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Analysis of the horizontal stress field acting on Vaca Muerta Formation in the Neuquén Basin, Argentina

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ABSTRACT

This study isolates and analyzes the orientations of the maximum horizontal stress (SHmax) using borehole breakout data from the Vaca Muerta Formation from 30 wells across the basin. The results indicate a predominant SHmax orientation trending WSW-ENE to E-W, influenced by regional tectonic forces, including the convergence of the Nazca and South American plates and topographic axes orientation. However, deviations in SHmax orientations towards SW-NE and SE-NW suggest additional controls from basement structures, notably Triassic-Jurassic half-grabens. The integration of breakout analysis with geological models highlights the interplay of first-, second-, and third-order stress controls, which are crucial for optimizing hydraulic fracturing strategies in this prolific shale formation. Understanding these stress regimes enhances the efficiency and sustainability of resource extraction in the Vaca Muerta Formation.

Keywords: Breakout, maximum horizontal stress, stress controls, hydraulic fracturing

RESUMEN

Análisis del campo de esfuerzo horizontal que actúa sobre la Formación Vaca Muerta en la Cuenca Neuquina, Argentina.
La Formación Vaca Muerta, es un importante reservorio de hidrocarburos de la Cuenca Neuquina, Argentina, caracterizado por la acción de fuerzas geológicas y tectónicas complejas que influyen en el campo de esfuerzos horizontales. Este estudio aísla y analiza las orientaciones del esfuerzo horizontal máximo (SHmax) para la Formación Vaca Muerta, utilizando datos de *breakouts* de pozos de 30 perforaciones a lo largo de la cuenca. Los resultados indican una orientación predominante del SHmax con tendencia OSO-ENE a E-O, influenciada por fuerzas tectónicas regionales, como la orientación de la convergencia de las placas de Nazca y Sudamérica, y la dirección de los ejes topográficos. Sin embargo, se observan desviaciones en las orientaciones del SHmax hacia el SO-NE y SE-NO que sugieren controles adicionales dados por la presencia de estructuras del basamento, como los hemigrabenes del Triásico-Jurásico. La integración del análisis de *breakouts* con modelos geológicos resalta la interacción de controles sobre la dirección del esfuerzo de primer, segundo y tercer orden, que es crucial estudiar para optimizar las estrategias de fracturamiento hidráulico en esta prolífica formación. Comprender estos regímenes de esfuerzos mejora la eficiencia y sustentabilidad de la extracción de recursos en la Formación Vaca Muerta.

Palabras clave: *Breakout*, esfuerzo horizontal máximo, control del esfuerzo, fracturamiento hidráulico.

INTRODUCTION

The principal stress orientation through the Neuquén Basin Andean retroarc is primarily influenced by forces generated by the Nazca-South American plate collision, with an azimuth of approximately 80º. Previous research has determined the maximum horizontal stress orientation from breakout data, yielding a mean azimuth of 89º with a 95% confidence interval of ±13º, ranging from SSW-NNE to E-W, aligning with expected values (Guzmán et al. 2007, 2009). However, this orientation can also be interpreted as being influenced by topographic forces generated by the presence of the Andes Mountains (Heidbach et al. 2010).

The World Stress Map database, first released in 1992, revealed that the contemporary orientation of the maximum horizontal compressional stress is primarily aligned subparallel to the absolute plate motion in extensive regions (wave-length stress patterns >2000 km) of North America, Western Europe, and South America (Zoback et al. 1989, Gregersen 1992, Richardson 1992, Zoback 1992, Heidbach et al. 2010). This suggests that plate boundary forces, such as ridge push and slab pull, exert a first-order control on the intraplate stress pattern (Zoback et al. 1989, Richardson 1992, Zoback 1992, Heidbach et al. 2010). Recent studies further emphasize that second-order stress patterns with spatial wavelengths of ~500 km can result from lithospheric flexure and intraplate lateral density contrasts, such as continental rifting, isostatic compensation, topography, and deglaciation (Heidbach et al. 2018, Tingay et al. 2010). Third-order stress patterns on a 1-100 km scale can be generated by local density and strength contrasts, position of basal detachment, basin geometry, topography, and active faulting (Bell 1996, Müller et al. 1997, Tingay et al. 2005a,b, 2006, Heidbach et al. 2007, Ziegler et al. 2016).

In this research, the horizontal stress orientation for the Vaca Muerta Formation was isolated for each of the wells analyzed in previous studies (Guzmán et al. 2007). The objectives are to identify and understand the sources of variations in the maximum horizontal stress orientation within the Vaca Muerta Formation. This involved a comprehensive analysis of the stress controls, integrating breakout data with geological and geomechanical models to interpret the influence of different stress sources.

The Vaca Muerta Formation is lithologically associated with a Late Jurassic mixed shale that developed throughout the Neuquén Basin, located in northern Patagonia, Argentina. It consists of dark bituminous shale, marl, and limestone deposited due to a rapid and widespread Paleopacific early Tithonian to early Valanginian marine transgression in the Neuquén Basin, west-central Argentina (Legarreta and Uliana, 1991, 1996). This lithostratigraphic unit is widely distributed over an area of 120,000 km² (Leanza et al. 1977, Uliana et al. 1977) and is considered the most effective source interval in the Neuquén Basin (Mitchum and Uliana 1985, Uliana and Legarreta 1993, Cruz et al. 2002, Kietzmann et al. 2014). It has a variable thickness ranging from 11 to 1250 meters.

The Vaca Muerta Formation has some of the best characteristics for shale-gas/oil systems, with high average total organic carbon (TOC) levels (>4.0%), moderate depth (~2400 m), and over-pressured conditions (Boyer et al. 2011, Giusiano et al. 2011). It is one of the largest potential areas for unconventional developments and is considered to have some of the greatest potential for hydrocarbon production in the world. Studies have ranked the Vaca Muerta Formation as third globally in technically recoverable gas and fourth in oil. This formation stands out due to its high pore pressure, complex stacking pattern of varying lithologies, and geomechanical complexity arising from the proximity of the Neuquén Basin to the Andes Mountains (Badessich et al. 2016). Due to its wide areal distribution, variable thickness, and overburden, Vaca Muerta Formation has produced all kinds of hydrocarbons.

Most wells have required massive hydraulic fractures to achieve commercial rates, maximize production, and reduce the development cycle of the play. Abnormally high fracture gradients have been found in some parts of the basin, significantly impacting completion strategies (Badessich et al. 2016). It is known that there are variations in fracture orientations. Understanding the Vaca Muerta Formation's geomechanics is crucial for proper field development and achieving the best results in hydraulic fracturing. This paper analyzes the impact of first, second, and third-order controls on the stress pattern obtained.

The specific objectives of this research include:

• Stress Orientation: Determine the horizontal stress orientation for individual wells in the Vaca Muerta Formation.

• Identifying Stress Sources: To identify and differentiate between the first, second, and third-order stress controls affecting the region.

• Optimizing Fracturing Strategies: To understand how variations in the stress field influence hydraulic fracturing and to provide recommendations for optimizing well completion strategies.

By achieving these objectives, this study aims to enhance the understanding of the geomechanical behavior of the Vaca Muerta Formation, ultimately contributing to more efficient and effective hydrocarbon extraction practices.

METHODS

The horizontal stress field in the Neuquén Basin was determined by analyzing borehole breakouts, which are stress-induced enlargements of the wellbore geometry. Borehole breakouts occur as stress-induced spalled regions on each side of the wellbore. Studies have demonstrated that the orientation of breakouts around a vertical borehole aligns with the least horizontal stress direction (Shmin), where the greatest compressive stress is concentrated (Reinecker et al. 2004). Consequently, the long axes of breakouts are oriented approximately perpendicular to the maximum horizontal stress (SHmax) orientation (Bell and Gough 1979; Bell and Babcock 1986, Plumb and Cox 1987, Gough and Bell 1981, Bell and Gough 1982, Zerwer and Yassir 1994).

Borehole breakouts from the Neuquén Basin were interpreted in a previous study using four-arm caliper log data. Among the numerous wells drilled in the Neuquén Basin, 115 wells were identified as having the necessary information for borehole breakout analysis. For each well, the four-arm caliper data were manually interpreted, and the mean breakout orientation was calculated. Only vertical wells were included in the analysis to ensure consistency (Bell and Gough 1979, Plumb and Hickman 1985, Zoback et al. 1985, Reinecker et al. 2004, Guzmán et al. 2007).

The average SHmax orientation and the standard deviation of the stress-induced features observed in each well were calculated using a circular statistical analysis as proposed by Mardia (1972). The average SHmax orientations for each well were quality-ranked according to the updated World Stress Map criteria. The resulting data are available in the World Stress Map 2008 database release (Heidbach et al. 2008, Heidbach et al. 2010). The stress data are well distributed within the basin, providing a coherent picture of SH orientation. Using the previously calculated data and formational tops information, it was possible to isolate the Vaca Muerta Formation breakout orientation along the Neuquén Basin, and 30 wells with this information could be obtained from the analysis.

This comprehensive methodology ensures accurate determination of the SHmax orientation in the Vaca Muerta Formation, providing valuable insights into the stress field distribution and its controlling factors. The integration of manual breakout identification, rigorous statistical analysis, and quality control measures, combined with the targeted isolation of formation-specific data, allows for a detailed and reliable stress orientation analysis in the Neuquén Basin.

RESULTS

From the analysis of 115 wells it could be isolated borehole breakout orientation for 30 wells, which are listed in Table 1 along with their breakout directions and locations. A total of 168 breakout intervals, with a combined length of nearly 4000 meters, were obtained for the Vaca Muerta Formation. The majority of these data are located in the southern part of the basin due to the availability of our information..

The distribution and orientation of the maximum horizontal stress (SHmax) across the 30 wells in the Neuquén Basin for the Vaca Muerta Formation are illustrated in figure 1. The figure also highlights the main forces and factors that can influence the horizontal stress field, including subduction forces, the topographic axis, and the Upper Triassic - Lower Jurassic extensional structures (Cristallini et al. 2006, Bechis et al. 2014).

From the SHmax directions shown in figure 1, it is evident that the general orientation of SHmax is predominantly WSW-ENE to E-W. However, the orientation is not uniform throughout the area. In the eastern part of the basin, SHmax rotates to an almost SW-NE and SE-NW direction, deviating from the general trend.

The SHmax in this sector of the Andean retroarc appears to be influenced by the convergence vector between the Nazca and South American plates (azimuth 080º, Angermann et al. 1999, Norabuena et al. 1999, Kendrick et al. 2003), the direction of the ridge push (E-W), and the topographic forces (generally WSW-ENE to E-W, perpendicular to the main topographic axis). These forces acting on this segment of the South American Plate have an approximate E-W orientation (Coblentz and Richardson 1996, Meijer et al. 1997); therefore, the expected SHmax directions should be roughly parallel (Guzman et al. 2007). This alignment explains the WSW-ENE orientations observed.

However, the SW-NE and SE-NW orientations do not align with these forces. To understand these rotations, SHmax directions were plotted against the basement structures (Fig. 1). Cristallini et al. (2006) and Bechis et al. (2014) have shown that the principal Triassic-Jurassic half-graben faults of the northeastern Neuquén Basin trend NW. When SHmax orientations are compared with the basement structures, it is clear that these ancient structures exert a significant control over the horizontal stress field of the Vaca Muerta Formation. The horizontal stress directions align with the half-grabens or transfer zones, indicating that the main control over the horizontal stress field in some places is controlled by the basement structures.

DISCUSION

The study of horizontal stress orientations in the Vaca Muerta Formation within the Neuquén Basin reveals a complex interplay of geological and tectonic forces. It can be seen in figure 1 that the horizontal stress field for the Vaca Muerta Formation is not homogeneous. As it was mentioned above, the stress field is controlled by different forces acting at the

Table 1: List of the 30 wells analyzed with their location, the mean breakout and Shmax orientation for the Vaca Muerta Formation.

Well	X (GK F2)	Y (GK F2)	Length (m)	Breakout Intervals	Mean Breakout Direction (Shmin) (º)	SHmax Direction (º)
1	2601884	5809458	9.8	1	51	141
2	2581462	5761928	114.8	2	127	37
3	2618193	5678570	3.2	1	128	38
4	2618662	5709978	18.0	3	168	78
5	2633213	5736738	269.8	4	169	79
6	2530946	5777385	372.6	17	4	94
7	2493984	5799122	11.6	9	180	90
8	2541081	5769772	278.1	14	170	80
9	2456820	5693593	9.8	3	40	130
10	2532366	5827317	23.8	1	152	62
11	2472712	5866903	395.2	10	165	75
12	2516206	5838293	53.8	4	175	85
13	2547085	5828331	20.3	2	37	127
14	2464041	5870435	122.0	5	169	79
15	2441181	5875795	2.6	1	167	77
16	2534685	5756046	144.0	8	13	103
17	2440166	5657350	51.5	11	151	61
18	2562393	5813316	290.8	4	205	115
19	2485131	5652478	147.8	9	160	70
20	2535254	5785452	320.5	3	166	76
21	2461146	5734284	730.7	8	173	83
22	2490910	5877645	48.3	10	155	65
23	2469129	5680444	78.5	2	150	60
24	2470109	5681487	13.5	2	169	79
25	2505665	5827113	192.0	1	173	83
26	2510198	5828105	143.8	15	169	79
27	2438115	5788215	15.3	13	4	94
28	2520835	5796947	16.5	1	21	111
29	2452197	5709625	68.0	3	150	60
30	2466078	5994141	61.9	1	169	79

same time. Other authors (Heidbach et al. 2010) mentioned that those forces can be classified into three categories: the first order forces include plate motion over large areas, plate boundary forces (such as ridge push, slab pull), the second order forces act in a spatial wavelengths of ~500 km, including lithospheric flexure, intraplate lateral density contrasts, continental rifting, isostatic compensation, topography and deglaciation. Finally, the third order includes stress patterns on a 1-100 km scale that may be generated by local density and strength contrasts, basal detachment, basin geometry, topography and active faulting (Fig. 2). Guzmán et al. (2009) previously analyzed stress orientations in the southernmost region of the Andean retroarc, suggesting a significant influence of topographic and basement structural controls. Building on this foundation, Díaz and Chiachiarelli (2022) provided further insights into stress orientation variability across the basin, particularly focusing on the implications for hydrocarbon exploration and production. This complexity results in a heterogeneous stress field that affects drilling operations and hydraulic fracturing strategies.

In previous research, Guzmán et al. (2007) analyzed the horizontal stress field using a mean breakout direction for 115 wells, and the horizontal stress trajectory map achieved for the Neuquén Basin shows that the SHmax is not completely uniform throughout the study area. To the north of the Colorado River, the SHmax shows an ESE tendency interpreted as being significantly influenced by the topographic forces. To the south of the Colorado River, SHmax has an ENE trend similar to what was predicted, based on plate boundary forces. To the southeast of the region, a NE direction was found, probably showing a basement structural control in the stress field geometry. Heidbach et al. (2010), suggested that the horizontal stress field for this region is only controlled by topographic forces, however when the results for the Vaca Muerta Formation

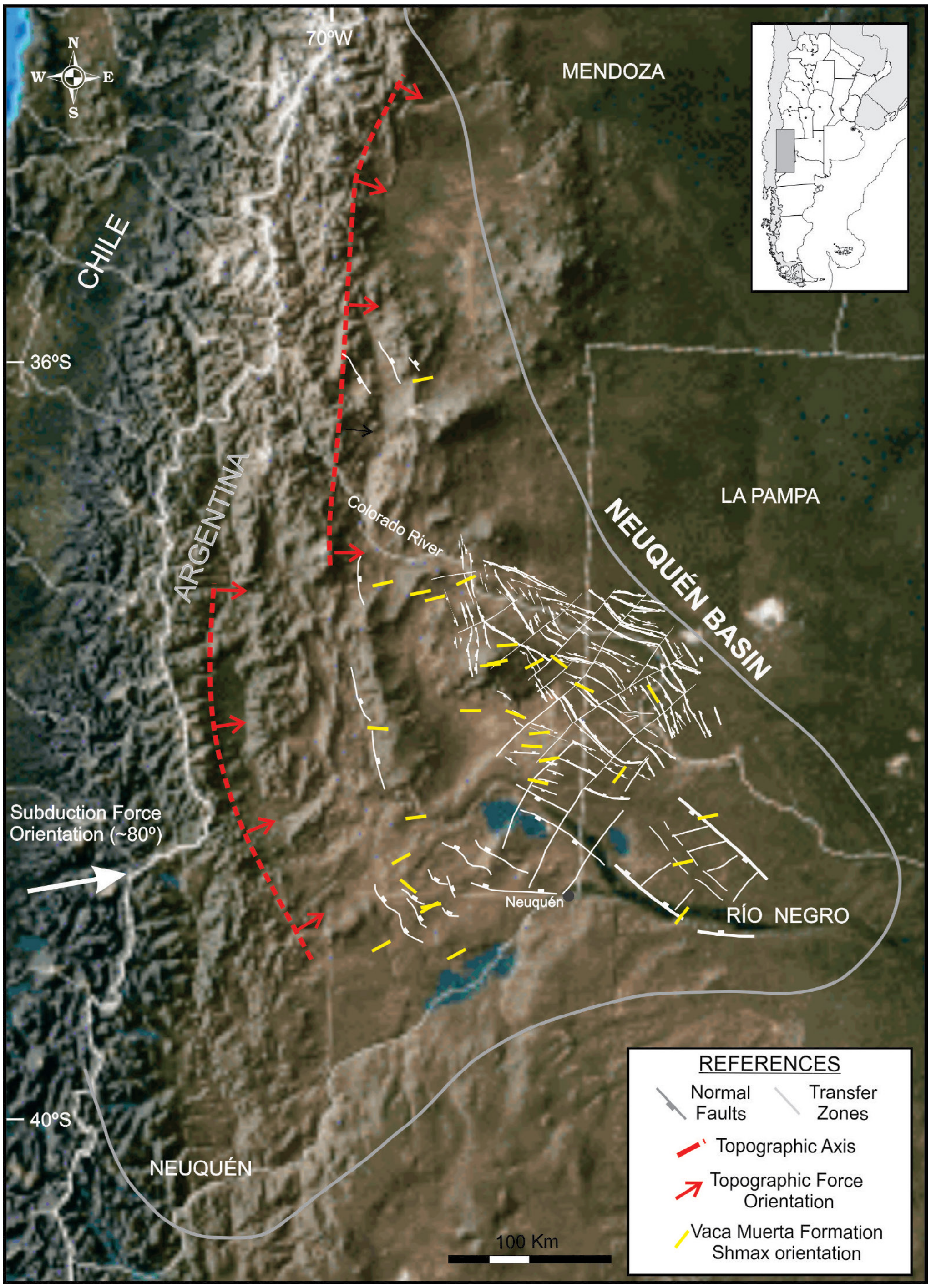

Figure 1: Maximum horizontal stress (SHmax) distribution, orientation for 30 wells distributed along the Neuquén Basin for the Vaca Muerta Formation. The main forces and controls acting over the horizontal stress field for the Vaca Muerta Formation are also shown: the subduction force, the topographic axis and the Upper Triassic - Lower Jurassic grabens (Cristallini et al. 2006, Bechis et al. 2014).

are plotted, it can be seen that is not really the case.

The western part of the Neuquén Basin exhibits a relatively consistent horizontal stress orientation, largely influenced by first and second order forces. These include the subduction forces exerted by the Nazca plate and associated ridge push and slab pull mechanisms (Heidbach et al. 2010). As observed in figure 1, the stress trajectories align predominantly parallel to the subduction force direction or perpendicular to major topographic axes, such as the Andes. Topographic forces can significantly influence the horizontal stress field by inducing stress variations aligned with surface relief and geological structures. These forces arise from gravitational loading such as mountains. In areas with elevated topography, the additional weight can cause horizontal compression in surrounding regions, for instance, the Andes mountains impose a considerable topographic load on adjacent regions, influencing the stress orientations in nearby basins, where stress patterns are partly aligned with the Andean topographic front. This alignment indicates a coherent response to regional tectonic forces over large spatial scales, contributing to a more predictable

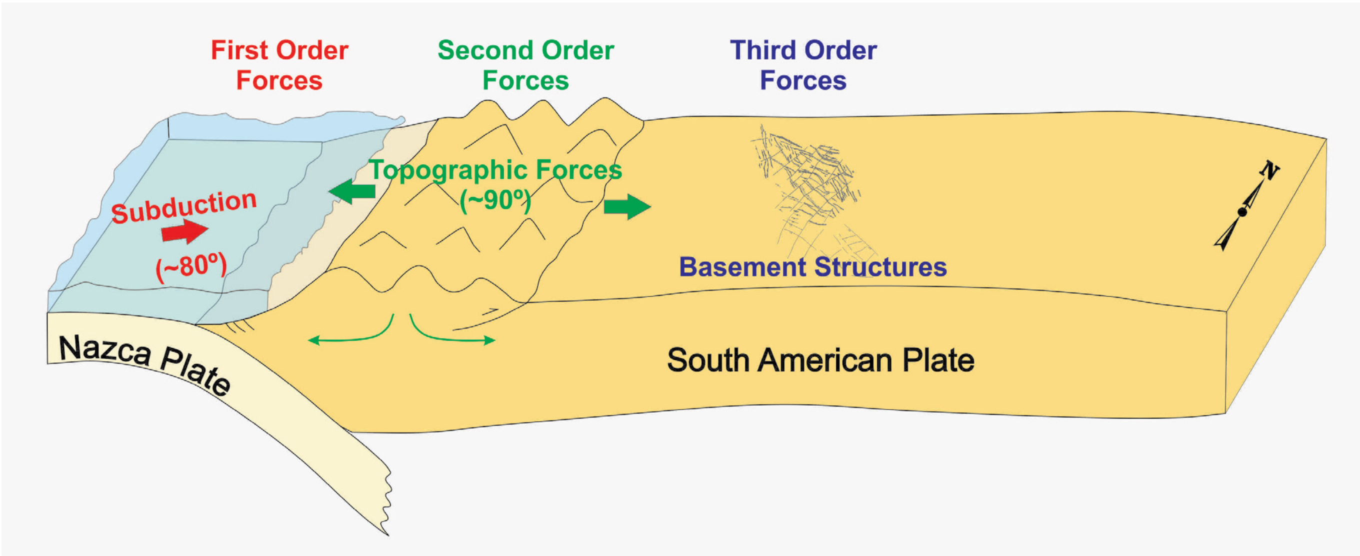

Figure 2: Principal forces acting in the Neuquén Basin and controlling the horizontal stress field for the Vaca Muerta Formation.

stress regime ideal for hydraulic fracturing operations, as fractures are more likely to propagate as expected, maximizing permeability and improving hydrocarbon extraction efficiency.

In contrast, the eastern part of the basin presents a more complex stress field. Díaz and Chiachiarelli (2022) highlight that stress orientations in this region deviate significantly from the regional trend observed in the west. Instead of aligning with the predominant tectonic forces, these orientations appear more chaotic and are influenced by third order forces related to basement structures (see figure 1 and figure 2). Specifically, the presence of grabens and associated transfer zones exerts a pronounced control on stress orientation. This phenomenon is well-documented in the literature, where differential subsidence within these structures leads to stress alignments parallel to fault systems, such as NW and WNW trending faults (Cristallini et al. 2009). These structures create localized stress deviations that can alter SHmax orientation, especially in regions where basement faults intersect or closely approach the overlying sedimentary layers. As a result, stress orientations deviate from the more predictable regional trends, aligning instead along these fault planes or structural features

Cristallini et al. (2006, 2009) proposed that there are two populations of grabens, one NW and other WNW and that there are normal faults concentrated over the oldest precuyano faults and over the hinges of the half-grabens. These normal faults have general NW directions and are developed parallel to NW family of precuyano faults. In turn, they are echelon over the WNW population, which can be explained as the result of the tension associated with the differential subsidence of the grabens and half-grabens infill (Fig. 3) (Cristallini et al. 2009).

The differential subsidence process is currently active in the Nequén Basin and may be producing an extension of the affected layers (such as the Vaca Muerta Formation). Taking this into account, the SHmax should be parallel to the orientation of the faults and Shmin should be perpendicular to them (Fig .4).

The influence of the basement on stress orientations is evident through breakout patterns, where borehole ovalization due to localized stress redistribution highlights the significant impact of underlying structures. This structural control is paramount for hydraulic fracturing as it may propagate in an unpredictable manner that can result in incomplete fracture networks or limited reservoir communication within structurally complex areas. Such irregularity, which relates to third-order control from basement faults and structural variances, suggests that wellbores drilled in these areas could undergo early fracturing or develop unwanted geometries of fracture networks.

Geomechanically, the irregular stress field along the Neuquén Basin, presents challenges for hydraulic fracturing operations, as fracture behavior becomes unpredictable in areas with strong basement influence. If shelf areas are impacted by basement faulting, the irregular propagation of fractures may result in unexpected fracture termination, limited lateral connectivity or even a change in fracture orientation. These effects can reduce total hydrocarbon recovery by restricting the ability of induced fractures to interact with natural ones, thus diminishing the permeability enhancement in an oil reservoir. Well design should therefore account for localized stress variations by optimizing drilling orientations to mitigate breakout risks and control fracture propagation.

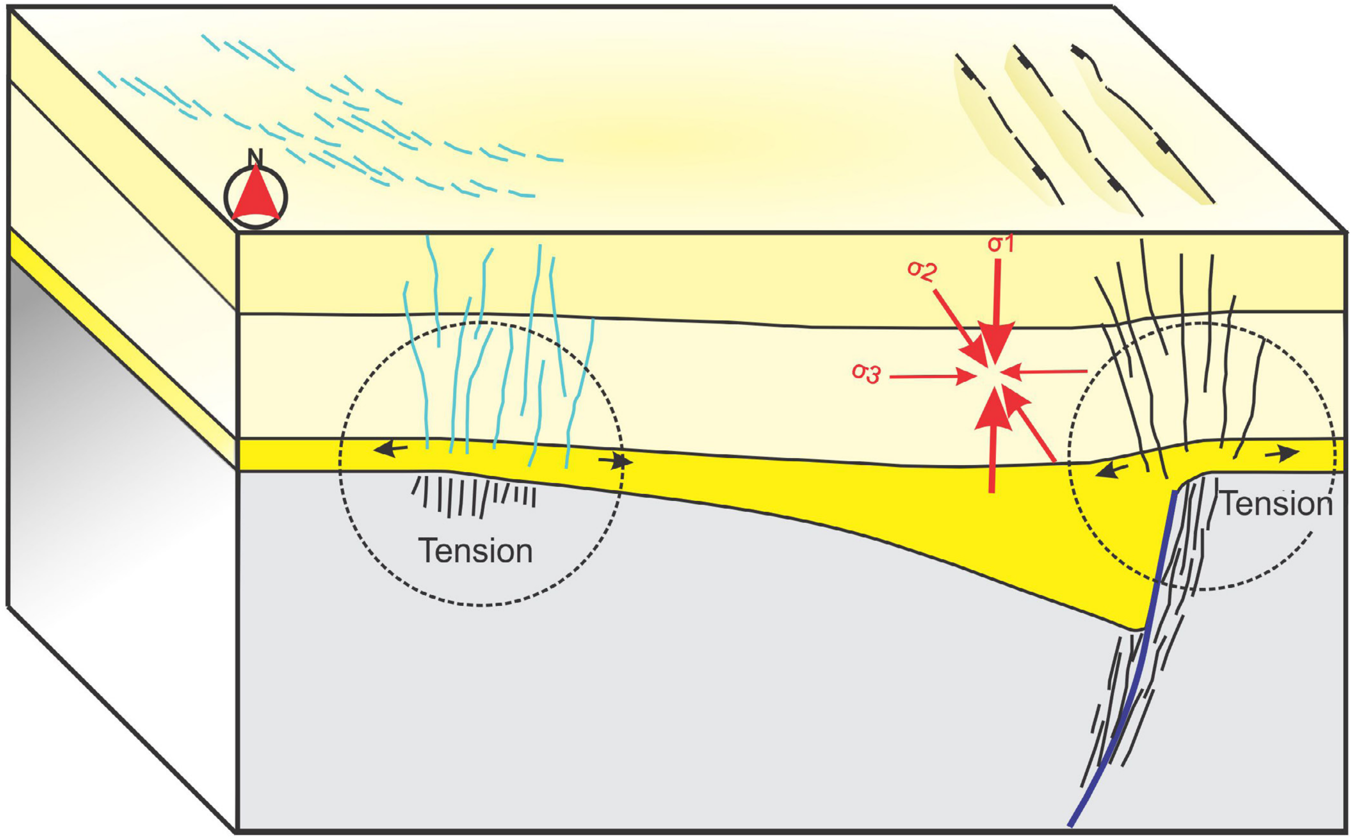

Figure 3: Normal faults developed as a result of the tension associated with differential subsidence (modified from Cristallini et al. 2009).

CONCLUSIONS

The principal horizontal stress directions acting in the Andean retroarc between 36º and 39º S for the Vaca Muerta Formation have been isolated using breakout information interpreted from dip-meter logs of 115 wells drilled in the Neuquén Basin. From the analysis, 30 wells with this information and 168 breakout intervals, with a combined length of nearly 4000 meters could be obtained.

Our results show that the horizontal stress field in the Vaca Muerta Formation is governed by a combination of first, second, and third order forces. While the western part of the Neuquén Basin shows a predominant influence of regional tectonic forces, the eastern part is characterized by the influence of local basement structures. This heterogeneity underscores the need for nuanced approaches in reservoir management and hydraulic fracturing design to optimize hydrocarbon recovery in this prolific basin.

Understanding these distinct stress regimes is crucial for optimizing hydrocarbon extraction strategies in the Vaca Muerta Formation. In the western basin, where stress orientations are more uniform and predictable, engineers can leverage this knowledge to design efficient hydraulic fracturing treatments aligned with regional stress gradients. Conversely, in the eastern basin, where stress orientations are influenced by local geological structures, tailored approaches that account for variable stress fields will be necessary to mitigate operational risks and enhance production efficiency.

This study provides a comprehensive view of stress distribution, offering valuable insights into the mechanisms governing stress fields at different scales. For improved predictability in hydraulic fracturing outcomes, further structural analysis is needed, especially in the eastern part of the basin. These analyses could offer critical insights into actual stress orientation deviations and their effects on fracturing efficiency. By incorporating a more detailed model of basement structures, operators could refine wellbore trajectories to minimize fracture interference from basement faults. This study highlights the importance of adapting drilling strategies to account for breakout-inducing structures in the Vaca Muerta Formation. A deeper understanding of these third-order stress orientation control could lead to more effective wellbore stability management and optimized fracturing strategies in the eastern area of the Neuquén Basin, where stress fields are strongly controlled by these forces.

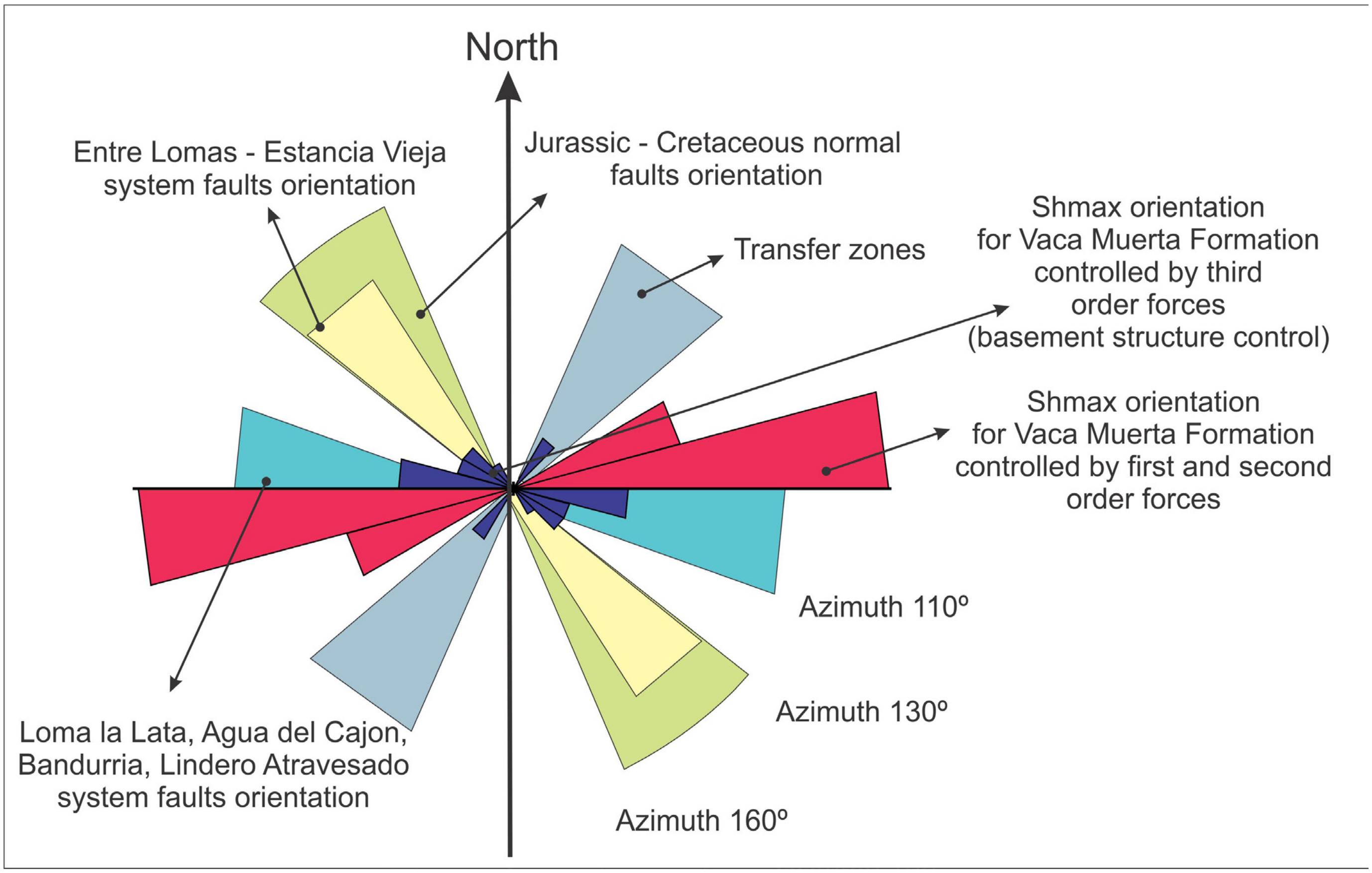

Figure 4: SHmax orientation obtained for the Vaca Muerta Formation plotted with the system faults as proposed by Cristallini et al. (2009). It can be seen that the SHmax orientations not controlled by subduction or topographic forces are controlled by the differential subsidence of the grabens and half-grabens infill or transfer zones.

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