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San Diego, CA, October 24, 2011

Investigation of Stimulation-Response Relationships for Complex Fracture Systems in Enhanced Geothermal Reservoirs

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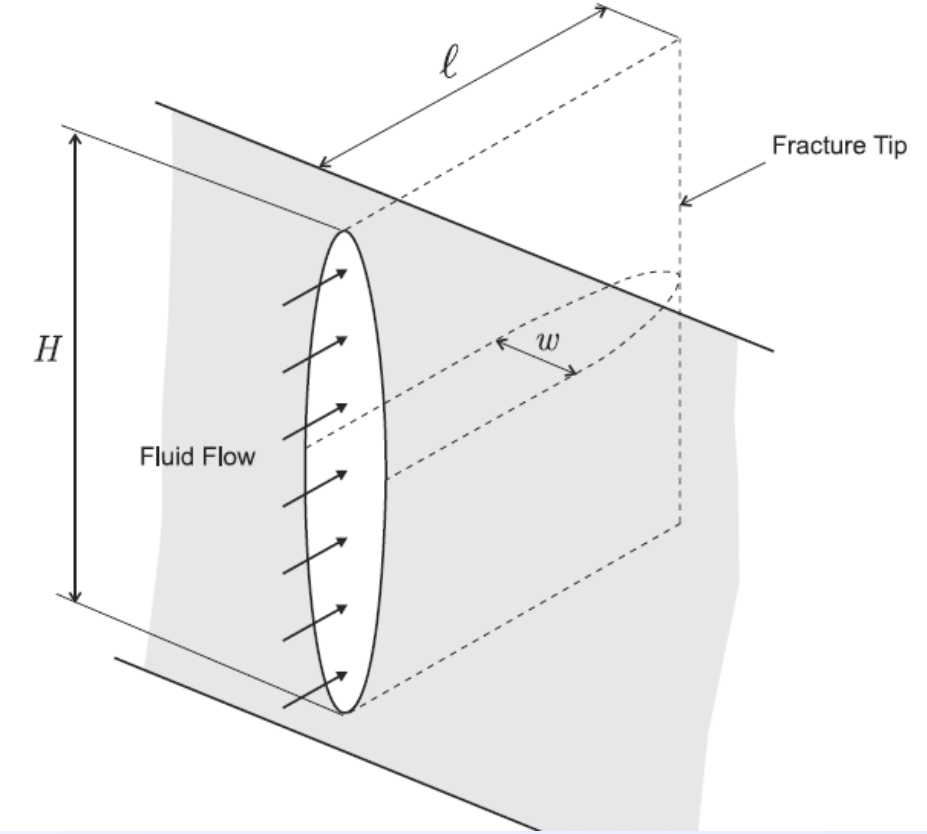
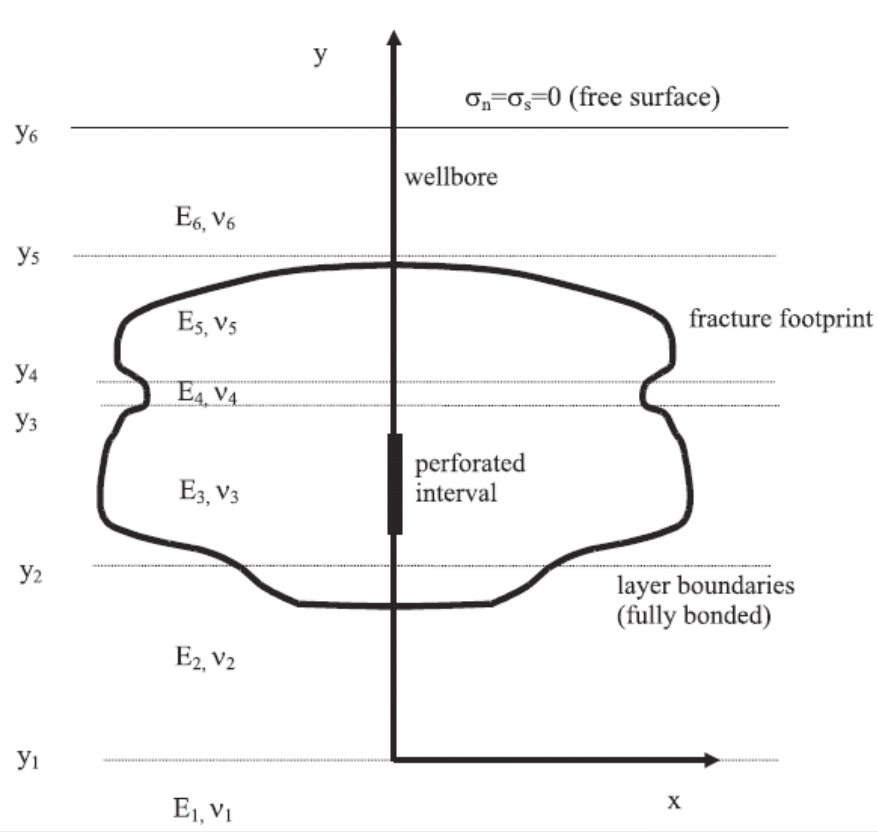
Conventional fracture models



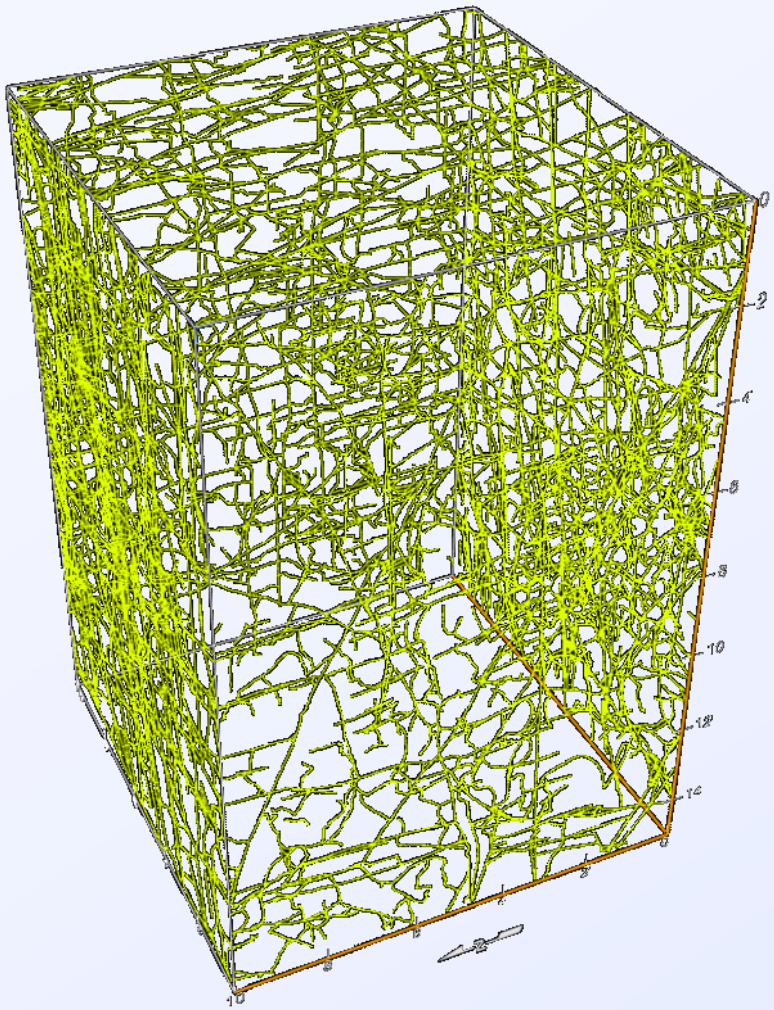
PKN model



PL3D model

(Image credit: Adachi et al. 2000)

How real fracture system looks like



(Large Block Test, Yucca Mountain. Wagoner, 2000)

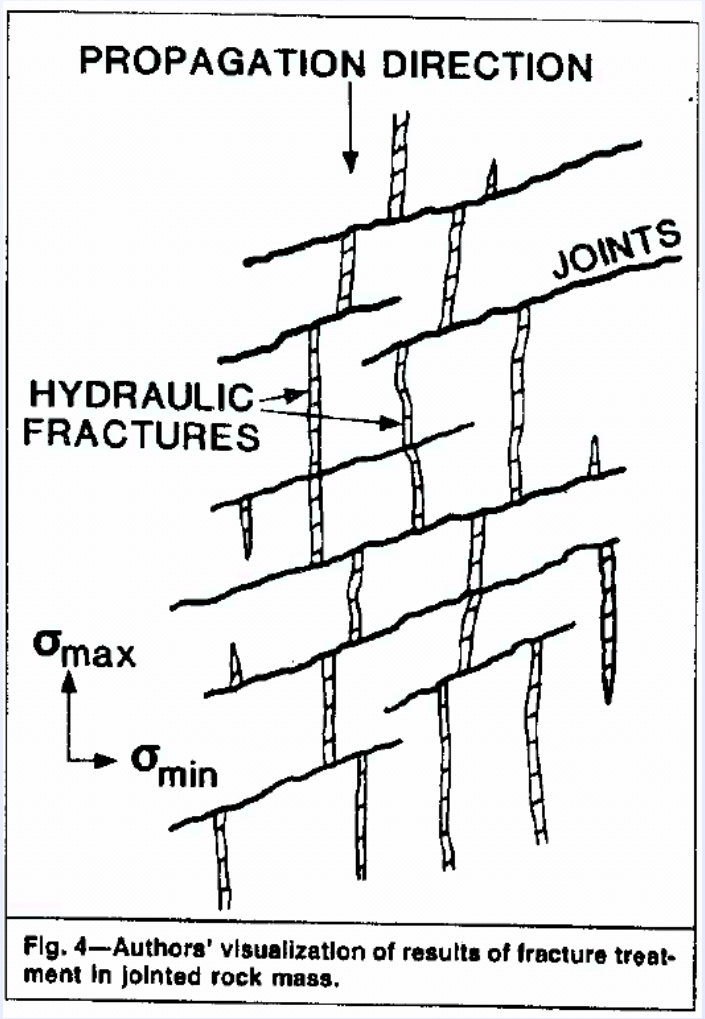
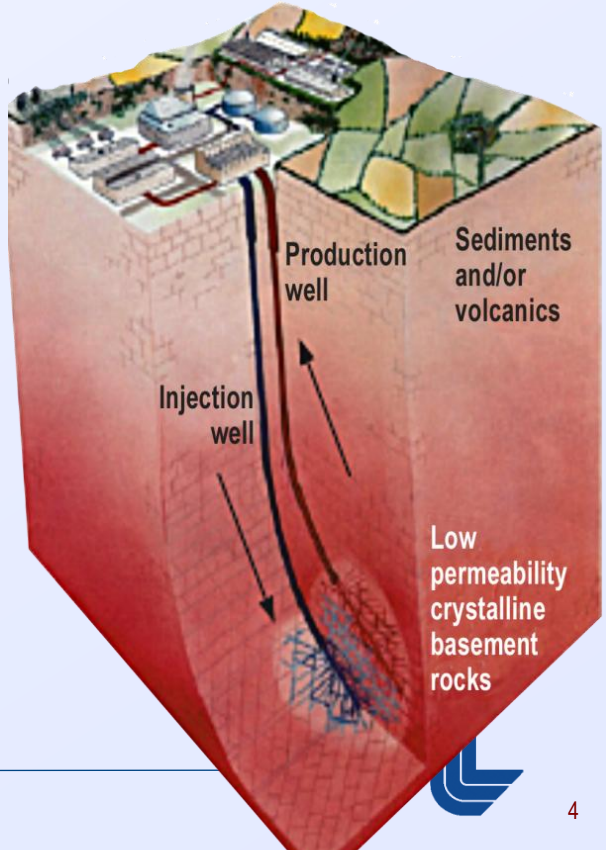


Fig. 4—Authors' visualization of results of fracture treatment in jointed rock mass.

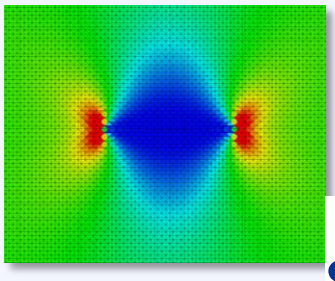
(Warpinski and Teufel, 1987)

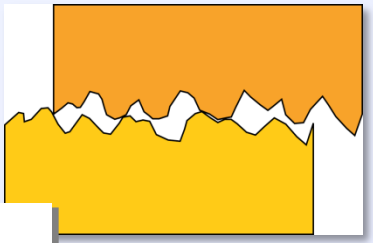
What do we need to simulate hydraulic stimulation of reservoir

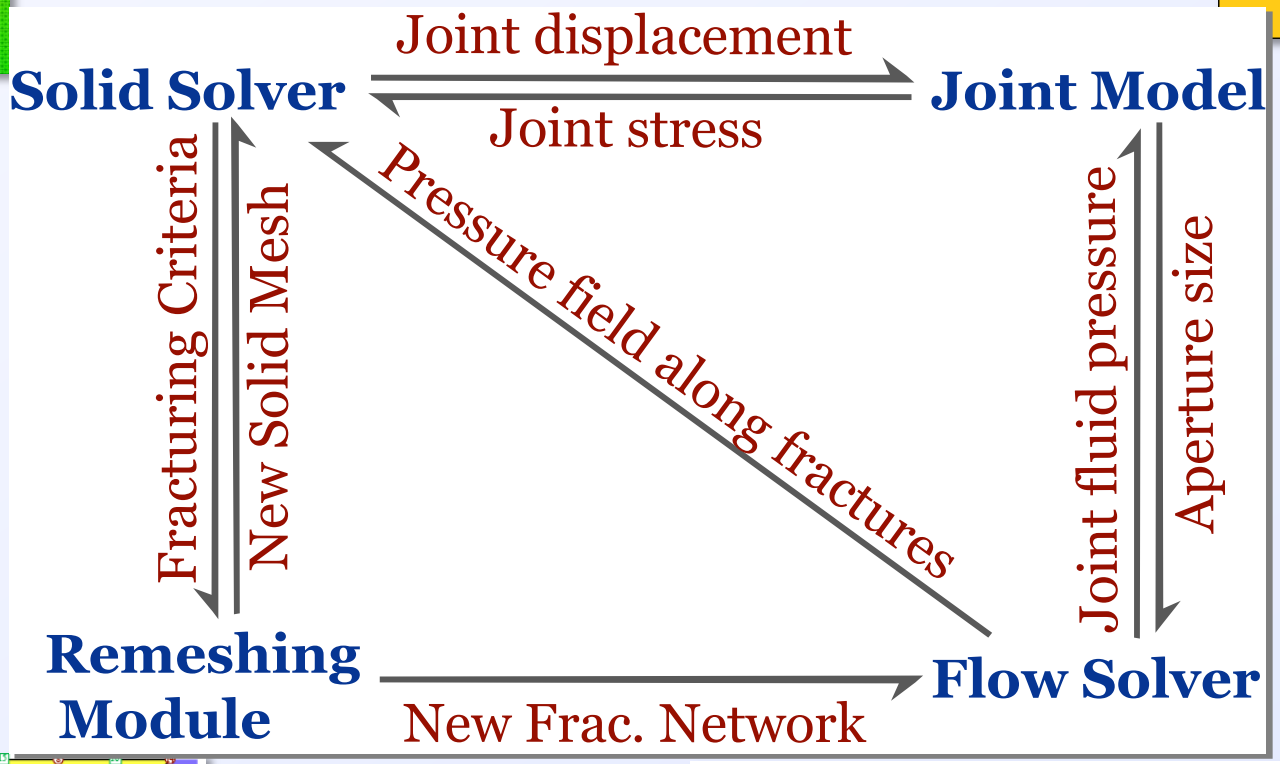
- Objective:
  - Study the effectiveness of stimulation strategies through simulating fluid-fracture and fracture-fracture interactions.
- Physical mechanisms need to be covered:
  - Fluid flow due to pressure gradient;
  - Rock deformation;
  - Variation of aperture width; and
  - Rock fracturing.
- Other variables:
  - Natural fracture system;
  - *In situ* stress;
  - Stimulation parameters.

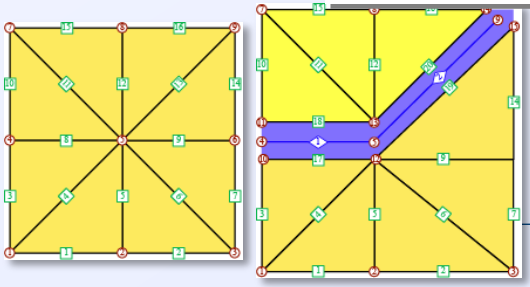


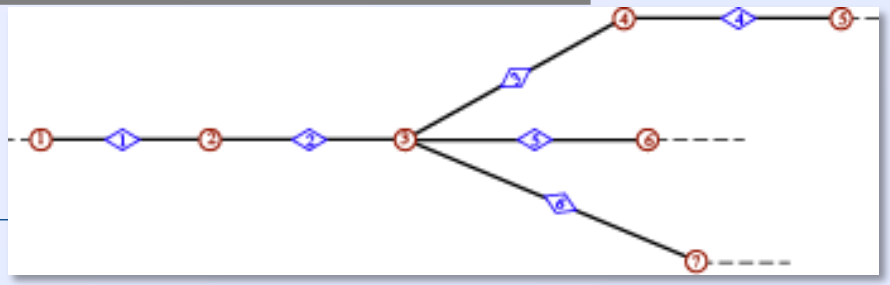
Modules and their coupling











Important Components

- Flow solver – Finite volume method

$$\frac{\partial q}{\partial l} + \frac{\partial w^h}{\partial t} = 0 \qquad \kappa \frac{\partial P}{\partial l} = -q$$

$$\kappa_{ij} = \frac{w_{ij}^{h3}}{6\mu(L_i + L_j)}$$

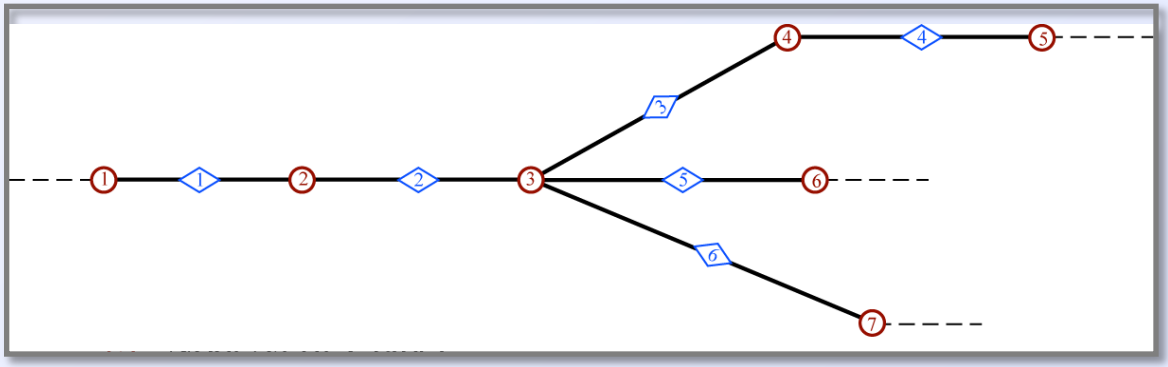
$$w_{ij}^{h3} = \frac{w_i^{h3} w_j^{h3} (L_i + L_j)}{w_i^{h3} L_j + w_j^{h3} L_i}$$

$$\dot{V}_{ij} = \kappa_{ij}(P_i - P_j)$$

$$P_i = \begin{cases} K\left(\frac{m_i}{V_i \rho_{ref}} - 1\right) & \text{if } m_i / V_i \geq \rho_{ref} \\ P_{vap} & \text{if } m_i / V_i < \rho_{ref} \end{cases}$$

Two mechanisms:

- Flow in fractures due to pressure gradient.
- Mass conservation with varying total fracture volume.

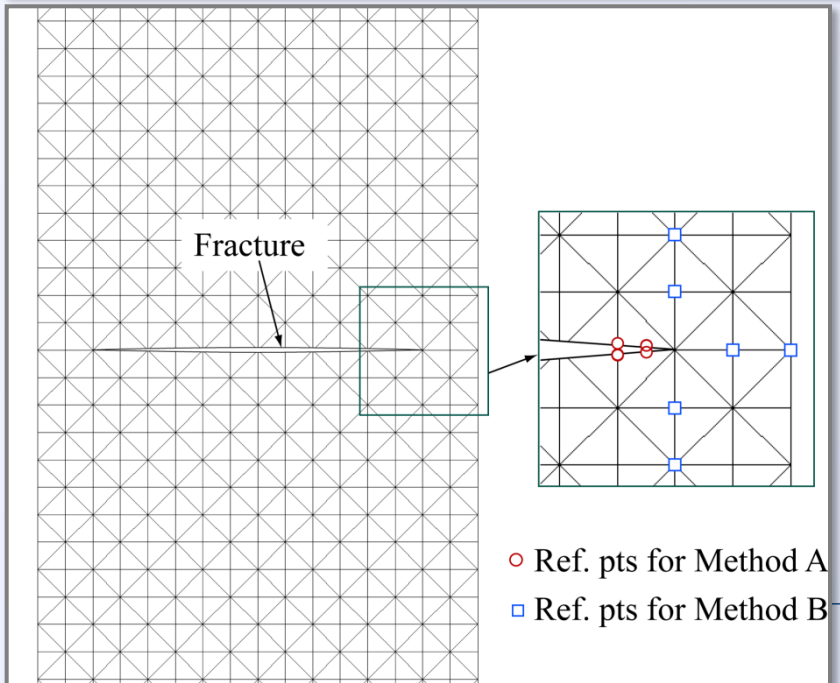


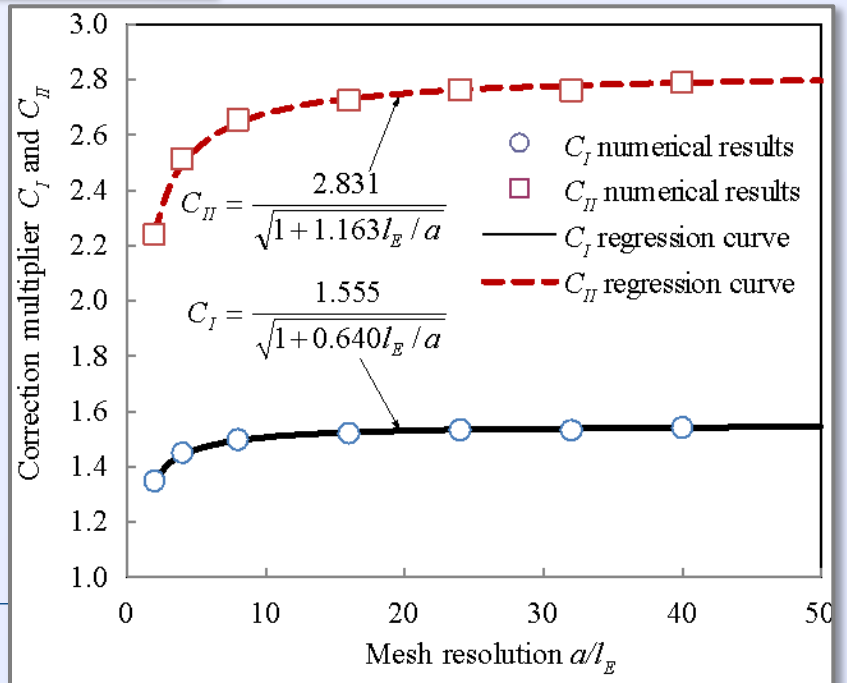
Important Components

- Fracturing criterion (LEFM)
  - Generalized displacement correlation method.
  - Based on critical stress intensity function

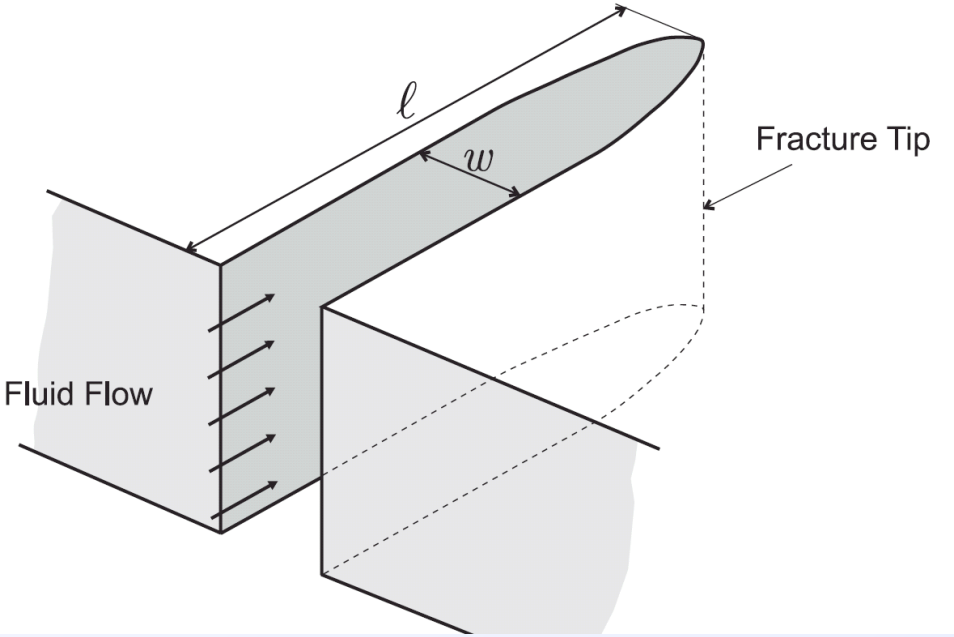
$$K_I = C_I \frac{2u_\theta(l_E/2,\pi) - 2u_\theta(l_E/2,-\pi) - u_\theta(l_E,\pi) + u_\theta(l_E,-\pi)}{(2\sqrt{2}-2)\sqrt{l_E}\, f_\theta^a(\pi)}$$

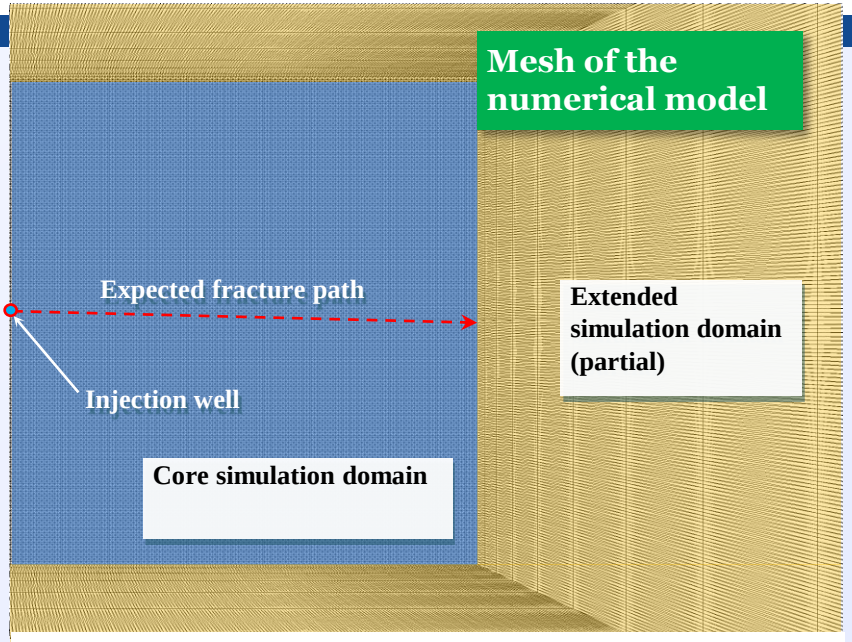
$$K_{II} = C_{II} \frac{2u_r(l_E/2,\pi) - 2u_r(l_E/2,-\pi) - u_r(l_E,\pi) + u_r(l_E,-\pi)}{(2\sqrt{2}-2)\sqrt{l_E}\, f_r^b(\pi)}$$



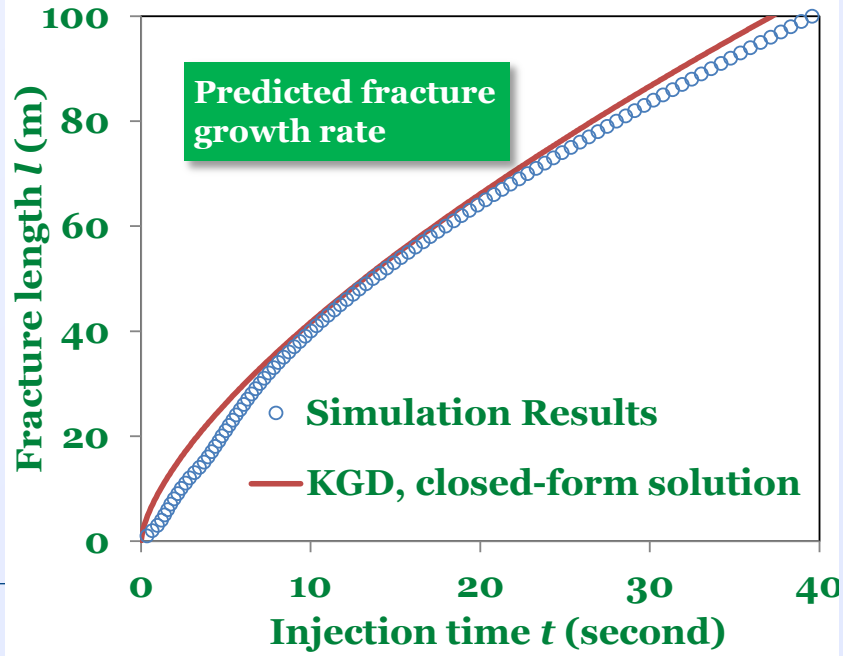


Model verification: classical KGD model

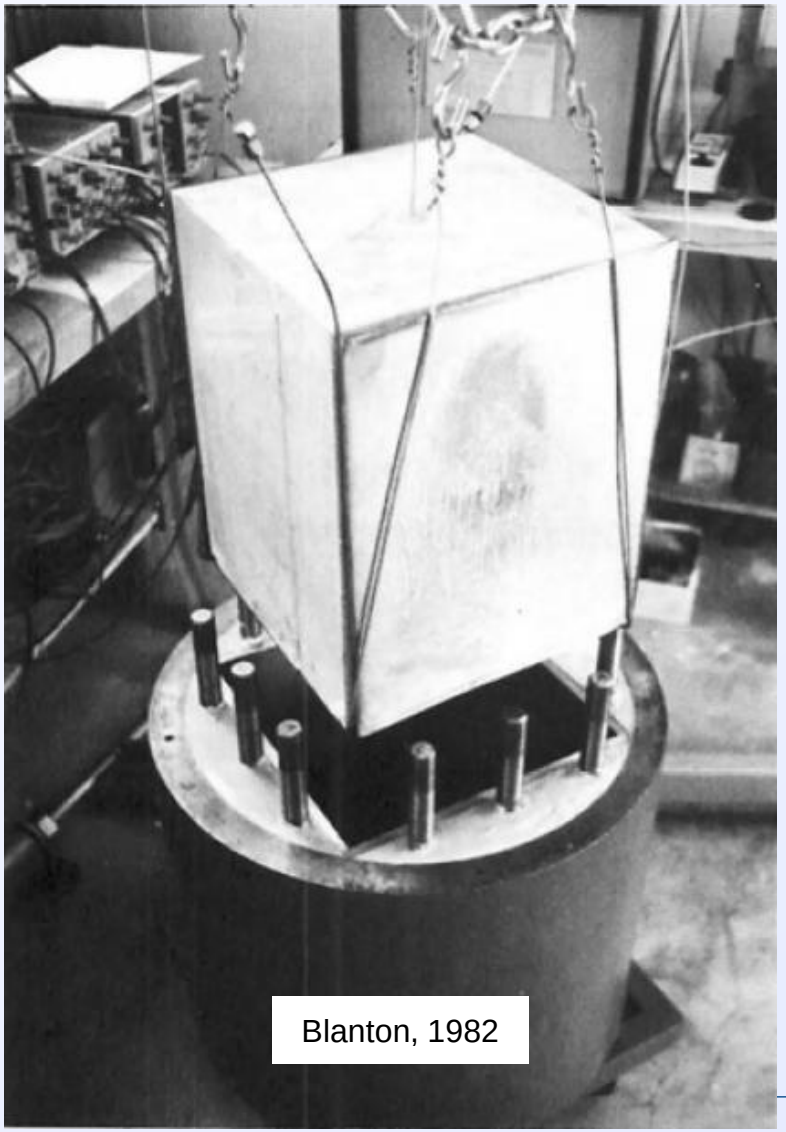




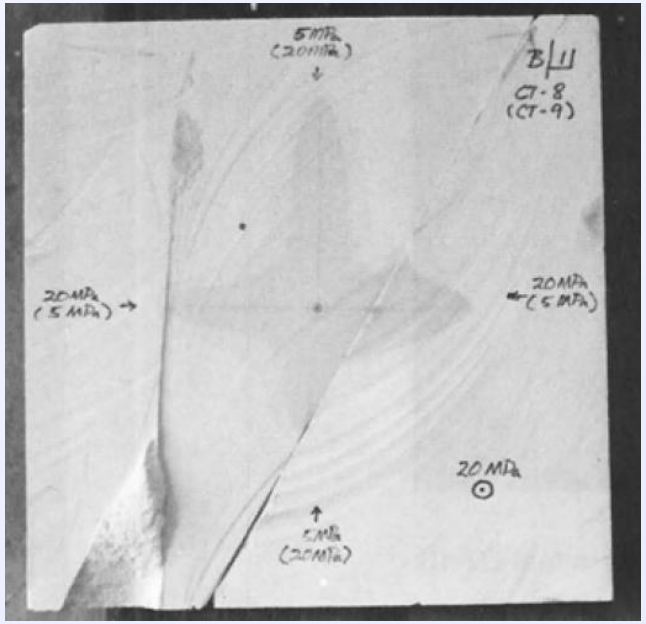
$$l(t) = 0.679 \left[\frac{G q_0^3}{\mu (1-\nu)} \right]^{\frac{1}{6}} t^{\frac{2}{3}}$$

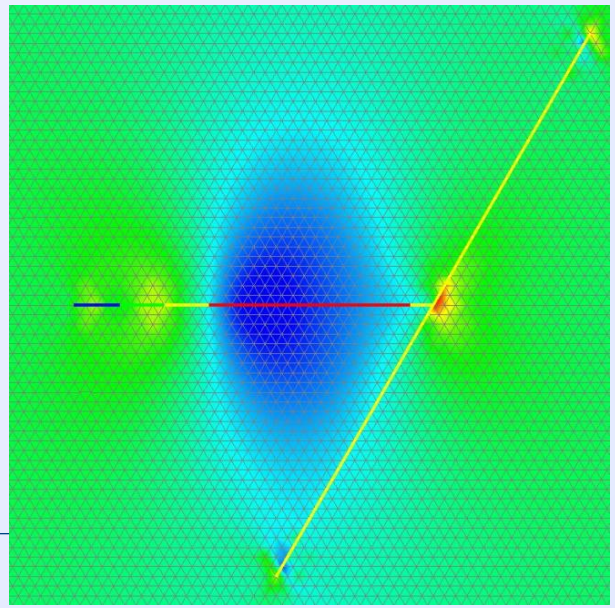


Model validation: lab test results

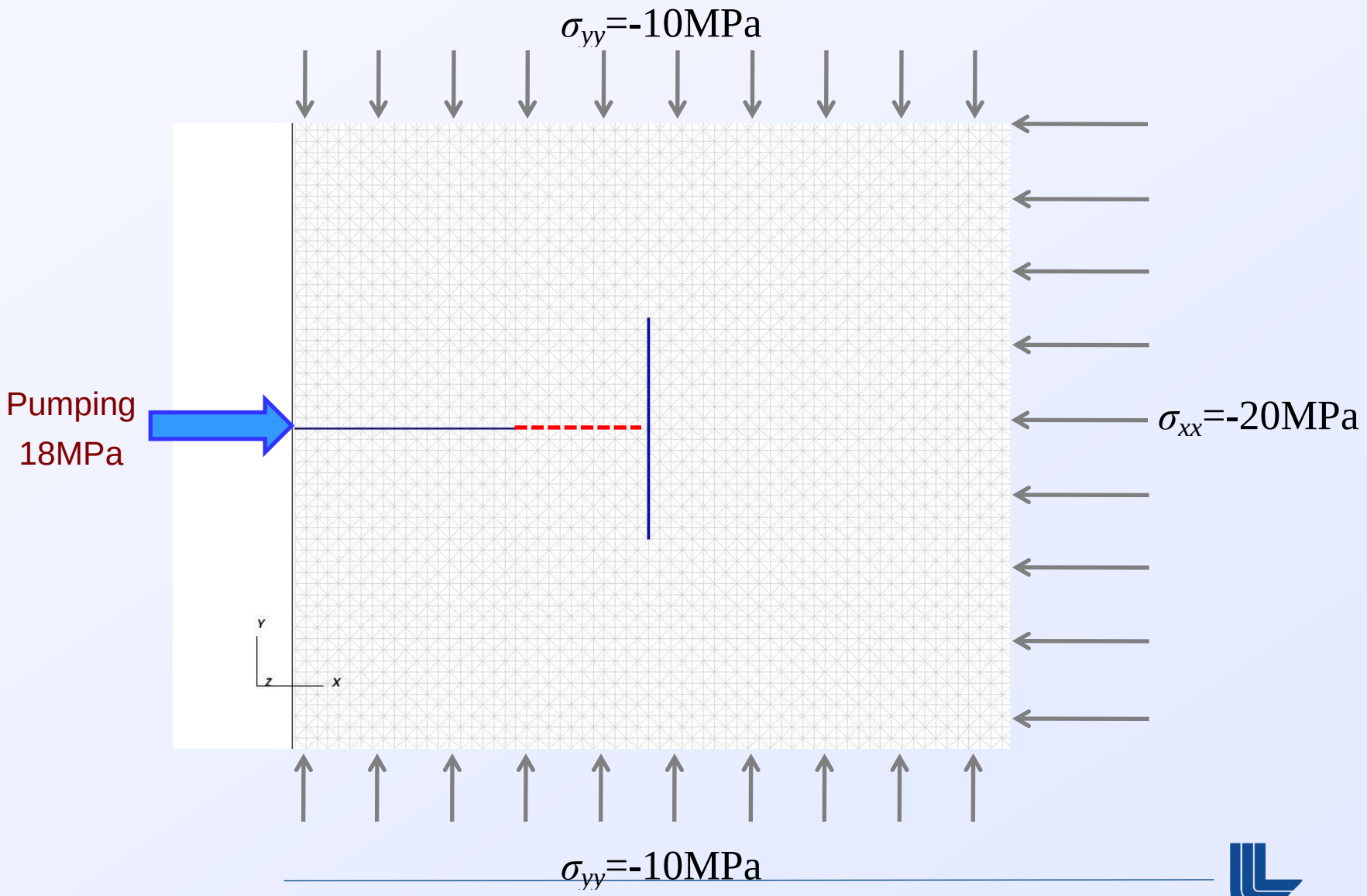


Blanton, 1982

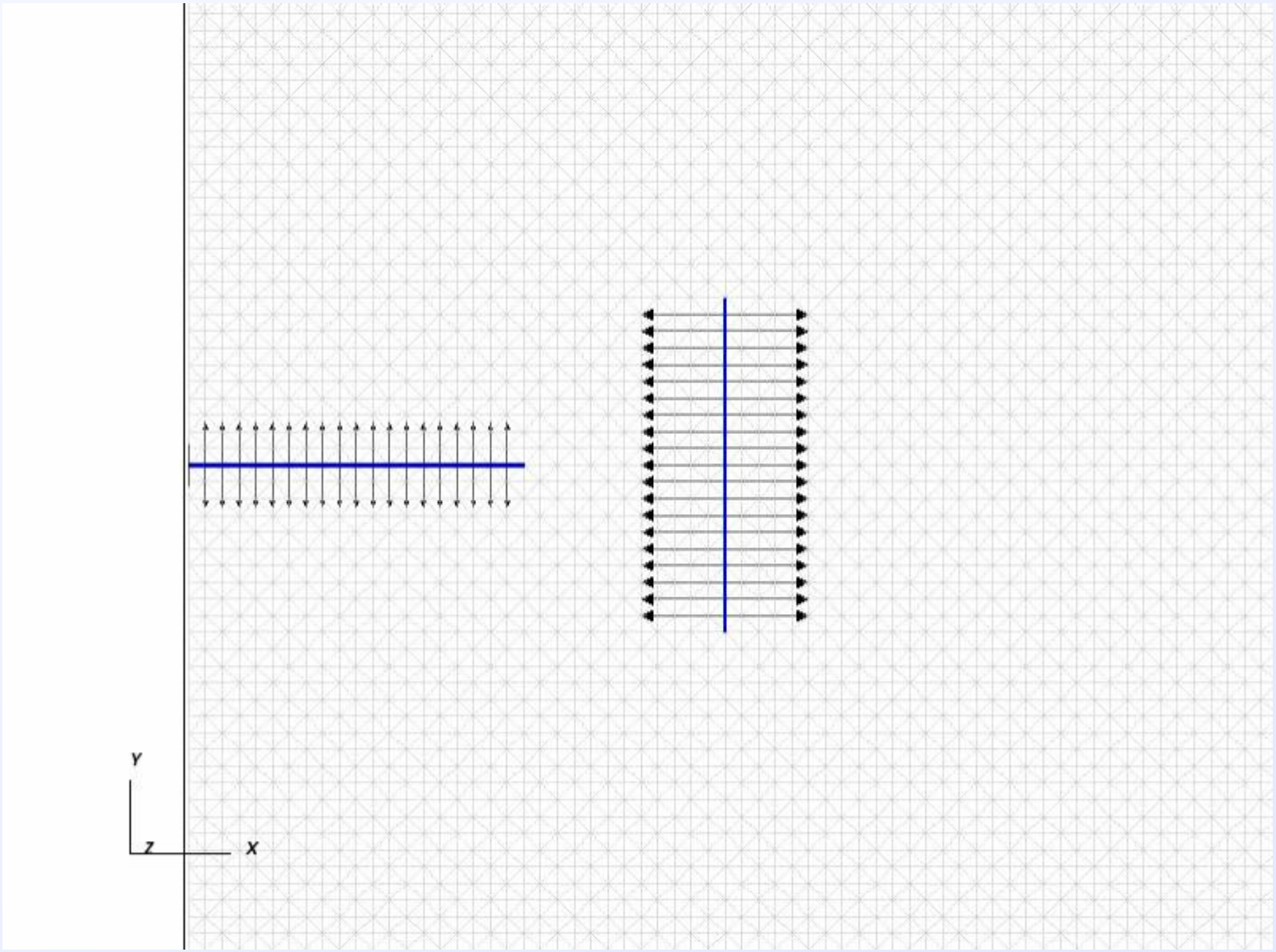




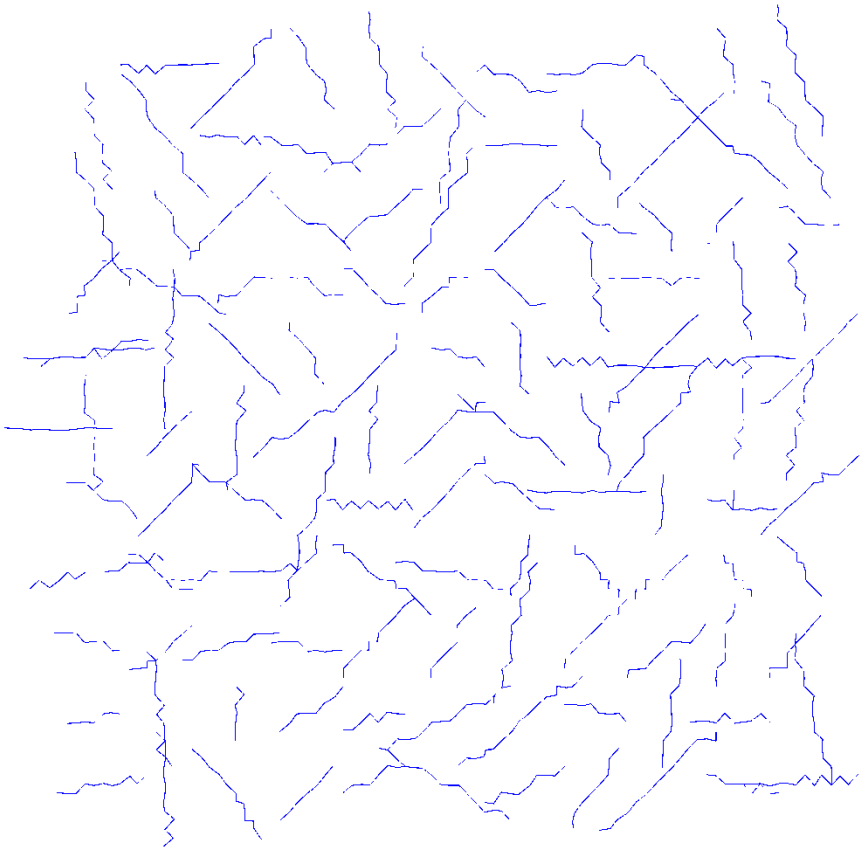
Interaction between propagating and existing fractures

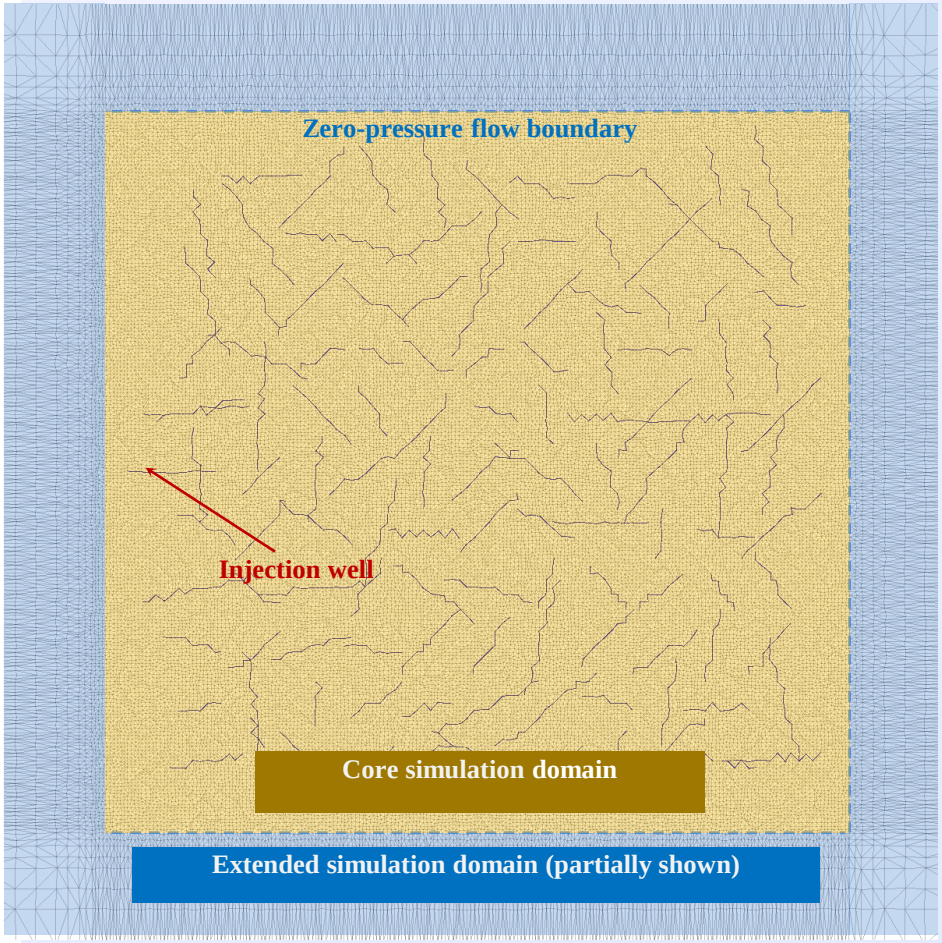


Interaction between propagating and existing Fractures

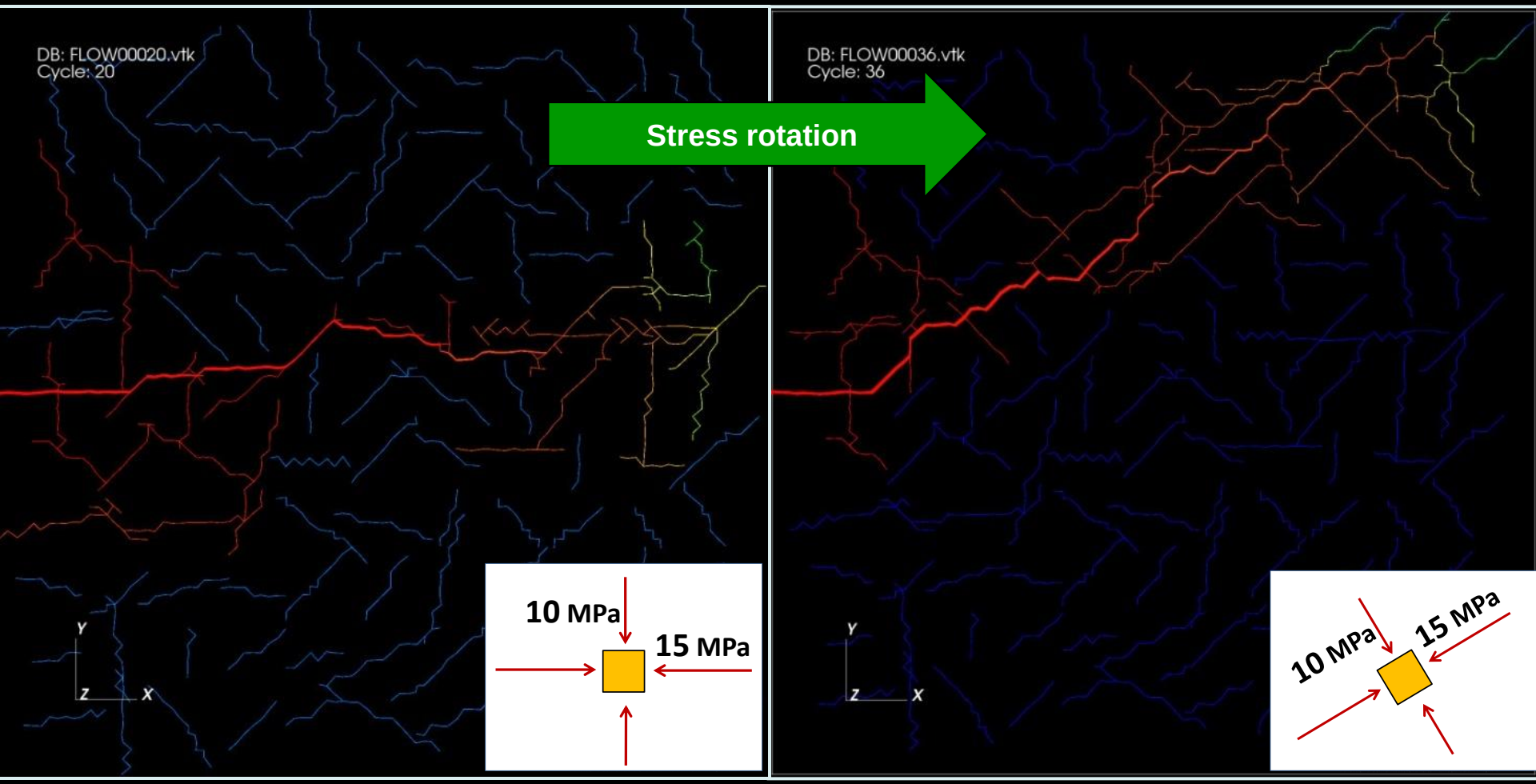


Application to more complex fracture networks





I: Effects of *in situ* stress: principal stress orientation & anisotropy



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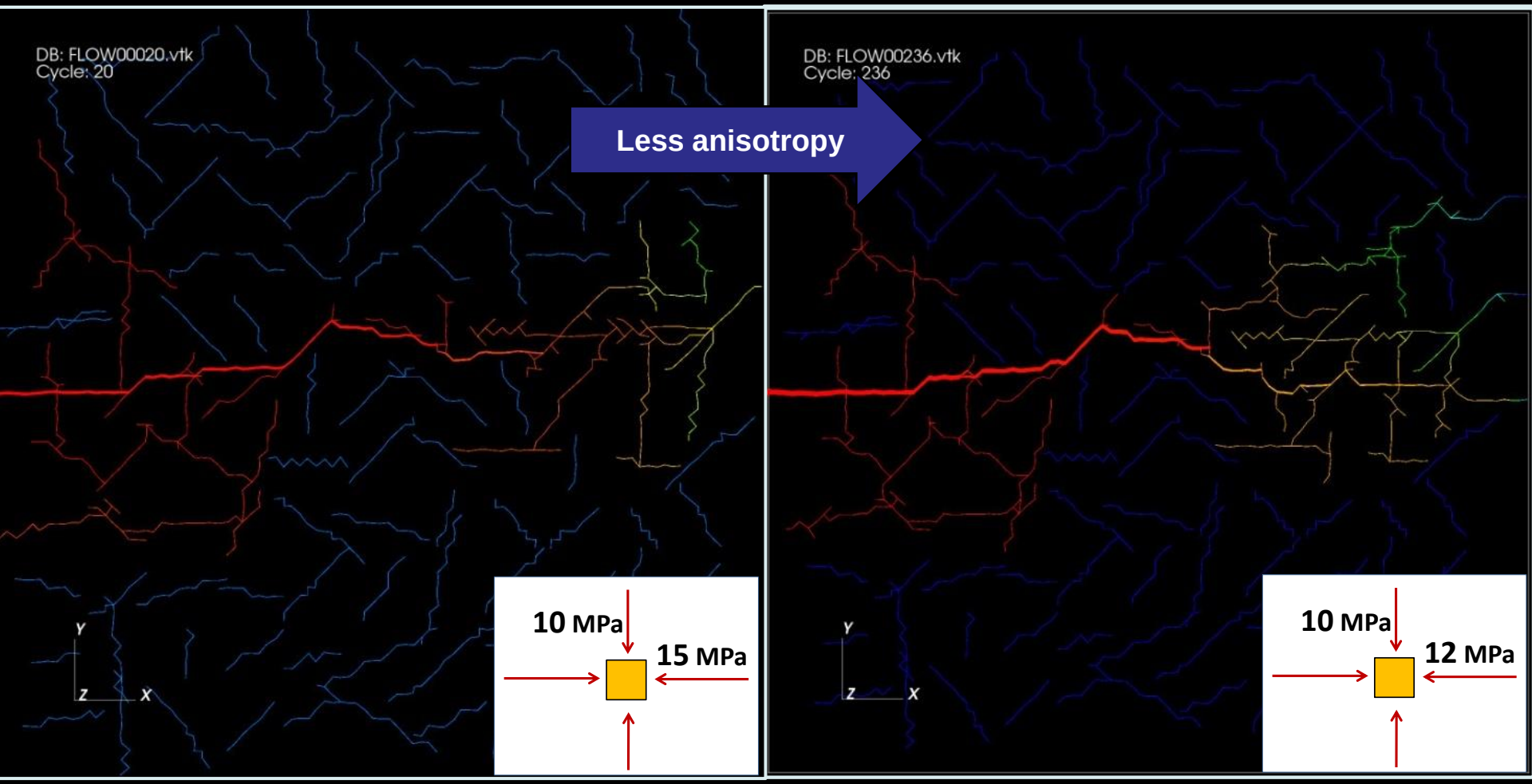
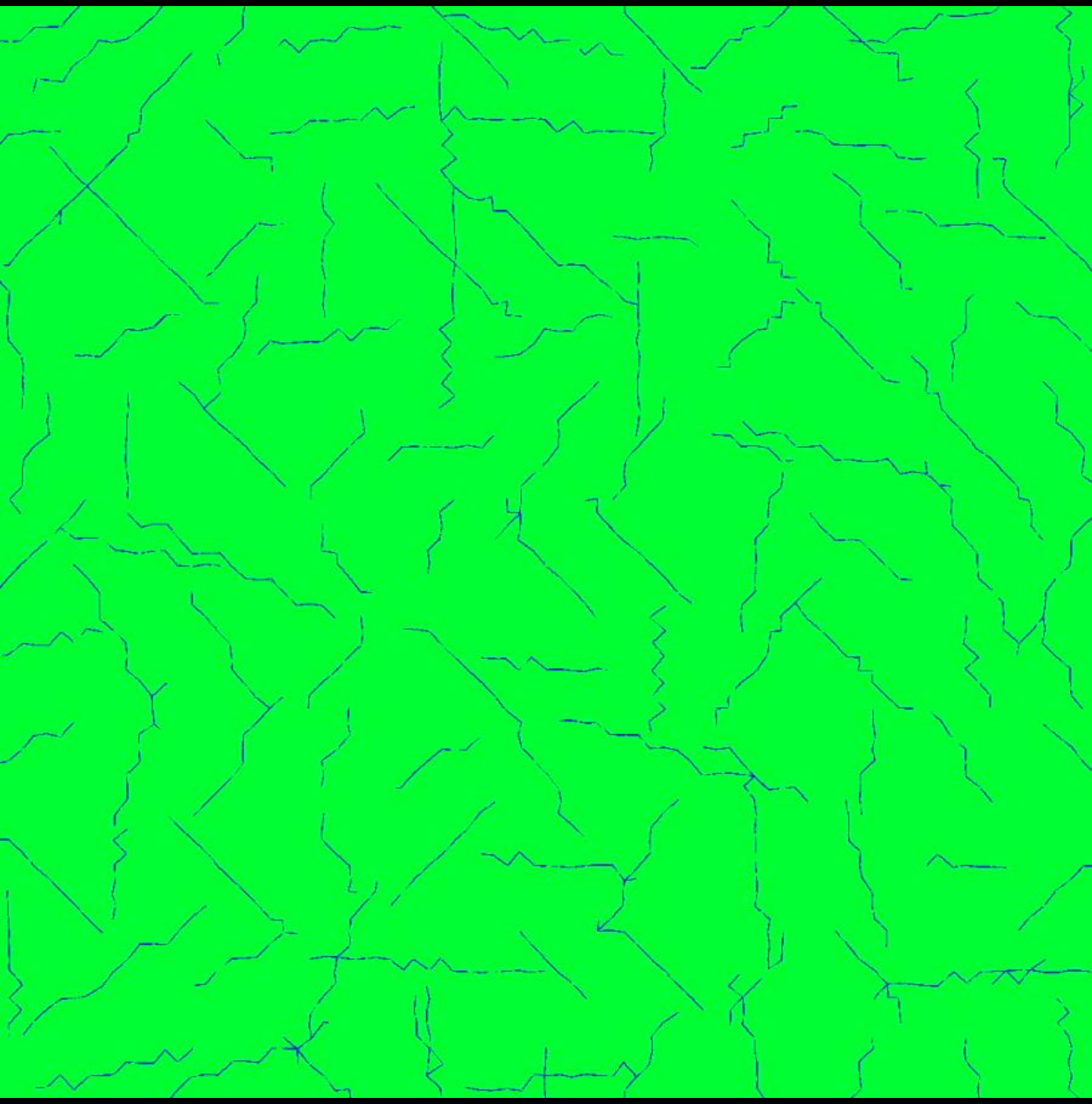
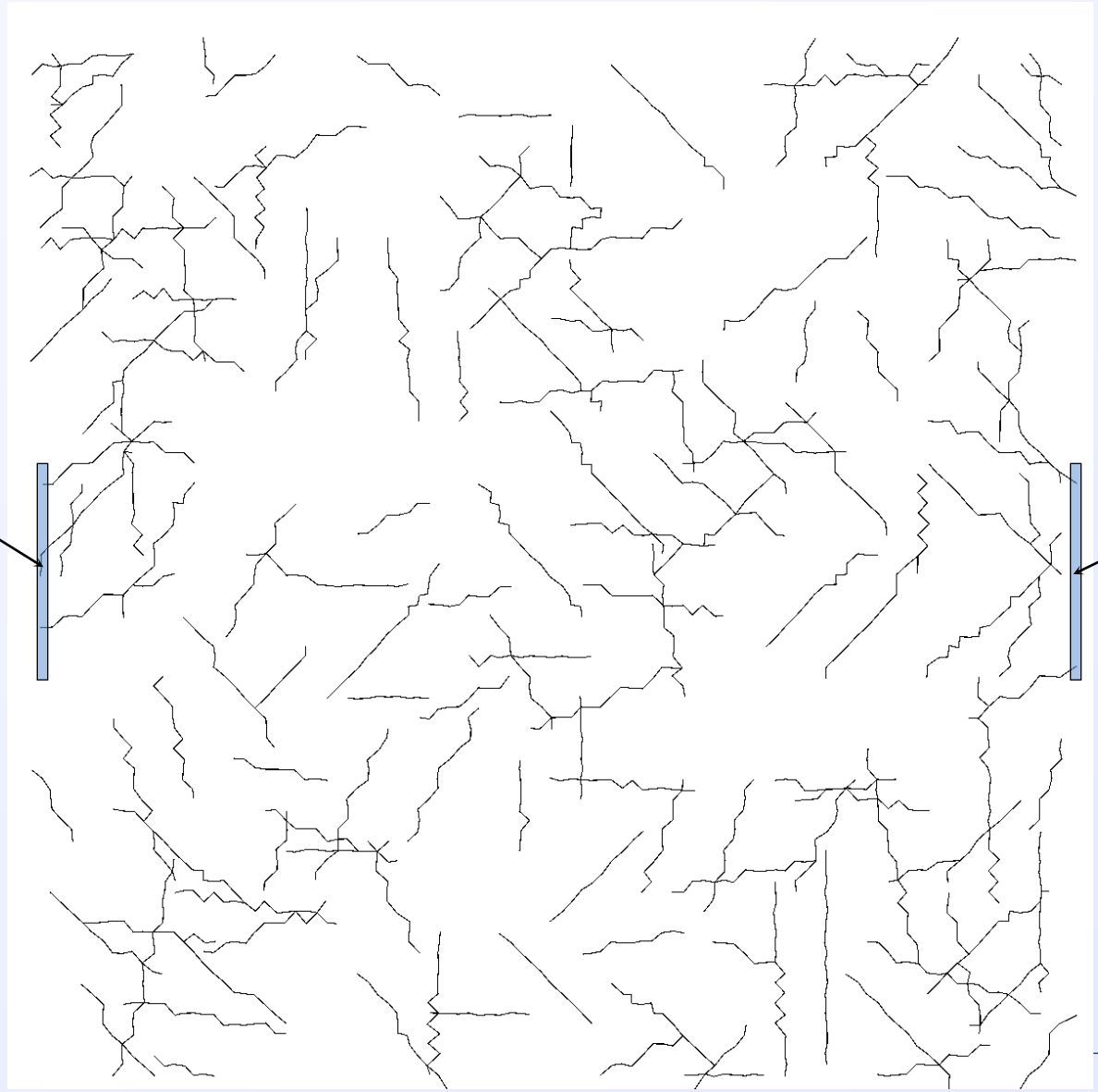
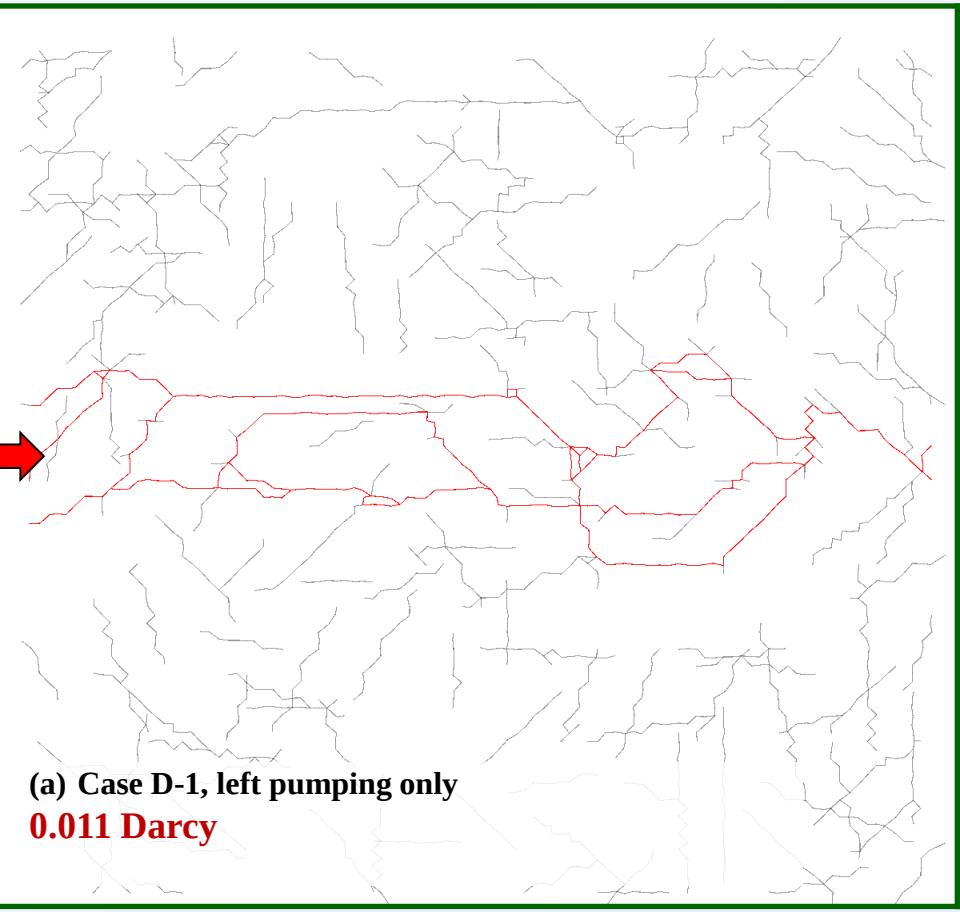




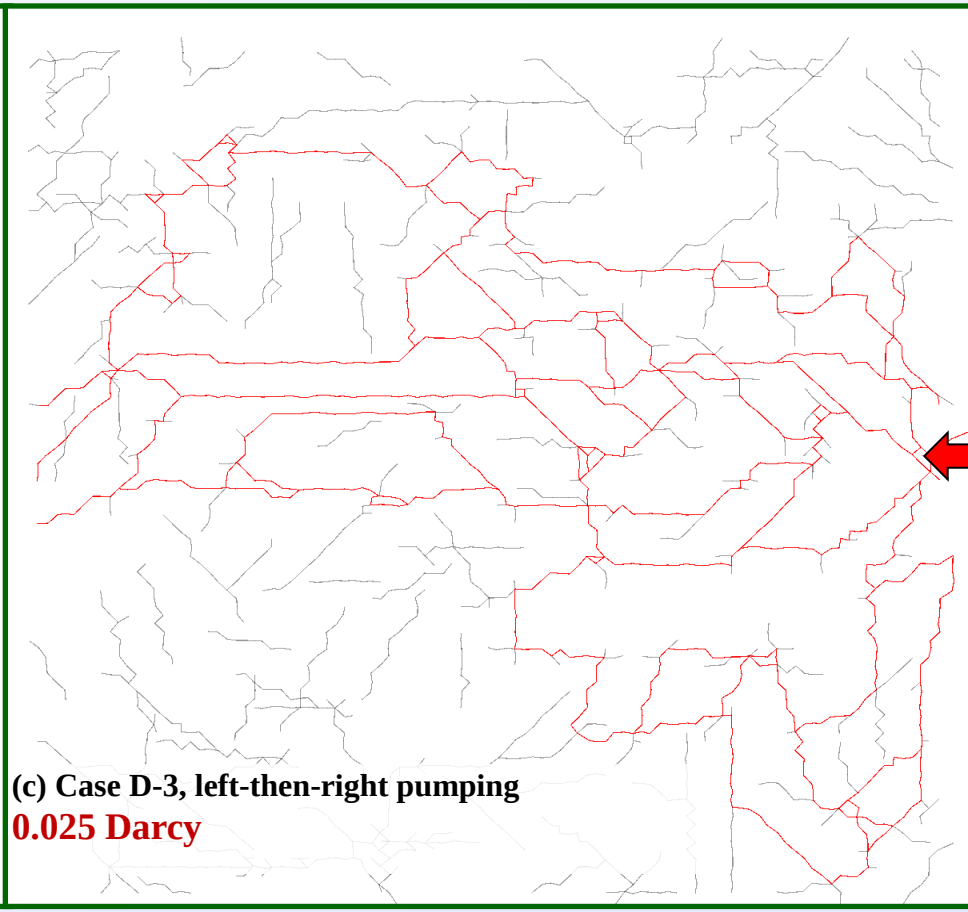
II: Multi-well stimulation





(a) Case D-1, left pumping only

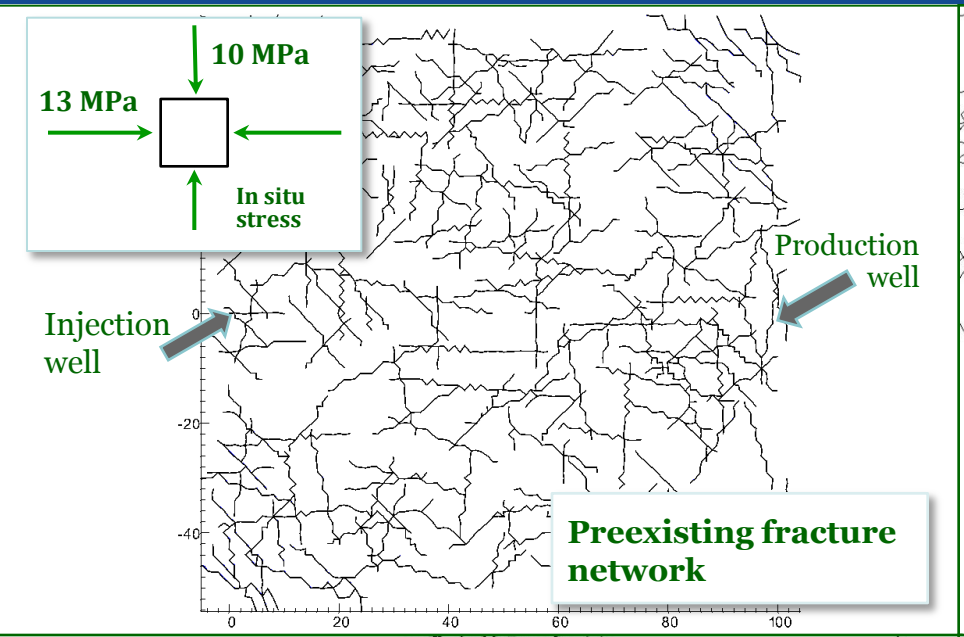
0.011 Darcy



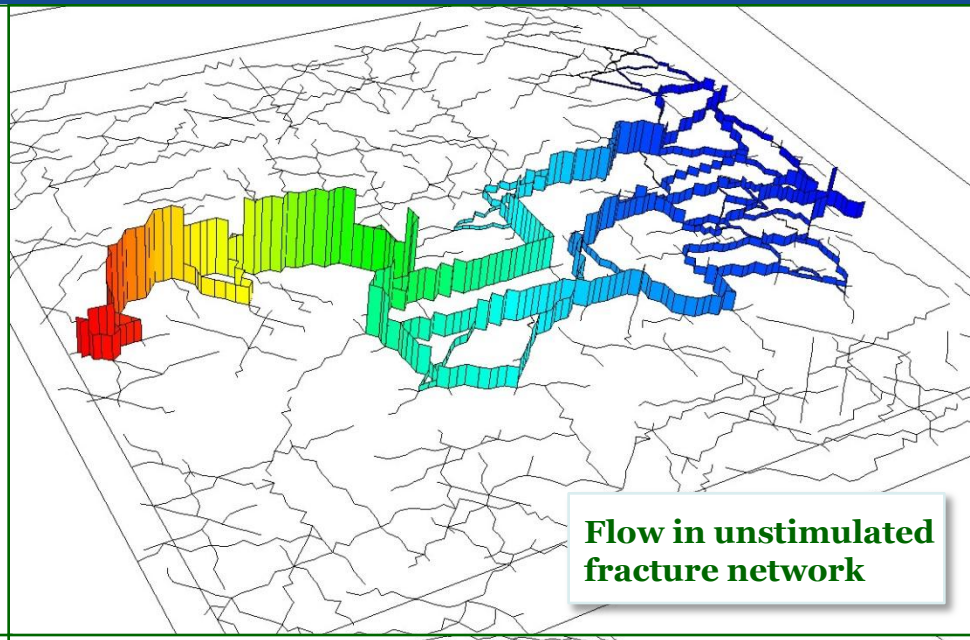
(c) Case D-3, left-then-right pumping

0.025 Darcy

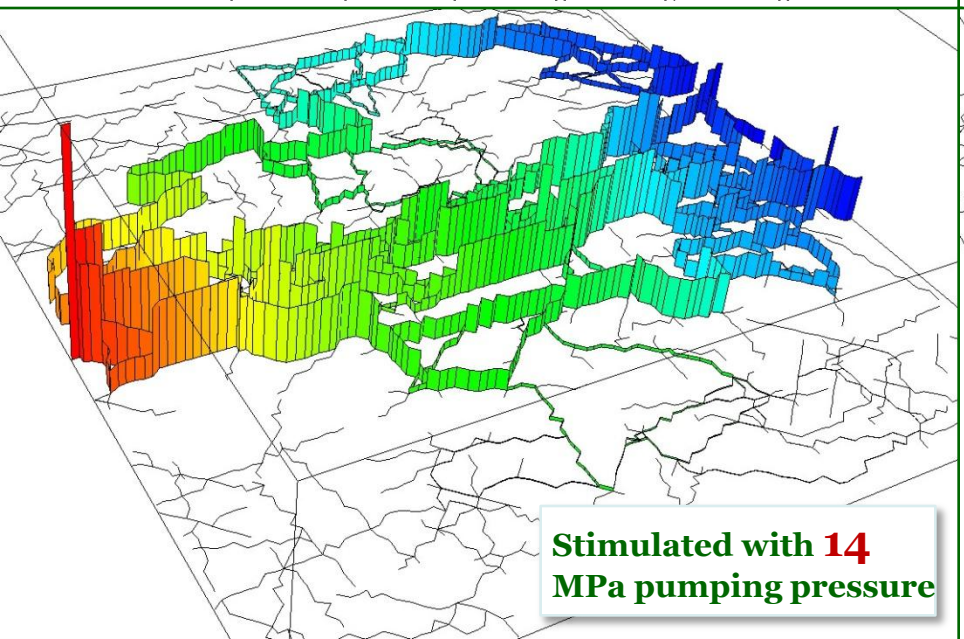
III: Effects of stimulation pressure



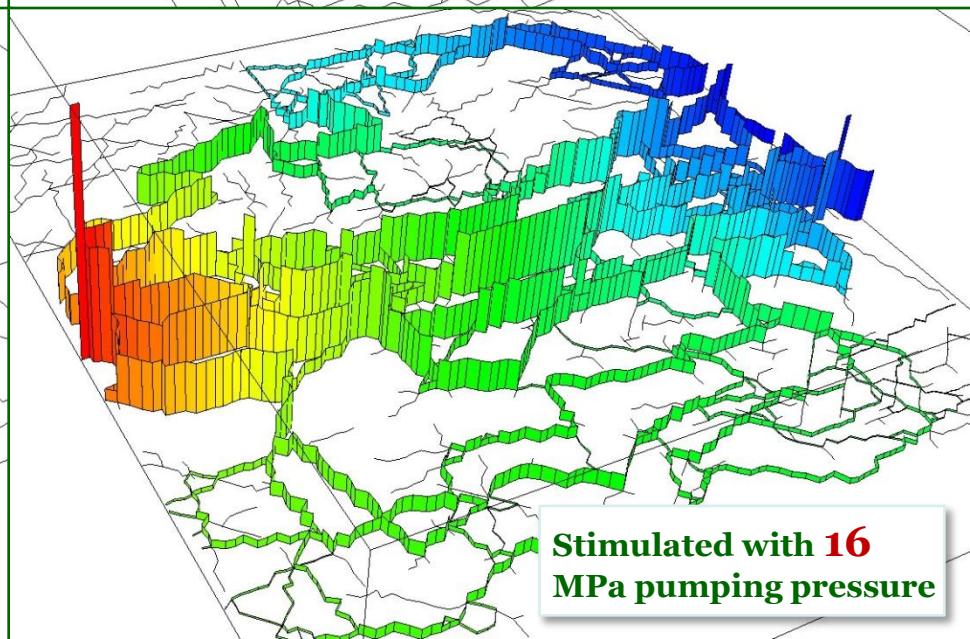
Preexisting fracture network



Flow in unstimulated fracture network

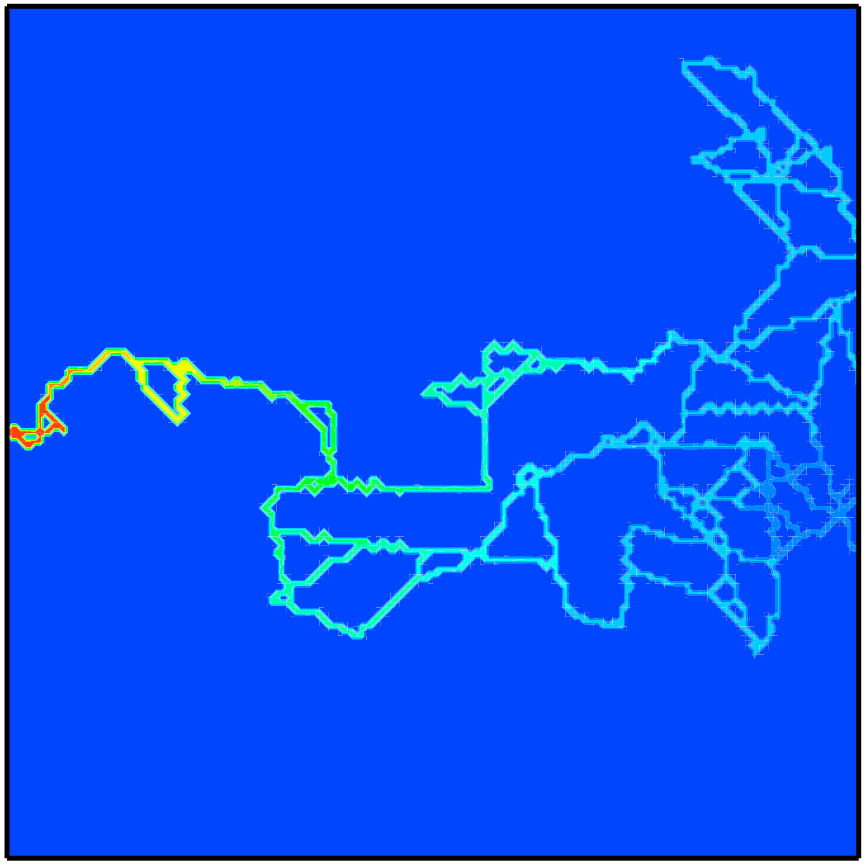


Stimulated with 14 MPa pumping pressure

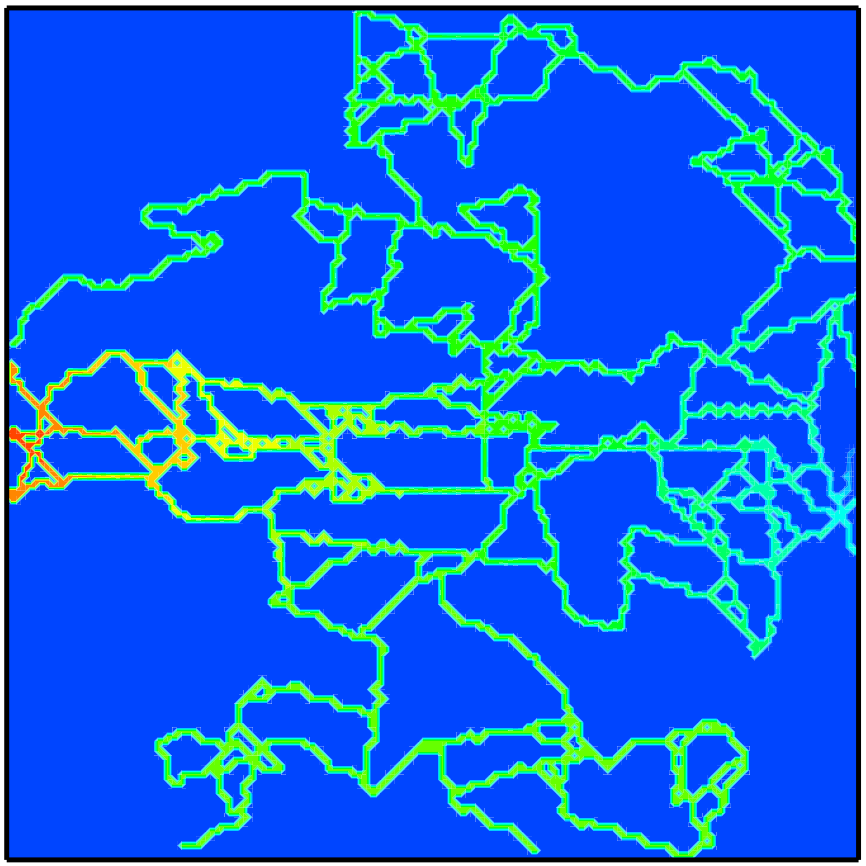


Stimulated with 16 MPa pumping pressure

Thermal analysis based on the predicted fracture network.



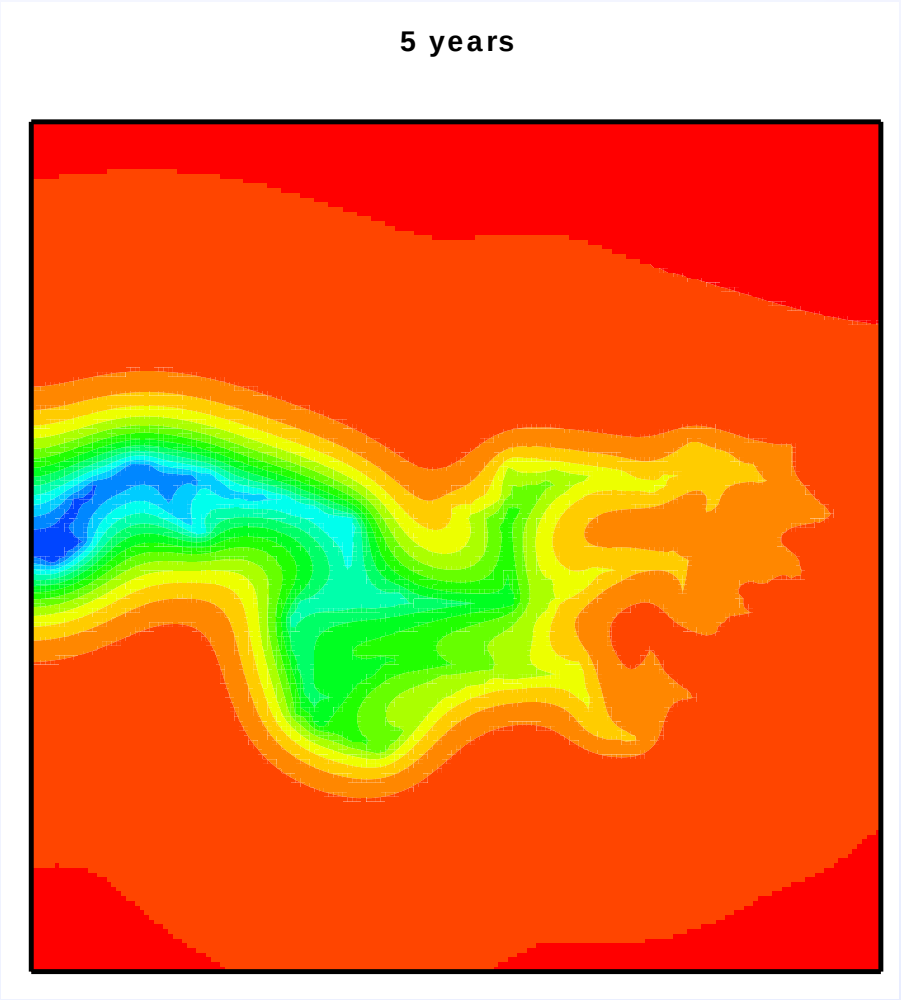
Before stimulation



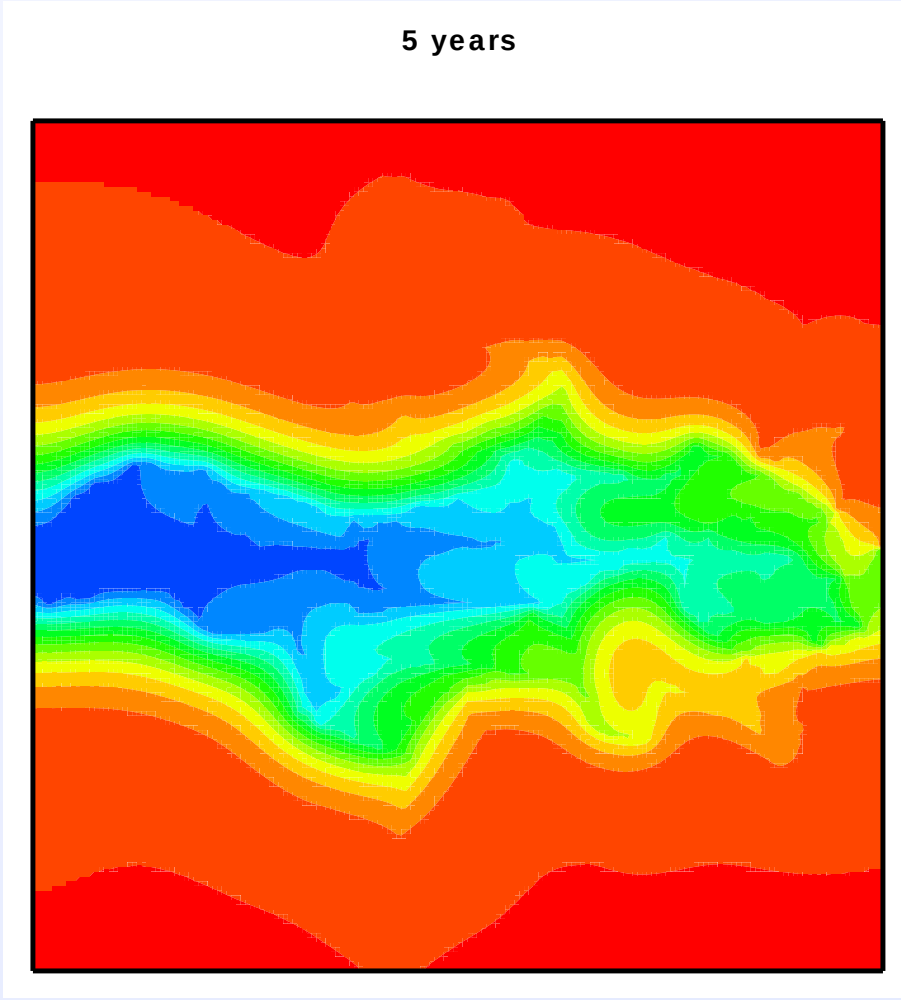
After stimulation

(Preliminary NUFT analysis results provided by Yue Hao at LLNL.)

Thermal analysis based on the predicted fracture network.



Without stimulation



With stimulation

(Preliminary NUFT analysis results provided by Yue Hao at LLNL.)

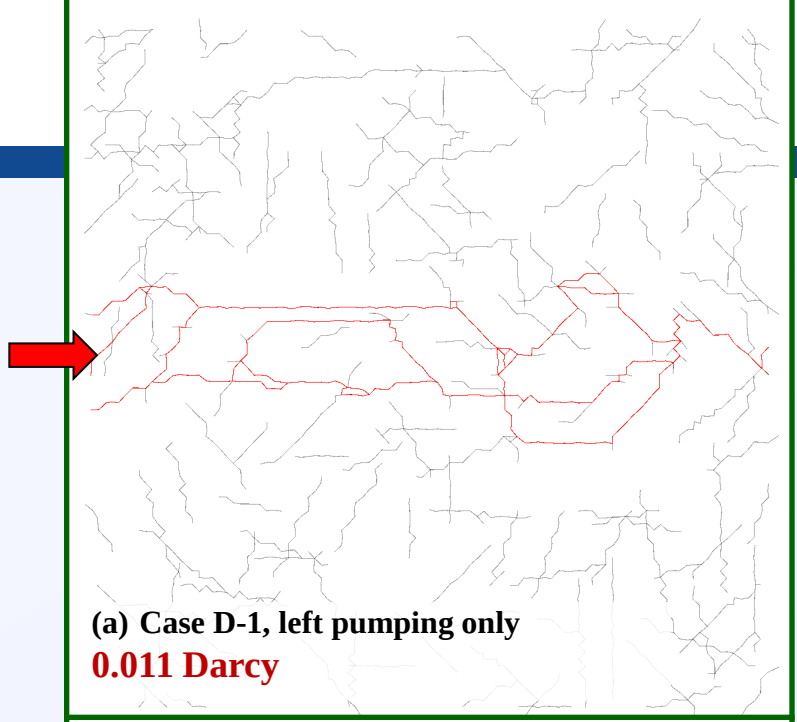
Concluding Remarks

- Challenges:
  - The coupling of multiple modules.
  - High computational cost.
- Benefits:
  - Explicit simulation of fracture-fracture and fracture-fluid interaction.
  - Capable of handling complex fracture networks.
  - Simple and physically meaningful input parameters.
- Further development, enhancement, and validation
  - Methodology works; preliminary results are reasonable and inspiring.
  - Collecting stimulation scenarios to investigate (poster on Tuesday).

Acknowledgments

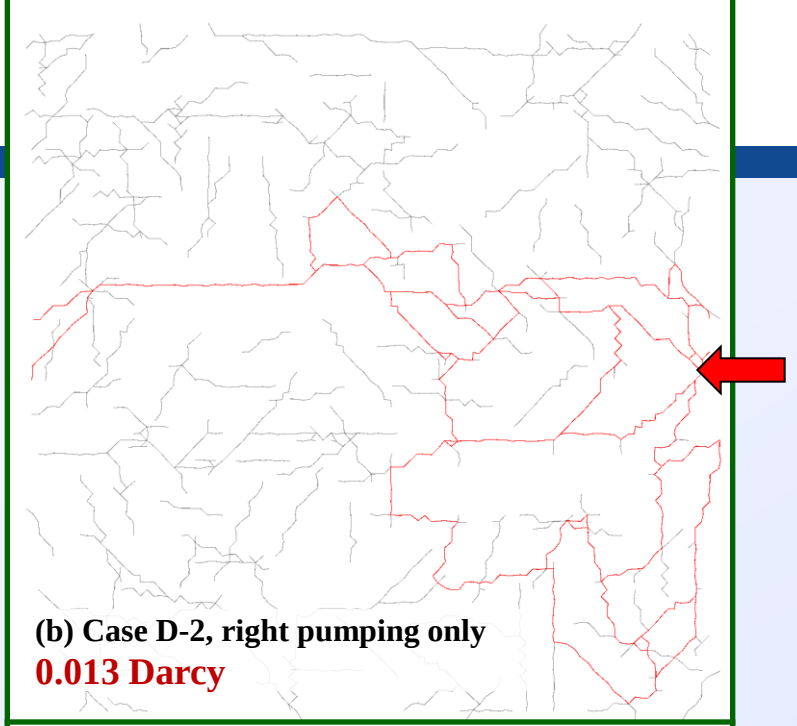
- This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Release number: LLNL-PRES-489801



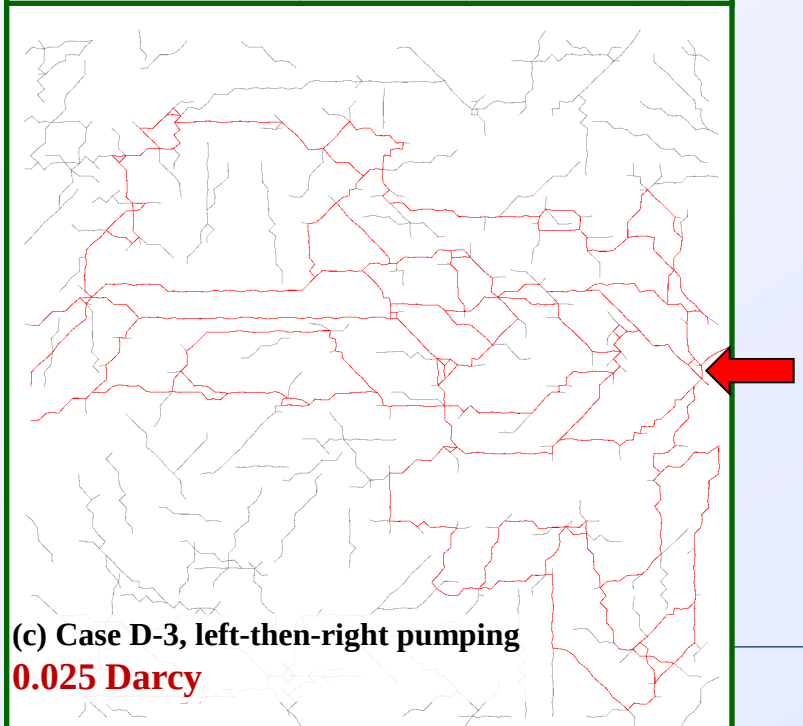
(a) Case D-1, left pumping only

0.011 Darcy



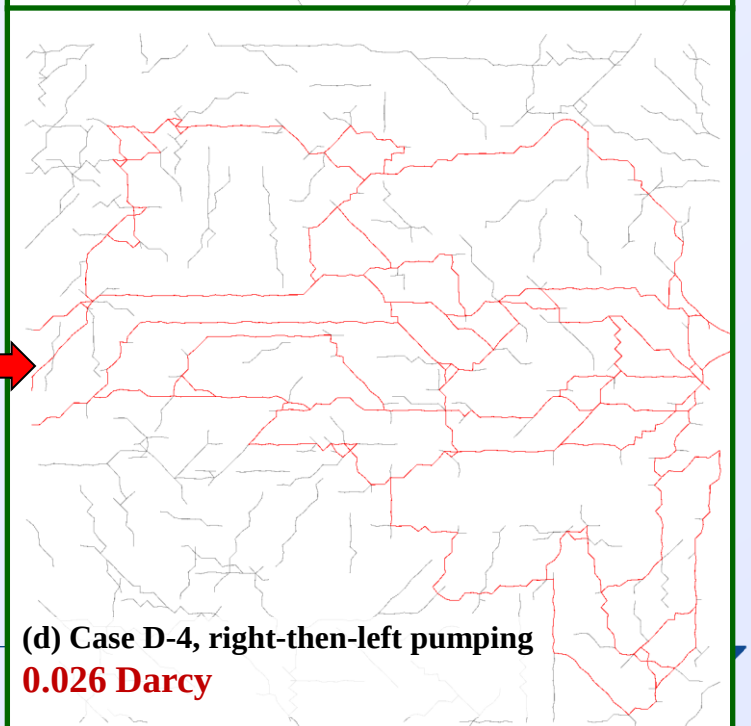
(b) Case D-2, right pumping only

0.013 Darcy



(c) Case D-3, left-then-right pumping

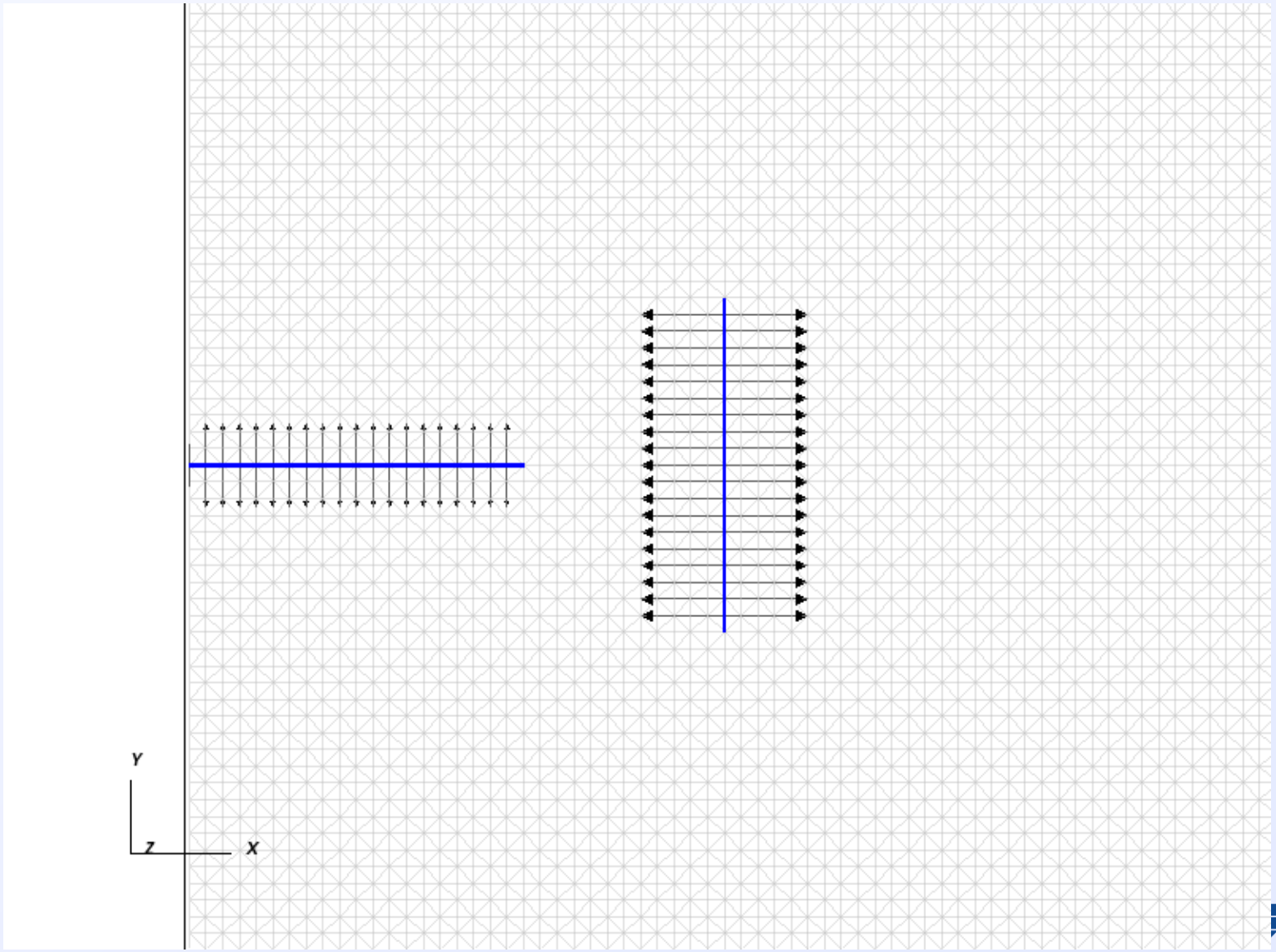
0.025 Darcy



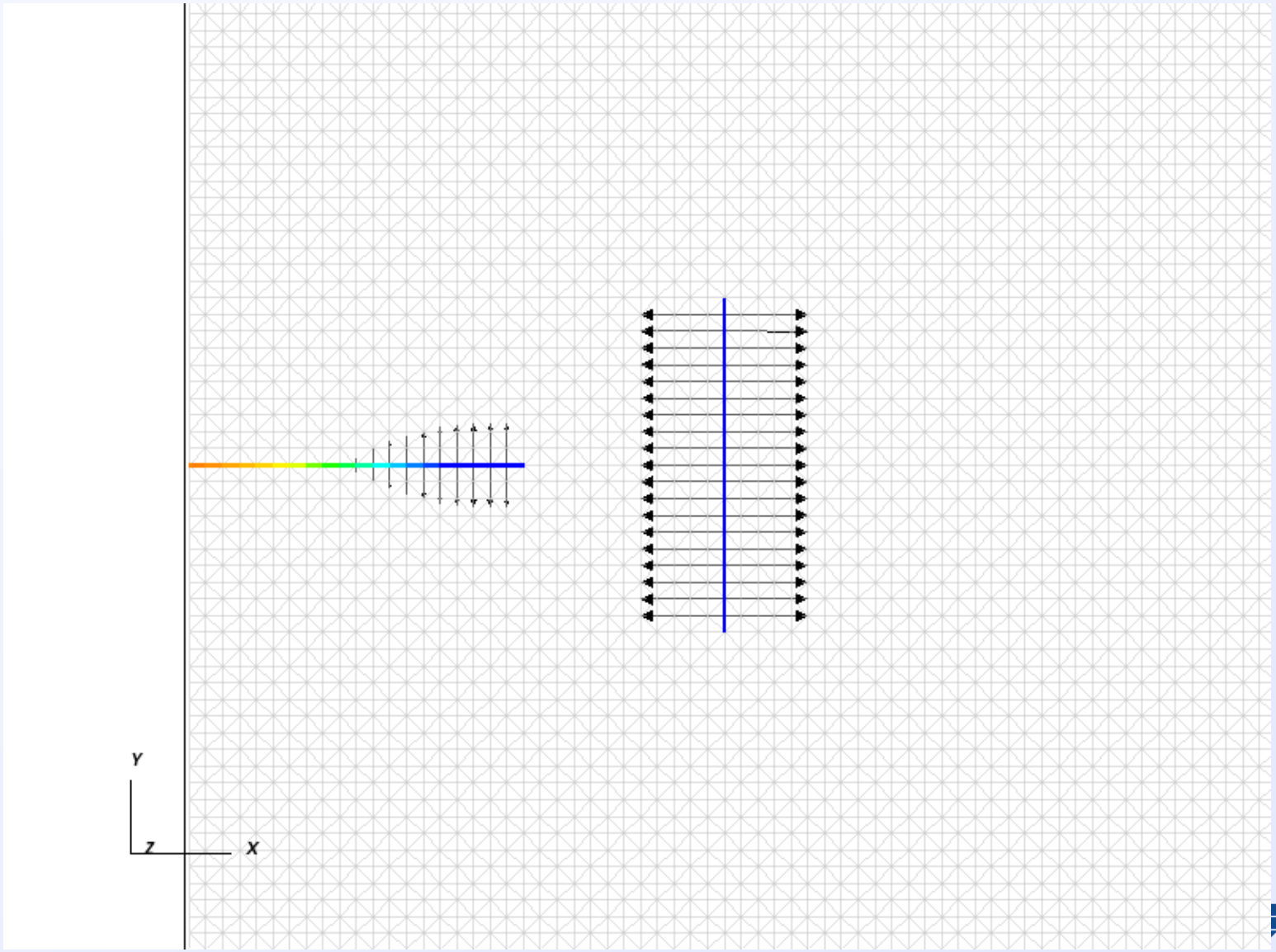
(d) Case D-4, right-then-left pumping

0.026 Darcy

Interaction Between Propagating and Existing Fractures



Interaction Between Propagating and Existing Fractures



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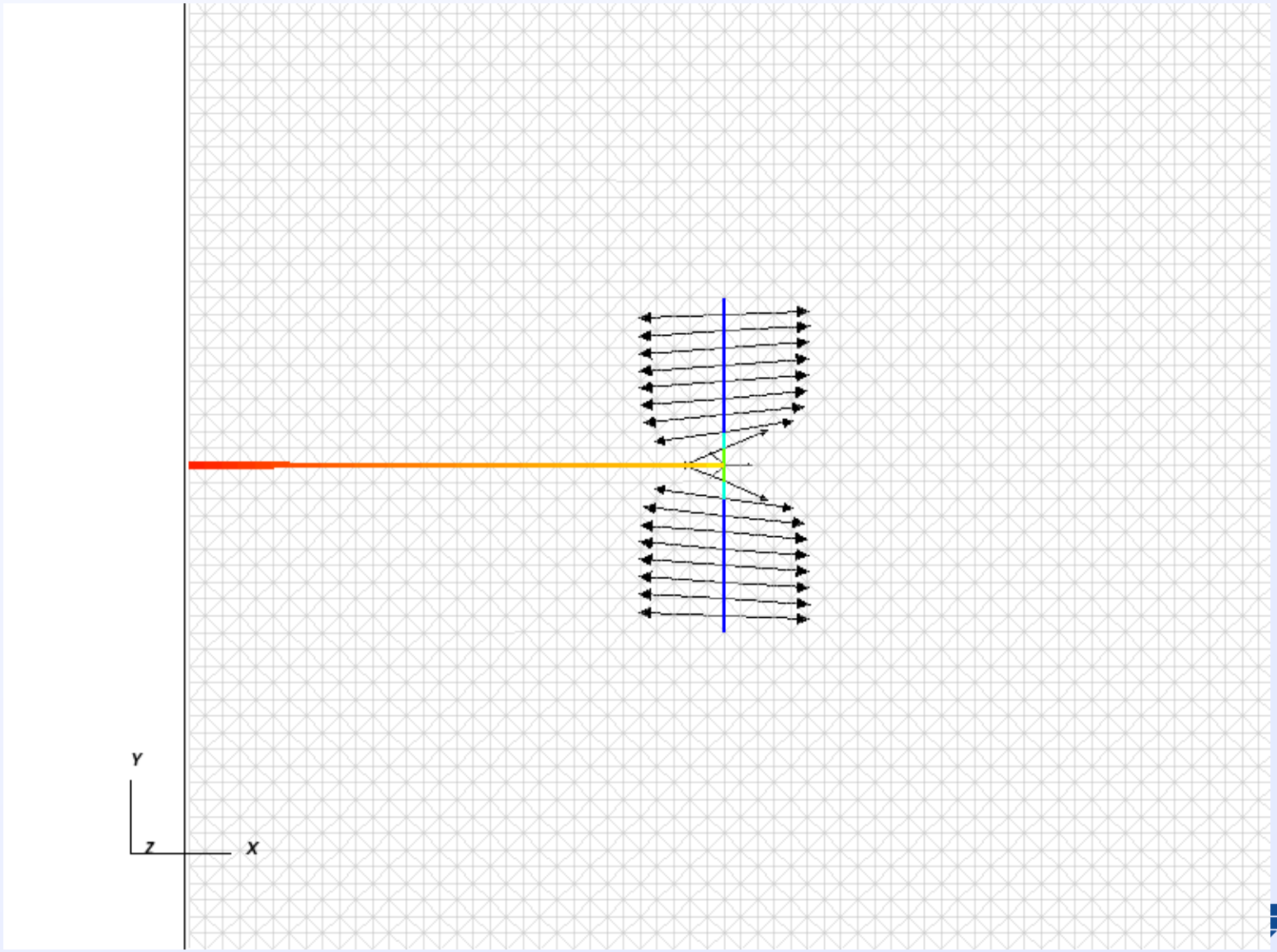
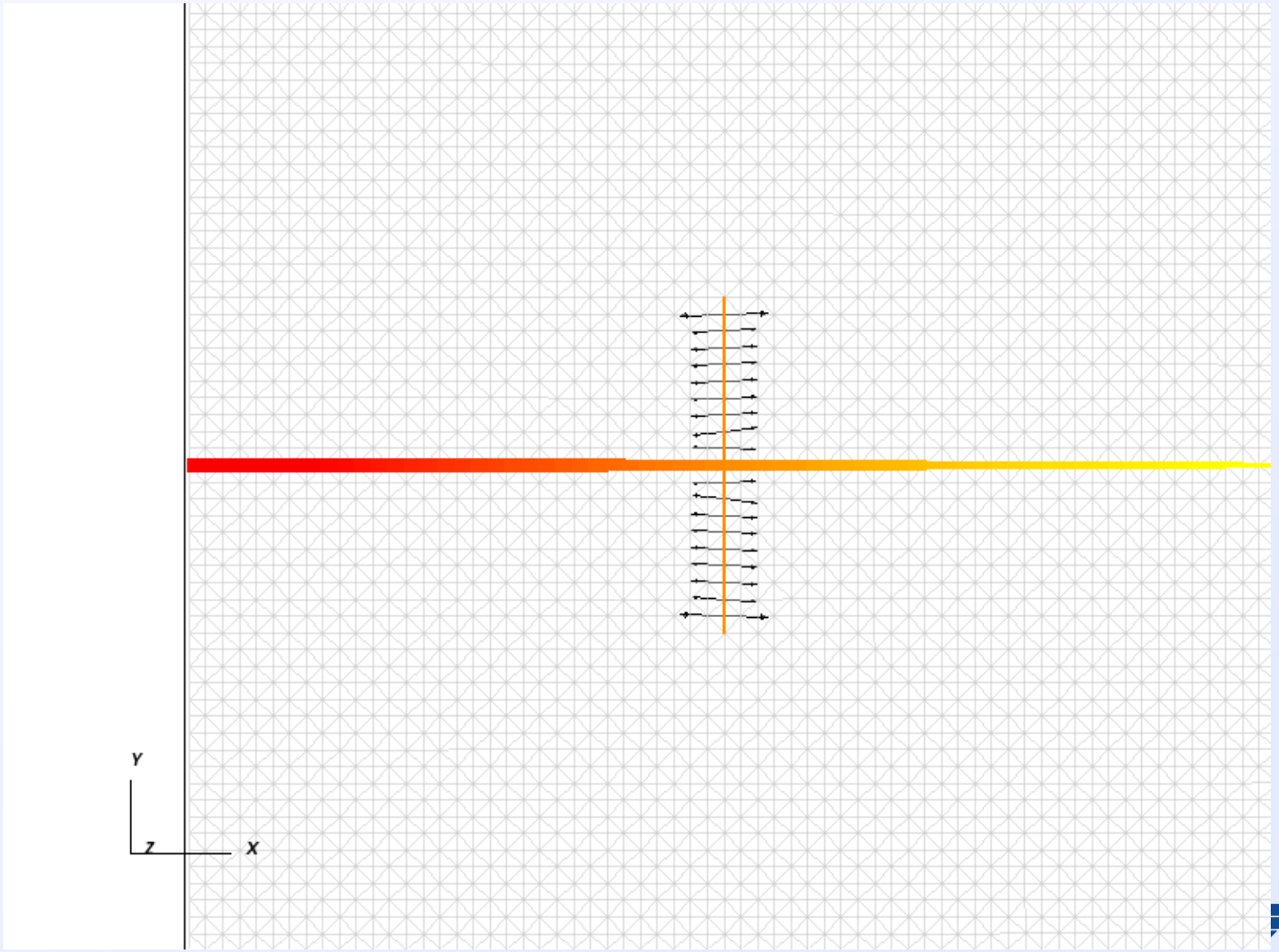
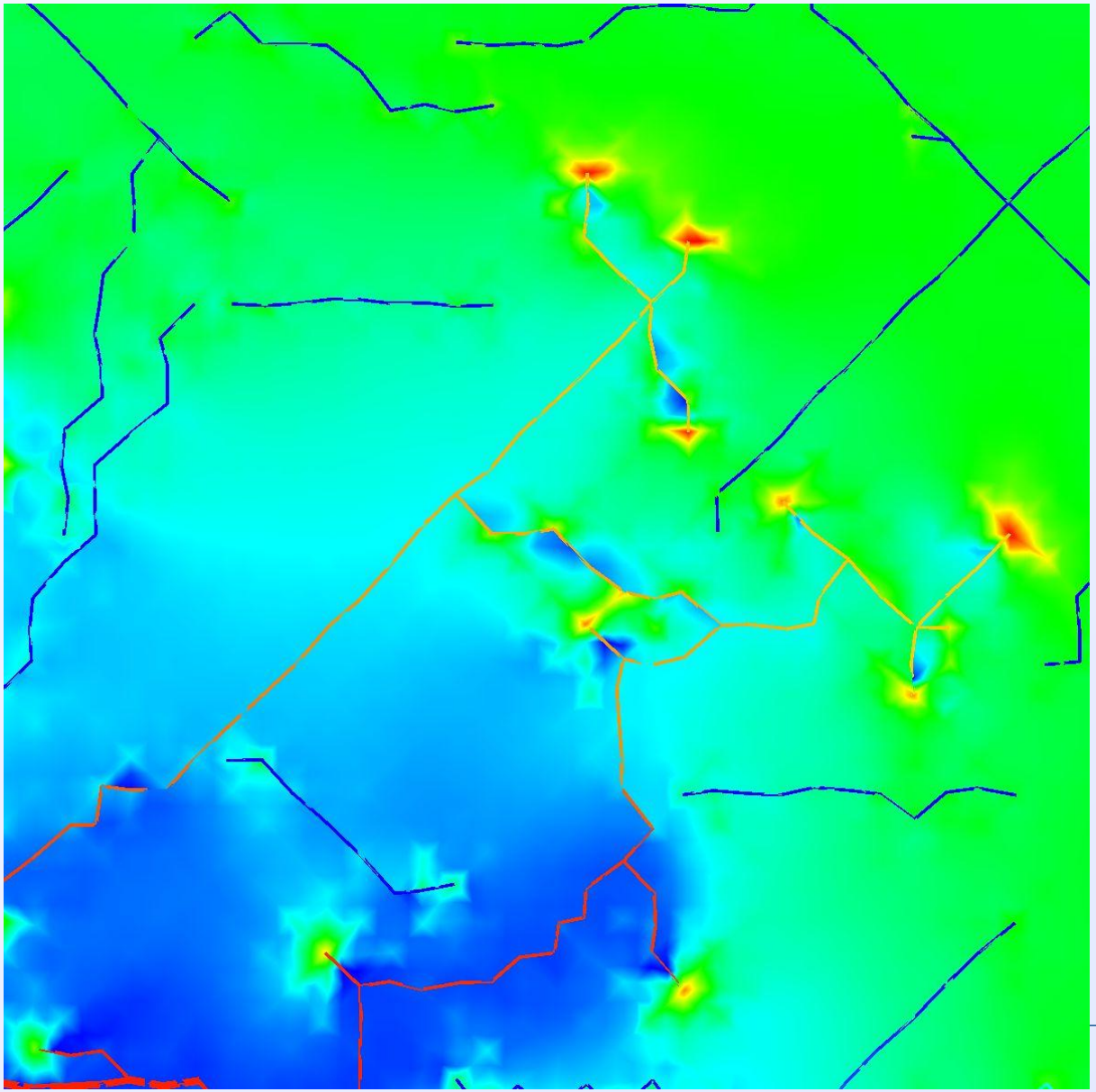


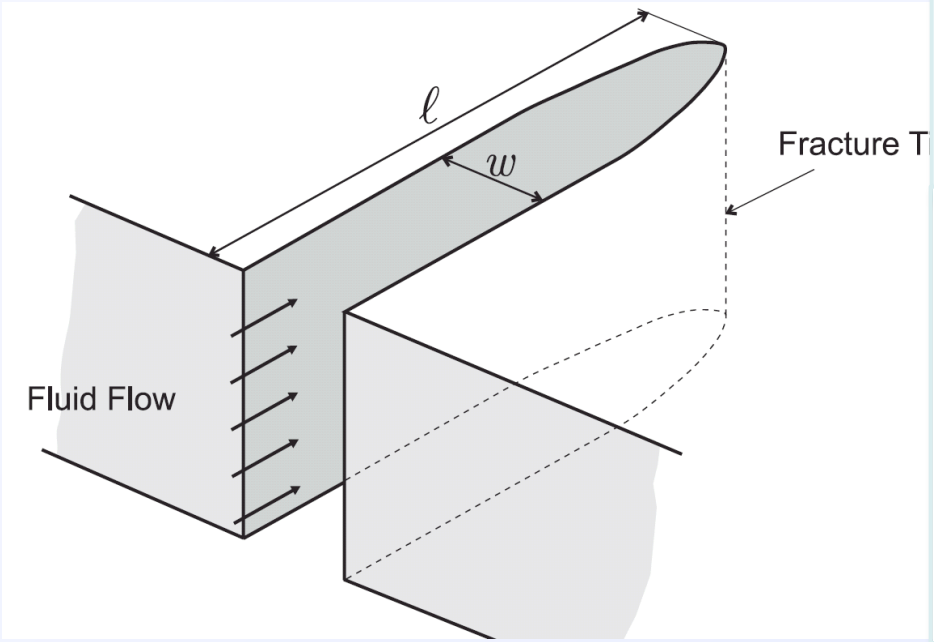
Interaction Between Propagating and Existing Fractures

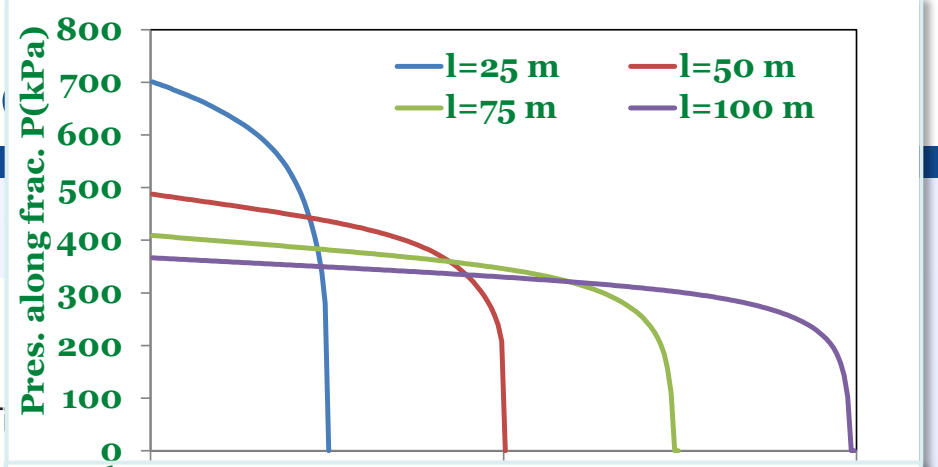


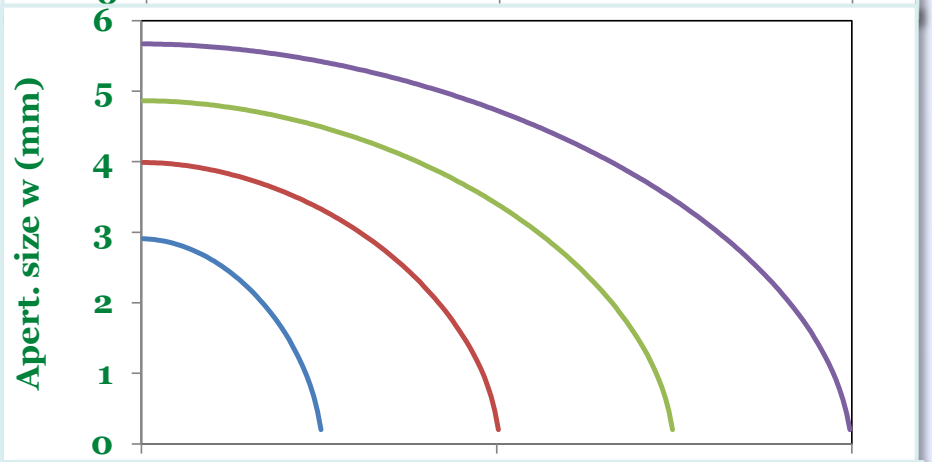
Application to more complex fracture networks

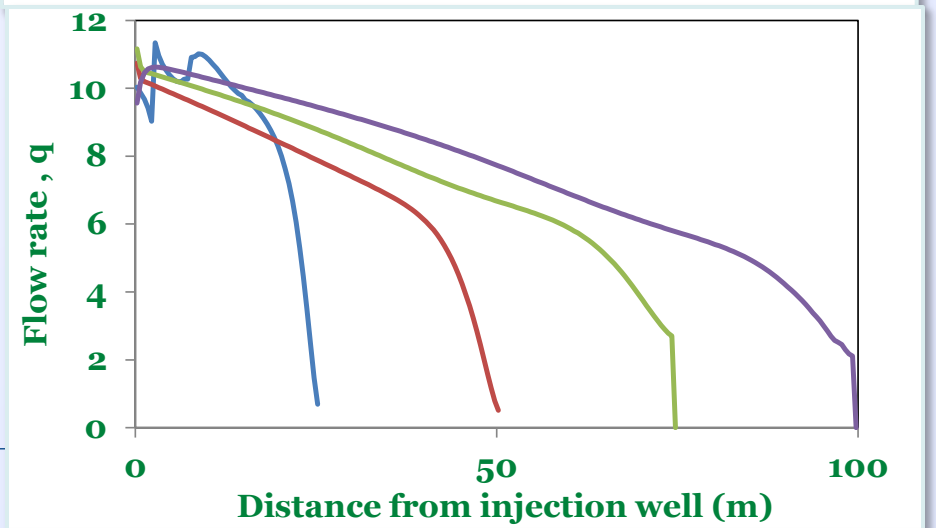


Model verification: classical KGD m









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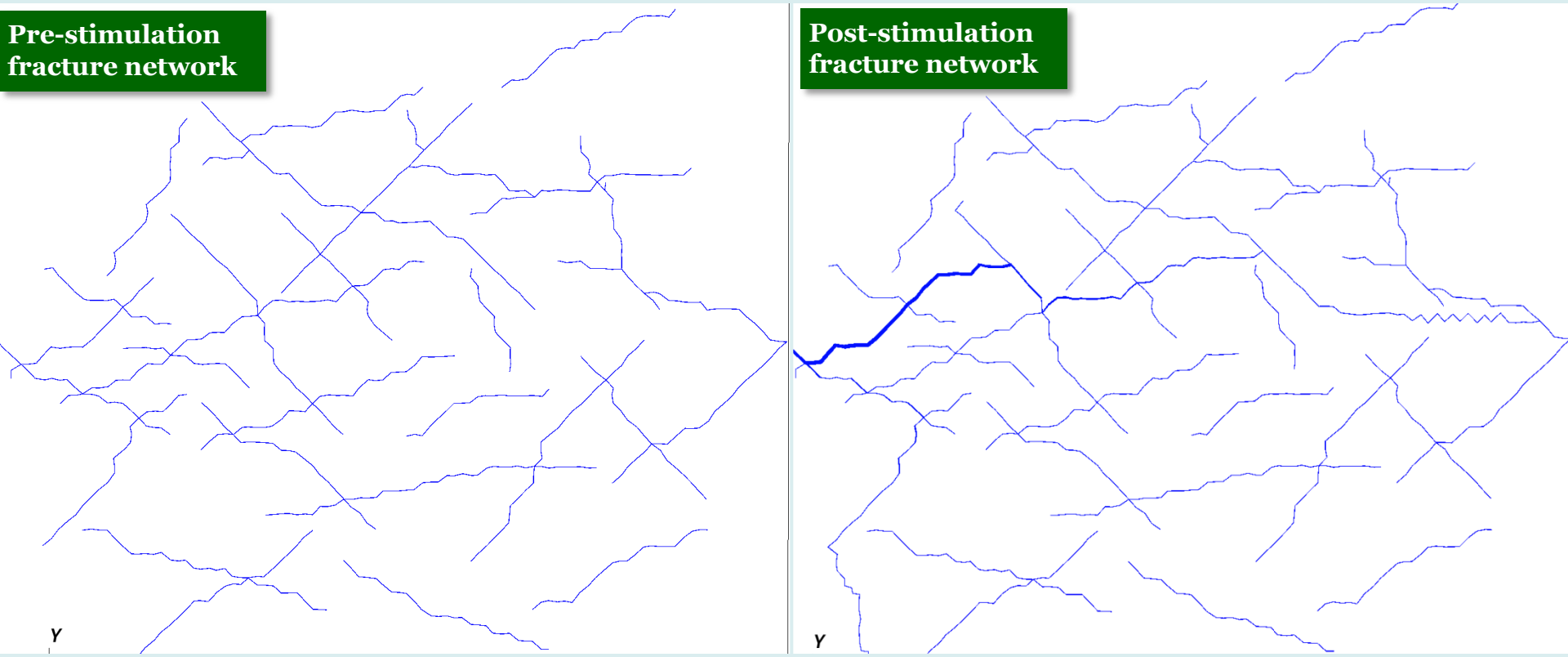
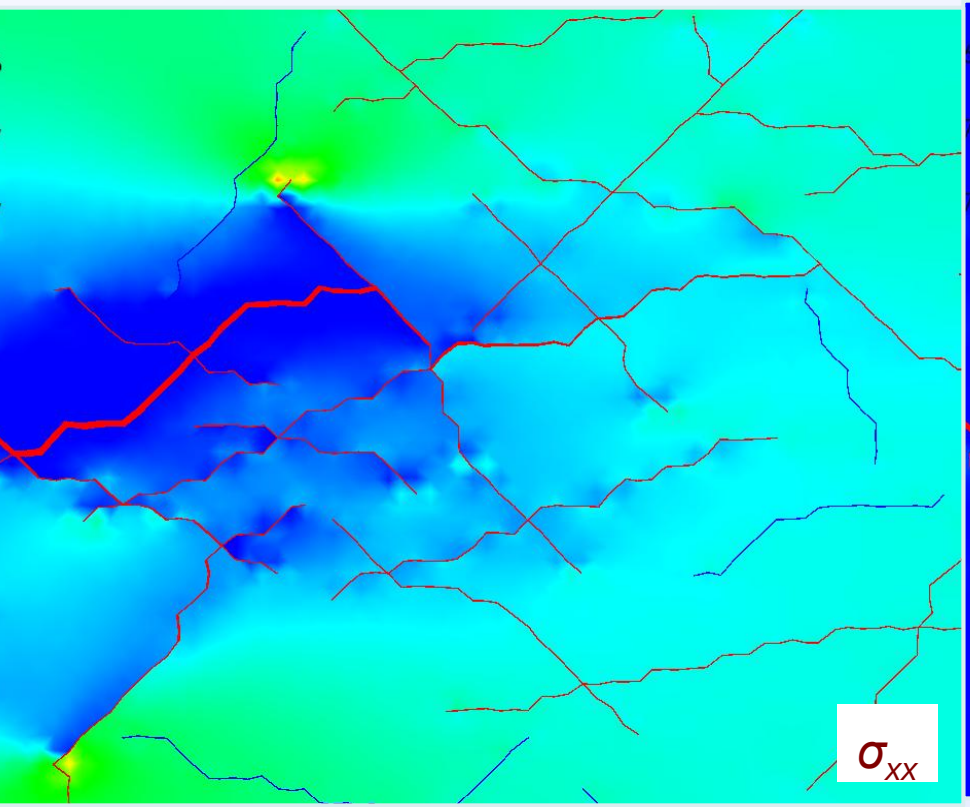
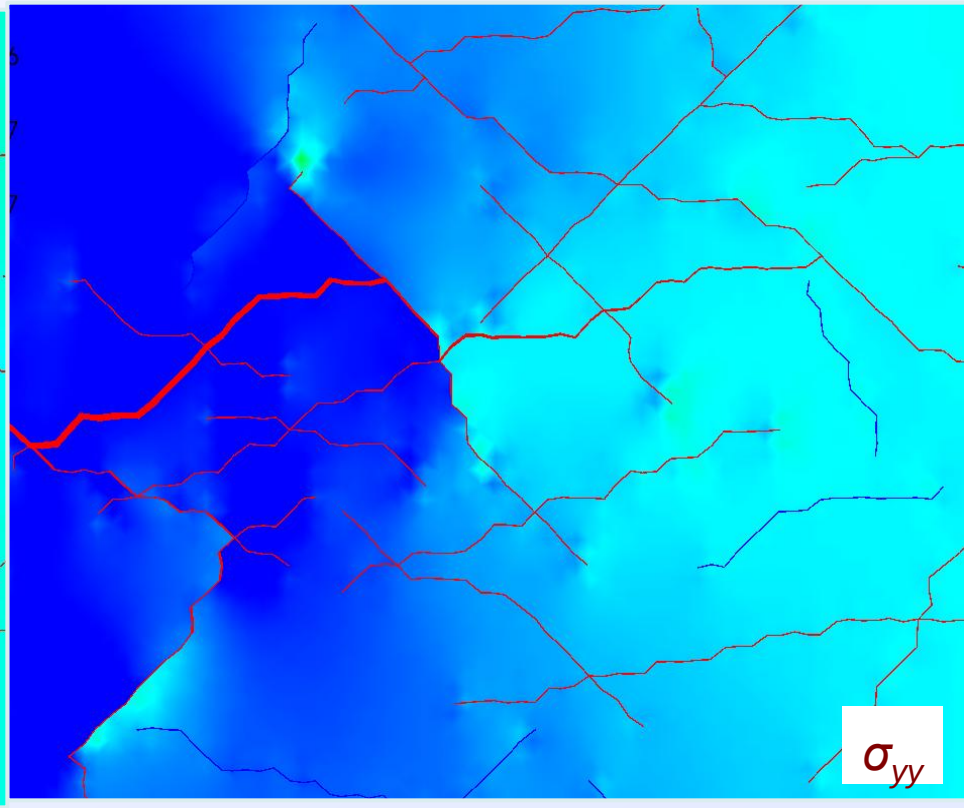
Application to more complex fracture networks



Application to more complex fracture networks





Results published in ARMA 2011 Symposium