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A framework based on diffraction traveltime parameters for estimating the orientation of symmetry axes in transversely isotropic media

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Abstract

Fractured subsurface media often exhibit anisotropic behavior, which is well-modeled by transversely isotropic (TI) symmetry. Estimating the orientation of the symmetry axis is critical for seismic interpretation. We propose a framework that detects anisotropy and estimates the axis orientation using diffraction traveltime parameters extracted from clustered events. By introducing a shift parameter into the phase velocity expression, we apply an ansatz to estimate Thomsen parameters and the tilt angle. Numerical tests in homogeneous and heterogeneous TI models demonstrate the method's robustness, even under lateral velocity variations. Results show that clustering enhances parameter stability. The proposed approach integrates efficiently into seismic workflows, offering a reliable and physically consistent tool for characterizing fractured media.

Introduction

Developing reliable tools to detect fractures from processed seismic data is essential for accurately characterizing natural reservoirs. However, extracting fracture-related information from seismic responses remains a challenging task. Studies have shown that fractured media can be modeled using equivalent anisotropic representations. In particular, Tsvankin (2001) demonstrated that the media containing aligned and oriented fractures can be described as transversely isotropic (TI) media, parameterized using the Thomsen framework introduced in Thomsen (1986).

For systems with parallel-dipping fractures, the medium can be described more accurately using a tilted transversely isotropic (TTI) model, in which the symmetry axis is inclined relative to the vertical and defined by a tilt angle. When the tilt angle is zero, the model corresponds to a vertical transversely isotropic (VTI) medium, commonly used to represent shale formations and horizontally aligned fractures. When the tilt angle reaches ninety degrees, the model becomes a horizontal transversely isotropic (HTI) medium, which is well suited for representing vertically aligned fracture systems.

A key challenge in seismic analysis is detecting anisotropy, which must be distinguished from purely heterogeneous effects in the data. One practical approach involves leveraging diffraction information, which can be isolated using a diffraction traveltime technique, as demonstrated by Faccipieri et al. (2016) and further detailed in Mundim et al. (2024). Building on this, Coimbra et al. (2024) introduced a framework that uses diffraction-based attributes to identify anomalies potentially associated with anisotropic behavior. In addition, such a framework has been validated through examples in VTI media across various models, including realistic geological scenarios.

In summary, we extend the framework introduced by Coimbra et al. (2024) to extract information about the symmetry axis directly from the diffraction panel. We change their ansatz to approximate the Thomsen parameters and the axis inclination by introducing a shift parameter into the phase velocity expression. We performed numerical experiments in TTI anisotropic media under homogeneous and heterogeneous conditions. The results indicate that this approach holds strong potential for integration into seismic processing workflows, offering additional tools for data interpretation.

Theory

The methodology utilizes the diffraction traveltime technique described in Faccipieri et al. (2016) to extract slope and velocity attributes from the diffraction response in the zero-offset (ZO) domain. We apply the procedure to the prestack dataset, where the slope is denoted by A and the estimated diffraction velocity by V_D, both derived from the diffraction traveltime surface. For a homogeneous anisotropic medium with transverse isotropy, Figure 1 shows V_D as a function of A for four distinct anisotropy configurations centered on a single diffraction. The response curves (in blue) correspond to a VTI model ($\phi = 0^o$) in panel (a), a HTI model ($\phi = 90^o$) in panel (b), a TTI model with moderate tilt ($\phi = 5^o$) in panel (c), and a TTI model with stronger tilt ($\phi = 20^o$) in panel (d). The red dashed curves represent the procedure response.

In order to quantify the axis inclination, we introduce the parameter ϕ. The following expressions incorporate this parameter in the phase velocity expression V, represented as $V_\phi = V(\beta - \phi)$,

$$A(\beta) = \frac{2\sin(\beta)}{V_\phi}\,, \quad \text{and} \quad V_{\mathsf{NMO}}(A(\beta)) = \frac{V_\phi}{\cos(\beta)} \left(\frac{\sqrt{1 + \dfrac{1}{V_\phi}\dfrac{\partial^2 V_\phi}{\partial \beta^2}}}{1 - \dfrac{\tan(\beta)}{V_\phi}\dfrac{\partial V_\phi}{\partial \beta}} \right), \tag{1}$$

for all phase-angle β and with the ansatz to best fit the V_D velocity function defined as

$$\Gamma = \arg\min \left\| V_D(A) - \left[\frac{2V_{\mathsf{NMO}}(A)}{\sqrt{4 + A^2 V_{\mathsf{NMO}}^2(A)}} \right] (1 + \alpha A) \right\|, \tag{2}$$

where $\Gamma = (V_p, V_s, \epsilon, \delta, \alpha, \phi)$. For the VTI case, corresponding to a zero tilt angle, the parameter α retains the interpretation proposed in Coimbra et al. (2024), representing a lateral velocity component attributed solely to heterogeneity effects.

Diffraction cluster

Analyzing a single diffraction in isolation within a region is not advisable in heterogeneous media. This limitation arises from the fact that higher-order spatial variations in wave-propagation velocity can emulate anisotropic behavior, potentially leading to misinterpretations. Moreover, in practical seismic data processing, diffraction separation is commonly performed using semblance-based techniques, which restrict the ability to extract reliable slope and velocity parameters from individual diffraction events.

To address this challenge, we identify regions where the diffraction separator emphasizes coherent diffractions and treat these as diffraction clusters. Following the methodology proposed by Coimbra et al. (2024), we compute a representative diffraction velocity, $V_D(A)$, by averaging the individual velocities associated with each diffraction over a shared range of inclination (slope) values. This averaging process effectively suppresses second-order and higher-order terms, thereby isolating the effects induced by lateral heterogeneity. Additionally, it enhances the stability and reliability of the estimated parameters by incorporating multiple local measurements rather than relying on a potentially noisy single observation. Therefore, we subsequently integrate this averaged velocity into the ansatz formulation and evaluate its effectiveness through ray-based numerical simulations.

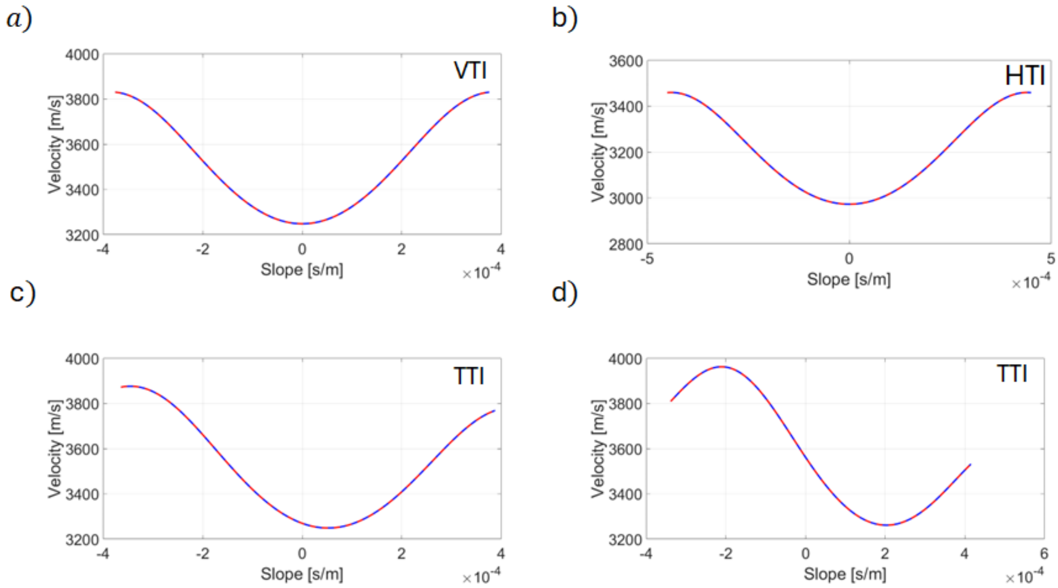

Figure 1: Illustration of the V_D velocity response curve (solid blue) relative an one single diffraction for $v_p = 3368$ (m/s), $v_s = 1829$ (m/s) with $\epsilon = 0.11$ and $\delta = -0.035$ in different scenarios.The ansatz given in eq. 2, here in dotted red, fits perfectly into the velocity function since $\alpha = 0$.

Experiment in a TTI heterogeneous medium

We consider a velocity model with vertical variation defined by $V_p(z) = 3368 + 0.5z$ [m/s] and a constant shear velocity $V_s = 1829$ [m/s], embedded in a TTI medium characterized by Thomsen parameters $\epsilon = 0.11$, $\delta = -0.035$, and a tilt angle of $5°$ with respect to the vertical axis. In this configuration, no lateral velocity variation is introduced by heterogeneity. Figure 2a illustrates a diffraction cluster and its time-domain response under the ZO configuration. The experiment comprises 20 diffractions centered around a reference point at depth $z = 1000$ [m]. Since the model includes only vertical velocity variation, the lateral heterogeneity parameter α is zero. As a result, the curve derived for V_D, shown in Figure 2b in solid blue, reflects the pure anisotropic influence without contamination from lateral heterogeneity. Notably, incorporating multiple diffractions does not distort the anisotropy signature in this scenario.

Given the absence of lateral variation, we set $\alpha = 0$ in the ansatz formulation (Eq. 2). The fit result, shown in dotted red in Figure 2b, yields the following estimated parameters: $V_p = 3786$ [m/s], $V_s = 1131$ [m/s], $\epsilon_E = 0.0992$, $\delta_E = -0.0695$, and tilt angle $\phi \approx 5°$. These results confirm that the estimated Thomsen parameters capture the anisotropy trend well and that the tilt angle is reliably inferred from the ansatz. The phase velocity used in the ansatz is the exact expression presented in Tsvankin (2001), incorporating the required shift correction. Once the tilt angle is estimated, the ansatz can be reapplied with the tilt fixed to refine the anisotropy parameter estimates. This iterative procedure demonstrates the framework's capability to detect anisotropy and effectively determine the symmetry axis orientation in TTI media.

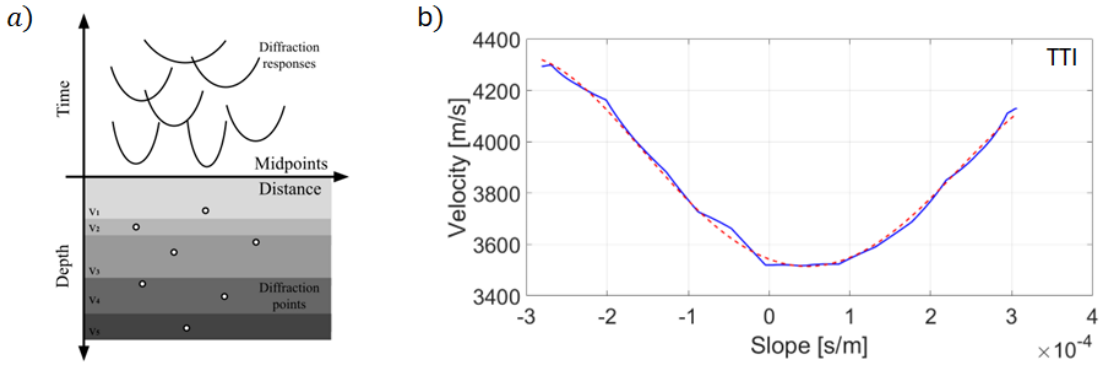

Figure 2: a) Illustrates the application of the proposed framework to a target region. b) Velocity response (solid blue) alongside the best-fit curve (dashed red) by the ansatz described in Eq. 2.

Conclusions

This technique effectively utilizes estimated diffraction separation results to construct the velocity curve $V_D(A)$ across target regions, enabling anomaly detection and parameter estimation using the ansatz. The method can be extended to any anisotropy, provided the exact phase velocity expression for the homogeneous case is available. Future developments will focus on automating region selection and integrating this approach into operational seismic processing workflows, enhancing its applicability in realistic models. This will offer a more efficient and robust tool for characterizing anisotropic features in fractured media.

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