

Predicción de producción de arenas 4D para optimización de terminación en las arenas del yacimiento Oxfordiano de los campos EB - Bahía de Campeche - México

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Resumen

Los campos EB se encuentran costa afuera de México en la bahía de Campeche. Ambos campos producen en carbonatos de la brecha Cretácico superior y de las arenas del Oxfordiano. Este yacimiento del Oxfordiano esta históricamente conocido por presentar problemas mayores de producción de arena y técnicas de control de arena que son necesarias para la producción. Recientemente Pemex ha empezado a perforar pozos horizontales y era necesario investigar la caída de presión segura para pozos horizontales y si las actuales técnicas de terminación usadas en pozos verticales y desviados podrían optimizarse para pozos horizontales. La estructura geológica en los campos EB es compleja. Los campos están separados por una estructura de sal que eleva las formaciones superiores. La dirección y magnitud de los esfuerzos principales son relativamente uniformes en ambos campos pero los yacimientos son maduros y la presión tiene hasta 70% de agotamiento. Para identificar la mejor técnica de control de arena para pozos horizontales, un equipo multidisciplinario formado por petrofísicos, geofísicos, especialistas en física de roca, geomecánicos e ingenieros de perforación/diseño estudiaron el campo para proponer una solución de ingeniería. Un modelo geomecánico del subsuelo unidimensional (1D M.E.M) fue construido a partir de la información de los 67 pozos existentes en ambos campos. Información como resultados de datos de ensayos mecánico en laboratorio, pruebas de goteo, registros de imagen de pozo, registros acústicos de nueva generación y eventos de perforación fueron utilizados para calibrar el 1 D M.E.M. El 1D M.E.M también fue validado con análisis post mortem de producción de arena. El equipo de especialistas en geología y geofísica actualizó y mejoraron el marco estructural existente aplicando técnicas de inversión sísmica y física de roca además de interpretación de fallas y fracturas. Información como cubo de densidad, velocidad de compresión/cizalla, porosidades efectiva/total, volúmenes mineralógicos y litológico 3D permitieron obtener los insumos espacial requeridos para la simulación geomecánica numérica 4D en el yacimiento y en particular en las arenas. El equipo multidisciplinario

usó una plataforma única para integrar todas las fallas/fracturas/ horizontes re-interpretadas y propiedades mecánicas 3D que fueron computados y guiados espacialmente a partir de los resultados de la inversión sísmica, física de roca y el cubo de litología. Los cubos de presión de poro y propiedades mecánicas, las fallas y fracturas se usaron para calibrar el estado de los esfuerzos principales actuando en las arenas antes de la producción en el yacimiento (pre-producción). El modelo de geomecánica del subsuelo 3D numérico de los esfuerzos y deformaciones de los campos EB se utilizó para estimar los valores de la caída de presión crítica 3D segura (sin riesgo de arenamiento) antes de la producción (a la presión original del yacimiento) y hasta la fecha, variando las presiones en los diferentes bloques del yacimientos para pozos verticales, desviados y horizontales. El modelo geomecánico del subsuelo numérico 4D confirmó que a la presión original del yacimiento los pozos verticales tenían mayor caída de presión crítica segura (sin riesgo de arenamiento) que los pozos horizontales. El modelo geomecánico 4D permitió identificar áreas con valores de caída de presión segura donde se podrían producir pozos horizontales sin riesgo de arenamiento, sin embargo, estas áreas se ubican en áreas invadidas con aguas y/o improductivas. A la presión de yacimiento actual, y donde aún existe hidrocarburos, no existe área segura sin producción de arena para cualquier trayectoria y en particular los pozos horizontales, y se concluyó que se requieren las mismas técnicas de control de arenas usadas en los pozos verticales y desviados.

Palabras clave: Producción de arenas, optimización de arenas, elementos finitos, geomecánica.

4D sanding prediction for completion optimization in the Oxfordian Sandstone of the EB Reservoir

Abstract

The EB fields are located offshore of Mexico in the Bay of Campeche. Both fields produce from the carbonates of the upper Cretaceous breach and from the sandstone of the Oxfordian. The Oxfordian reservoir is historically known to present major sand production problems and sand control is required to ensure sand-free production. Recently, Pemex has started to drill horizontal wells and it was necessary to investigate if the current completion techniques for vertical and deviated wells should be optimized for horizontal wells. The geological structure in the EB fields is complex. The fields are separated by a salt structure that has uplifted the formation. Direction and magnitude of stresses are fairly uniform throughout the fields but reservoirs are 70% depleted in the Oxfordian sandstone. To identify the best sand control technique for horizontal wells, a multidisciplinary team consisting of petrophysicist, geophysicist, rock physicist, geomechanics specialist and drilling engineers addressed the problem. A 1D Mechanical Earth Model (1D M.E.M) was built from the information in the 67 existing wells. Information such as results from mechanical core test data, leak off tests data, wellbore image logs, new-generation acoustic logs, and drilling events were used to calibrate the 1D M.E.M. The 1D M.E.M was also validated against sanding production post mortem analysis. The geological and geophysical team updated the existing structural framework model and improved the seismic information by applying seismic inversion and rock physics-based techniques. Information such as density, compressional and shear velocity, and 3D LithoCube allow obtain the required spatial input for geomechanics simulation. The multidisciplinary team used a single platform to integrate all the interpreted faults and horizons, and 3D mechanical properties which were computed and guided from seismic inversion results and constrained spatially with the litho-cube. The 3D pore pressure and the 3D mechanical properties were used to calibrate the pre-production stresses to prepare for the 3D and 4D geomechanics simulation in the sandstone reservoirs. The preproduction stress model of the EB fields was used to evaluate the past and present day 3D Safe Critical drawdown in order to prevent sanding for vertical and horizontal wells. The numerical mechanical earth model confirms at original reservoir pressure vertical wells have higher critical drawdown to prevent sanding than horizontal wells. At present day reservoir pressure, the numerical model helped spot in all the reservoirs the best area where we could drill horizontal wells with minimum risk of sand production. However those areas are located in non-productive zone. Today regardless of well geometry, there is no benefits of drilling horizontal well in term of getting higher safe critical drawdown, the reservoir has already reach its critical reservoir pressure sand control is required.

Keywords: Sanding production, geomechanics, completion optimization, finite element.

Introduction

The EB fields are located offshore of Mexico in the Bay of Campeche. Both Fields are producing from the carbonates of the upper Cretaceous breach and from the sandstone of the Oxfordian. The Oxfordian reservoir is historically known to present major sanding production problems and sand controls are required to ensure sand free production. Recently, Pemex has started to drill horizontal wells and it was necessary to investigate if the current completion techniques for vertical and deviated wells should be optimized for horizontal wells. To achieve this objective, a full 4D Mechanical Earth Model was built to investigate the safe drawdown required to prevent sanding in the reservoirs of the horizontal wells.

Methodology

A one dimensional mechanical earth model (1D M.E.M) was built from available information of the 67 wells drilled in the EB fields. Key information such as rock mechanics parameter from laboratory results, breakouts interpreted from image logs and/or oriented caliper, closure pressure interpretation from leak off test information, horizontal stress anisotropy from new generation of acoustic tools were key to constrain the characterization of strength, geo-pressures and stresses profiles in the EB fields. In parallel geophysicist integrated the existing seismic information (CRP gathers from PSDM with normal move out and two high picking interval velocity

in time and depth domain) and perform seismic inversion to obtain density, velocity (Shear and compressional). The seismic inversion results in combination with petrophysical evaluation and rock physics techniques allow to compute a full 3D LithoCube that capture the lateral variation in the whole field but in particular in the Oxfordian Sandstone. On the other hands, geologist worked in the structural model by including faults, fractures and horizons to ensure a proper spatial mapping of the reservoirs. Finally, the 1D MEM findings in combinations with the G&G results were integrated in a single platform for 3D and 4D Geomechanics simulations to calibrate the sand failure in the reservoirs observed in the past and predict it for horizontal wells.

Building the mechanical earth model

Geomechanics data audit

At the beginning of the study, the EB fields had already 67 wells drilled. A data audit was perform in order to select and organized the key information from geological, logs, drilling, seismic and production data, required for building the 1D and then the 4D MEM. The following picture describes the quantity of available information gathered during the data audit from 67 wells and boreholes. From experience in running similar projects that guaranty a predictive mechanical earth model, a minimum of 40% of available information should be gathered from the extensive "wish" list of necessary information.

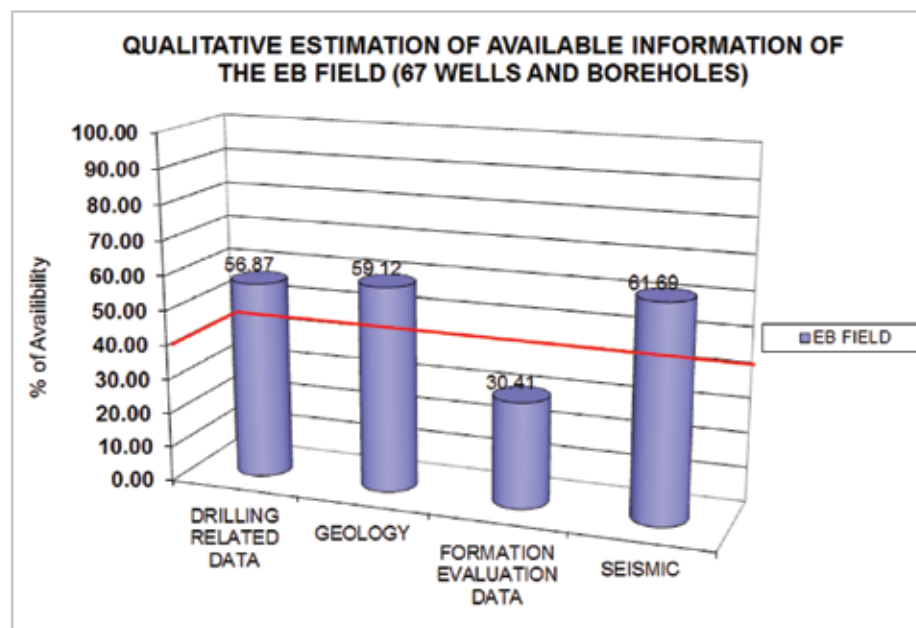


Figure 1. Qualitative estimation of available information in the EB field from 67 wells and boreholes.

The data was organized in a comprehensive manner to qualify and quantify the possible impact on the quality of the M.E.M.

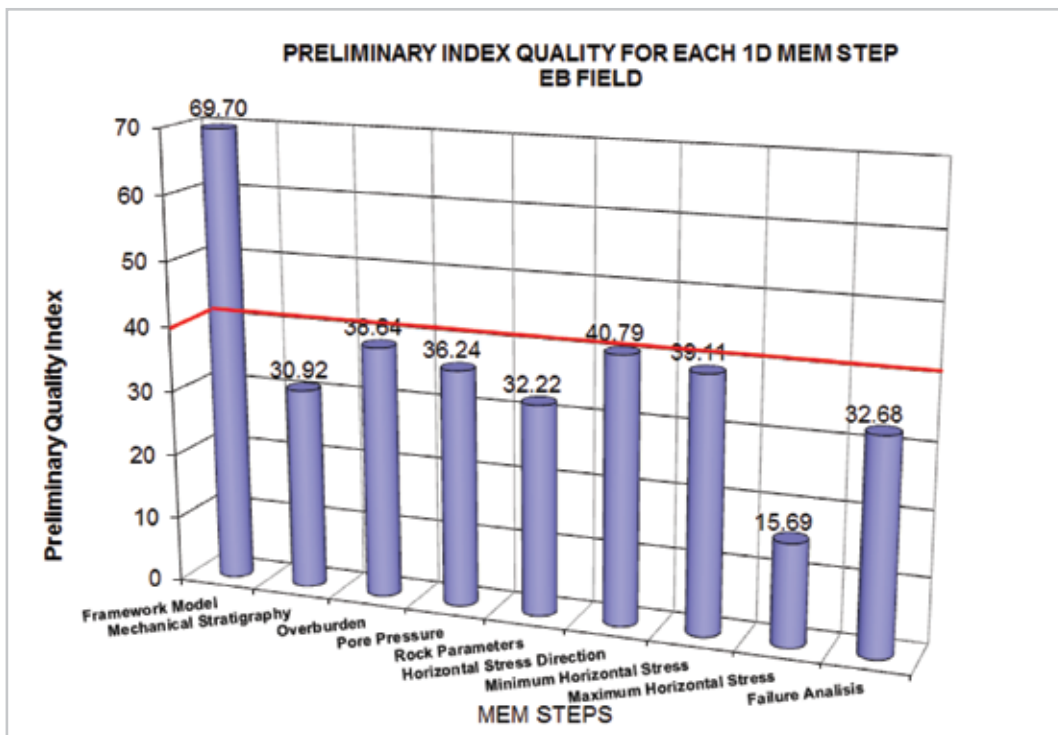


Figure 2. Quantitative estimation of the impact on each 1D MEM steps from available information in the EB field from 67 wells and boreholes.

For the EB fields the formation evaluation data is falling below the 40% threshold which as a consequence impacts most of the MEM steps. However, the seismic inversion and rock physics techniques and spatial characterization will help overcome and mitigate the impact for the mechanical earth modeling.

Framework model

The framework model is fundamental when the overall objective of a study is to build a 3D/4D Mechanical Earth Model. For this part of the project, various geoscientists integrated worked with the seismic and geological information. The seismic inversion analysis allowed capturing the lateral variation of the velocity, (compressional and shear) and density in the field, **Figure 2**.

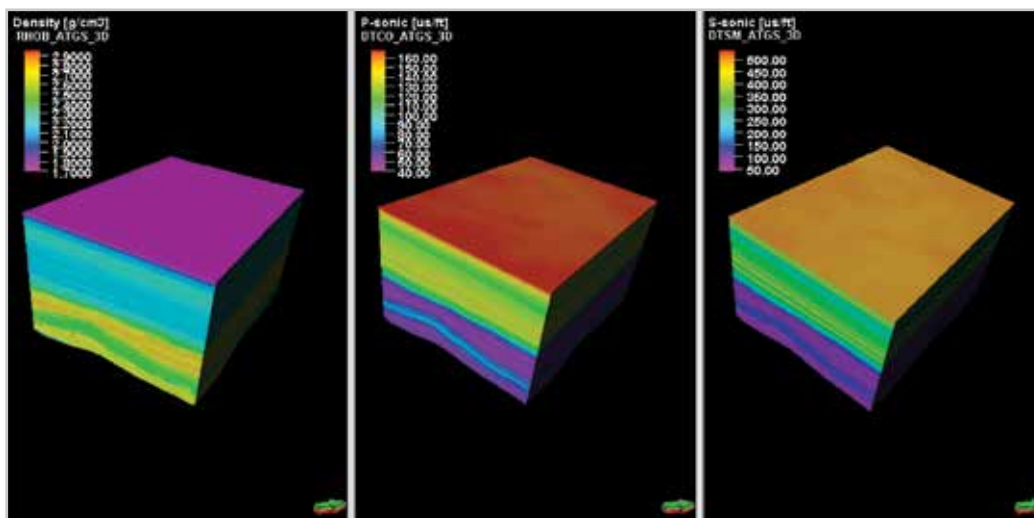


Figure 2. Seismic Inversion results: RHOB, Vp and VS in the EB fields.

A total of 28 horizons and 57 faults were interpreted from tertiary and Mesozoic formations. Finally, the rock physics results in combination with the natural

fractures interpretation from borehole image and seismic discontinuity attributes were integrated to build a discrete fracture network, **Figure 3**.

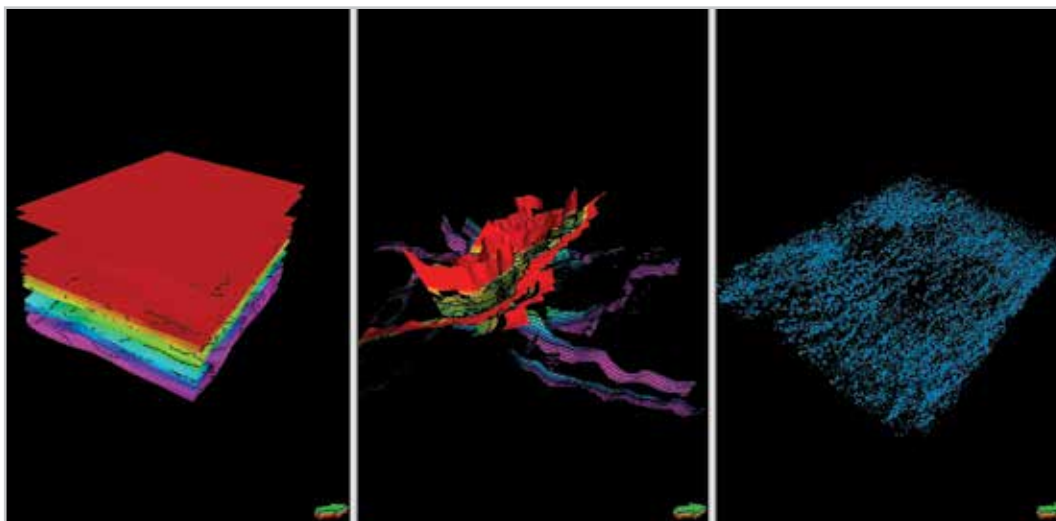


Figure 3. Horizons, faults and fractures network in the EB field.

Mechanical stratigraphy

Lithologies in the EB field are complex and include a combination of clastic sediments (Shale and sands), carbonate (Dolomite and mudstone) and evaporate (Salt and Halite). A rock physics approach combined with petrophysical evaluation allows obtaining 3D volumes of minerals, porosity (Total and effective) and a LithoCube. A total of eight (8) different families were discriminated,

Figure 4—Left picture. However for geomechanics calculation the concept of mechanical stratigraphy is required. By definition, this is the discrimination of the different family that is believed to have a similar deformation and/or failure behavior. The mud logging information in combination with caliper information, actual logs and petrophysical information allow discriminate up to 11 families of mechanical stratigraphy (**Figure 4** – right picture).

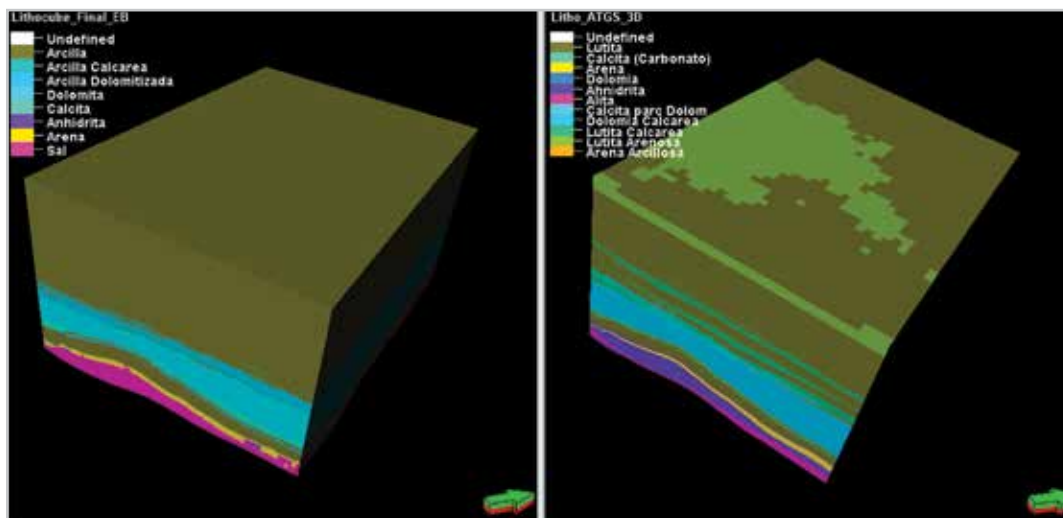


Figure 4. LithoCube vs Mechanical Stratigraphy Cube of the EB field.

Vertical stress and pore pressure

The preliminary vertical stress cube was estimated from the existing density cube and integrated mathematically along the depth. The shallow depth density was also corrected using correlation calibrated from density profile from geotechnical report. In the chapter 2.2, we will briefly

discuss the differences between a vertical stress from finite element numerical modeling (S_{zz}) that takes in account the geological complexity of a field and the analytical vertical stress S_v at it is generally known. The tertiary pore pressure was calibrated against drilling events such as gas and water influx, mud weight profile.

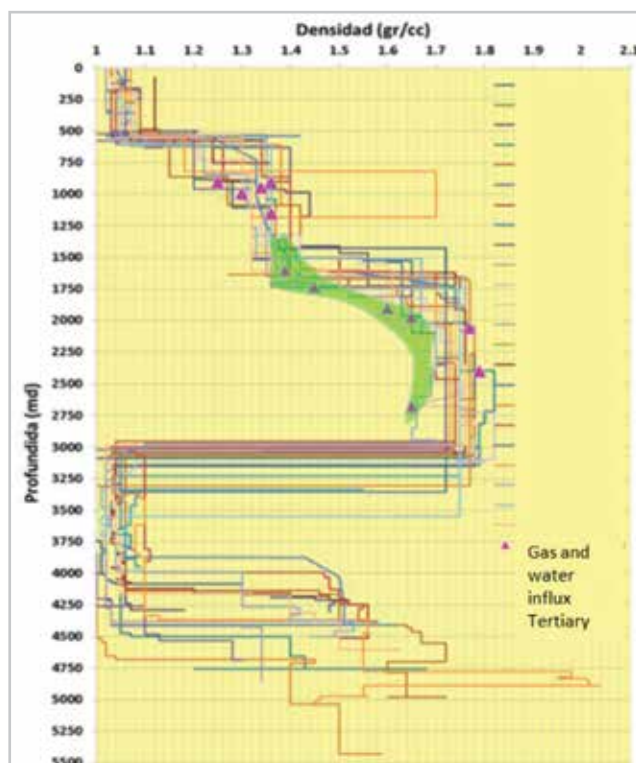


Figure 5. Mud weight profile in the EB field.

A consistent Eaton approach, (Trend line and coefficient), allow calibrate the tertiary pore pressure for the entire field.

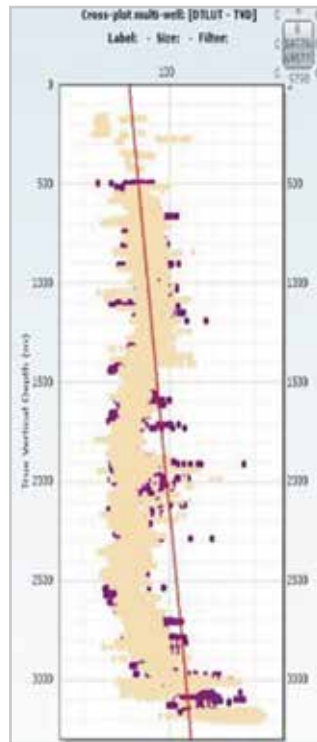


Figure 5. Consistent trend line used for Tertiary pore pressure prediction in the EB field.

The history of measured reservoir pressure was used as an input to calibrate the pore pressure in the carbonates of the cretaceous and in the sandstone of the Oxfordian.

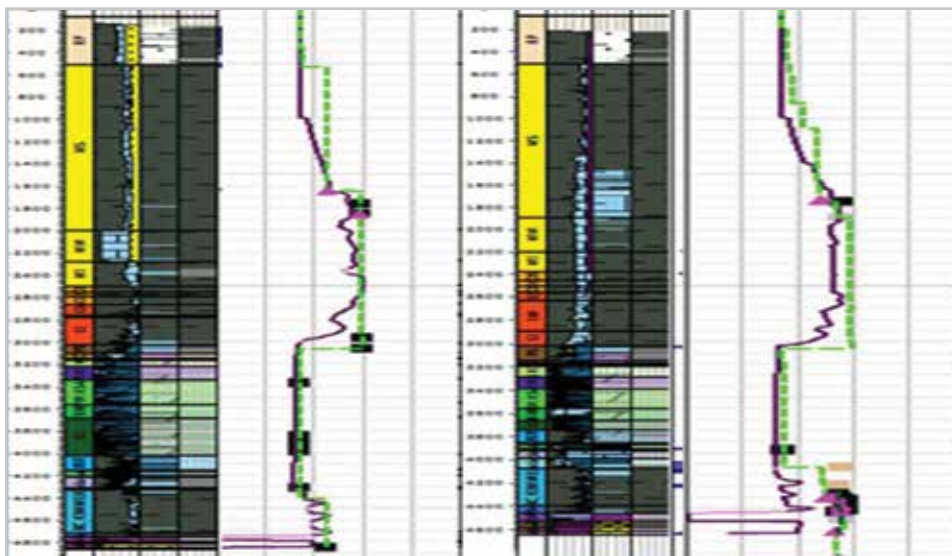


Figure 5. Example of the Pore pressure calibration in 2 key wells of the EB field. Pink triangle represents gas and water influx.

The velocity to effective stress transform calibrated from the wells along with the results of the Vp, Vs, RHOB and mechanical stratigraphy cube allow to compute a pore pressure cube for the whole field, **Figure 6** and **7**.

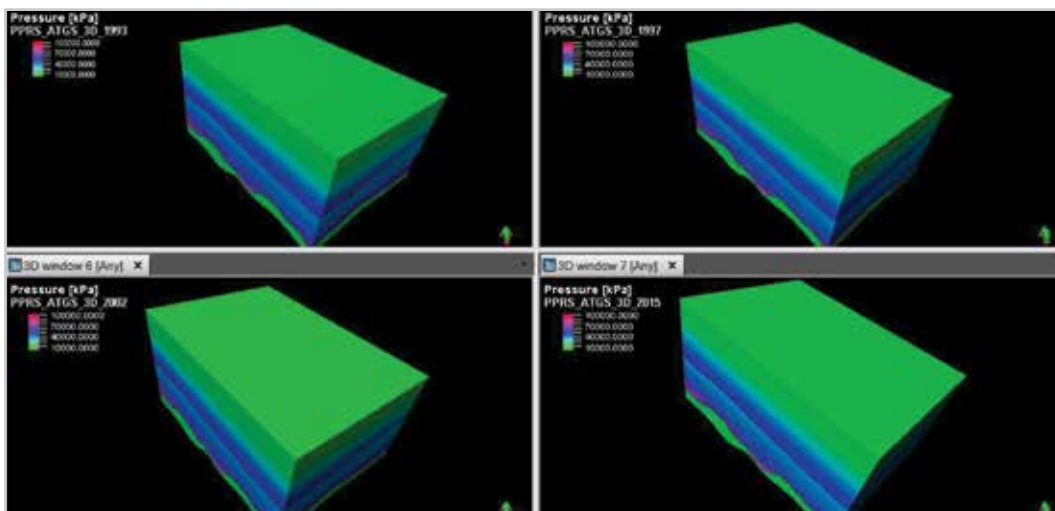


Figure 6. Pore pressure cube from 1993 to 2015.

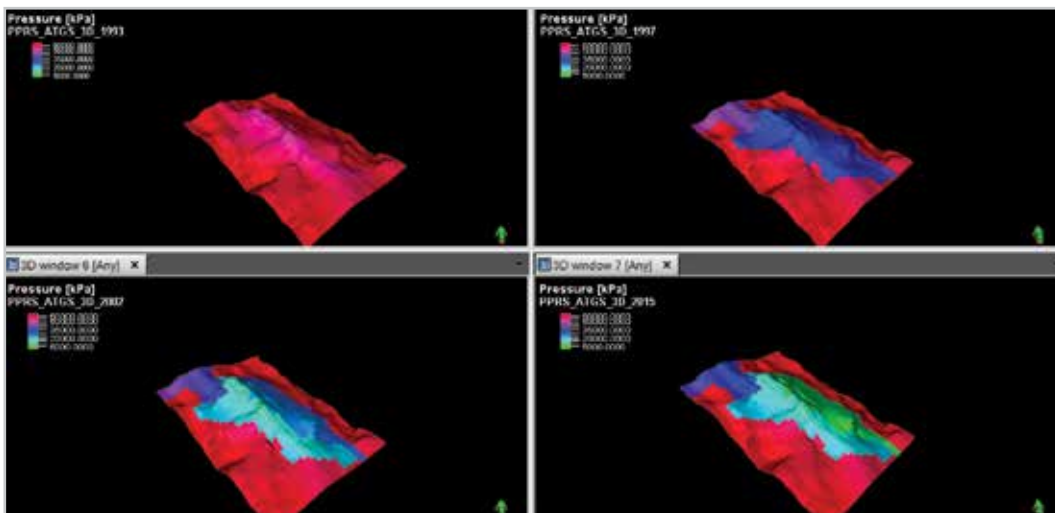


Figure 7. Variation of the reservoir pressure in the Oxfordian reservoir from 1993 to 2015.

Rock strength parameters

EB fields have mechanical core test information only in the sandstone reservoirs of the Oxfordian. Triaxial test,

unconfined compressive strength test and hydrostatic tests are available and correlations were established in order to reconstruct strength and elastic profiles, **Figure 6**.

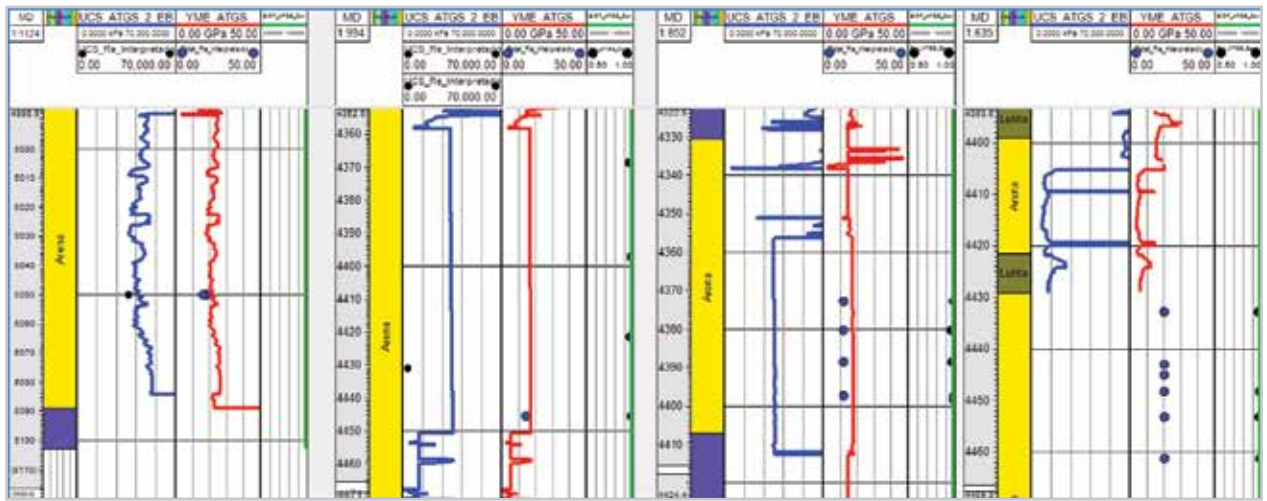


Figure 6. Example of the elastic properties and rock strength profile along four wells of the EB field, (Track 1 to 5: Depth, Lithology, UCS, Static Young Modulus and Biot Coefficient).

The 1D equation of mechanical parameters calibrated against core test along with the results of the Vp, Vs, RHOB, porosity and mechanical stratigraphy cube allow computing elastic parameters and rock strength cube for the whole field, **Figure 8**.

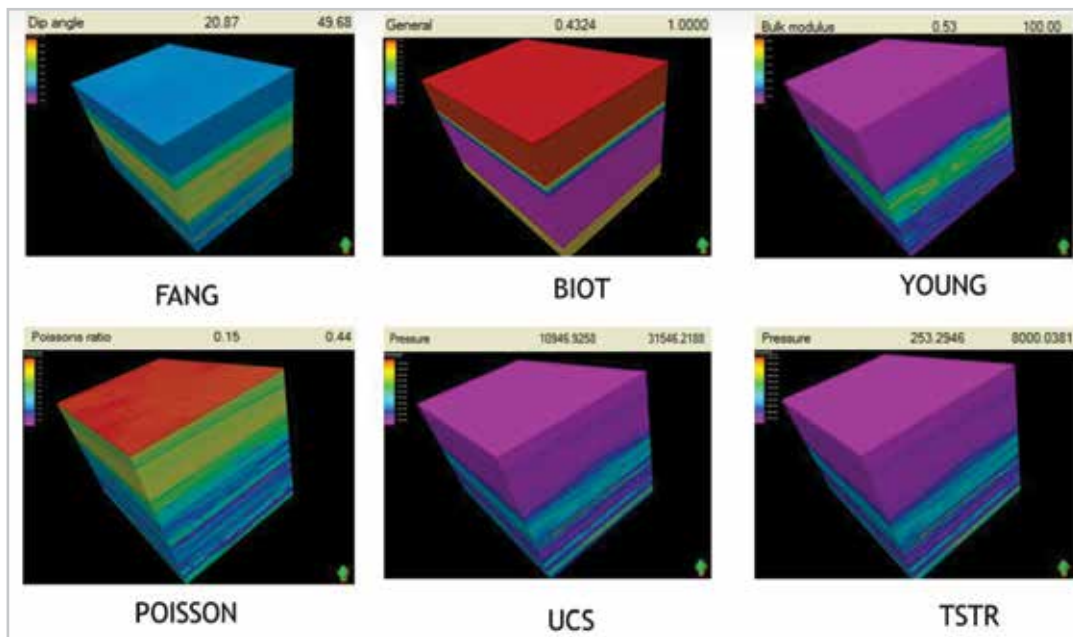


Figure 8. 3D Elastic properties and rock strength parameters cubes.

Horizontal stress direction

Twelve image logs and 17 oriented caliper were interpreted in order to calibrate local stress direction. Even though the EB field has salt tectonic acting below the Oxfordian and the

reservoir has more than 70% depletion, the interpretation still indicated a consistent horizontal stress directions between wells, (SH max azimuth of 50 +/- 10 degrees with respect to north).

Analytical fracture gradient and horizontal stresses magnitudes

Mini-frac, leak off test, induced mud losses events and upper limit of equivalent circulating density were gathered and

analyzed. A Matthews and Kelly³ type of correlation was established to build the complete 1D fracture gradient profile for the field. The analysis indicated the effective fracture stress to be highly dependent with lithology, **Figure 7**.

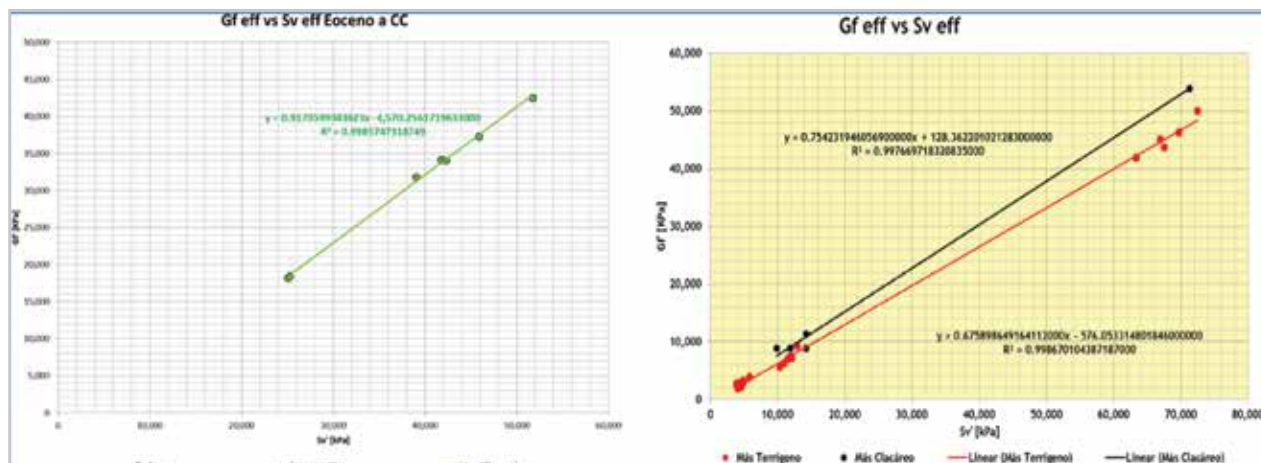


Figure 7. Lithology dependent effective fracture stress vs. effective vertical stress, (left picture: Calcareous shale of the Eocene), right picture (Tertiary and Jurassic shale and carbonates of the Cretaceous).

The closure interpretation from the mini-frac and leak off test indicated an average ratio of five percent (5%) between Fracture gradient and closure pressure. The preliminary stress profile was assumed to be:

$$Sh_{min} = 0.95 * Fracture Gradient$$

Maximum horizontal stress calibration points were inverted from four different approaches: Adnoy⁹ method (Inversion from interpreted breakdown pressure of leak off test or Mini-Frac test). This approach usually overestimates the horizontal stress anisotropy, **Figure 8**. In the following figures we observed horizontal stress anisotropy up to 60% which is unreasonable from this part of the world.

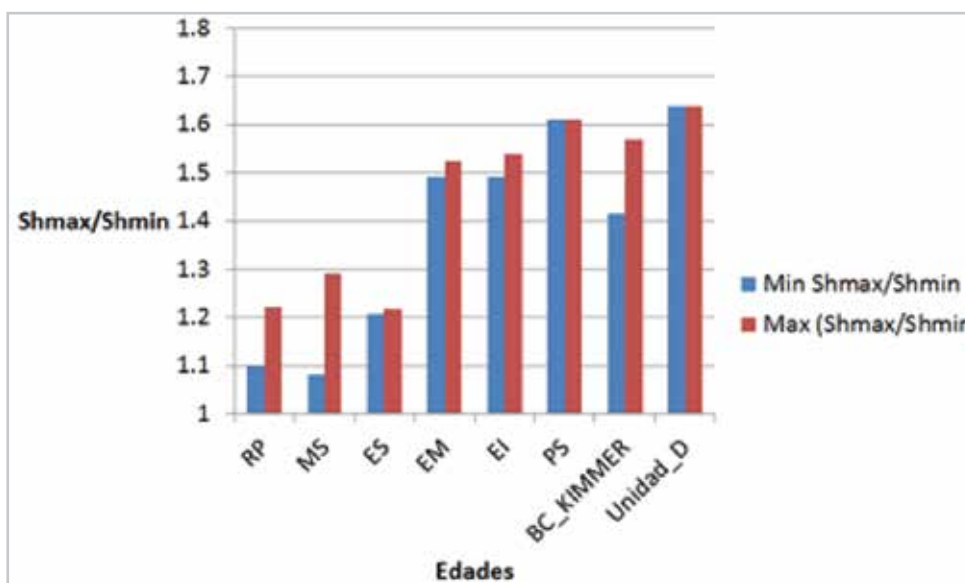


Figure 8. Variation of the minimum and maximum horizontal stress anisotropy along the geological column of the EB field.

A second approach consisted of inverting the horizontal stress anisotropy at the depth where a failure had been interpreted in a borehole image or an oriented caliper, **Figure 9**. This method indicated low stress anisotropy in

the Tertiary and to a maximum of 17% of horizontal stress anisotropy in the carbonates formation of the Mesozoic. In the sandstone reservoir of the Oxfordian, this method indicated 3% horizontal stress anisotropy.

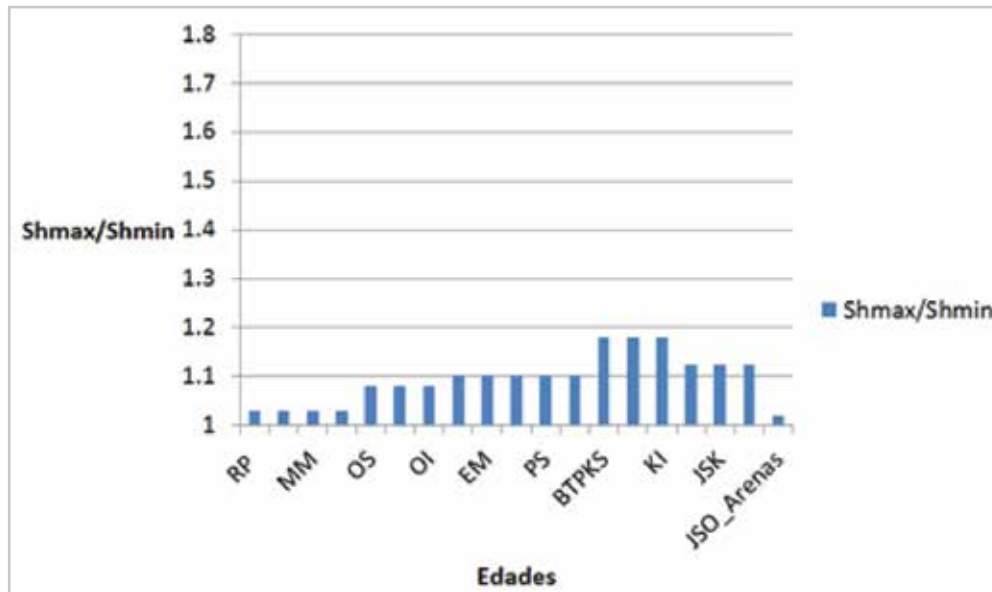


Figure 9. Variation of the horizontal stress anisotropy along the geological column of the EB field inverted from failure observed in oriented caliper and borehole image logs.

The method of Etchecopar⁴ and all consist of a least square method from multi-well borehole failure information that investigate all the possible scenario stress direction and shape factor Q, ($Q = f(R) = (s_2 - s_3) / (s_1 - s_3)$) that will match the azimuth of the maximum value of tangential stress

around the borehole (location of the interpreted failure in borehole images and/or oriented caliper). Using this technique, the horizontal stress anisotropy in the EB field also varies from 10% up to 17% in the carbonates formation of the Jurassic, **Figure 10**.

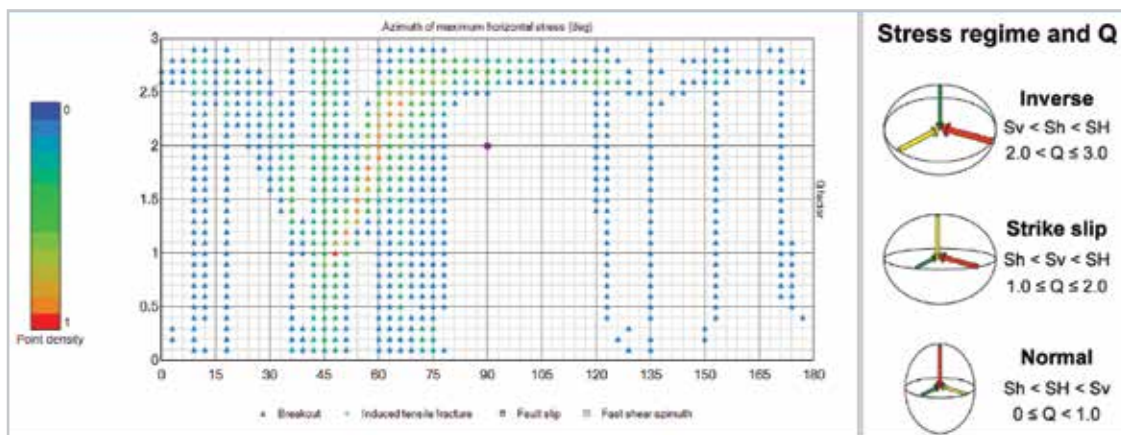


Figure 9. Example of the possibility of the stress regime and Q factor in the Jurassic Kimmeridgian of the EB field ($Q=R= 1$, SH_{max} Azimuth - 45 - 75 degrees) - Knowing vertical and minimum stress magnitude, SH_{max} can be easily calculated.

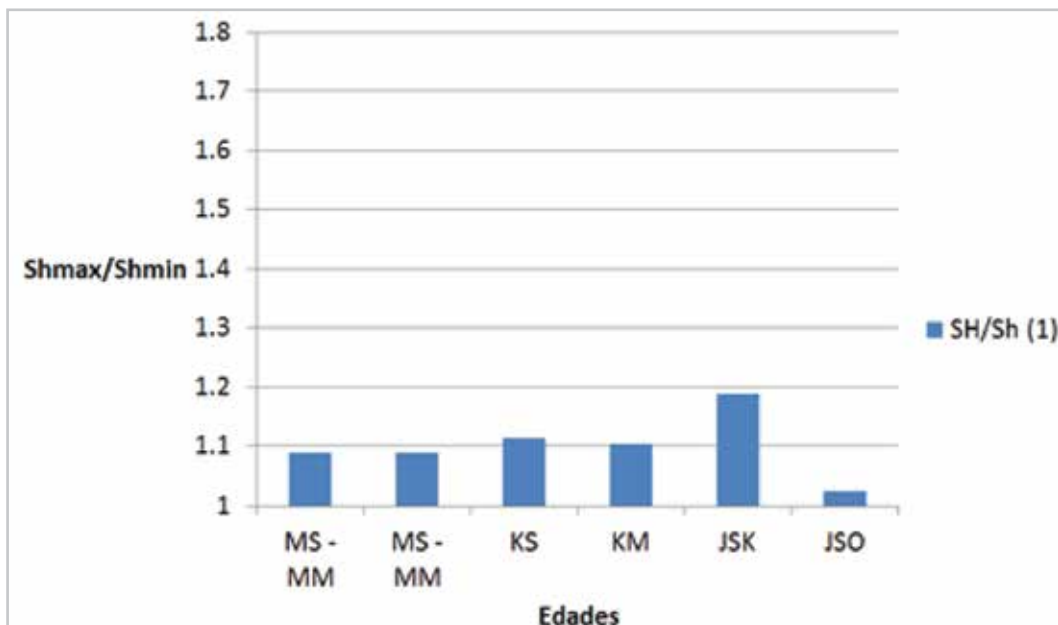


Figure 10. Variation of the horizontal stress anisotropy along the geological column of the EB field inverted from Etchecopar techniques.

Finally the last method used was the availability of an acoustic tool of new generation which allows getting the magnitude of the maximum horizontal stress in the Jurassic Kimmeridgian. We will not in details in this paper on the

technique, many publications already exists^{4,5} and ⁶. The horizontal stress anisotropy from these methods indicated a 7 to 10% of horizontal stress anisotropy.

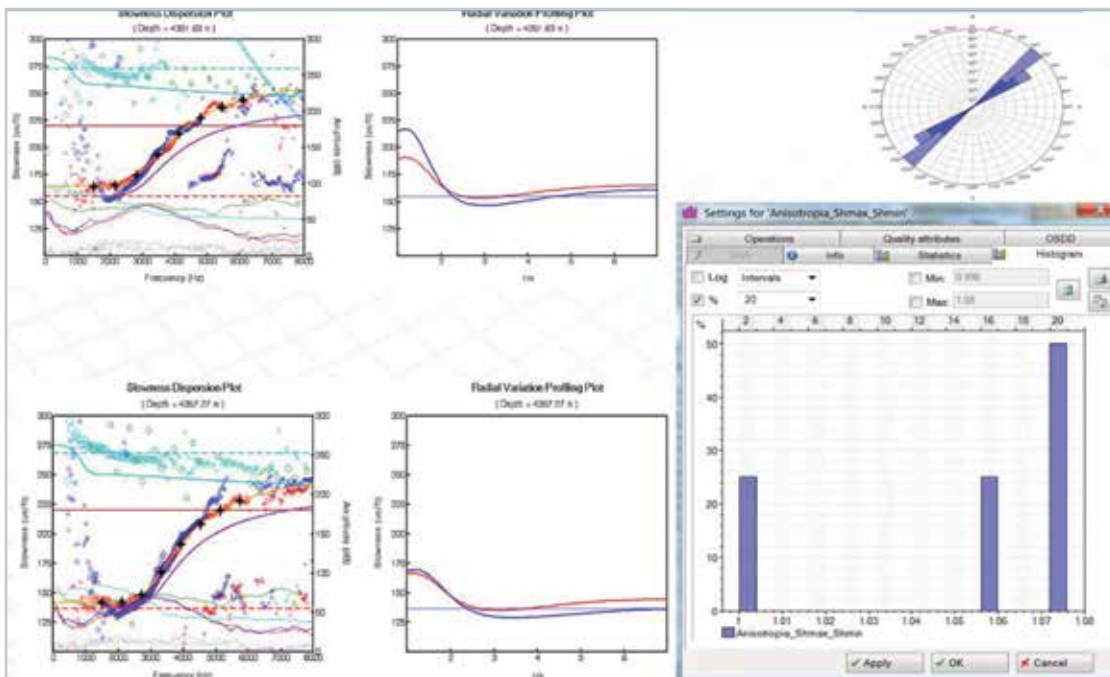


Figure 12. Horizontal stress anisotropy from new generation of acoustic tool in the Jurassic Kimmeridgian - 7 to 10% SHmax/Shmin.

All those calibration points for maximum horizontal stress along with all the interpreted closure pressure for minimum horizontal stress were used to get the horizontal tectonic

strain (ϵ_h, ϵ_H) in each formation and for each lithology from the generalized Hooke's law equation to compute a complete horizontal stress profile of the EB field.

$$d\sigma_h^e = \frac{\nu}{1-\nu} d\sigma_z - \frac{\nu}{1-\nu} \alpha dp + \frac{E}{1-\nu^2} d\epsilon_h + \frac{\nu E}{1-\nu^2} d\epsilon_H$$

$$d\sigma_H^e = \frac{\nu}{1-\nu} d\sigma_z - \frac{\nu}{1-\nu} \alpha dp + \frac{E}{1-\nu^2} d\epsilon_H + \frac{\nu E}{1-\nu^2} d\epsilon_h$$

Figure 13. Generalized Hooke's law equation - Warspinky, (See Reference 1).

Analytical stress regime is normal in the tertiary formation and strike-slip in Mesozoic, except for the sandstone of the Oxfordian which has a normal stress regime. An

inverse stress regime can be observed locally in some of the carbonates and shaly carbonated interval of the Jurassic, **Figure 14**.

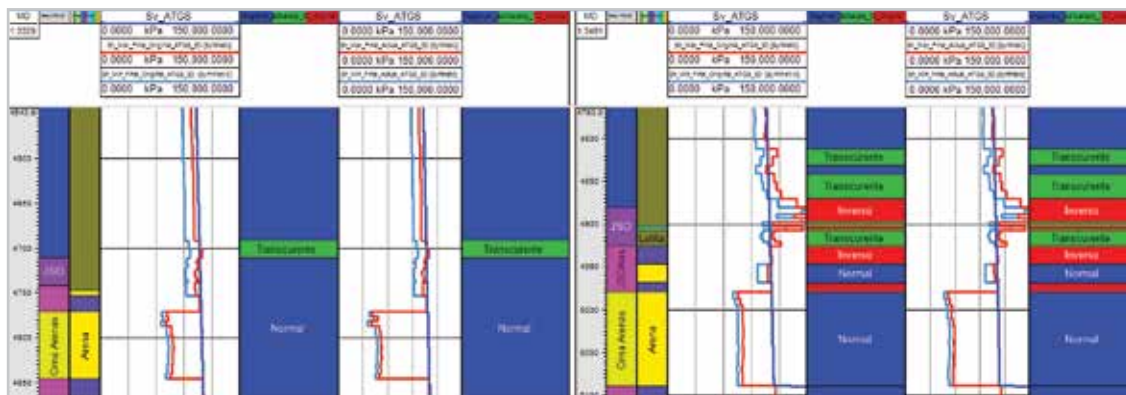


Figure 14. Example of the stress regime in two wells of the EB field tracks: Depth, geological ages, lithology, original stresses, original stress regime, actual stresses, actual stress regime, (normal regime - dark blue, Strike-Slip - green; inverse regime - red).

3D/4D Sanding potential prediction analysis

Most of the wells, at the early time of their well testing, presented sand production problems. From the 19 wells analyzed the drawdown at which sanding production was observed vary from 5 Kg /cm² psi to 80 Kg /cm². In order to capture better the sanding failure mechanism in this sandstone reservoir, an elastic-plastic numerical simulation approach was conducted in order to compute the principal stress magnitude and direction of the EB field and in

particular in the Oxfordian sandstone reservoirs. In order to validate the computed numerical stress, the estimated numerical principal stresses were compared in magnitude and in direction against the 1D analytical horizontal stresses, **Figure 15** and **16**). Even though the presence of rotation is captured around faults, at well location the numerical stress direction is consistent with the local stress direction, **Figure 15**. In the case of stress magnitude the numerical simulation capture better the increase of stress in carbonates lithology than the analytical solution, **Figure 16**.

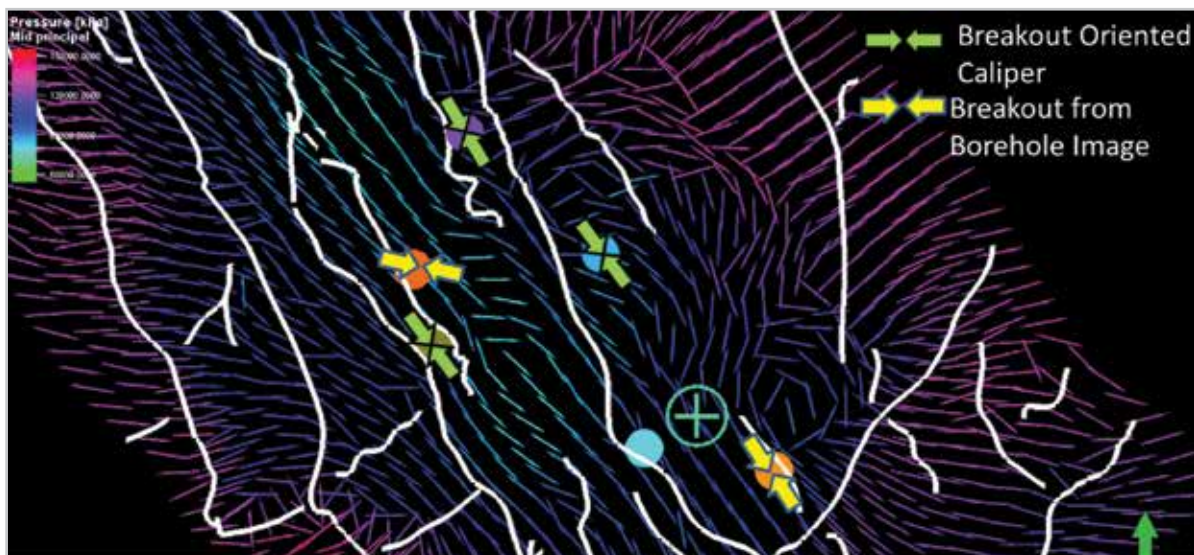


Figure 15. Stress direction map (Shmin) vs local stress direction from oriented caliper and borehole image, (Oxfordian Sandstone) - EB field.

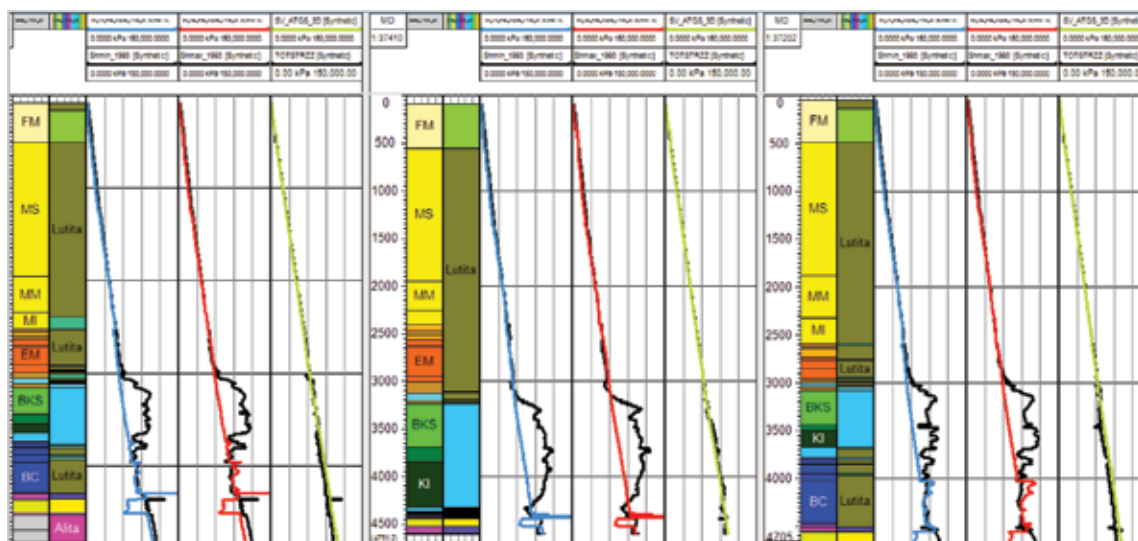


Figure 16. Comparison of numerical vertical, minimum and maximum horizontal Stress (Black) vs. analytical stress, (blue, red and green).

The numerical stress simulation allows computing the stress regime for any place and at any time in the reservoir. The initial stress regime in the reservoir was mainly inverse and strike slip, however the actual stress regime is normal.

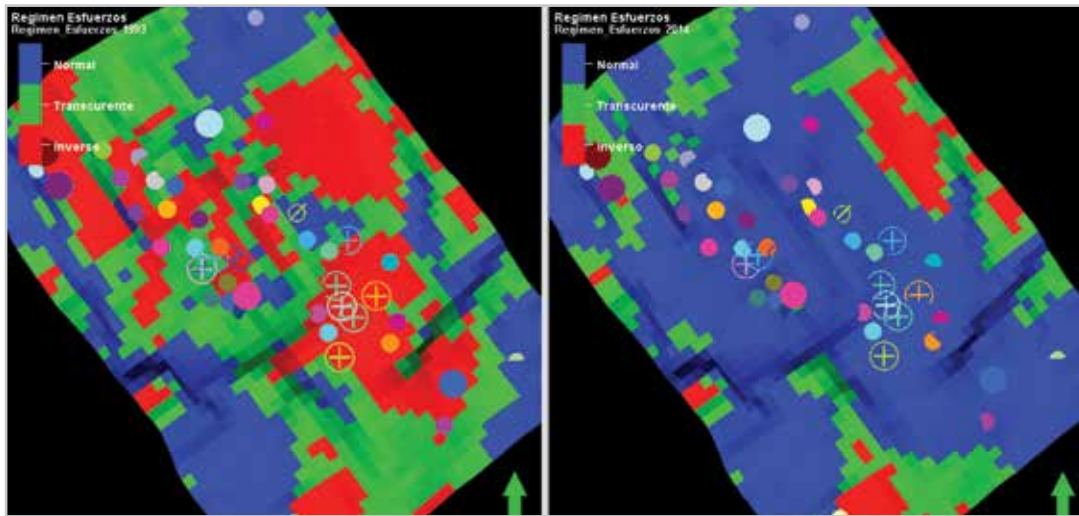


Figure 17. Comparison of numerical stress regime at original pressure vs. actual pressure, (blue is normal stress regime, green-strike slip and red-inverse).

The numerical horizontal stress anisotropy in the producing reservoir was also compared at original and at present day reservoir pressure. Present day horizontal stress anisotropy is higher than original horizontal stress anisotropy. Values

are still consistent with all the method detailed previously to invert for maximum stress calibration from failure interpreted from oriented caliper and borehole image.

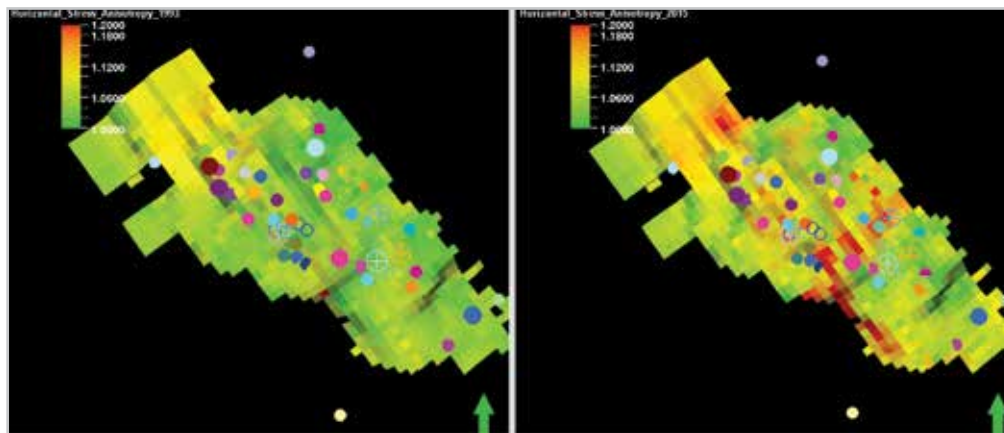


Figure 18. Comparison of numerical horizontal stress anisotropy in the reservoir at original and present day reservoir pressure.

Once the numerical stresses calibration was achieved in direction and magnitude, a sanding failure criterion was calibrated for the EB field against sanding production observed during production of 19 wells of the EB field. The failure criteria was calibrated in 1D, initially with the

condition that drawdown at which the sanding production has been observed in the wells, **Figure 19** – blue curve, is partially lower than the critical drawdown at which the rock fails and produces sand in the perforated interval, **Figure 19** – red curve.

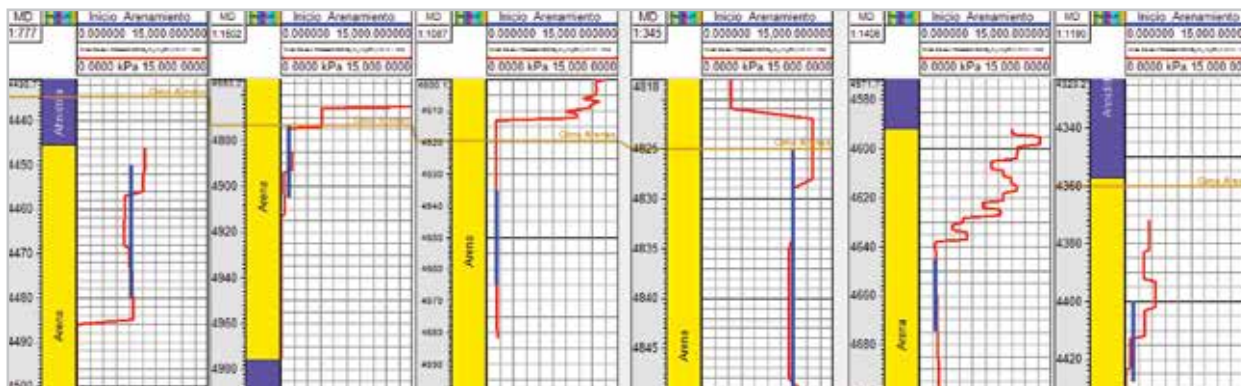


Figure 19. Example of predicted critical drawdown (red curve) vs drawdown at which sanding production has been observed, (blue curve).

The calibrated failure criteria was then apply in 3D to the numerical principal stress at original pressure and then at actual reservoir pressure. At original pressure the reservoirs had many area where the reservoir could have been tested and produce without sand production, however the Geomechanics behavior of the reservoir would have required in many places a drawdown lower than 50 Kg/cm². Figure 20 is showing the critical

drawdown for any vertical well at original pressure. Red cells represent area in the reservoir that requires a maximum of 10 Kg/cm² of drawdown to keep the rock from failing. Orange area represents cells in the reservoir that require a maximum of 50 Kg/cm² of drawdown to keep the rock from failing. Green are represent cells in the reservoir where drawdown can be 100 Kg/cm² without risk of producing sands.

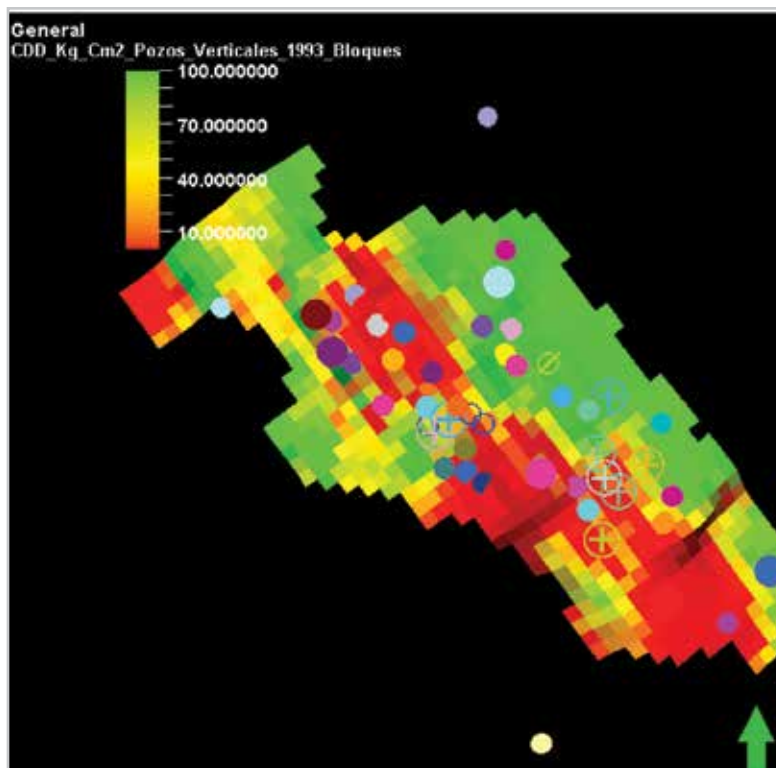


Figure 20. Critical drawdown in the reservoir for vertical well at original reservoir pressure.

Figure 21 is showing the critical drawdown for any vertical well drilled at present reservoir pressure. Red cells represent area in the reservoir that requires a maximum of 10 Kg/cm² of drawdown to keep the rock from failing. Orange area

represents cells in the reservoir that require a maximum of 50 Kg/cm² of drawdown to keep the rock from failing. Green area represents cells in the reservoir where drawdown can be 100 Kg/cm² without risk of producing sands.

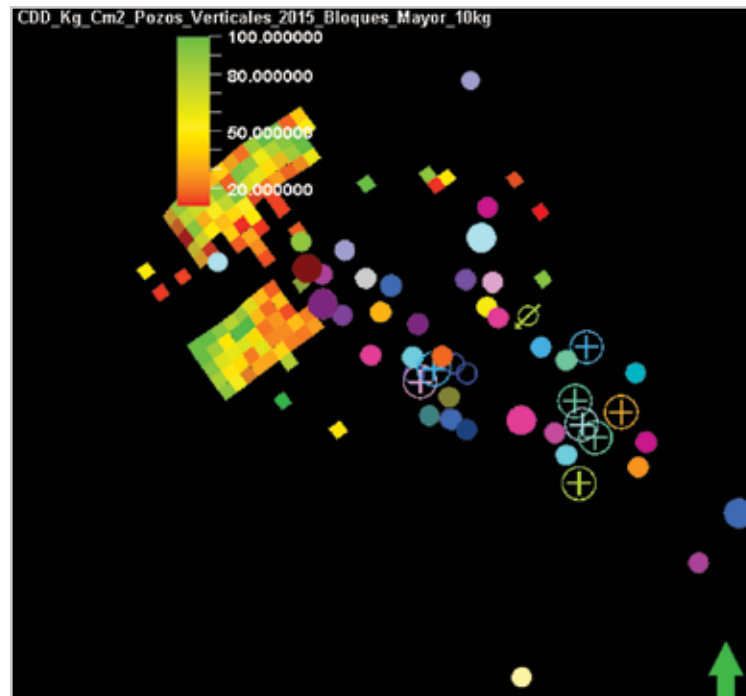


Figure 21. Critical drawdown in the reservoir for vertical well at actual reservoir pressure.

Since last year, a campaign of horizontal drilling has started and it was of interest to investigate up to which drawdown the wells could be in production reducing the risk of sanding production. The first horizontal well in production today is producing with standalone screen with a drawdown of 3 Kg/cm². **Figure 22** is showing the critical drawdown for any horizontal well drilled in the regional minimum stress

direction, (140 degrees) at original pressure. Red cells represent area in the reservoir that requires a maximum of 10 Kg/cm² of drawdown to keep the rock from failing. Orange area represents cells in the reservoir that require a maximum of 50 Kg/cm² of drawdown to keep the rock from failing. Green area represent cells in the reservoir where drawdown can be 100 Kg/cm² without risk of producing sands.

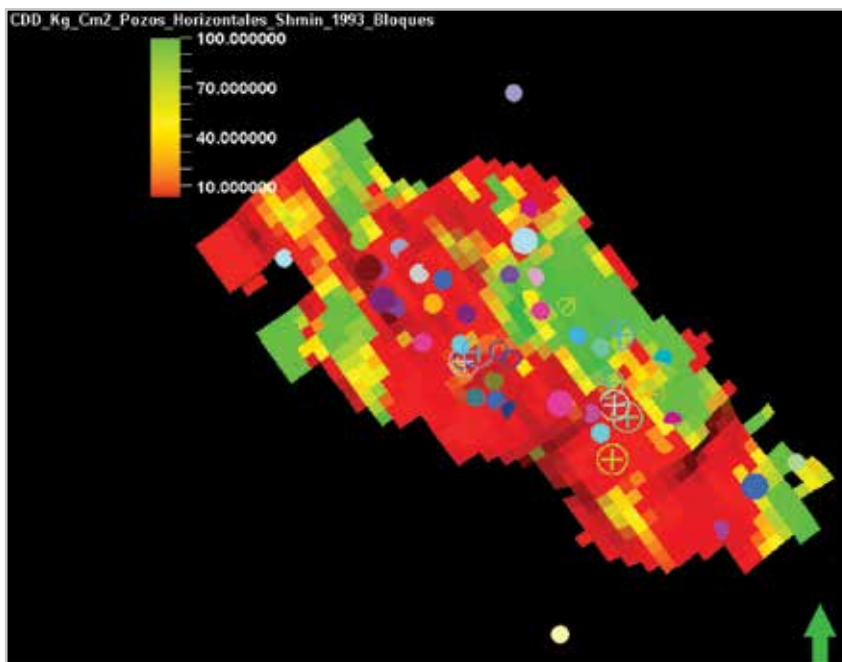


Figure 22. Critical drawdown in the reservoir for horizontal well drilled @ 140 degrees (regional minimum horizontal stress direction) at original reservoir pressure.

Left picture in Figure 21 shows the different layers where a vertical well would have a higher drawdown than a horizontal well drilled @ 140 degrees azimuth at original reservoir pressure. Right picture in Figure 24 shows the different layers where a horizontal well drilled @ 140

degrees azimuth would have a higher drawdown than a vertical well at original pressure. At original pressure due to the stress regime at that time there was more area with higher drawdown for vertical well rather than horizontal well.

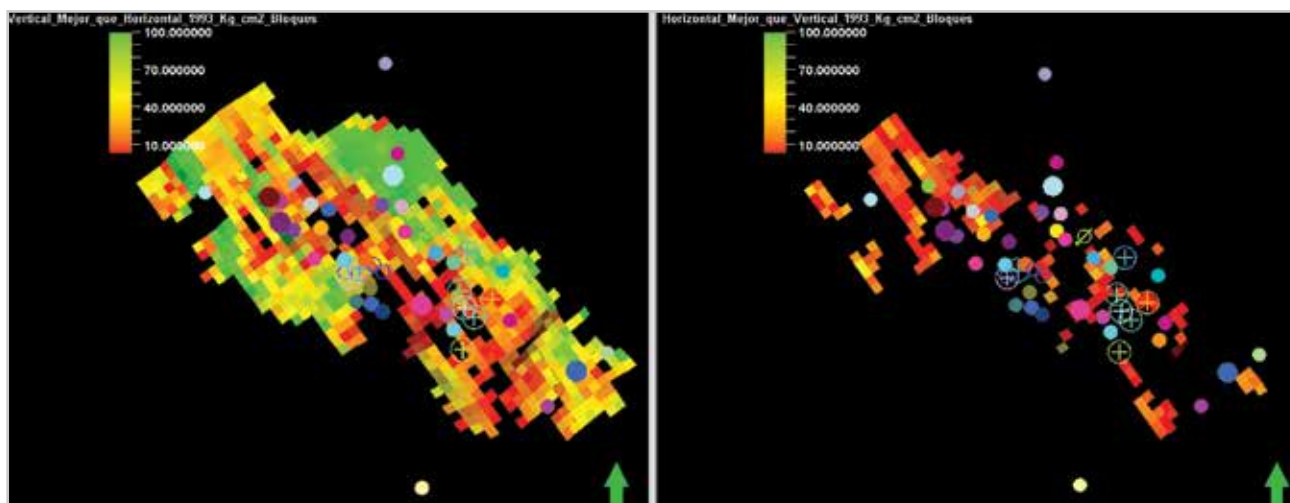


Figure 23. Comparison of layers where critical drawdown is higher in a vertical well, (left picture) or higher in a horizontal well drilled at 140 degrees, (right picture).

Finally, **Figure 24** shows the only area where a horizontal well drilled in the regional minimum stress direction could produce with drawdown higher than 3 Kg/cm² at present

day reservoir pressure. The only areas that can be produced without sand control are in a non-productive area in the north western part of the reservoirs.

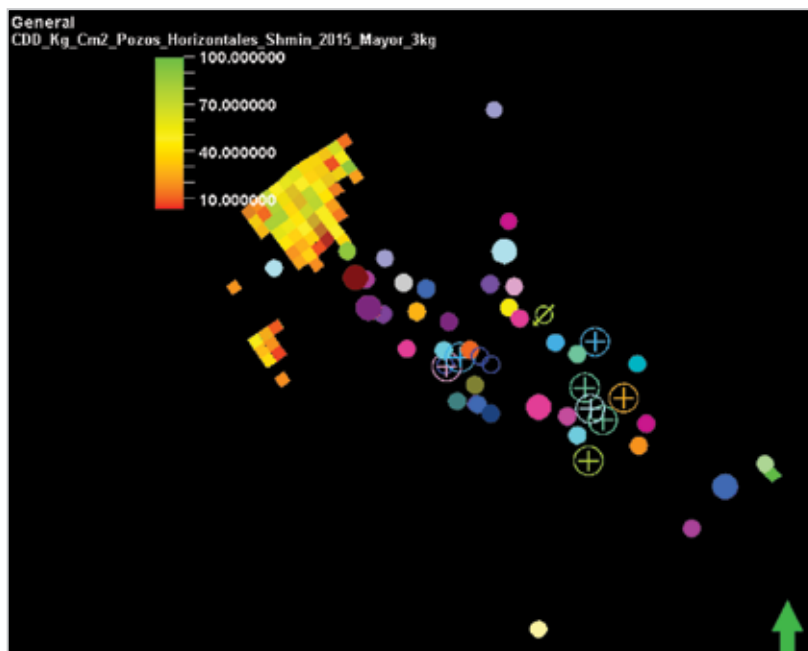


Figure 24. Critical drawdown > 3kg/cm² in the reservoir for horizontal well drilled at 140 degrees.

Conclusions

A multidisciplinary study was conducted to characterize the critical drawdown in the Oxfordian sandstone reservoir of the EB field. The study integrated state of the art seismic inversion, rock physics and advanced geomechanics numerical modeling in order to reduce uncertainty in the sanding prediction. At original reservoir pressure, the study shows that vertical wells were having higher critical drawdown than horizontal well. At present day pressure, where the depletion in the Oxfordian reservoir is up to 70%, results of the simulation did not indicate any benefits between horizontal well and vertical well in term of risk of sanding or in terms of higher critical drawdown. At present day, regardless of the well geometry, the reservoir required sand control.

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