

## Seismic anisotropy in Overburden

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### Summary

Seismic anisotropy produced by shales and fine shale/sandstone sequences in overburden is analyzed by using laboratory data. qP-wave anisotropy is weak for small propagation angles ( $\theta < \text{about } 30^\circ$ ) and strong for large propagation angles ( $\theta > \text{about } 30^\circ$ ). qSV-wave anisotropy is strong in moderate propagation angles (about  $20^\circ < \theta < \text{about } 70^\circ$ ). Strong qSV-wave anisotropy may cause group velocity cusp that results in qSV-wave waveform distortion.

### Introduction

Seismic survey may acquire large angle seismic reflections, for example, very long-offset seismic reflections in marine survey and shallow seismic reflections in the northern Alberta. However, conventional seismic data processing and interpretation technologies cannot handle far offset seismic reflections. It is important to do further seismic physics analysis for far-offset seismic reflections from both large-scale overburden anisotropy and small-scale heterogeneous reservoirs by integrating rock physics and log data (Wang, 2001). This work discusses propagation effects of seismic wave in anisotropic overburden.

### Theory and algorithm

The Characteristic equation for qP and qSV waves in transverse isotropy expressed through Thomsen parameters can be written as

$$(1 + 2\varepsilon)k_x^4 + 2[1 + \delta + \frac{\alpha_0^2}{\beta_0^2}(\varepsilon - \delta)]k_x^2k_z^2 - \frac{\omega^2}{\beta_0^2}(1 + 2\varepsilon + \frac{\beta_0^2}{\alpha_0^2})k_x^2 - \frac{\omega^2}{\beta_0^2}(1 + \frac{\beta_0^2}{\alpha_0^2})k_z^2 + k_z^4 + \frac{\omega^4}{\alpha_0^2\beta_0^2} = 0. \quad (1)$$

where  $\alpha_0$  is the vertical qP-wave velocity and  $\beta_0$  is the vertical qSV-wave velocity.  $\varepsilon$  and  $\delta$  are two dimensionless Thomsen parameters.  $k_x = \omega \sin \theta / v_p(\theta)$  and  $k_z = \omega \cos \theta / v_p(\theta)$  are the horizontal and vertical wavenumbers, respectively.  $\omega$  is angle frequency and  $v_p(\theta)$  is the phase velocity along the propagation direction of  $\theta$ .

The phase velocities of qP-wave ( $v_{p+}$ ) and qSV-wave ( $v_{p-}$ ) can be derived by Eq. (1)

$$v_{p\pm}(\theta) = \alpha_0 \left\{ 1 + \varepsilon \sin^2 \theta - \frac{f}{2} \pm \frac{1}{2} \sqrt{f^2 + 4f \sin^2 \theta (2\delta \cos^2 \theta - \varepsilon \cos 2\theta) + 4\varepsilon^2 \sin^4 \theta} \right\}^{1/2}. \quad (2)$$

Eq. (2) (Tsvankin, 1996) shows that propagation velocity in TI medium varies with direction. Direction-dependent propagation velocity results in phase and group velocities are not equal (Winterstein, 1990). The corresponding group velocities in horizontal ( $v_{gx+}$  for qP-wave and  $v_{gx-}$  for qSV-wave) and vertical directions ( $v_{gz+}$  for qP-wave and  $v_{gz-}$  for qSV-wave) can be written as

$$v_{gz\pm}(\theta) = \frac{v_{p\pm}(\theta) \cos \theta}{2A} \left[ 2\Delta \cos^2 \theta + \Omega \sin^2 \theta \pm \frac{\sin^2 \theta (\chi \cos^2 \theta - \xi \sin^2 \theta)}{\sqrt{B^2 - 4A}} \right],$$

$$v_{gx\pm}(\theta) = \frac{v_{p\pm}(\theta) \sin \theta}{2A} \left[ 2\Theta \sin^2 \theta + \Omega \cos^2 \theta \pm \frac{\cos^2 \theta (\chi \cos^2 \theta - \xi \sin^2 \theta)}{\sqrt{B^2 - 4A}} \right],$$

$$\phi_{g\pm} = \text{actg} \left( \frac{v_{gz\pm}(\theta)}{v_{gx\pm}(\theta)} \right),$$

$$\chi = 2\Delta(\Theta + 1) - \Omega(\Delta + 1),$$

$$\xi = 2\Theta(\Delta + 1) - \Omega(\Theta + 1),$$

$$A = \Delta \cos^4 \theta + \Omega \cos^2 \theta \sin^2 \theta + \Theta \sin^4 \theta,$$

$$B = (\Delta + 1) \cos^2 \theta + (\Theta + 1) \sin^2 \theta,$$

## Anisotropy

$$\begin{aligned}\Omega &= 2\Delta[1 + \delta + (\varepsilon - \delta)\Delta], \\ \Theta &= (1 + 2\varepsilon)\Delta, \\ f &= 1 - \Delta, \\ \Delta &= \alpha_0^2 / \beta_0^2.\end{aligned}\tag{3}$$

### Overburden anisotropy

In sedimentary basin, shales (or clays) and fine layering are two main reasons to cause seismic anisotropy. Wang (2002) experimentally studied in detail the anisotropy of rocks from different oil fields in the world and showed that intrinsic anisotropy ranges from 6% to 33% for qP-wave and 2% to 55% for qSV-wave in shales and usually less 5% for qP-wave and qSV-wave in sands and carbonates. Thin periodic layered structures can be seen as an overall anisotropy (Backus, 1962). Composite anisotropy produced by fine shale/sand or shale/carbonate sequence may have stronger anisotropy than shales. Most of rocks in sedimentary basin are shales and so overburden anisotropy may have significant influence on seismic reflections.

Table 1 is the measured Thomsen anisotropy parameters for 10 kinds of shales and coal and sand from Wang (2002). Figure 1 shows that calculated phase (Figure 1a for qP-wave (thick lines) and Figure 1b for qSV-wave) and group (Figure 1a for qP-wave (thin lines) and Figure 1c for qSV-wave) velocities. It can be seen from Figure 1a that for qP-wave the propagation velocity is slow along vertical direction ( $\theta = 0^\circ$ ) and fast along horizontal direction ( $\theta = 90^\circ$ ), the changes of qP-wave phase and group velocities are small for small incident angles ( $\theta < \text{about } 30^\circ$ ) and large for large incident angles ( $\theta > \text{about } 30^\circ$ ).

Figure 1b and 1c show the calculated phase and group velocities for qSV-wave. It can be seen that properties of qSV-wave are much more complex than those of qP-wave. There is a convex portion (high propagation velocity) in the middle of propagation angles (about  $20^\circ < \theta < \text{about } 70^\circ$ ) for qSV-wave phase velocity. The rapid variation of phase velocity in the convex portion results in the existence of the cuspidal triangle (or cusp) in the curves of group velocity in Figure 1c. No cusp appears for weak qSV-wave anisotropy like as Gulf Coast shale C1. The cusp means that there are three qSV-waves which travel at different velocities and arrive at the observation point at different times, the later arriving qSV-waves may be separated arrivals, or superimpose on the first arrival qSV-wave and cause constructive and destructive interferences which result in qSV-wave waveform distortion. Note that qSV-wave cusp is different from shear wave splitting or birefringence phenomenon, the later is the superimposition of horizontally (SH) and vertically (qSV) polarized shear waves.

Figure 2 shows the calculated phase (Figure 2a for qP-wave (thick lines) and Figure 2b for qSV-wave) and group (Figure 2a for qP-wave (thin lines) and Figure 2c for qSV-wave) velocities for shale/sandstone sequences by taking Backus's averaging. It can be seen the anisotropy in Figure 2 is stronger than that in Figure 1. This is because the heterogeneity between shale and sand is incorporated in anisotropy. The larger the contrast of elastic property between two kinds of constituent materials is, the stronger the composite anisotropy is. It can be seen that the changes of qP-wave phase and group velocities are similar to Figure 1a except with a little stronger anisotropy. The changes of velocities by layering are small for small incident angles ( $\theta < \text{about } 30^\circ$ ) and large for large incident angles ( $\theta > \text{about } 30^\circ$ ). These indicate that anisotropy produced by shale/sand sequences can be ignored for small incident angles or near offsets. However, the influence of anisotropy for large incident angle is strong as seen in far-offset P-wave NMO correction.

Figure 2b and 2c show the calculated phase and group velocities for qSV-wave. It can be seen that the changes of qSV-wave phase and group velocities are similar to Figure 1b and 1c except with stronger anisotropy because the combination effect of two kinds of constituent materials for shale/sandstone sequences. The interference of 3 qSV-waves with different arrived times may have significant influence on shear wave waveform distortion because of thick overburden.

### Conclusions and discussions

The converted wave seismic survey from long offset seismic reflections shows that reflection shear wave is much more complex than reflection P-wave. Seismic properties are affected in complex ways by many factors. Case study by integrating rock physics and log data would help us better to understand seismic reflection characterization within sedimentary sequences.

### References

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Table 1. Measured anisotropy Thomsen parameters in shales, coal, and sand (Wang, 2002).

Sample number	$\rho(\text{g/cm}^3)$	$\alpha_0(m/s)$	$\beta_0(m/s)$	$\epsilon$	$\gamma$	$\delta$	$\sigma$	$\eta$
Brine-saturated Africa shales D1	2.408	3199	1603	0.121	0.138	0.046	0.299	0.069
E5	2.535	3374	1699	0.299	0.509	0.242	0.224	0.038
Brine-saturated North Sea shales A1	2.319	2291	1341	0.195	0.152	-0.014	0.610	0.215
G1	2.439	3354	1579	0.097	0.113	0.096	0.005	0.001
Brine-saturated Gulf Coast shale C1	2.440	3004	1434	0.202	0.200	0.198	0.017	0.003
Brine-saturated Hard shales G3	2.605	3727	2378	0.252	0.187	0.035	0.534	0.204
G30	2.560	3703	2265	0.265	0.180	0.099	0.442	0.138
Brine-saturated siliceous shale B2	1.949	2993	1637	0.022	0.012	-0.170	0.643	0.291
Brine-saturated shaly coal G31	1.783	2678	1464	0.416	0.385	-0.017	1.449	0.448
Brine-saturated shaly coal G31	1.725	2515	1467	0.512	0.425	-0.174	2.016	1.049
Brine-saturated tight sand G17	2.689	4519	2609	0.027	0.016	-0.022	0.147	0.051

$$\sigma = (\epsilon - \delta)\alpha_0^2 / \beta_0^2, \eta = (\epsilon - \delta)/(1 + 2\delta).$$

