Seismic physical modeling applied to azimuthal anisotropy P-wave analysis

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Abstract

A seismic physical model experiment has been conducted to acquire multi-offset and multi-azimuth data. A physical model was built using aligned acrylic plaques to represent a set of fractures arranged in vertical layers, simulating a HTI media. It was acquired CMP (Common Mid Point) shot gathers varying the azimuthal angle and using ultrasonic transducers as source and receiver. The data were processed by surface consistent true relative amplitudes so they can be used for amplitude analysis. Azimuthal P-wave attributes analysis (amplitude, travel time, velocity, reflection coefficient and AVO gradient) was performed to validate the information obtained through seismic using the knowledge about the properties of the physical model. The results reveal that is possible extract information about the direction of fractures in a HTI medium using these combined methods. The offset-depth ratio affects significantly the azimuthal analyses and the elliptical adjusts, being a key parameter in amplitude and travel time analyzes.

Introduction

The importance and application of seismic anisotropy to solve geophysical problems has been widely used since its first observation (Lynn and Thomsen, 1986). The advances in acquisition setups, data quality, data processing, and parameter estimation allowed the oil industry to include the anisotropy in the data analysis, which reduces considerably uncertainty in interpretation (Tvasnkin et al., 2010).

Kommentar [MC1]: To include

Seismic modelling is one of the methods for studying the effects of anisotropy caused by fractures on seismic data. When seismic waves travel through, or are reflected from the boundaries of fractured layers, the fractures will leave footprints in the seismic data, affecting the amplitudes and travel-times of both P- and S-waves (Mahmoudian, 2013). Using the azimuthal variation analysis of the amplitude, travel time, frequency and reflection coefficient attributes, it was possible characterize the anisotropy present in the model, due to the seismic attributes are azimuthally dependent and show elliptical distribution with azimuth.

According to Qian (2009), the seismic anisotropy could be the bridge to fill the gap between fractures determined by logs, and extrapolated from outcrop analogues, and those inferred from seismic data. Azimuthal seismic anisotropy studies based on physical model data can help us to understand the physical reasons for using azimuthal seismic attributes to detect fracture information. It will also help us to know the potential of applying azimuthal seismic methods to field data, because physical model data have the physical background close to field data.

Kommentar [MC2]: To fill

Kommentar [MC3]: Have the

As demonstrated by the equivalent medium theories, seismic attributes, such as amplitudes and travel-time, are azimuthally dependent and show elliptical distribution with azimuth. It was produced an azimuthal anisotropy analysis using physical modelling seismic data.

Kommentar [MC4]: Sugiro adicionar uma referência que dê suporte a esta afirmação

For the P-wave, there are four attributes that can be used for azimuthal anisotropy analysis, which are amplitude, AVO gradient, velocity and travel time. The amplitude and AVO gradient are actually based on the same reflectivity attribute, and velocity and travel time are basically the same for a given ray-path. The travel time may show elliptical variation with azimuth in media with vertically aligned fractures and has the potential to be used to estimate fracture orientation and intensity (Sayers and Ebrom, 1997). NMO velocity in HTI media also shows elliptical variation with azimuth (Grechka and Tsvankin, 1998). The azimuth dependence of P-wave seismic attributes suggests the possibility of detecting subsurface fracture information through azimuthal anisotropy analysis on seismic data (Qian, 2009).

In this study, a similar HTI symmetry system physical model was constructed and used in an ultrasonic experiment to analyse the variation of the seismic reflections attributes with azimuth. It was acquired seven CMP (Common Mid Point) shot gathers varying the azimuthal angle and their analysis allows us to extract information about the orientation and the location of fractures.

Kommentar [MC5]: Analyze

Method

In this work a simplified representation of a HTI medium was constructed, Figure 1, to be used in ultrasonic experiments. The physical model consists of one horizontal fractured layer made from isotropic acrylic plates compressed together. Each plate has 2mm thick, 50mm high and 200mm long. The model dimensions were designed to allow the simulation of parallel vertical fractures and to provide a sufficiently large area for conducting a multi-azimuthal survey (Silva et al., 2014).

The model has P-wave velocity of 2500m/s, density of 2.43g/cm3 and was built with a scale of 1:10,000. Table 1 shows the measured velocities and density of the fractured layer filled with water. Table 2 lists the estimated anisotropic parameters using measured velocities.

The set-up of the laboratory equipment used in these experiments is very similar to that described by Mahmoudian (2013). It consists of an ultrasonic pulse source and receiver system, an analogue/digital converter, and a motor-driven positioning system. Flat-faced piezoelectric transducers are used as sources and receivers, both types having an active element 12.6mm in diameter. The compressional-wave transducer (Panametrics V103) is sensitive to displacement normal to the contact face and produce an acoustic wavelength of ~ 22mm, corresponding to a wavelet with a scaled center frequency of 10Hz for P-waves.

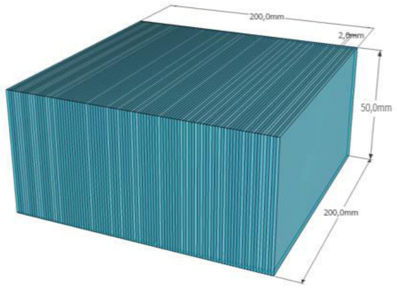

Figure 1 - *HTI model is used to describe a system of parallel vertical cracks in an isotropic background medium (Ruger, 2001). The two vertical symmetry planes are called the "isotropy plane" (parallel to the cracks) and the "symmetry-axis plane" (orthogonal to the cracks).*

Table 1 - *Model properties.*

	P-wave velocity (m/s)	S-wave velocity (m/s)	Density (g/cc)
Water	1450	≈0.25	1.00
Acrylic	2500 (‖) 2250 (⊥)	1500 (‖) 1470 (⊥)	2.43

Table 2 - *Anisotropic parameters.*

ε	γ	δ	η
0.1	0.02	-0.15	0.35

A common-midpoint (CMP) shooting arrangement experiment was carried out in the marine acquisition system of North Fluminense State University (Figure 2). A total of seven large offset CMP seismic lines were recorded along azimuthal directions of 0°(perpendicular to fractures), 15°, 30°, 45°, 60°, 75° and 90° (parallel to fractures) measured from the x1-axis (symmetry axis). In Figure 3, there is a map view of the acquisition geometry of the CMP survey lines.

A multi-azimuth P-wave reflection survey was recorded on the water surface and the selected point was sampled varying offset and azimuth angle. The minimum offset is 610m and the maximum offset is 2000m. Though the physical model dataset is acquired in the laboratory, they have almost the same features of field data, and are different from numerical data based on theoretical calculation. Figure 4 shows the CMP lines referred to 0° (symmetry-axis) and 90° (fracture strike) acquisition. The data from 0° azimuth have a high attenuation of the bottom, especially in larges offsets. The data quality is quite similar to that of a field data with medium signal to noise ratio. Thereby, the data is suitable for analyzing the influence of anisotropy caused by fractures on seismic data.

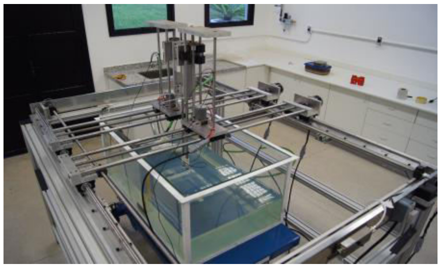

Figure 2 - *Marine acquisition system of the Physical Modelling Laboratory at North Fluminense State University.*

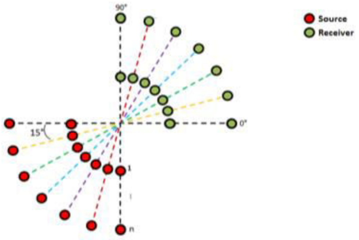

Figure 3 - *A map view of the acquisition geometry of the CMP survey lines. Receivers are shown in green, and the sources are shown in red. The azimuth angle of survey lines is with respect to the symmetry axis of the simulated fractured layer (horizontal axis). The acquired lines were respect to 0°, 15°, 30°, 45°, 60°, 75° and 90° azimuth angles.*

The processing flow includes: geometry loading, noise attenuation, velocity analysis, NMO (Normal Moveout) correction, amplitude corrections and azimuthal analysis. After noise attenuation processing, there are still some traces of noise in the data, but the overall noise level is very low relative to the signal energy and the data are acceptable for azimuthal analysis for anisotropy detection.

The long offset NMO correction was applied (Figure 5), using Tsvankin and Thomsen's non-hyperbolic method. This method allows the inclusion of anisotropic parameter η (eta), which represents the HTI anisotropy. Since the data exhibits HTI behavior, the velocity of acoustic waves traveling horizontally differently from the velocity of acoustic waves traveling vertically, then the parameter η is used in the NMO equation in addition to velocity and offset.

Kommentar [MC6]: Behavior

The most important factors that disturb seismic amplitudes are geometrical spreading, transmission loss, anelastic attenuation, interference of primary and ghost reflections due to a free surface, interbed multiples, and source/receiver array response (Spratt et al., 1993). Such effects alter amplitudes and are independent of the model properties and should be compensated for, so that the reflection amplitudes represent the reflection coefficients of an interface.

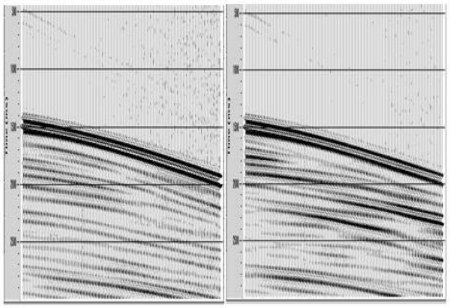

Figure 4 *– CMP shot gather. Symmetry-axis (left) and fracture strike (right).*

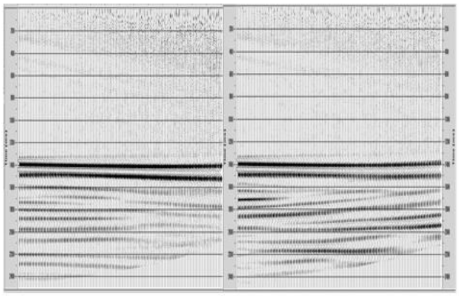

Figure 5 *- CMP shot gather after NMO correction. Symmetry-axis (left) and fracture strike (right).*

Results

The offsets of the data range from 610m to 2000m, so that the straight ray-path incident angles range from 5° to 37° for the reflections at the bottom of the fracture layer. Since the ray-paths are not normally straight in practice, we use the offset-depth ratio to represent incident angle. The azimuth of the seismic data ranges from 0° to 90° and the azimuthal sampling interval is 15°.

Azimuthal travel-time variations measure the accumulative effect of P-wave azimuthal anisotropy. Figure 6 shows the azimuthal variations of P-wave travel-time and amplitude at the top of the model with different offset-depth ratio. In azimuthal travel time analysis, all the traces involved at an analysis point should have the same offset to avoid effects of residual normal moveout after NMO correction. The top reflection event of the fracture layer is properly flattened, however, the bottom reflection event shows azimuthal residual moveout for some azimuth, which is associated with azimuthal velocity variation within the fractured layer. Figure 11 displays the travel time variations for selected offsets, represented by offset-depth ratio of 0.7 (a), 1.0 (b), 1.2 (c) and 1.6 (d).

It is possible observe that for small offset-depth ratio, the variation of travel time by azimuth is close to a circle, being almost ignorable, and with the increasing of offset-depth ratio it tends to become close to an ellipse in a smooth way. The major axis of the adjusted ellipse is aligned with the symmetry axis (Azimuth 0º), confirming that the wave propagation is slower in symmetry axis than in fracture direction (Azimuth 90º).

The amplitude analysis presents an opposite behavior of travel time, only data with offset-depth ratio less than 1.2 is suitable for ellipse fitting. Whenever the offset-depth ratio is 0.7, amplitudes display an elliptical distribution with azimuth; or if the offset-depth ratio ranges from 1.0 to 1.2, the azimuthal amplitude distribution can still be fitted for an ellipse with the major axis in the fracture strike direction. However, when the offset-depth ratio is 1.6, the amplitudes show a complicated shape distribution with azimuth.

This result reveals that the presence of noise affects significantly the amplitude analysis even with sufficient offset coverage (offset-depth ratio equals 1.2). Therefore, for amplitude attribute, it is more important to reduce the noise level and preserve the reflection amplitude than to increase the offset coverage. The opposite occurs with travel-time attribute. The travel-time attribute requires sufficient offset coverage to allow the azimuthal travel-time variation to be sufficiently developed.

In accordance with Ruger (2001), studies of the azimuthal variation of the reflection coefficient can help to identify the orientation of the anisotropy symmetry system with no previous knowledge regarding the parameters of the medium. Figure 8 presents the variation of the reflection coefficient with the incidence angle, considering azimuths varying from 0 ° to 90 ° and an analog model of two layers - one isotropic (water) and one with HTI symmetry. For incidence angles smaller than 15°, the reflection coefficient presents a uniform decreasing. However, according to the increase of incidence angle, the reflection coefficients related to the small azimuths show a strong attenuation, attributed to the approximation of symmetry axis. At the same time, for incidence angles above 15°, reflection coefficients related to higher azimuths show a smooth drop due to the proximity with the fracture strike. It is also possible to notice the explicit behavior of the AVO gradient, since, due to the contribution of the B_{ani} term, the greatest curvature (black and red) occurs in the azimuths near the symmetry axis.

Kommentar [MC7]: According to

Figure 9 shows the coefficient reflection in relation to the azimuth for incidence angles between 10° and 40°. For the incidence of 10° (black), the coefficient is invariant over the entire azimuth range; there is a soft variation for incidence angles of 20° and 30° (red and blue). For 40° (green) the reflection coefficient presents a variation in all the intervals, being more accentuated starting at azimuth 30°, suggesting a reduction of the anisotropy influence on HTI symmetry with the increase of the azimuth angle. The greatest values of reflection coefficient indicate the fracture strike and, in this case, the azimuth of 90° for incidence angles above 20° presents the higher values, corroborating the previous knowledge about the model.

Kommentar [MC8]: indicate

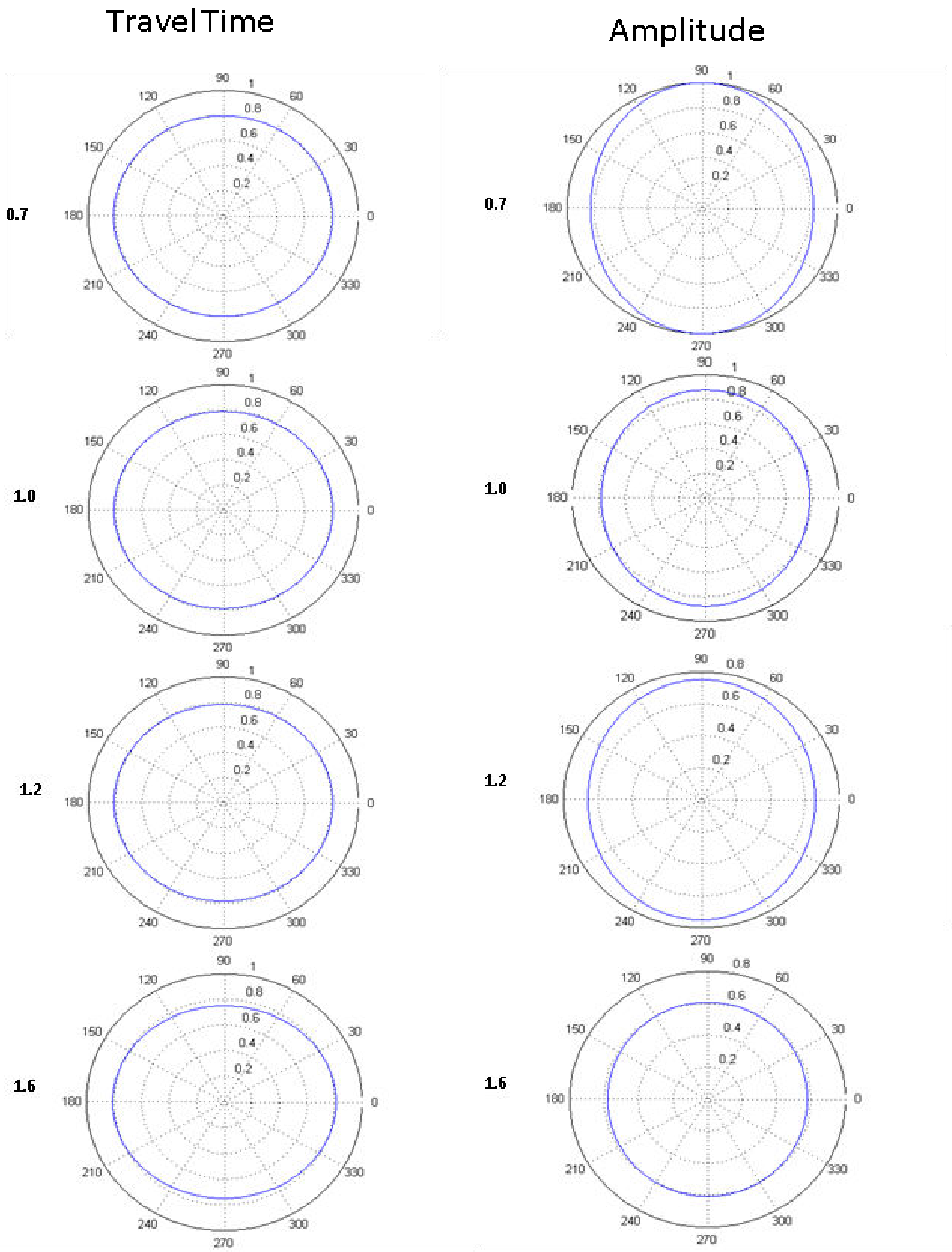

Figure 7 - *Azimuthal variations of P-wave travel-time (left) and amplitude (right) at the top of the fractured layer, with the offset to depth ratios of 0.7, 1.0, 1.2 and 1.6.*

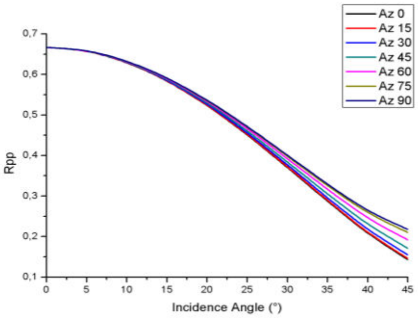

***Figure 8 -** Reflection coefficient for an HTI medium and azimuth angles from 0° to 90°.*

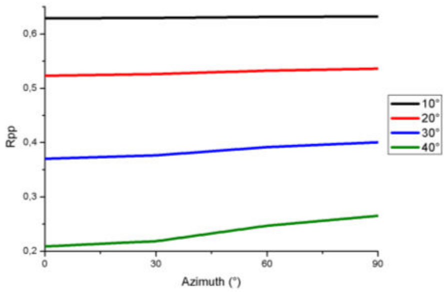

***Figure 9 -** Reflection coefficient for the HTI medium as a function of azimuth angle. Incidence angles of 10° (black), 20° (red), 30° (blue) and 40° (green).*

Figure 10 shows a variation of the amplitude with the azimuth for different offset-depth ratios. For analysis performed at offset-depth <= 1.2 (in black, red and blue), the peak amplitude is easily identified and associated with a known fracture direction. However, regarding depth> 1.2 (in green and pink), the low prominence of the amplitude peak inserts uncertainties in the identification of the direction of fractures, which could be solved through a reflection coefficient analysis.

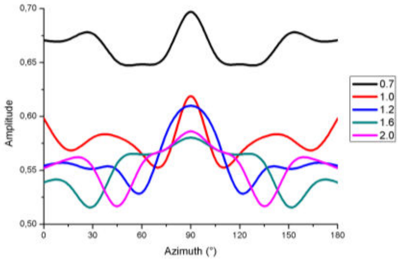

***Figure 10 -** Amplitude variation with azimuth for offset-depth ratio of 0.7 (black), 1.0 (red), 1.2 (blue), 1.6 (green) and 2.0 (pink).*

Conclusions

In this study, a physical model that represents an HTI medium was used in a seismic ultrasonic experiment. It allowed analyzing azimuthal variations of the P-wave attributes: travel-time, amplitude and reflection coefficient. Azimuthal variations of travel-time attribute are better fitted with an offset-depth ratio greater than 1.0. Therefore, large offsets are indicated to improve travel-time analysis on the fracture. Amplitude variations are more sensitive than travel-time changes on the fracture by the analysis of fitting curvature. However, the results from the amplitude attribute are affected by the presence of noise on the data, and it demands a good signal to noise ratio to be reliable. The time-frequency spectra provide information about frequency components attenuation. When the waves pass along the fracture strike, the high frequency components are highly attenuated. This work shows that the offset-depth ratio is a key parameter for obtains useful results from the ultrasonic P-wave technique.

This study can be used as a methodology for obtaining information about fractures orientation in anisotropic media with HTI symmetry system. The proposed method can help in the characterization of field seismic data, using combined seismic attributes analyses to obtain information of fractures and anisotropy present in the medium.

Acknowledgments

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