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# Analisys of Linear Variation of HTI Axes from VSP Data: a Model Study

S.B. Gorshkalev* (Institute of Petroleum Geology & Geophysics SB RAS), W.V. Karsten (Institute of Petroleum Geology & Geophysics SB RAS), I.A. Karpov (Novosibirsk State University) & D.M. Vishnevskiy (Institute of Petroleum Geology & Geophysics SB RAS)

## SUMMARY

A 3D horizontal layered model with two HTI layers with linear variation of symmetry axes direction is used for finite difference VSP data modeling. The model data is used to test the ability of polarization analysis methods to determine the symmetry axes orientation near the borehole and its variations. Both pseudo-rotation and cross-correlation techniques produced the results with accuracy of few degrees.

## Introduction

Investigating fractured reservoirs with geophysical methods is important for petroleum industry. Permeability in these reservoirs is related to the fracture orientation and this makes the determining the cracks direction essential for proper planning of field exploitation. Drilling over different oil fields indicate that the fracturing orientation is likely to vary in lateral direction.

Aligned fracturing results anisotropy of the medium, and if the fractures are close to vertical the model is HTI. The 3-component VSP provides a powerful tool for fracture characterization. The downgoing and reflected converted PS-waves split in the azimuthally anisotropic layers. Analyzing the shear waves polarization can reveal the prevailing fracture orientation since the fast shear wave in this medium is polarized parallel to the crack direction. The purpose of this study is to estimate the feasibility of a VSP survey to explore lateral changes in fracture orientation resulting in variation of anisotropy axes direction of the HTI medium near the borehole using the synthetic wavefield modelling.

## Mathematical modeling of the wave field

One of the examples or the laterally varying HTI reservoir is the Yurubchen-Tokhomo oilfield in the Eastern Siberia, where the producing interval is the Riphean carbonates. Investigations accomplished in the area demonstrate that near surface is azimuthally anisotropic as well and symmetry directions in the near surface vary rapidly (*Gorshkalev, S.B. et al, 2007*). This is caused by cracks developed in the carbonate topmost layer due to inhomogeneous stress field resulting from rugged topography.

To conduct the current study, a generalized model representing the Yurubchen-Tokhomo geological section was created. The 3D model is horizontally layered and contains two HTI beds simulating the vertically fractured strata, the upper layer relating to the near surface anisotropy and the lower one to the production interval. The model parameters are presented in Table 1. In the both layers the anisotropy magnitude was kept constant and the infinite-fold symmetry axis remained horizontal but the axis directions continuously varied linearly with x-coordinate by 10° per 500 m with opposite signs in the two layers. In the y-coordinate direction the axis orientations were constant. Full wave field was computed using Lebedev finite difference scheme on staggered grids (Lisitsa, V.V. & Vishnevsky, D.M., 2010). Two vertical impact sources, located at X = 0 m and Y = ±900 m, and 2850 m deep well at X = 900 m and Y = 0 m were simulated.

| Horizons | Bottom depth, m | $V_P$, m/s | $V_S$, m/s | ρ, kg/m$^3$ | ε | δ | λ |
|---|---|---|---|---|---|---|---|
| | 170 | 2000 | 900 | 2.10 | 0.138 | 0.084 | 0.138 |
| $H_0$ | 470 | 3600 | 1700 | 2.40 | | | |
| | 870 | 5600 | 3100 | 2.65 | | | |
| $K_1$ | 1070 | 6500 | 3500 | 2.75 | | | |
| $K_2$ | 1320 | 4800 | 2700 | 2.50 | | | |
| $У_0$ | 1600 | 6100 | 3200 | 2.70 | | | |
| B | 2100 | 5250 | 2850 | 2.60 | | | |
| A | 2220 | 6300 | 3400 | 2.75 | | | |
| $R_0$ | 2300 | 5300 | 2800 | 2.60 | | | |
| $R_4$ | 2760 | 6900 | 3400 | 2.80 | 0.105 | 0.057 | 0.105 |
| | ∞ | 3700 | 1500 | 2.40 | | | |

***Table 1** Parameters of the model.*

## Method

HTI anisotropy of the production layer causes splitting of the propagating shear waves. The pure shear waves generated from the source undergo splitting in the near surface layer as well, and obtain a complicated polarization. Moreover, in a field experiment these waves tend to have substantially lower frequencies. The converted PS-waves are better suited for this study. The downgoing waves converted to shear above the target layer could provide the necessary information, but if the recording takes place within the production layer, the rays of these waves propagate near the borehole in this layer, giving information about a very close vicinity of the borehole only. Extending the observed range requires recording further below the target depth which is rarely the case in practice.

The waves reflected and converted of the bottom of the target anisotropic layer provide wider offset coverage, since the higher above the target layer the receiver is located, the further from the well the reflection takes place, as shown in figure 1. Although the uppermost part of the borehole can rarely be used in practice due to intensive head waves and reverberation, the analyzed line may extend to one-quarter or one-third of the source offset. Utilizing shots with different offsets allows further extension of the analyzed line.

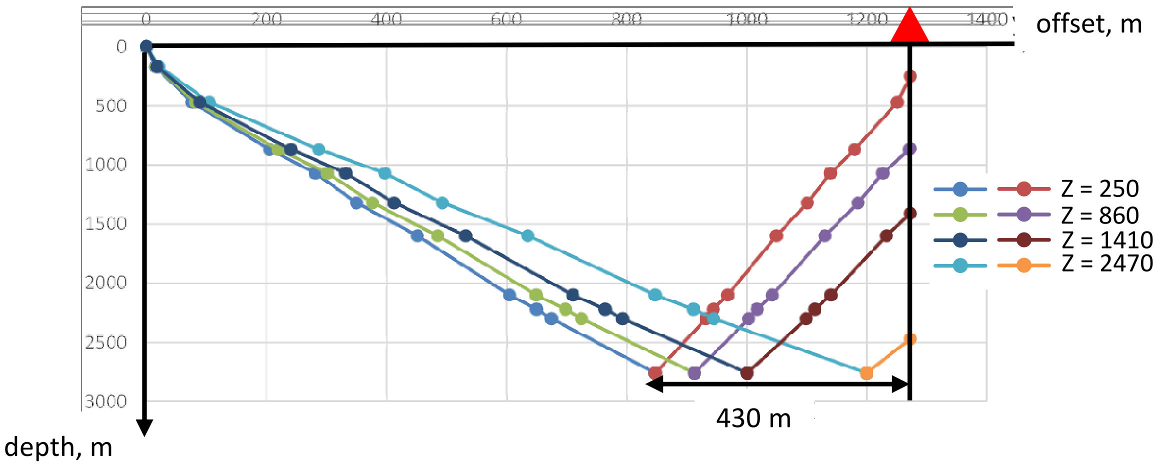


***Figure 1*** *PS-wave converted at the bottom of the target anisotropic layer. Rays recorded at different depth levels, projection onto the incidence plane.*

The analyzed reflected waves interfere with different downgoing waves, so the parametric wavefield separation was implemented on the model data. This resulted in obtaining the field of upgoing shear waves on the horizontal components.

The polarisation analysis of converted waves was carried out with pseudo-rotation method (MacBeth, C., 1996) adapted for onshore VSP (Gorshkalev, S.B. *et al*, 2004). This approach was selected due to its higher noise immunity and reliability of the results independently on amplitude ratio of the split shear waves. At each recording depth the 4-component data matrix obtained from the two shots with equal offsets in orthogonal directions was rotated through the angle φ, and the direction minimizing the sum of the off-diagonal components energy in the time window of shear waves provided the horizontal projections of $PS_1$ and $PS_2$ waves displacement vectors. Due to difference in source offset directions relating to the anisotropy axes the travel times of the concerted waves from these two sources were somewhat different. Since the pseudo-rotation method requires the off-diagonal components of the data matrix be identical, this time difference was corrected with the static shift applied to one of the sources and determined at each depth level by cross-correlating the off-diagonal components.

Besides the noise resulting from interference with scattered wavefield and smearing effect of separation processing, the anisotropy of the near surface could affect the polarization analysis results as it causes deviation of the incident P-wave ray near the source. Deviation of P-wave downgoing ray in the target layer takes place as well, but these were not taken into account for its possibly less effect on shear wave polarization.

The polarization analysis algorithm based on searching the cross-correlation maximum of the two components (Obolentseva, I.R., Gorshkalev, S.B., 1986) was tested as well. This algorithm is less reliable but it can be implemented for the data from one source point only, and can take the deviation of the shear-wave polarisation plane into account.

## Results

The azimuths determined in such a manner vary regularly with registration depth. A subvertically propagating fast quasi-shear wave has the displacement vector parallel to the jointing. There is a good agreement between the modelled cracking direction and the direction derived by the minimi-zation of total off-diagonal components energy.

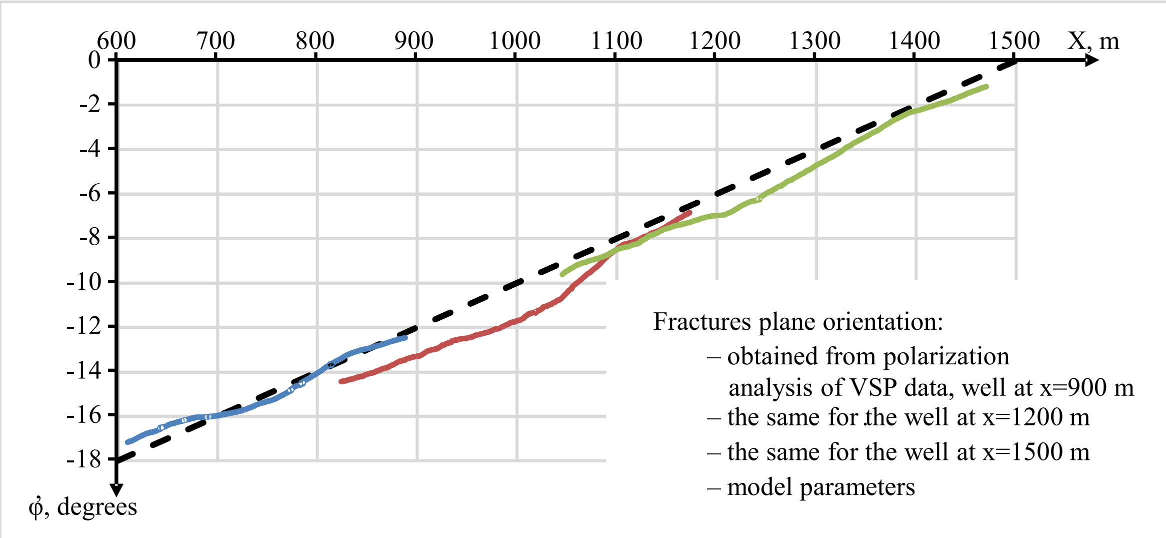


***Figure 2*** *Polarisation of PS-reflected waves determined with pseudo-rotation method.*

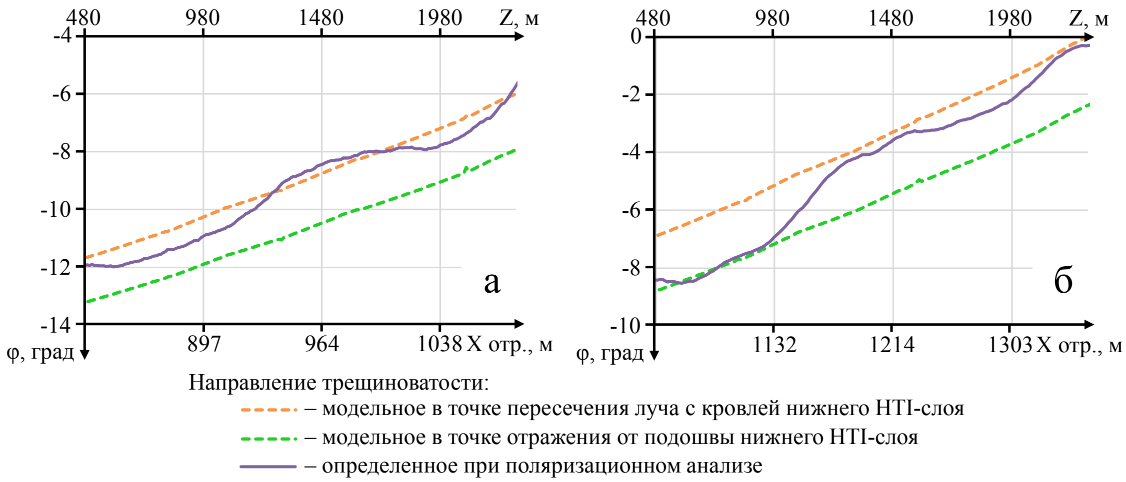


***Figure 3*** *Polarisation of PS-reflected waves determined with cross-correlation maximum method.*

## Conclusions

Thus, the work demonstrates a conceptual possibility of analysis of fracturing direction variation in a heterogeneous anisotropic layer using VSP data.

**References**

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