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A PWave Anisotropy Study for an Unconventional Play - Fracture Network Estimation in Vaca Muerta Fm, Argentina

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Summary

The main objective of the paper is to show the results from an AVAz seismic study and the way it impacts the reservoir characterization and drilling strategy for an unconventional shale oil play in Vaca Muerta Fm, Neuquen Basin, Argentina, which holds the second largest shale gas resources and the fourth largest resources of shale oil worldwide (US Department of Administration of Energy, Kuuskraa et. al., 2013). For is the first time in YPF, the Argentinean national company, an AVAz seismic attributes is generated in order to improve the characterization of this type of unconventional plays. From the interpretation it can be said that here is a very good correlation between the stress field estimated using well log data and azimuthal seismic pre stack data. After a careful parameterization of the processing sequence, pre stack anisotropic inversion delivered enough data to corroborate de geological model and formulate a better exploration well completion scheme.The well drilled following this interpretation strategy led to a better productivity in the field.

Introduction

Since 2010, the exploration activity in the Vaca Muerta Formation, a shale-oil/shale-gas play at Neuquén Basin, Argentina, has increased rapidly from a couple of wells since then, up to more than 100 wells in 2016. Due to the increase in drilling activity, it was necessary to launch a technically-driven characterization program in order to gather all geoscientist disciplines and available information and achieve the best scenario for exploration and appraisal well positioning. These disciplines include geology (well log and core data acquisition and interpretation), geophysics (seismic data reprocessing, micro seismic acquisition), petrophysics, geomechanics and geochemistry. Typically for these types of plays, a conductive pathway is artificially generated by hydraulic stimulation between the reservoir and the wellbore, where a large amount of water is injected in the formation at high pressure in order to break the rock inducing fractures and therefore creating an artificial fluid connectivity network. The *"three-dimensional spreading"* of such fractures depends on many properties such as rock petrophysics, formation overpressure, pre-existing natural fractures and mechanical parameters. The anisotropic behavior of P and S waves can lead to a better understanding of natural fracture and stress field distribution and therefore to a better planning of the completion strategy in shale oil/shale gas reservoirs. In this paper, for the first time in the Vaca Muerta Fm., pre stack seismic data is analyzed in the P-wave azimuthal domain in order to estimate fracture density and orientation.

The seismic results coming from this analysis corroborated the regional stress field and fracture orientation locally estimated using well log data. The seismic interpretation based on AVAz attributes also added information for de-risking future landing zones.

Method and/or Theory

Based on the analysis contained on angle-dependent reflection amplitudes and transmission coefficients, it is possible to obtain information about the rock properties on both sides of an interface in a media (Castagna et.al., 1993). Consequently, the interpretation of the pre-stack gathers amplitudes as a function of incident angle (offset), mostly known as AVO analysis, is usually used to assist the reservoir characterization workflows. A medium is called anisotropic with respect to a certain parameter if this parameter changes with the direction of measurement (Tsvankin, 2001). When this variation is with the azimuth, the media behaves with Horizontal Transverse Isotropy (HTI). If the variations develop in the vertical direction, the media has Vertical Transverse Isotropy. So in case of anisotropic media, amplitudes not only vary with incident angle, but also with azimuth. The interpretation of such amplitudes is frequently called AVAz (Amplitude Variation with Azimuth).

Even for the isotropic case, stating the exact equations of the reflection coefficients as a function of incident angle are difficult to express in a simplistic way. The exact expressions of the reflection coefficients for an anisotropic media (either VTI or HTI) are not easy to follow and they are neither often used in seismic processing. Instead, there are approximations for the amplitude variation with angle of incidence and azimuth that can be applied assuming weak-anisotropy (Rüger, 2002). Rearranging the equations given by Jenner (2002), the P-wave reflectivity as a function of incidence angle and azimuth for an HTI layer overlain by an isotropic overburden can be written as:

$$R_{PP}(\theta,\phi) = A + \left[B_{ISO} + B_{ANI}\cos^2(\phi-\beta)\right]\sin^2\theta \qquad (1),$$

where A and B_{ISO} are the isotropic intercept and gradient respectively, and B_{ANI} the anisotropic gradient along the fracture orientation, according to Grechka and Tsvankin (1998).

For the first time in the company and in this type of unconventional play, AVAz inversion was performed, for each depth sample by fitting surfaces based on Equation 1 to the full azimuth 3D migrated gather in order to estimate either R_{pp}, A, B_{ISO}, B_{ANI} and β. Due to the periodicity of squared sine and cosine, the two solutions (A, B_{ISO}, B_2, β) and (A, B_{ISO}, B_2, β-$\pi/2$) are totally equivalent. The solution usually taken as valid is frequently the closer one to the background value which is defined based on geological data and stress field orientation.

Study Area and Geological Settings

The area of interest is located within a structural low on the northern flank of what is known as "Bajo de Añelo" low, with a subtle increase in slope towards the east-northeast direction (Zunino et al 2014). The zone of this study is placed within the Neuquén embayment, close to the paleo platform limit (Figure 1a). In this area, the thickness of the shale section consists of more than 350 m of marls with a variable content of carbonate/quartz and a low percentage of clays minerals (5 – 19%). The TOC average in the upper section of the unit is 3.5% and in the lower section is among 6%. Porosity ranges from 6 to 11% in the whole section. The maturity is close to 1% of vitrinite reflectance (Ro), so the play is *shale – oil*. Total thickness of the sedimentary Jurassic- Cretaceous column is around 6000 meters (Figure 1c).

The Vaca Muerta Fm. is widely distributed over an area of 120,000 Km^2 of the Neuquén Basin (Leanza et. al. 1977) and it was deposited during the upper Jurassic to early Cretaceous (Middle Tithonian - Lower Berrasian), in a semi restricted basin connected with the Pacific Ocean. The sequences were originated in a mix clastic and carbonatic system. The lithology is mainly silicoclastic to calcareous mudstones interbeded with claystones and siltstones with variable content of carbonates (Figure 1b). At basin scale the unit has very variable thickness from less than 30 m in most proximal areas to over 1,200 m in the most distal settings. This is the main source rock of the Neuquén Basin, having generated more than 75% of the discovered hidrocarbons in the basin (Uliana et. al. 1999), with excellent geochemical attributes in terms of TOC. The maturity goes from less than 0.5% Ro toward the east, north and south (basin edges) to 2.5% Ro in the inner part of the Basin. The kerogene is Type II, marine, with a large amount of amorphous material. Due to the HC generation the unit in some places is overpressured. The average porosity goes from 6% to 12% and in terms of mineralogy content, the unit is mainly composed by quartz and carbonates with variable proportions of clays minerals (between 5% and 30%).

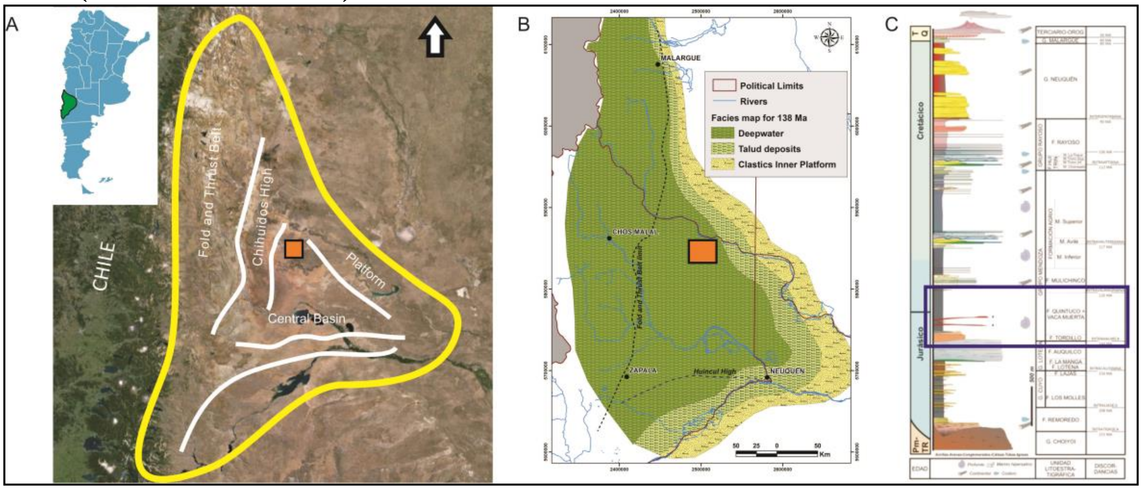

Figure 1 *A) Neuquén Basin, including the regional limits and morphostructural elements. B) Vaca Muerta Fm. facies map for the mid to late Jurassic, after Legarreta and Uliana (1991), in orange, the zona of interest. C) Neuquén basin stratigraphic column and Vaca Muerta Fm. highlighted in blue.*

AVAz Resutls and Interpertation

3D Seismic data was carefully reprocessed in the depth domain (PSDM) and horizon markers were re interpreted. A seismic-to-well calibration is shown in Figure 2 where the top and base of Vaca Muerta Fm. is easily identified and tracked along the whole 3D survey.

Two main volumes are generated after a AVAz processing, namely fracture density (based on the B_{ANI}/B_{ISO} ratio) and orientation. These two volumes are jointly interpreted together with any well log data in order to obtain a well-consistent 3D characterization of the fracture field along the main reservoir target (Vaca Muerta Fm.).

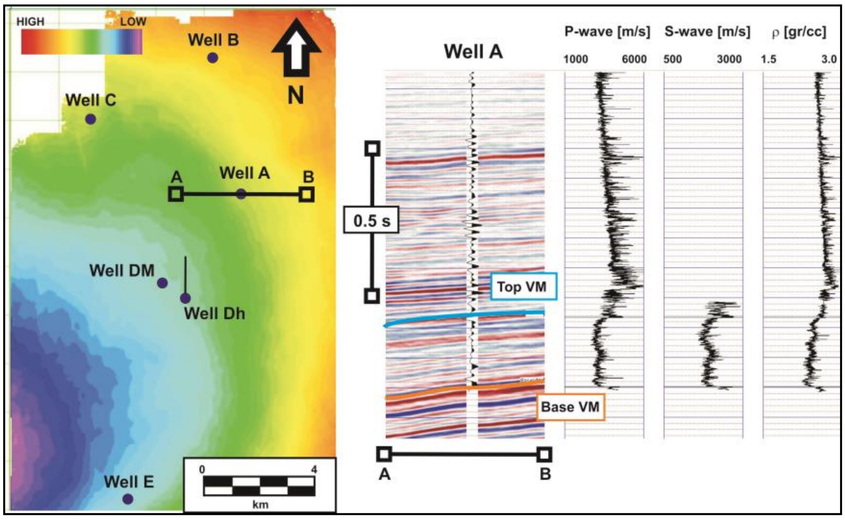

Figure 2 *Left, base of Vaca Muerta time structural map, note that the horizon does not have a structural closure as it is a source rock that has been proved as a shale reservoir. On the right, a well-to-seismic tie, shown the continuity of the seismic events (top and base of Vaca Muerta). Wells A though E were used for PSDM velocity model calibration. Well Dh is the first horizontal well drilled in the North-South direction in the area with target exclusively on Vaca Muerta Fm. Well DM is a vertical well used to monitor microseismic events from the stimulation program on well Dh.*

Figure 3a shows the average of the fracture density and azimuth taken in a window based on an interpreted horizon near the mid of Vaca Muerta Fm. In colour the fracture density ranges from low (hot colours) to high (cold colours) whereas the azimuth is drawn as sticks where the size of the stick is also proportional to the fracture density. Note that in most of the cases the fracture density is relatively low and follows an east-west trend. This trend was verified against the regional structural stress. Figure 3b shows an estimation of fracture density orientation and density estimated from exploratory Well A image logs. Both, the estimation from well log and the ones using the seismic data are coincident.

The AVAz seismic data was also used in order to verify the geological model. During the exploration appraisal, well Dh was drilled following a new exploration strategy with main target on this unconventional play and well DM was also drilled as monitor well for a microseismic program. The intention of this new strategy was to optimise the penetrated section, considering the best mechanical properties identified in the area using both AVAz seismic interpretation and previous drilled well log data, i.e.: low fracture density and well path perpendicular to the main stress field orientation. The well was supposed to be drilled in a down deep structural position within Vaca Muerta Fm. in a high angle fashion. According to Figure 3c, the fracture density and orientation estimated in well DM was in agreement to what was expected from the AVAz study. Figure 3d shows the productivity of the horizontal well being higher than the vertical well since a dendritic fracture spreading configuration was achieved due to higher stimulated rock volume (SRV) according to microseismic, and low natural fractures density could play a fundamental role in the hydraulic fracs effectiveness. It must be mentioned that stimulation strategy was changed in the horizontal well (regarding the previous vertical) in order to get more complex hydraulic fracs and diminishing their conductivity to improve efficiently the SRV. This really shows the importance of incorporating multi-scale data into a characterization workflow for this kind of (unconvencional) plays.

Conclusions

This is the first time in the company that an AVAz seismic attributes is generated in order to improve the characterization of a shale-oil unconventional play in Vaca Muerta Fm., Neuquén basin, Argentina.

There is a very good correlation between the stress field estimated using well log data and azimuthal seismic pre stack data.

After a careful parameterization of the processing sequence, pre stack anisotropic inversion delivered enough data to corroborate de geological model and formulate a better exploration well completion scheme.

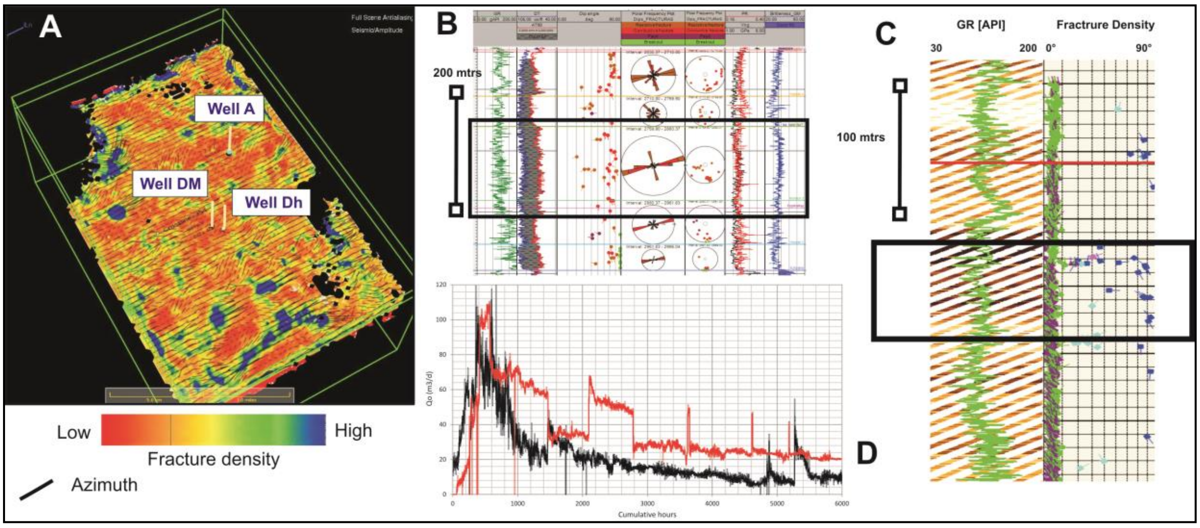

Figure 3 *A) time structural map, corresponding to the mid of Vaca Muerta Fm., coloured based on the average of the fracture density taken in a symmetric time window, black sticks indicates fracture orientation. B) shows exploration well A and all the suite of geomechanical logs. C), well logs from monitor well DM. The black box highlights the upper mid of Vaca Muerta Fm. where a higher density of natural fracs were interpreted (the well landed bellow it). The first track shows GR and resistivity image log and the second, the low angle dipping beds and low density vertical fracs but a higher density of low angle fracs (highlighted) above the navigated zone. Both tracks show coherence with the AVAz indicators. D), oil production from vertical well A (black curve, 6 hydraulic fracs) and horizontal well (red curve, eight hydraulic fracs). It can be clearly seen that well productivity tends to be higher with the same choke management but different completion program.*

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