10º Congreso de Exploración y Desarrollo de Hidrocarburos
Simposio de Recursos No Convencionales: Hacia una Nueva Convención

TESTING HYDRAULIC FRACTURING SIMULATION SCENARIOS IN A CONCEPTUAL DISCRETE FRACTURE NETWORK MODEL OF VACA MUERTA PLAY, NEUQUÉN BASIN, ARGENTINA

Pedram Zarian[1], Orlando Ortega[1], Hooman Hosseinpour[2], Daniel Samake[1], Fernando Sanchez Ferrer[1]

1: Shell Exploration and Production Inc., pedram.zarian@shell.com, orlando.ortega@shell.com, daniel.samake@shell.com, f.sanchez-serrer@shell.com

2: Golder Associates Inc., hooman_hosseinpour@golder.com

Keywords: **Natural Fractures, DFN, Hydraulic Fracturing, Unconventionals, Vaca Muerta**

RESUMEN

Experimentando escenarios de estimulación de fracturamiento hidráulico en un modelo conceptual de Vaca Muerta con fracturas naturales discretas, Cuenca Neuquina, Argentina.

La compleja historia tectónica de la cuenca Neuquina ocasionó la propagación de fracturas naturales en la Formación Vaca Muerta. Sin embargo, el impacto de las fracturas naturales en el fracturamiento hidráulico de Vaca Muerta no es solo poco conocido, sino también normalmente ignorado. Así como la producción final estimada de los pozos terminados en Vaca Muerta es variable geográficamente, también varían la orientación e inclinación dominante de las fracturas y el máximo esfuerzo compresivo. La relación entre producción y fracturas naturales no ha sido aún demostrada en la cuenca.

En este trabajo, construimos un modelo conceptual de fracturas naturales para investigar su impacto en el fracturamiento hidráulico. El modelo de fracturas naturales fue derivado de información proveniente de afloramientos, símica 3D, registros de imágenes de sondeos e información de muestras de roca extraídas de pozos. Los módulos elásticos son de Vaca Muerta y se definieron hasta cuatro sistemas de fracturas naturales. En este modelo se colocó un pozo horizontal típico de Vaca Muerta en condiciones de esfuerzo similares a las observadas en pozos ya perforados.

Estudiamos 7 variaciones de parámetros en este modelo conceptual, las cuales incluyen la orientación y magnitud de los esfuerzos principales, así como la orientación de las fracturas naturales y la orientación de los pozos horizontales. Investigamos asimismo la posible interferencia vertical entre pozos horizontales perforados, en función de la presencia o ausencia de un nivel hipotético de carbonatos, situado por encima y debajo del nivel de navegación. Los resultados de la investigación muestran que las fracturas naturales impactan en la geometría del volumen de roca estimulado. Concluimos que, a pesar de mantener parámetros constantes en las fracturas hidráulicas, al cambiar la orientación de las fracturas o el esfuerzo se producen diferentes resultados de altura y longitud promedio de fracturas inducida. También, el estado de esfuerzos, la conectividad del sistema fracturado y el espesor de la unidad carbonática, determinan si esta última actuaría como barrera de propagación a las fracturas hidráulicas. Finalmente, el modelado muestra que la secuencia de estimulación de los pozos puede tener gran influencia en las probabilidades de interferencia de producción entre estos.

INTRODUCTION

Considering the complex tectono-stratigraphic history of the Neuquén basin, the presence of natural fractures in the Vaca Muerta Fm. is to be expected. However, the impact of natural fractures on hydraulic fracturing in the Vaca Muerta Fm. is not well understood, and is often ignored. Currently there is no direct evidence advocating an increase or decrease of production from Vaca Muerta Fm. due to the impact of natural fractures. Yet, there are examples of inter-well or cross-well communication across the play that have been attributed to the natural fracture network, e.g., Rimedio *et al.*, (2015). Estimated Ultimate Recovery (EUR) of wells are variable across the basin, along with the dominant orientation of natural fracture sets and the current maximum compressive stress orientation, Guzman *et al.*, (2007, 2009). Despite several attempts to investigate hydraulic and natural fractures interaction through experimental or numerical modeling, e.g. Blanton (1982), Olson and Dahi-Taleghani (2009), Weng *et al.*, (2011), Keshavarzi and Jahanbakhshi (2013), a relationship between EUR and natural fractures in the unconventional plays still remains elusive.

To investigate how natural fractures impact hydraulic fracturing in the Vaca Muerta Fm., a conceptual Discrete Fracture Network (DFN) model has been built, using information derived from a number of outcrop studies, interpretation of 3D seismic volumes, borehole image logs and core data. The model is then used to test the different scenarios described in this paper. The derived learnings might be used to risk the effectiveness of hydraulic fracturing in the Vaca Muerta Fm. at a regional scale.

Regional changes are observed in the orientation of the natural fractures, as interpreted on the borehole image logs from different parts of the Neuquén basin, as well as the seismic imaging of lineaments mapped at different intervals of Vaca Muerta Fm., e.g. Gangui, *et al.*, (2014). Comparison of fracture sets measured on the Vaca Muerta outcrops with the ones interpreted from seismic attribute analysis and borehole image logs, provided constraints on the regional variation of natural fracture sets; constraints that were applied to this conceptual model. Four main fracture sets are identified: ENE, NE, NNW, and WNW (Fig. 1). In this modeling exercise, we considered the ENE fracture set to be the most dominant one. As a result, a discrete fracture network is generated in

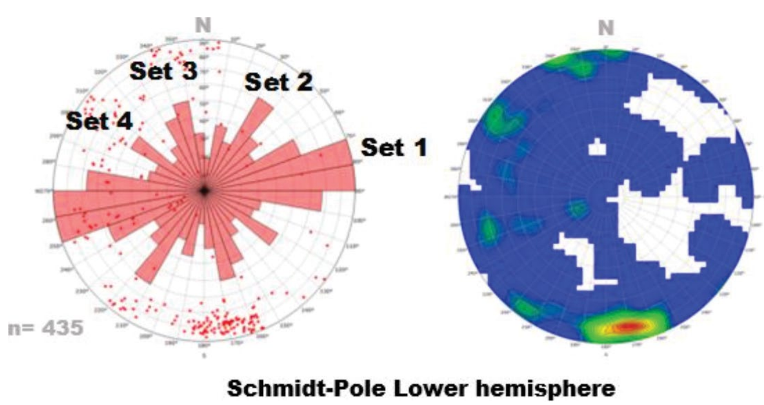

Figure 1. Example of distribution of the orientation of the natural fractures identified from the interpretation of borehole image logs. Four main fracture sets are defined in the rose diagram.

which, the simulation is constrained to match representative wells and regional seismic data. Since the conceptual model is kept simple, small bedding-parallel veins of fibrous calcite known as "beef", sensu Cobbold *et al.*, (2013) and large regional faults are not taken into consideration.

METHODOLOGY

A simplified, layer cake conceptual model is built with a 4Km x 4Km dimension, and a vertical resolution of 10m. A horizontal well, resembling a typical Vaca Muerta well, is created and assumed to land within the layered model. The model is constrained by elastic moduli and stress conditions observed in representative Vaca Muerta wells (Fig. 2). To reduce processing time, only three fracturing stages are simulated. The elastic moduli and stress condition are simulated based on actual data from Vaca Muerta wells. To provide a representative distribution of natural fractures intensities, statistical parameters such as P10 and P32, Dershowitz and Herda (1992), were calculated for each fracture set, based on the measurements from borehole image logs and the studied outcrops, and then applied to individual grids in the model. Subsequently, the model is used to run seven different test scenarios, including varying principal stress orientation and magnitudes, varying natural fracture orientations, and varying layer thicknesses. The first five tests focus on changes in the orientation, whilst the last two on the vertical interference with variation of the layer thickness. A brief description of these test scenarios is followed by the simulation results.

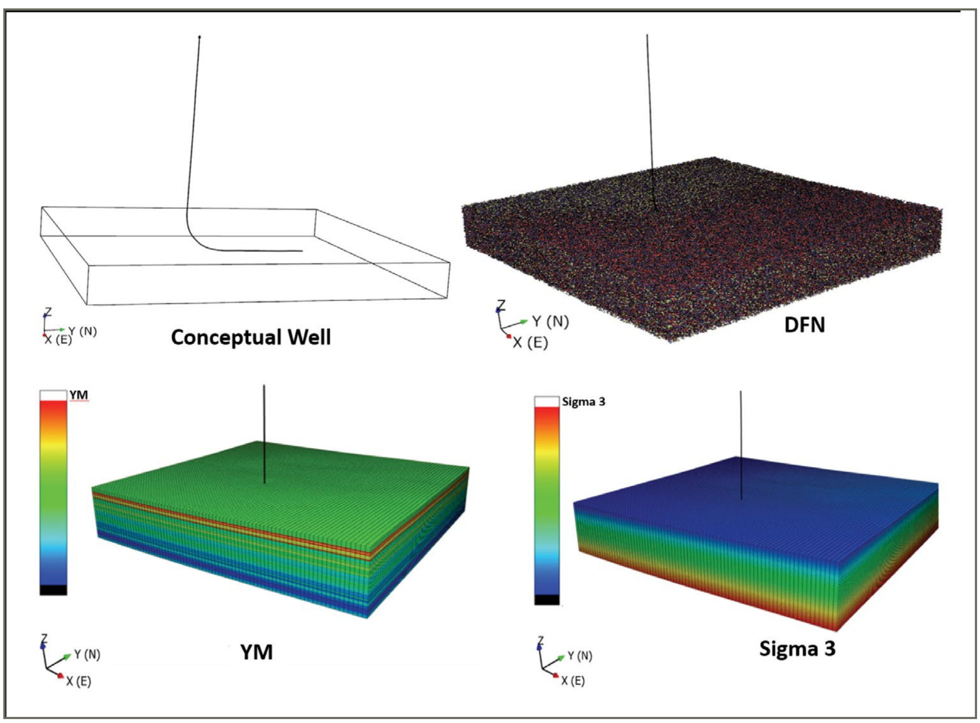

Figure 2. A simplified conceptual model representing a typical horizontal well in the Vaca Muerta Fm. The elastic moduli and stress conditions populated in the model are based on actual data from Vaca Muerta wells. Please note that only 22% of fractures are displayed in the DFN model.

Test Scenario 1: Absence of Natural Fractures

In this test scenario, no natural fractures are included, only the propagation of the hydraulically induced fractures is modeled. The maximum horizontal stress (SHmax) orientation is assumed to be trending E-W and the well trajectory in N-S direction. Upon completion of the simulation, the modeled-induced microseismic events showed a simple bi-wing geometry for the hydraulically induced fractures (Fig. 3). In the absence of any lateral heterogeneity in the model, the geometry of the hydraulically induced fractures proved symmetrical, following the stress path as expected. Although Hydraulic Fracture half-length (Xf) and Fracture Height (Hf) parameters are also modelled (Fig. 3), it is important to note that these generic estimates are only used in a relative sense, as providing a reference case for comparison with the other test scenarios.

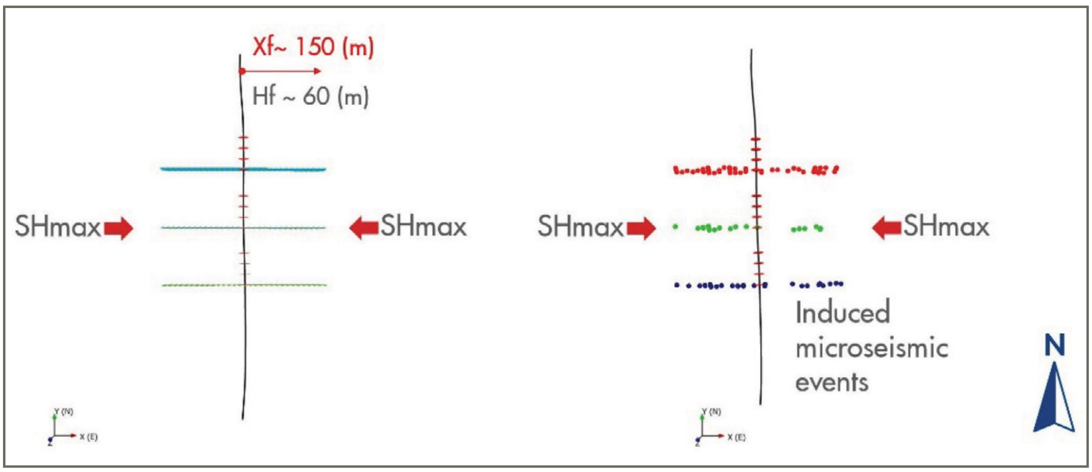

Figure 3. Test Scenario 1 (map view): absence of natural fractures. The image to the left shows the geometry of hydraulically-induced fractures. The image to the right shows the induced microseismic events, simulated by the modeling program.

Test Scenario 2: Presence of Natural Fractures

Test scenario 2 is similar to the first, in terms of the completion parameters and the state of stress; the main difference is the presence of natural fractures. The modeling shows the network of inflated natural fractures after the treatment (Fig. 4) and a change in the orientation of the induced microseismic events in comparison to the previous test. The same amount of fluid is now mostly distributed in the inflated natural fractures, reducing the Xf but increasing the Hf, hence increasing the Stimulated Rock Volume (SRV). Vertical connectivity of natural fractures plays an important role in defining the geometry of the stimulated rock volume. The model indicates that the induced microseismic events show an ENE trend, similar to what is generally observed in microseismic field data from the Vaca Muerta Fm.

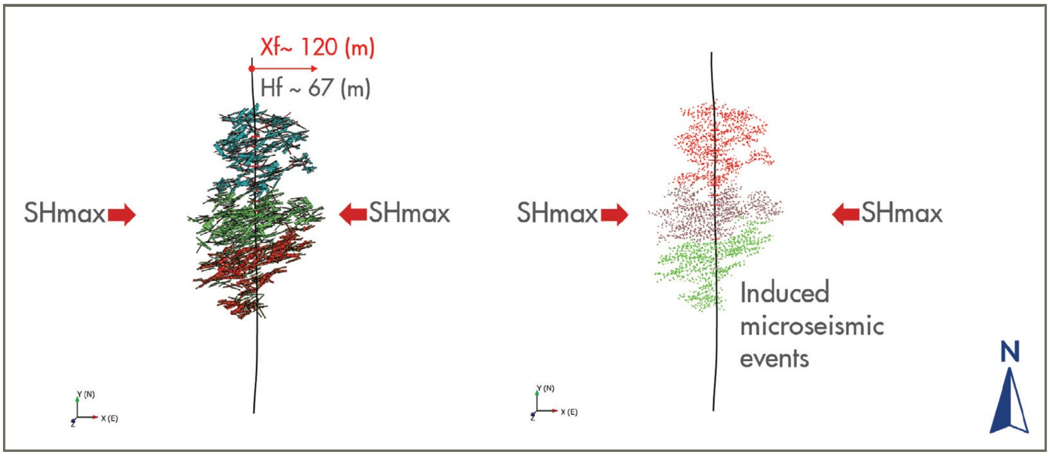

Figure 4. Test Scenario 2 (map view): presence of natural fractures. The left image shows the geometry of inflated natural fractures. The image to the right shows the induced microseismic events.

Test Scenario 3: Changing Orientation of SHmax

Variations in the orientation of the SHmax across the Neuquén basin is quite common and observed from well to well, locally even within a relatively short distance. In this test scenario, only the orientation of the SHmax is changed from E-W to NW-SE (N45oW), while keeping the natural fractures in the same orientation as before. The simulation shows a small reduction in Hf and a larger decrease in Xf, as well as a more symmetrical geometry for the hydraulic fractures (Fig. 5). The Xf is important for well spacing considerations.

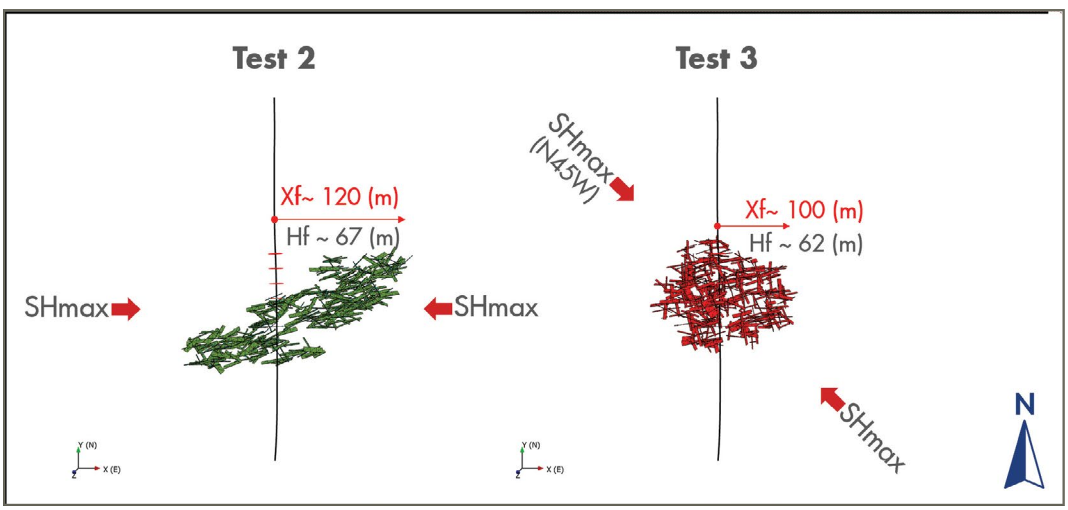

Figure 5. Test Scenario 3 (map view): changing orientation of SHmax. Note a 45o clock-wise rotation in SHmax from test 2 (left) to test 3 (right), and a consequent change in the geometry of the stimulated rock volume.

Test Scenario 4: Isotropic Stress Effects

Regionally in the Neuquén basin, the state of the in-situ stress is mostly strike-slip, meaning that SHmax>Sv>Shmin. However, stress isotropy is also observed in the Vaca Muerta Fm., particularly close to its base, where pore pressure is highest. Increased pore pressure causes the convergence of magnitudes of the three principal stresses toward a more isotropic condition, Zoback (2007). To test such a condition, the fourth test scenario assumed equal magnitude of minimum and maximum horizontal stresses. The simulation results indicated a drastic reduction in fracture half-length and a dense concentration of the induced microseismic events in the vicinity of the wellbore (Fig. 6). Such a situation can potentially provide better drainage for the areas close to the borehole, but will result in an overall smaller SRV.

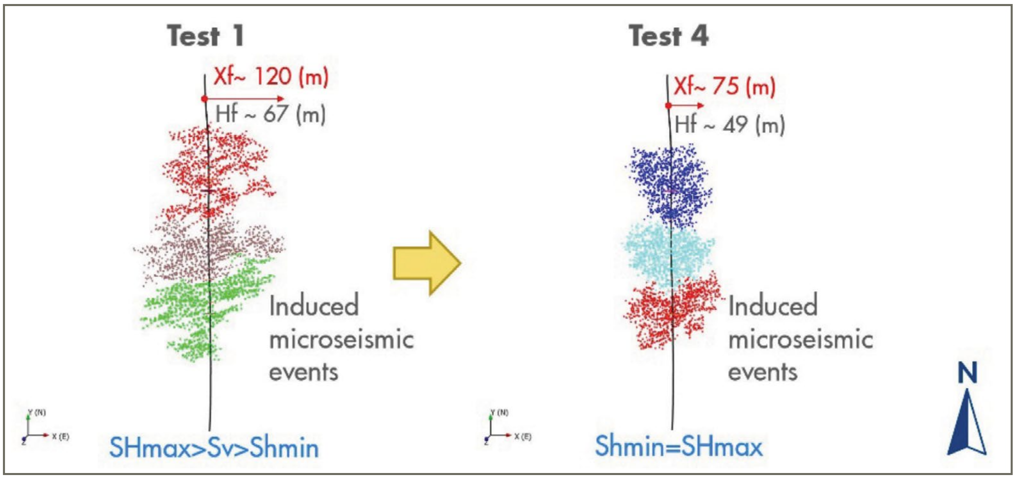

Figure 6. Test Scenario 4 (map view): isotropic stress effects. Induced microseismic events in a strike slip (left) and isotropic (right) stress regimes.

Test Scenario 5: Changing Orientation of Natural Fracture Sets

In this test scenario, the orientation of natural fracture sets is changed from a dominant ENE trend to a dominant NNW trend, keeping the same orientation of the regional SHmax. The simulation results are quite surprising as it was expected that the ENE trending fracture set would show a larger Xf. Instead, the results show a stimulated fracture corridor in SE direction, which resulted from the reactivation of multiple intersecting fracture sets (Fig. 7). These results illustrate that predicting the behavior of natural fracture networks is challenging and reaffirms that the reactivation of natural fractures can result in widening the treatment zone (Gale *et al*., 2007).

Test Scenario 6: Vertical Interference with Presence of Basal Carbonate Unit

The vertical interferences between two horizontal landing zones in the presence of a carbonate unit, situated above and below the landing zones, were investigated in this test scenario.

From the seismic Rock Typing volume created from Youngs Modulus cross-plots, calibrated to core and well data, a basal carbonate unit in the Vaca Muerta Fm. can be imaged between the so-called Sequence 1 (i.e., 'Cocina') and the overlying Sequence 2 (Fig. 8).

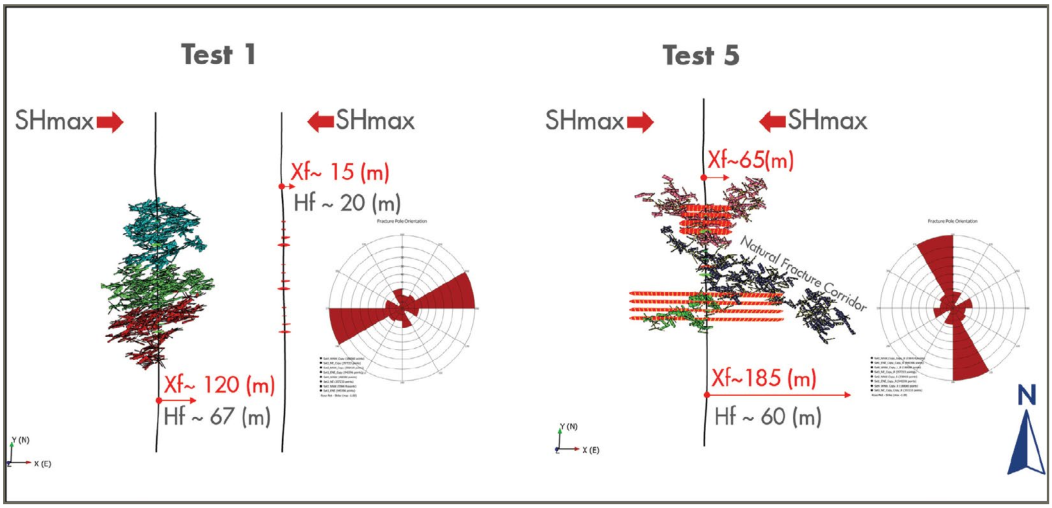

Figure 7. Test Scenario 5 (map view): changing orientation of natural fracture sets, illustrating the impact of dominant natural fracture sets orientation.

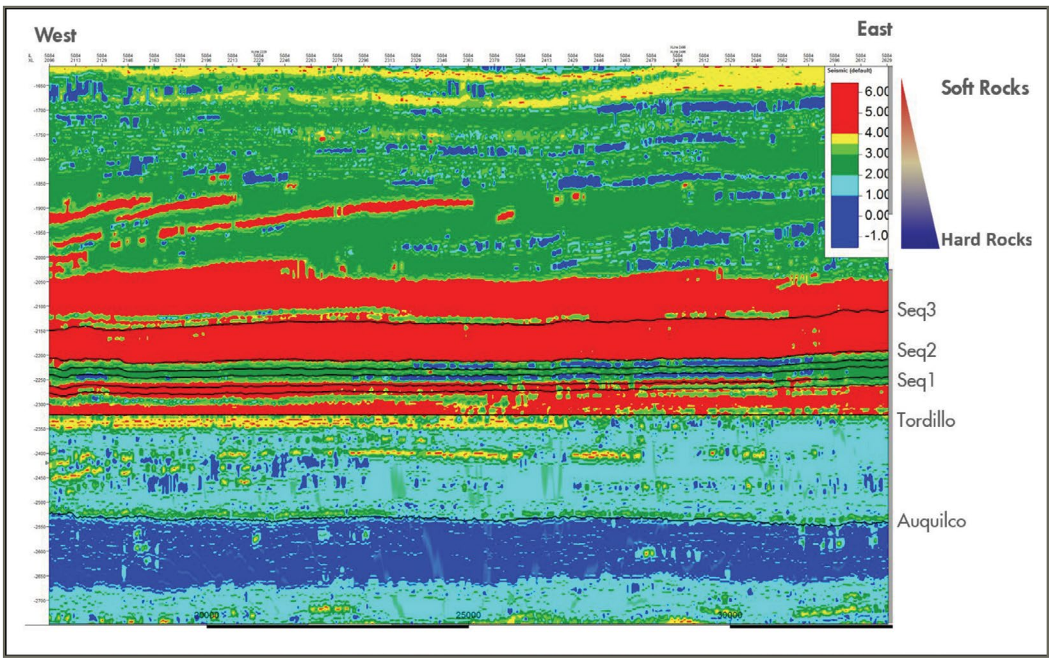

Figure 8. Regional cross section of the RockType volume flattened on the base of Vaca Muerta Fm.

In parts of the basin, such carbonate unit is known as Los Catutos member, Leanza and Zeiss (1990), Kietzmann *et al*., (2014), Rodriguez Blanco (2016), and can potentially act as a fracture barrier. In our first test run of this scenario, the thickness of the carbonate unit was assumed to be about 20 m, and the stress condition similar to a typical Vaca Muerta well. This simulation indicates that the basal carbonate unit is not likely to act as a barrier to the hydraulic fracture propagation, since some of the inflated natural fractures clearly cross through the unit (Fig. 9a).

A slight increase in the stress condition in the second attempt made the basal carbonate act as a fracture barrier (Fig. 9b). The increased stress applied is within the range of stresses observed across the Neuquén basin at the base of the Vaca Muerta interval. Landing a second horizontal well above the basal carbonate unit shows that it can also act as a fracture barrier for the upper well, completely separating the two wells (Fig. 9c).

Decreasing the thickness of the basal carbonate down to 10 m, even with the same increased-stress condition, can promote again vertical interference between the two wells (Fig. 9d). Therefore, there is a threshold for stress and thickness under which the basal carbonate unit may act as a barrier to hydraulic fracture propagation. This threshold can be found by multiple iteration of the simulation and changing assumptions for the thickness and stress condition.

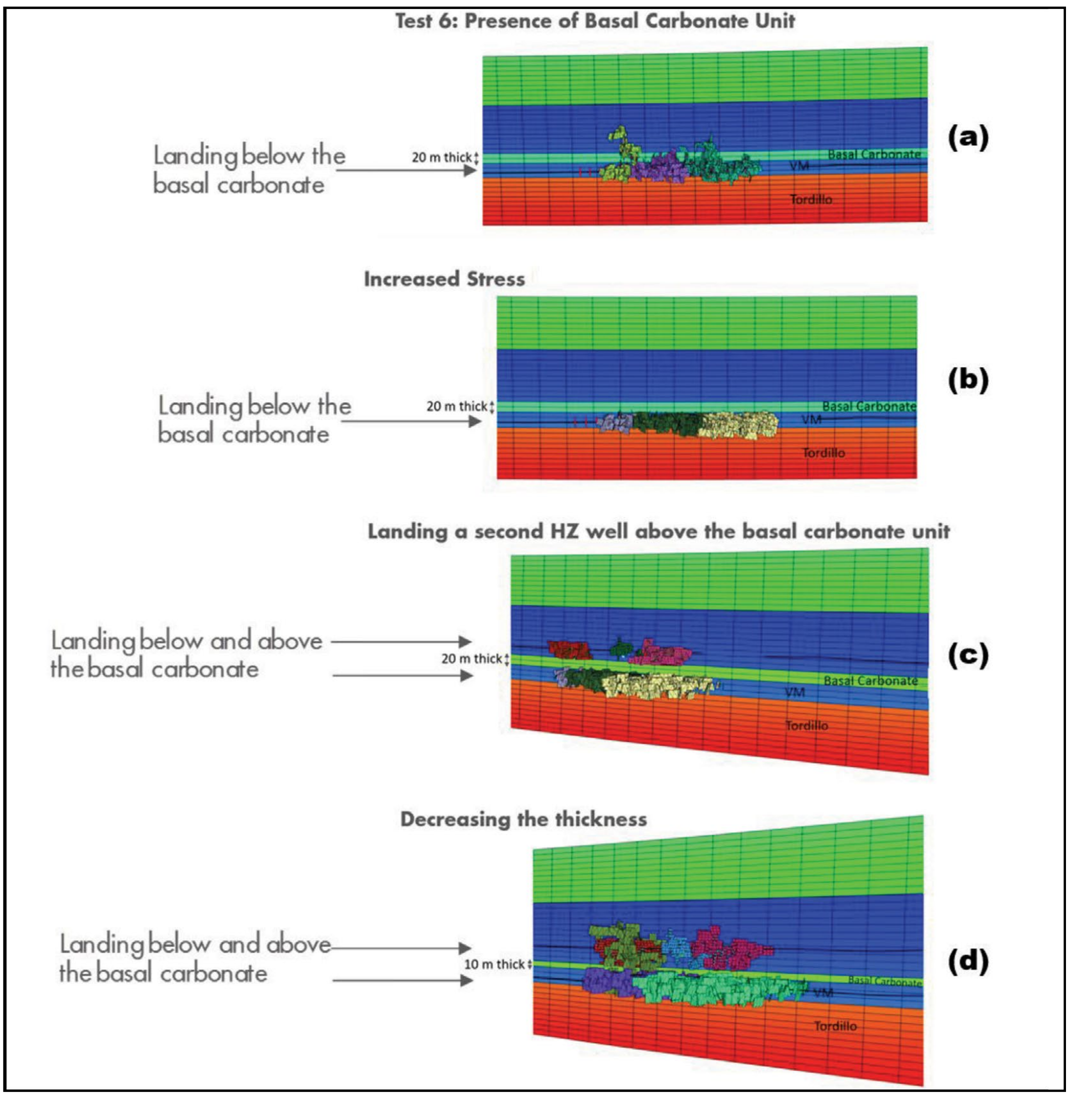

Figure 9. Vertical interference through natural fractures tested between two landing zones in presence of a basal carbonate unit.

Test Scenario 7: Vertical Interference in the Absence of Basal Carbonate Unit

Considering the absence of a basal carbonate unit in some areas of the Neuquén basin, this last simulation assumed two horizontal wells with landing zones vertically separated by a distance equal to the average thickness of one Landing Zone (LZ), which was considered to be 50m. In the first test run, the lower landing zone (LZ2) was treated first, which triggered vertical interference between the two landing zones. In the second test, the completion sequence is changed, to treat the upper landing zone first. The modelling showed that hydraulic stimulation changes the state of stress in the vicinity of the inflated fractures, thus resulting in a higher stress in the areas where completion is performed first. By the time the bottom well is treated, the inflated fractures try to avoid higher stress zones above, hence decreasing the possibility for vertical well interference. The stress profile considered in this model causes in general most of fractures to propagate upwards.

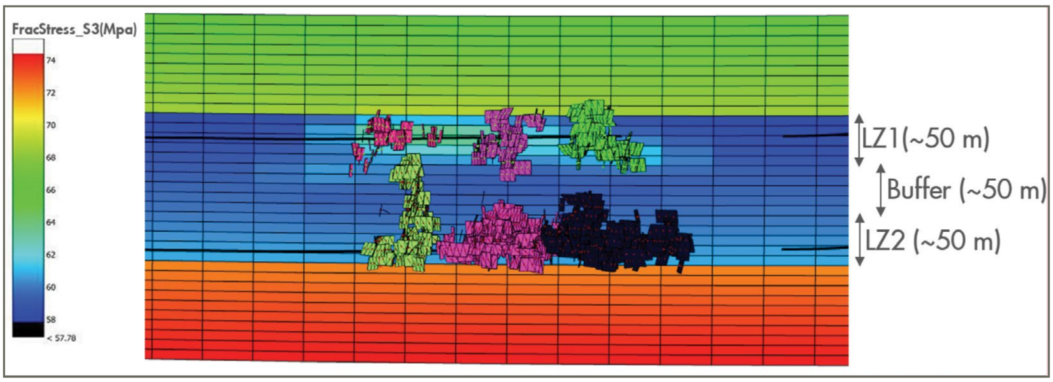

Figure 10. Showing impact of Treatment Sequencing between two horizontal wells. The inflated natural fractures from the lower well, propagating upward, stop at the high stress zone of the previously treated well above. No vertical interference is observed in the absence of a basal carbonate unit, in this test scenario

CONCLUSIONS

The scenarios tested helped visualize the impact of natural fractures on hydraulic fracture treatment under different stress conditions and orientations. Although Hydraulic Fracture half-length (Xf) and Fracture Height (Hf) were modelled, it is important to note that these generic estimates are only used in a relative sense, providing references for comparison between the test scenarios.

The results show that natural fractures impact the geometry of stimulated rock volume (test 2). Based on our simulations, keeping the same well geometry and injection volume, while changing the stress orientation, can lead to different Hf and Xf, and therefore EUR estimates (test 3). At the base of the Vaca Muerta Fm., where the stress condition gets nearly isotropic due to the elevated pore pressure, the simulation shows that hydraulic fracture dimensions can be reduced drastically, concentrating most of the rock stimulation in the close proximity of the wellbore (test 4). Changes in the orientation of natural fractures (test 5) can have a considerable impact on hydraulic fracture geometry. The large fracture fairway that appeared during test 5 simulation, resulted from the reactivation of multiple intersecting fracture sets and showed the difficulty in predicting the effects of natural fractures orientation with respect to the regional stress field. A similar phenomenon in subsurface can cause lateral interference between wells. The stress-state, fracture connectivity, and thickness of a hypothetical carbonate unit, located between two landing zones will determine if the latter is likely to act as a fracture barrier (test 6). Finally, the modelling suggests that the Sequence of completion (test 7) can have a large impact on vertical interference results, especially in the absence of a fracture barrier. The type of simulations presented in this work help us to better understand the geometry of the stimulated rock volume, under different hypothetical conditions, and can inform our choices of well-spacing, landing zone separation and sequencing of completion, to optimize unconventional production.

ACKNOWLEDGMENTS

The authors would like to thank Shell Exploration and Production Inc., Latin America Regional Studies Team for the permission to publish this study, as well as the Golder Associates Inc. Special thanks to Ed Cavallerano for the processing and interpretation of the borehole image logs and for reviewing this work, and to Leifeng Zhou, Mitchell Prante, Aaron Fox and Paul La Pointe for their technical support with this study. Finally, the authors are grateful to Daniel Minisini for the review of this manuscript.

CITED REFERENCES

Blanton, T.L. Experimental study of interaction between hydraulically induced and pre-existing fractures. United States: N. p., 1982. Web.

Cobbold, P.R., Zanella, A., Rodrigues, N., Løseth, H., 2013. Bedding-parallel fibrous veins (beef and cone-in-cone): worldwide occurrence and possible significance in terms of fluid overpressure, hydrocarbon generation and mineralization. Mar. Pet. Geol. 43, 1e20,. http://dx.doi.org/10.1016/j.marpetgeo.2013.01.010.

Dershowitz, W.S. and Herda, H.H. (1992). "Interpretation of fracture spacing and intensity", Proceedings of the 33rd U.S. Symposium on Rock Mechanics, eds. Tillerson, J. R., and Wawersik, W. R., Rotterdam, Balkema. pp. 757-766.

Rimedio, M, Shannon, C., Monti L., Lerza, A.,Roberts, M., and Quiroga, J., 2015 Interference Behavior Analysis in Vaca Muerta Shale Oil Development, Loma Campana Field, Argentina Unconventional Resources Technology Conference URTeC: 2154850

Gale, J. F.W., Reed, R. m. and Holder, J. 2007, Natural fractures in the Barnett Shale and their importance for hydraulic fracture treatments reservoirs:

AAPG Bulletin, v. 91, no. 4 (April 2007), pp. 603–622

Gangui, A. y Graussem, M. 2014. "Estilos estructurales y tectonismo del intervaloTithoniano-Valanginiano en el Engolfamiento Neuquino: implicancias sobre la propagación de la estimulación hidráulica de la Fm. Vaca Muerta". IX Congreso de Exploración y Desarrollo de Hidrocarburos. p.: 341-364. Mendoza, Argentina.

Guzmán, C., Cristallini, E., and Bottesi, G., 2007, Contemporary stress orientations in the Andean retroarc between 34°and 39°S from borehole breakout analysis: Tectonics, v. 26, TC3016.

Guzmán, C., Cristallini, E., 2009. Contemporary stress orientations from borehole breakout analysis in the southernmost flat-slab boundary Andean retroarc (32°44' and 33°40'S). Journal of Geophysical Research 114, B02406, doi:10.1029/2007JB005505.

Keshavarzi, R., and Jahanbakhshi, R., 2013, Investigation of Hydraulic and Natural Fracture Interaction: Numerical Modeling or Artificial Intelligence? Effective and Sustainable Hydraulic Fracturing Rob Jeffrey, IntechOpen, DOI: 10.5772/56382.

Kietzmann, D.A., Palma, R.M., Riccardi, A.C., Martín-Chivelet, J., and López-Gómez, J., 2014, Sedimentology and sequence stratigraphy of a Tithonian–Valanginian carbonate ramp (Vaca Muerta Formation): A misunderstood exceptional source rock in the Southern Mendoza area of the Neuquén Basin, Argentina: Sedimentary Geology, v. 302, p. 64-86.

Leanza, H. and Zeiss, A., 1990. Upper Jurassic Lithographic Limestones from Argentina (Neuquén Basin): Stratigraphy and Fossils. Facies, 22:169-186

Olson, J.E., and Dahi-Taleghani, 2009, A.: "Modeling simultaneous growth of multiple hydraulic fractures and their interaction with natural fractures," SPE 119739, 2009 SPE Hydraulic Fracturing Technology Conference, The Woodlands, Texas, USA, 19–21

Rodriguez Blanco, Leticia, 2016 "Distribution and Source of Carbonate-Rich Intervals within the Vaca Muerta-Quintuco Mixed System, Neuquén Basin, Argentina." Open Access Theses. 622.

Weng, X., Kresse, O., Cohen, C., Wu, R., and Gu, H.: "Modeling of hydraulic fracture network propagation in a naturally fractured formation," SPE 140253, SPE Hydraulic Fracturing Technical Conference and Exhibition, The Woodlands, Texas, January 24-26, 2011.

Zoback, M., 2007, Reservoir geomechanics, Cambridge University Press, New York, 449 p.

10° CONGRESO DE
EXPLORACIÓN Y
DESARROLLO DE
HIDROCARBUROS

Energía y Sociedad
aliados inseparables
Mendoza 2018