Numerical Models as Important Component of EGS Design and Operation

New Frontiers in EGS Technology

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Palm Springs, CA
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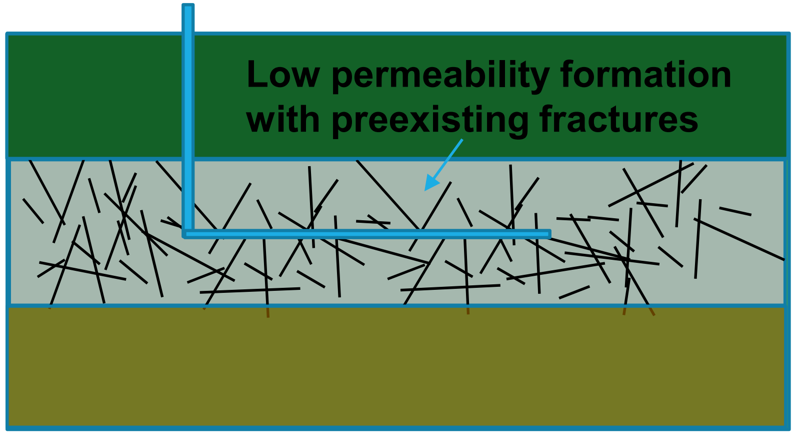
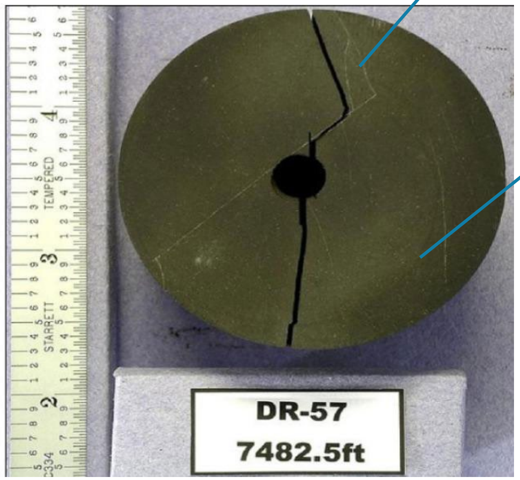
Fracture Network Engineering

- **How can we better engineer a discrete fractured network?**
- Examples in different industries include
  - Hydraulic fracturing of petroleum reservoirs
  - Development of enhanced geothermal systems
  - Block-caving mines
  - Radioactive waste storage
  - CO_2 sequestration





Fracture diversion along a mineral vein

Core sample of Horn River shale

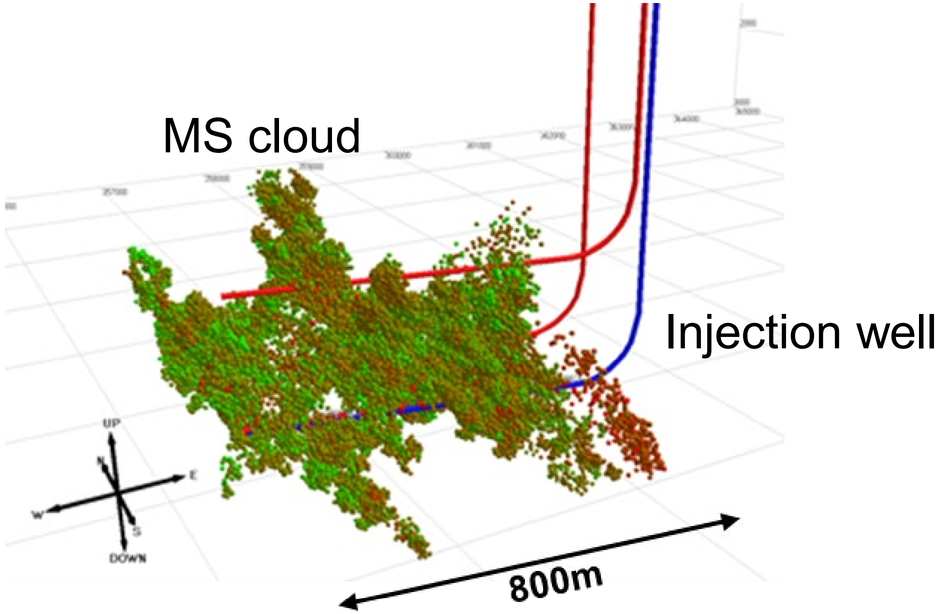
From Beaudoin et al., SPE 147510-MS, 2011

Applications of Numerical Modeling

1. **Constraining the uncertainty** of input data as a complementarity tool to field measurements

2. **Optimization of design** and **operations**, including
   - selecting optimum landing depth, orientation and completion design,
   - evaluation of the effectiveness of stimulation strategies (hydraulic fractures or just hydro-shearing),
   - prediction of performance during operation.

3. **Microseismic** calculation, risk assessment and model calibration



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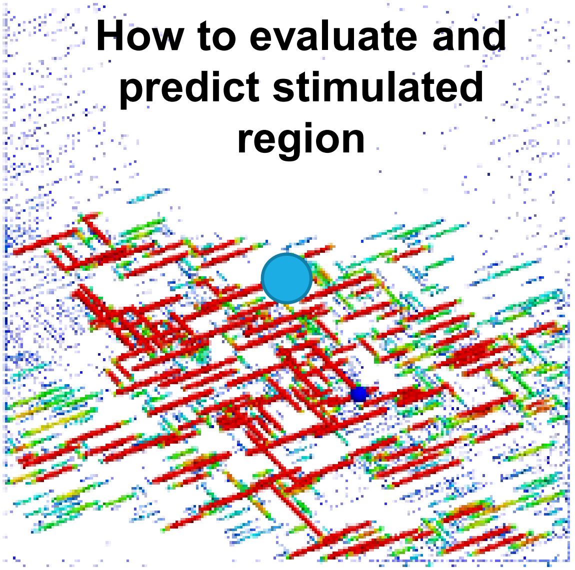
EGS Validation Study

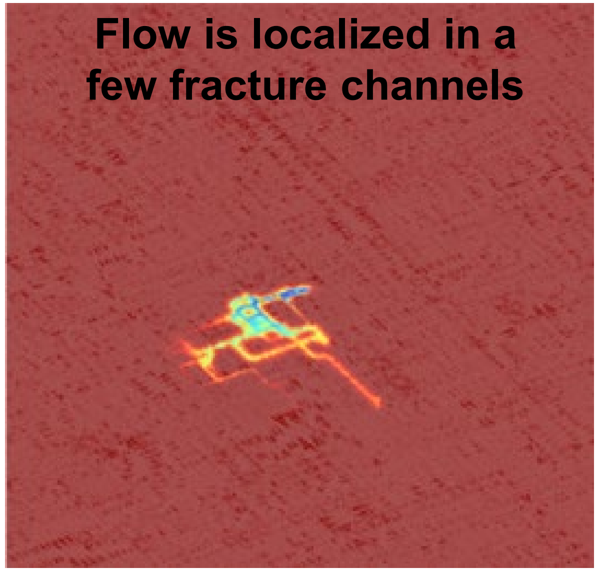
Objectives of the EGS validation study were to evaluate in-situ conditions and operational parameters that would result in economically viable EGS. (Is 5MW of electricity possible?)

- Flow rates of 80 kg/s at reasonable pressures, and
- Maintaining the rate of thermal drawdown to ~2°C per year for extended period of years (decades).

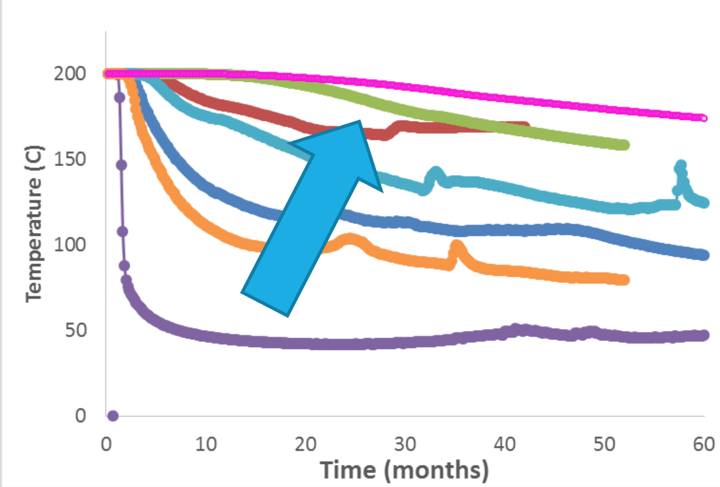
Stimulation Phase
Weeks



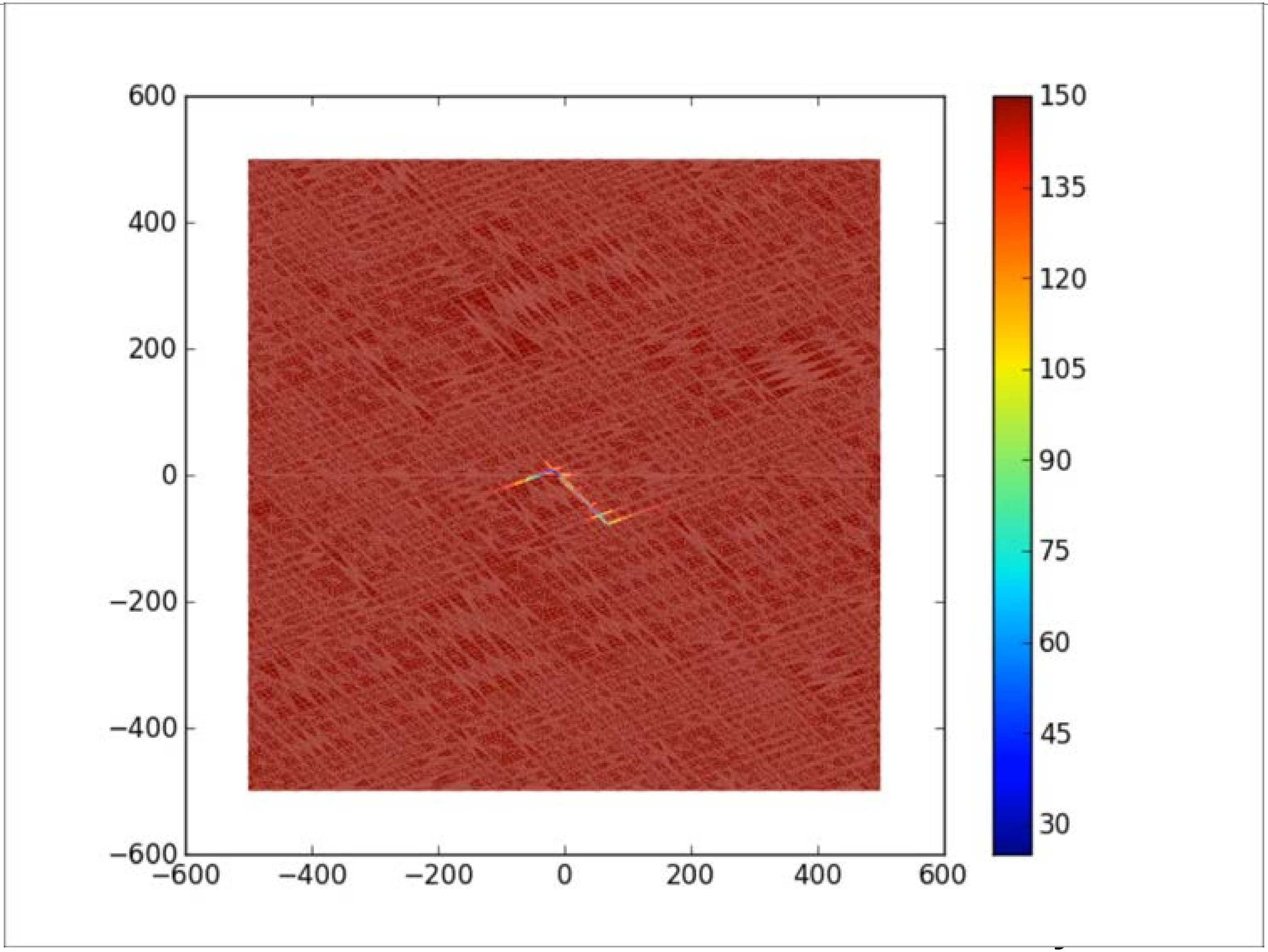
Production Phase
30 Years



The challenge is how to maintain a rate of 2°C thermal draw down per year



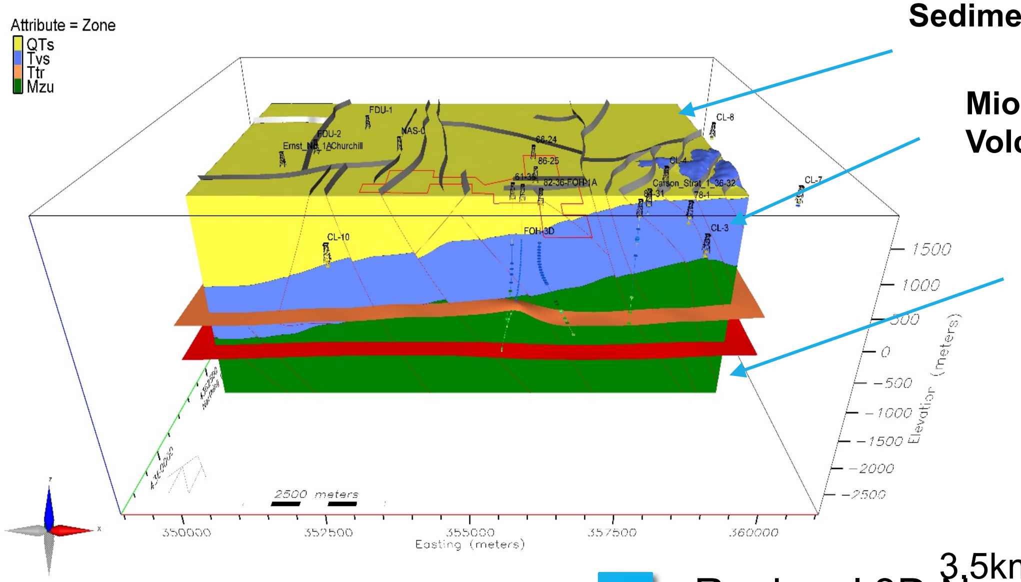
Rock Temperature Evolution in EGS



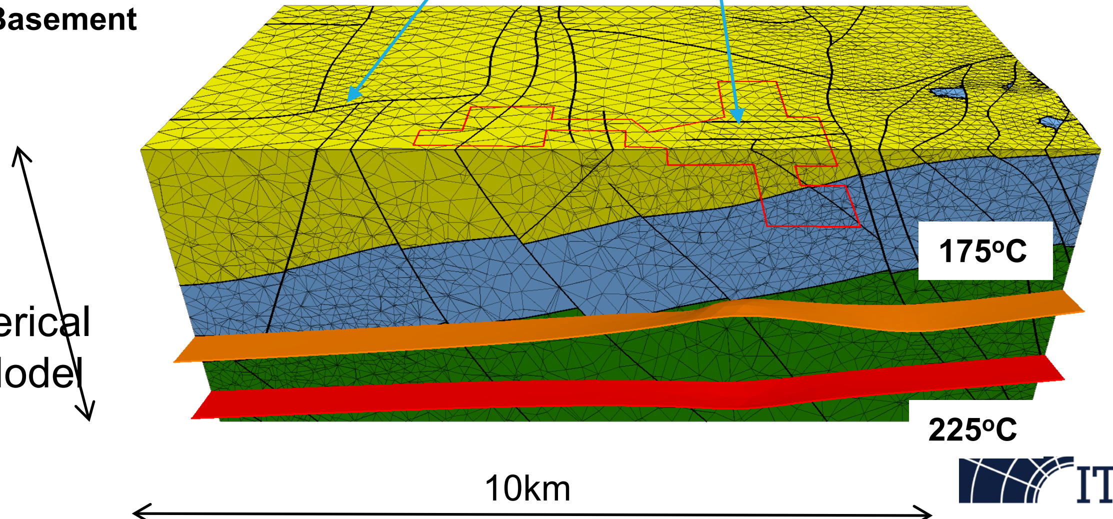
Numerical Modeling for Fallon Project

- Stress characterization
- Evaluation of different designs on reservoir stimulation
- Assessment of induced seismic hazard and potential for fault activation

Fallon Geological Model



Regional 3D Numerical Geomechanical Model

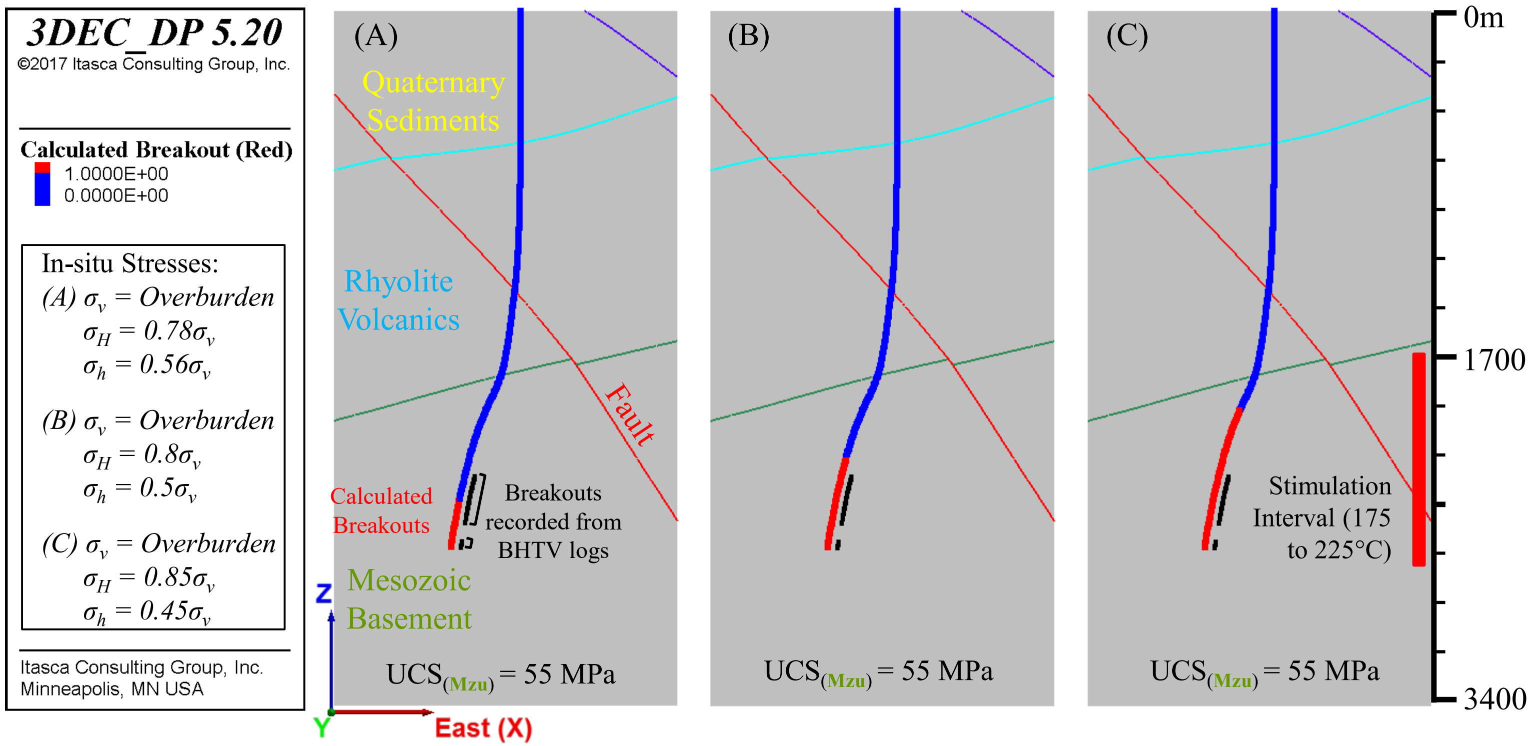


Itasca created a regional model based on USGS info, papers and reports from Brady's and Desert Peak

Stress Characterization: Assumptions

- **The in-situ stress regime is considered normal faulting** with the maximum principal stress oriented vertically and the magnitude equal to the overburden.
- **The strata are homogenous and isotropic** for the three layers (i.e., Quaternary Sediments, Rhyolite Volcanics and Mesozoic basement). The Uniaxial Compressive Strength (UCS) of the rock in the Mesozoic basement was assumed to be 55 MPa.
- **The pore pressure is assumed to be hydrostatic** along the strata column and does not change due to the temperature gradient. The water table was assumed to be 20 m below the surface.

Stress Characterization: Breakout Stability Analysis



$$\left\{ \begin{array}{c} 0.78\sigma_v < \sigma_H < 0.80\sigma_v \\ 0.50\sigma_v < \sigma_h < 0.56\sigma_v \end{array} \right\}$$

Stress Characterization: Minimum Horizontal In-situ Stress from Fracture Slip Analysis

$$\boldsymbol{\sigma_n' = \sigma_n - P_p}$$

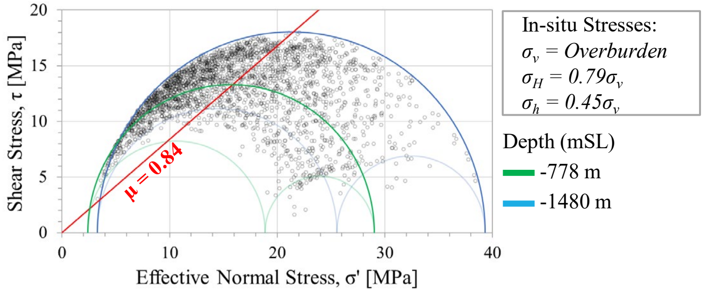
$\sigma_n' = Normal\ effective\ stress$
$\sigma_n = Normal\ stress$
$P_p = Pore\ pressure$

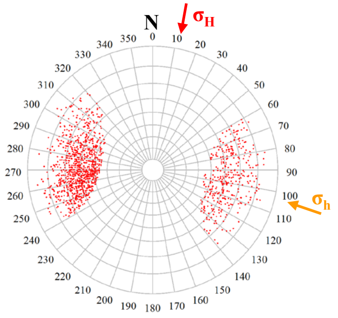
$$\boldsymbol{\tau_s = \sigma_n' tan\theta}$$

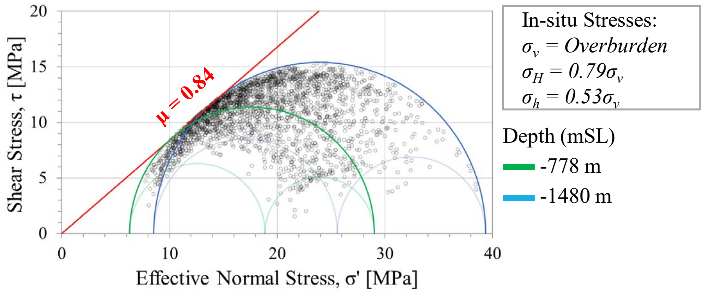
$\tau_s = Shear\ stress$
$\theta = Friction\ angle$

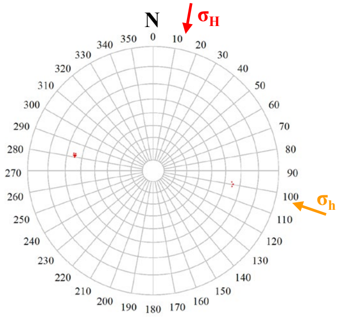
assume θ is 40°

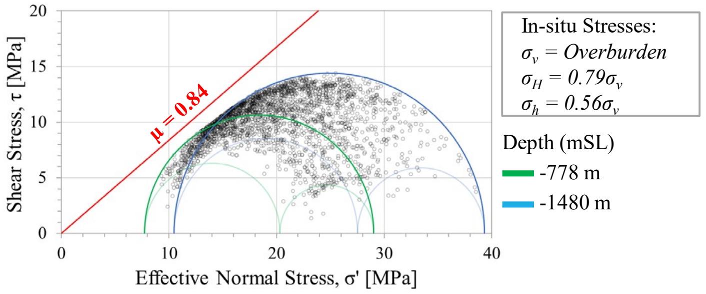
$$\boxed{\sigma_h = 0.53\sigma_v}$$

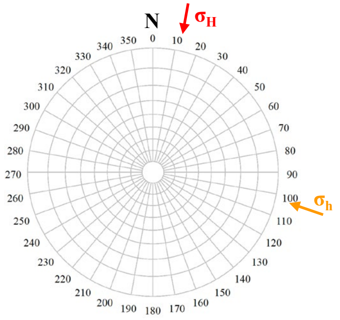












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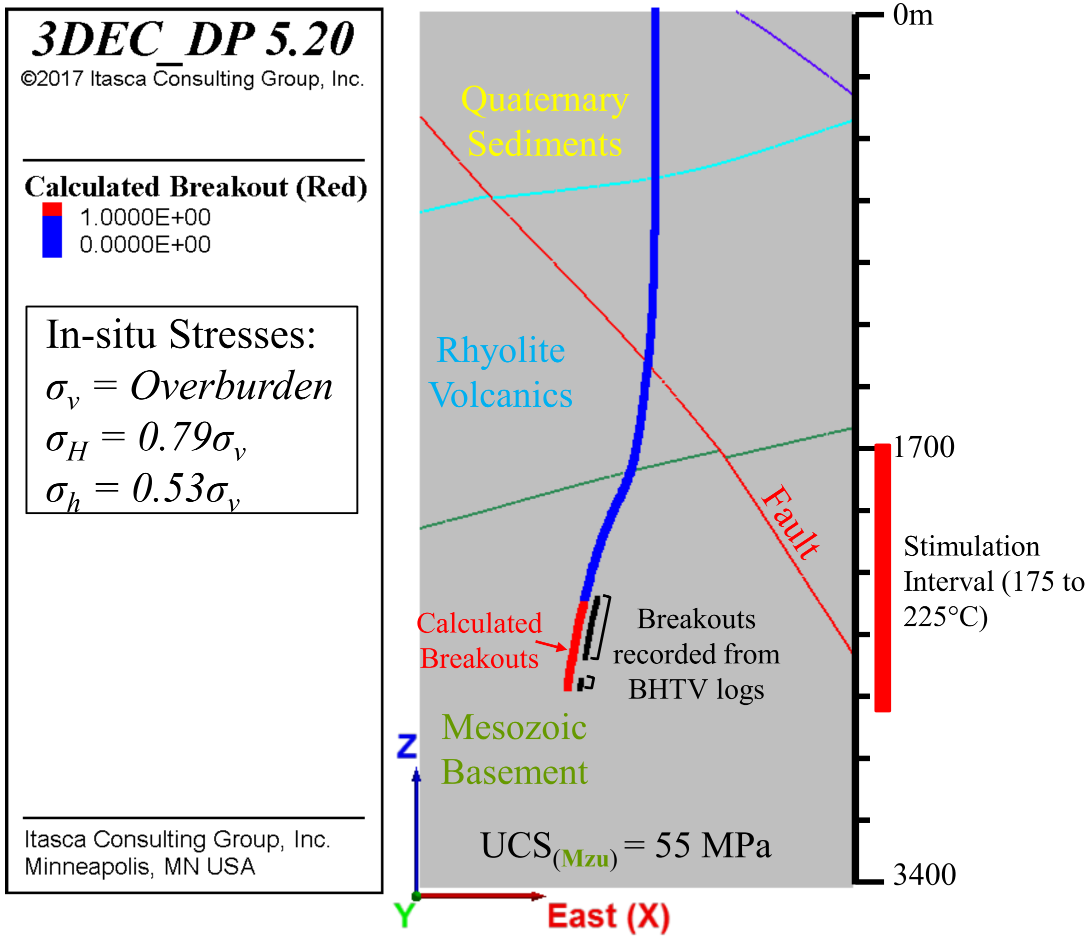
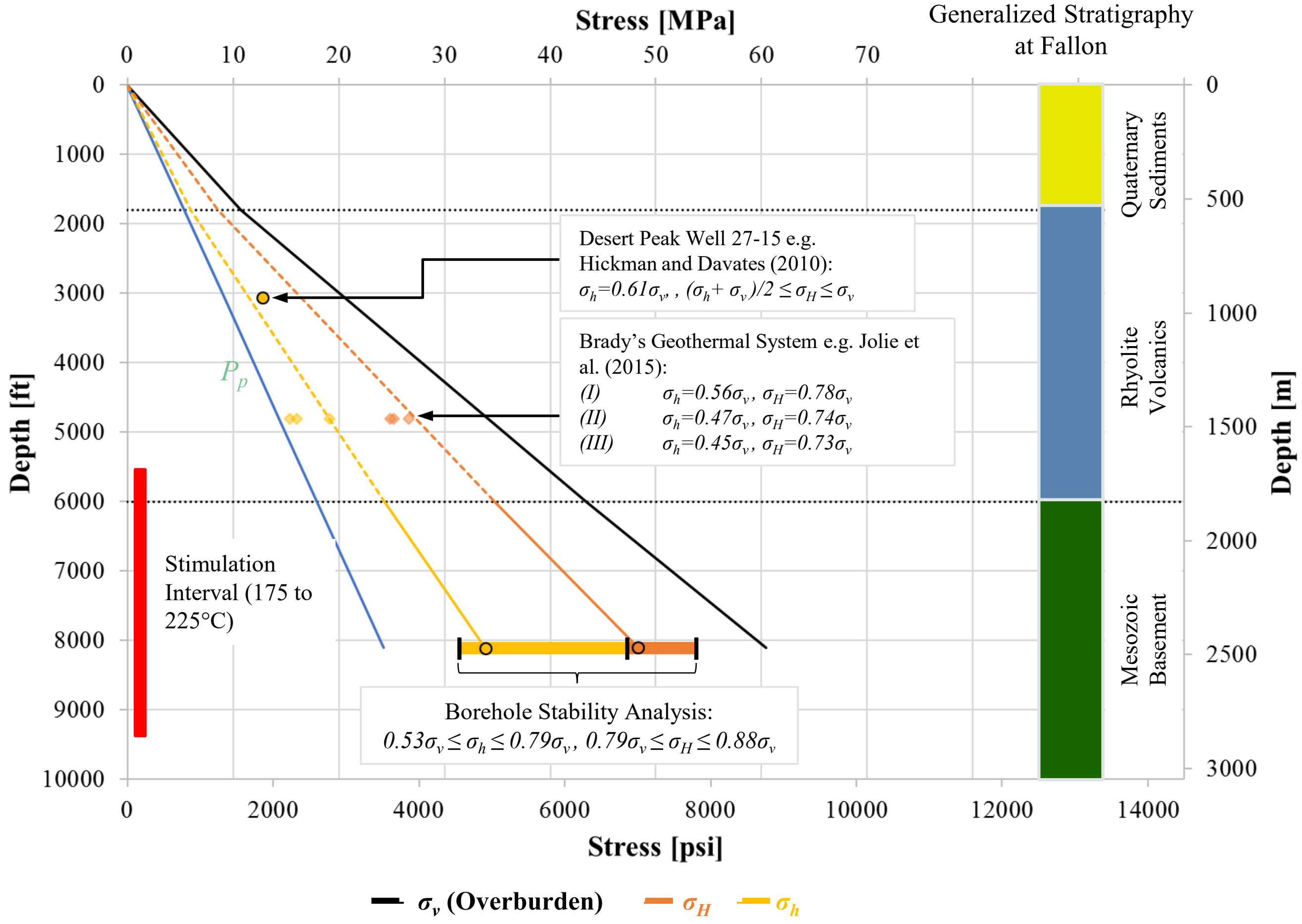
Stress Characterization: σ_H when $\sigma_h = 0.53\sigma_v$



Stress Characterization: Comparison with Nearby Stress Data

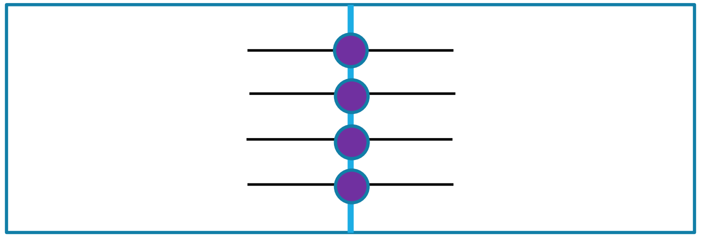
- Breakout stability analysis gives "large" range of possible in-situ stress values.
- Comparing with local measurements gives confidence as to what part of the range the in-situ stresses occupy.

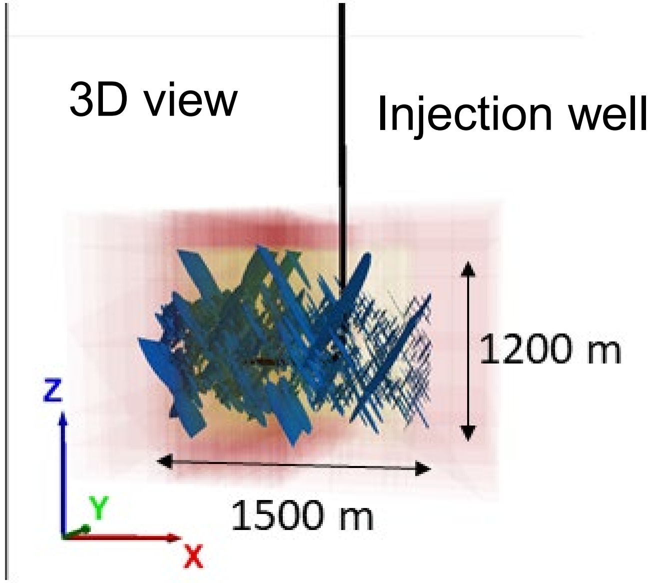


Important Components of Geomechanical Models

- Geomechanical models should be capable to simulate:
  - ❖ Pre-existing fracture network
  - ❖ Hydraulic fracturing using multiple stages and clusters
  - ❖ Leak-off
  - ❖ Proppant transport and placement
  - ❖ Fluid volume distribution within HF planes, DFN, bedding planes and sealed portion of fractures.
  - ❖ Synthetic microseismic (MS) modeling
    - time,
    - location,
    - moment magnitude, and
    - vertical and lateral distribution of cumulative moments.

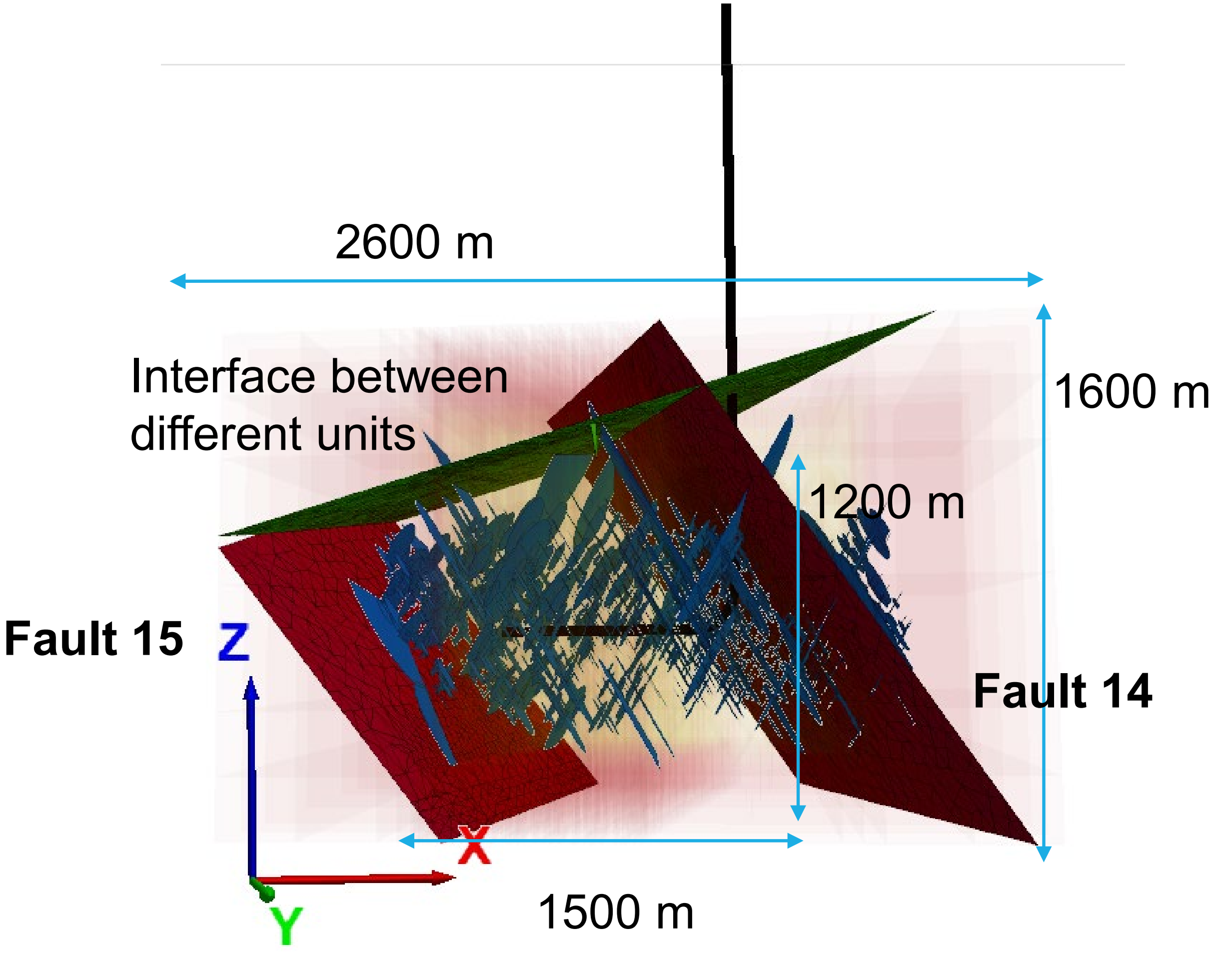
Plan view of adjacent clusters





Geomechanical Modeling: Reservoir Geometry and Input

- DFN was constructed from borehole log, P10, and fracture orientation
- Explicit representation of DFN in the core region of 1500×1200×1200 m
- Relevant structures, Fault 14, Fault 15, and the interface between Mesozoic unit and the Rhyolite unit are presented deterministically
- σ_v =61 MPa, σ_h =34 MPa and σ_H =49 MPa (calculated based on borehole analysis)
- Fractures were assigned an initial aperture of 3×10^{-5} m



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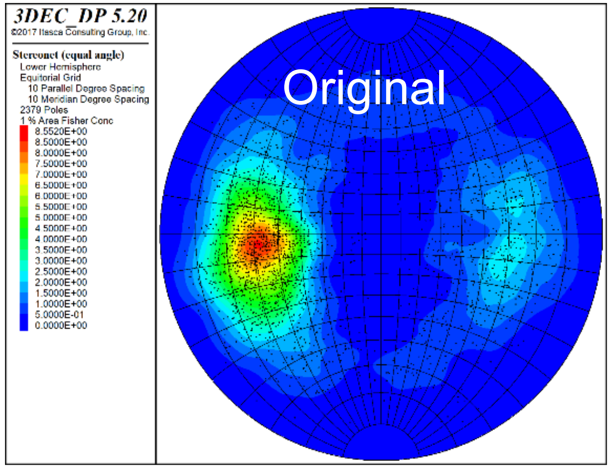
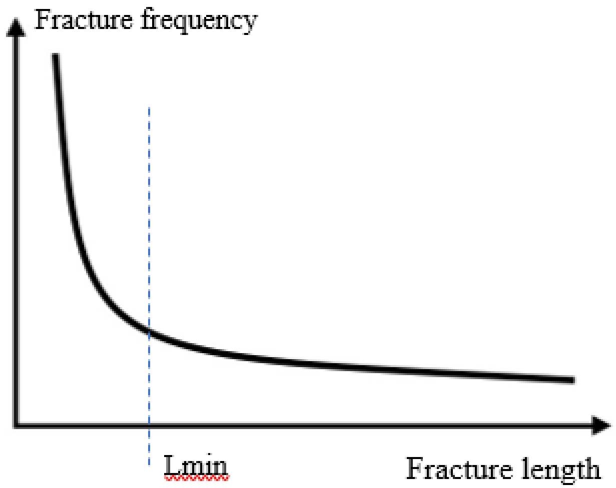
Geomechanical Modeling: Synthetic DFN

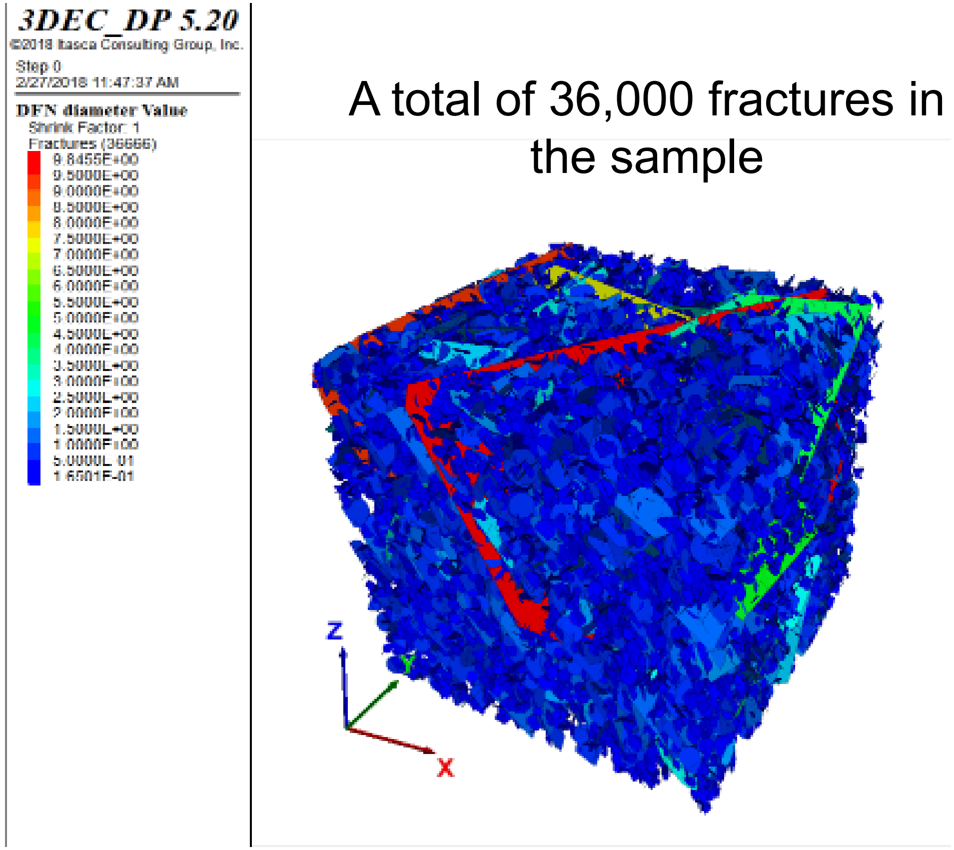
- Borehole data can lead to identifying one or more fracture sets, with an average mean orientation and variation about a mean angle.
- Typical information includes P10 (fracture frequency per unit length of the borehole), and fracture orientation.
- Fracture size is often not characterized, it is assumed fracture size follows a power law distribution with a negative exponent between 2.5 and 4.
- Sometimes information about percentage of open versus sealed fractures is available.





Geomechanical Modeling: DFN Simplification

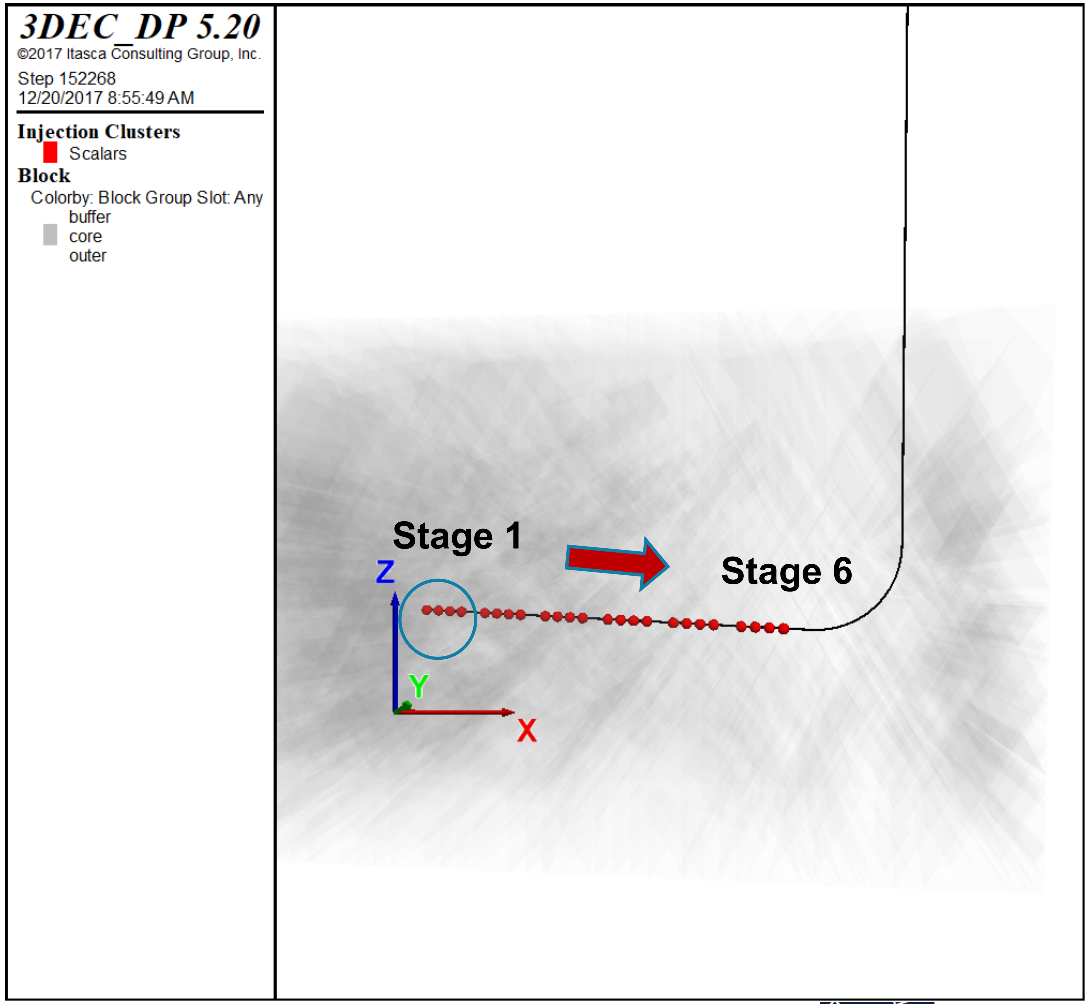
- The DFN simplification: procedures that are necessary because of **computational constraints**, such model size and run time.
- The main objective of the DFN simplification processes is to **preserve the properties of the rock mass, i.e., mechanical, hydraulic and thermal properties**, while reducing the number of fractures.



A 10×10 m cube with the P10 density observed from FOH-3D borehole. Fractures colored by size.

Geomechanical Modeling: Evaluation of Different Designs

- During stimulation water is injected into the reservoir.
- A horizontal well layout is considered.
- Multi-stage stimulations are analyzed.
- Different well completions (openhole versus cased borehole).
- Different injection scenarios are considered.



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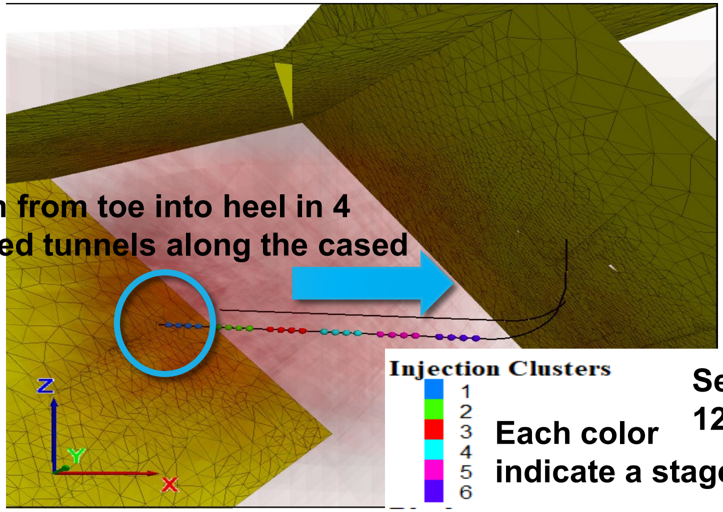
Geomechanical Modeling: Two Designs

- A horizontal well layout with six stimulation stages are assumed.
- ***Openhole completion*** uses a constant injection rate of 5 kg/s for 5 hours per stage (125 m length of stage stage).
- ***Cased borehole with perforation clusters*** applies a relatively high injection rate of 80 kg/s for half and hour (with objective to create hydraulic fractures) followed by 4.5 hours of a injection at 5 kg/s.

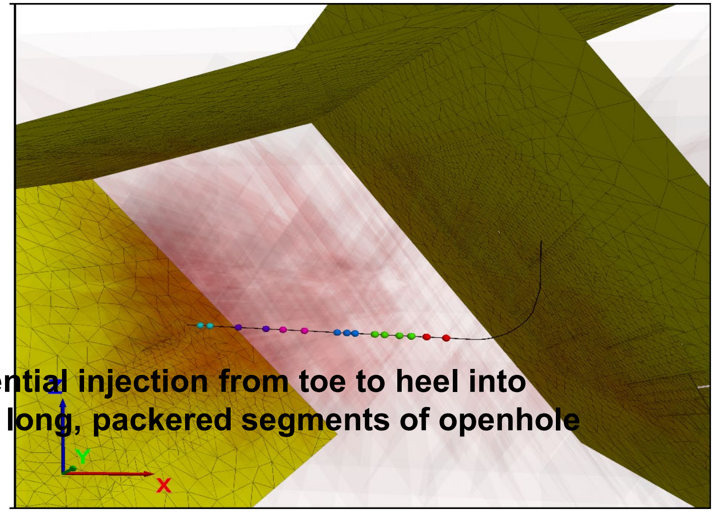
Sequential injection from toe into heel in 4 clusters of perforated tunnels along the cased wellbore



Each color indicate a stage

Cased borehole

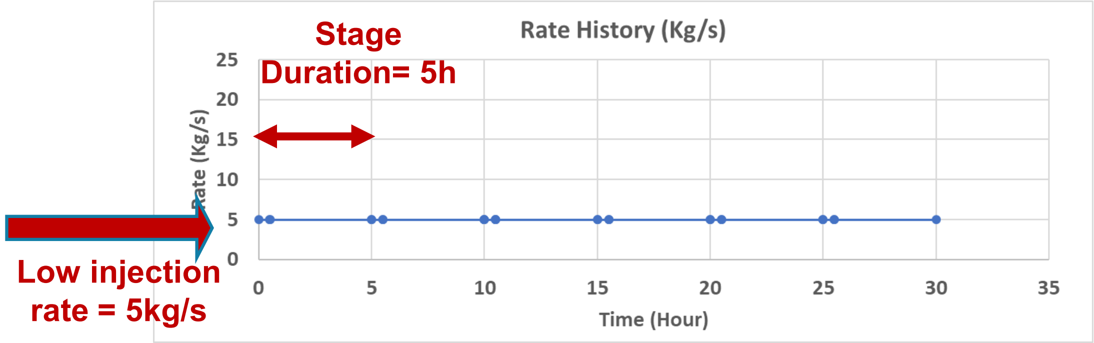
Sequential injection from toe to heel into 125 m long, packered segments of openhole



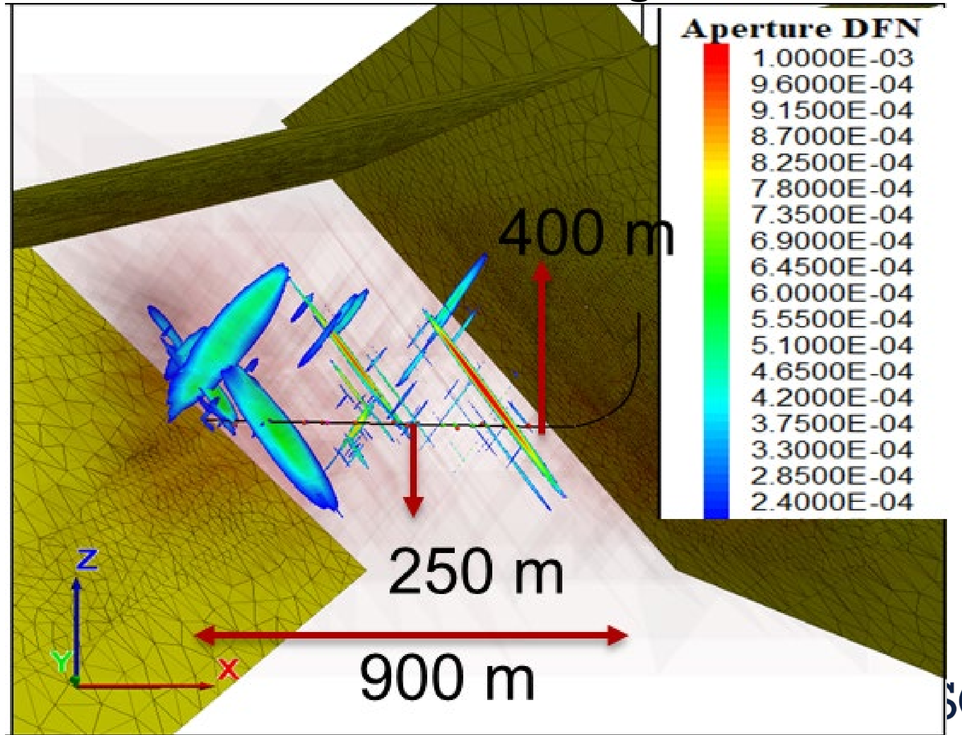
Openhole

Geomechanical Modeling: Openhole Model

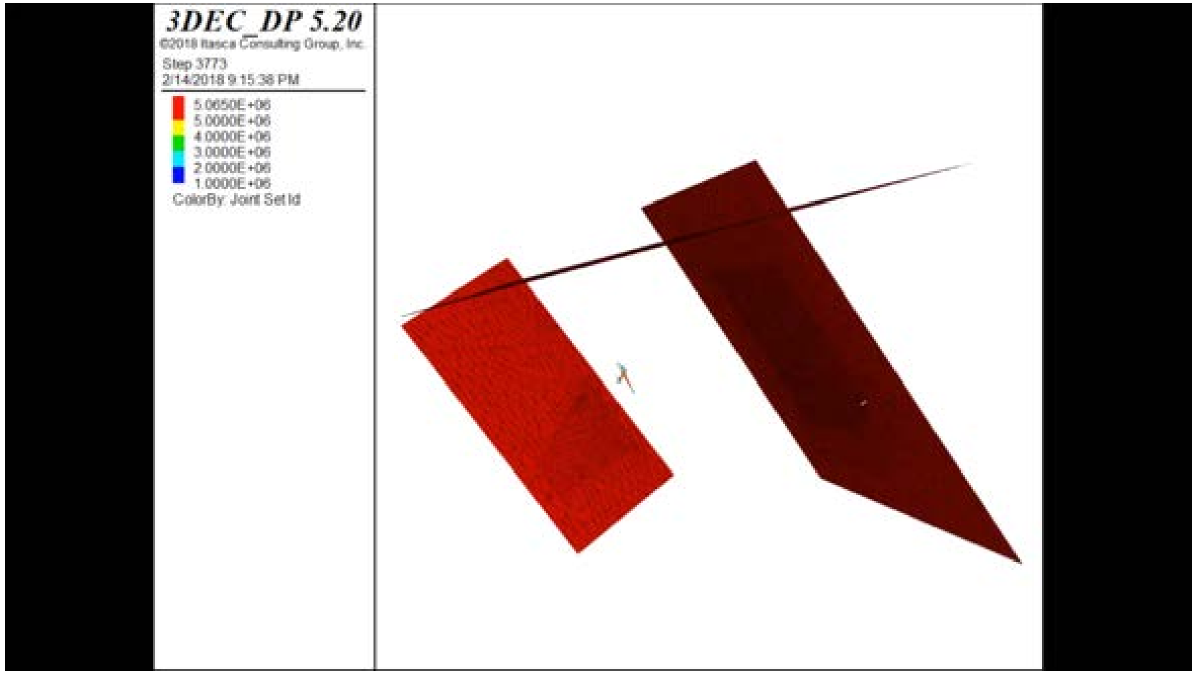
- Duration of all six stages = 30 hours of injection
- Rate: 5 kg/s
- Injection takes place through the natural fractures intersecting the borehole.
- Stimulation is more upward (height-wise) w.r.t the elevation of the injection well.
- The openhole model resulted in shear stimulation of fractures in a relatively large volume.
- Using staged stimulation, it is possible to stimulate a relatively large region of the reservoir horizontally.

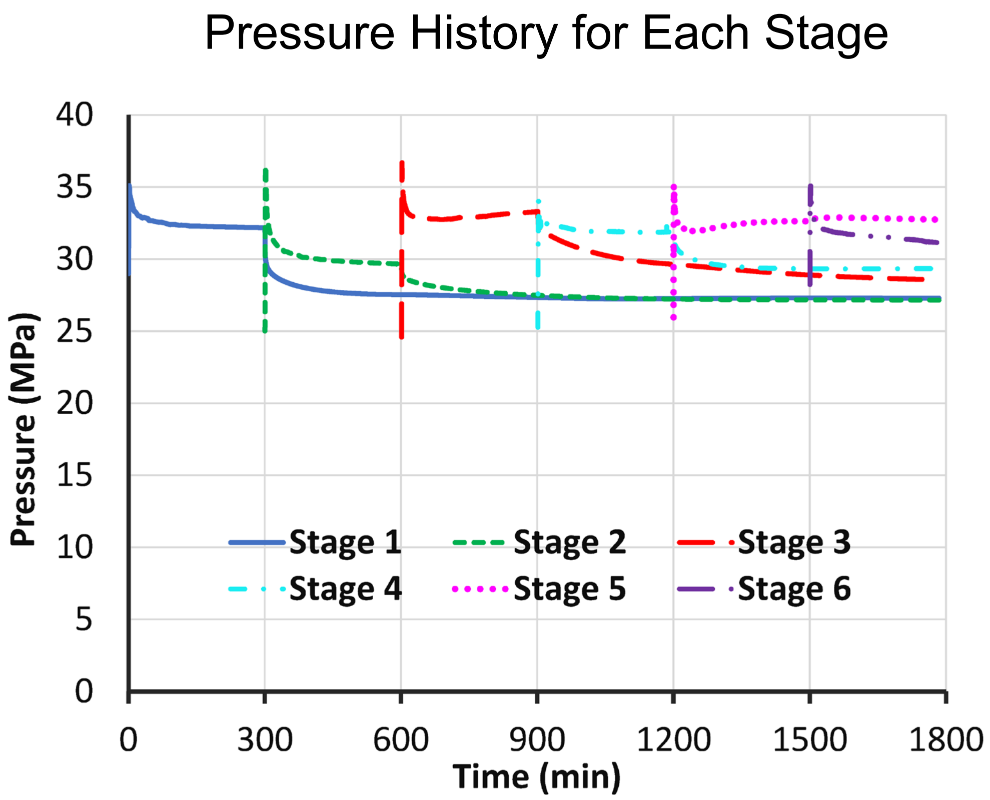


Shear Stimulated Region



Geomechanical Modeling: Pressure History in Openhole Model





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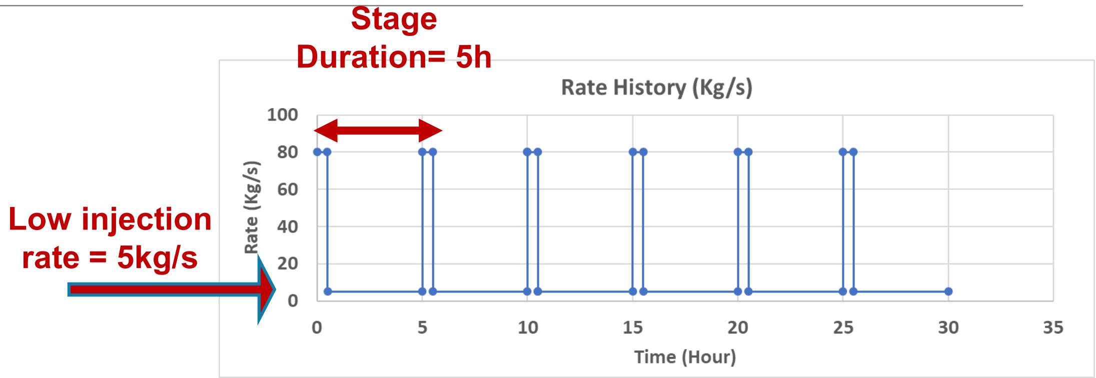
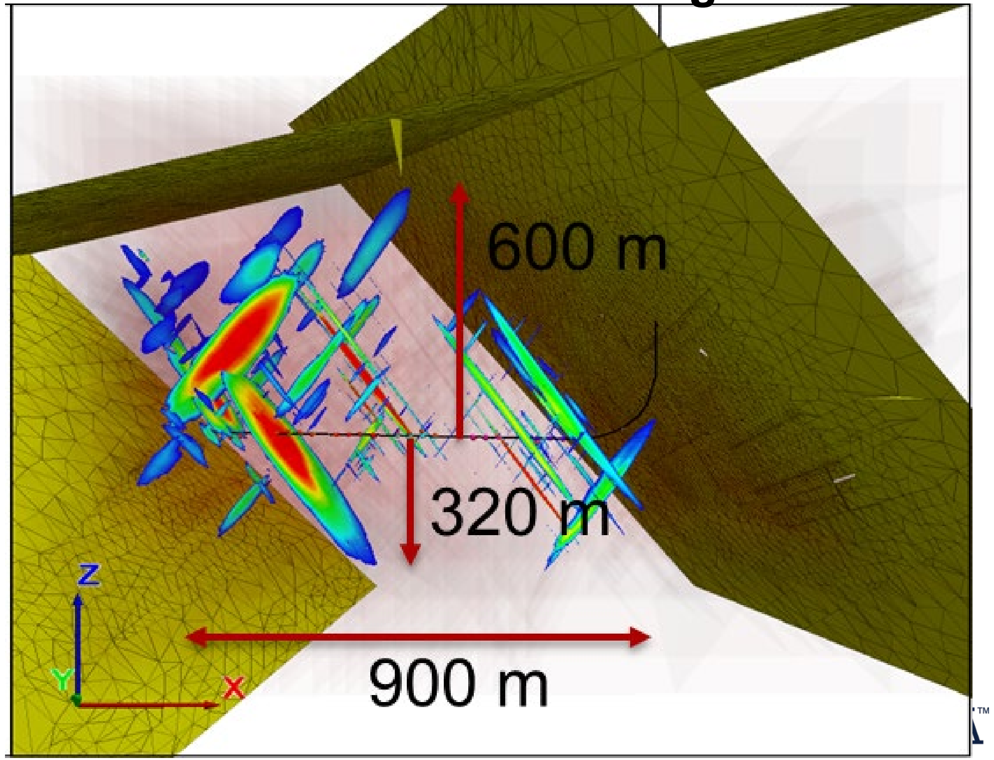
Geomechanical Modeling: Cased Borehole Model

- Duration of all six stages = 30 hours of injection
- Rate: combined 5 and 80 kg/s
  - The combined high-low injection rate results in the creation of hydraulic fractures.
  - The purpose of hydraulic fracturing is to provide better connectivity with the discrete fractures in the reservoir.
  - Neither of the two scenarios resulted in fluid pressure dissipation into either of the two faults nor slip of those faults.

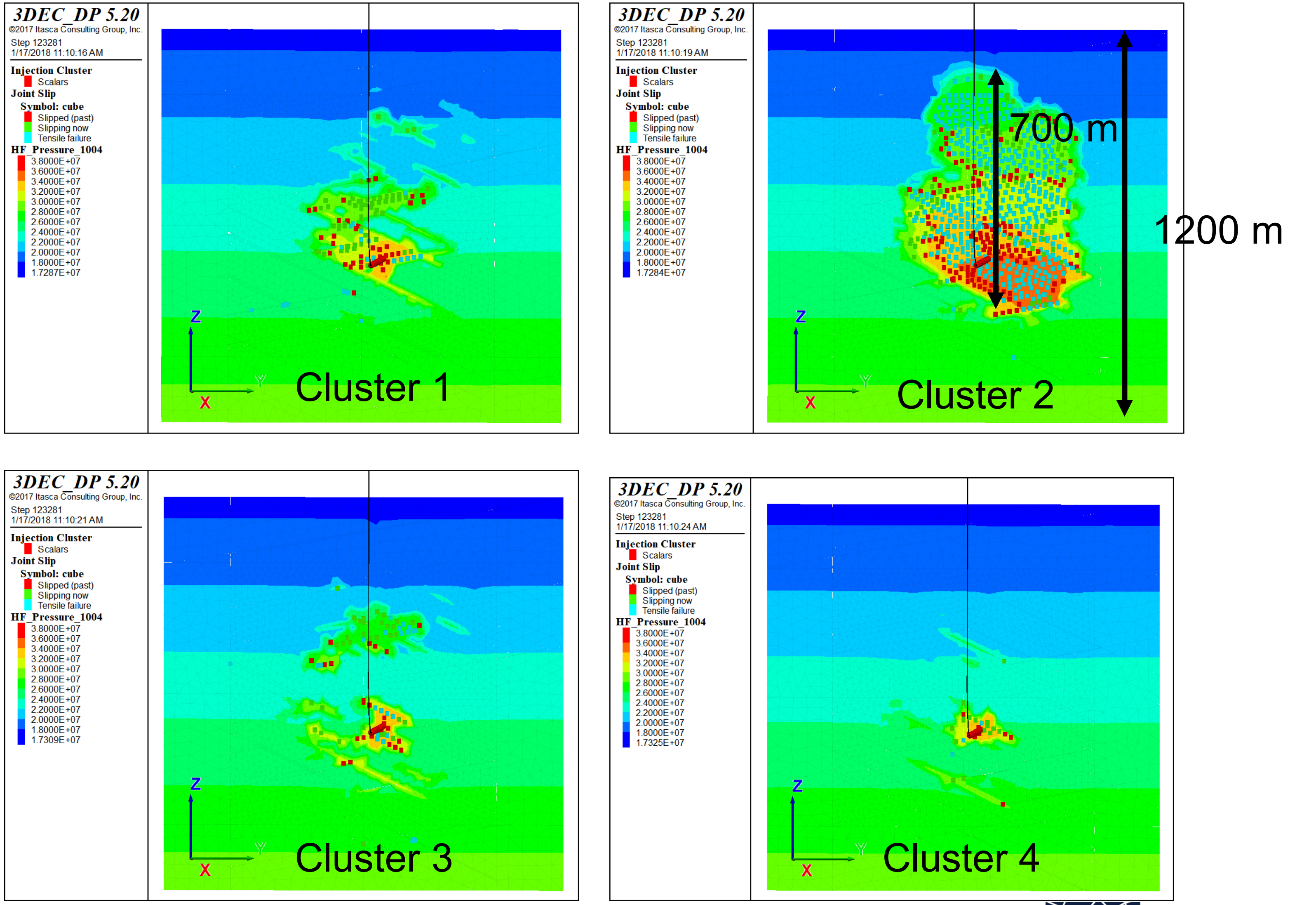


Shear Stimulated Region



Geomechanical Modeling: Pressures at the End of High Rate Regime

- Usually one out of four clusters resulted in substantial hydraulic fracturing
- Hydraulic fractures preferentially grow in an upward direction



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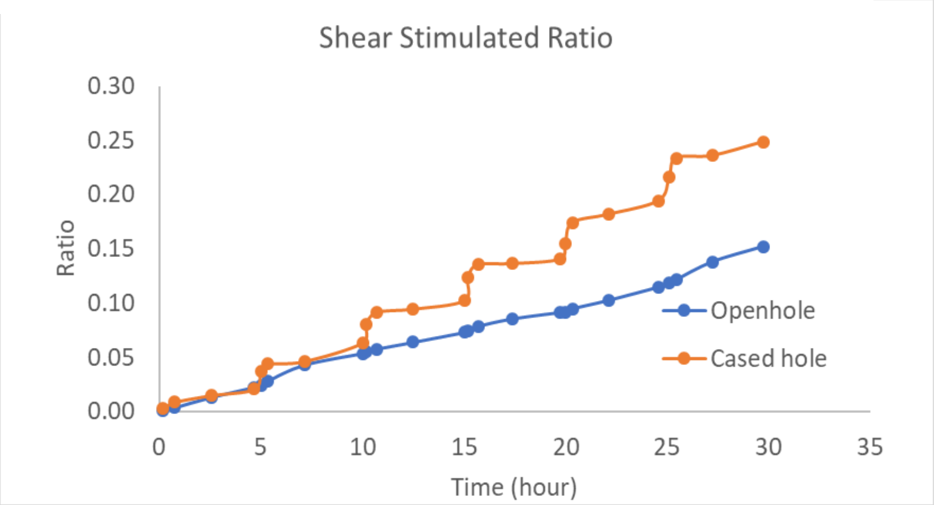
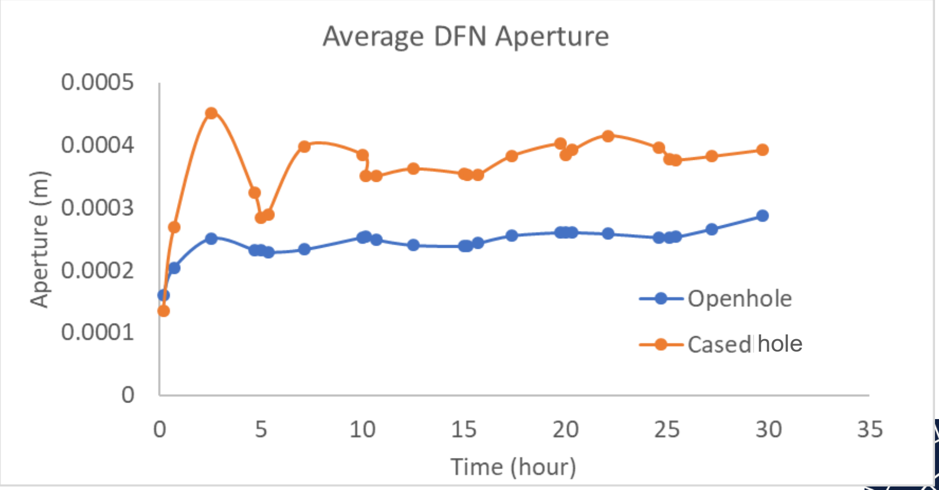
Geomechanical Modeling: Evaluation of Effectiveness of Stimulation

- Quantifying metrics were developed and evaluated:
  - Shear stimulated area: area of fractures with slip more than 0.01 mm,
  - Shear stimulated ratio: ratio of stimulated area over the total DFN area, and
  - Leakoff volume/total injected volume ratio.
- An average aperture increase of ten times was observed in the sheared fractures.





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Microseismic Analysis: Seismicity due to Slip on Existing Joints

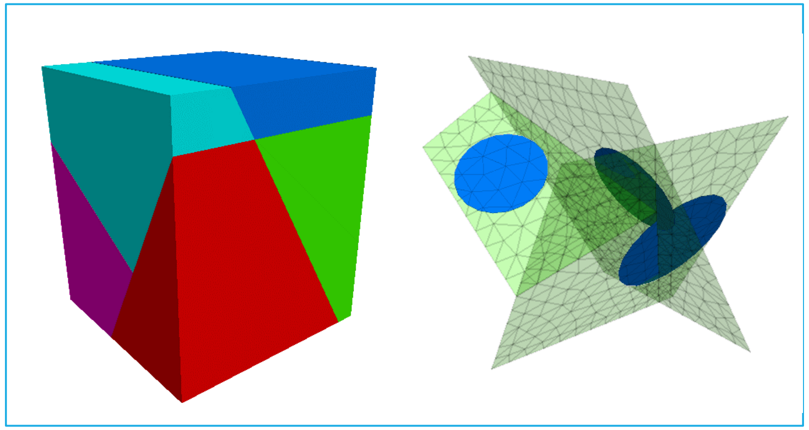
- How to get seismic information from slip on joints?
- Moment calculated from *shear modulus*, *fault area* and *fault slip*

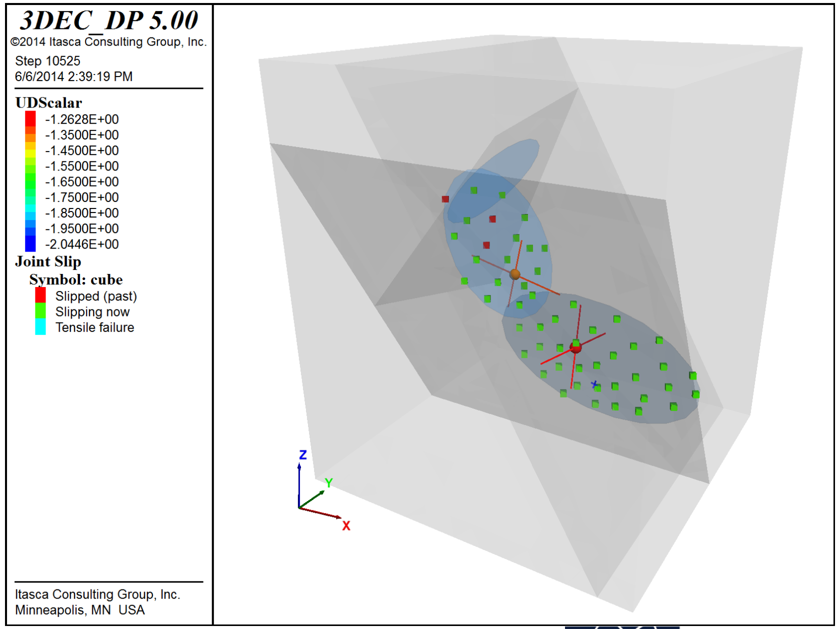
$$M_0 = \mu A \Delta u$$

- Magnitude calculated by

$$M_w = \frac{2}{3}\log M_0 - 6$$

- Challenges of numerical modeling of microseismicity
  - ❖ How to differentiate between seismic versus aseismic events
  - ❖ How to cluster events in time and space

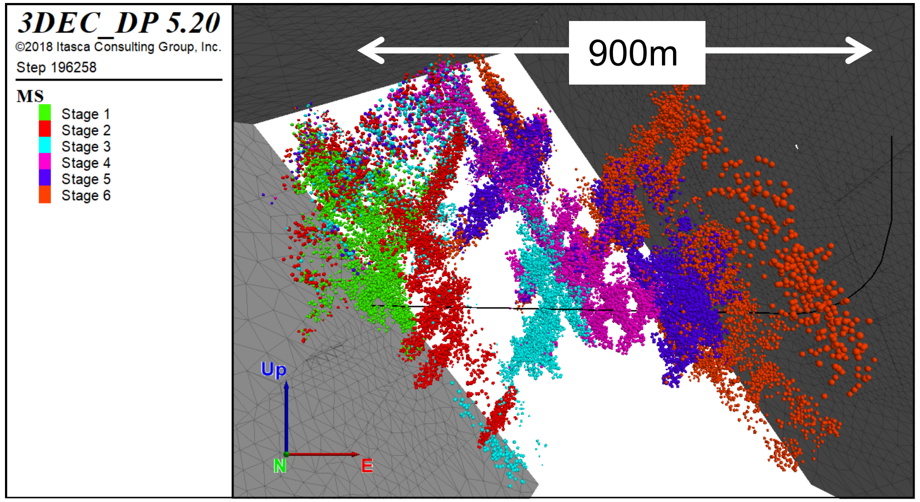




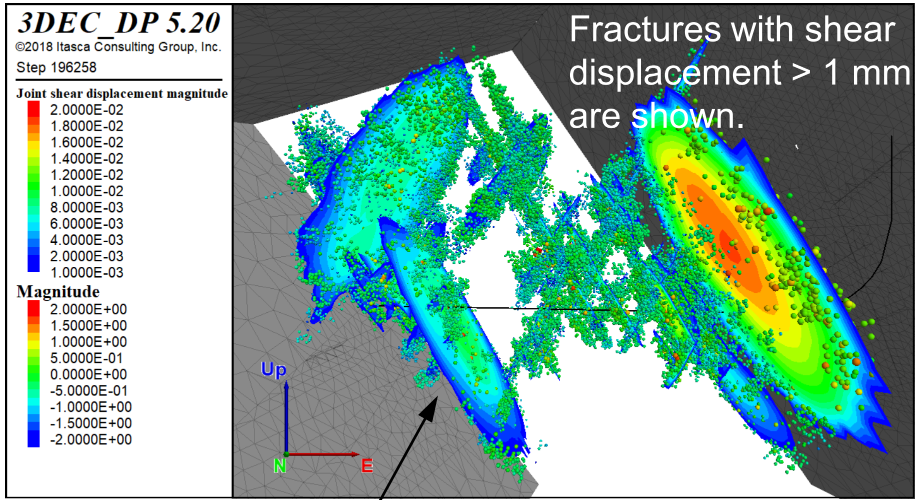
Microseismic Analysis: Synthetic Cloud

Openhole model

Events colored by stage

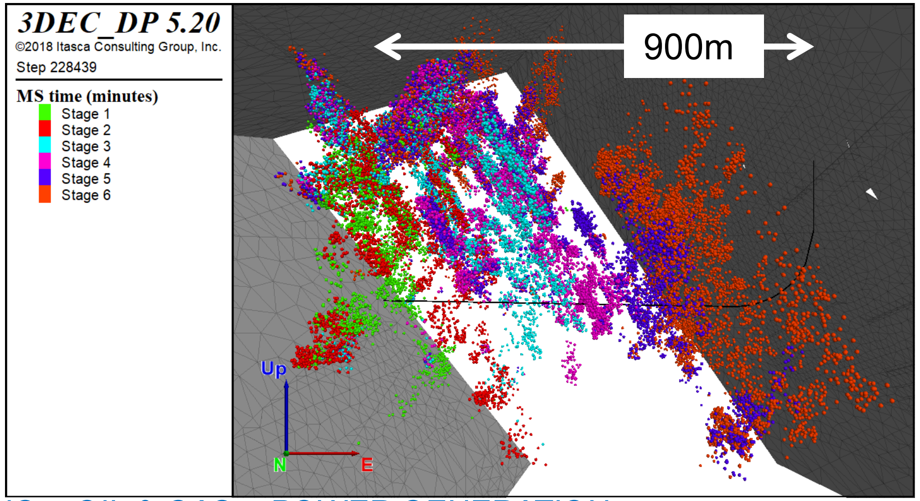


Events colored by magnitude: Maximum magnitude = 2.1

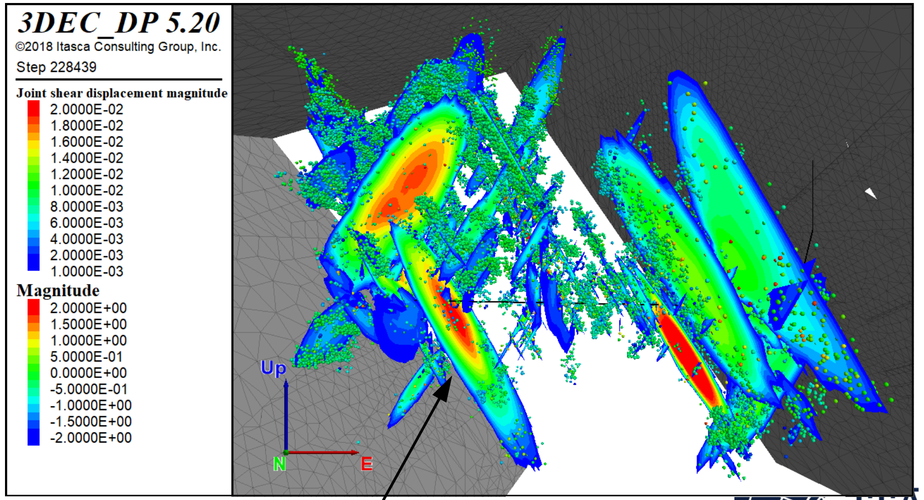


Cased borehole model

Events colored by stage

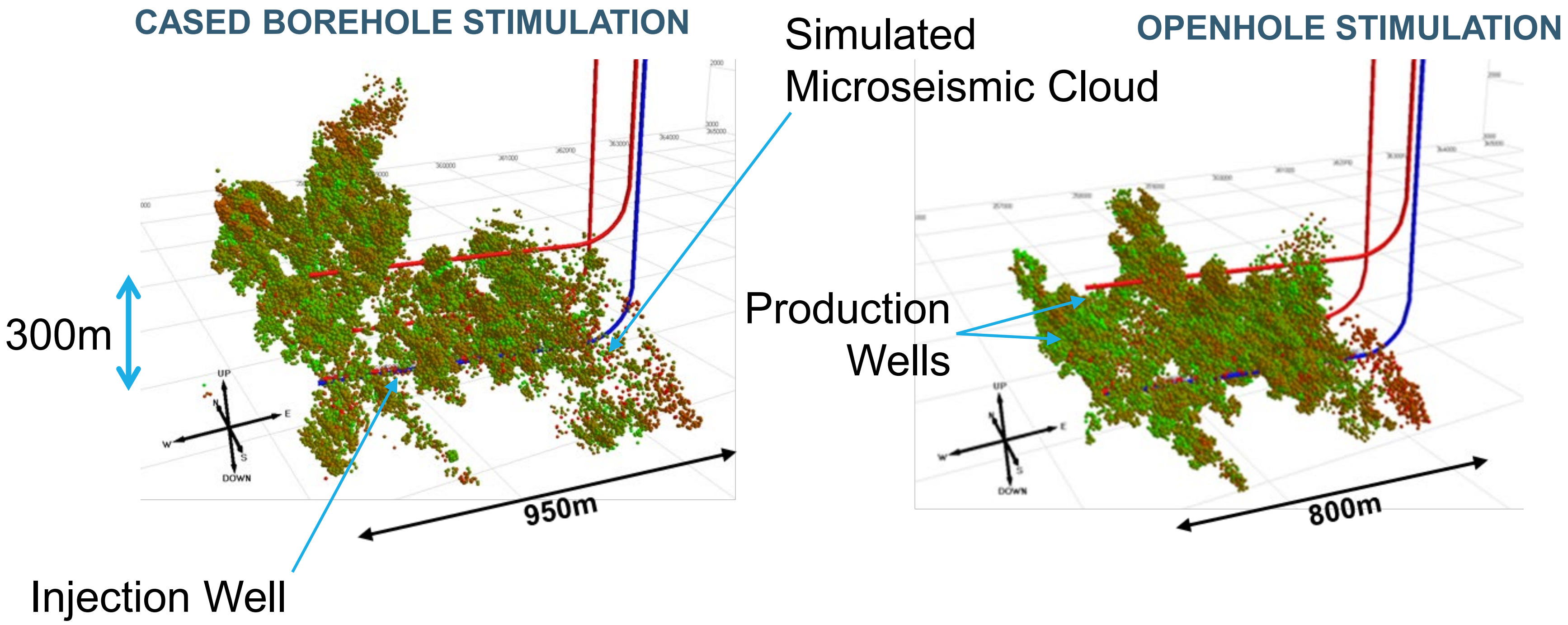


Events colored by magnitude: Maximum magnitude = 2.4



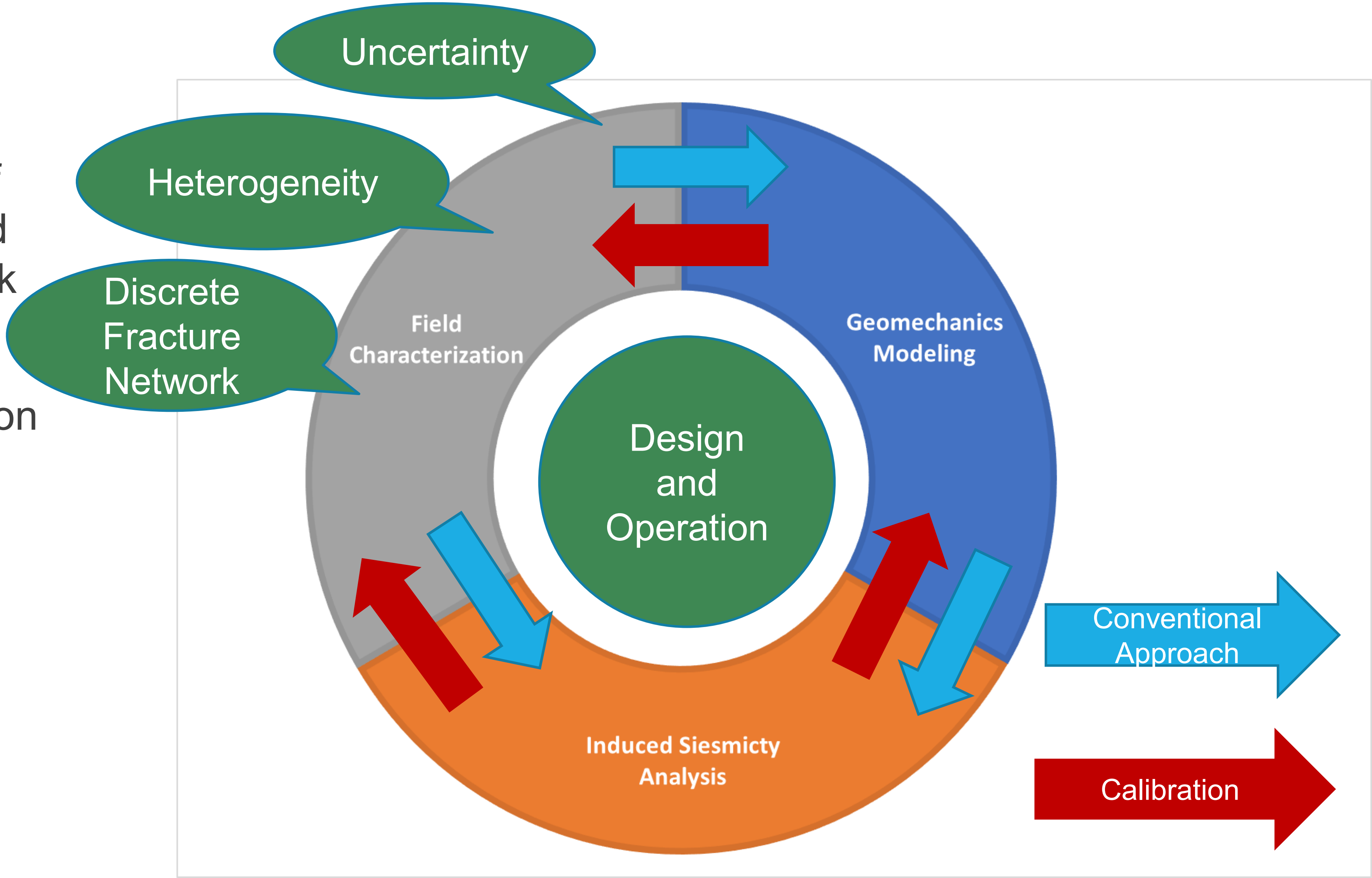
Microseismic Analysis: Interpretation

- No fault activation
- Simulated microseismicity highlights the shear-stimulated volume and aids well placement design
- Only the area of the joints with increased fluid pressure slips seismically (wet events)
- Microseismicity is strongly dependent on the size and properties of fractures in the discrete fracture network



Fracture Network Engineering

- Numerical modeling should be treated as an important component of engineering of EGS and broader fracture network engineering.
- Iterative model calibration can constrain data uncertainty and lead to reliable predictive and design tools.



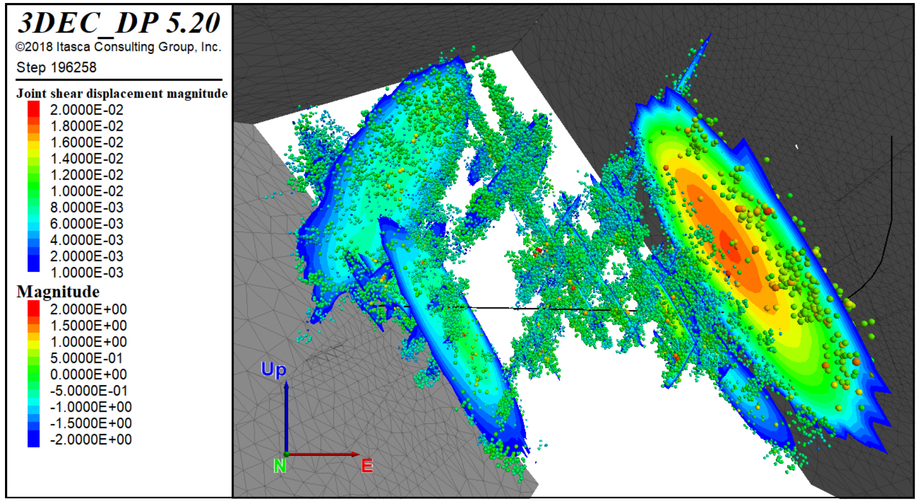
Conclusions

- Geomechanical model was used for:
  - stress characterization,
  - microseismic modeling to assess the risk associated with faults activation and induced seismicity,
  - Evaluation of designs and operational strategies.
- Calibration of geomechanics models using microseismic data is key to creating reliable predictive tools.
- Both hydraulic fracturing and hydro-shearing of discrete fracture network are important components of stimulation of EGS.
- Zonal isolation can play a key role in effective stimulation of an EGS along the entire length of the horizontal well.

Future Directions

- Constraining the uncertainty through more rigorous calibration processes
- Stochastical model generation and multi-scenario simulation to address effects of uncertainty and spatial variability of stress and petrophysical properties, and effects of DFN realizations
- Realistic representation of DFNs through DFN simplification processes
- Extending synthetic MS modeling research to better differentiate seismic and aseismic events, and clustering events by location and time.
- Developing in faster numerical solutions of larger models (parallel processing, efficient solvers)

MS cloud is extended vertically; large events on large fractures



Thank you