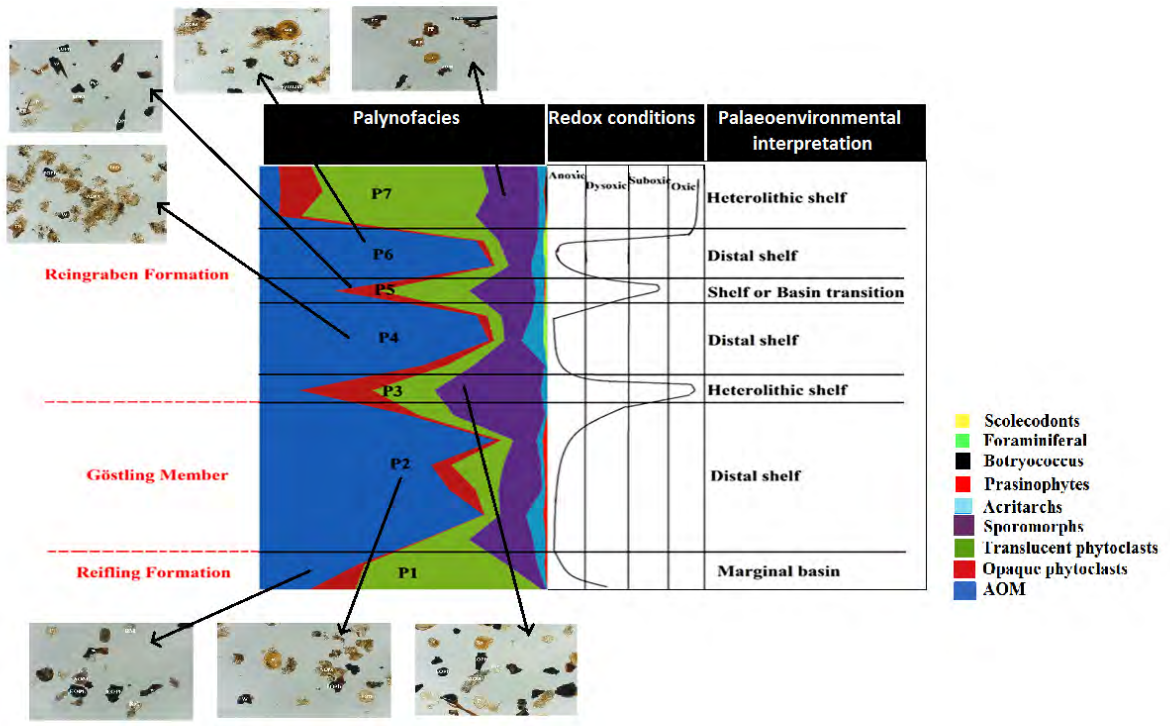

Fig.3: Palynofacies, redox conditions and palaeoenvironmental interpretation throughout the succession. The images are representatives of each palynofacies (Panou, 2015)

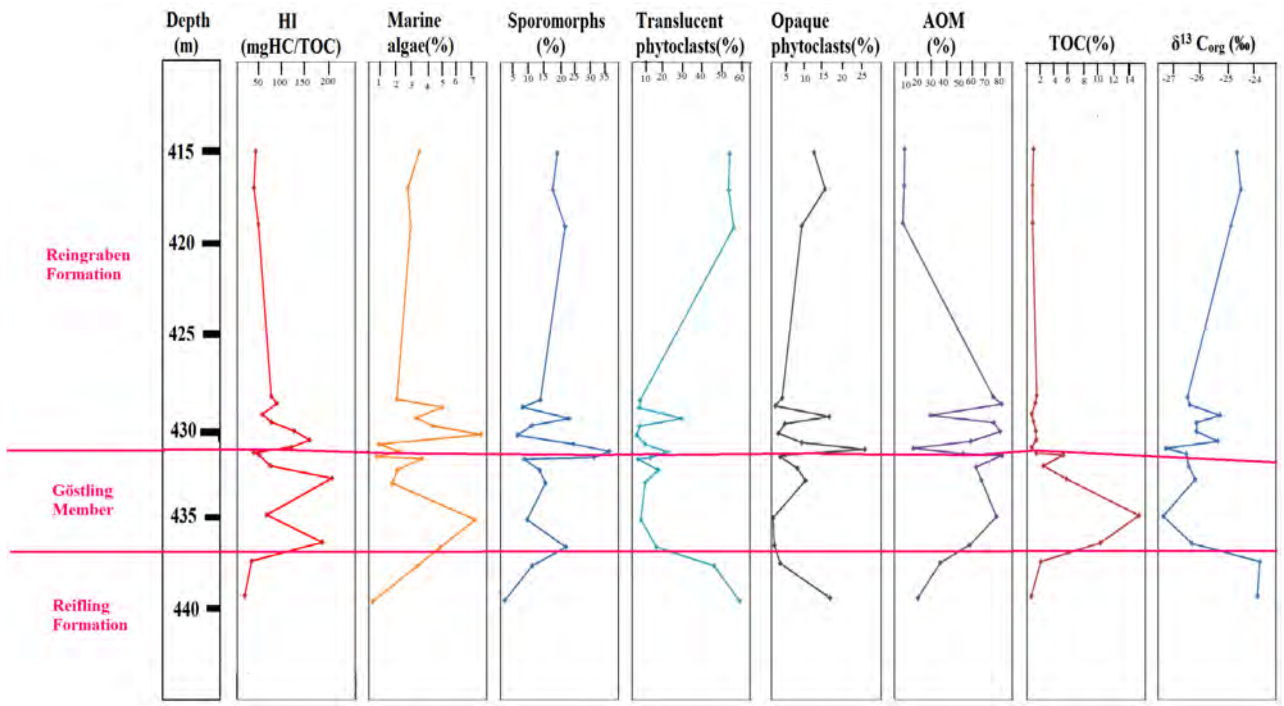

Fig. 4: The main palynofacies categories compared to HI, TOC and $\delta^{13}C_{org}$ (Panou, 2015)

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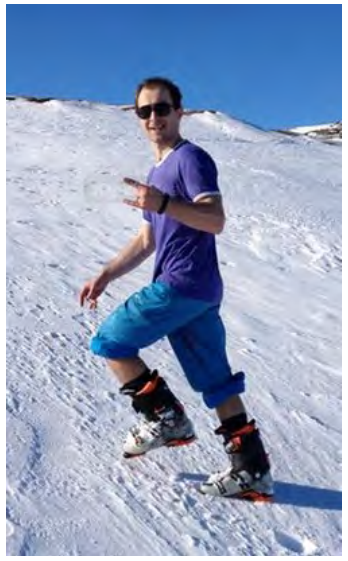
P-wave AVO in tilted transversely isotropic media

by Yuriy Ivanov, NTNU, Trondheim



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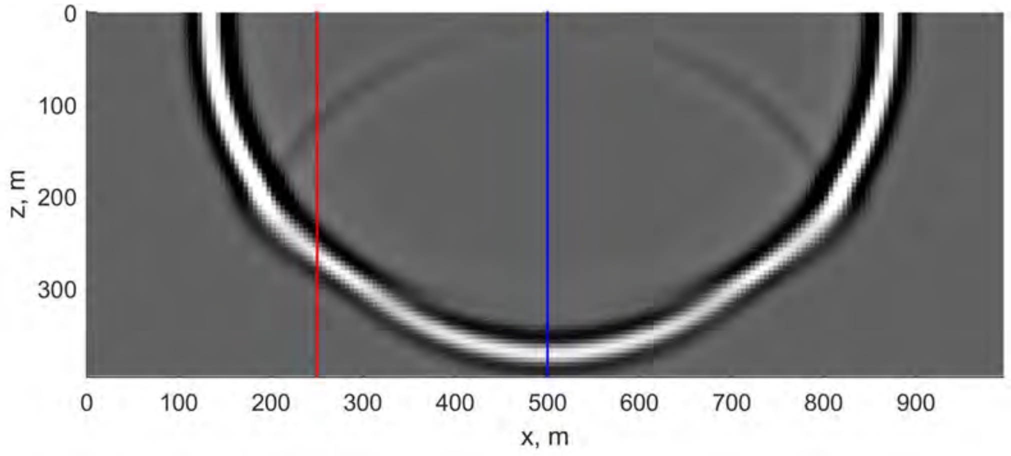
The importance of accounting for seismic anisotropy in seismic exploration and reservoir exploitation has become an accepted fact somewhat two decades ago. Nowadays, modern processing work flow would include seismic anisotropy and very often seismic acquisition is planned in such a way that seismic anisotropy can be estimated.

Anisotropy is the dependence of a physical property (in seismic case, we are talking about seismic wave propagation velocity v) upon the direction of measurement. Mathematically it can be formulated in the following way:

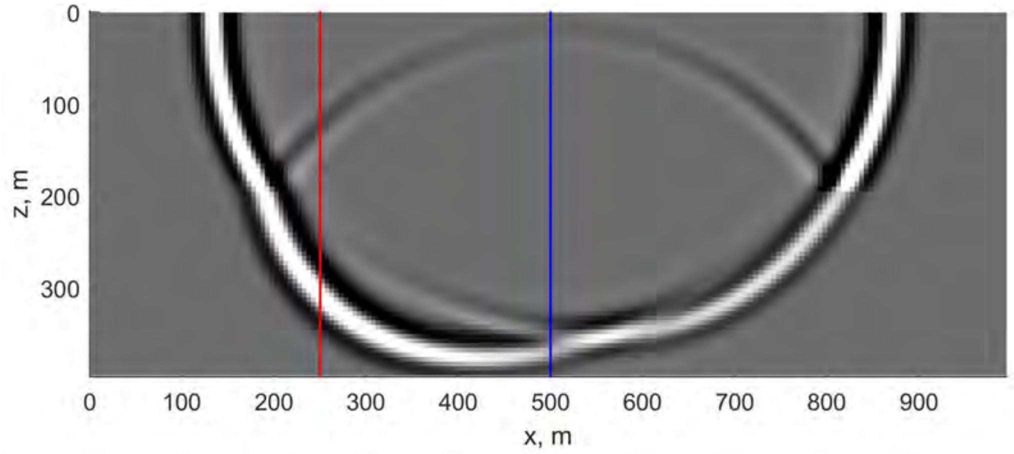
$$v \equiv v(\vec{x}, \vec{n}),$$

velocity v is measured at the point $\vec{x}$ in space along the direction $\vec{n}$. As a result, anisotropy affects both kinematic and dynamic properties of the wavefield, and if we are to obtain a reliable subsurface image, it cannot be ignored. Anisotropy in subsurface is very often associated with intrinsic properties of rocks, fine layering, or sets of fractures (which can occur due to e.g. special stress regime). Understanding of the seismic anisotropy can be useful in exploration and reservoir characterization since it can provide additional important information. For example, shale reservoirs are very often discovered based on the effect of seismic anisotropy. There is number of different mathematical models to describe seismic anisotropy. The simplest and the most commonly used one is vertical transverse isotropy or VTI model. Finely (compared to the wavelength) layered medium will exhibit VTI properties, affecting seismic wave propagation through it.

Amplitude variation with offset techniques are widely used nowadays, because reflection amplitudes are highly resolved in depth/time, unlike traveltime methods, providing a detailed measure of local properties of the subsurface. It has been also noticed that effect of seismic anisotropy on reflected and transmitted amplitudes is strong even when the magnitude of anisotropy is small (Ruger, 1998) and, hence, can be estimated using AVO analysis. Understanding the behavior of P-wave reflection coefficient in presence of anisotropy

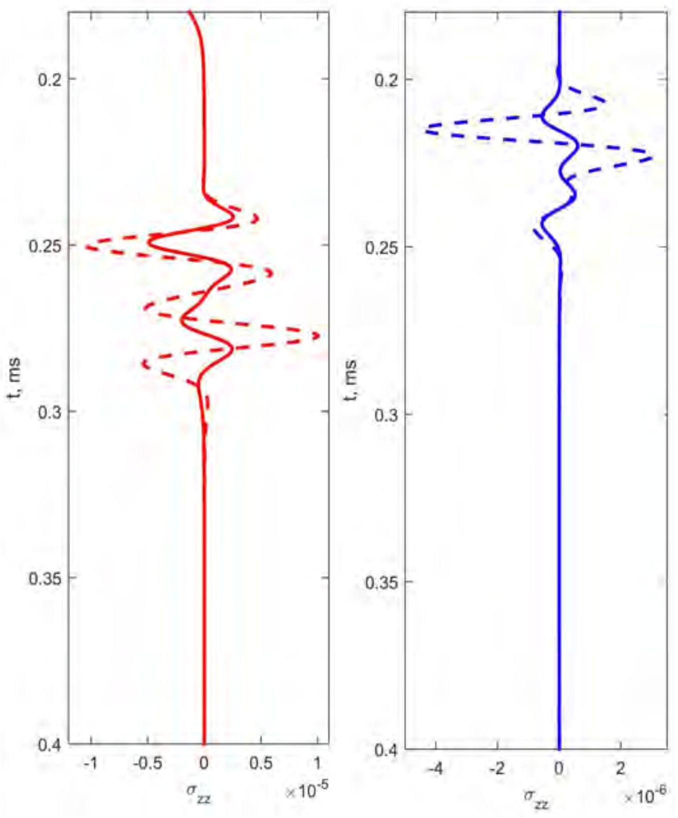


(a) VTI layer



(b) TTI layer

Figure 1: Wavefront distortion due to presence of TTI anisotropy



(a) Receiver at 250m

(b) Receiver at 500m

Figure 2: Distortion of reflected amplitudesdue to presence of TTI anisotropy

is crucial for this purposes. Analytical expression for P-wave reflection coefficient even in the case of isotropic media is too complicated to provide insight into the influence of medium parameters. In order to overcome this problem, various approximations are developed in the assumption of weak contrast at the reflection boundary and weak anisotropy (Thomsen, 1986). Existing approximations are developed in case of vertical (VTI) or horizontal (horizontal transverse isotropy or HTI) symmetry axis (equivalent to horizontal and vertical stratification or fractures). However, in reality, it is not rare to find rock beds or set of fractures tilted with respect to the reflection boundary. These complex situations can be described by a more general model such as transverse isotropy with a tilted axis of symmetry (TTI), and can occur, for example, near the flanks of salt domes or in fold-and-thrust belts (Isaac and Lawton, 2004). The importance of fracture sets, especially dipping, characterization for the industry has been increased over the past decade. As an example, fractures in the Emilio field (Adriatic Sea) are identified and characterized by Angerer et al. (2002). One important effect of TTI anisotropy is that reflected *S*-wave can occur on vertical and near-vertical *P*-wave incidence angles.

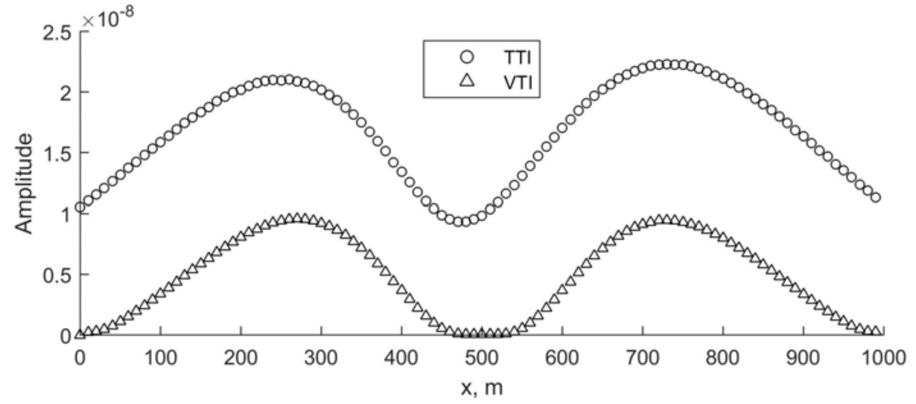


Figure 3: Comparison of P-wave AVO curves for VTI and TTI models

In present study, I demonstrate the effect of tilt angle on wavefield and in particular, on the reflected amplitudes. Proposed 3D approximation for the 3D plane-wave *P*-wave reflection coefficient at the boundary between TTI half-spaces is not shown here due to complexity of the expression (Ivanov and Stovas, 2015). Figure 1 shows how tilt affects the wavefront of the P-wave traveling in TTI layer after it has encountered a boundary. Model consists of two layers with a horizontal boundary at the depth of 200 m, top layer is isotropic, bottom - TTI. Layers have identical properties (v_{P0}=2.3 km/s, v_{S0}=1.8 km/s (velocities along the symmetry axis for anisotropic layer), ρ=2.3 g/cm3 anisotropy is introduced into layer 2 (ε=0.25, δ=–0.2).

P-wave source is located at the surface at x=500 m. Receivers are located at the surface z=0. In Figure 1a tilt angle introduced into layer two is 0°, we observe symmetrical wavefront, whereas tilt of 45° (counterclockwise) is introduced into layer two in Figure 1b. Wavefront distortion is clearly visible. Effect of the tilt angle upon amplitudes can be seen in Figure 2, where color represents the receiver where signal was measured (according to (Figure 1), solid line corresponds to VTI case, and dashed line - to TTI. Reflected P-wave AVO curves extracted from recorded seismograms are show in Figure 3. It can be seen that overall amplitude along the profile is higher for the model with TTI layer. Another important observation is that minimum of the TTI amplitude curve is shifted from the normal incidence location (offset=0) towards the "dip of layers" constituting TTI medium.

Present study shows that dependence of the P-wave refection coefficient on the direction of symmetry axis even for a weakly anisotropic medium is strong and complex and cannot be neglected. Using of anisotropic (TTI) AVO in combination with other methods of fracture characterization can be used to increase the amount and accuracy of information about fractured reservoirs derived from conventional seismic data.

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Depth migration model building and model verification sequence

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The importance of using a correct velocity model for seismic migration process is not deniable. Nevertheless, even for the most sophisticated modern migration algorithms velocity model building is ignored or simplified to an interval seismic velocity. In this article, we will share a very simple and effective way of constructing velocity models for migrations and depth conversions. Also, we will show how radically better well known Kirchhoff Anisotropic Wavefront Propagation Depth migration result (based on proper velocity building model and appropriate applied pre-migration processing sequences) can be compared to depth migrated data by one of the modern algorithms.

PSS-Geo provides Kirchhoff Anisotropic (TVI &TTI) Wavefront Propagation Depth migration from anisotropic interval velocity models. Such models are built in a step by step manner involving integration of diverse geophysical information in multiple iterations of imaging at progressively deeper depths to continuously update and verify the model.

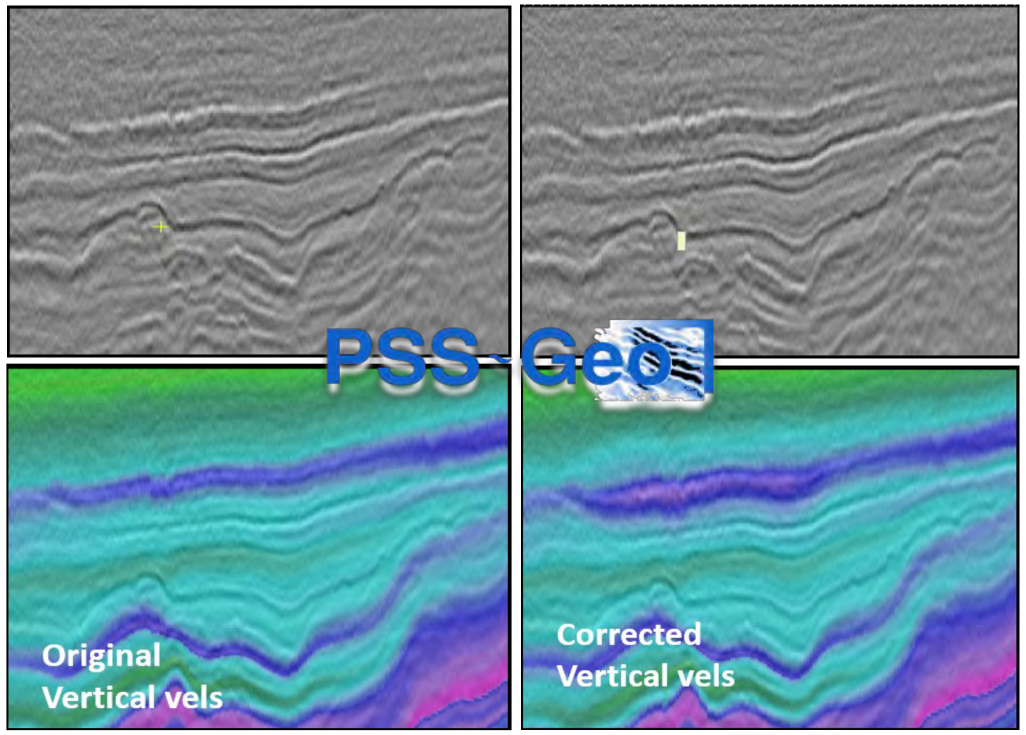
Our methodology is based on the definition of a vertical interval velocity model and an anisotropy field. As a rule of thumb the vertical velocity field should represent a valid Time/depth function typically used for depth conversion in interpretation work; the anisotropy field should be congruous with surface seismic velocities as for its sub horizontal raypaths.

We are focused on the creation of models that are both correct in the time and depth relationship and highly plausible from the geological interpretive point of view. The objective of the anisotropic approach is to optimize the image quality - flat gathers - and to tie the main reflectors to the wells within 1% whilst still maintaining a geologically sensible spatial distribution of the velocities for each layer. A typical sequence will include a:

1) Building a starting interval anisotropic velocity model

- Build an initial vertical velocity model using suitable check-shots within the survey and time interpreted horizons. The check-shot could be verified/optimized by doing a well-tie to the PSTM stacks.

  An initial horizontal (anisotropy) velocity model can be derived using Dix converted and smoothed RMS velocities or from an isotropic V0 model with corresponding gradients (k).
- Near surface sub resolution velocity anomalies (pull-ups/down) can be detected and modelled to avoid distortion on deeper horizons.
- Depth migrate well tie or target lines. Measure anisotropy parameters in well positions, and build an anisotropy model. Typically initial anisotropy model is created interpolating the anisotropy between wells and supplied horizons. The anisotropy model can be updated/adjusted in each iteration



Original interval seismic velocity and corrected velocity models. Corrected velocity model built by using logs data and anisotropic VTI/TTI gridded tomographic solution trough iterations approach. Bottom right picture shows anomaly appearance. Top two pictures are original seismic data