# *Modeling Responses of Naturally Fractured Geothermal Reservoir to Low-Pressure Stimulation*

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Lawrence Livermore National Laboratory

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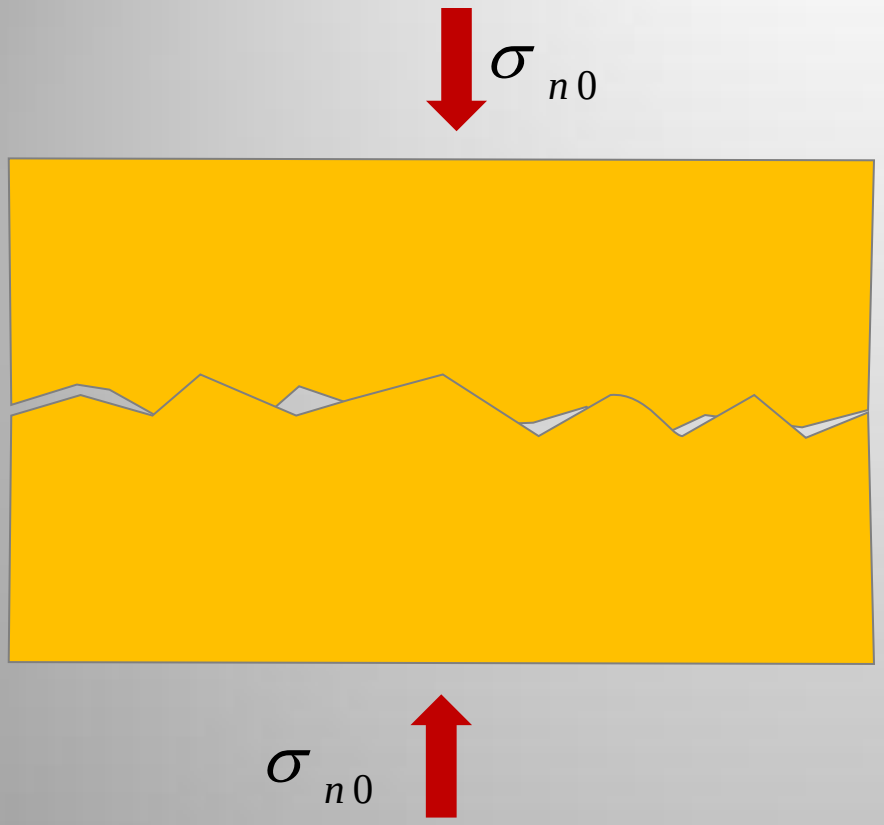
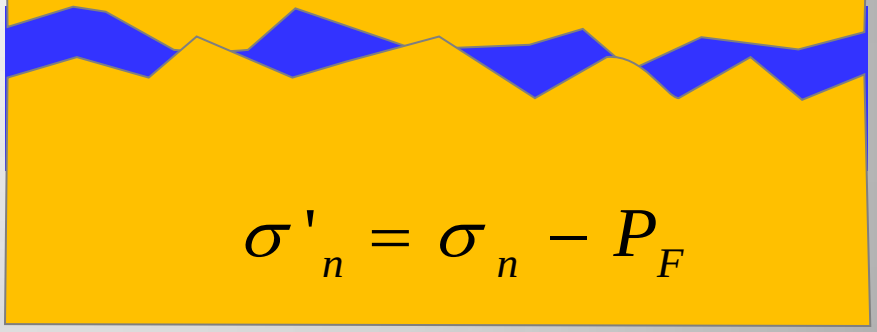
# Background

- Project: *Predicting stimulation-response relationships for engineered geothermal reservoirs*
- We need simulation capability for:
  - Reservoir stimulation with hydraulic-fracturing
  - Reservoir stimulation with hydraulic-shearing
  - Thermal effects on long term production
- Discrete Fracture Network-based approach (2D and 3D)
- Validation and demonstration with field data

# Interaction between rock-joint-fluid




$P_F < \sigma_{n0}$



$\sigma'_n = \sigma_n - P_F$

$P_F > \sigma_{n0}$

$\sigma'_n = 0$

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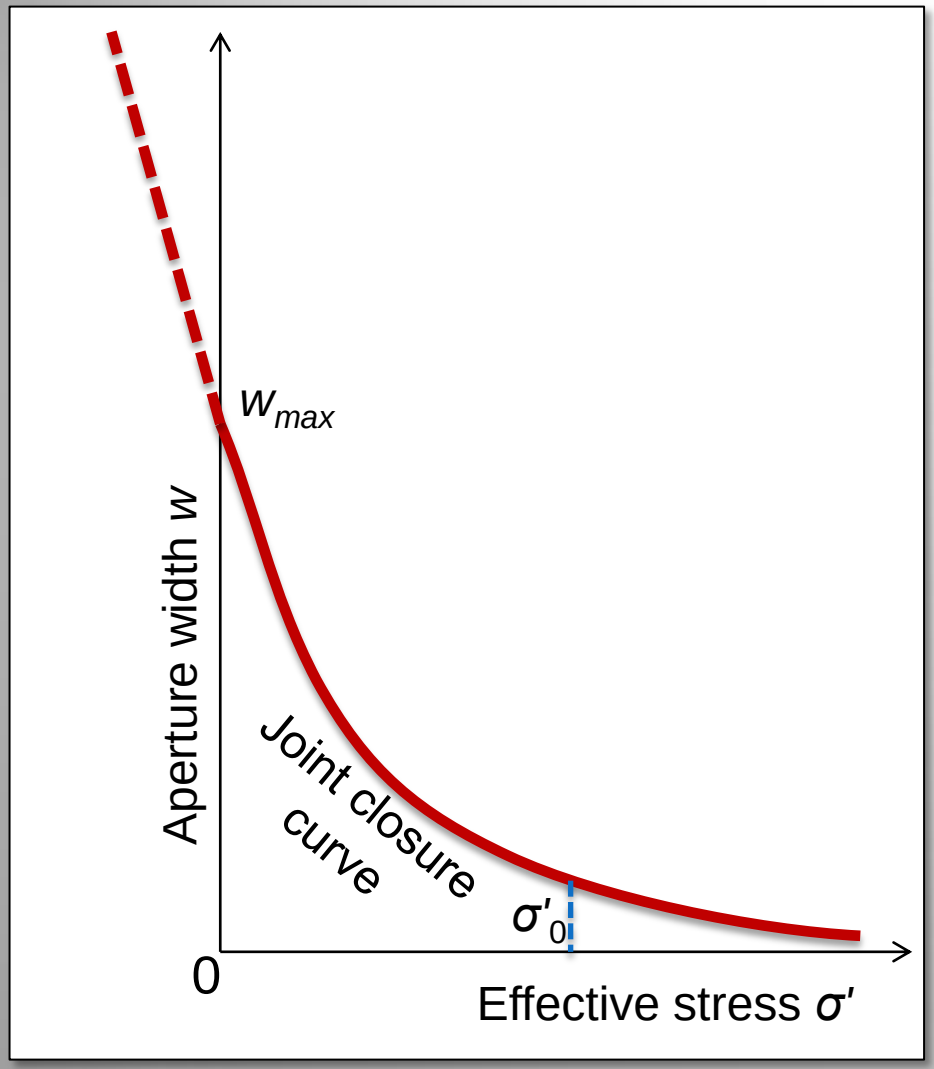
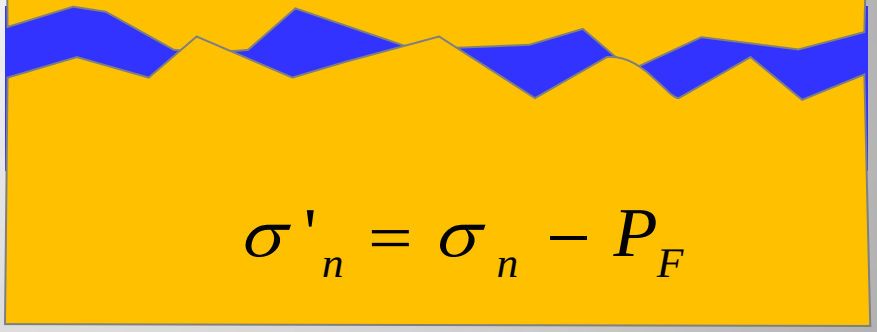



$$P_F < \sigma_{n0}$$

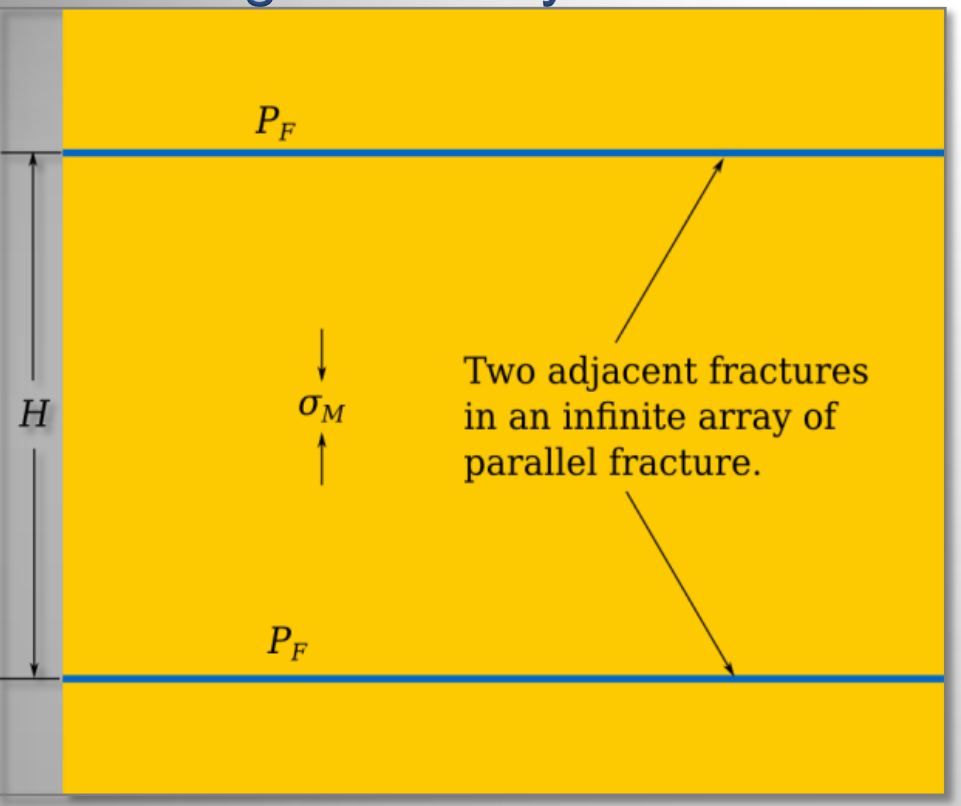


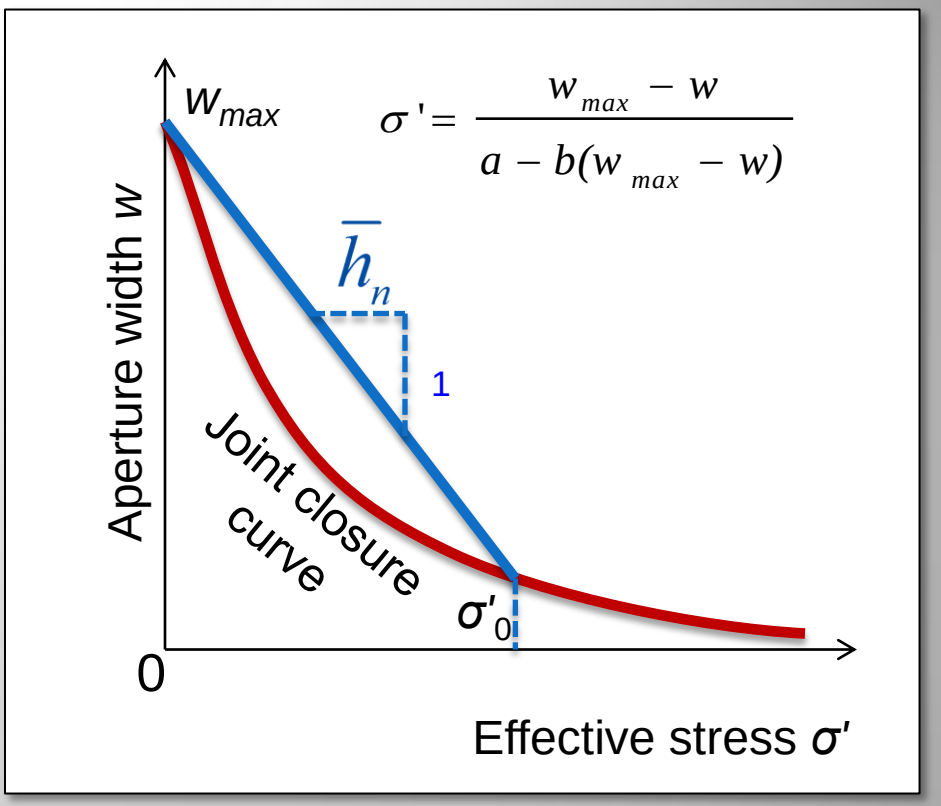
$$\sigma'_n = \sigma_n - P_F$$

$$P_F > \sigma_{n0}$$

$$\sigma'_n = 0$$

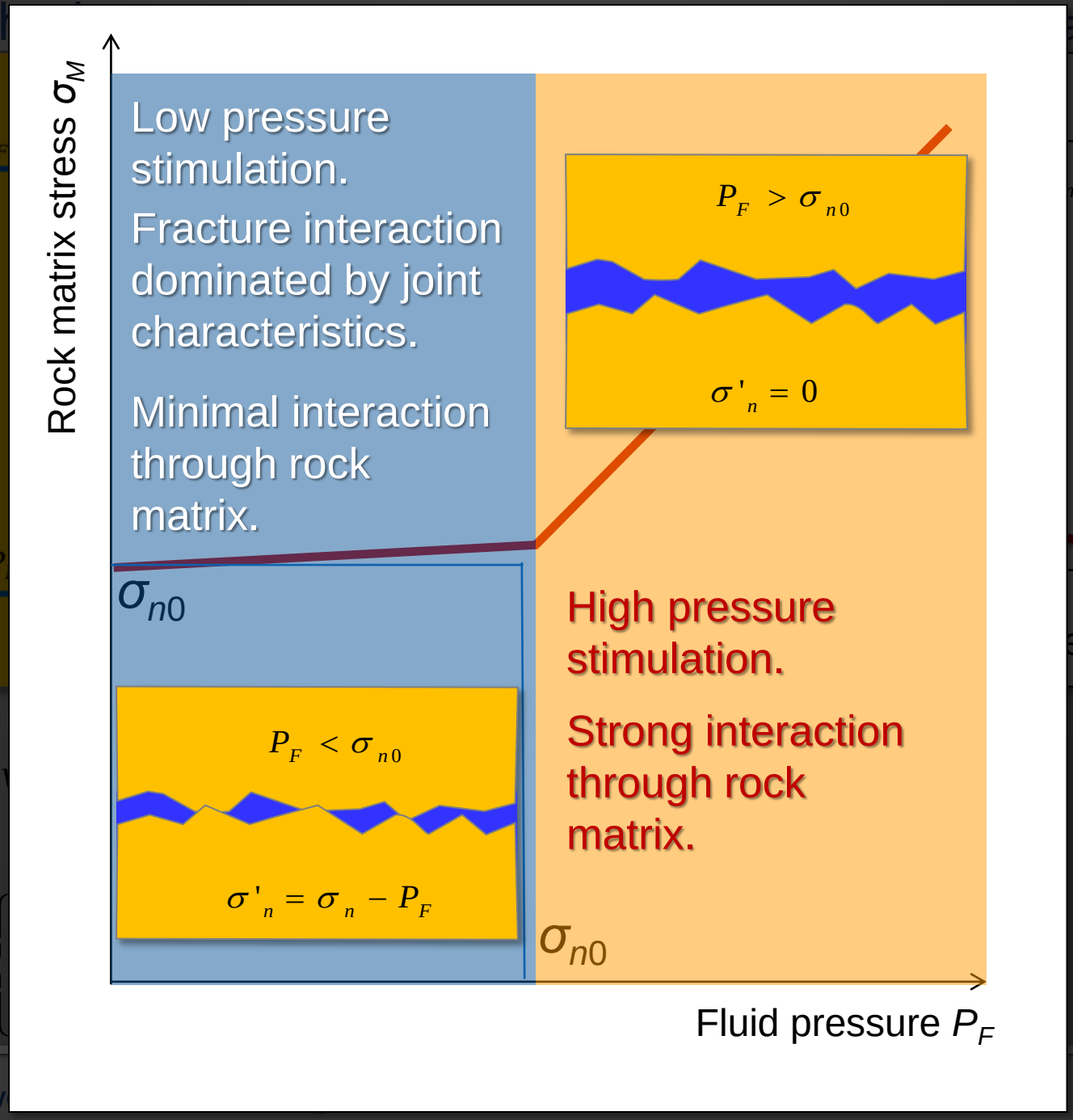
# Two regimes of hydraulic stimulation



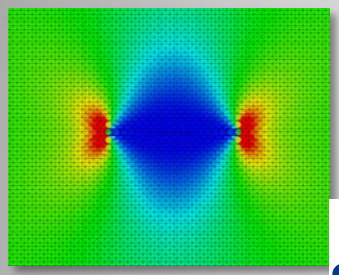



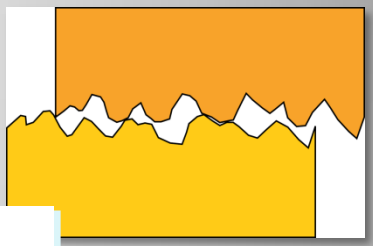

$$w(\sigma'_J) - w_i = \frac{(\sigma_M - \sigma_{Mi})H}{E'}$$

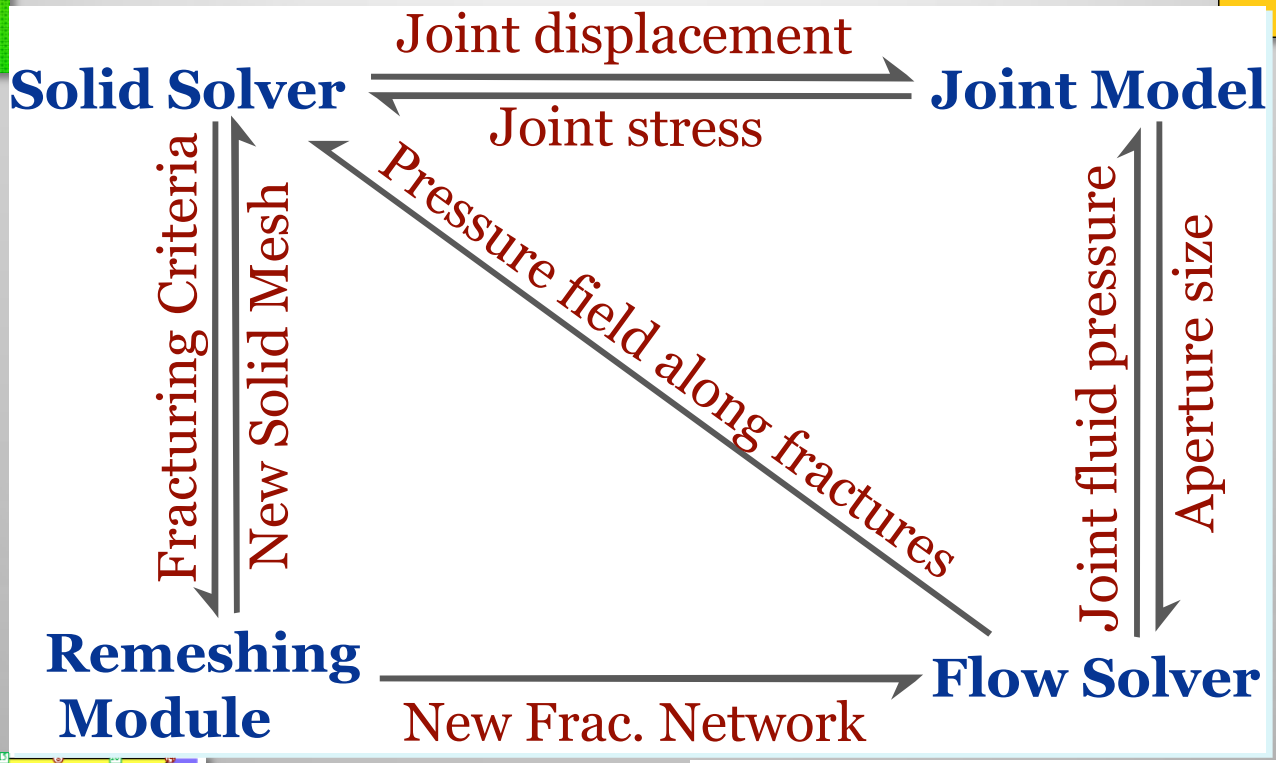
$$\Delta\sigma_M = \begin{cases} P_F / (1 + H / \bar{h}_n) & \text{if } P_F \le \sigma_{Mi}(1 + \bar{h}_n / H) \\ P_F - \sigma_{Mi} & \text{otherwise} \end{cases}$$

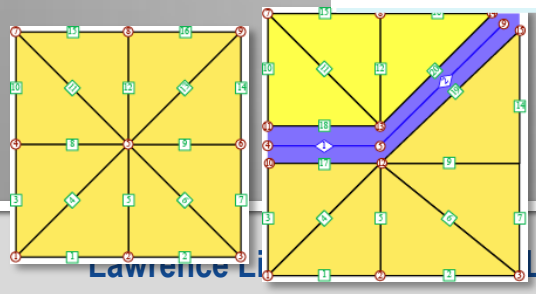

Rock matrix stress $\sigma_M$
Low pressure stimulation.
Fracture interaction dominated by joint characteristics.
Minimal interaction through rock matrix.
$P_F > \sigma_{n0}$
$\sigma'_n = 0$
$\sigma_{n0}$
$P_F < \sigma_{n0}$
$\sigma'_n = \sigma_n - P_F$
High pressure stimulation.
Strong interaction through rock matrix.
$\sigma_{n0}$
Fluid pressure $P_F$

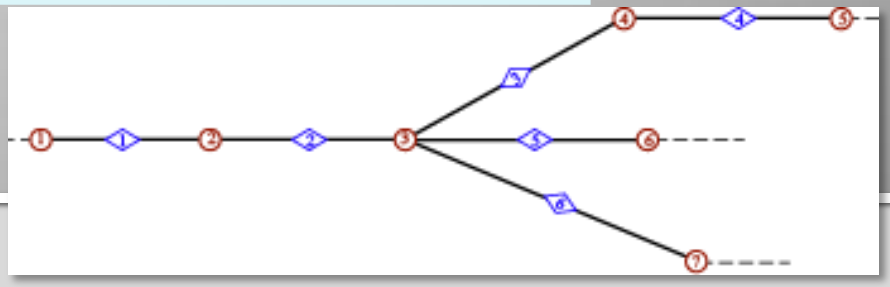
# Fluid-solid coupling for high pressure regime









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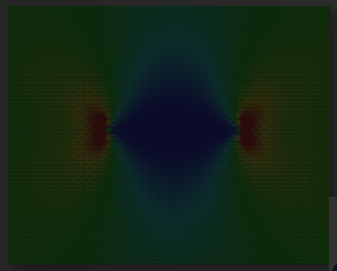

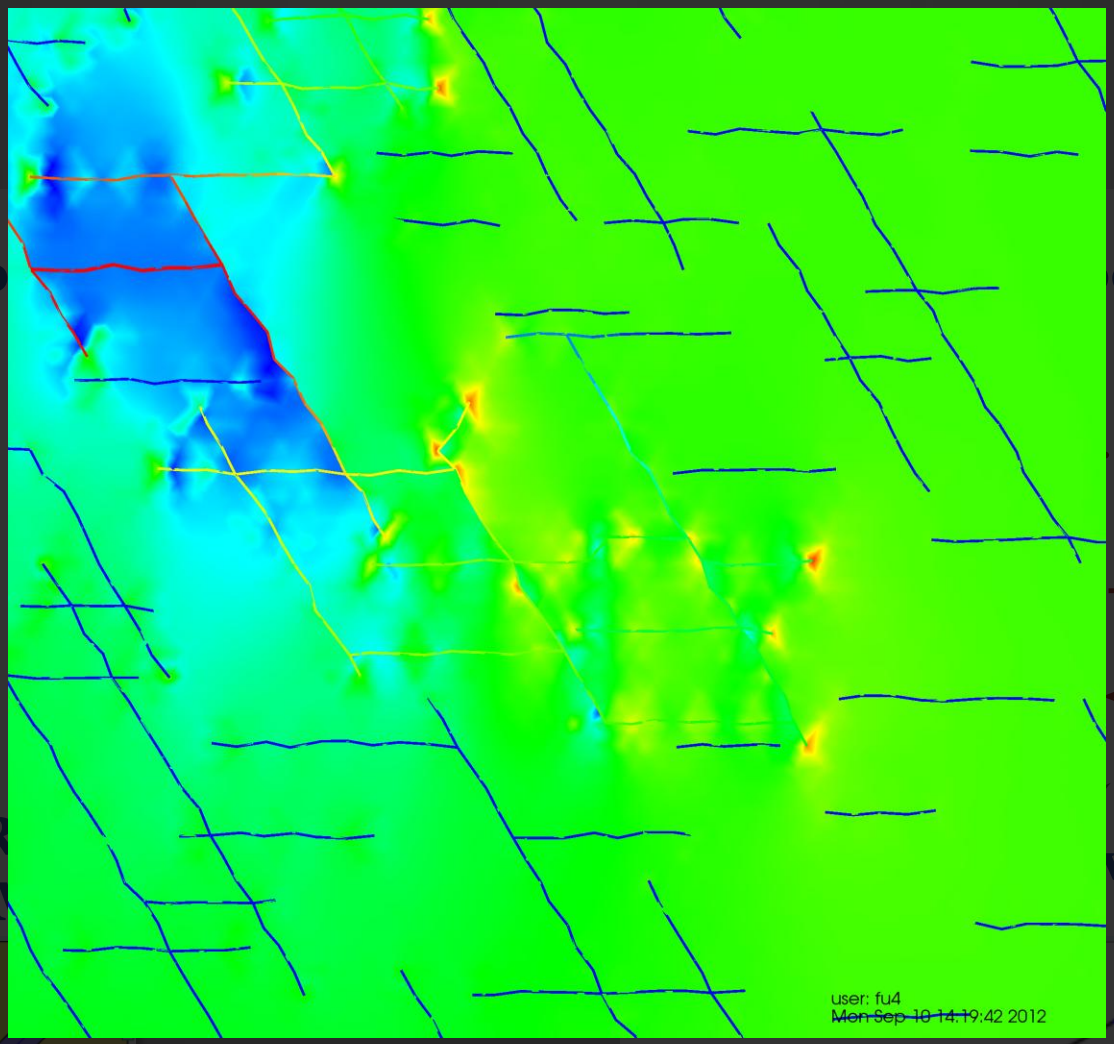


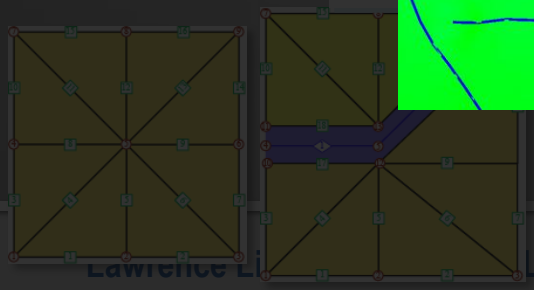

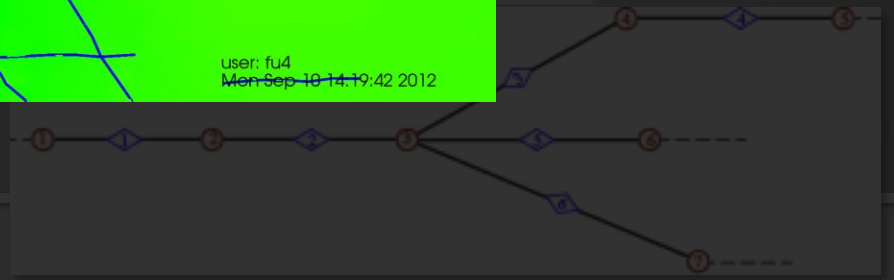

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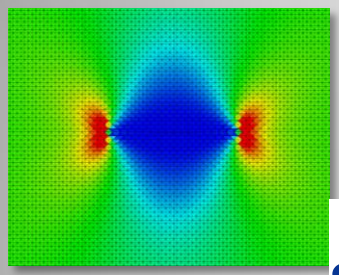
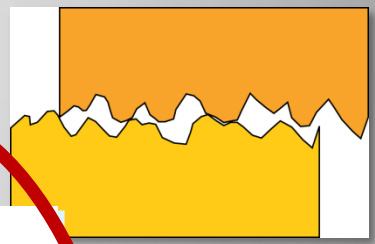
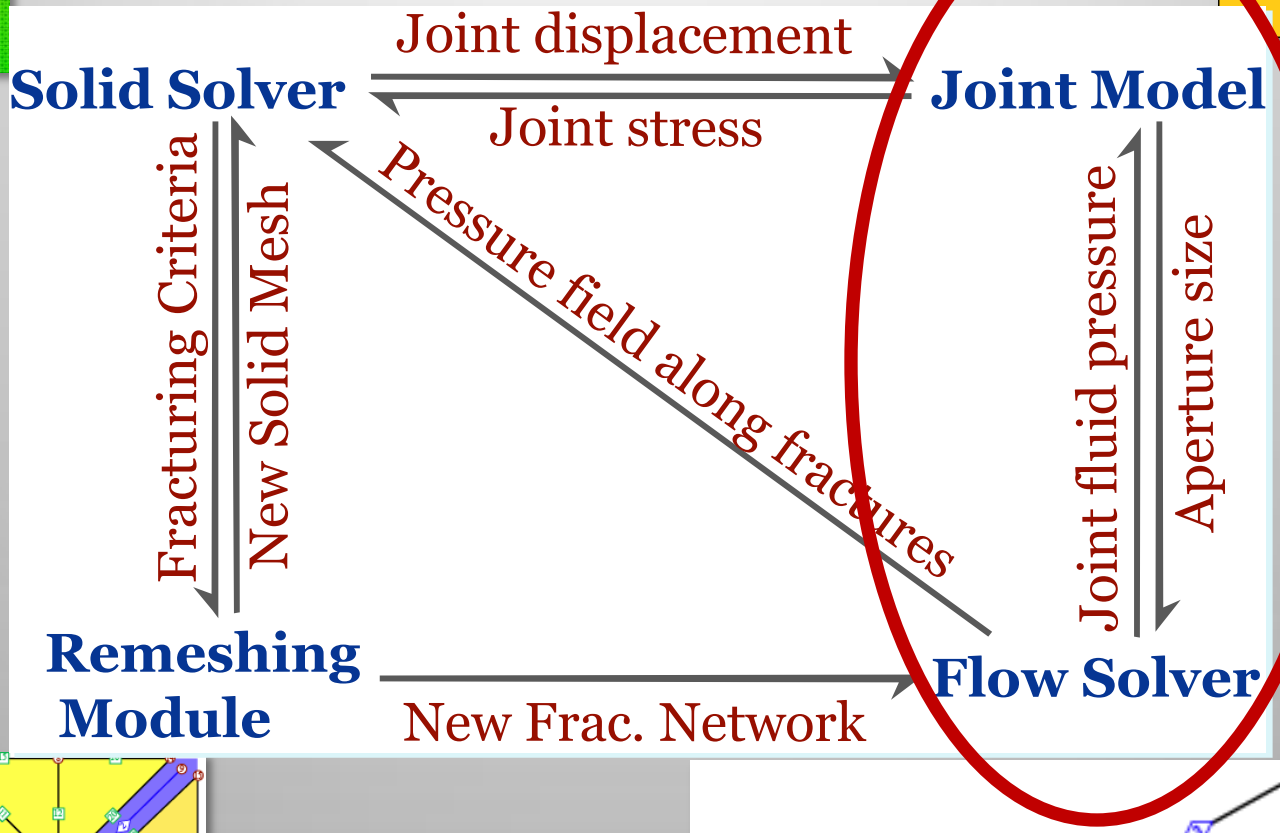
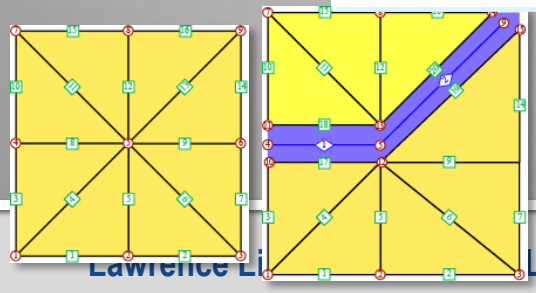
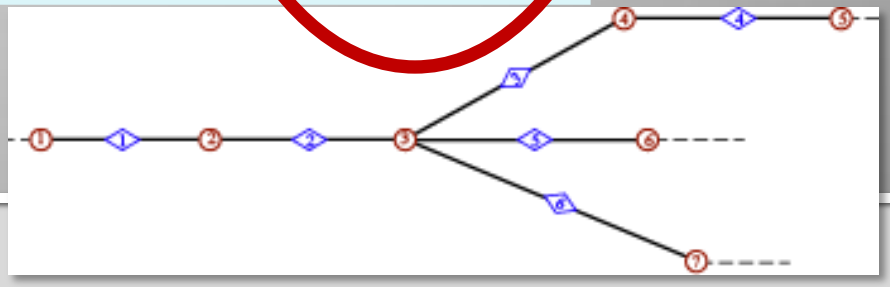




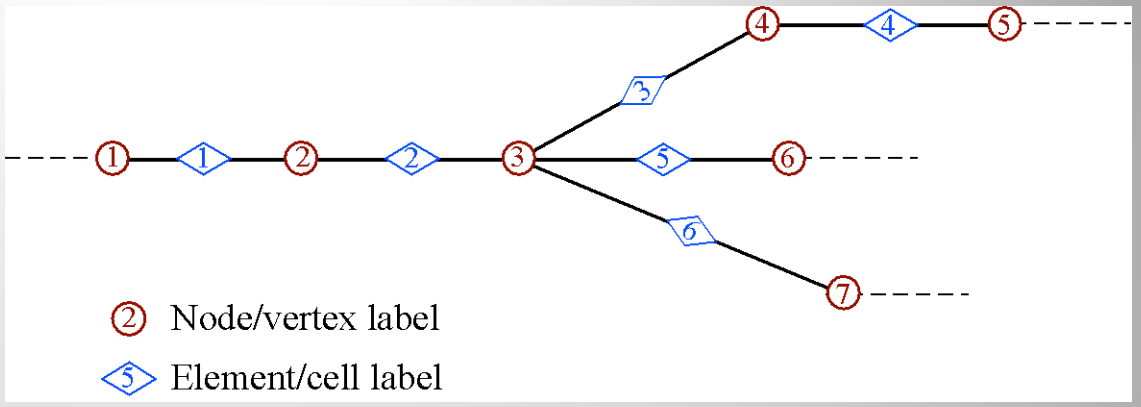




# Fluid-solid coupling for low pressure regime

$$\sigma' = \frac{w_{max} - w}{a - b(w_{max} - w)}$$




$$P_F = \begin{cases} K_F \left(1 - \dfrac{\rho_{ref} L_C w}{m_C}\right) & \text{if } m_C / L_C w \geq \rho_{ref} \\ P_{vap} & \text{if } m_C / L_C w < \rho_{ref} \end{cases}$$

$$w = w_{max} - \frac{Aa + Bb + 1 - [(Aa + Bb + 1)^2 - 4AaBb]^{0.5}}{2Ab}$$

$A = K_F \rho_{ref} L_C / m_C$ and $B = \sigma_M - K_F + A w_{max}$

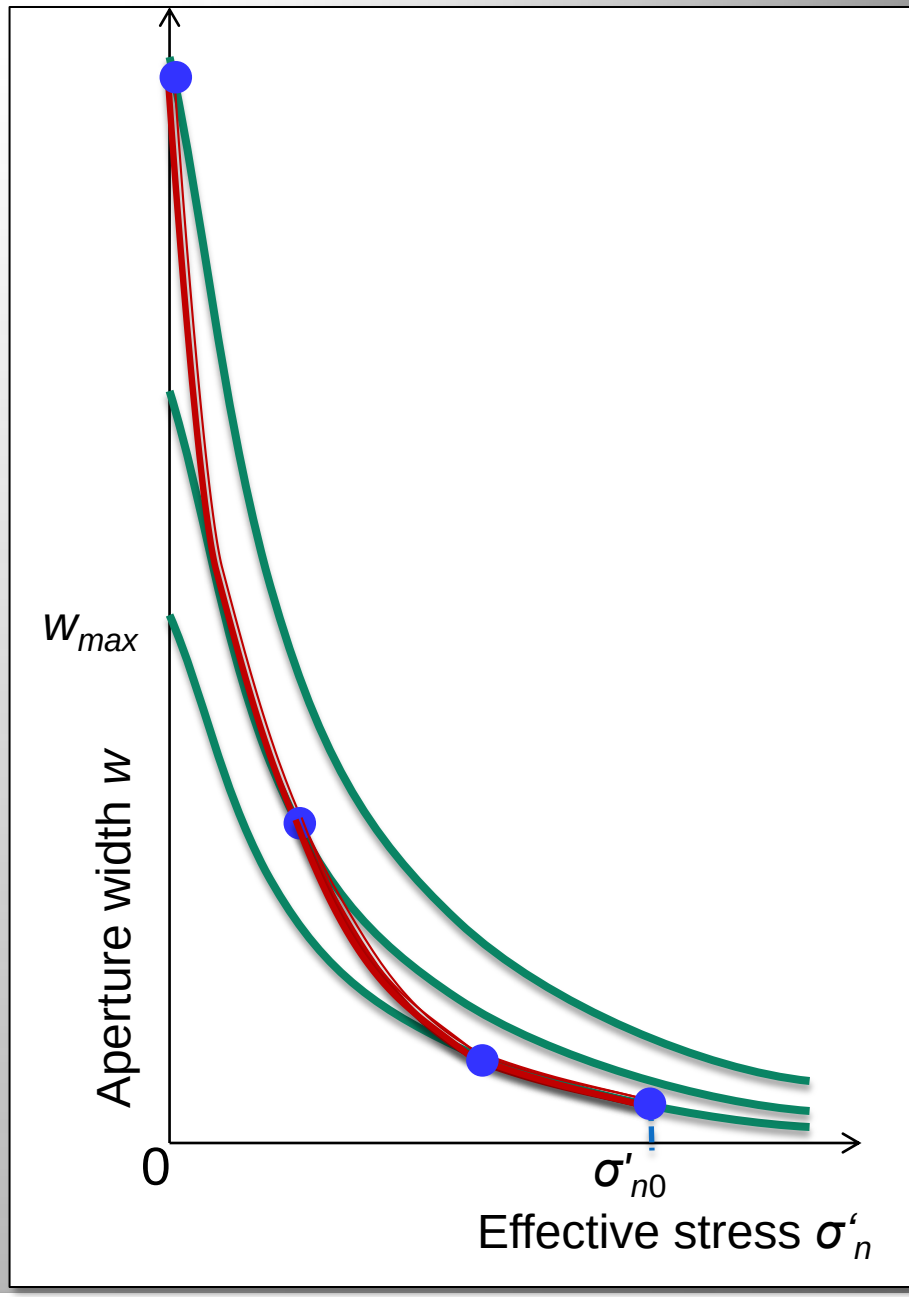
# Shear dilation

Excess shear stress

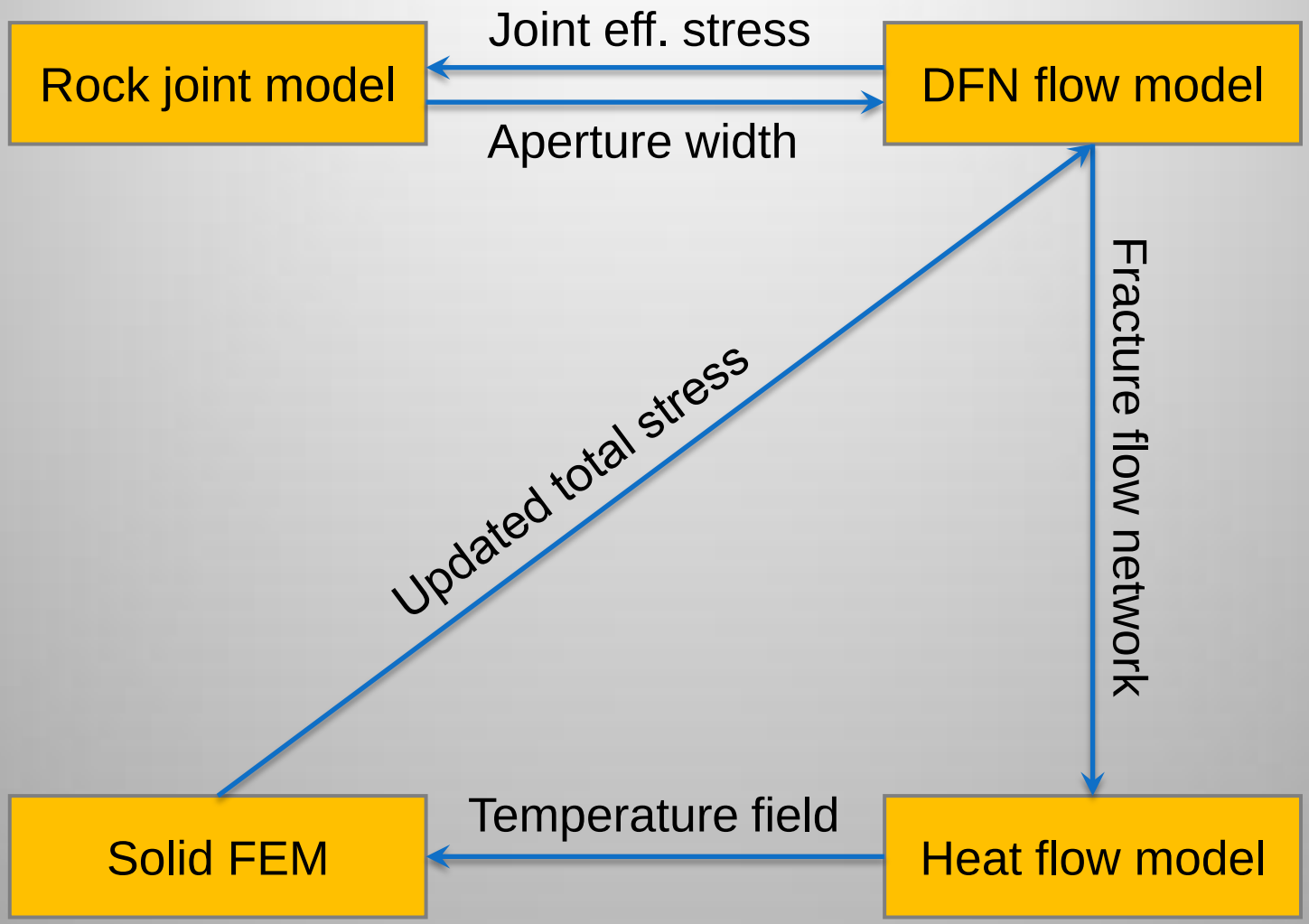
$$\tau' = \tau_0 - \sigma' \mu$$

$$w = w(\sigma', S) = S w(\sigma')$$

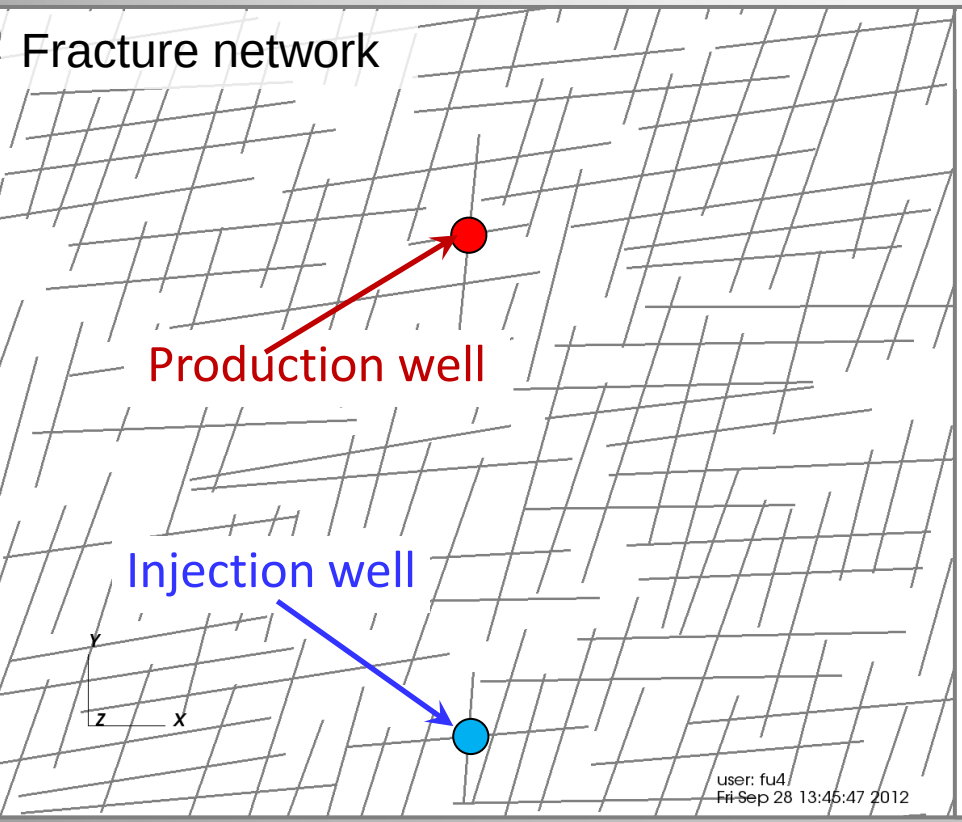
$$S = \begin{cases} 1 + \tau'_{max} (S_{max} - 1) / \tau'_s & \text{if } \tau'_{max} < \tau'_s \\ S_{max} & \text{otherwise} \end{cases}$$

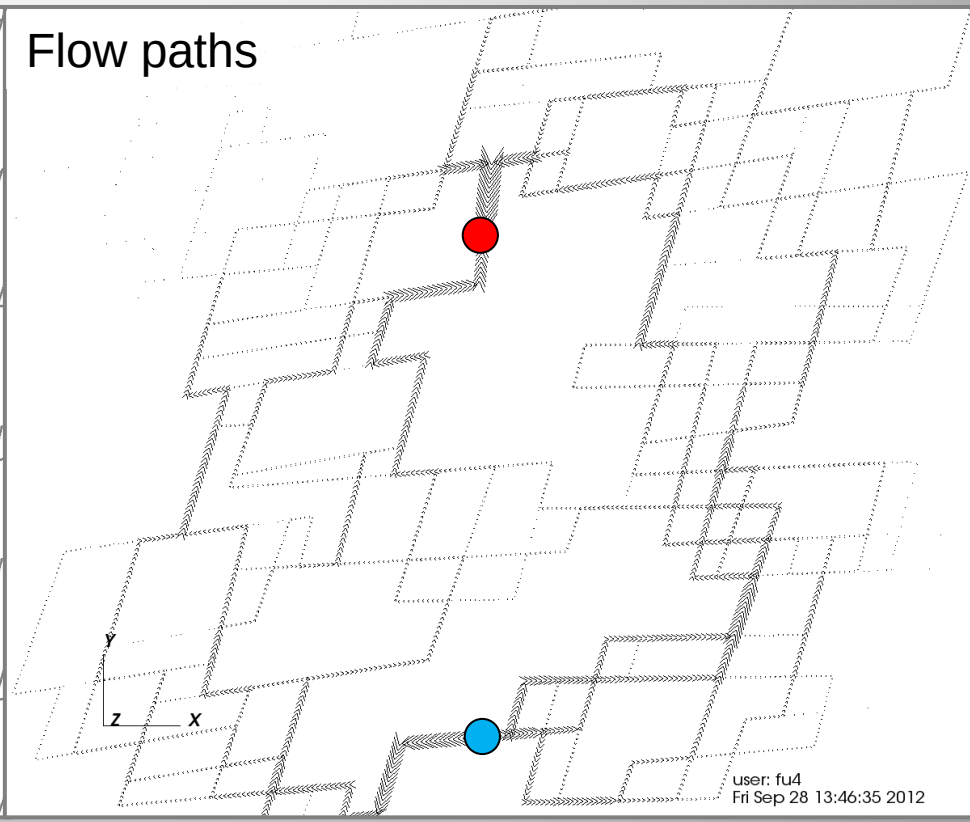


# Coupling with thermal module



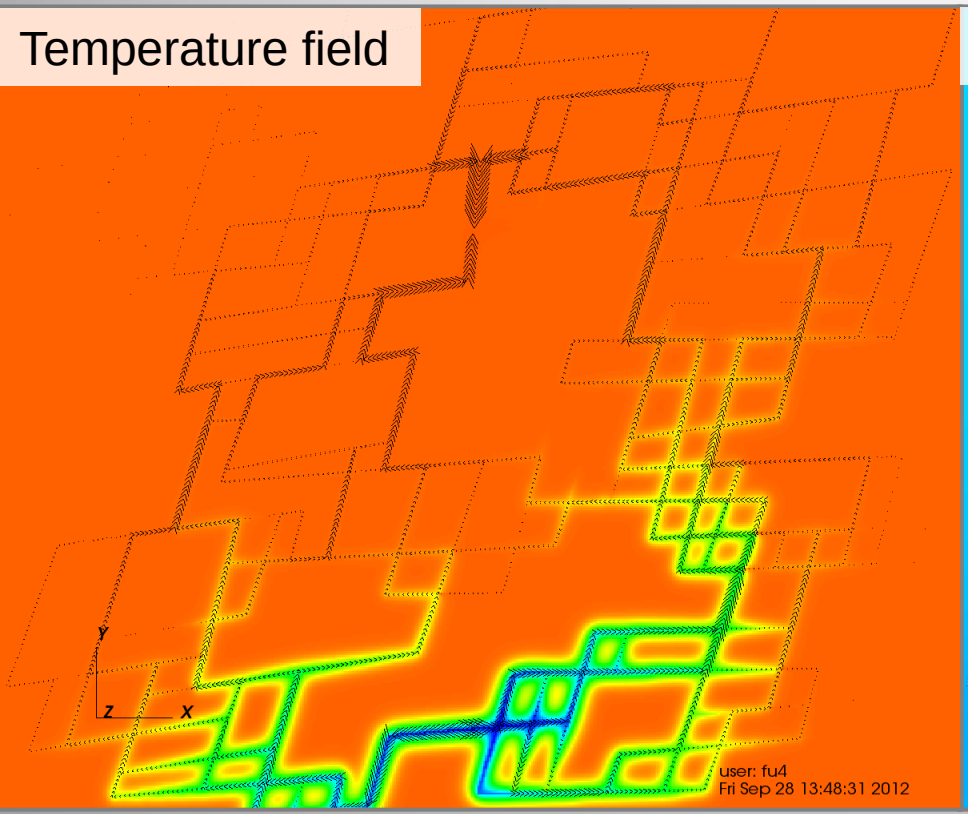
# Num. example in 2D



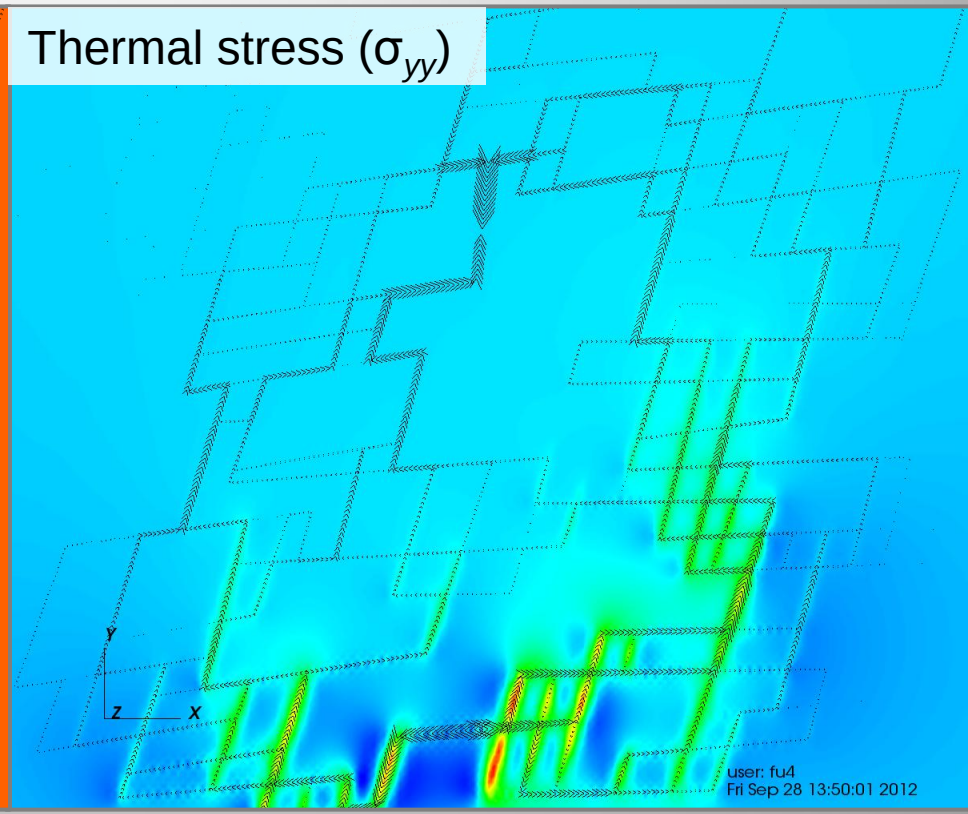



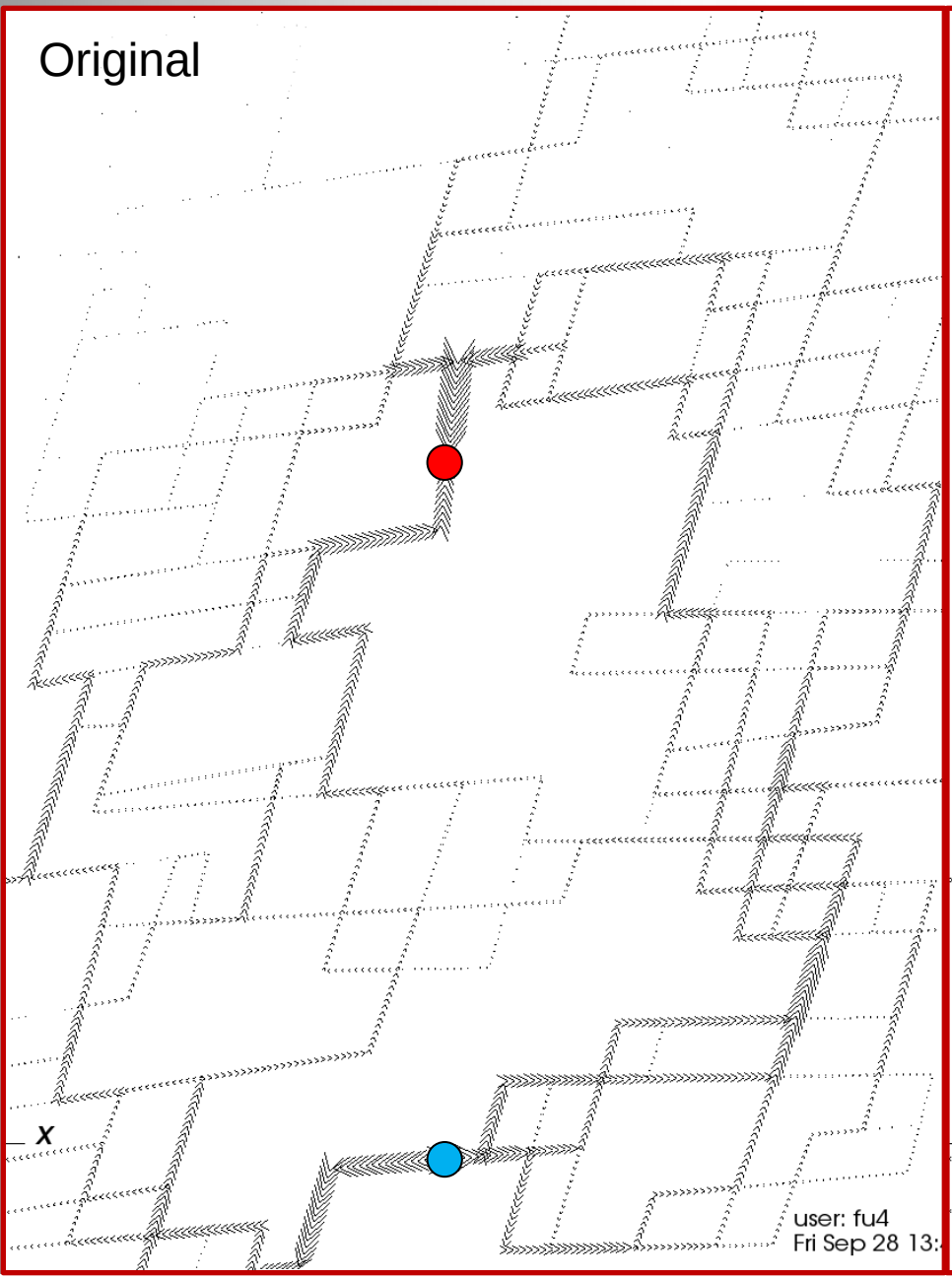
# Num. example in 2D

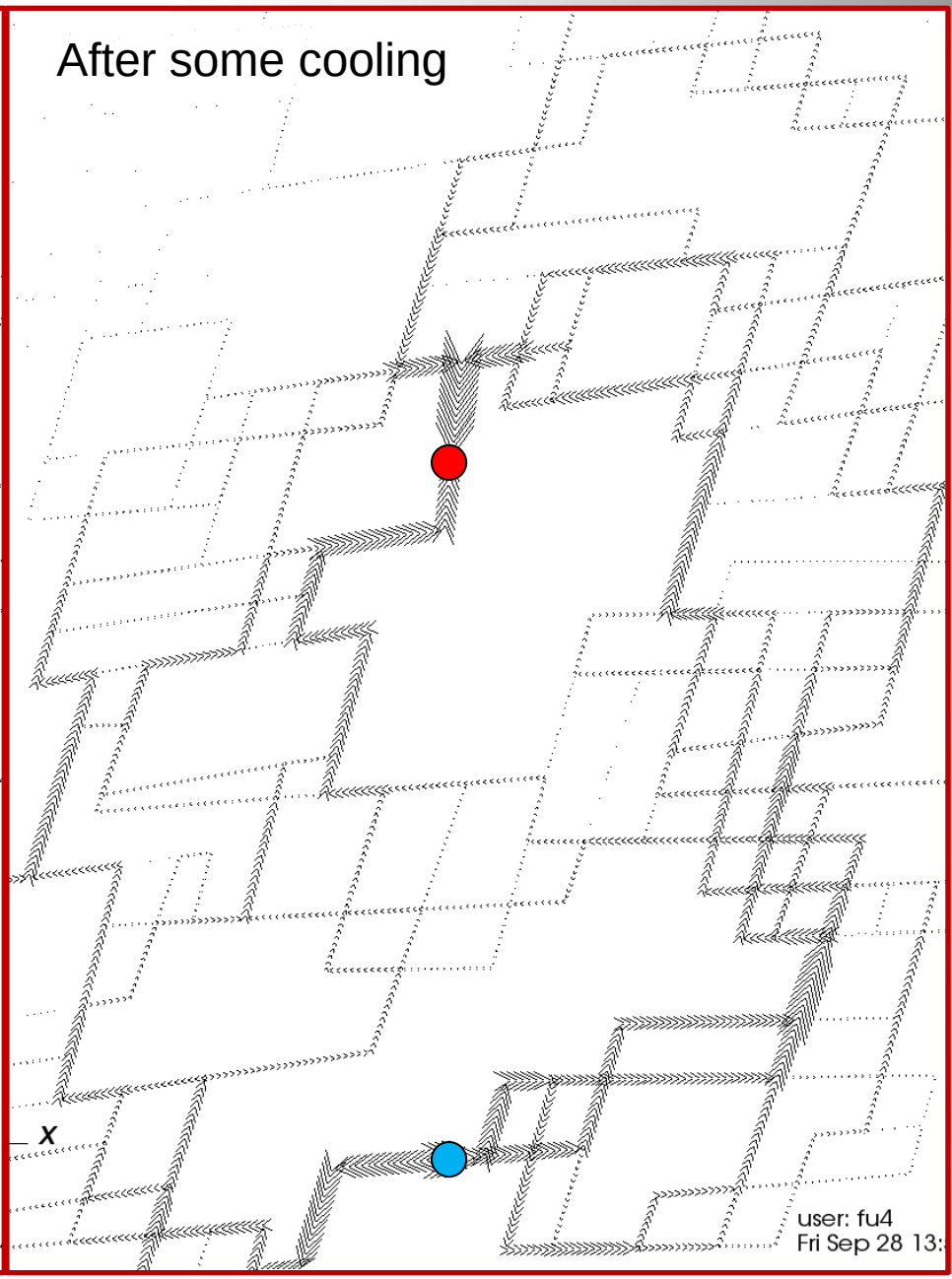
Temperature field




Thermal stress ($\sigma_{yy}$)




Original
X
user: fu4
Fri Sep 28 13:


After some cooling
X
user: fu4
Fri Sep 28 13:

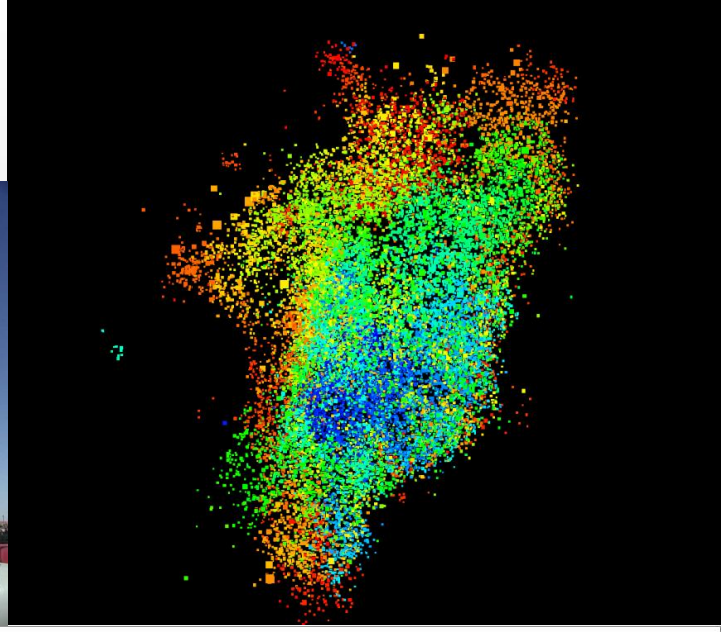
# Model validation and demonstration

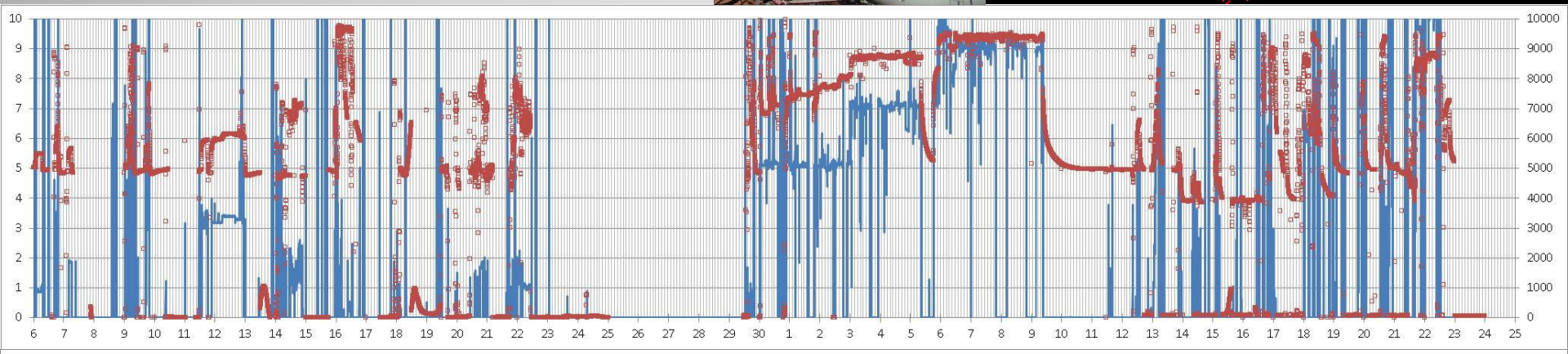
## with Habanero data from Cooper Basin

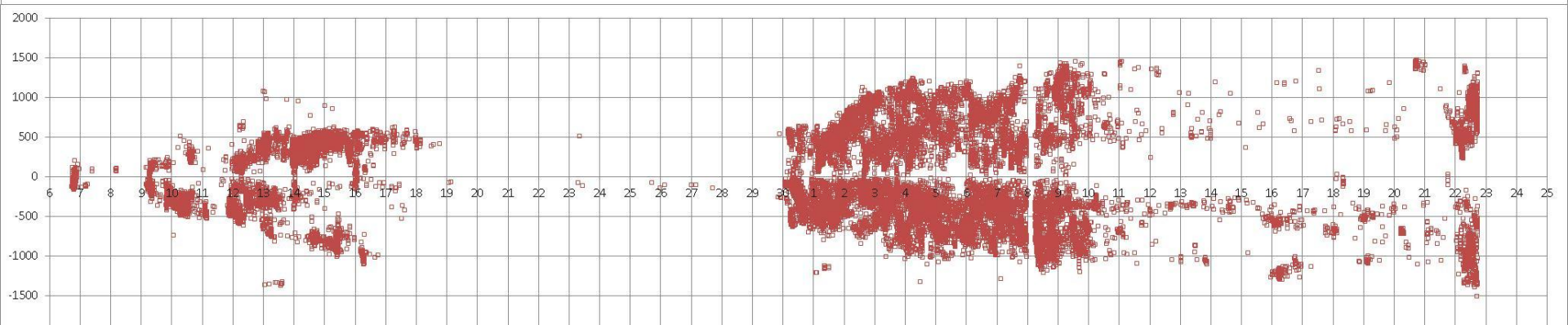
origin energy

GEODYNAMICS LIMITED

Photo credit: Geodynamics

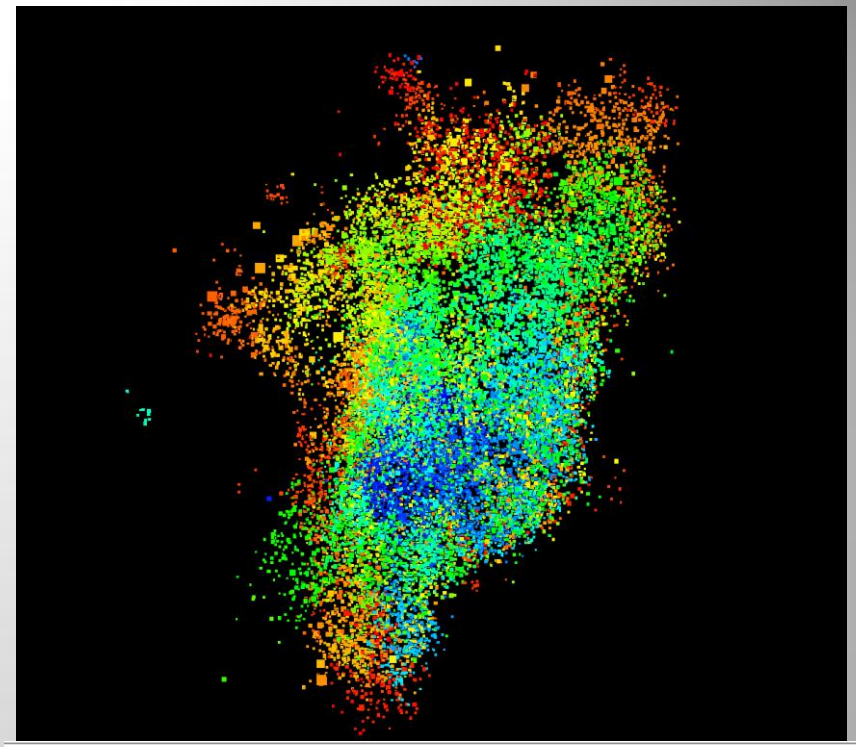


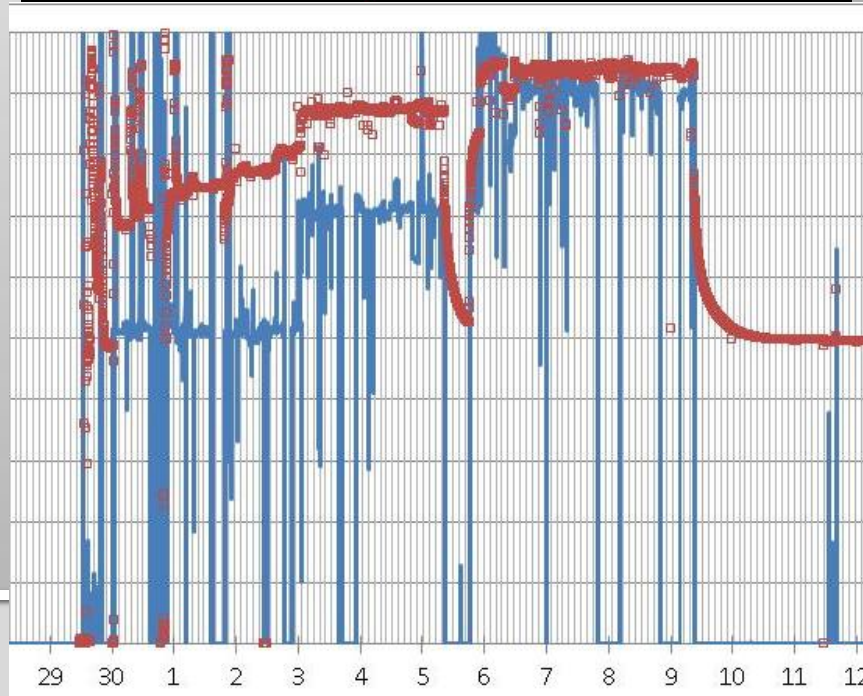


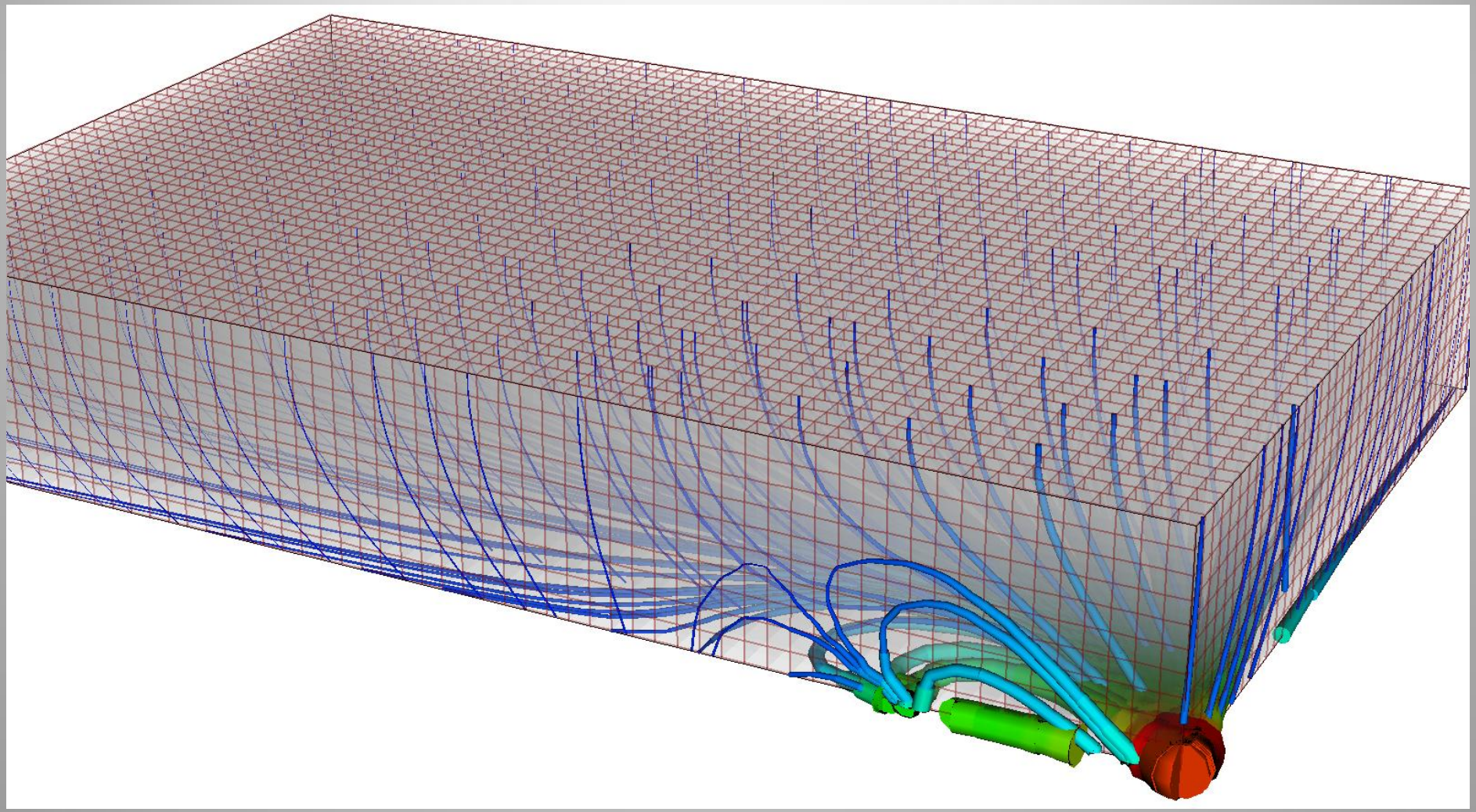
# What information to use:

- Relationships of
  - Seismic cloud extent vs. fluid volume injected.
  - Injection pressure vs. flow rate.
  - Pressure decay after shut-in.
  - Production test data.





# Preliminary model



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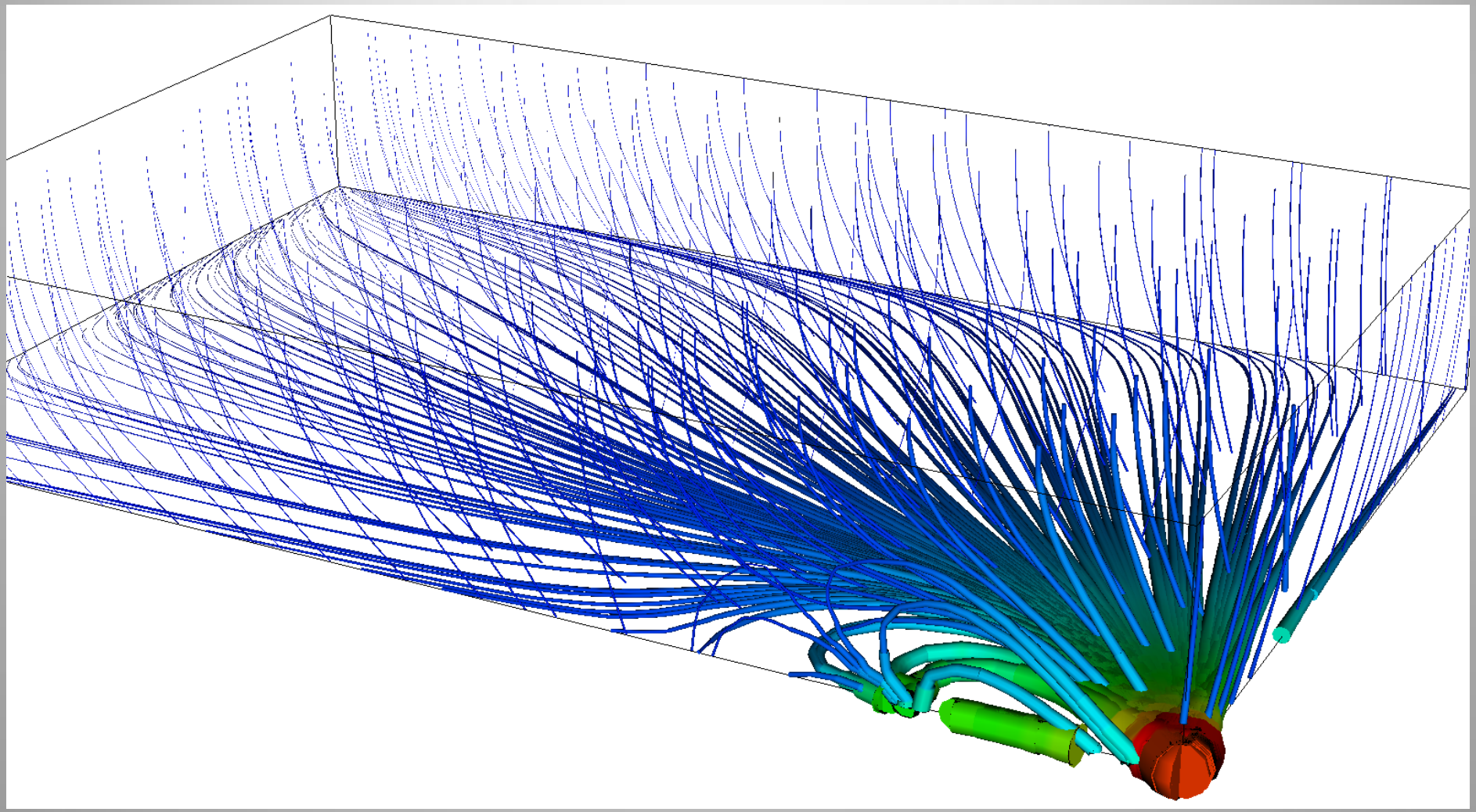
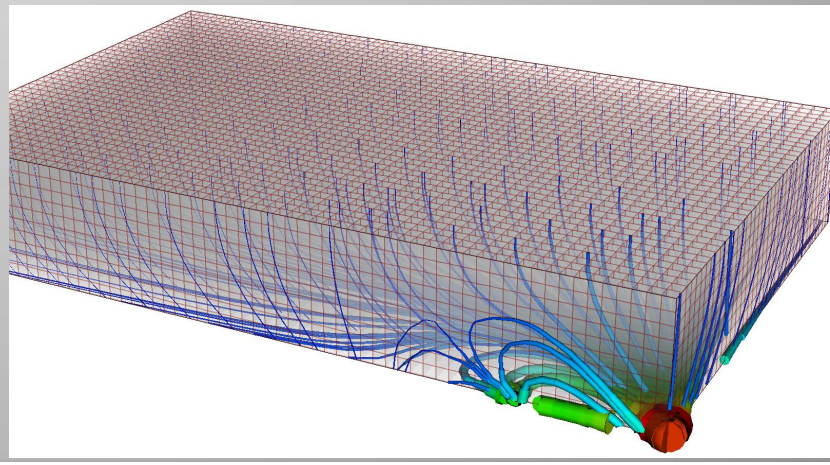


# How can the model help?

- Test and validate hypothetical conceptual models.
- Optimize stimulation strategy.
- Optimize production strategy and parameters.


Photo credit: Geodynamics



# Acknowledgments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Release number: LLNL-PRES-586695