Benchmarking and Calibration of 3D Geomechanical Models*

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Abstract

Knowledge of the stress orientation and magnitude are critical factors when planning well completions and inferring the adequate injection type into the reservoir (i.e. matrix vs fracture injection). When scarcity of data is an issue and reservoir stress state is unknown, then offset well estimations and regional orientations of the closest or most recent faults are used as a proxy. However, in areas of complex geology with presence of salt domes and faulting, such assumptions result in misleading interpretations and become invalid.

A 3D dynamic geomechanical model of a deepwater field in the Gulf of Mexico was built with geomechanical input data from five wells (Figure 1). Simulations results show that integrated modeling of 3D reservoir-geomechanics can deliver reliable predictions. A recent interpretation of caliper logs, from a well not incorporated during the model construction, shows breakouts nearly 90 degrees from the Maximum Horizontal Stress (S_{Hmax}) orientation calculated in the 3D model, thus corroborating the accuracy of stress predictions.

Furthermore, contrary to what would be expected from geological observations, the S_{Hmax} orientation is not aligned with the strike of the closest fault to the well, but rotated 50 degrees from it. As it will be described later, in areas where there is high uncertainty of stress orientation, this type of model allows an optimum trajectories design that would warrant low hydraulic fracturing pressures and locations that provide preferential sweep towards the producers through matrix injection.

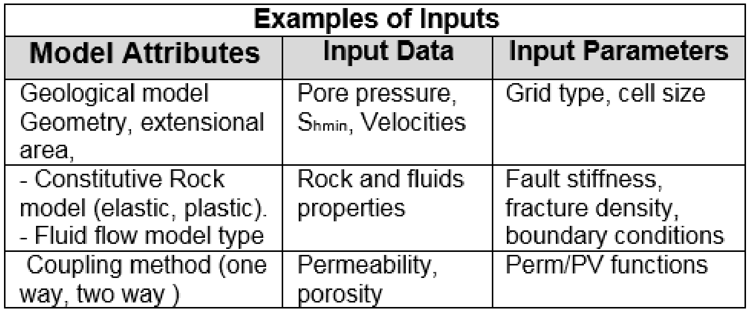
In addition to calibration of stress magnitudes and orientations, shear deformation can be used as an extra parameter for calibration and/or benchmarking, something that is commonly overlooked in coupled fluid flow-geomechanics modeling. The analysis from 1D modeling in wells that were drilled before and after depletion indicated the presence of shear failure.

Results from 3D simulations not only showed shear failure at the same well locations but also development of shear yielding in other zones as the confining pressure changes. This prediction was only possible when the proper input model was used, in this case the incorporation of an elastoplastic rock model, which can be calibrated to pre-production strain levels without the effort of restauration models.

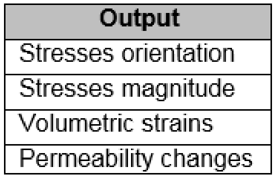
It is important to know that the calibration practice requires the modeler to judge how different types of inputs can provide the same results during the calibration process but may not provide the same quality of prediction. One should aim to make 3D geomechanical modeling a predictive tool, rather than just a matching exercise of past events.

Examples of Model Components

i. Model attributes: Relationships that describe the interaction among physical quantities, such as fluid-flow in a porous media or a constitutive rock behavior (Mohr-Coulomb, Cam-Clay, etc. for elastic or elastoplastic rock behavior).
ii. Input data: Refers to the actual field or laboratory measured data (hard data) needed either to populate the constitutive models or to calibrate against them.
iii. Input parameters: Refers to non-measured data (soft data) such as assumptions, hypotheses, boundary and initial conditions and some of them with high uncertainty



Examples of Inputs		
Model Attributes	**Input Data**	**Input Parameters**
Geological model Geometry, extensional area,	Pore pressure, S_{hmin}, Velocities	Grid type, cell size
- Constitutive Rock model (elastic, plastic). - Fluid flow model type	Rock and fluids properties	Fault stiffness, fracture density, boundary conditions
Coupling method (one way, two way)	Permeability, porosity	Perm/PV functions



Output
Stresses orientation
Stresses magnitude
Volumetric strains
Permeability changes

Benchmarking of Stress Orientation and Fine-Tuning

A benchmark test using caliper analysis of a producer well, which data was not used as input into the model, shows predominant breakout directions at approximately 90 degrees apart from the S_{Hmax} orientation, same direction as predicted from the 3D model at the same location (Figure 2).

Contrary to what would be expected from geological observations, the S_{Hmax} orientation is not aligned with the strike of the closest fault to the well, but rotated 50 degrees from it. This helps to minimize the risk of drilling and completing wells with misleading interpretations from conventional assumptions.

The reservoir is under a fold belt below thick salt layers with more recent faults than others. It is then suggested to lower the values of the fault stiffness to get better effects on stress directionality. Therefore, in this case the calculated initial stress state required fine-tuning during initialization by adjusting the above mentioned input parameters independently of the model input chosen. This means that there is a point during initialization of stresses at which the stress does not change significantly even if the rock model is changed or the initial boundary conditions are reduced/increased. When this happens, the input parameters related to material properties may need to be altered

Different inputs can affect one single output, for instance, if the 1D profile of Minimum Horizontal Stress (S_{hmin}) is too low after the first attempt to reach the stress equilibration, then two options are possible, either the entire S_{hmin} profile needs to be shifted to match the expected values or only one section at a given depth of the profile needs to be adjusted. In the first case, modifications of the boundary conditions might be sufficient. In the second case, two other options can be explored: (a) Modification of input data such as the rock stiffness of the over/under-burden, or (b) Modification of model attributes, such as geometry (i.e. aspect ratio of grid cells size).

Implications for Injector-Producer Configurations

(a) Ideal injector-producer line configuration: The “injector-producer line” should be above 50^0 from the S_{Hmax} azimuth. The shaded area defined by the three blue dots defines the optimum azimuths range location of an injector with respect to the producer (Figure 3a).

(b) For this azimuth and inclination low hydraulic fracturing pressures will be required and preferential sweep towards the producer will be guaranteed (i.e. water breakthrough risk is minimized) (Figure 3b).

Calibration to Shear Deformation

Shear deformation can be used as an extra parameter of calibration or benchmarking, something that is commonly overlooked in coupled fluid flow geomechanics modeling (Figure 4). Shear deformation from the 3D simulations were calibrated against the observed drilling conditions (i.e. if drilled at an underbalanced condition, the well would have experienced significant shear, especially through depleted zones) . This also suggests how close the reservoir is or has been transitioned from a brittle behavior to a more ductile behavior as it was depleted. To achieve calibration of shear yielding events, adjustments need to come from a proper input of models that reflect the elastoplastic behavior of the reservoir, rather than adjustment of elastic mechanical properties.

Benchmarking of Shear deformation can be achieved through pressure transient analysis (PTA): near-wellbore formation damage zone. Baffles and slump zones are flow barriers that could be associated with shear bands that were either induced or naturally in place.

Conclusions

- Rough assumptions of stress orientations results in costly interpretations and become invalid.
- Calibration of 3D geomechanical models involve systematic adjustment of different type of inputs so that model outputs more accurately reflect benchmarks.
- Events such as shear failure are commonly experienced in the field and are usually overlooked when validating 3D models.

- Suitable 3D reservoir-geomechanical modeling may result in a good predictive tool, provided of course that models are properly calibrated and benchmarked.
- Equivalent plastic strains can be related to PTA analysis, wellbore stability, faulting or hydraulic fracturing and can be used as an extra calibration and benchmark for 3D geomechanical models

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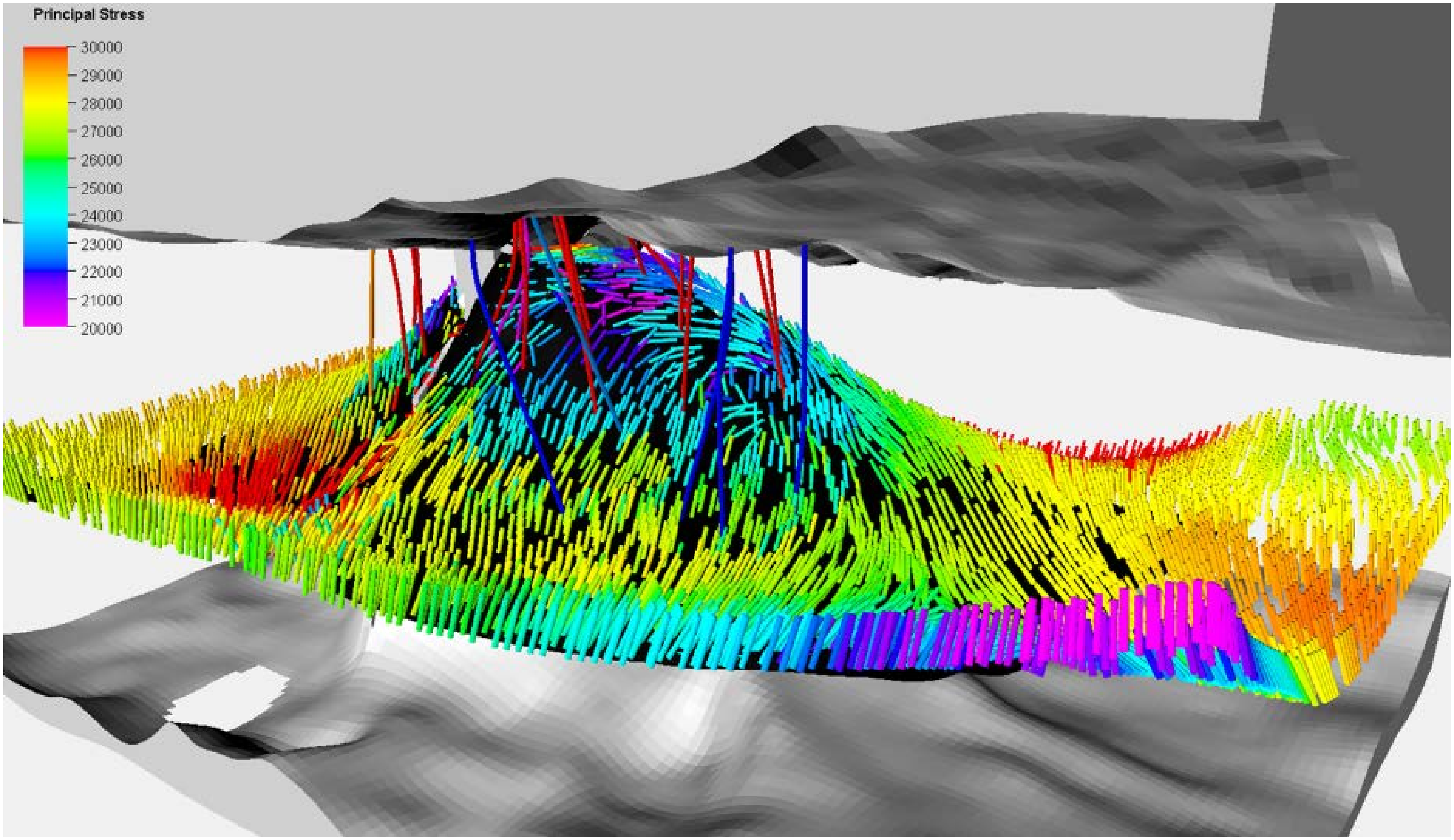

Figure 1. Maximum principal stress orientation after 5 years of production.

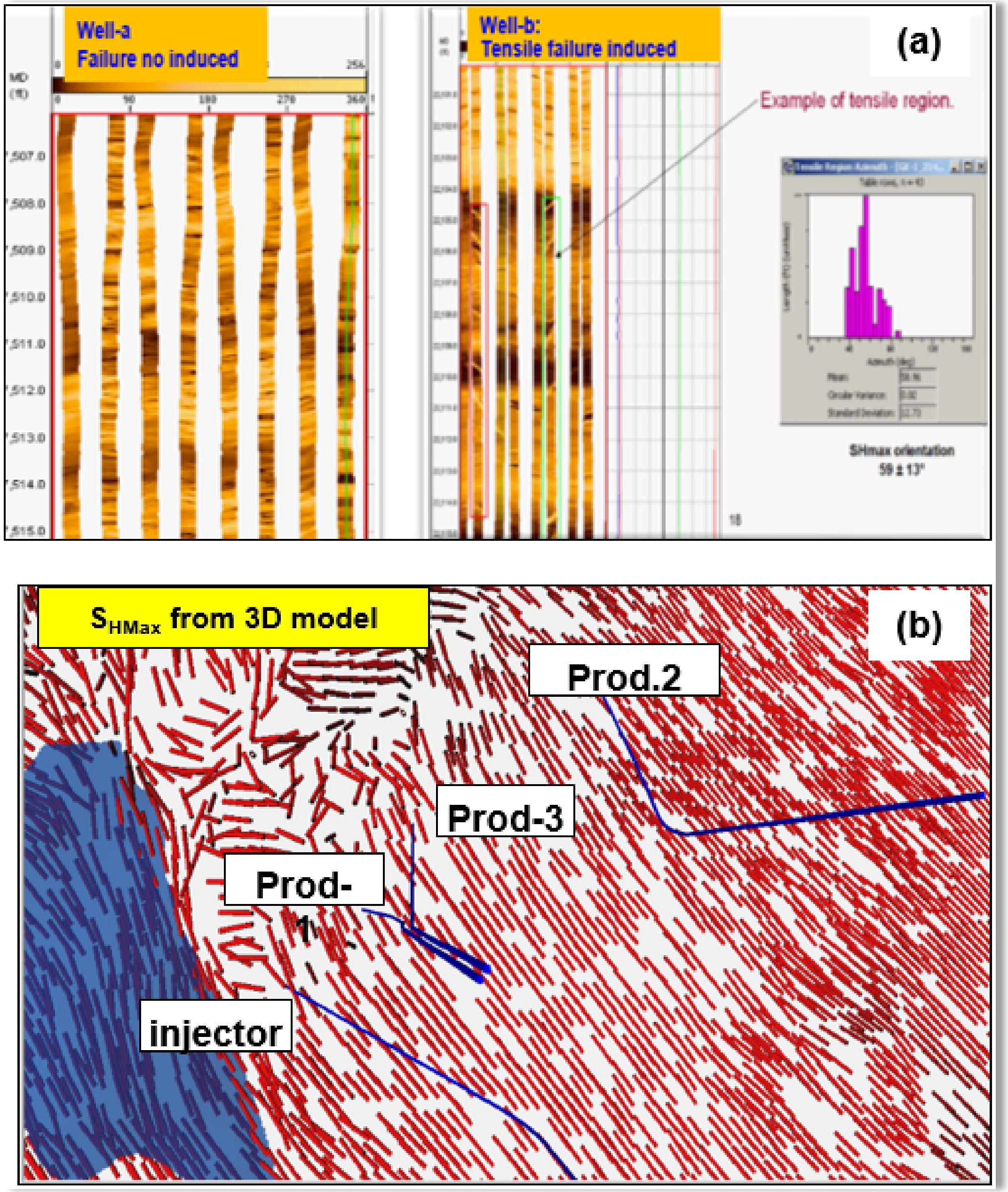

Figure 2. (a) The analysis from 1D modeling in wells that were drilled before and after depletion indicated the presence of shear failure. (b) Map of S_{Hmax} from the 3D model.

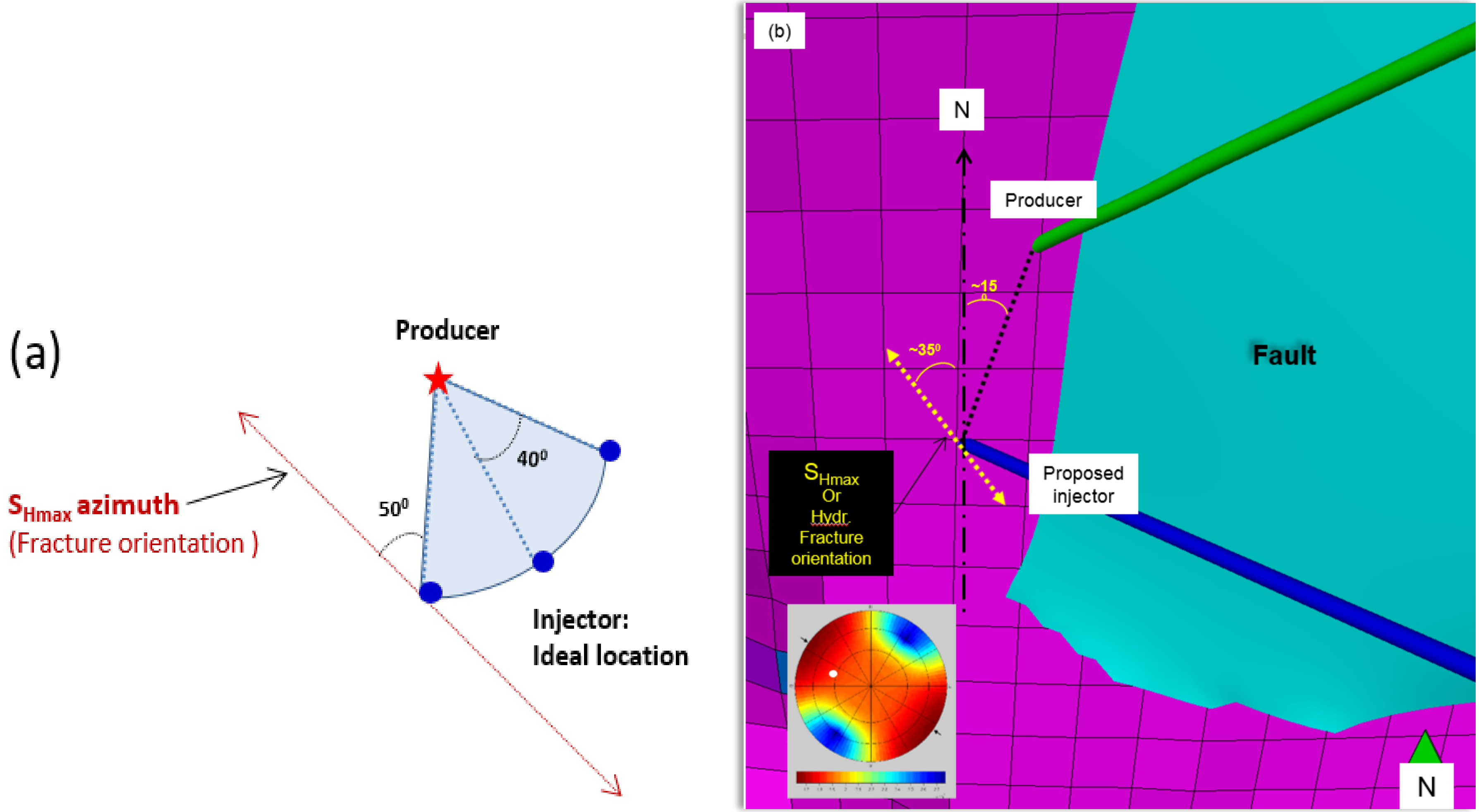

Figure 3. (a) Ideal injector-producer line configuration: The “injector-producer line” should be above 50^{o} from the S_{Hmax} azimuth. The shaded area defined by the three blue dots defines the optimum azimuths range location of an injector with respect to the producer. (b) For this azimuth and inclination low hydraulic fracturing pressures will be required and preferential sweep towards the producer will be guaranteed (i.e. water breakthrough risk is minimized).

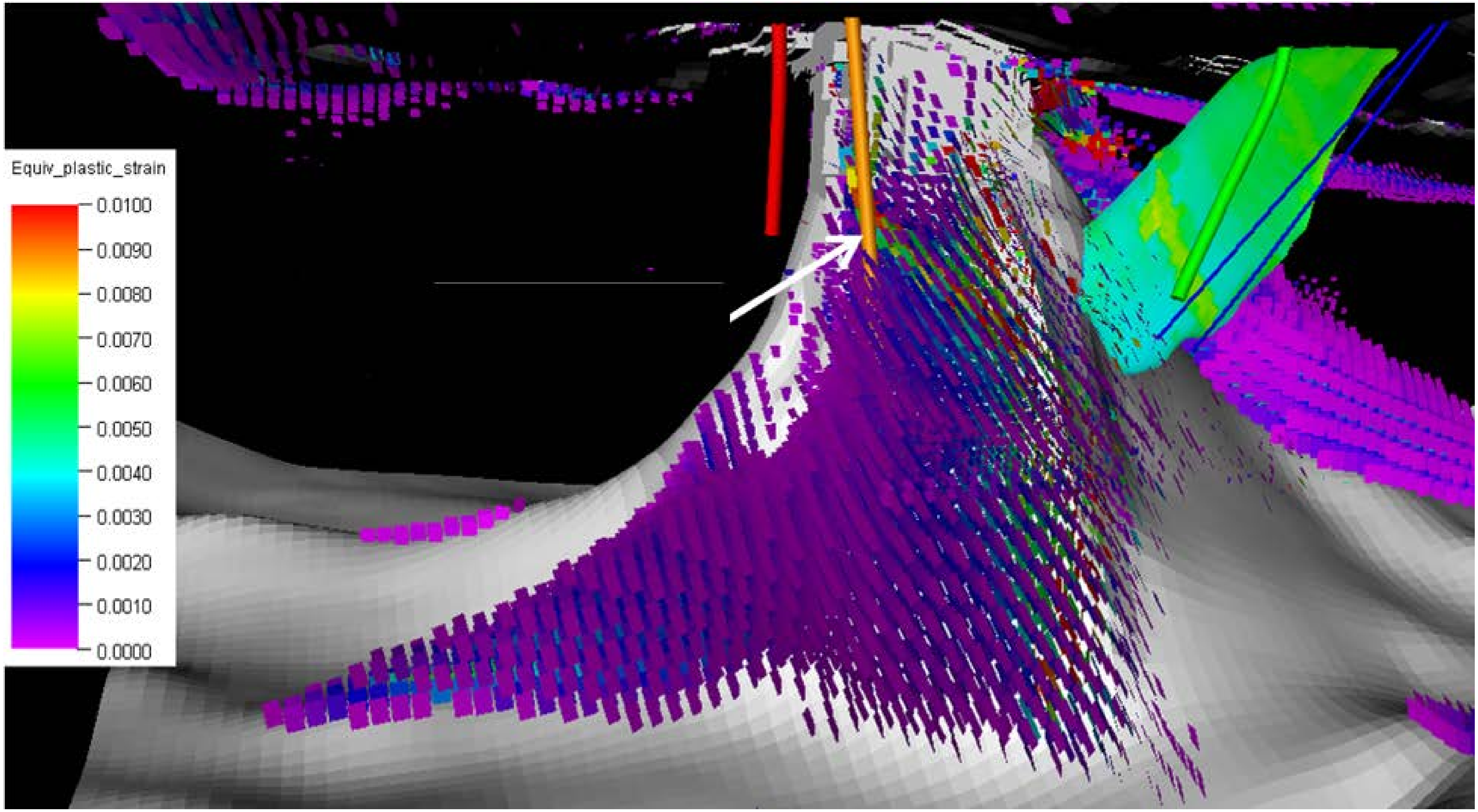

Figure 4. Shear deformation zones near to wells and salt flanks.