Role of Geomechanics and Integrated Reservoir Characterization in Production Enhancement from a Heterogeneous Carbonate Reservoir: A Success Story from Kuwait

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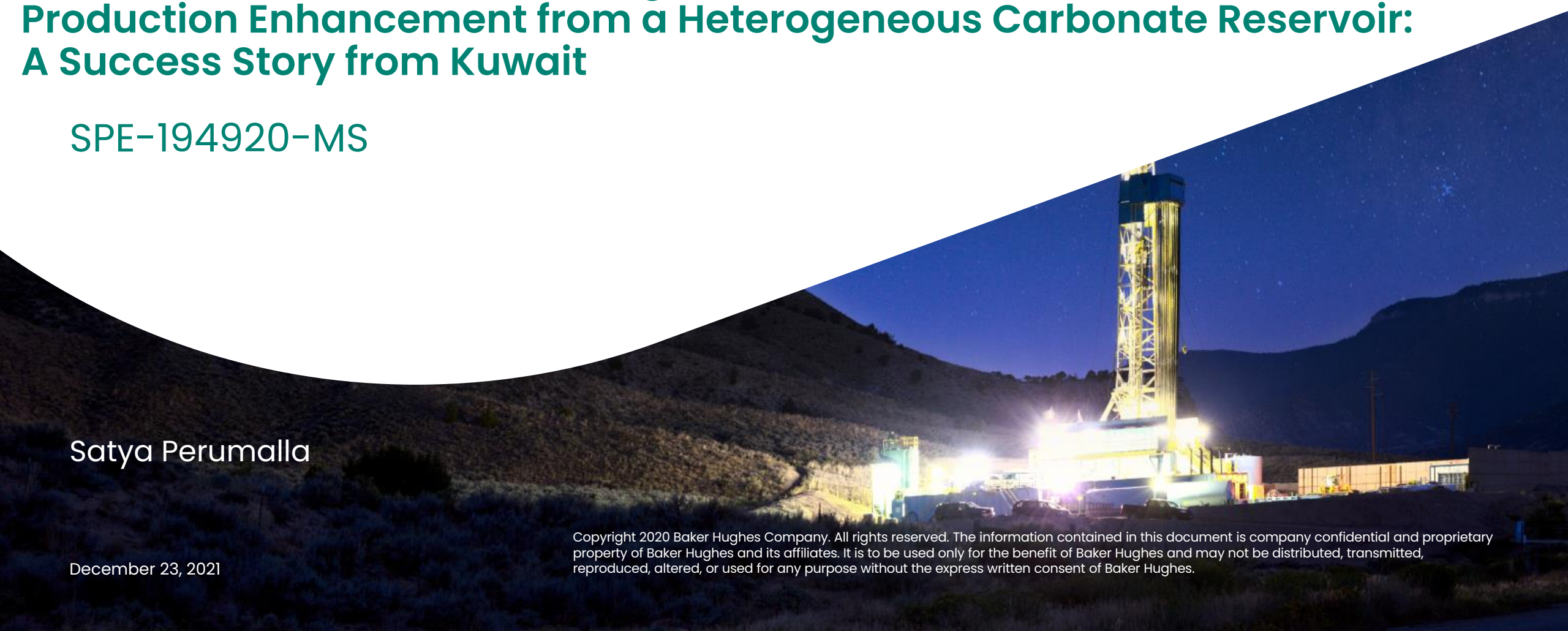

Satya Perumalla

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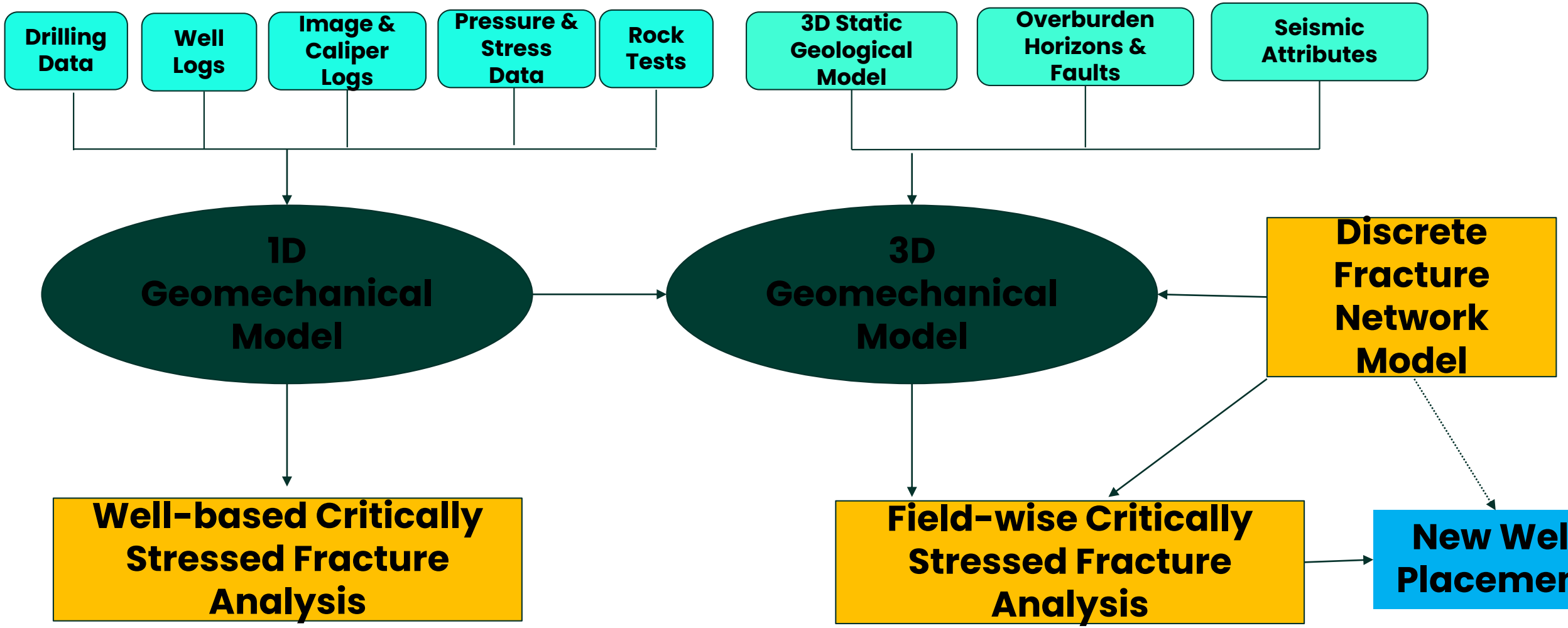
Outline

- Objectives of the study
- Study workflow
- Concept of Critically Stressed Fractures (CSF) Analysis
- 1D Geomechanical Modeling
- Well-based CSF Analysis
- 3D Geomechanical Modeling
- 3D CSF Analysis – Integration of Existing DFN model with Geomechanics
- New Well Proposal
- Summary

Objectives of the Study

- Naturally fractured carbonate reservoir
- Existing Discrete Fracture Network (DFN) was built using well and seismic data
- Various wells have been planned and placed using existing DFN model
- However, mechanical response of natural fractures & multi-stage stimulation to production contribution is unknown
- Integration of Geomechanics with DFN model is carried out to find out Geomechanical sweet spots in terms of critically stressed fractures (fractures prone to shear-slip)
- New wells placed to intersect the maximum number of critically stressed fractures for maximizing the production

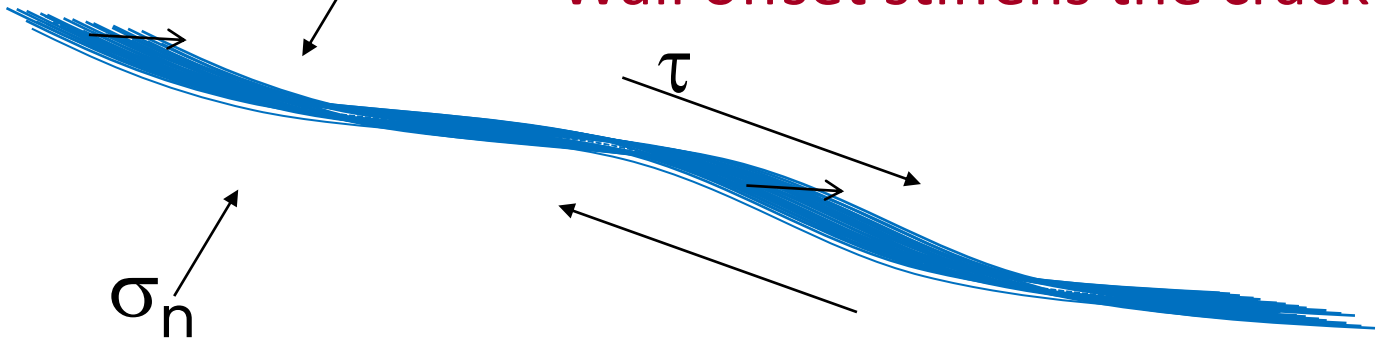
Study Workflow



Shear (Coulomb failure model) crack:

Slips, creating opening, if $\tau - \mu\sigma_n - S_o > 0$

Wall offset stiffens the crack

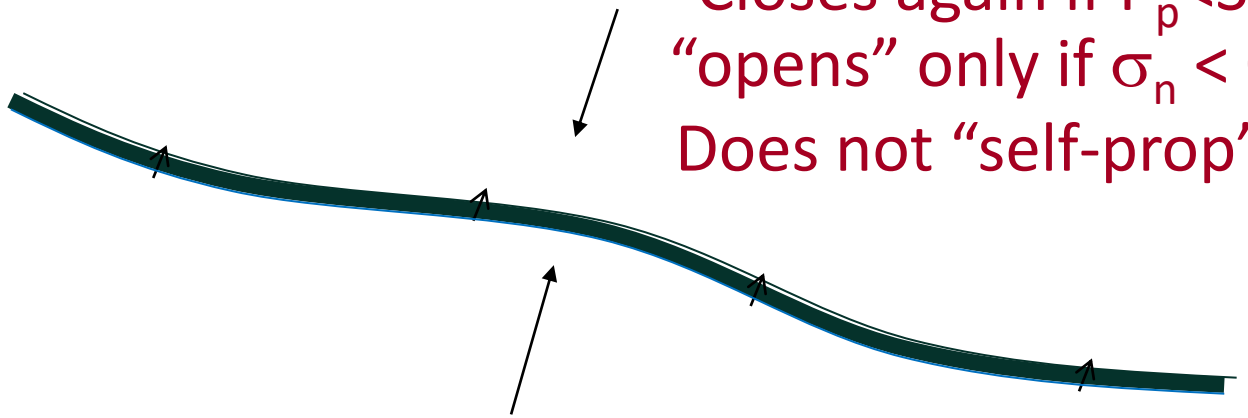


Mode 1 (extensile) crack:

Closes again if $P_p < S_3$

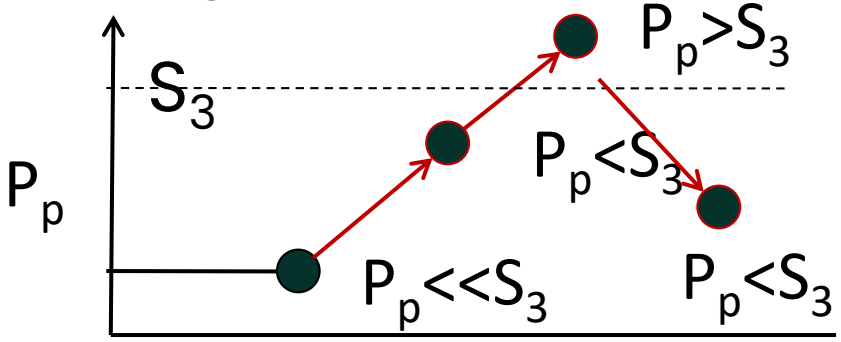
"opens" only if $\sigma_n < 0$

Does not "self-prop"



$\sigma_n = S_n - P_p$

Injection Pressure



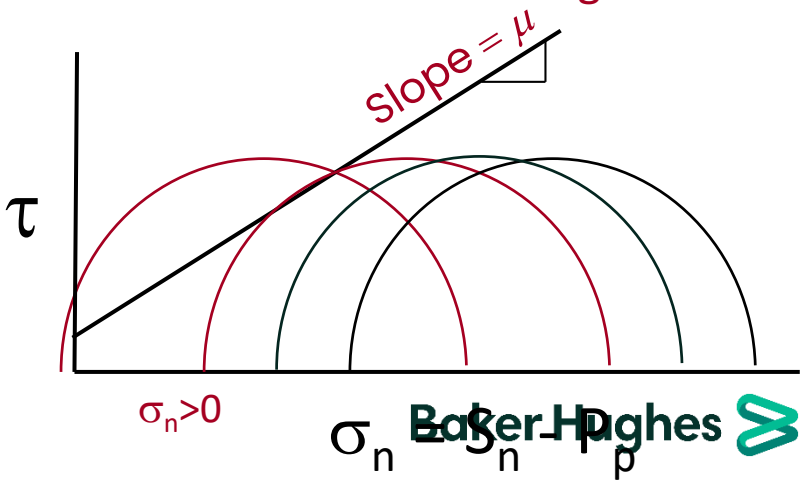
Mohr Diagram

Initial stress state

Condition for slip on a shear crack

Condition to "open" a Mode 1 crack

"Mode 1" cracks close again



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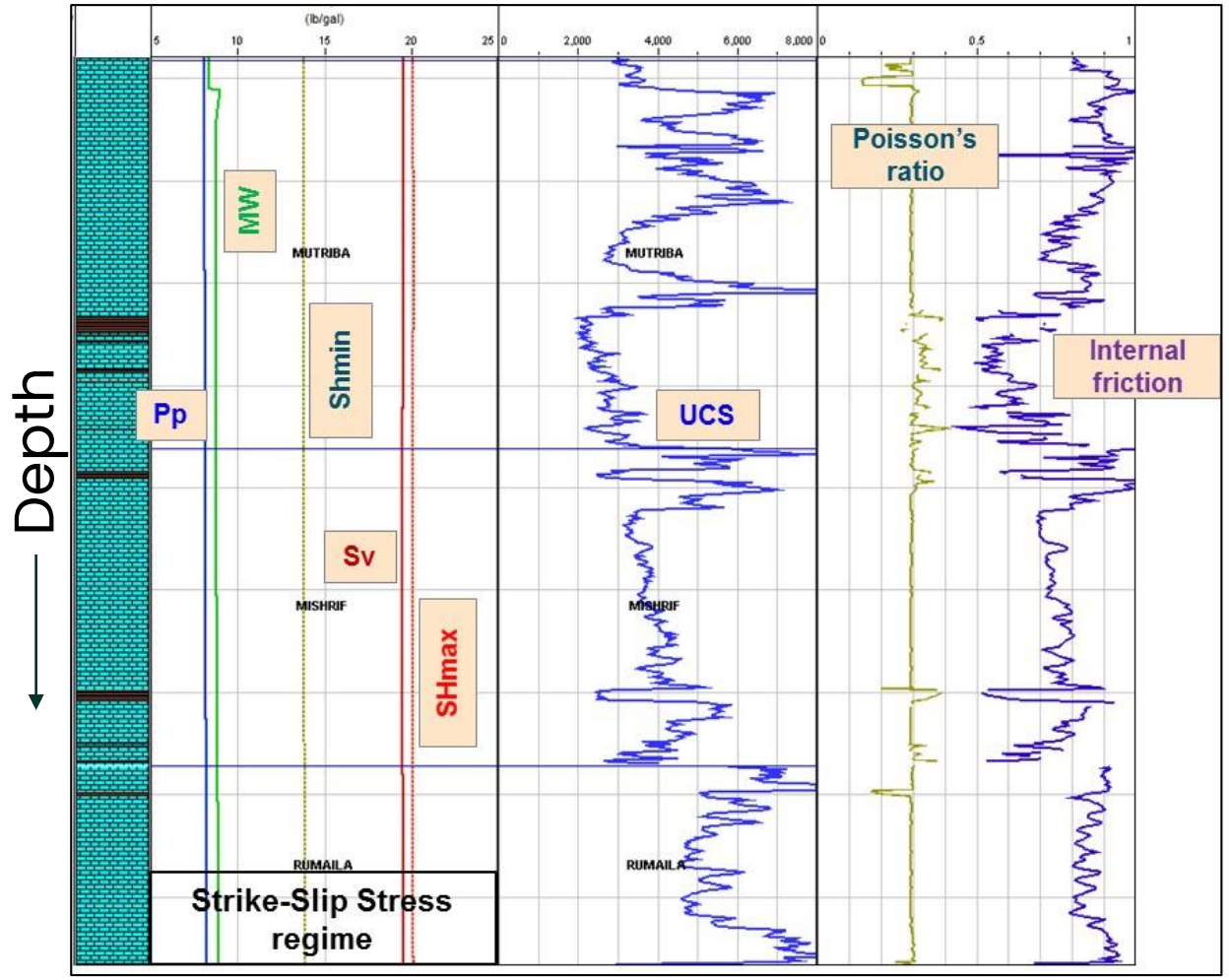
1D Geomechanical Model

- Strike-slip stress setting where
  SHmax > Sv > Shmin
- Vertical stress is estimated by integration of density log
- Pore pressure is hydrostatic and is constrained by formation pressure measurements
- Shmin is calibrated by leak-off test data
- Rock mechanical properties are calibrated by rock tests
- SHmax is constrained using Stress Polygon Theory



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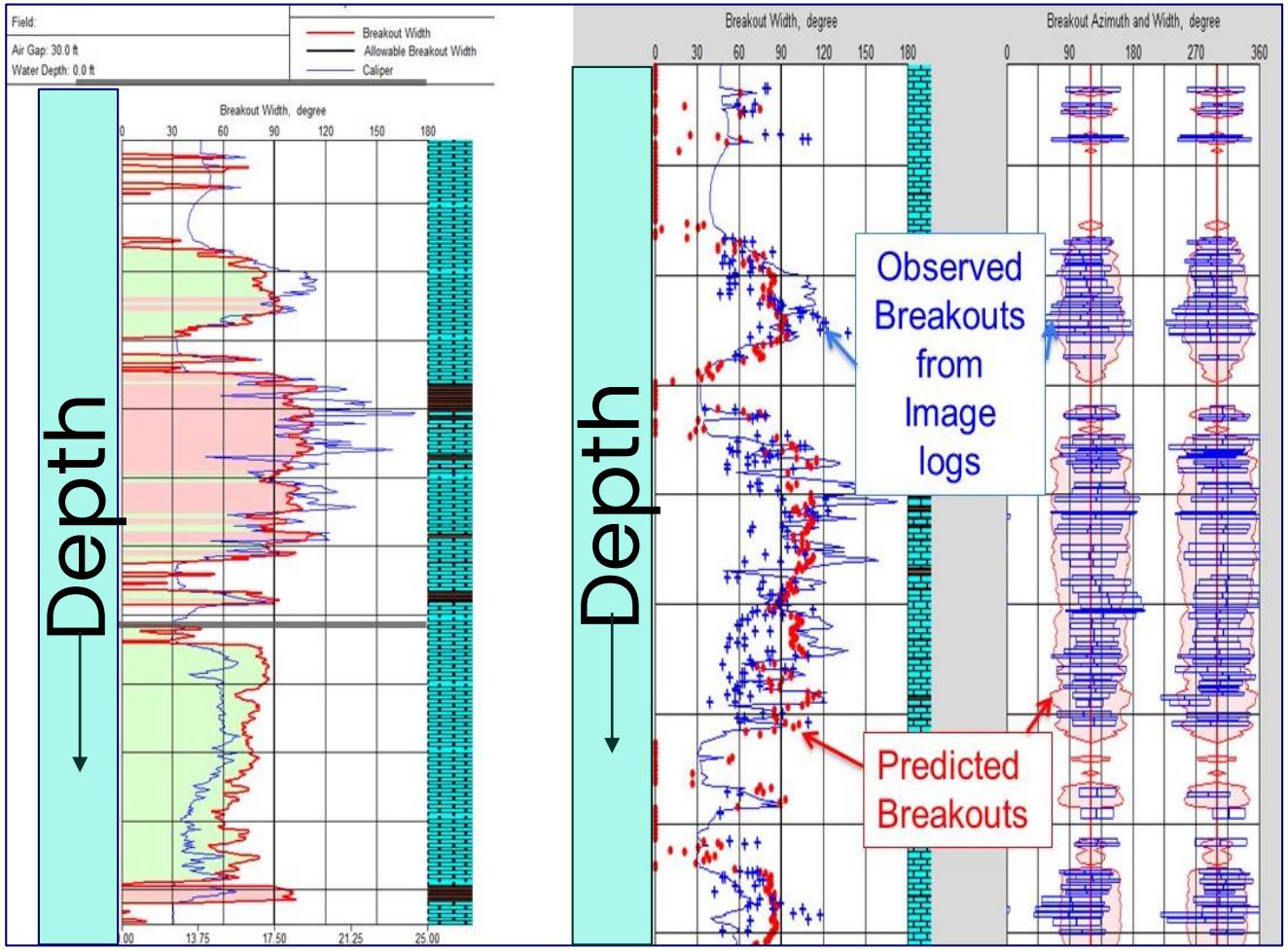
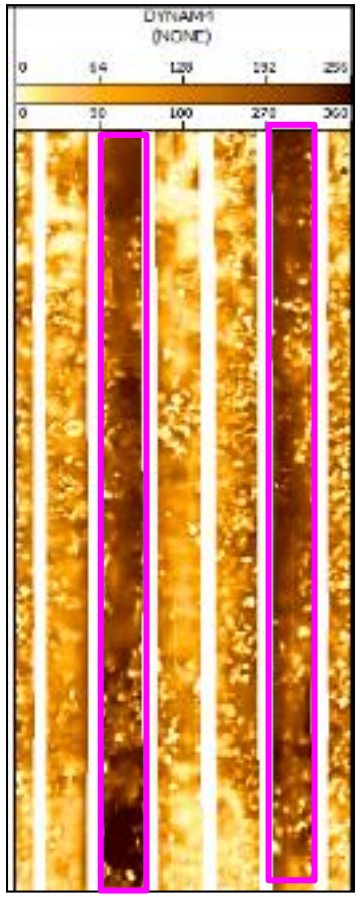
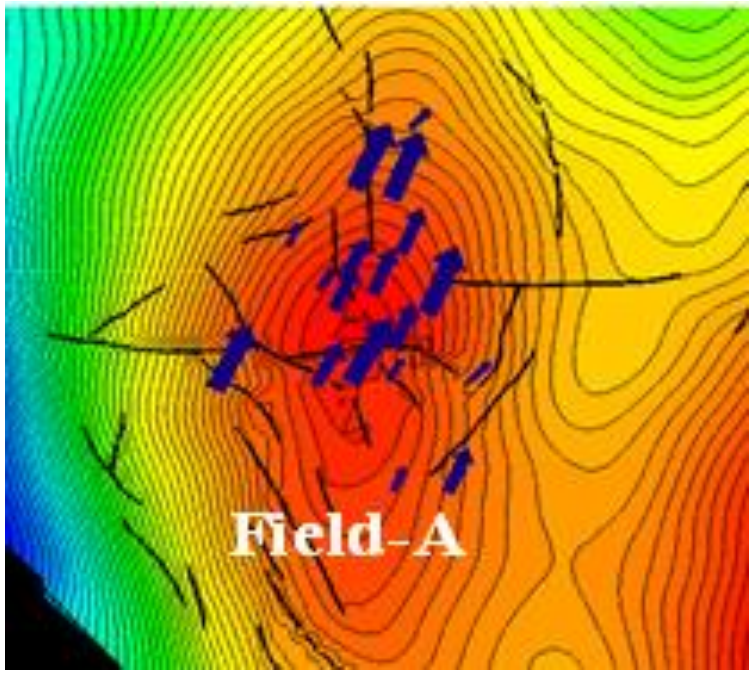
Calibration of 1D Geomechanical Model



Stress Orientation from Image Logs





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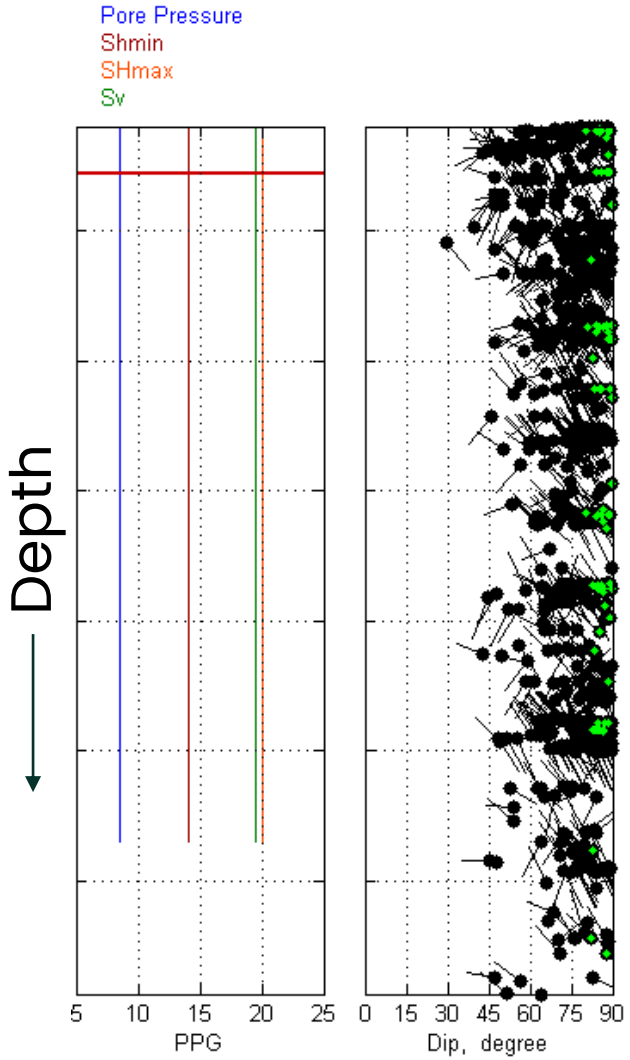
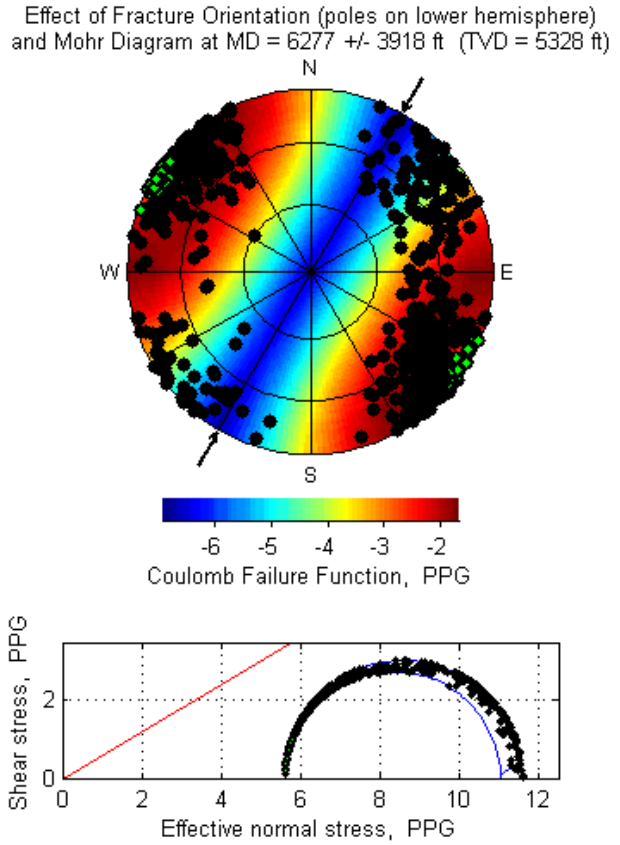
CSF at Well-scale – Initial Pressure

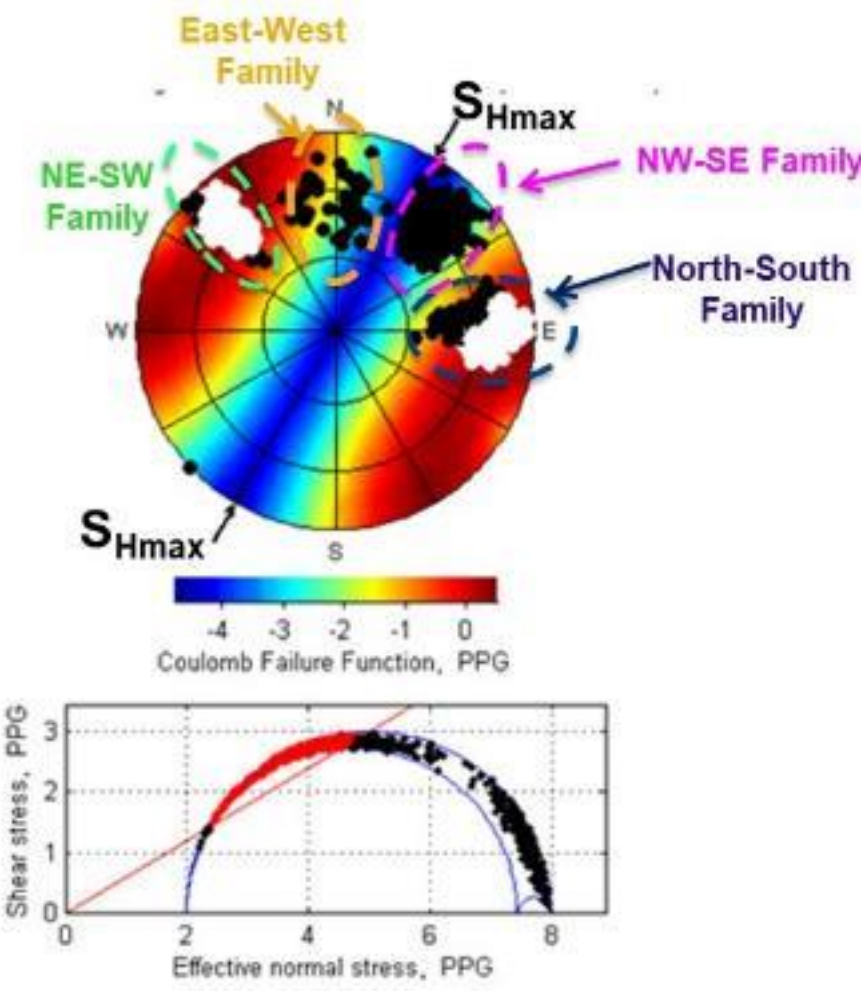
- At present day in-situ stress / sub-hydrostatic pressure conditions, none of the fractures is sensitive to stress
- Therefore the current production is possibly coming from pre-existing set of naturally permeable fractures and matrix





CSF at Well-scale – Increasing Injection Pressure

- Any additional **fluid pressure (stimulation pressure/injection pressure)** appears to have role in turning some of these fractures into critically stressed.
- **Fracture families trending: NE-SW and North-South** appears to be sensitive to additional pressure to shear slip and become hydraulically conductive.
- High start-up production rates possibly explain the role of stimulation pressures on these optimally oriented natural fractures



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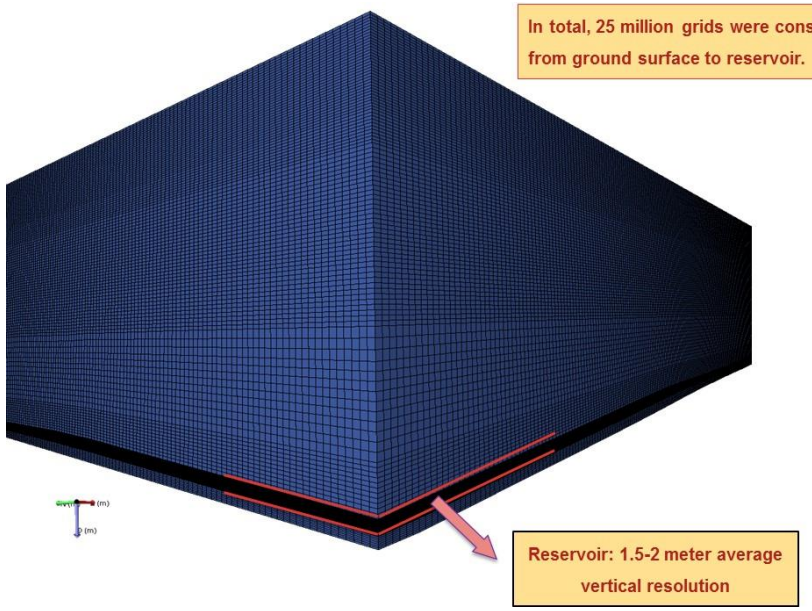
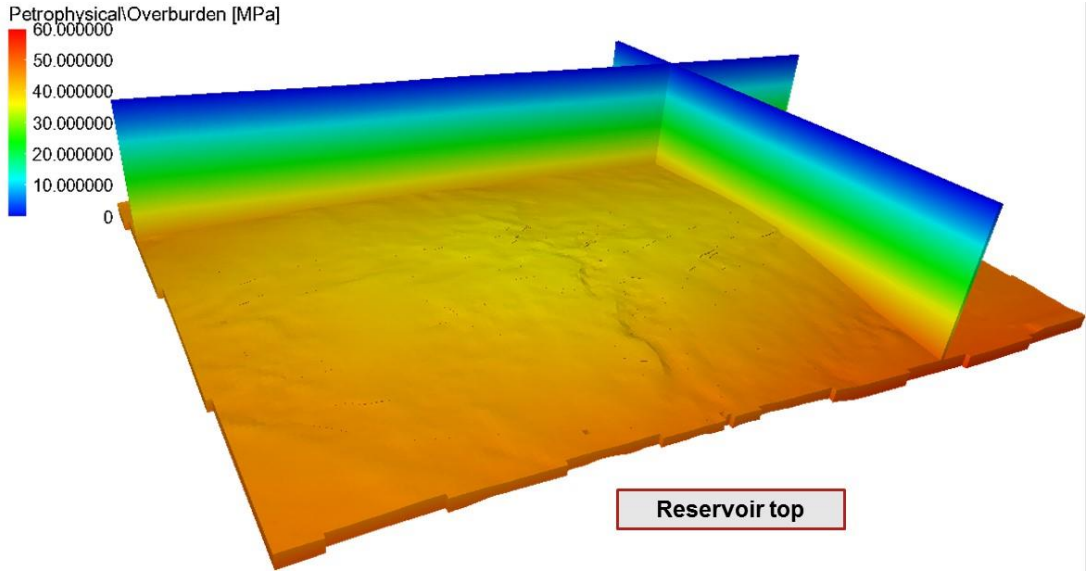
3D Geomechanical Model

- Calibrated 1D Geomechanical models of 20 offset wells have been used to build 3D Geomechanical model

- 3D Geomechanical model is built from ground surface to reservoir and includes overburden horizons from seismic interpretations and reservoir horizons from static geological models

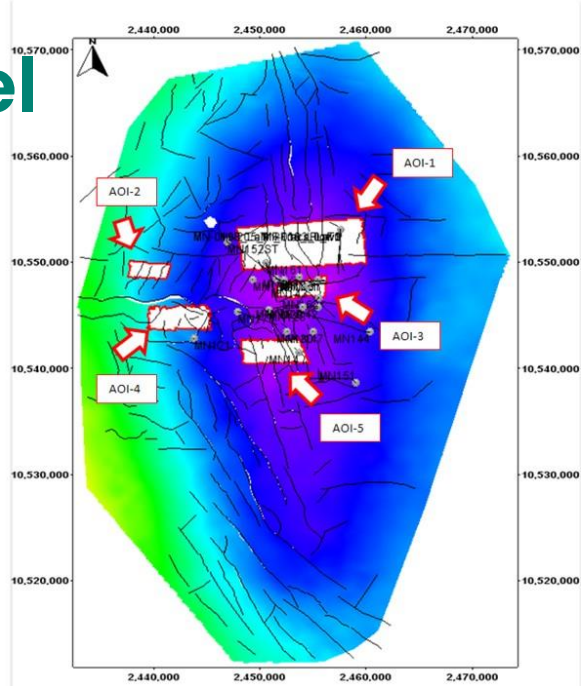
- 3D Geomechanical model has Sv, Shmin, SHmax, Density, Unconfined Compressive Strength (UCS), Young's Modulus and Poisson's Ratio



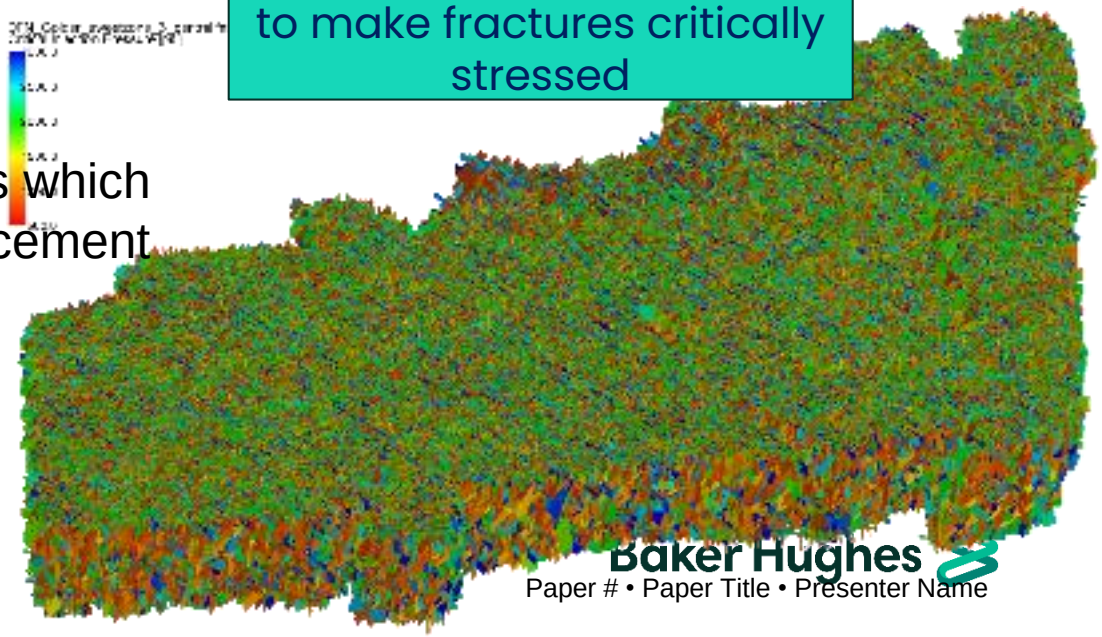


Existing Discrete Fracture Network (DFN) Model

- Existing DFN was built using geological, geophysical, petrophysical and production data
- This existing DFN model was integrated with 3D Geomechanical model in order to evaluate stress-sensitivity of the modelled natural fractures
- Performed stress-sensitive fracture permeability analysis of 6 sweet spot zones (based on geological characterization)
- This would help to understand the areas of sweet spot zones which can have better response to stimulation so that new well placement can be optimized



Critical Injection Pressure to make fractures critically stressed

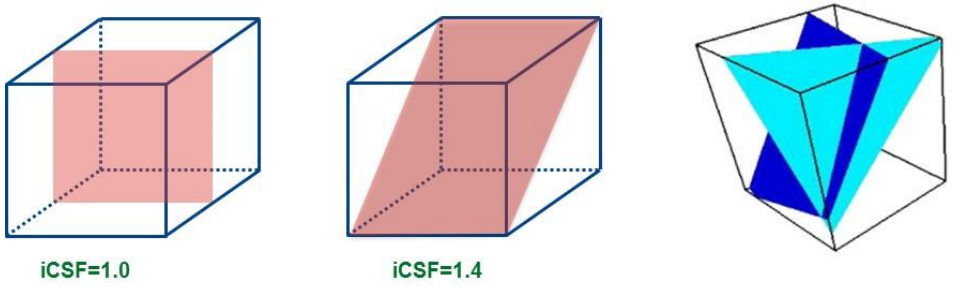


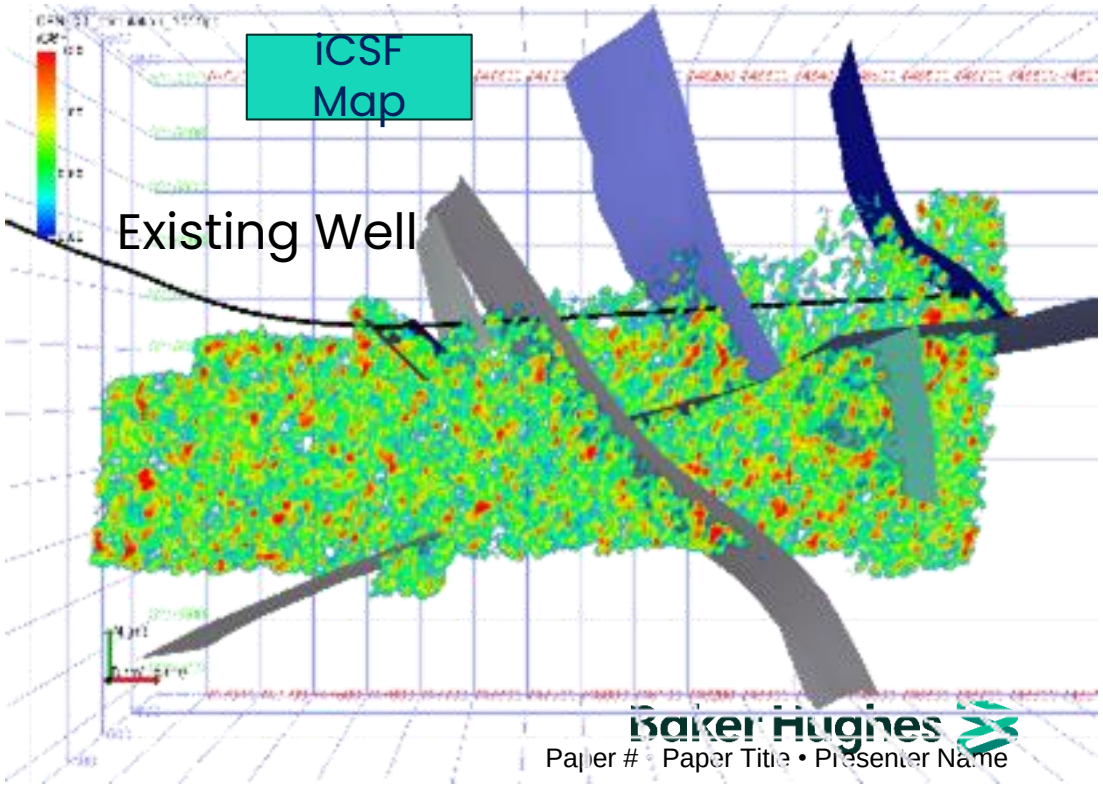
3D Critically Stressed Fracture Analysis

- Index of Critically Stressed Fractures (iCSF) which defines total intersection areas (sq. m) of those critically stressed fractures in each pre-determined cubic cell (5*5*5 m) and then divided by cell volume (cu. m)

- iCSF (per m) represents area concentration where fracture intersections are likely acting as fluid conduits and hence contributing to flow

- Contoured iCSF plots can be smoothly visualized in JewelSuite through GUI, through which the well trajectory planning becomes easily possible





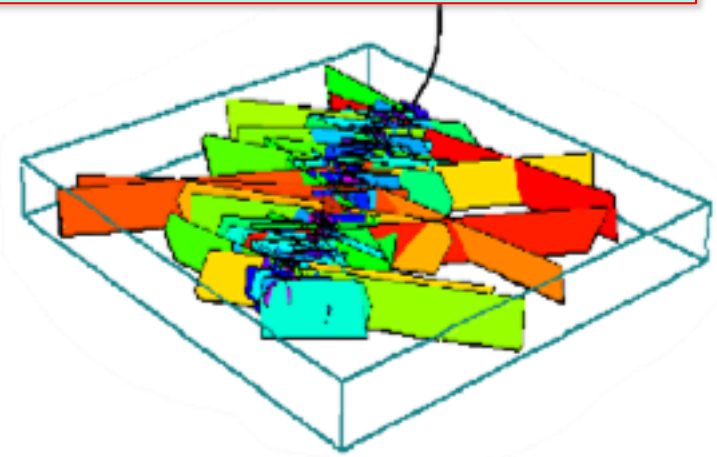
New Well Placement

Maximize the numbers and intersection areas of critically stressed fractures

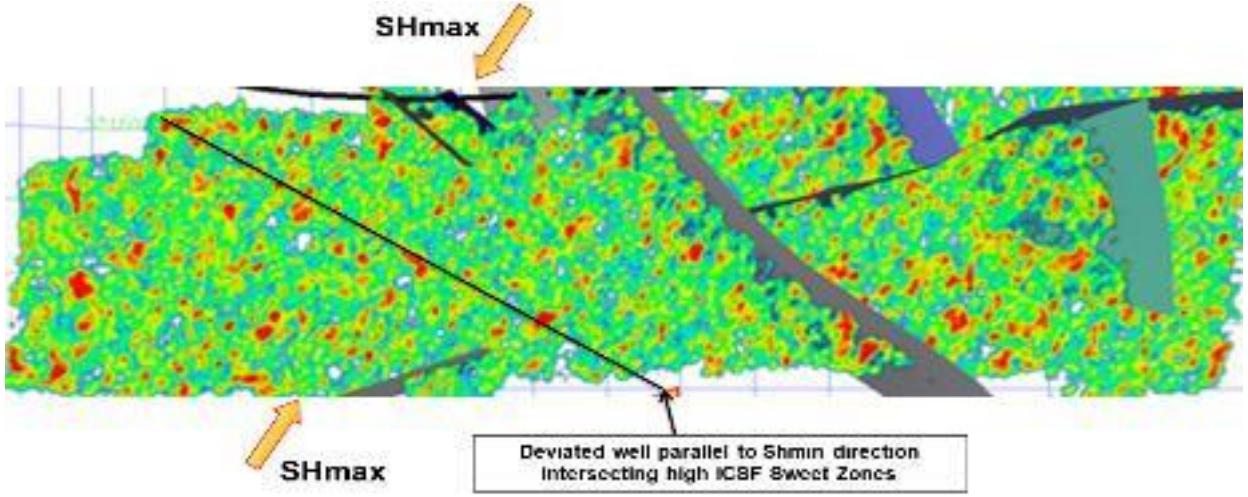
- New Well have been planned considering iCSF & orientation of stresses to intersect maximum number of critically stressed fractures

DFN Sweet Zone	Total Number of Fractures	Extreme Stress sensitivity of Fractures to Stimulation Pressure (Friction coefficient: 0.6)		
		1,000 psi	1,500 psi	2,000 psi
1 North	4,364,476	36%	55%	69%
2 West	549,790	20%	52%	62%
3 Central	663,501	38%	56%	70%
4 West 2	1,256,798	24%	53%	63%
5 Central 2	1,393,851	36%	55%	68%
6 South	859,181	35%	55%	68%

More fractures can be made critically stressed by increasing injection pressure



Well placement and completion recommendations:
optimized path = highest production



Summary

- Naturally fractured carbonate reservoir & key production contribution through fractures
- There is a need to include natural fractures as part of stimulation plan for maximizing the production.
- Existing DFN model is integrated with Geomechanics to locate critically stressed fractures (shear-slip)
- Higher number of fractures can be made critically stressed by increasing injection pressure
- iCSF indicates index of critically stressed fractures which is the area of fractures intersected in cell to cell volume
- New well placement has been decided based on Geomechanical sweet spot (iCSF index) and stress orientation for maximizing the production.

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