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Simposio de Geofísica: La Geofísica como vínculo entre el conocimiento de la tierra y la sociedad

REDUCING GEOMECHANICAL MODEL UNCERTAINITIES: ANISOTROPY STUDY USING A MULTICOMPONENT WALK-AWAY VSP AND WALK-AROUND VSP, NEUQUINA BASIN, ARGENTINA

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RESUMEN

El presente trabajo presenta la metodología y el análisis de un perfil sísmico vertical multicomponente (3C VSP) VSP walkaway (WAW) aplicado a estudios de anisotropía sísmica y un perfil sísmico vertical multicomponente VSP walkaround (WAR) aplicado a reducir las incertidumbres en la caracterización de fracturas e integrar los resultados con estudios de variación de amplitud con distanciamiento (AVO), variación con azimut (AVOaz) y estudios de anisotropía polar realizados en un reservorio no convencional ubicado en la Cuenca Neuquina.
El objetivo principal de este proyecto fue estimar los parámetros de Thomsen que se utilizarán en un flujo de trabajo que incluye datos de VSP, datos de sísmica de superficie, datos microsísmicos y geomecánica.
De acuerdo a la metodología presentada, a partir del análisis de dos líneas ortogonales WAW se obtuvieron los parámetros de Thomsen δ y ε; la diferencia en el valor de δ es cero, mientras que la diferencia en ε es de aproximadamente 6%. En consecuencia la simetría se puede aproximar como una isotropía transversal vertical (VTI). La determinación del parámetro γ abarca otro análisis.
El estudio WAR registró ondas de compresión y ondas de corte convertidas en la zona de interés, que proveen eventos sísmicos clave para detectar y analizar la anisotropía azimutal de las formaciones Punta Rosada Media y Lajas. Las relaciones de amplitud transversal horizontal (HT) / transversal vertical (VT) y los hodogramas de polarización VT- HT se calculan a partir de las ondas de corte descendentes.
A partir del análisis WAR, las relaciones de amplitud horizontal transversal (HT) / transversal vertical (VT) y los hodogramas de polarización VT-HT se calculan a partir de las ondas de corte descendentes. Estos atributos pueden proporcionar evidencia de anisotropía azimutal a través del análisis de transmisión. De acuerdo a esta metodología, el análisis de diferentes atributos de birrefringencia mostró evidencia de anisotropía azimutal en el sector Noroeste de la zona de estudio y en el rango de profundidad cubierto por el conjunto de receptores, lo que sugiere la presencia de fracturas naturales en el sector Noroeste. En los demás sectores la anisotropía azimutal es débil. Esta información es un factor clave para el diseño de fracturación hidráulica, la planificación del desarrollo y cálculos del índice de productividad.

INTRODUCTION

The characterization of seismic anisotropy is crucial for the exploration and development of unconventional reservoirs. It contributes to the reduction of risk on the mispositioning of seismic reflectors, angles and amplitude distortion from target reservoir (amplitude versus offset (AVO)), and microseismic location. In addition, it contributes to pore pressure and geomechanical studies.

The acquisition of high fold 3D surface seismic and microseismic data in Rio Neuquén field (located in Neuquina basin) stimulated interest in designing a workflow that integrates 3C VSP, 3D surface seismic and microseismic data (Figure 1). The design of this workflow was motivated by the following questions: Which would be the calibration for anisotropic seismic migration? How can the uncertainties of the microseismic location be reduced? Does it help in the interpretation of azimuthal AVO (AVOaz) and other seismic attributes studies related to fractures? (Curcio *et al.*, 2016; Taylor and Curcio, 2014).

Natural fractures play a critical role for unconventional reservoirs. Their presence significantly affects hydraulic fracturing and their associated stimulation plans to bring economic success. Although the mechanics and geologic conditions to generate natural fractures are generally understood, the lack of hard data makes them difficult to describe in the subsurface. There is a need for geoscientists and engineers to consider the presence or absence of natural fractures in unconventional reservoir models to better understand their effect on hydraulic fracturing and production enhancement.

The first step toward answering these questions was to study seismic anisotropy from 3C walkaway VSP (WAW) and walkaround VSP (WAR).

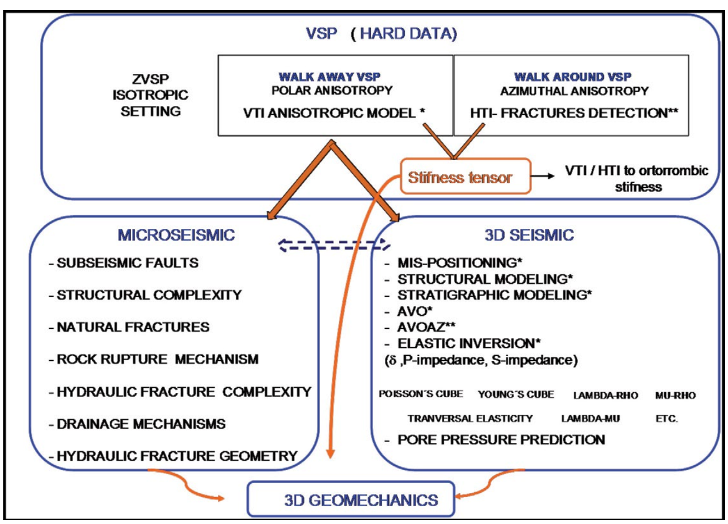

Figure 1. 3C VSP to geomechanics workflow showing the importance of understanding the 3C WAW and WAR as hard data for 3D seismic and its contribution to 3D geomechanics; this is intrinsically related to anisotropy parameters through the stiffness tensor (Curcio *et al*. 2016).

THEORETICAL BACKGROUND

An elastic media is defined as anisotropic when seismic velocities depend on the direction of wave propagation at some physical points (Grechka 2009). Mathematically, Christoffel equations under Voight notation express the eigenvalue and eigenvector problem for a symmetrical and definite positive matrix G:

$$\left[G_{il}(n) - V^2\delta_{il}\right]U_l = 0 \qquad (1)$$

where G is the Christoffel matrix, U is the polarization vector, and δ is the Dirac distribution. Under this formalism, the eigenvalues of G are the squared phase velocities, and the eigenvectors are the polarization modes.

Under the weak anisotropic assumption, Thomsen (1986) states a set of phase velocities equations:

$$V_P(\theta) \approx \alpha\left(1 + \delta \sin^2\theta \cos^2(\theta) + \varepsilon \sin^4(\theta)\right) \qquad (2)$$

$$V_{SV}(\theta) \approx \beta\left(1 + \frac{\alpha^2}{\beta^2}(\varepsilon - \delta)\sin^2(\theta)\cos^2(\theta)\right) \qquad (3)$$

$$V_{SH}(\theta) \approx \beta\left(1 + \gamma \sin^2(\theta)\right) \qquad (4)$$

and group velocity

$$g = Vn + \frac{\partial V}{\partial\theta_1}\frac{\partial n}{\partial\theta_1} + \frac{1}{\sin^2\theta_1}\frac{\partial V}{\partial\theta_2}\frac{\partial n}{\partial\theta_2} \qquad (5)$$

Where n is the normal wavefront specified by two directional angles θ_1 and θ_2, and α, β, γ, δ, ε are Thomsen parameters, defined from the phase velocities at 0° and 90°. Seismic rays are traced from a source point to a receiver location using the shooting method, which sends a ray from the source with different take-off group angles. After the raypaths are found, the traveltime is integrated along the path using the group velocity (Pei *et al.* 2011).

In terms of anisotropy estimation, Grechka (2009) affirms that the best means of determining the effective anisotropy is to use first-break times measured downhole. The determination of accurate Thomsen parameters on the seismic scale is ensured by a traveltime inversion of the multicomponent downhole data because the data have much a greater signal-to-noise ratio and higher resolution than surface seismic; it provides an accurate depth-velocity model. In addition, WAW provides rich information from near to far offsets, giving precise velocity analysis and

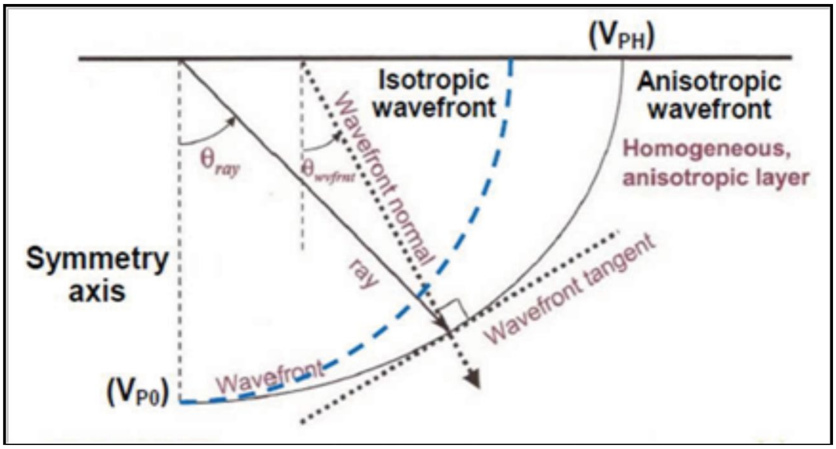

Figure 2. Scheme of phase velocities, slowness, polarization and group or ray velocities of a plane wave.

structural imaging over a wide range around the well. Consequently, WAW provides more advantages in inverting anisotropic parameters than any other type of seismic method (Curcio *et al.* 2016; Liu. *et al.* 2013).

The analysis of the WAR data comprises a shear wave splitting analysis. In the anisotropic media, the shear wave physically splits in two modes traveling with two different velocities. Mathematically, the phase velocities are two of the eigenvalues of Christoffel´s equation, and they are associated with the phase velocities of the Horizontal Shear - Mode (SH) and Vertical Shear - Mode (SV) waves (Grechka 2009).

Shear wave splitting provides perhaps the most direct evidence of seismic anisotropy and is considered to be one of the most successful methods for detecting and characterizing fractures (Crampin *et al.* 1985; Li *et al.* 1997).

In a vertically fractured media, a maximum linearity and maximum radial polarization will be observed in the symmetry planes corresponding to the planes parallel and perpendicular to the fracture strike. After entering such an anisotropic medium, shear wave energy splits into fast and slow modes with two distinct polarizations and velocities. These unique properties can reveal and help to characterize the orientation and density of a vertical fracture system. Such a fracture system is often represented by a symmetry called horizontal transverse isotropy (HTI).

Because both converted shear waves and reflected shear waves generated on a major lithology boundary may also carry shear wave information, a WAR 3C VSP acquired by P-wave sources can be used for fracture characterization. The shear waves may be present on the vertical transverse component and on the horizontal transverse component as a result of birefringence.

CASE STUDY IN NEUQUINA BASIN

GEOLOGICAL SETTING

The Río Neuquén field is located in the eastern sector of the Neuquina basin, approximately 22 km north of the city of Neuquén (Figure 3). The units involved in this study are the Punta Rosada and Lajas Formations.

The Punta Rosada is represented by medium to coarse grained sandstones and conglomerates arranged in thickening and coarsening upward cycles. This arrangement is the result of the progradation of terrigenous sediments onto the marine realm, represented by Las Lajas and Los Molles formations.

The Punta Rosada is characterized by strong lateral and vertical facies changes as a result of important wide variations in relative sea level, sediment supply, and tectonic influence. The Lajas formation comprises the transition from deltaic deposits in the basal section to sandy fluvial channelized bodies to the top. The total thickness of both units is approximately 1000 meters, and its top is characterized by the presence of an important regional unconformity. The structure under study is a pop-up structure, generated by a strike-slip fault.

SURVEY DESIGN AND DATA ACQUISITION

The primary objective of this study was to estimate the overburden anisotropy of Punta Rosada Media and Lajas Formations through WAW and fracture characterization through WAR. A secondary objective was to perform PP and PS imaging of the reservoir.

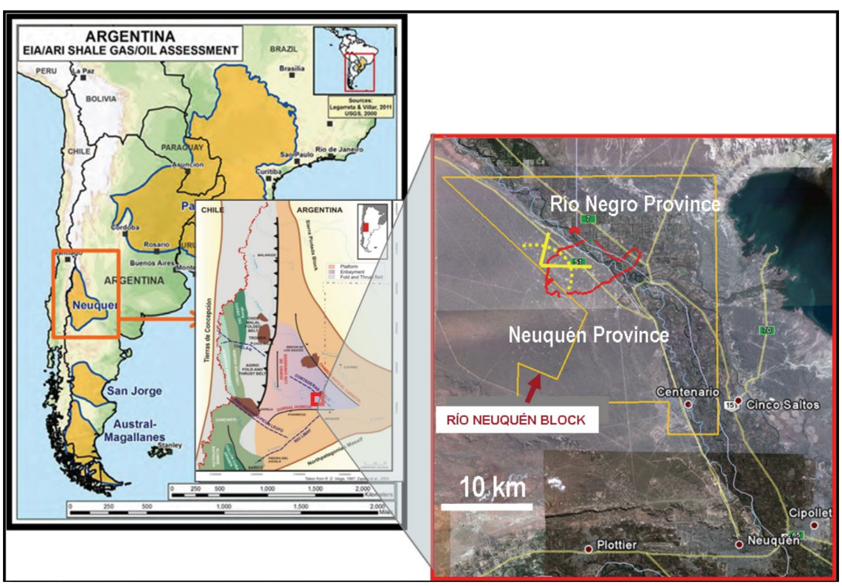

Figure 3. (Left) Study location map from the Neuquén province and Neuquina Basin (Ari 2013; Gonzalez Riga 2003). (Right) In yellow, the setup of WAW and WAR.

WAW survey includes two orthogonal walkaway VSP lines. One of these is parallel to the dip of the popup structure; it has a maximum offset of 3400 m (Line 1). The second line is perpendicular to the dip of the pop-up structure (Line 2) (Figure 4); it has a maximum offset of 5300 m. A total of 40 3C receiver levels spaced 15 m apart and covering a depth interval of 585 m (3425 to 4010 m depth) were acquired in the vertical section of the well.

WAR survey design primarily consists of optimizing the shot and receiver positions to detect fracture-induced azimuthal anisotropy. The receivers are located along the study formation, with some located above it to detect any pattern differences. The ideal shot offset to generate converted S-waves at the top of the reservoir was defined by the Zoeppritz equation introducing the Vp/Vs relation and the densities for the top and bottom layers.

Ideally, the WAR sources should be set as a full circle around the well; however, because of location limitations, the WAR acquisition consisted of 21 shot-points along a semicircle of approximately 200°. The semicircle was superposed to the "pop-up" related to the wrench system (Figure 4). A total of 14 levels were located in the interval of 3800 to 4000 m.

Two 60,000 lb P-vibrators worked as seismic source, in a frequency range from 6 Hz to 96 Hz with sweeps of 12 seconds and sampling frequency of 1 millisecond.

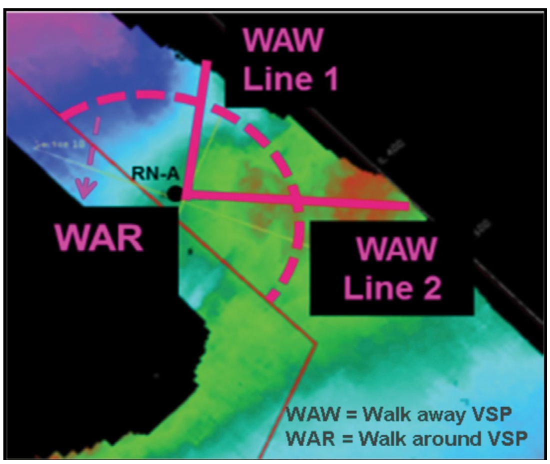

Figure 4. Scheme of the WAW pink lines and WAR pink semiarc superposed to the "pop-up" related to a wrench system.

DETERMINATION OF THOMSEN PARAMETERS

The walkaway data was processed following a workflow that includes 3C rotation of the data to the source-receiver plane and picking first break arrivals (observed traveltimes) on the radial component shot gathers.

Note that the VSP is unique in that it records the downgoing reverberant wavefield as well as the upgoing wavefield. The downgoing information can be used to design an operator that provides effective deconvolution of the upgoing energy. This deconvolution is performed by using a deterministic process and is normally applied on a trace-by-trace basis. However, for this survey an average operator was applied based on sediment arrivals from the east side of the borehole. Figure 5 and Figure 6 shows Upgoing P-wavefield and S-Wavefield after deconvolution for Line 2.

Thomsen parameters were estimated for each WAW line through an iterative traveltime inversion. The WAW had good quality data. As γ parameter requires another analysis, it is explained only the determination of δ and ε Thomsen parameters.

First, a planar VP0 and VS0 model from the zero-offset VSP was built (Figure 7). Then, the velocity model was used to calculate traveltimes for a range of Thomsen parameters using a 2D ray tracing technique and search for the best-fit anisotropic parameters that match observed traveltimes. This process was applied in a stripping fashion for three depth zones: the overburden (from velocity datum to top of Punta Rosada formation), Punta Rosada formation, and Lajas formation (Figure 8).

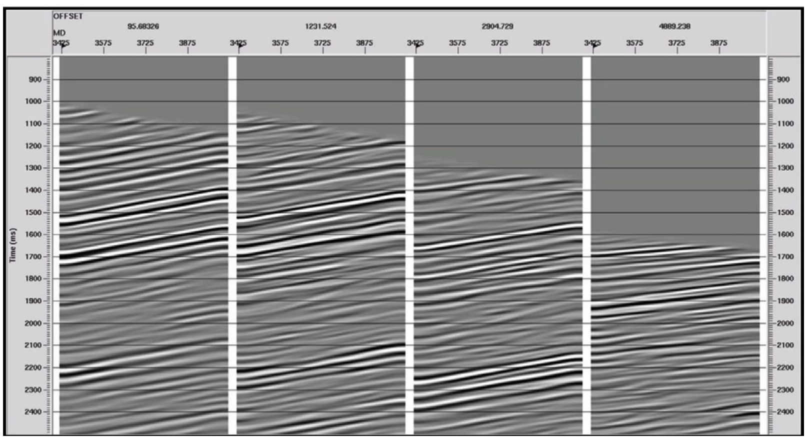

Figure 5. Line 2 Upgoing P-wavefield after deconvolution.

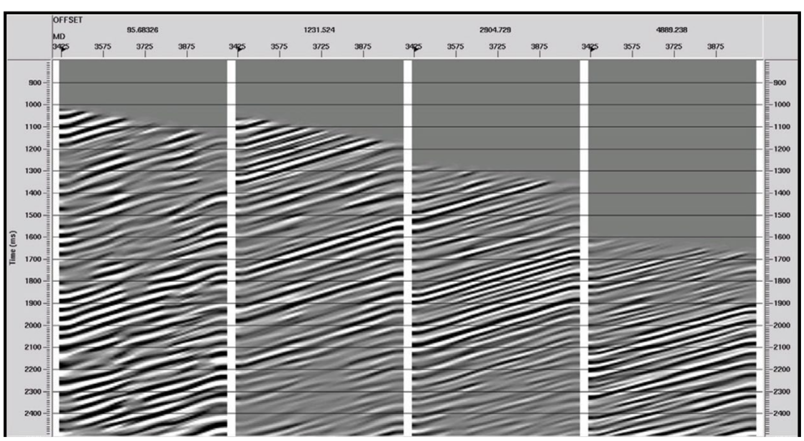

Figure 6. Line 2 Upgoing S-wavefield after deconvolution.

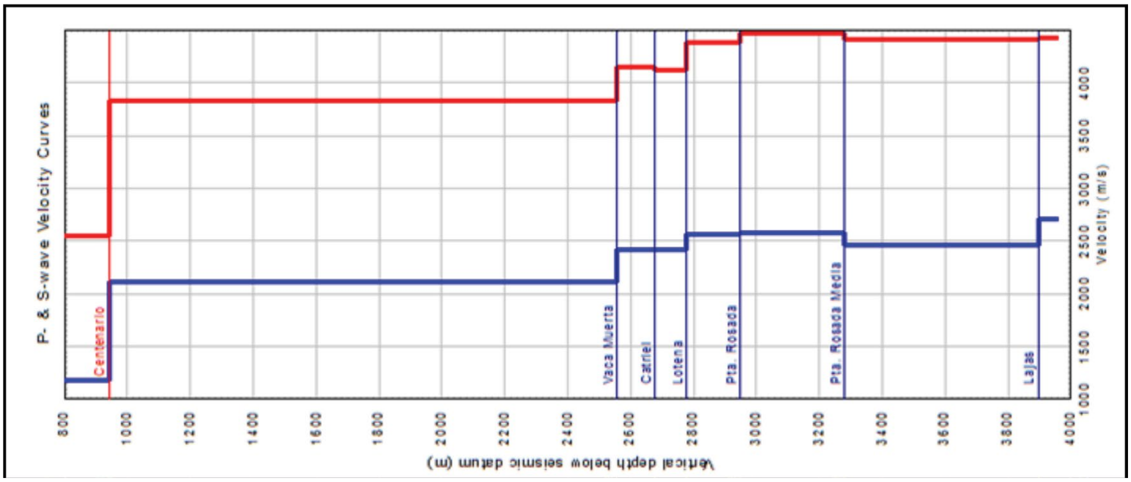

Figure 7. VP0 (red) and VS0 (blue) initial model, obtained from the zero-offset VSP.

For simplicity, the results shown correspond to Line 2, overburden and the Punta Rosada formation. The overburden anisotropy values calculated are δ_2=0 and ε_2=6% (Figure 9).

The layer-stripping for Punta Rosada media shows that the best fit is also δ_2=0% and ε_2=6% (Figure 10). In this approach, also it is desirable to demonstrate whether or not a local 3D VTI symmetry can be considered. In this case, expected values include $\varepsilon_1=\varepsilon_2$ and $\delta_1=\delta_2$ or at least $\varepsilon_1 \sim \varepsilon_2$ and $\delta_1 \sim \delta_2$. Values other than those expected indicate the existence of another type of 3D symmetry. From the traveltime inversion, the delta difference between line 1 and line 2 was found to be zero, $|\delta_1-\delta_2|=0$, whereas the difference for epsilon $|\varepsilon_1-\varepsilon_2|=$ 6%. These differences indicate that, under weak approximation, far offset distorts the P-wave-field in a different way along and perpendicular to the pop-up structure. However, VTI symmetry could be considered.

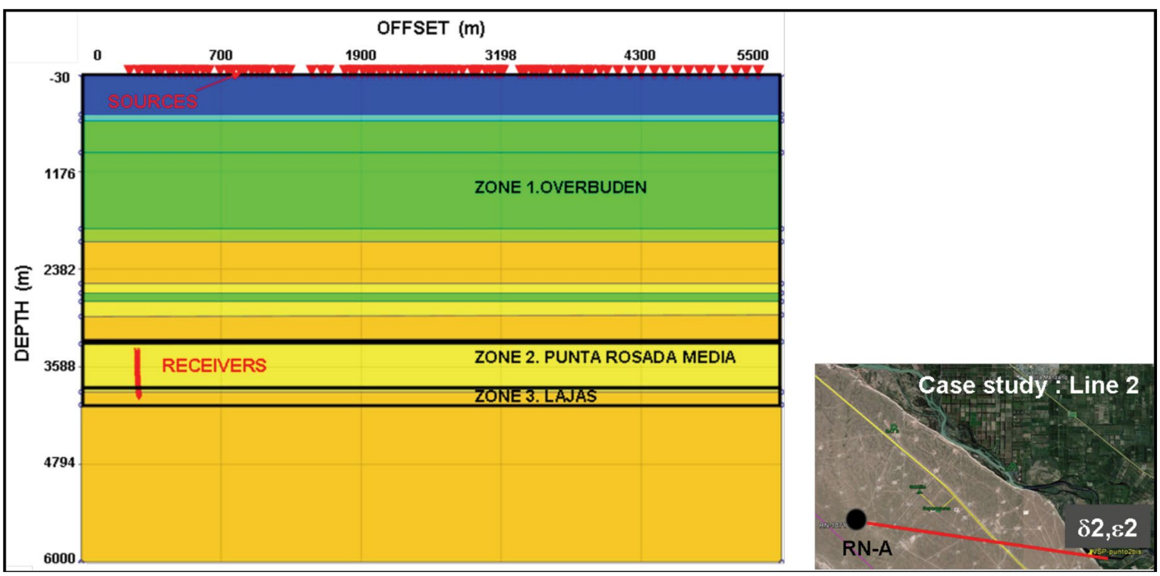

Figure 8. Depth zones of the layered model: 1. Overburden section in which its heterogeneity often creates distortions in the measured travel times that cannot be explained by any anisotropic model; 2. Punta Rosada Media section; 3. Lajas section.

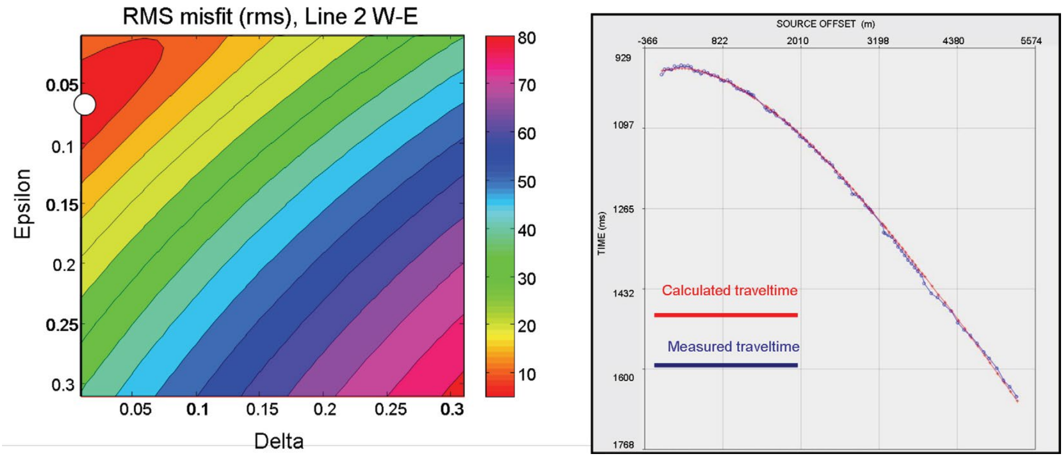

Figure 9. (Left) Overburden P-wave anisotropy. RMS map error indicates that the best fit converges to δ=0 and ε=6% (white circle) with RMS of 5.04 ms. (Right) Traveltime plot for common receiver gather. In blue, measured traveltime and in red calculated traveltime for the best fit.

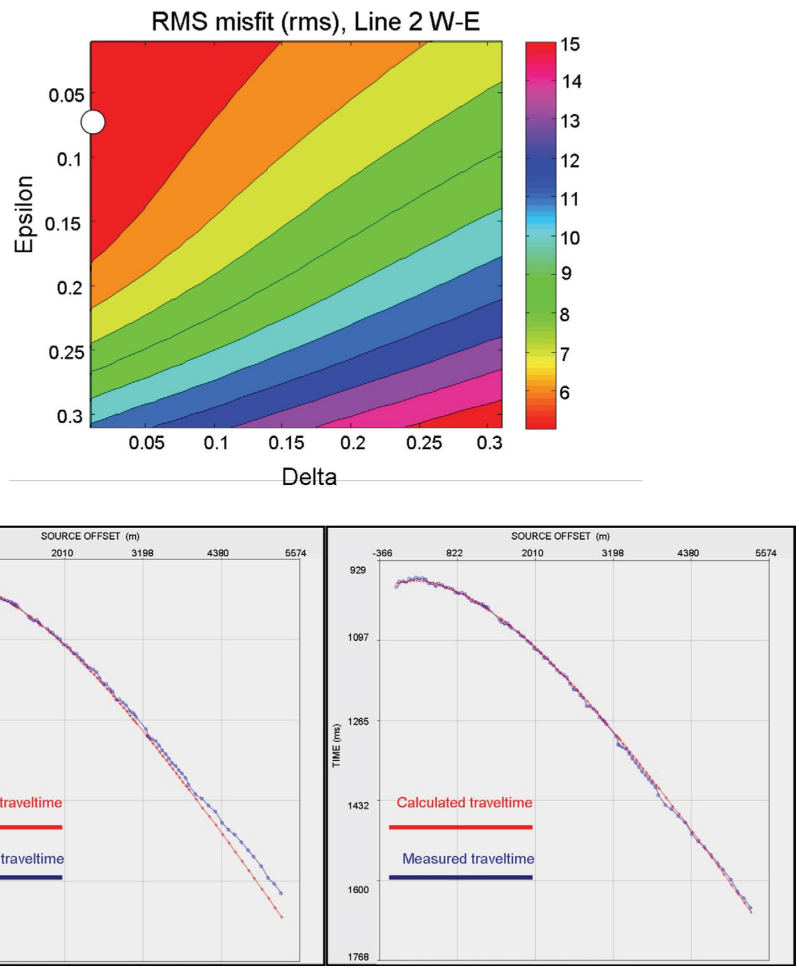

Figure 10. (Top) P-wave anisotropy of the Punta Rosada Formation. RMS map error indicates that the best fit converges to d=0 and e=6% (white circle) with RMS of 5.2 ms. (Bottom, left) Traveltime plot for common receiver gather. It is shown the fit for the isotropic case, in which the far offset is observed to differ from the isotropic case (RMS 15.1 ms). (Bottom, right) The best fit is for the anisotropic case δ=0 and ε=6% (RMS 5.2 ms).

SHEAR WAVE ANALYSIS

The WAR had good quality data, and P-wave and mode-converted shear waves were recorded in the zone of interest, which provided key seismic events to analyze the azimuthal anisotropy of Punta Rosada Media and Lajas Formations.

The data pre-processing consisted of trace header inspection, data editing and stacking, first break picking, and tool orientation to the Cartesian system. The data are then rotated horizontally using the azimuthal polarization angle to maximize the direct P-wave energy in the radial

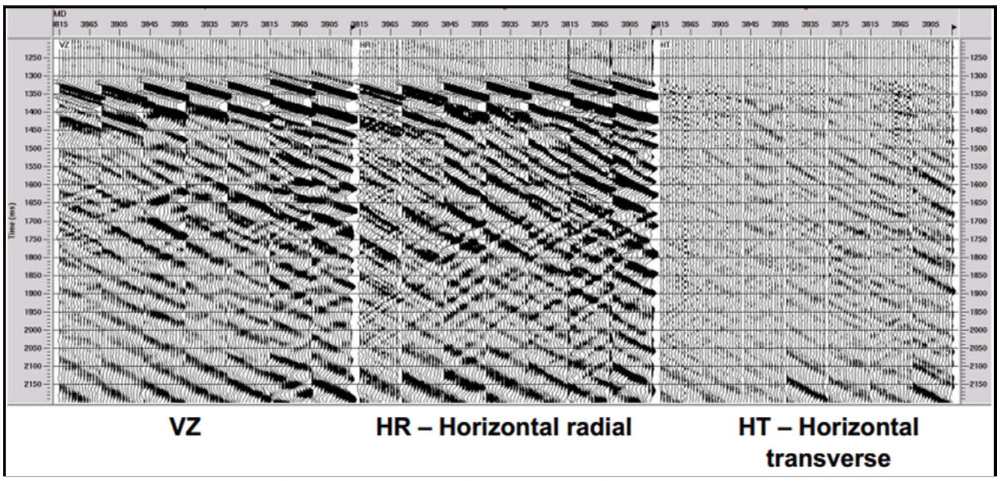

Figure 11. Example of VT and HT shot gather after 3-component rotations.

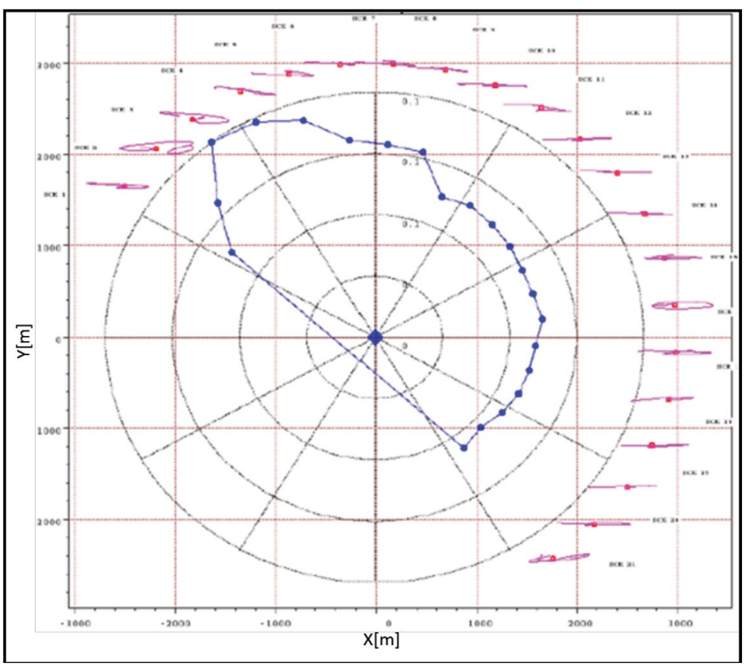

Figure 12. HT/VT amplitude ratio rose diagram and particle motion hodograms. MD 4010 m.

component (HR), with the other horizontal component, transverse (HT), oriented 90° from the radial. A vertical rotation is then applied in the vertical-radial components. These rotations help to isolate the compressional and shear wave-modes onto different components to help in wavefield separation (Figure 11).

The HT/VT RMS amplitude ratio was computed over a time window of 35 ms before and 35 ms after aligning the data on the S-wave event pick correspondent to Lajas formation conversion. Figure 12 shows the particle motion hodograms together with the polar amplitude ratio.

Although the VT-HT particle motion hodograms and polar amplitude ratio show birefringence behavior in the NW area of the rose diagram (Figure 12), is not clear a maximum and minimum birefringence behavior in the rest of the rose diagram, which correlates with the high linear particle motion of hodograms. These evidences support the hypothesis that the azimuthal anisotropy is weak in the depth range covered by receiver array; consequently, the presence of natural fractures between the base of the Lajas formation and the Punta Rosada formation would be weak.

CONCLUSIONS

A WAW and WAR VSP was acquired in Rio Neuquén field in a tight gas sandstone reservoir. The main objectives were to determine Thomsen parameters, reduce the uncertainties about the presence of natural fractures and integrate the results into a workflow that included high fold 3D surface seismic, walkaway VSP, microseismic monitoring, and well log data. The final aim of implementing this workflow was to calibrate the 3D geomechanical model to improve hydraulic fracture characterization and field development plan.

A VTI symmetry means that the two axes perpendicular to the vertical have the same Thomsen parameters. The WAW analysis tested this hypothesis to determine whether or not line 1 and line 2 have same anisotropy parameters ε and δ. It was found that δ Parameter is the same for both lines. However, the ε parameter was found to differ by 6% between both directions. Although this difference is weak, it is important to consider a 3D VTI (ε, δ, γ) situation in seismic migration and microseismic event location. Determination of γ requires another analysis. This downhole multicomponent study provides the most accurate determination of the Thomsen parameters that that contribute to the construction of the stiffness tensor.

Weak shear conversion evidence was found in the HT component. HT/VT ratios show azimuthal variation behavior in locations at northwest quadrant. The VT-HT hodograms of the same S-wave events for the same geophones do not show significant variations in the linearity of hodograms; instead, the hodograms show linearity motion in the VT direction. It was concluded that, under this methodology, the non-linear motion found is considered weak.

RECOMMENDATIONS

It is recommended to perform a full elastic VTI/orthorrombic numerical inversion.
It is recommended to perform the WAR acquisition in the full azimuth (360°) if possible.

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