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# ESTIMATING TRANSVERSE ANISOTROPY USING A WALKAWAY AND WALKAROUND VSP AS WELL AS SURFACE MICROSEISMIC IN THE VACA MUERTA FORMATION

**David Curia[1], Luisely Linares[2], Martin Paris[2], Eduardo Corti[3]**

1: Wintershall, david.curia@wintershall.com

2: BHGE, luisely.linares@bhge.com, martin.paris@bhge.com

3: Geofísico consultor, eduardo_corti@hotmail.com

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## ABSTRACT

Estimación de Anisotropía Transversal Usando VSP Walkaway y Walkaround, así como Microsísmica de Superficie en la Formación Vaca MuertaLa caracterización de la anisotropía en la formación Vaca Muerta (VM) en la provincia de Neuquén, Argentina, se realizó a partir de la adquisición de dos tipos de levantamientos de perfiles sísmicos verticales (VSP), un walkaround y un walkaway multi-acimut. Con los tiempos de propagación de la onda de corte (onda S) y el radio de amplitud entre las componentes transversal y radial obtenidas del walkaround, fue posible determinar la dirección de las fracturas naturales y deducir la dirección del esfuerzo horizontal máximo.

Los resultados obtenidos con los VSP concuerdan con la dirección predominante de los eventos microsismicos detectados, mecanismos focales y el acimut del esfuerzo horizontal máximo obtenido independientemente del análisis de imágenesen el mismo pozo.

La caracterización de la anisotropía sísmica se realizó para optimizar el desarrollo del reservorio no convencional Vaca Muerta. Los parámetros de anisotropía obtenidos se utilizaron como datos de entrada para el modelo geomecánico 3D y proporcionaron información adicional a la interpretación microsísmica, así como también, mejoras en la definición del espaciamiento entre pozos, orientación y diseño del fracturamiento hidráulico.

## INTRODUCTION

Consideration of anisotropy of rocks has become a more common oilfield reservoir characterization practice today, particularly in unconventional reservoirs,where permeabilities are low and some type of additional stimulation is required to allow for economic production (Warpinski *et al.* 2009).

To obtain optimal fracking, it is necessary to understand the natural fracture network and the geomechanical stress system. Early analysis of whether natural fractures are present and in what form, orientation, and distribution is vital to understanding later production.In particular, for low permeability reservoirs, the key is how these fractures are likely to react to stimulation and possible interactions with any fractures created by the hydraulic stimulation treatment (Bishop 2015).

In Vaca Muerta, as in general for all unconventional reservoirs, improved production rates are achieved by hydraulic fracturing, therefore, the ability to characterize fracture systems improves the performance of hydraulic fractures and is critical for production optimization.

In this study, seismic attributes, such as anisotropy, for natural fracture characterization or direction of maximum horizontal stress are evaluated. A Walkaround and Walkaway VSP were acquired to measure the seismic anisotropy andhow it relates to hydraulic fracture information from microseismic monitoring and borehole imaging.

## GEOLOGY

The study area is located in the central part of the Neuquén basin, 140 km to the NNW of the city of Neuquén, near the town of Añelo (Figure 1). The study area does not have a high degree of structural complexity, although it is adjacent to normal and strike-slip fault systems. These tectonics affect various stratigraphic levels.

The Fm. Vaca Muerta is composed of marls and calcareous clays of deep marine origin with anoxic character of Tithonian age - Lower Valanginian (Jurassic sup-Cretaceous inf), and it was

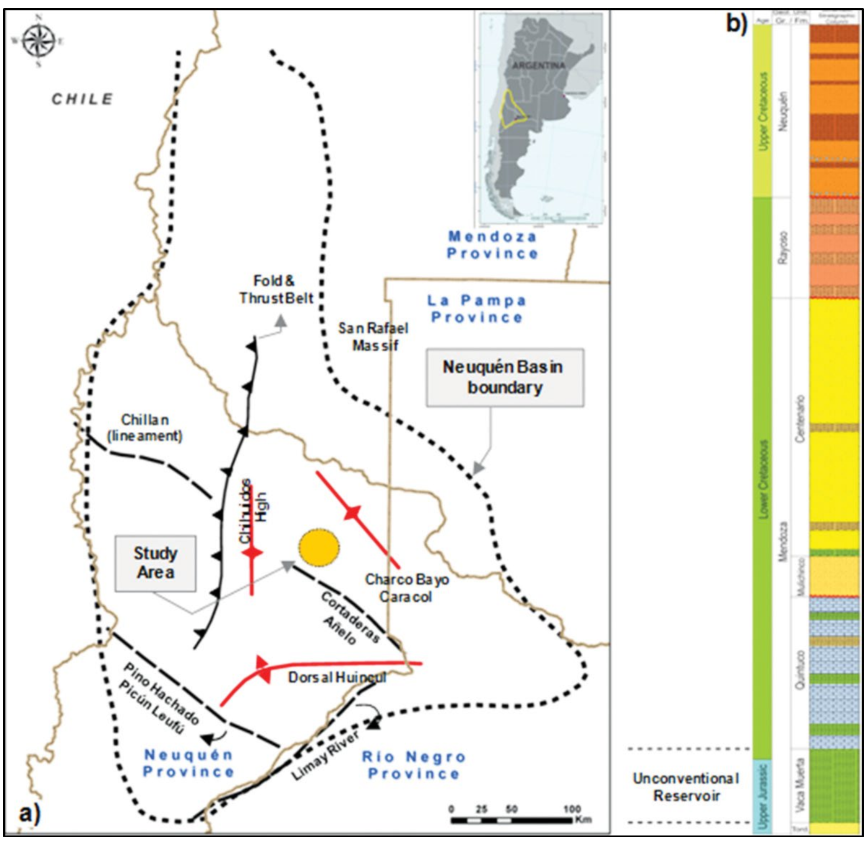


Figure 1. a) Main geological structural framework in the surrounding study area b) Schematic stratigraphic column. Taken from Curia, D. *et al.* 2016

deposited during a major marine transgression (Leanza 1973).

The paleogeography of the basin corresponds to a restricted marine basin where the entry of the sea would have occurred from the west-northwest. It is inferred that the bathymetry has not exceeded 250 m depth (Mitchum *et al.* 1985) with fossils associated with temperate waters (Leanza *et al.* 2001). The basal 30 meters of the formation, in general, is consists of marls with abundant organic matter, deposited in a reducing environment that allowed for its preservation.

The Tithonian transgression resulted inan environment with abundant organic matter. This level is known as "Hot Shale" or "kitchen", where most of the hydrocarbon produced in the Neuquén basin was generated.

The complete sedimentary cycle (Figure 2) regional transgressive and regressive cycle, consisting of the Vaca Muerta and Quintuco formations. This cycle is underlain by the eolian deposits of the Tordillo formation and underlies the shallow marine deposits of the Mulichinco formation (Mitchum and Uliana 1985, Legarreta and Gulisano 1989).

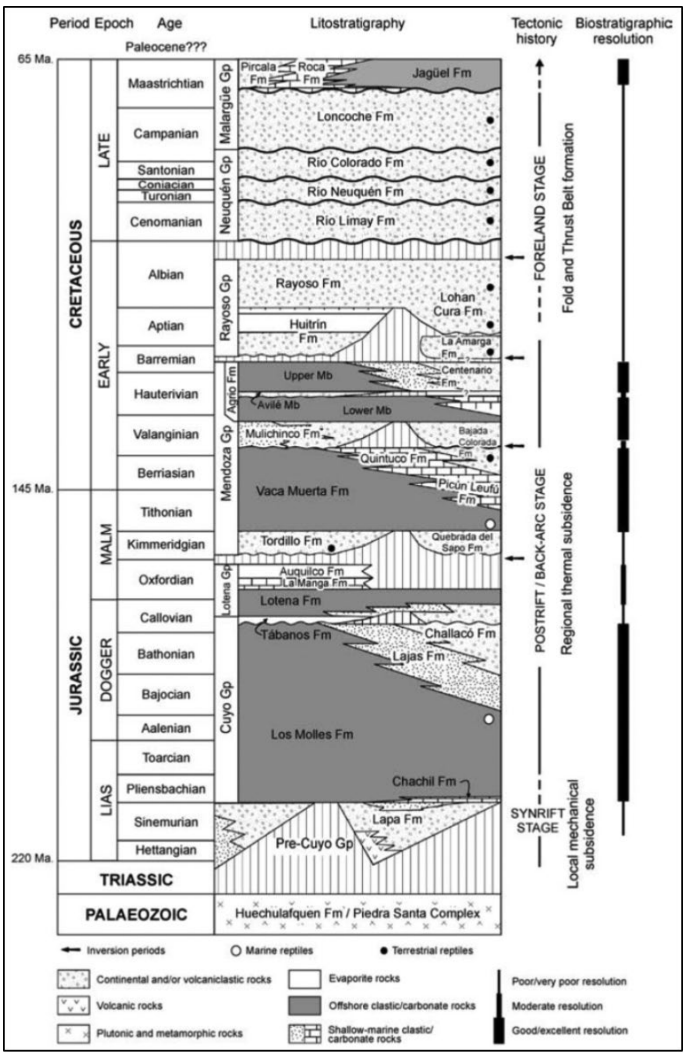


Figure 2. Stratigraphic column. Taken from Paris, M. *et al.*, 2014

## SEISMIC ANISOTROPY

Azimuthal anisotropy can be induced by various physical mechanisms, such as aligned fracture systems or depositional fabrics. These systems can be critically important to the successful exploitation of hydrocarbon reservoirs since they may control or impact the fluid flow. It is therefore of benefitto measure anisotropy. This can be achieved using various VSP geometries. (Horne 2000).

Shear wave anisotropy is often estimated by measuring shear wave splitting(Alford 1986; Crampin 1985) in VSP data(Figure 3). The elastic constants of anisotropic rocks control the polarizations and the velocities of the S waves. For a given direction of propagation in a homogeneous, anisotropic rock, the elastic constants generally allow two S waves to travel at different velocities with roughly orthogonal polarizations. This difference in velocity of differently polarized S waves is called S-wave birefringence or S-wave splitting. In simple cases, the polarization of the faster S-wave in birefringent rock lies along the direction of maximum horizontal stress or dominant fracture strike (Winterstein y Meadows 1995).

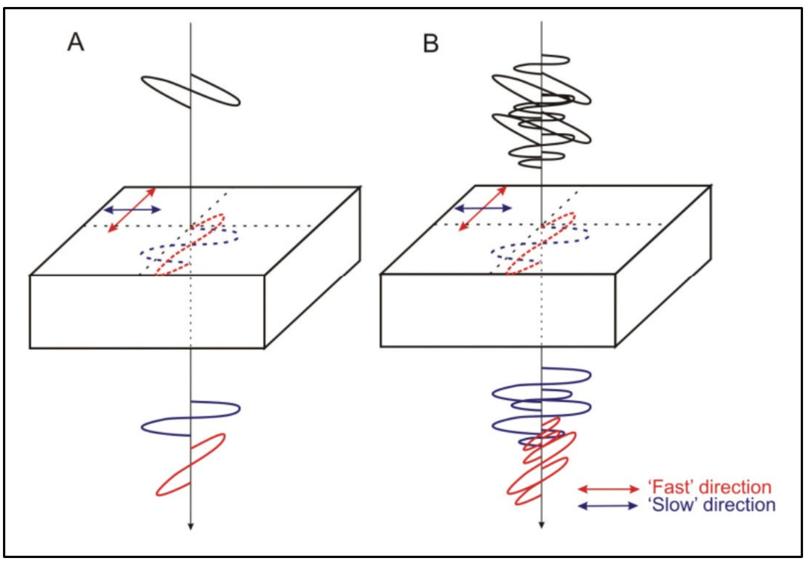


Figure 3. Shear wave splitting due to propagation through azimuthally anisotropic media phenomena (Winterstein y Meadows 1995).

The method described by Horne (2000) was applied to determine azimuthal anisotropy directions through an examination of energy or amplitudes recorded in the radial and transverse components and the analysis of the time delay between fast and slow shear waves with the azimuth on the VSP data. The purpose of the analysis was to correlate birefringence effects with formation properties, such as direction of maximum horizontal stress.

## VSP DESIGN AND ACQUISITION

The survey (Figure 4) was designed to detect and define the VTI and the HTI anisotropy in the Vaca Muerta formation (VM), while the zero offset VSP provides the vertical velocity (Vz) necessary to define the anisotropy parameters. The full survey was designedas:

- A walkaround VSP with 16 source locations every 12°, from 45°N to 239°N, covering 194° to detect HTI anisotropy. Source offset must produce incidence angles >30°to generate shear waves while avoiding refracted paths. Locations were altered from the original planning because of bad weather conditions.
- Three walkaway VSPs, in three directions separated by 60° (at 20°N, 80°N and 140°N) to detect VTI anisotropy and verify the HTI optimally measured by the walkaround. The walkaway source positions must follow the same requirements for the angles of incidence.
- Source type: Mertz 60.000lb Vibroseis, Sweep Length: 12sec, upsweep: 8 to 90Hz, Taper: 300msec.
- Tool type: 18 levels Maxiwave, 20m interval between tools.

## VSP DATA PROCESSING

The processing of the walkaround and walkaway VSP was tailored to extract reliable first arrival times from the direct P-wave and times and amplitudes from converted P to S waves. All these attributes must be measurable and interpretable as a function of azimuth to relate any noticeable variation to an azimuthal anisotropic model.

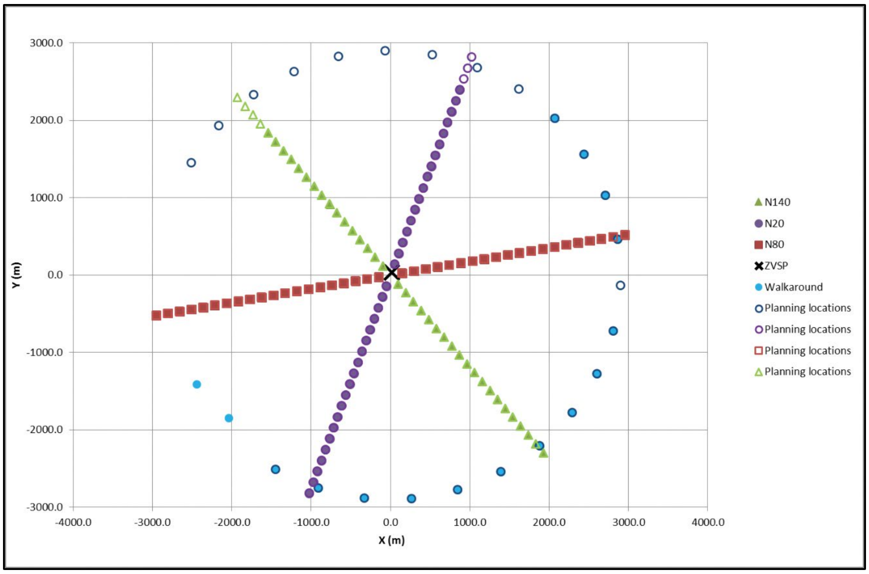


Figure 4. Walkaround and walkaway VSP geometry.

The processing strategy was separated into three distinct steps. Unless the true horizontal axis angle was physically measured using a gyro tool at the time the data was recorded, the orientation of the horizontal axes must be estimated at each receiver position. The first step aims to re-orientate the two horizontal components of the VSP tools towards north and east respectively to relate seismic attributes with a known azimuth.

The second step of the processing separates the four wavefields, downgoing P and S and upgoing P and S, while carefully preserving the azimuthal variation of the recorded amplitude. A series of median filters, fan filter in the F-K domain and model-based rotation were used to estimate each wavefield.

The third step includes analyzing the walkaway VSP direct arrivals to generate Thomsen anisotropy parameters. A travel-time optimization and generalized inversion approach was used to obtain the Thomsen parameters using the measured zero offset VSP vertical interval velocities and the direct arrival times of each walkaway VSP line.

The generated VTI models highlighted higher values of the Thomsen parameter Epsilon above the Vaca Muerta Formation, 11% against 8%, along the azimuths N80° and N140° than along N20°.

The analysis of the shear wave splitting on the walkaround VSP indicatesa maximum stress direction (or fracture direction) from variations in amplitude and apparent velocity. In a flat subsurface, vertically fractured system, the Transverse/Radial (T/R) amplitude ratio should have values, close to 1, at 45° from the fracture strike and normal directions. Low values, close to 0, shouldbe observed along the fracture strike and normal directions, because no shear-wave splitting occurs along these azimuths.

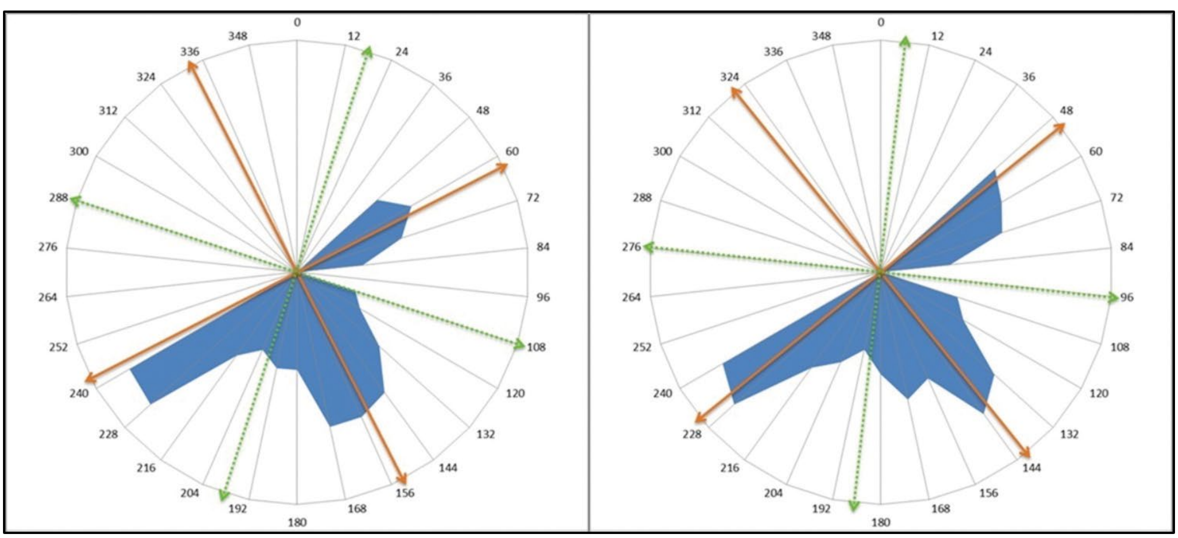


**Figure 5. Rose diagrams of the shear-wave conversion. The plot shows the T/R amplitude ratio above Vaca Muerta (left plot) and within the Vaca Muerta formation (right plot). The orange arrows show the maximum ratio and the green line shows the minimum ratio**

Figure 5 shows the average transverse-to-radial RMS amplitude ratio for the 6 geophones above Vaca Muerta and for the18 geophones positioned within the fractured reservoir as a function of shot azimuth. A possible fracture orientation is therefore detected around N96° or N186° in Vaca Muerta.

The walkaround VSP attributes, shear-wave apparent velocity (or time propagation along the tool array, Figure 6) show that the S-waves travel faster around approximately N100°, indicating that the predominant fracture direction is N96°.

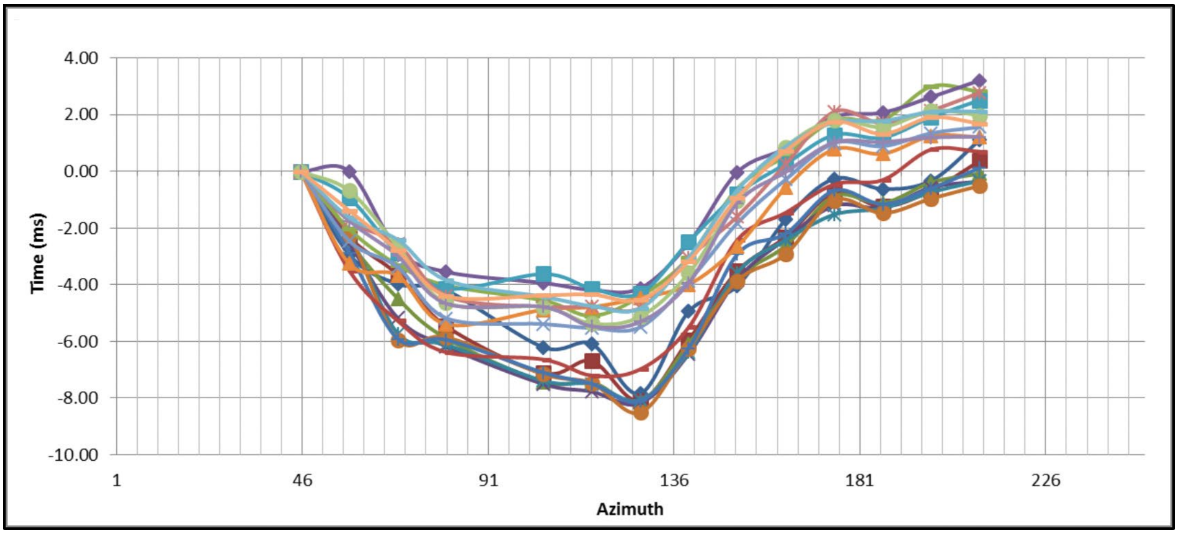


Figure 6. Difference in downgoing S time as a function of the source azimuth.

Upgoing shear waves were also analyzed using the same methodology. Unfortunately, regional dip complicated the interpretation of the azimuthal variations.

## MICROSEISMIC AND BOREHOLE IMAGE LOG ANALYSIS

Surface microseismic monitoring of hydraulic treatments was part of completion operations in the study area. The microseismic data provide information to understand the fracture network created and stress distribution that can be correlated with the VSP results.

The completion of well A was monitored with a surface geophone array consisting of 10 lines, approximately 3 km long and of 214 channels each, placed symmetrically around the well surface location (Fig 7). The hydraulic fracture consisted of 4 stages using differing numbers of perforation shots per stage, penetrating the Upper, Middle, and Lower Vaca Muerta. Hydraulic fractures will usually propagate in the direction of current maximum horizontal stress (Higgins 2006).

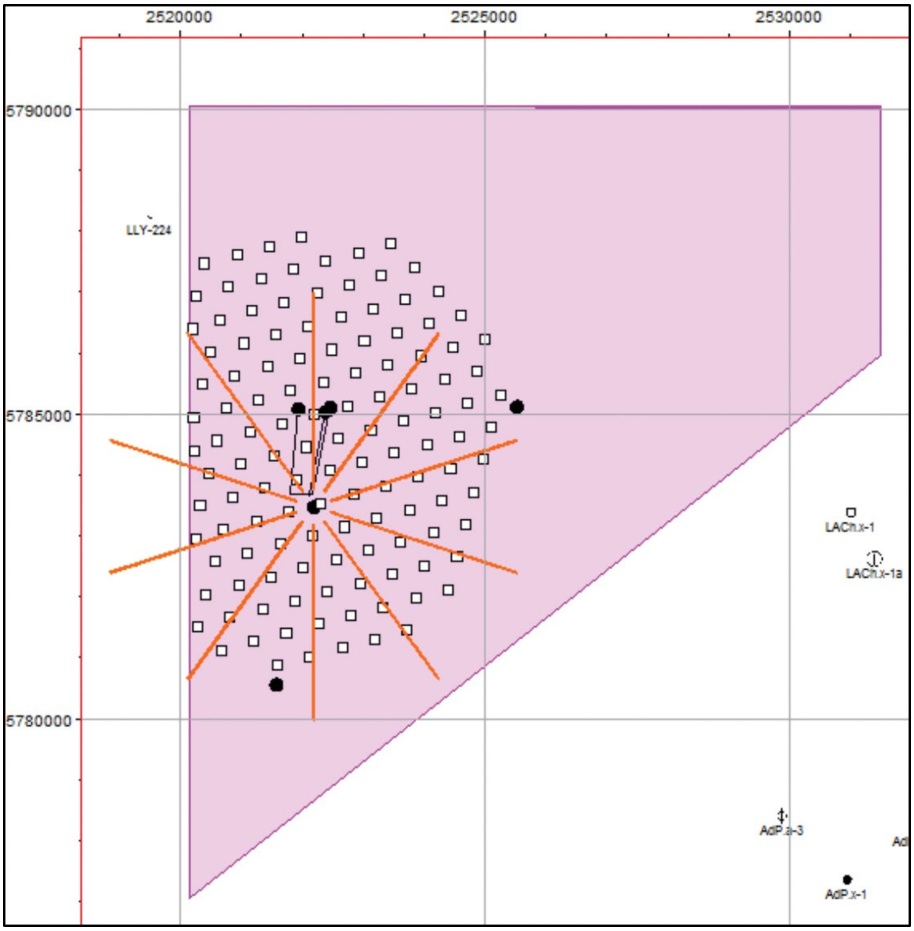


Figure 7. Location map of the stimulated wells and monitoring arrays in the Aguada Federal block. Surface and microseismic buried array locations are shown as orange lines and white squares, respectively. The vertical A well is located at the indicated red circle.

Stage 4 contained 97% of all detected eventsand Figure 8 represents the geographic azimuth of the fractures using data from all stagesandoccurs around ~N108E. The stereographic moment tensor (SMT) plot of the poles of the best-fitting fault planes for 43 events of high confidence is shown on Figure 9. Most events appear to be dip-slip in type with a vertical nodal plane in the N30°E direction and another nodal plane closer to horizontal (Figure 8, right). Although the first interpretation is often taken to be more reliable, in this dataset, the second interpretation appears to have a better match with the direction of extension of the microseismic cloud and the directions of maximum stress.

Stress determination published by Bishop 2015 shows the maximum horizontal stress direction from drilling induced fractures is approximately E-W (Fig 10). The induced fractures are observed in the middle to upper Vaca Muerta and are completely absent from the lower

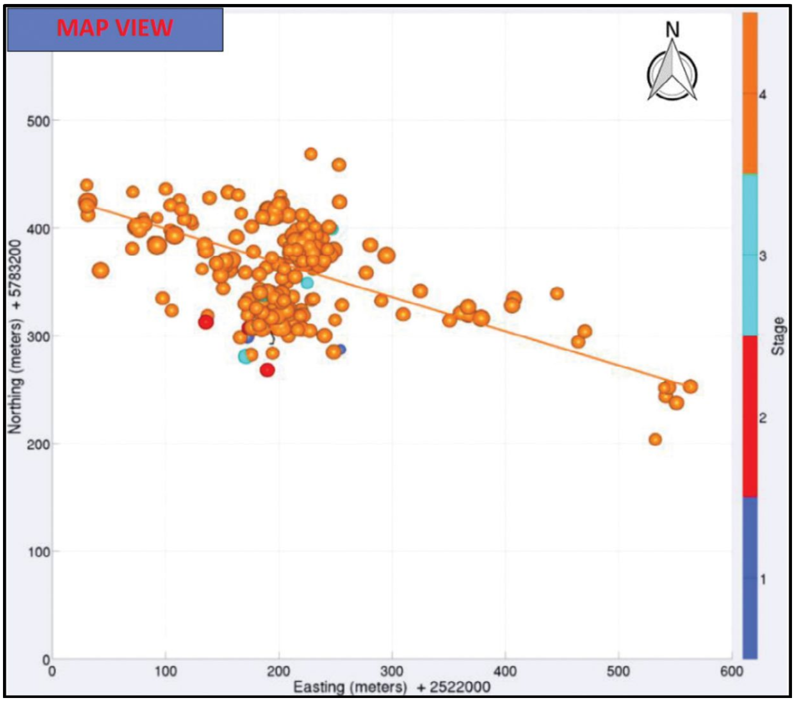


Figure 8. Map View of all events located. The orange line represents the mean geographical azimuth of N108E

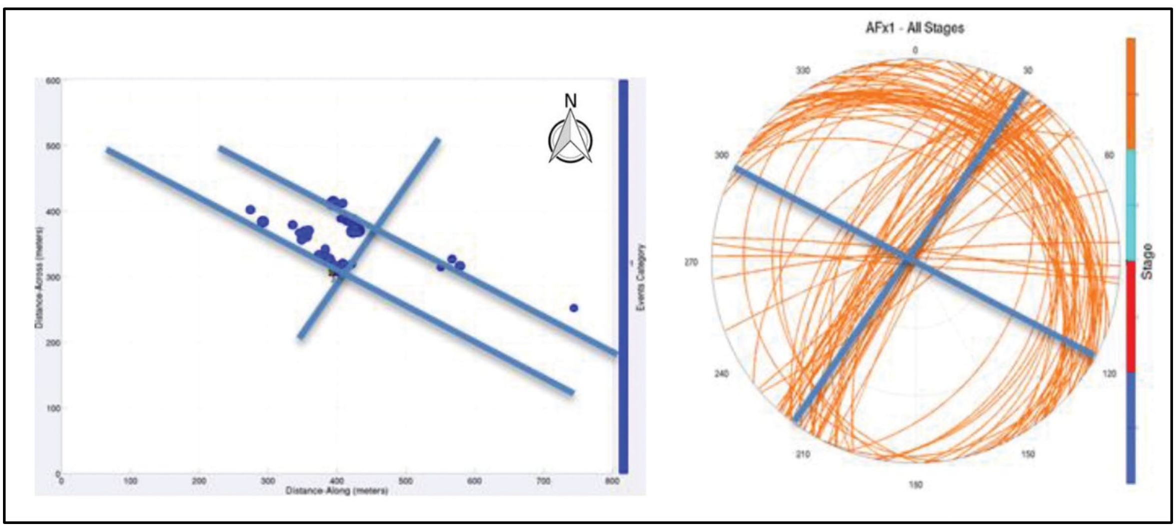


Figure 9. Left: map view of high confidence events, Right: SMT of high confidence events, The blue lines highlight the average planes for each focal plane solution.

intervals of the image. In contrast, borehole breakout is uniquely observed in the Quintuco. The borehole breakout orientation corresponds to a minimum horizontal stress oriented N20-200°. Comparing these orientations to VSP results in the area corroborates that these values are in line.

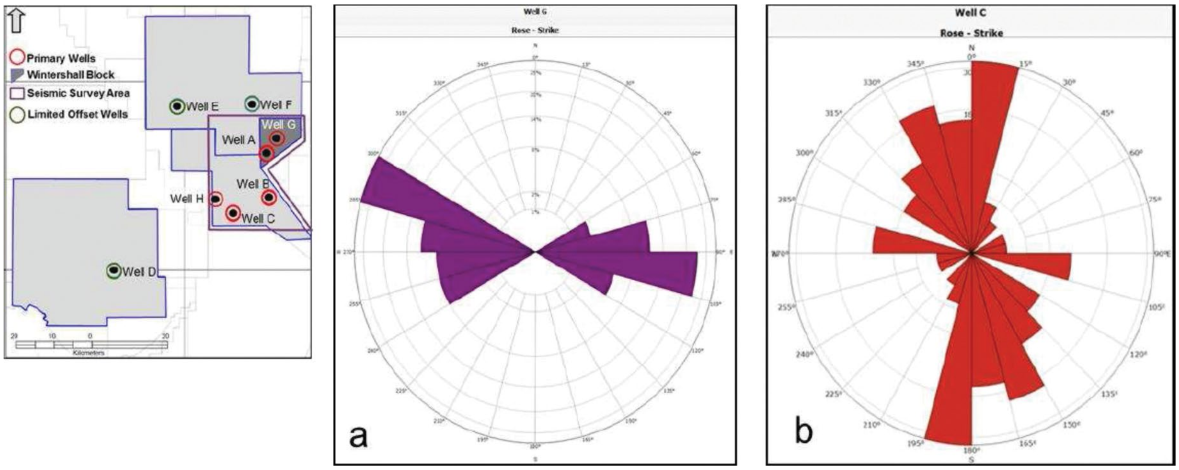


Figure 10. Wellbore Failure results indicating the principal stress orientations: a) Induced fractures from Well G indicate a maximum horizontal stress oriented approximately E-W, b) Borehole breakout seen in Well C indicating a minimum horizontal stress oriented approximately N-S (Bishop 2015).

The following table summarizes the directions of maximum horizontal stress with different technologies. Although the methods and resolution are different between them the results are very consistent.

| | Vaca Muerta Fm |
|---|---|
| VSP | 96° |
| Microseismic (mean azimuth events) | 108° |
| Microsismica (HQ focal mechanism) | 94° |
| Borehole Image Logs | 95°-100° |

Table 1. Stress in situ determined for the study area.

## CONCLUSIONS

To characterize the seismic anisotropy in the central Neuquén basin at Vaca Muerta, a set of VSPs was designed, acquired and processed. The walkaround VSP data was analyzed in terms of systematic azimuthal variations of seismic attributes using amplitude and apparent velocity. From the analysis, the maximum and minimum stress direction was inferred.

The microseismic monitoring showedthat hydraulic fracture propagation follows the orientation of natural fractures as well as maximum horizontal stress and the induced fractures identifiedfrom borehole images also indicate a maximum horizontal stress oriented approximately E-W.

The characterization of seismic anisotropy was conducted to optimize the development of the unconventional play in VM. The anisotropy parameters obtained with this VSP survey were used as input to the 3D geomechanical model and provided additional information to the microseismic interpretation as well as improvements to the well spacing estimation, orientation and hydraulic fracture design.

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