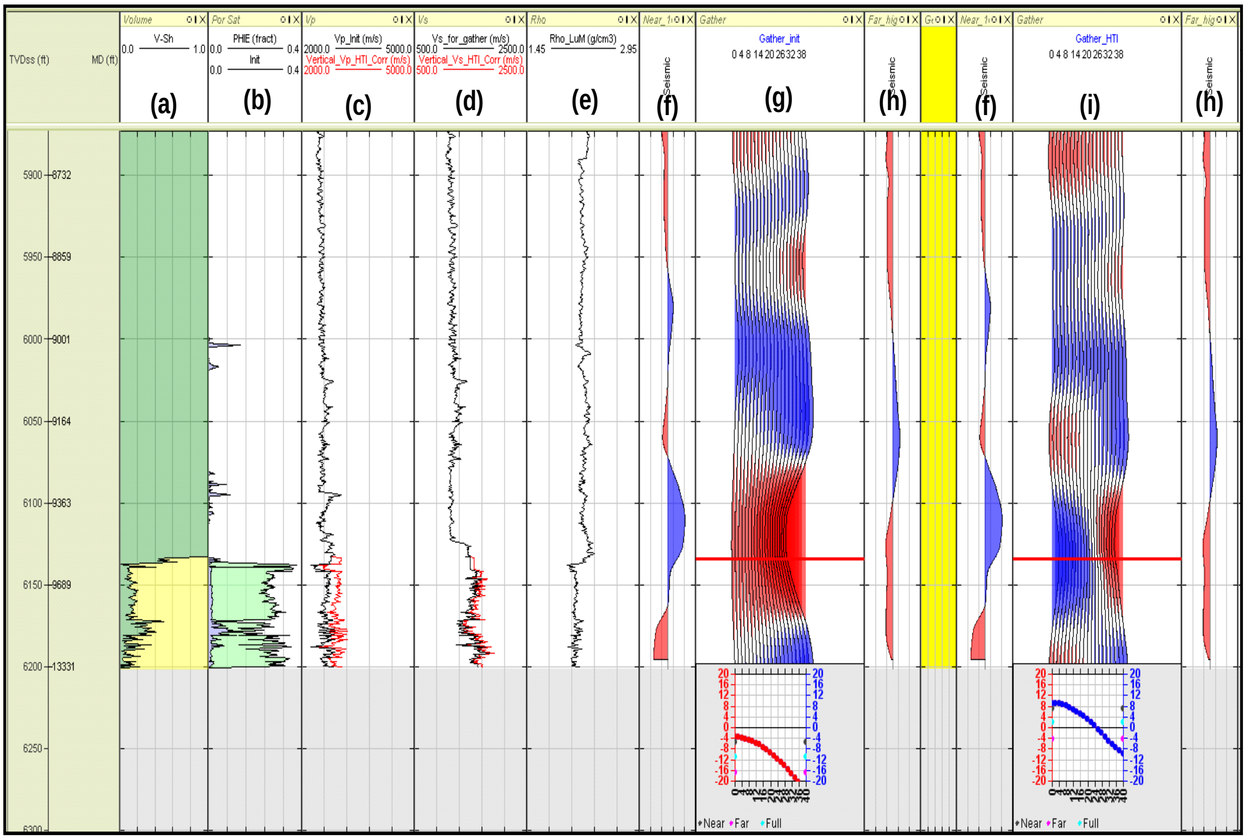


Figure 8: Comparison of the well tie and AVO modelling before and after verticalisation of the deviated well sonic logs. *Track (a)* = shale volume fraction,*(b)* = porosity and saturation,*(c)* = initial (*black*) and verticalised (*red*) P-wave velocity,*(d)* = initial (*black*) and verticalised (*red*) S-wave velocity,*(e)* = density, *(f)* = near stack seismic trace, *(g)* = synthetic angle gather generated using the initial log data, *(h)* = far stack seismic trace, *(i)* = synthetic angle gather generated using the verticalised log data.

Case Study 3: The benefit of shear – An OBC feasibility study

Variations in the seismic reflection amplitude as a function of offset (seismic AVO) are now routinely studied as part of the exploration workflow. Seismic anisotropy modifies the AVO response. The seismic reflection amplitude from an interface between two anisotropic layers varies not only with offset but also as a function of observation azimuth (Figure 9). Once understood, amplitude variations with both offset and azimuth (AVOA) can be exploited to interpret sub-seismic properties (Hall & Kendall, 2003).

One example application of AVOA analysis is the study of fracturing within a sandstone reservoir. Subsurface stress regimes are considered to preferentially close cracks and fractures perpendicular to the axis of maximum horizontal stress. Hence, open fractures within a reservoir are likely to exhibit a preferential alignment, which will result in an anisotropic medium with HTI symmetry. The seismic reflection AVOA from a typical shale/sandstone interface is shown in Figure 9. At far offsets (incidence angles >30°) the HTI sandstone model exhibits a change in reflectivity with azimuth. The particle motion of shear waves in the plane perpendicular to the direction of propagation makes shear waves more sensitive to anisotropic media with HTI symmetry. The AVOA behaviour of a P-to-S wave conversion for the shale/sandstone interface is shown in Figure 10. The azimuthal variations in reflectivity are observed to be much greater for the PS converted wave than the conventional P wave.

In order to observe the azimuthal variations shown in Figures 9 & 10 it is necessary to collect seismic data from a range of offsets and azimuths. Further, to record the more sensitive PS converted wave response it is necessary to record the seismic data with multi-component receivers. Ocean bottom cable (OBC) surveys are one solution to this data requirement; multi-component sensors are laid on the seabed while shots are collected in a grid pattern to ensure full azimuth and offset distribution. An OBC survey can be extremely beneficial to understanding the stress and fracture distribution within the reservoir and overburden, which can lead to improved reservoir exploitation and management. However, they come at a cost. The rock physics modelling tools shown in this article create the opportunity to explore the benefits to a particular reservoir prior to commissioning an OBC survey.

Summary

Anisotropy is an important rock property that can enhance our understanding of both the reservoir and overburden. Modelling and analysis workflows to characterise and understand anisotropy are now available using the RokDoc® toolbox.

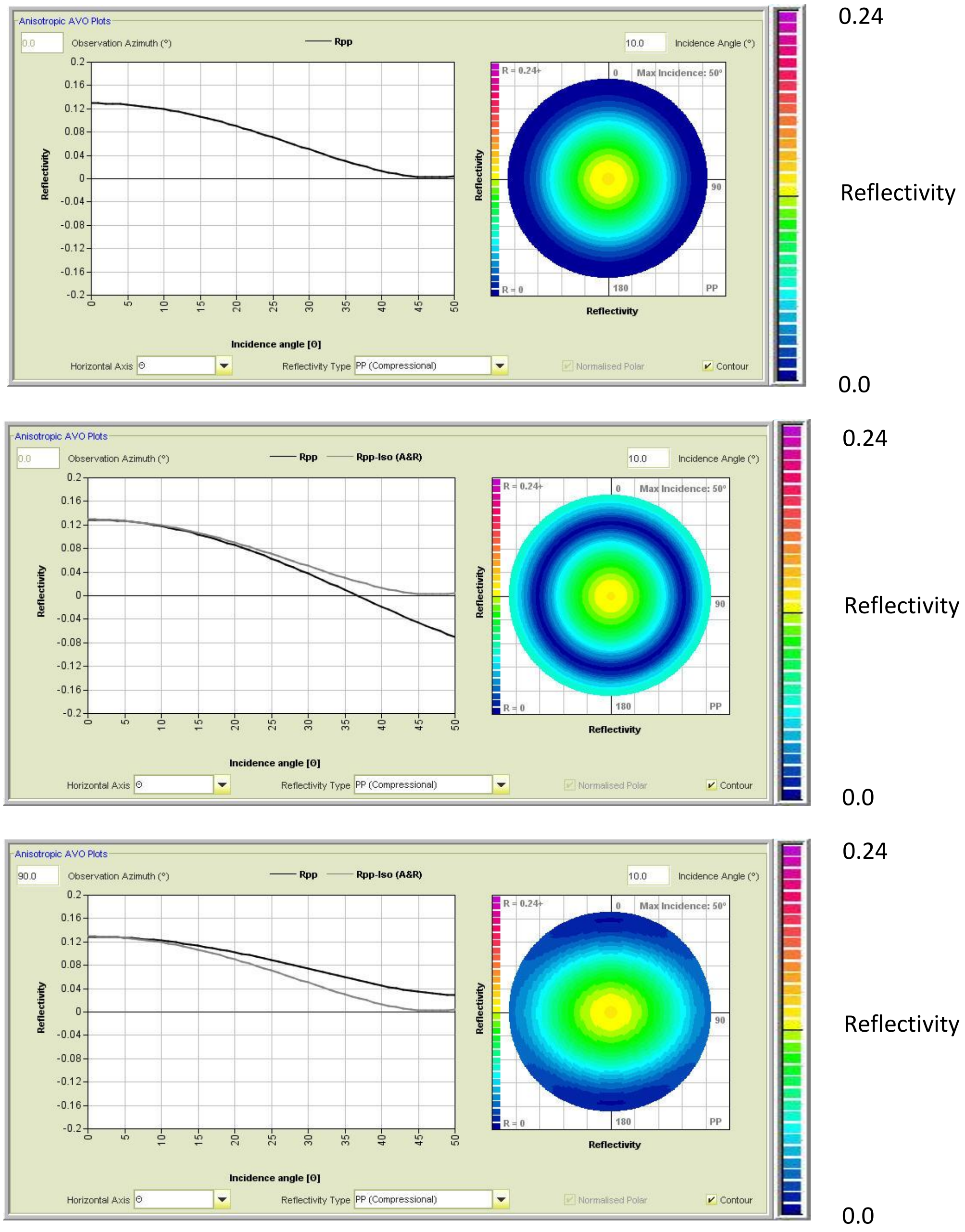
References

Hall S. A. & Kendall J-M., 2003. Fracture characterization at Valhall: Application of P-wave amplitude variation with offset and azimuth (AVOA) analysis to a 3D ocean-bottom cable data set, Geophysics, 68, No. 4, 1150-1160.

MacBeth C., 2002. Multi-component VSP analysis for applied seismic anisotropy, Handbook of geophysical exploration, Volume 26, Pergamon.

Thomsen L., 1986. Weak elastic anisotropy, Geophysics, 51, No. 10, 1954-1966.

Wild P. W., Kemper M., Lu L. & MacBeth C. D., 2008. Modelling anisotropy for improved velocities, synthetics and well ties, EAGE Expanded abstracts P235.



Anisotropic AVO Plots

Observation Azimuth (°): 0.0

Incidence Angle (°): 10.0

Horizontal Axis: Θ

Reflectivity Type: PP (Compressional)

☑ Normalised Polar

☑ Contour

Anisotropic AVO Plots

Observation Azimuth (°): 0.0

Incidence Angle (°): 10.0

Horizontal Axis: Θ

Reflectivity Type: PP (Compressional)

☑ Normalised Polar

☑ Contour

Anisotropic AVO Plots

Observation Azimuth (°): 90.0

Incidence Angle (°): 10.0

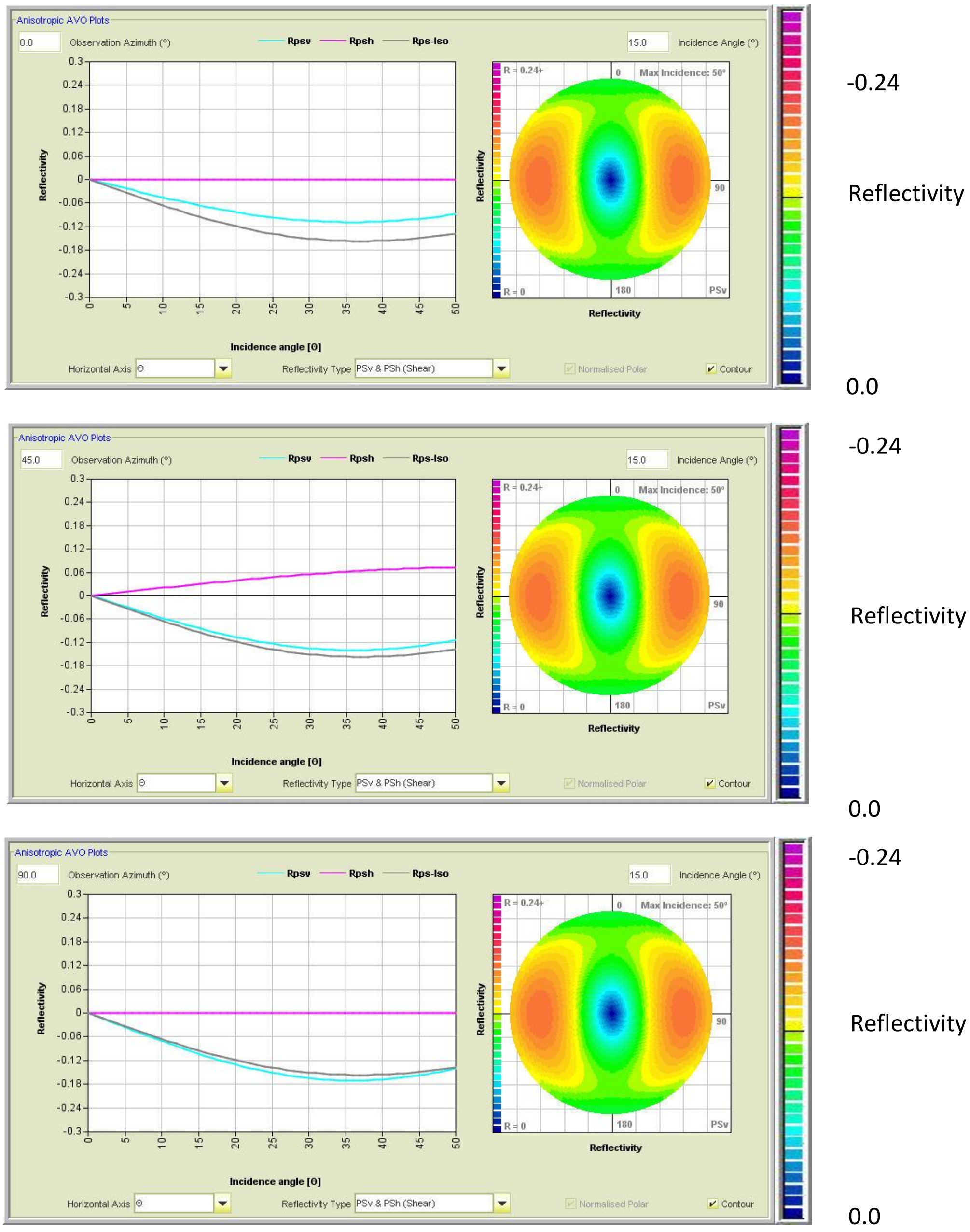
Horizontal Axis: Θ

Reflectivity Type: PP (Compressional)

☑ Normalised Polar

☑ Contour

Figure 9: Seismic reflection amplitude variations as a function of offset (*left*) and azimuth (*right*) for a typical shale/sandstone interface. *Top:* Purely isotropic response – the interface generates a positive reflectivity that decreases with offset (Class I); the response is independent of azimuth, as observed by the concentric reflectivity pattern. *Middle:* VTI shale overburden – inclusion of anisotropy in the overburden generates a change in the AVO at far offsets (incidence angles >30°); the interface's reflectivity is observed to be azimuth independent. The *grey* curve shows the equivalent reflectivity for a purely isotropic model. *Lower:* HTI sandstone – the AVO is observed to vary with observation azimuth; a maximum difference in AVO occurs when the observation azimuth is perpendicular and parallel to the medium's symmetry axis.



Anisotropic AVO Plots
0.0 Observation Azimuth (°)
15.0 Incidence Angle (°)
Horizontal Axis Θ
Reflectivity Type PSv & PSh (Shear)
☑ Normalised Polar
☑ Contour

Anisotropic AVO Plots
45.0 Observation Azimuth (°)
15.0 Incidence Angle (°)
Horizontal Axis Θ
Reflectivity Type PSv & PSh (Shear)
☑ Normalised Polar
☑ Contour

Anisotropic AVO Plots
90.0 Observation Azimuth (°)
15.0 Incidence Angle (°)
Horizontal Axis Θ
Reflectivity Type PSv & PSh (Shear)
☑ Normalised Polar
☑ Contour

Figure 10: P-to-S wave reflection amplitude variations as a function of offset (*left*) and azimuth (*right*) for a typical shale/sandstone interface. The sandstone is considered to exhibit HTI symmetry, which results in an azimuth dependent reflectivity. *Top:* PS reflectivity in the plane parallel to the symmetry axis; in this plane only reflection energy in the vertical shear wave component (*cyan*) is excited. *Middle*: PS reflectivity in the plane at 45° to the symmetry axis; the generation of a horizontal shear wave reflection (*pink*) is indicative of HTI anisotropy. *Lower:* PS reflectivity in the plane perpendicular to the symmetry axis. The *grey* curve shows the equivalent PS reflectivity for a purely isotropic model. The colour plots to the *right* of the figure show the reflectivity of the vertical shear component as a function of offset and azimuth.