# AN INTEGRATED GEOMECHANICAL MODELING APPROACH TO INVESTIGATE CASING INTEGRITY INCIDENTS IN THE VACA MUERTA FORMATION

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## RESUMEN

Durante la perforación de pozos en la formación Vaca Muerta de la Cuenca Neuquina, los operadores petroleros han enfrentado retos técnicos y económicos. Para que los pozos en esta área sean económicamente viables, hay que estimularlos hidráulicamente. Para diseñar trabajos de fractura es determinante conocer las características mecánicas de la formación y los esfuerzos in-situ. Cuando los trabajos de estimulación son ejecutados, problemas relacionados con la geomecánica pueden afectar la capacidad de producción del pozo. En el área de Vaca Muerta se han registrado muchas fallas debido a la deformación de revestidores. Muchos de los incidentes se han observado en el pozo que está siendo estimulado o en pozos cercanos. Estos incidentes son costosos y en muchos casos pueden resultar en el abandono del pozo. El presente trabajo describe la aplicación de técnicas de modelaje numérico para investigar el impacto de esfuerzos de cizalla como mecanismo responsable de los incidentes de deformación de revestidores observados en la formación Vaca Muerta en Argentina.

## INTRODUCTION

Geomechanical modeling of unconventional reservoirs requires a strong understanding of the variability in rock facies driven by diagenetic changes in texture and composition. Shale is characterized by thinly laminated parallel layering or bedding and exhibits transverse isotropic properties, with symmetry axes perpendicular to the bedding. In addition to this intrinsic complexity of shale, several sections of the Vaca Muerta formation exhibit intercalations of organic shale with limestone, ash beds, and calcite veins. Furthermore, different measurements suggest a tectonic strike-slip regime in the Vaca Muerta (Frydman *et al.* 2016; Pichon *et al.* 2018). The combined effect of the reduced stress difference and the material fabric may promote horizontal or fishbone fractures.

Numerous incidents of casing deformation have been reported in the Vaca Muerta shale play, Argentina, in relation to multi-stage hydraulic fracturing treatments (Garcia *et al* 2013; Rimedio *et al.* 2015). Wells must be stimulated for economic production, and this hydraulically fracturing procedure is strongly influenced by the rock fabric and in-situ stress. Failure was observed in the stimulated wells or offset wells, and in most cases at the interface between stiff and compliant rock formations. In a detailed review, many operational problems were found that resulted in extended casing rectification work including coiled tubing (CT) to perform milling operations to rotate the plugs.

This paper describes the application of a pad-scale 3D geomechanical simulation combined with high-resolution cylindrical models for a candidate well, its completion and surrounding formation. The 3D geomechanical model is set up and calibrated using single-well analyses from the Vaca Muerta formation. Subsequently, the hydraulic stimulation is simulated in this model using suitable assumptions on the treatment design (fracture geometry, fracture pressure, etc.). The geomechanical simulation allows to compute the initial in-situ stress state of the pad and the changes in stress, deformation, and rock displacement during the stimulation phase, which includes potential bedding parallel displacement. By combining this simulation with high-resolution near-wellbore models around the candidate wells, the impact of such shear deformation on wellbore integrity can be analyzed.

The obtained results contribute to the understanding of stress distribution in unconventional reservoirs during stimulation in a tectonic environment. This modeling approach can serve as the starting point for further well-centric numerical modeling on a representative volume to identify how many variables are contributing to casing deformation in specific locations in the Vaca Muerta and similar settings in other parts of the world.

## Mechanical Earth Model (MEM)

A Mechanical Earth Model (MEM) is a representation of the state of stress and the rock mechanical properties for a specific stratigraphic section in a field or basin (Plumb *et al.* 2000). Figure 1 is a conceptual representation of such a model and shows its creation from the structural framework, to the mechanical stratigraphy with rock properties describing elastic behavior and rock strength, to the pressure and stress profiles. As implemented by Schlumberger, an MEM is a logical compilation of all the relevant information about subsurface stresses and rock mechanical properties in an area, with the natural capability to be updated rapidly and sufficiently detailed to serve as guidance for drilling operations and reservoir management. Relevant information is sourced from various domains, such as geophysics, geology, reservoir engineering, and drilling.

The first step in constructing an MEM is the understanding of the local and regional geology (left). The detailed mechanical stratigraphy provides information about facies types and local deformation mechanism (middle). From this detailed first analysis, the profiles of elastic and rock strength parameters are generated and calibrated with rock mechanics laboratory data. The prediction of the subsurface pore pressure and the calculation of the in-situ stresses in agreement with the mechanical properties complete the process.

An MEM can be generated in 1D and in 3D depending on the objectives, the stage of field development and the available information. The generation of 1D MEMs along well trajectories, with varying level of complexity, has become standard industry practice in recent years. 1D MEMs integrate all the available log and core data for a well and incorporate drilling events such as, for example, kicks, loss circulation, breakouts, etc., as calibration data for defining the operational drilling mud window.

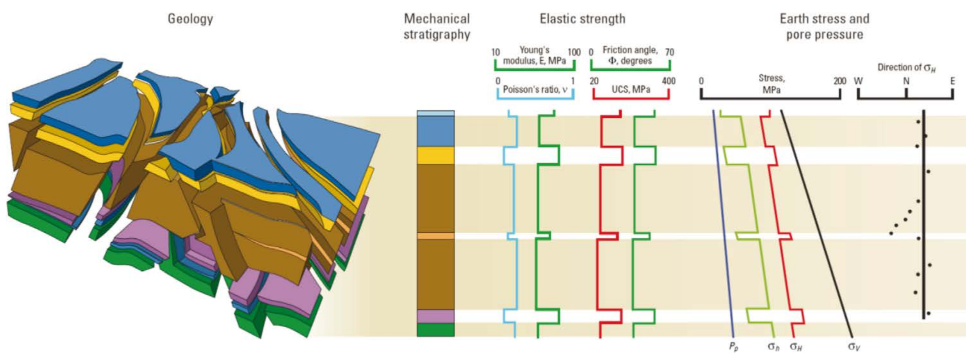



Figure 1. Concept of the mechanical earth model (after Plumb *et al.* 2000)

However, these 1D representations cannot take into consideration the lateral variation of the mechanical properties and the in-situ stress, and the impact of structural discontinuities. This can be realized in 3D MEMs along with incorporating the detailed subsurface geometry as provided by seismic interpretation with a comprehensive stratigraphic model and complex structural features such as fault networks (Frydman *et al.* 2017) and salt domes (Serra de Souza *et al.* 2012).

## 1D Modeling

The constitutive model for rocks applied in a 3D model must be derived from rock mechanical laboratory core testing. In this work, the correlations developed by Varela and Hasbani (2017) and Frydman *et al.* (2016) are used. These correlations are built using hundreds of rock mechanical tests on core samples from all around the Neuquén basin. The overburden stress gradient is about 1.0 psi/ft at the top of Quintuco level, and 1.03 psi/ft at Vaca Muerta level, and it is apparently consistent across the field. The minimum horizontal stress was measured in the area with different stress tests using the pump-in flow back rebound test (Raaen

& Brudy 2001) technique through the vertical extent of the Vaca Muerta section to improve the accuracy of the stress model (Pichon *et al.* 2018). The pore pressure measurements from mini-falloff tests (MFO) were used for the entire Vaca Muerta vertical extent. The data suggest that the pore pressure gradient is approximately 0.89 psi/ft, which is the gradient used in this study as the assumed pore pressure. Anisotropic 1D MEMs were developed based on methodology developed by Frydman *et al.* (2016) incorporating all this information. Figure 2 shows the mechanical properties of a representative 1D MEM used in this study comparing laboratory-derived and log-derived elastic anisotropic properties.

In Figure 2, horizontal gridlines delineate 25 m intervals. Log-derived mechanical properties

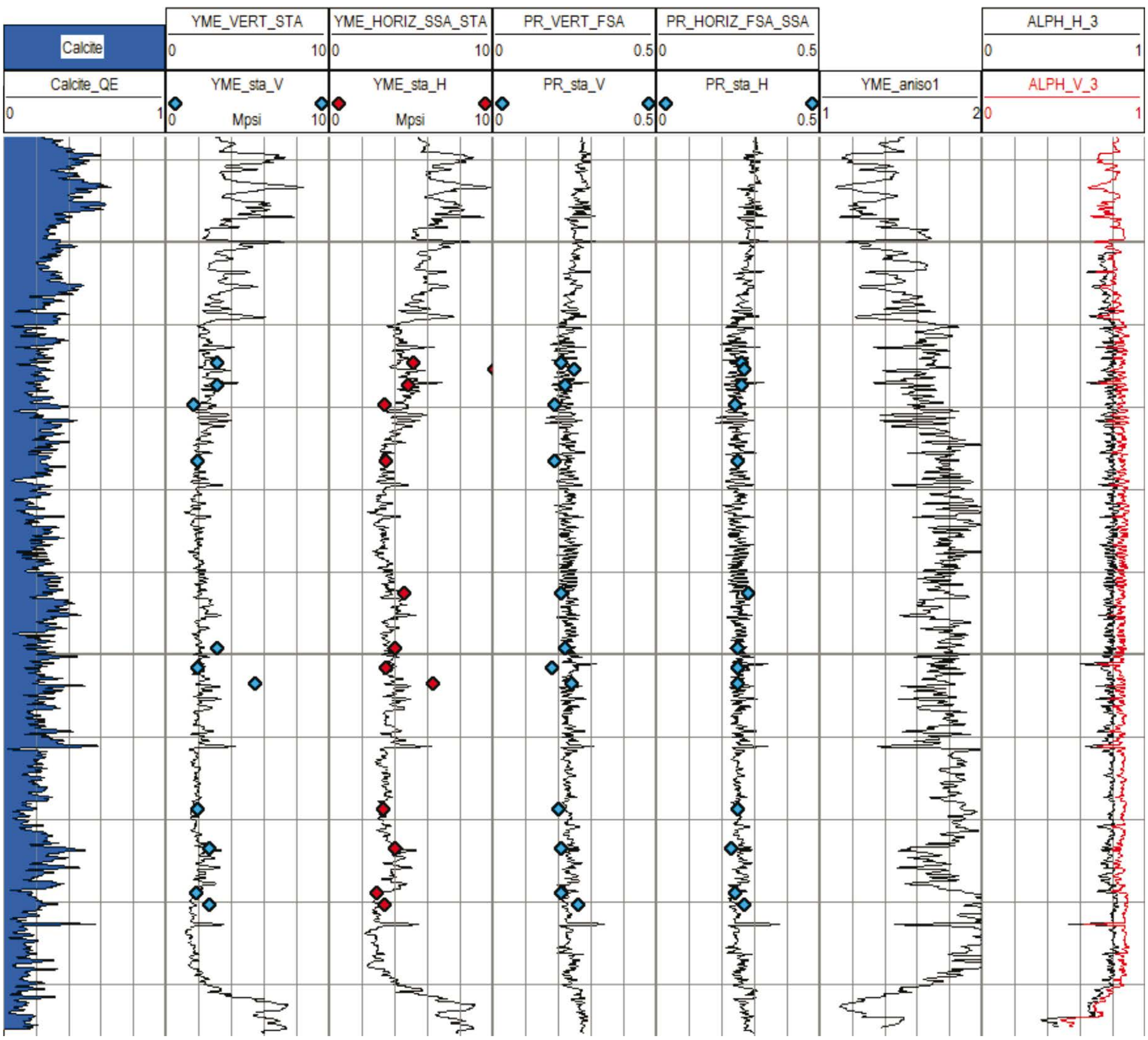


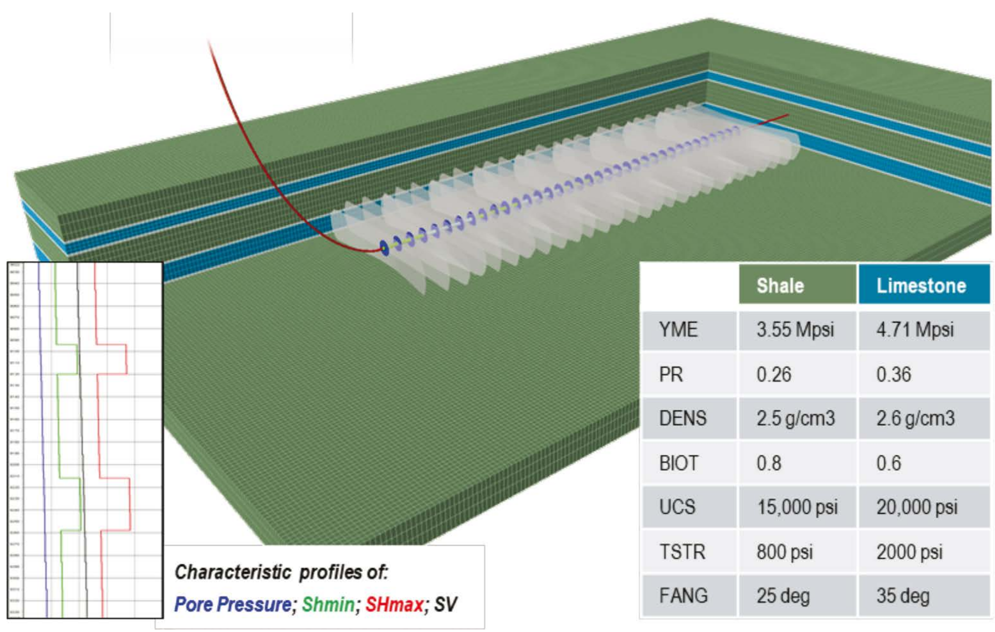

**Figure 2. Comparison of laboratory-derived and log-derived elastic anisotropic properties (after Frydman *et al.* 2017). Track 1 is showing the calcite content. Track 2 and 3 are showing the vertical and horizontal static Young's modulus, respectively. Track 4 and 5 are showing the vertical and horizontal static Poisson's ration respectively. Track 6 is showing elastic anisotropy between the vertical and horizontal Young's modulus. Track 7 is showing the horizontal and vertical Biot coefficient.**

are based on locally calibrated correlations. The elastic anisotropy in track 6 is defined here as the relationship between vertical and horizontal static Young's moduli. We observe that for high Young's moduli, rocks are more isotropic, whereas for softer rocks, anisotropy can be up to 200%. Similar results were obtained by Suarez-Rivera *et al.* (2011). Anisotropic Biot coefficients (horizontal and vertical) were also included in this study and are represented in track 7. These mechanical property profiles are used to calculate stress profiles, from which a representative section is used as calibration data for the 3D model.

### 3D Modeling

Geomechanical simulations based on the finite element method can be used to compute the in-situ stress field in the subsurface on the basis of 3D MEMs and predict the impact of subsurface operations, such as stimulation and production, on the in-situ stress field and thus on the stability of formations and structural discontinuities.

In this study, a pad-scale geomechanical model is generated covering an area of about 900m x 1500m and total depth interval of 95m. With a horizontal resolution of 3m x 3m and a vertical resolution varying between 1m and 7m, this structured grid contains about 3.8 million elements. The internal layering of the 3D MEM reflects the mechanical stratigraphy captured by the 1D MEM for a representative depth interval with the typical interlayering of shale and limestone as found in the field. No horizontal property variation is considered in this model. The applied parameters are summarized in the table in Figure 3.




| | Shale | Limestone |
|---|---|---|
| YME | 3.55 Mpsi | 4.71 Mpsi |
| PR | 0.26 | 0.36 |
| DENS | 2.5 g/cm3 | 2.6 g/cm3 |
| BIOT | 0.8 | 0.6 |
| UCS | 15,000 psi | 20,000 psi |
| TSTR | 800 psi | 2000 psi |
| FANG | 25 deg | 35 deg |

Figure 3. 3D pad-scale geomechanical model showing the well (red), the hydraulic fractures (white), and the mechanical stratigraphy with parameter values listed in the table. The track on the left shows the final characteristic set of pressure and stress profiles vertically through the model.

The pore pressure gradient specified in the model is 0.89 psi/ft. Displacement boundaries are applied to initialize the pre-stimulation in-situ stress field, which is calibrated to a characteristic strike-slip profile (Figure 3). The resulting overburden stress gradient is 1.02 psi/ft. At the transition from the stiff limestone to the softer shale layers, planes of weakness are defined in the model exhibiting low shear stiffness and low strength (zero cohesion, 10° friction angle).

A hydraulic fracture simulator was applied to generate realistic hydraulic fractures in the 3D model using nine stages with four perforations per stage with a perforation spacing of 75 ft. The generated fractures have a half-length of about 500 ft with a height of about 80 ft. Figure 4 shows the unstructured grid that resolves the hydraulic fractures in high resolution.

This grid is used by the geomechanical finite element simulator to compute the change of stress, deformation and rock displacement during the stimulation phase, including potential bedding parallel shearing. This simulation considers the fracture pressure inside the hydraulic

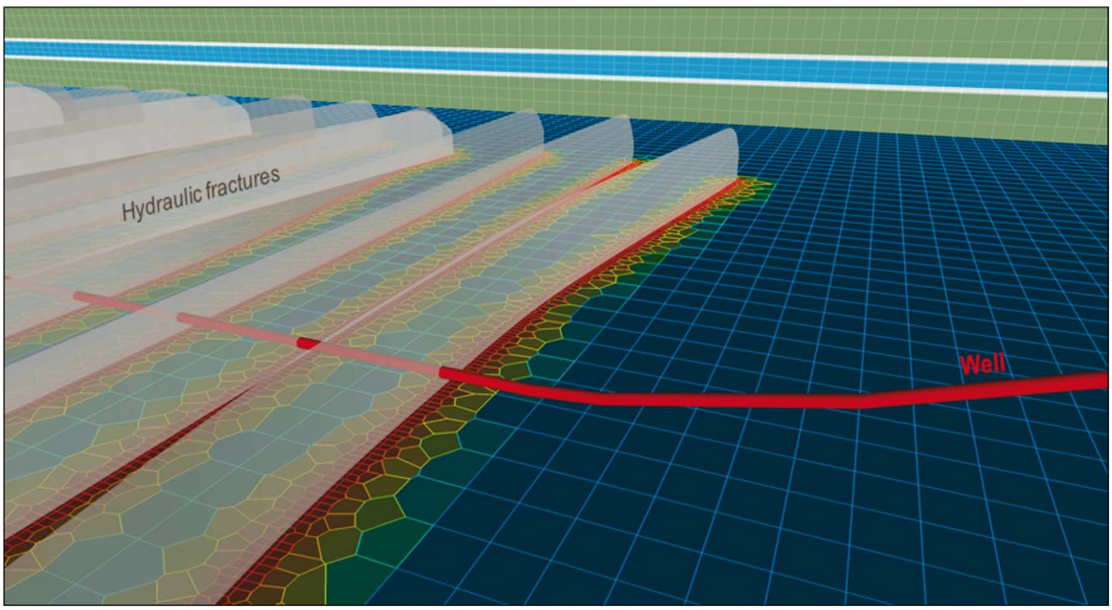
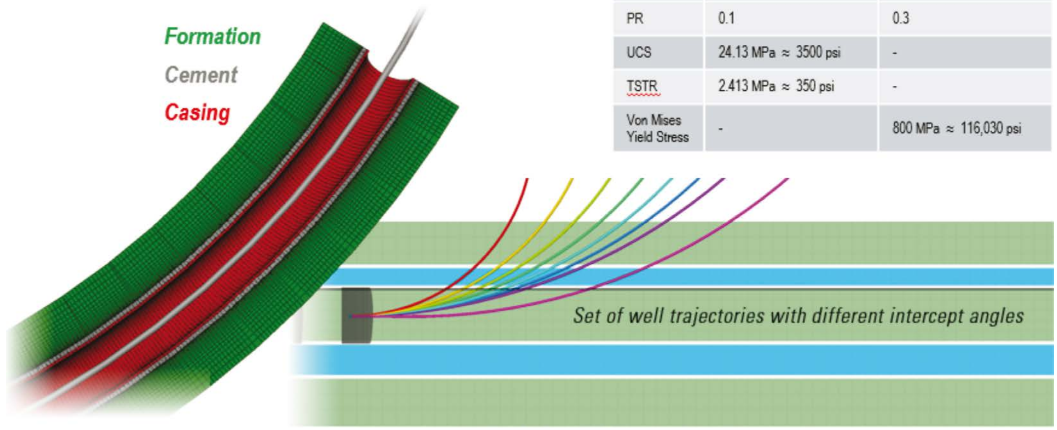



**Figure 4. Hydraulic fractures (white) are resolved in high resolution in the unstructured grid used in the geomechanical simulation of the stimulation phase.**

fractures, which is close to the vertical stress, and then computes the linear elastic response, as well as the non-linear visco-plastic behavior and failure of the rock and the planes of weakness.

To study the impact of the computed stress and displacement changes during stimulation on the well casing, a cylindrical numerical model is built around the candidate well, which incorporates casing, cement, and surrounding rock formation. The near-wellbore model considers the well completion with realistic material parameters for casing and cement (Figure 5). Mechanical properties for the rock formation are mapped directly from the pad-scale model onto the geomechanical near-wellbore model.

Multiple trajectories were designed exhibiting different intercept angles at the planes of weakness included in the 3D model (Figure 5). Each cylindrical near-wellbore model comprises about 860,000 elements. The results from the geomechanical simulations on the pad-scale models for stress field initialization and for the stimulation phase are applied to initialize the near-wellbore models and impose the stimulation-induced stress and displacement changes, respectively. The well-centric models now allow to study the amount of deformation and peak stress in the casing.




| | Cement | Casing |
|---|---|---|
| YME | 13 GPa ≈ 1,885,491 psi | 200 GPa ≈ 29,007,548 psi |
| PR | 0.1 | 0.3 |
| UCS | 24.13 MPa ≈ 3500 psi | - |
| TSTR | 2.413 MPa ≈ 350 psi | - |
| Von Mises Yield Stress | - | 800 MPa ≈ 116,030 psi |

Figure 5. Cylindrical near-wellbore model along the candidate well showing the casing, cement, and rock formation layering (left). The table summarizes the applied mechanical properties (top right). Multiple trajectories varying in their intercept angle at the bedding planes are considered in this study (bottom right).

## Results

The results show that during stimulation, weak bedding planes can significantly facilitate differential displacements between lithologies, which has the potential to impact the integrity of wellbores until the point of irreversible failure. Driven by the low shear resistance of the modeled bedding planes, the stimulation-induced horizontal displacements are focused on the stimulated shale, and a significant displacement contrast emerges to the overlying and underlying limestone. During the stimulation, each hydraulic fracture is pressurized close to the vertical stress and opens, which induces failure at the weak bedding planes and lateral displacement.

Figure 6 shows the failure for the weak interfaces between the limestone and the organic shale. Failure is represented on this plot by a failure value, which is zero at the point of failure and indicates the proximity to failure with negative values and the amount of failure occurring with positive values. The results show that failure is concentrated at the heel and toe of the well, and all four planes of weakness below and above the limestone layers are affected.

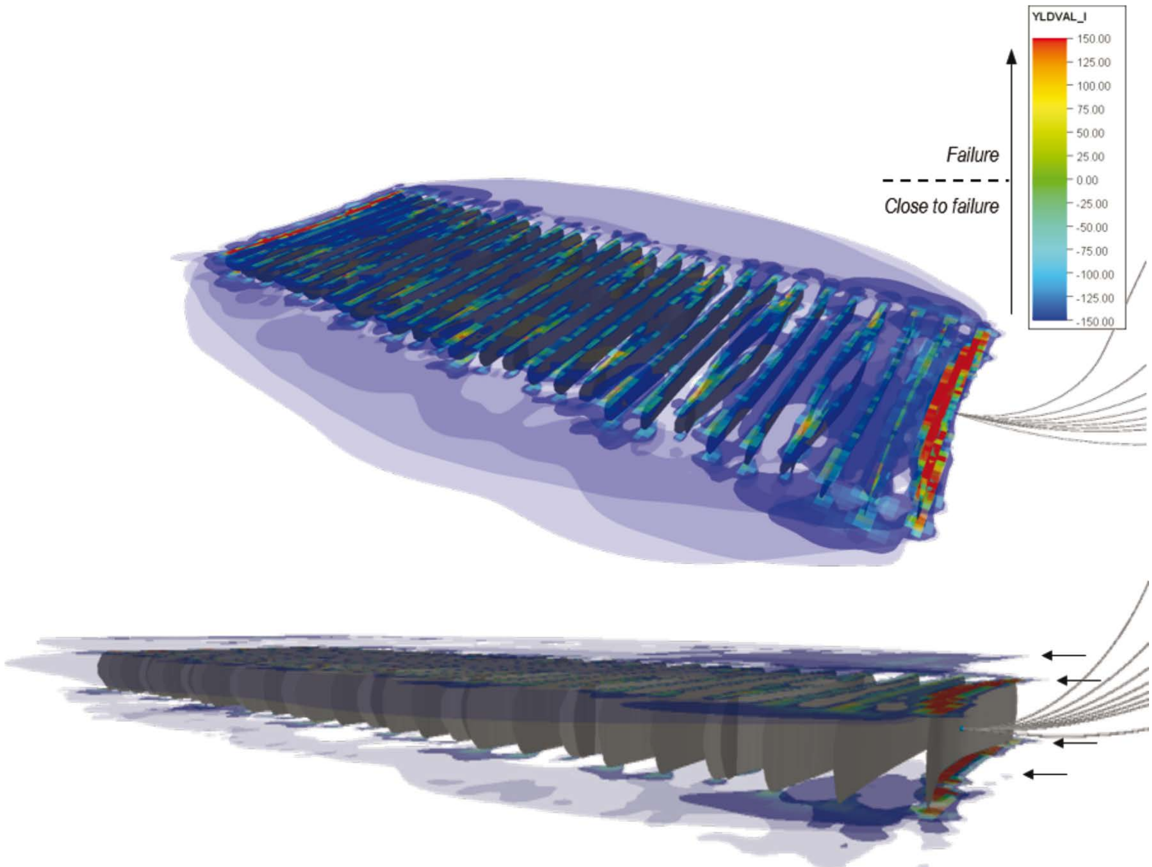



Figure 6. Visualization of failure of the plane of weakness during the stimulation phase. All four weak bedding planes are affected.

Figure 7 represents the 3D displacement on a vertical cross section along the well trajectory. The results show a sharp displacement contrast at the weak interface, where the organic shale is bordering the limestone layers. Maximum displacement in this scenario is about 0.06 ft.

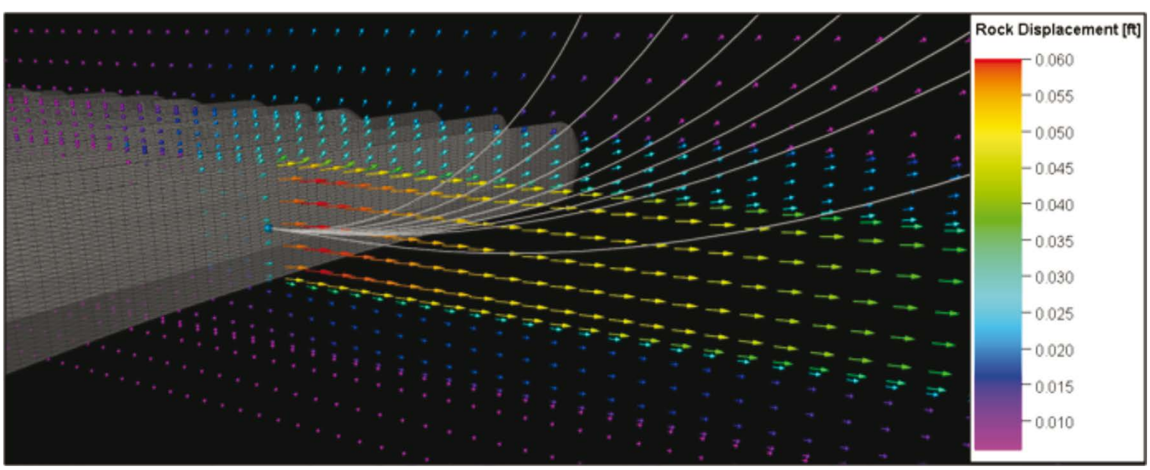



Figure 7. Rock displacements induced during the stimulation phase.

The particular amount of displacement generated during the stimulation depends on multiple variables including the hydraulic fracture geometry, the applied fracture pressure, and the mechanical properties of the stimulated layer. The results indicate that displacements of <0.15 ft of maximum horizontal displacement can already induce Von-Mises stresses above the assumed maximum yield stress of the casing steel of 116,000 psi (Figure 8).

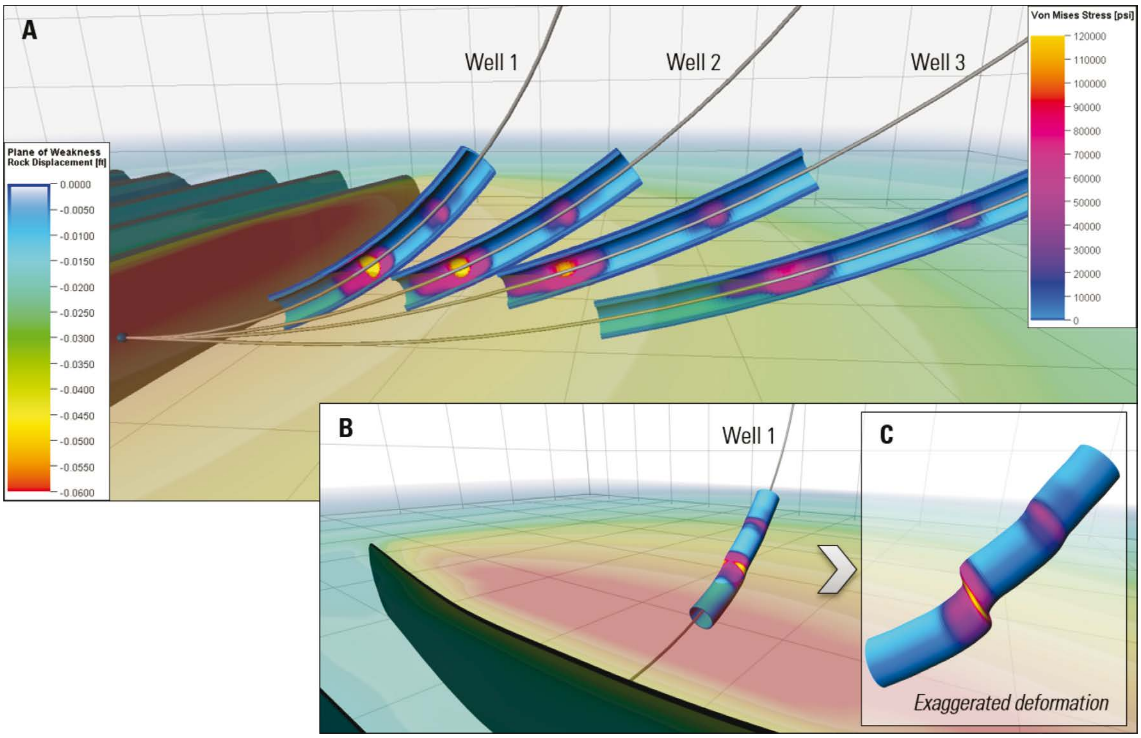



**Figure 8. A) Von-Mises stress results in the steel casing of four wells with different trajectories shown in combination with the displacement field. B) Rotated view on the casing of well 1. C) Exaggerated visualization of the casing deformation of well 1.**

## Conclusions

A case study for the Vaca Muerta was presented. The mechanical stratigraphy reflects a typical interlayering of shale and limestone as found in the field. In the same way, the near-wellbore model that includes the well completion with casing and cement considers realistic material parameters. The displacements caused by the opening of the hydraulic fractures during stimulation and the corresponding deformation and stress change are computed by a geomechanical finite element simulator. Stress changes emerging from the imposed displacements and corresponding deformation of the wellbore were analyzed and could cause the casing deformation observed in the field.

The results show that during stimulation, weak bedding planes can significantly promote differential displacements between lithologies, which has the potential to impact the integrity of wellbores until the point of irreversible failure. The study demonstrates the power of numerical modeling in an integrated workflow combining multiple types of grids and geomechanical simulations to investigate root causes of well integrity incidents. This workflow allows to obtain information to plan mitigation and countermeasures against potential casing failure, which include different types of casing, cement, well design and optimized well trajectories.

The obtained results also contribute to the understanding of stress development during stimulation in tectonic environment. This methodology creates a systematic approach to well planning that reduces casing deformation risks of unconventional plays in similar environment.

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