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Simulating Complex Fracture Systems in Geothermal Reservoirs Using an Explicitly Coupled Hydro-Geomechanical Model

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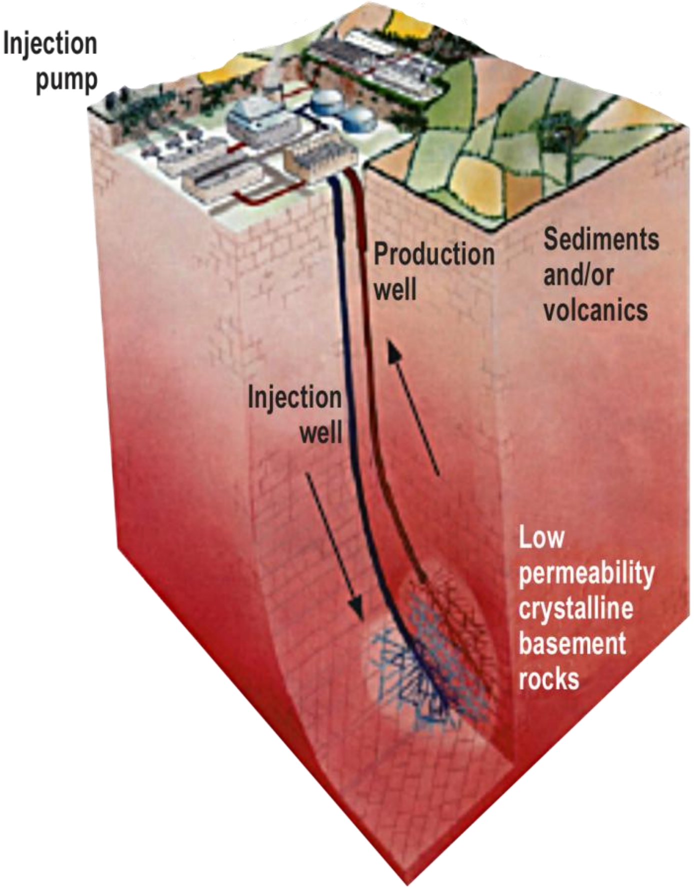
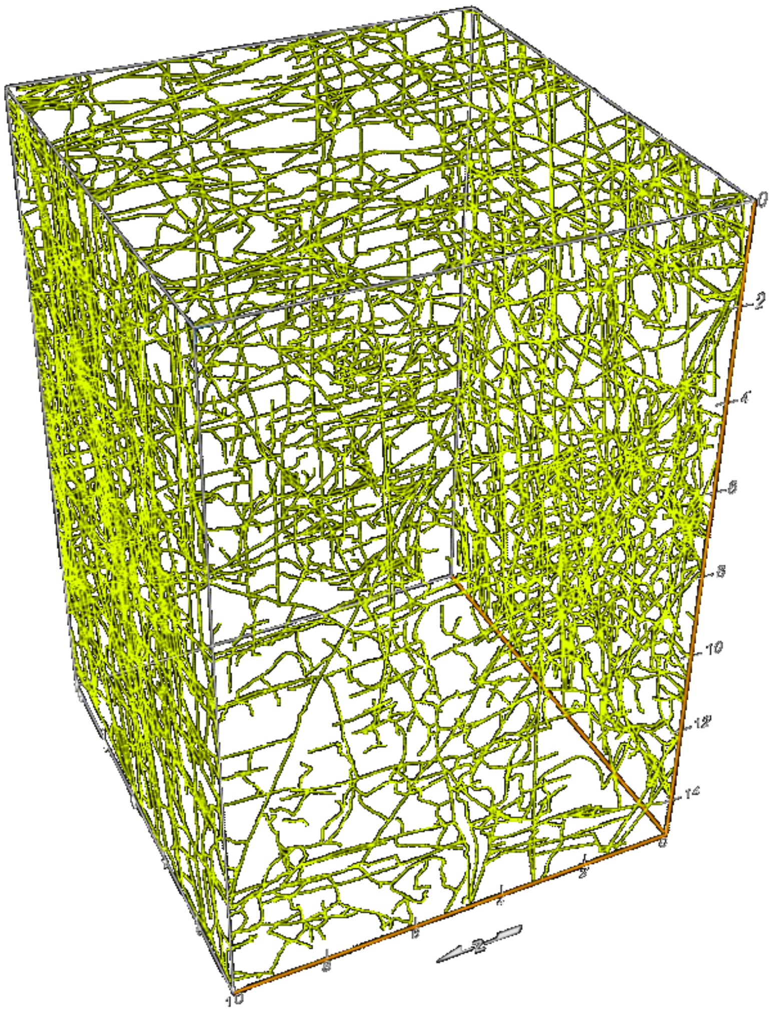
Background

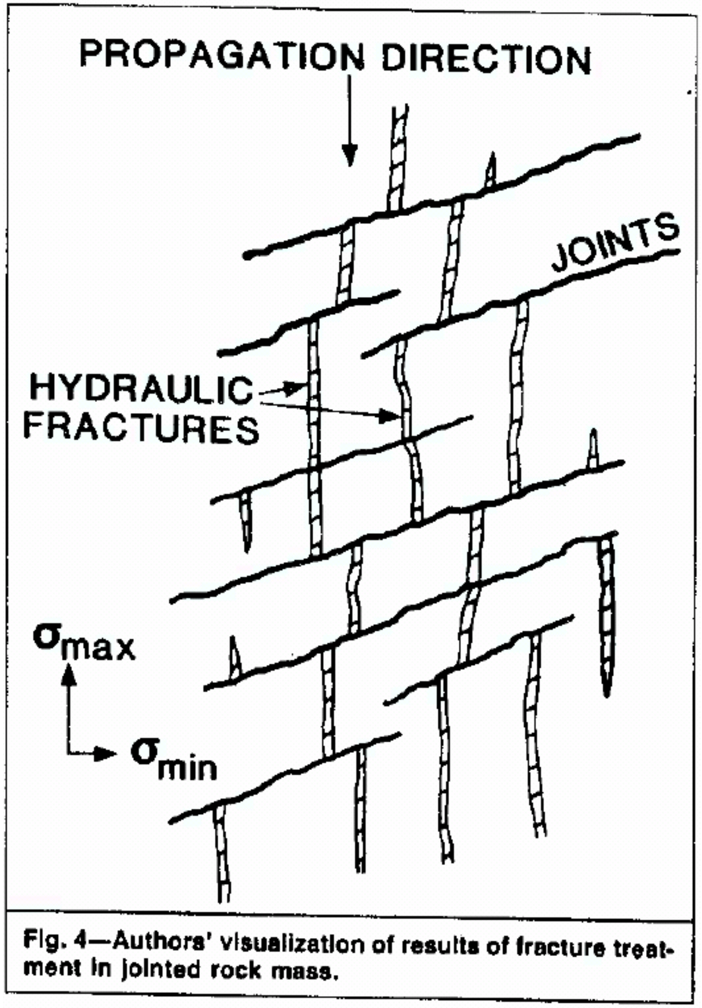
- Hydraulic fracturing is an effective method for enhancing permeability of geological formations.



How real fracture system looks like

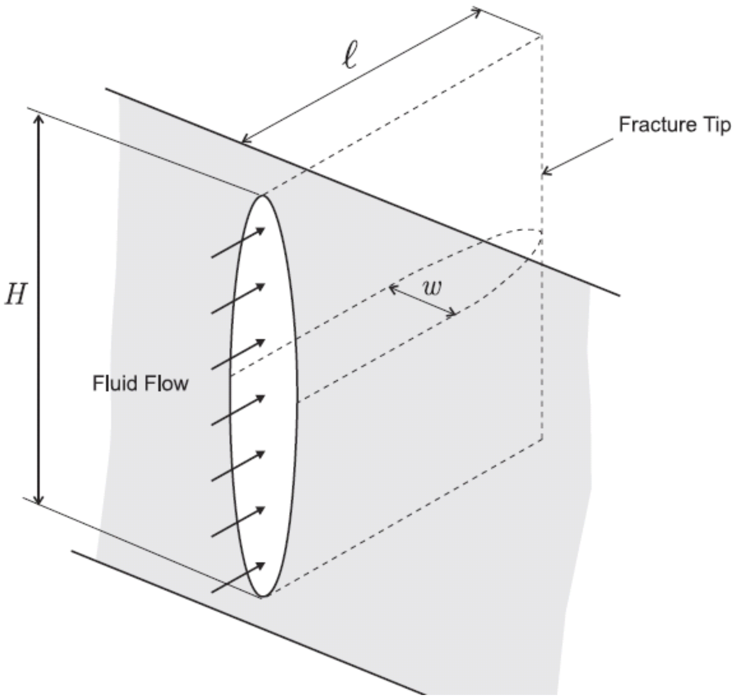


(Large Block Test, Yucca Mountain. Wagoner, 2000)

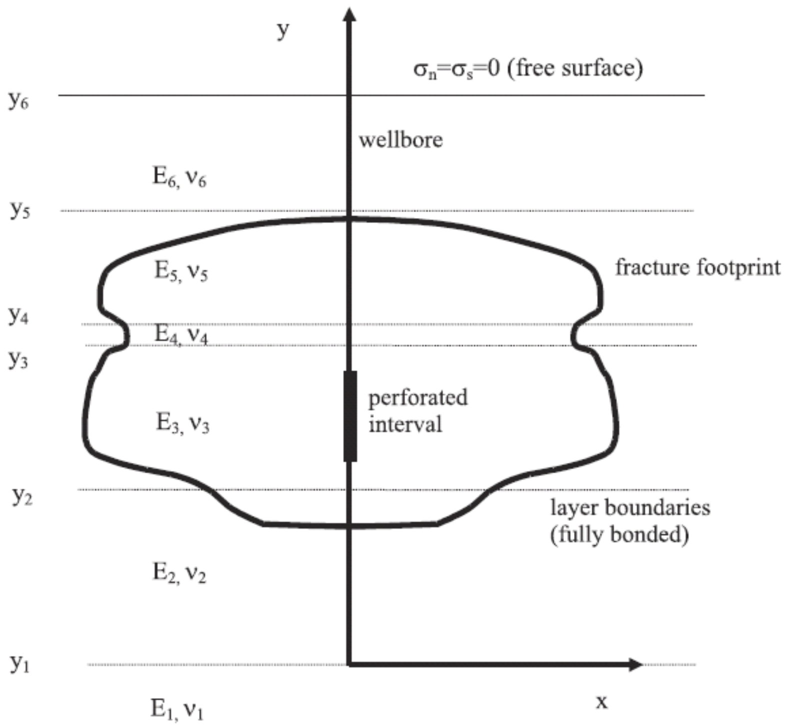


(Warpinski and Teufel, 1987)

State of the art



PKN model



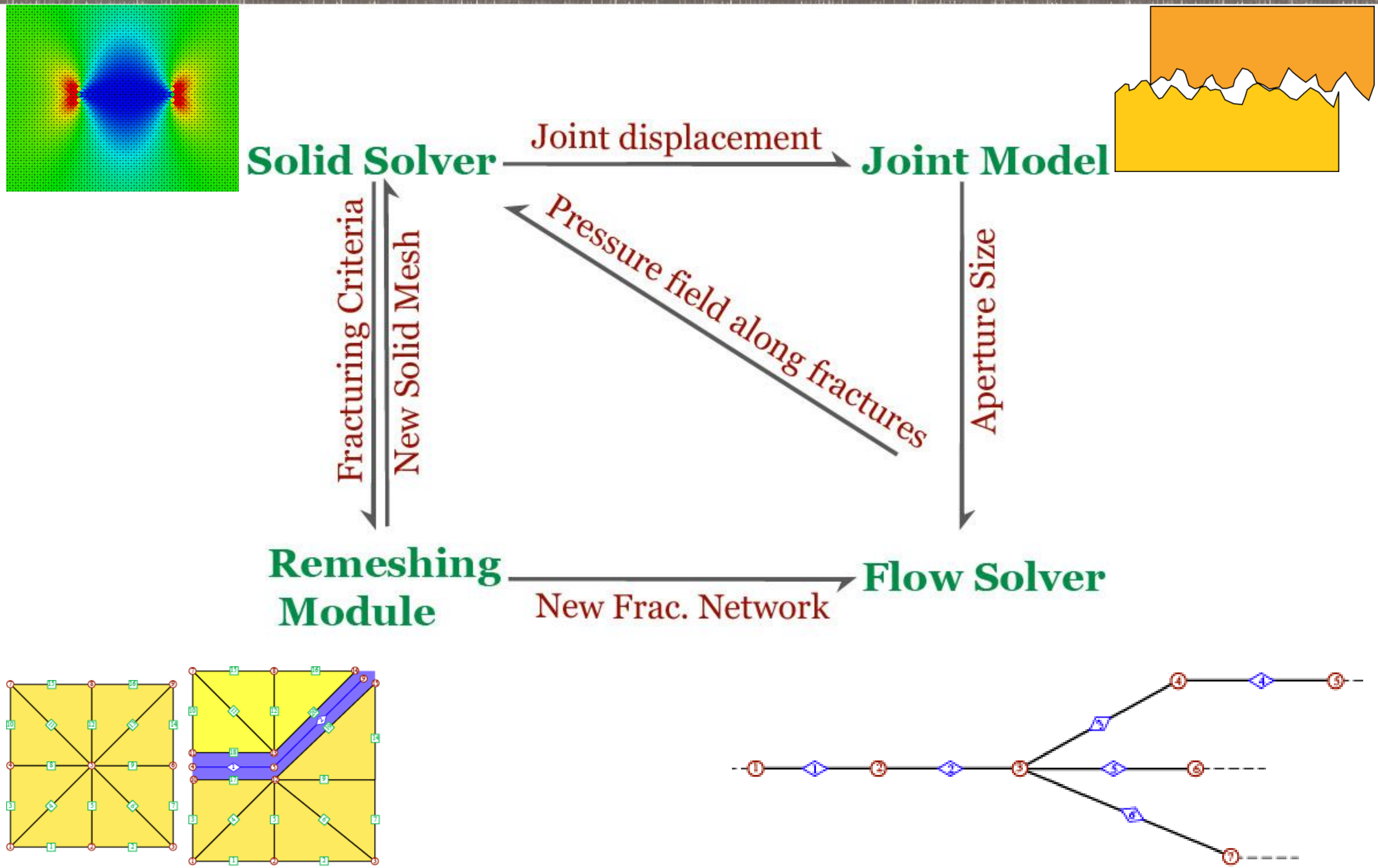
PL3D model

(Adachi et al. 2000)

What do we need to simulate hydrofrac?

- Physical processes need to be covered:
  - Fluid flow due to pressure gradient;
  - Rock deformation;
  - Variation of aperture width; and
  - Rock fracturing.

Modules and their coupling



Important Components

- Flow solver – Finite volume method

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

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

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

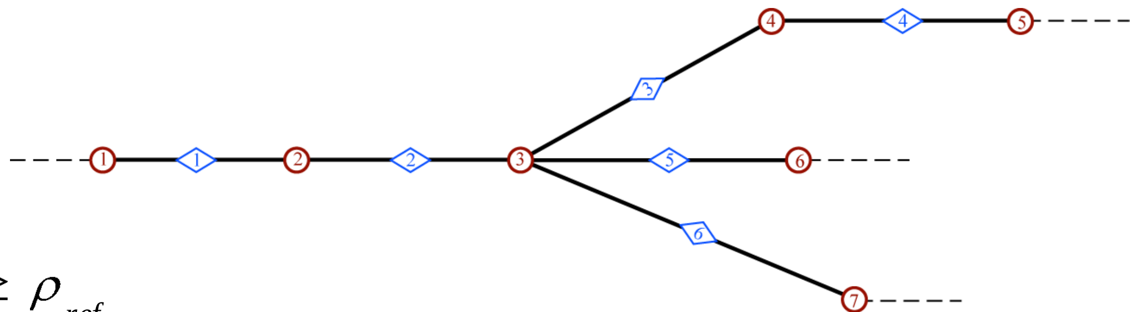
$$\dot{V}_{ij} = \kappa_{ij}(P_i - P_j)$$

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

Two mechanisms:

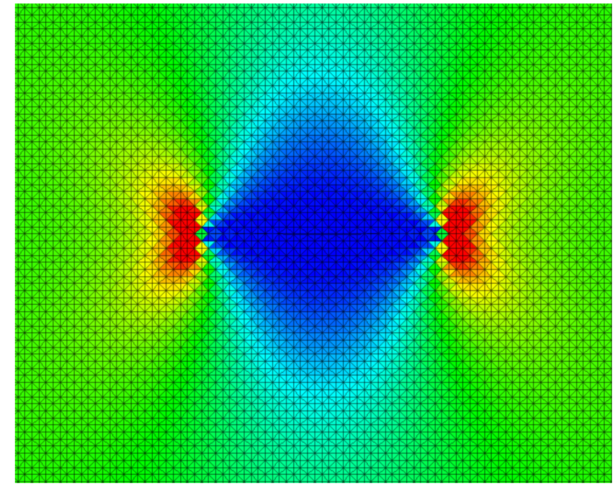
– Flow in fractures due to pressure gradient.

– Mass conservation with varying total fracture volume.

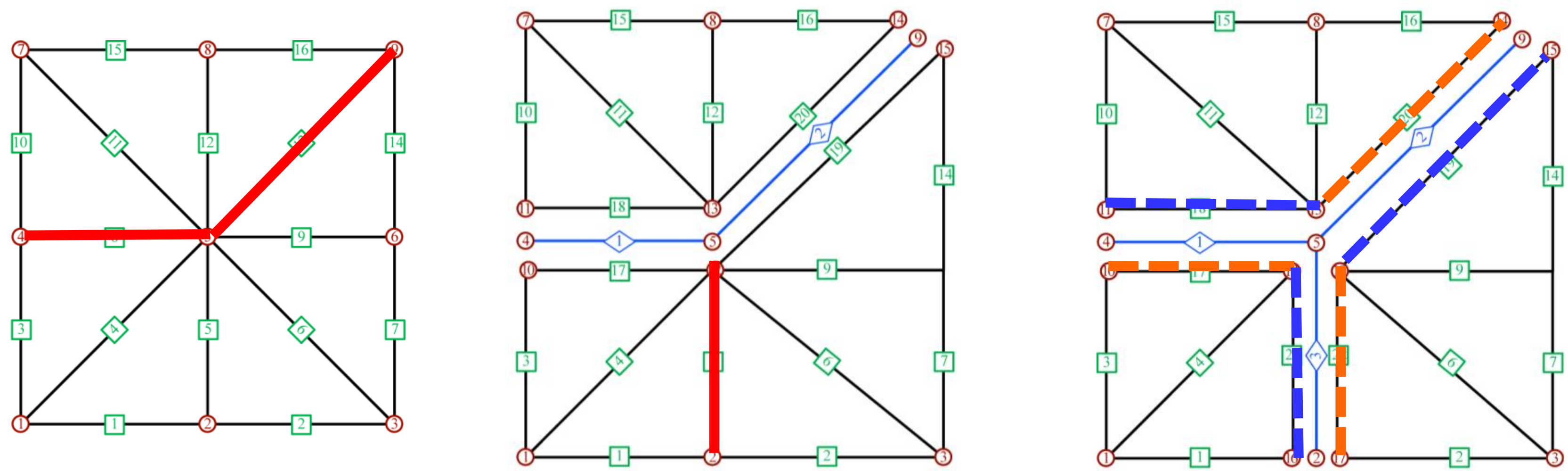


Important Components

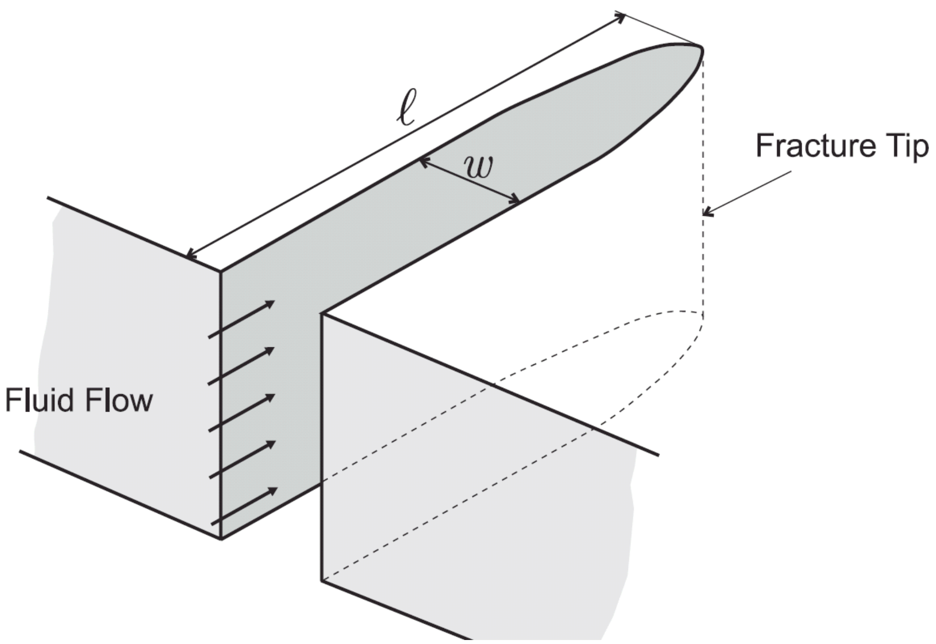
- Fracturing criterion
  - Estimates stress intensity factors using a generalized displacement correlation method
  - Handles mixed mode fractures

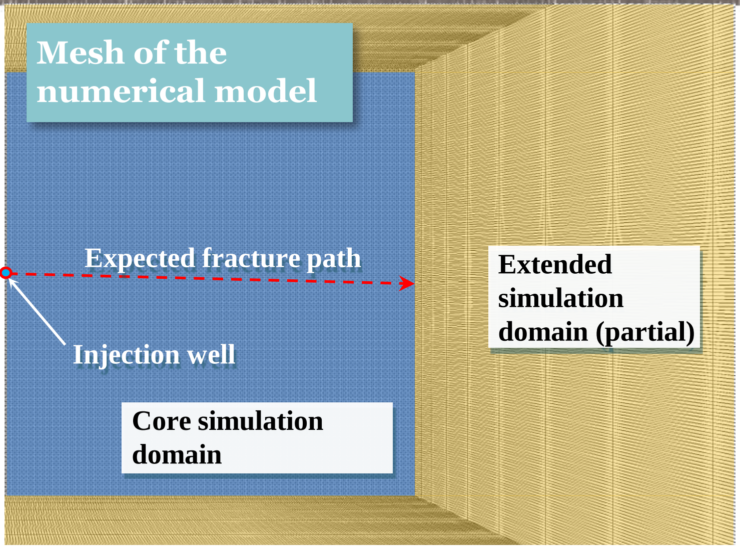


- Adaptive remeshing

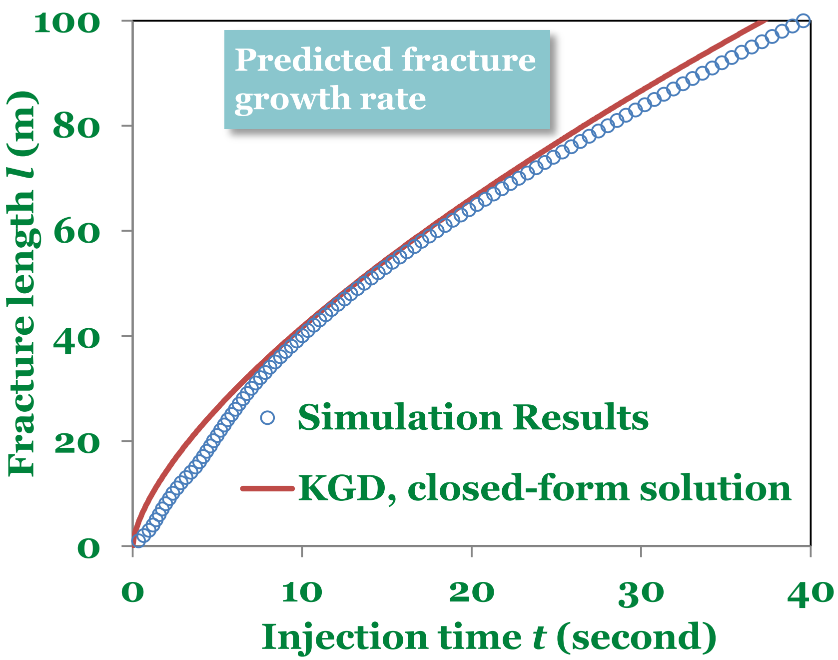


Model verification: classical KGD model

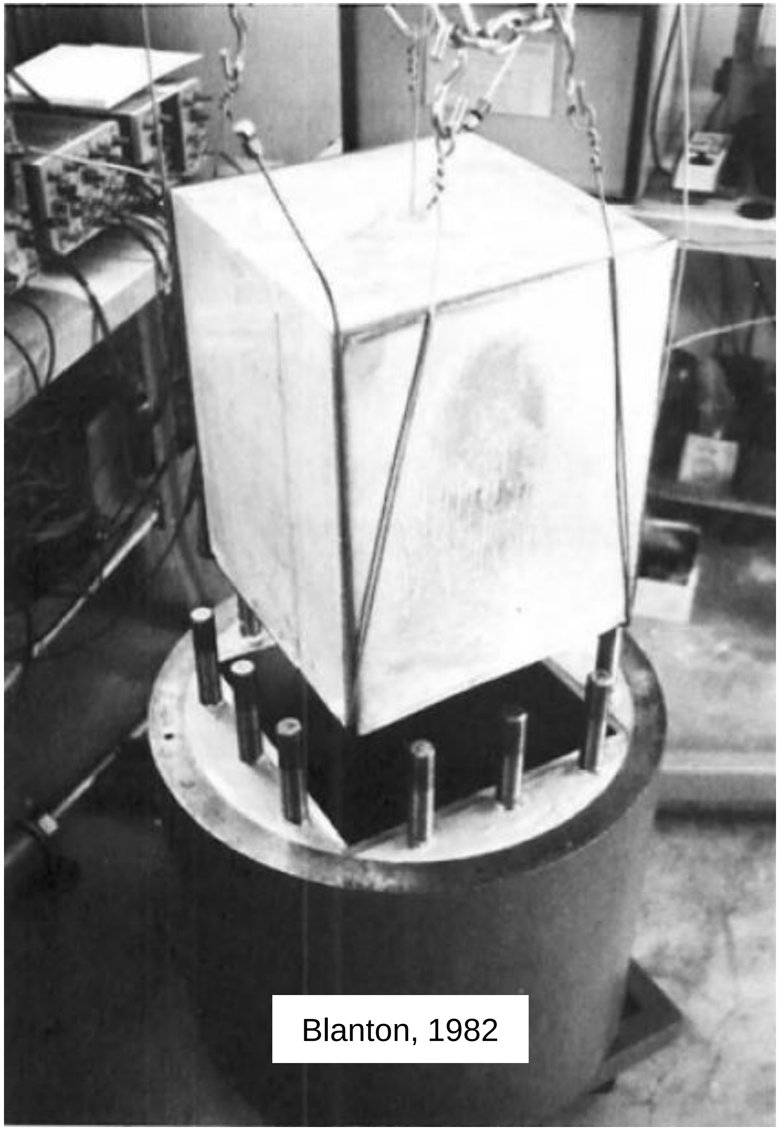




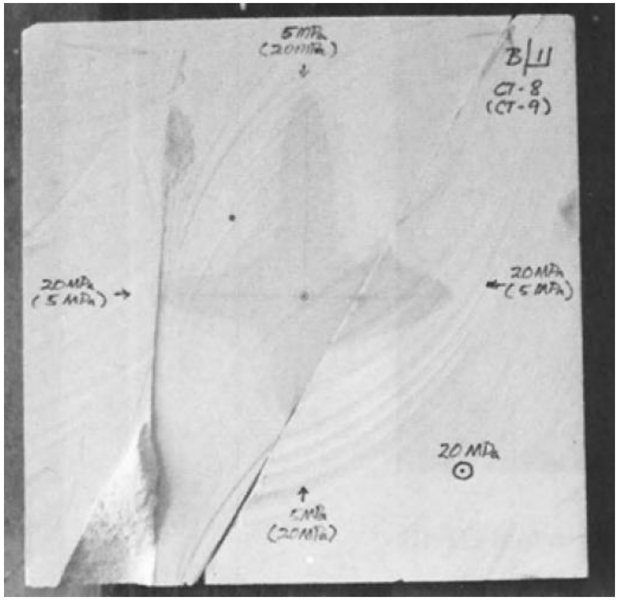
$$l(t) = 0.679\left[\frac{Gq_0^3}{\mu(1-\nu)}\right]^{\frac{1}{6}} t^{\frac{2}{3}}$$

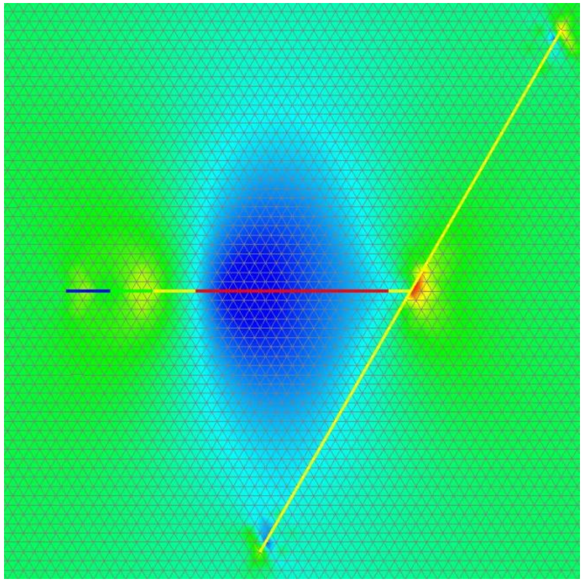


Model validation: lab test results

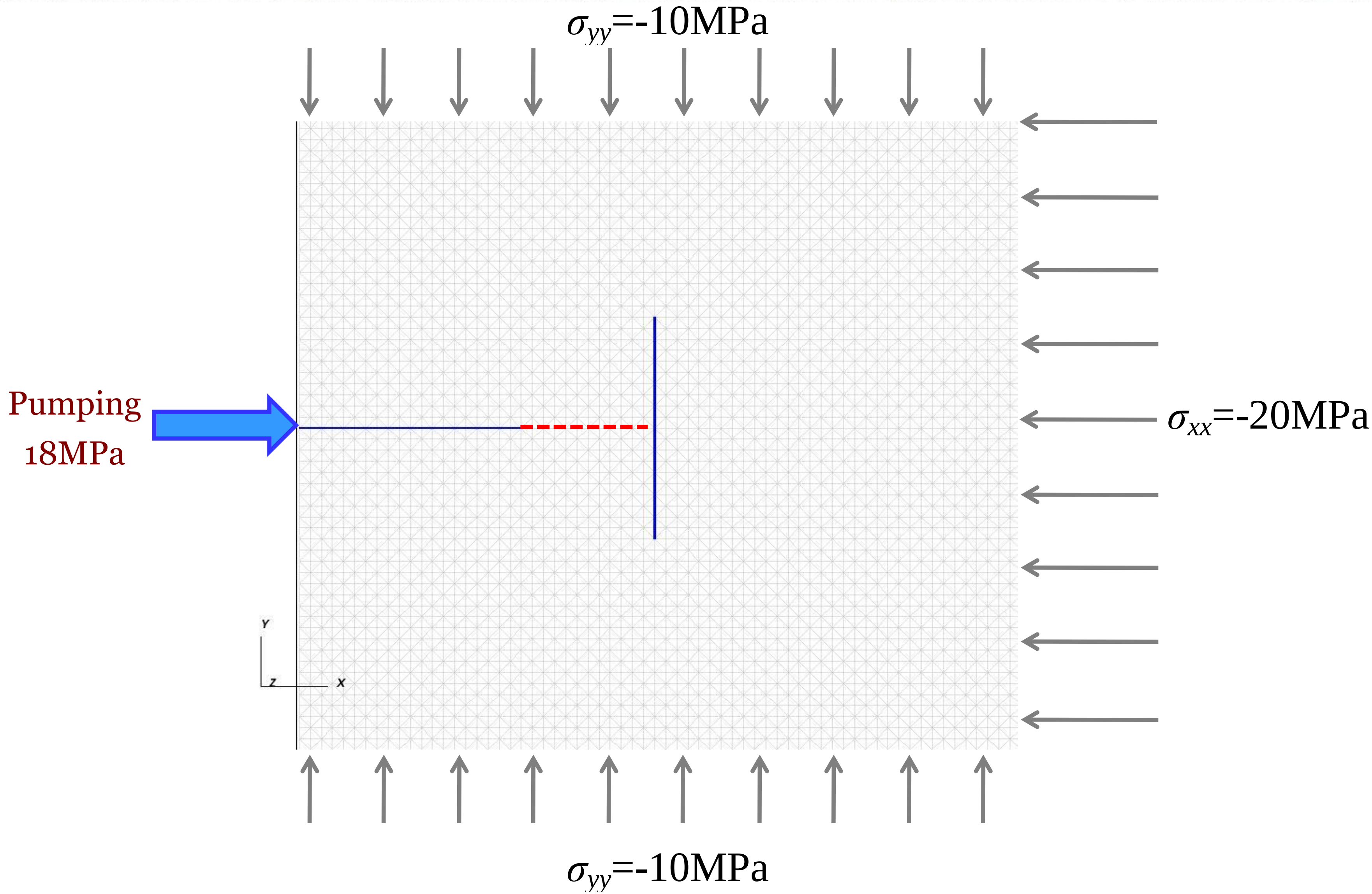


Blanton, 1982





Interaction Between Propagating and Existing Fractures



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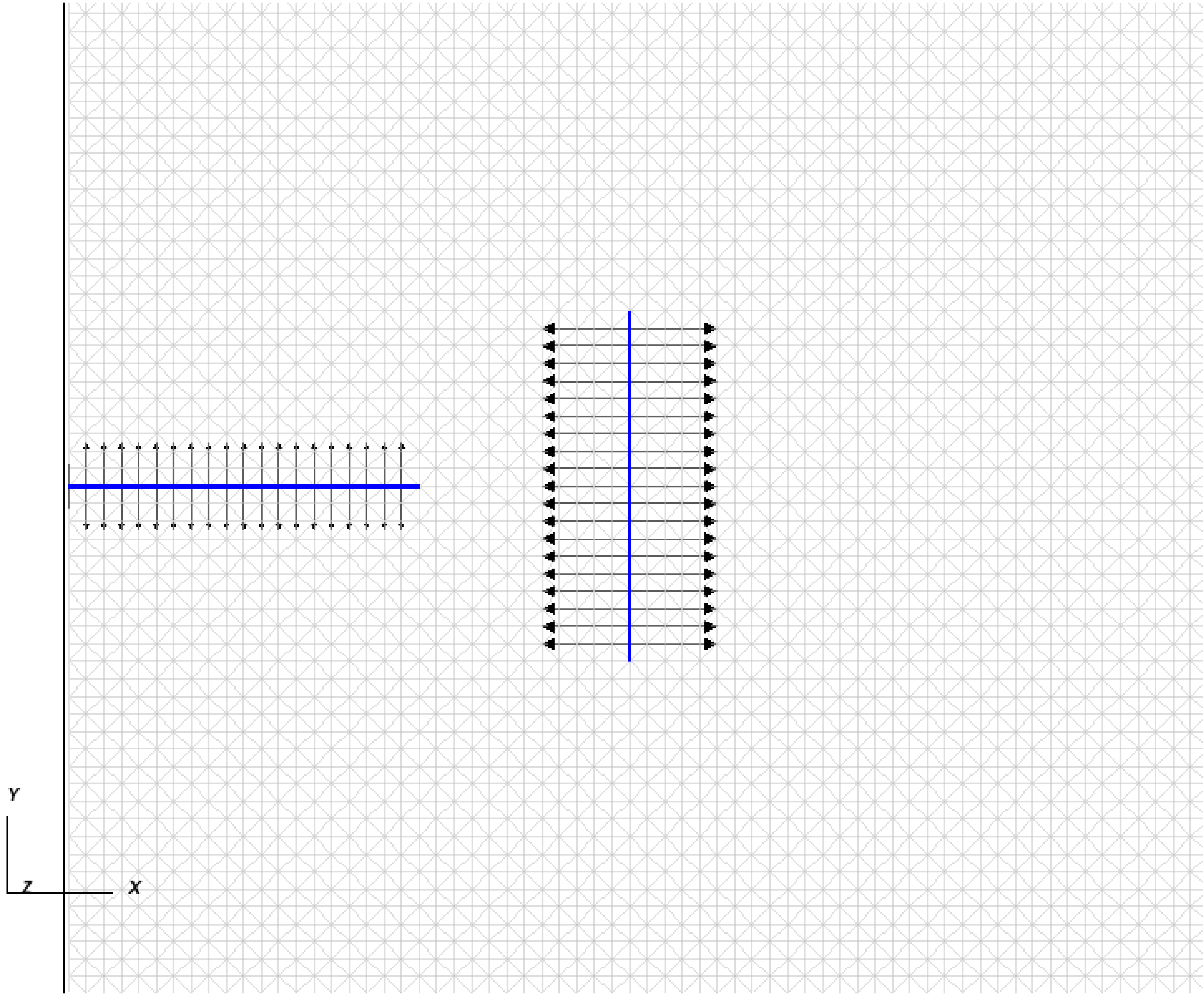

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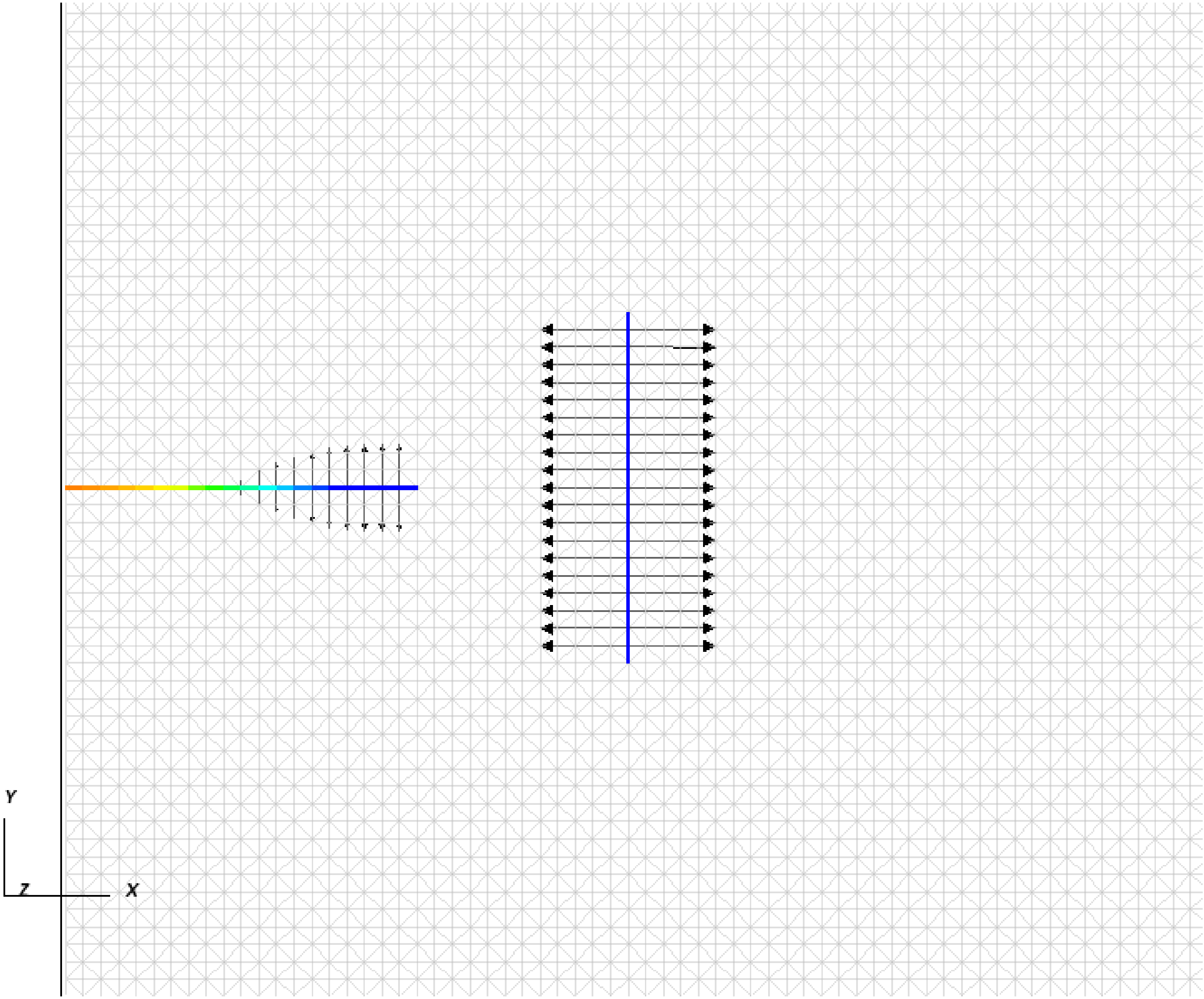

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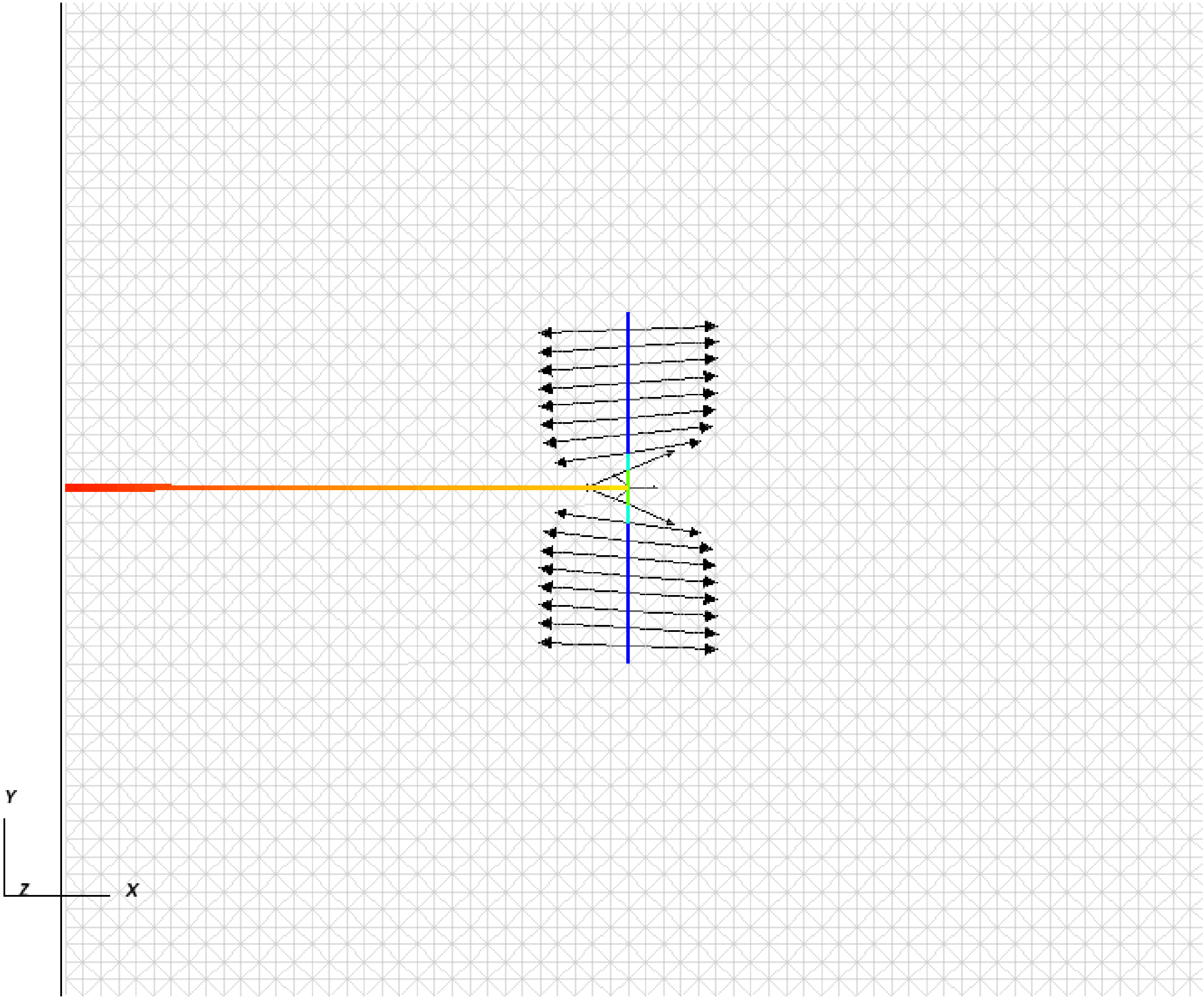

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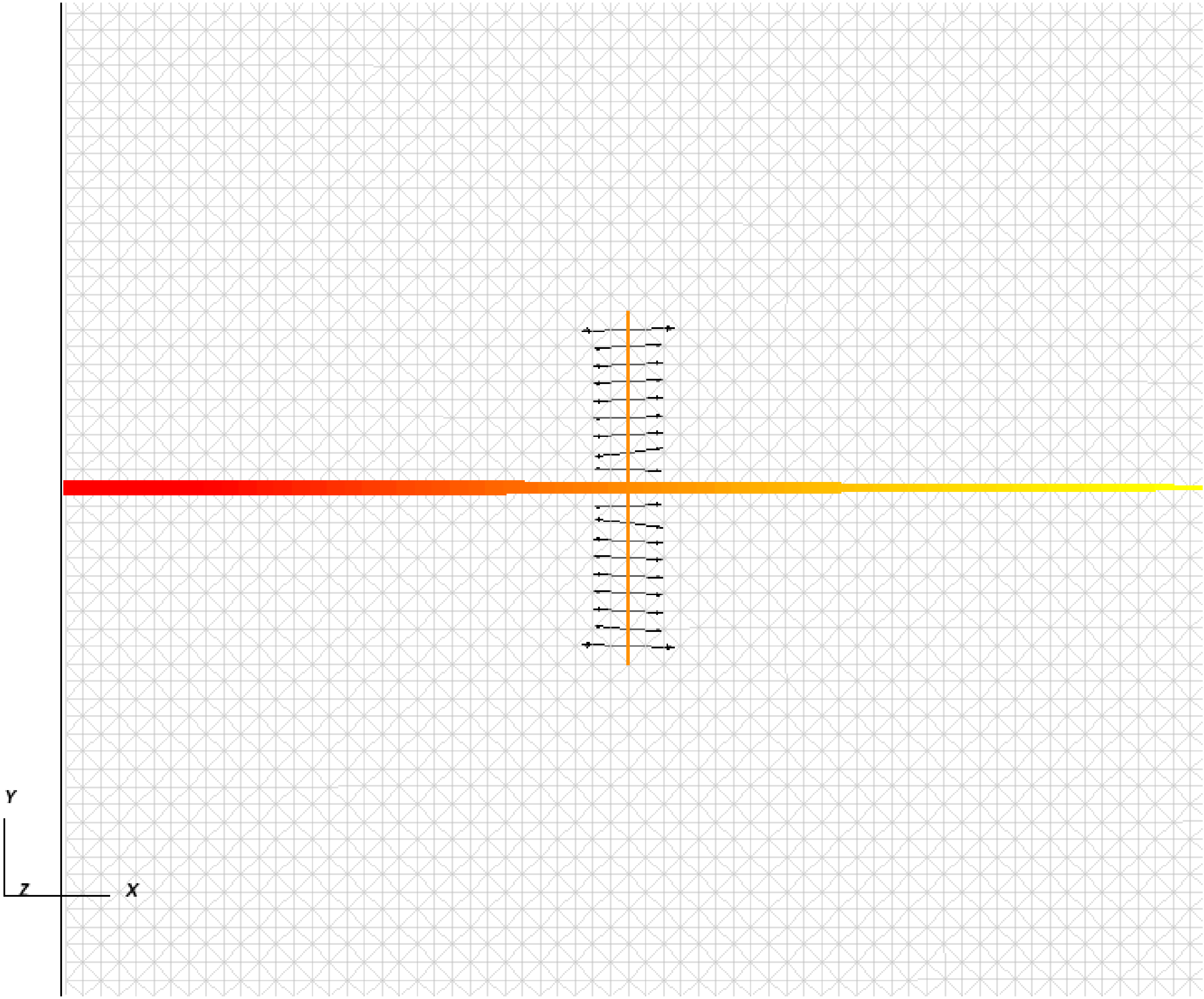

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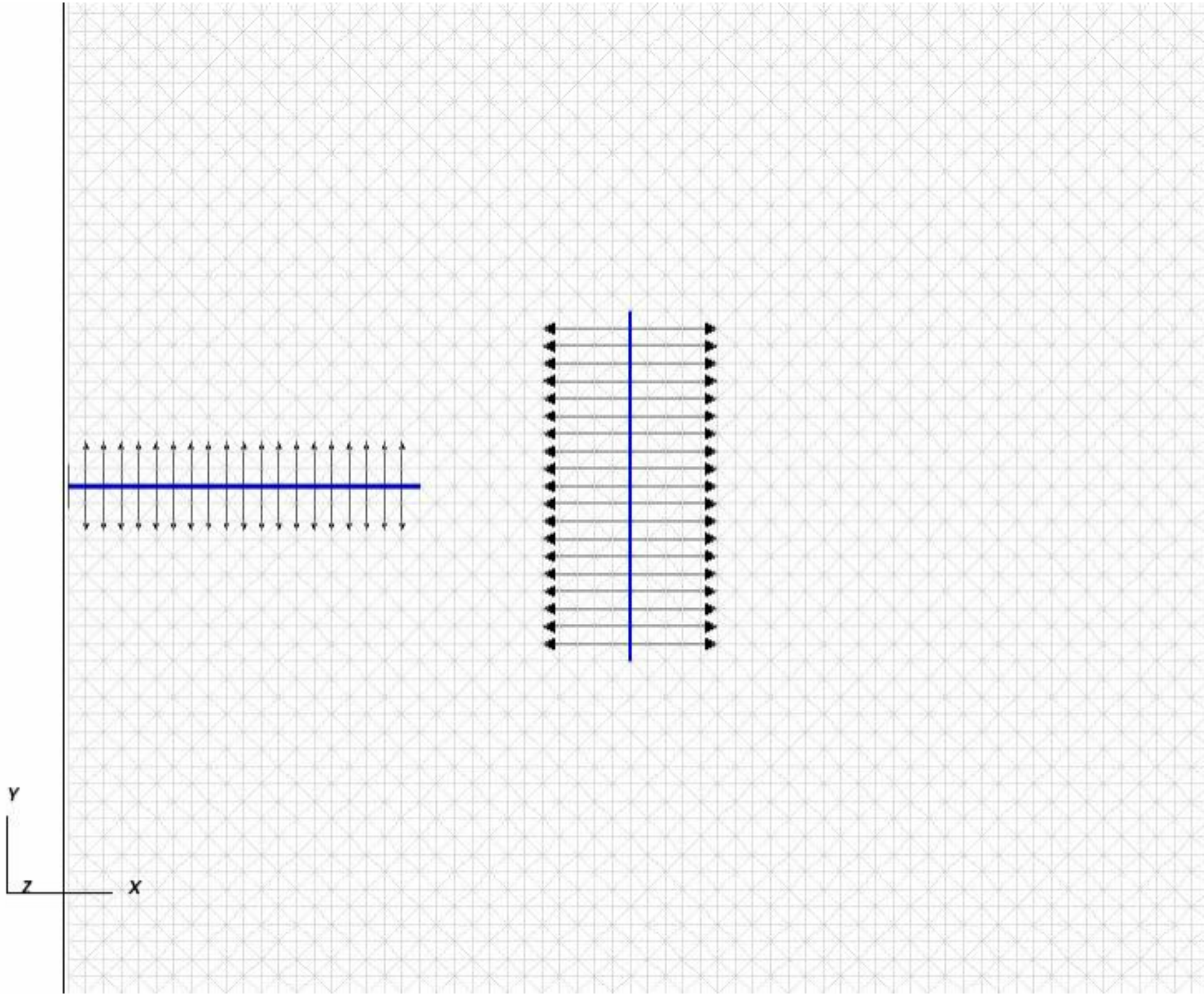

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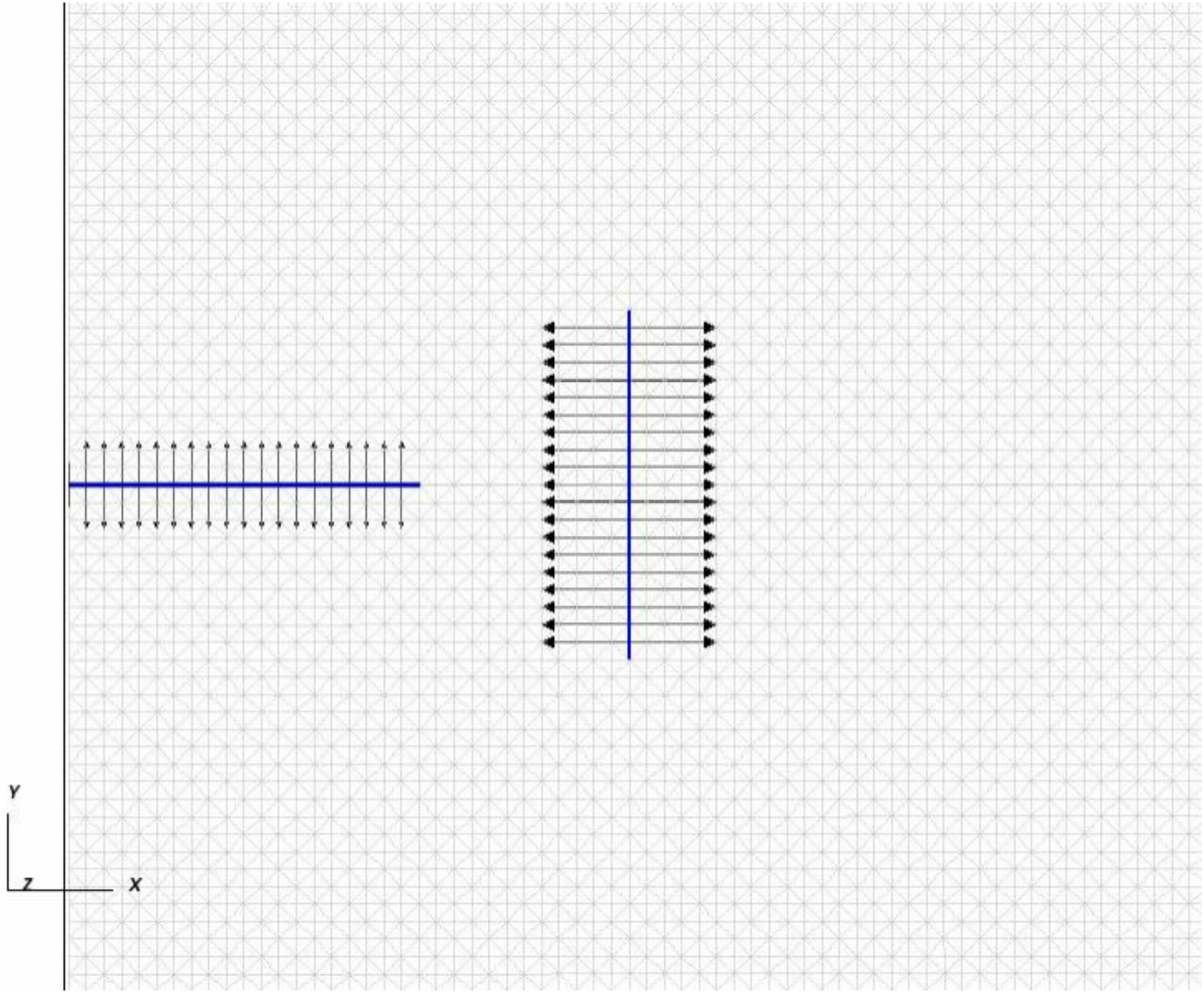
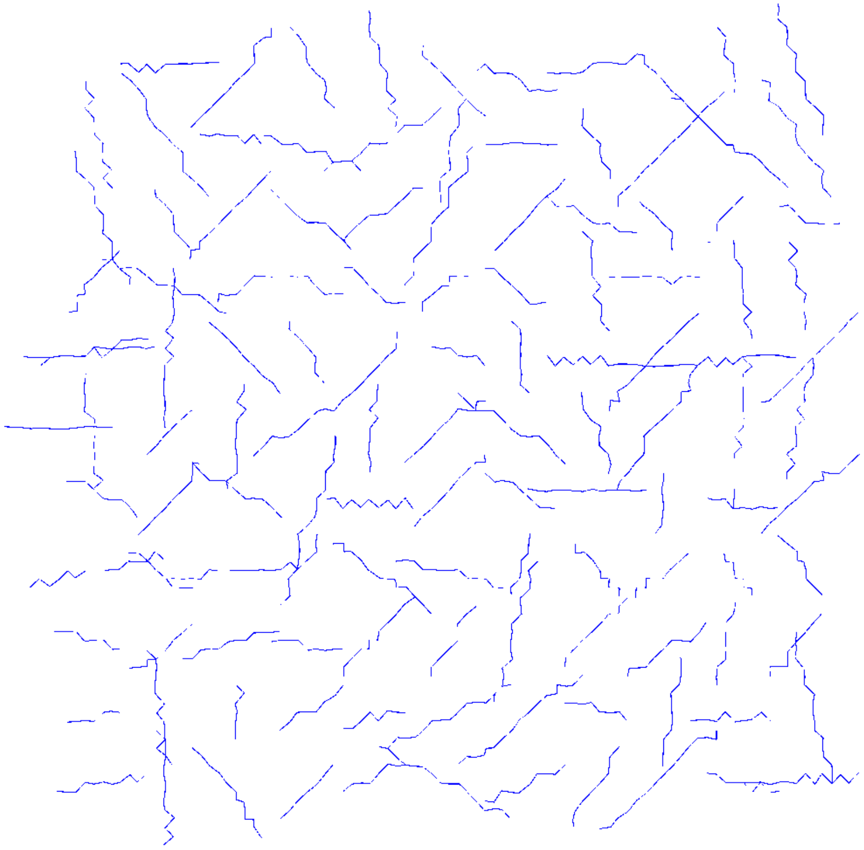
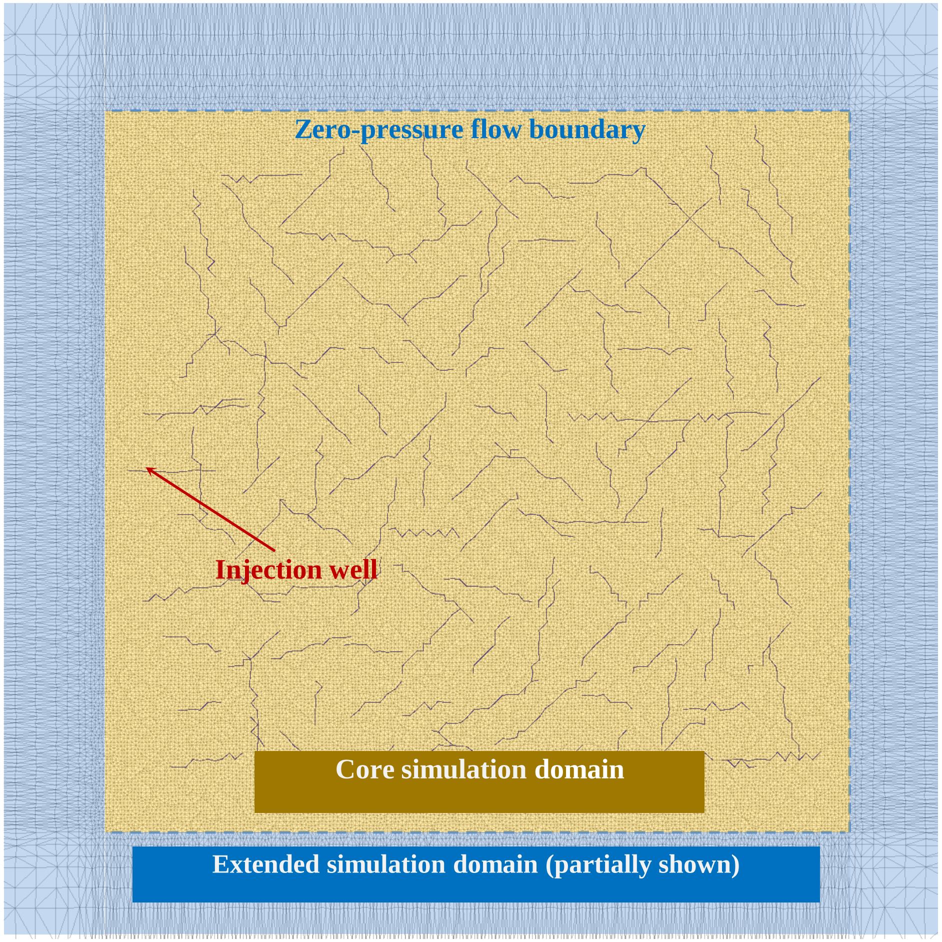


Application to more complex fracture networks





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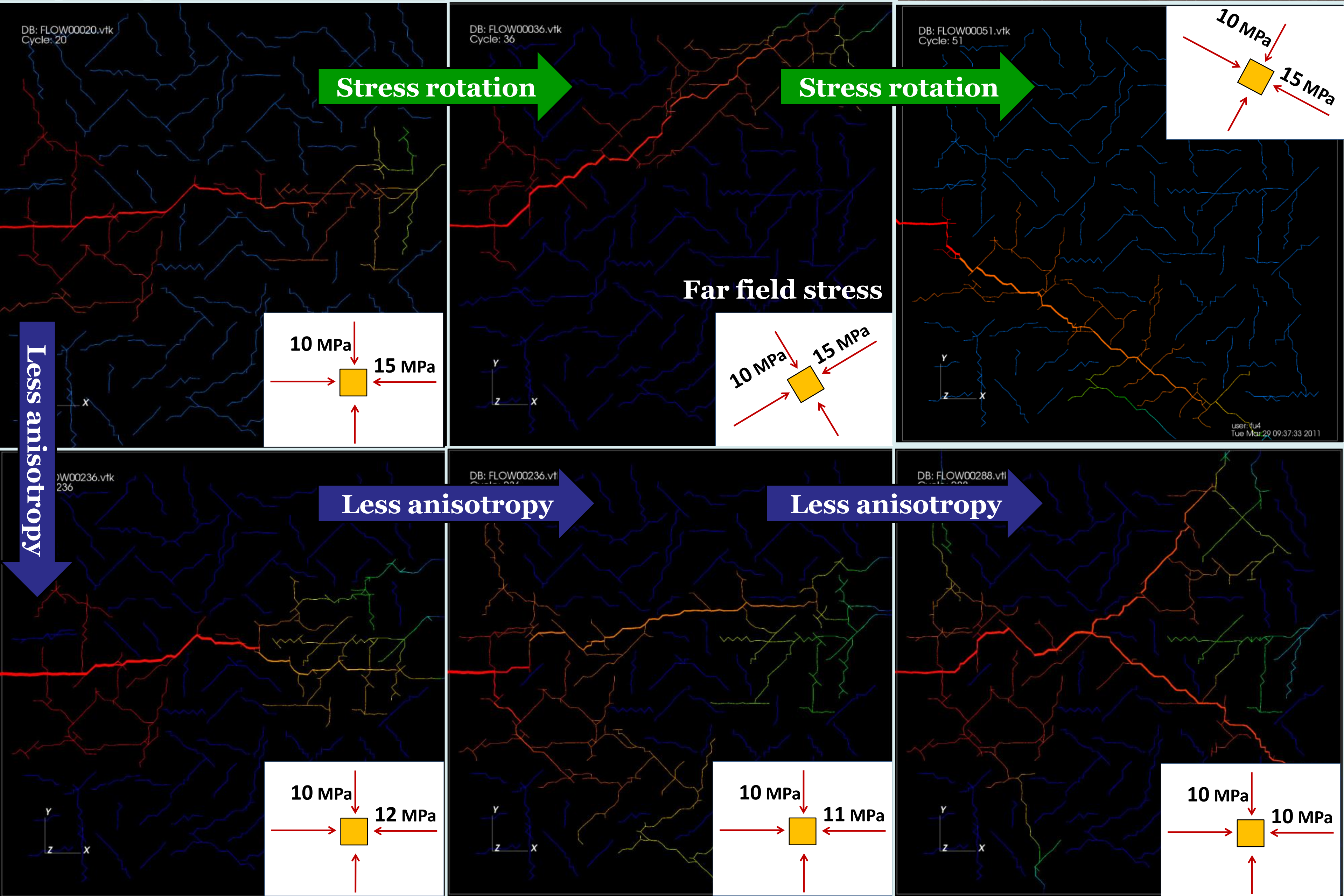

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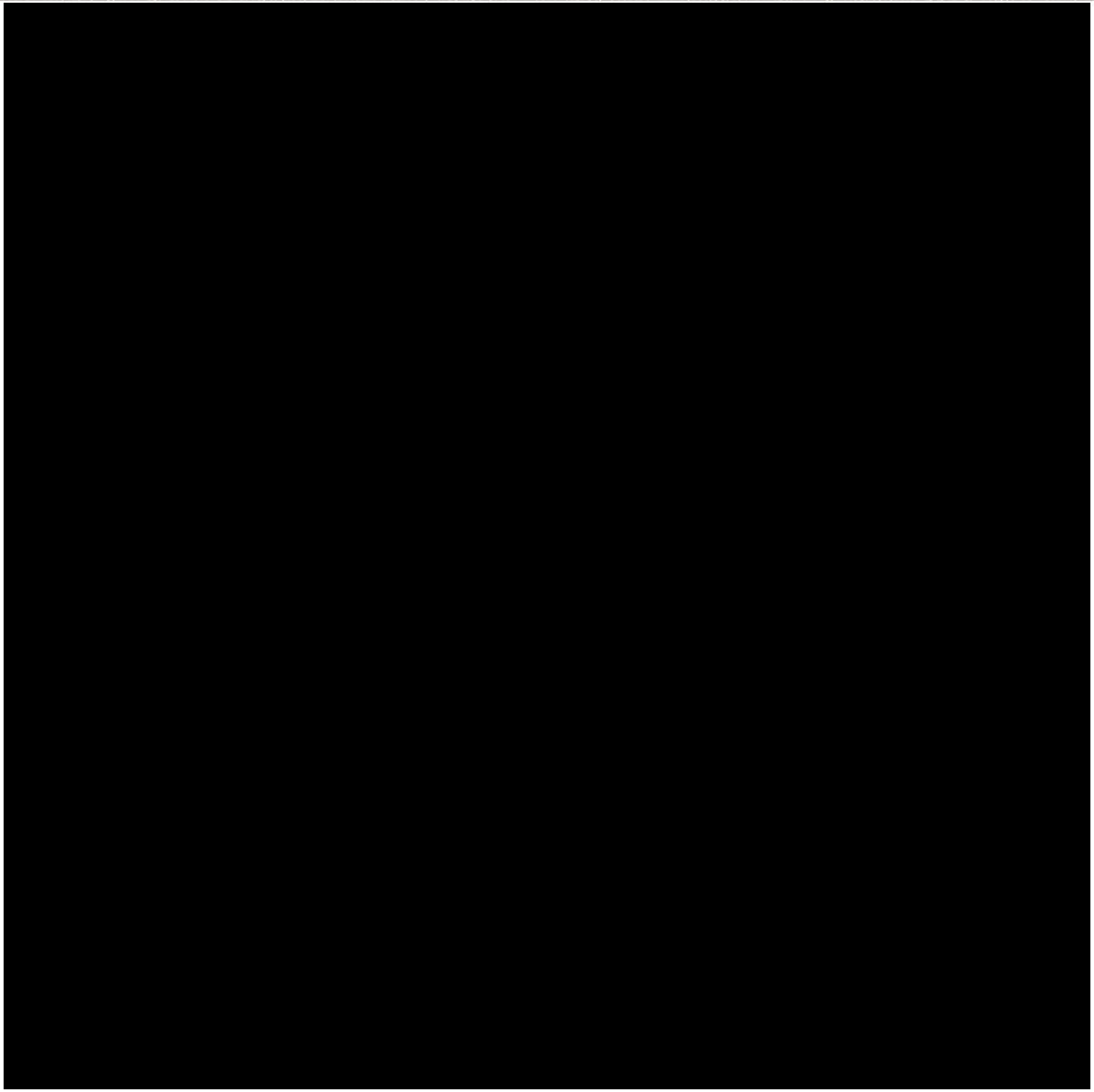

Concluding Remarks

- 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.
  - Induced seismicity naturally emerges in the simulation.
- Further development, enhancement, and validation

Acknowledgements

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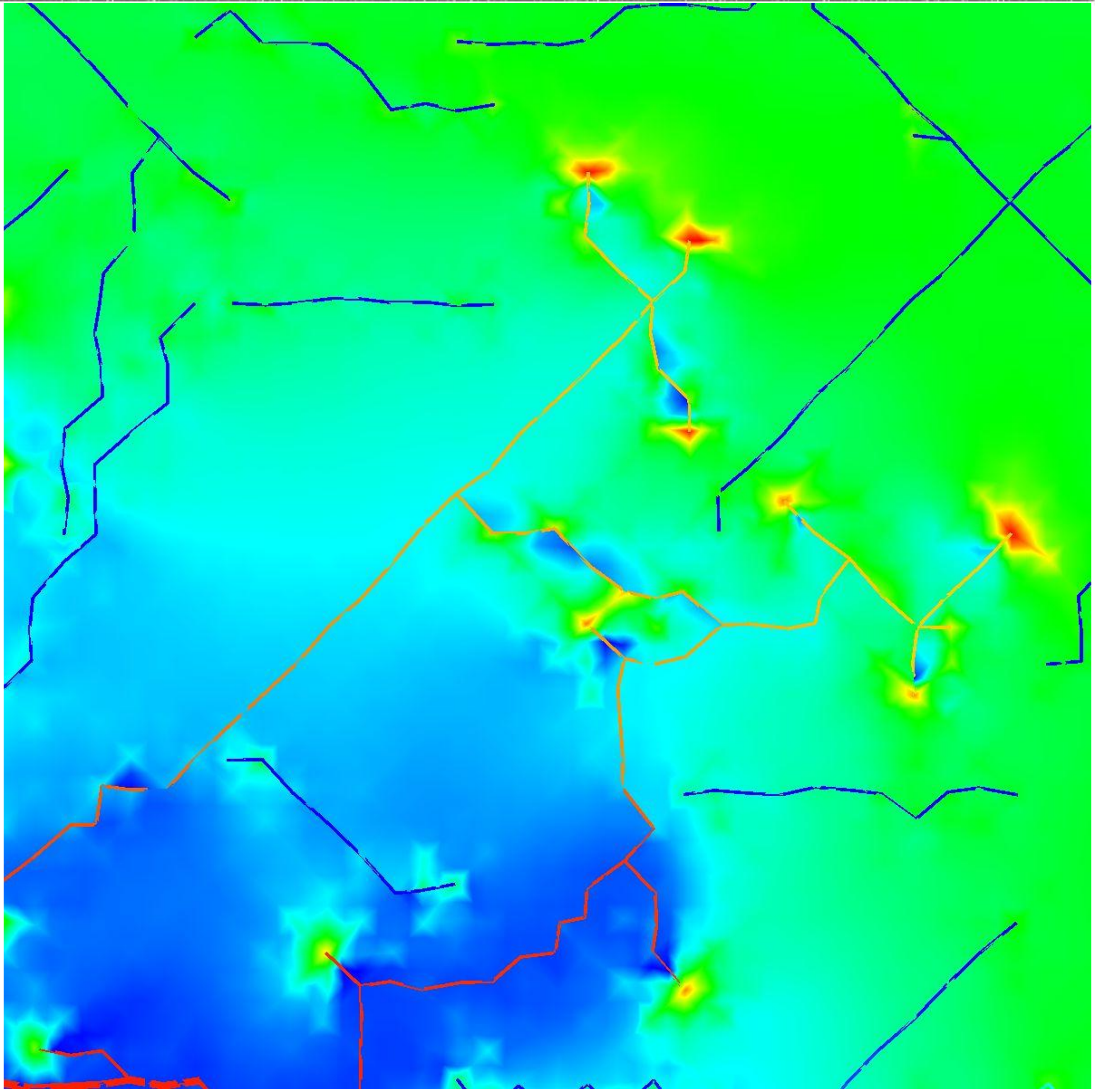
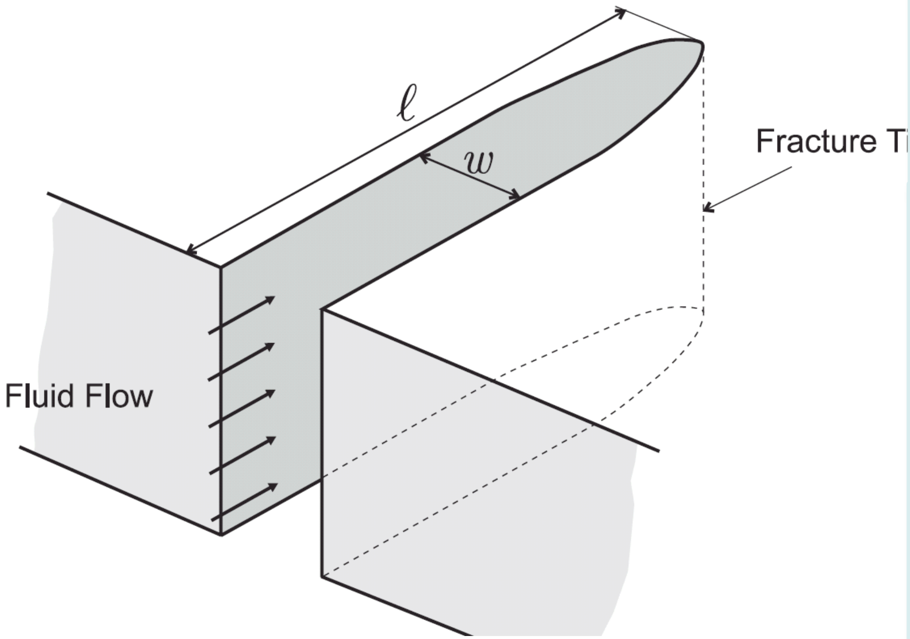


Model verification



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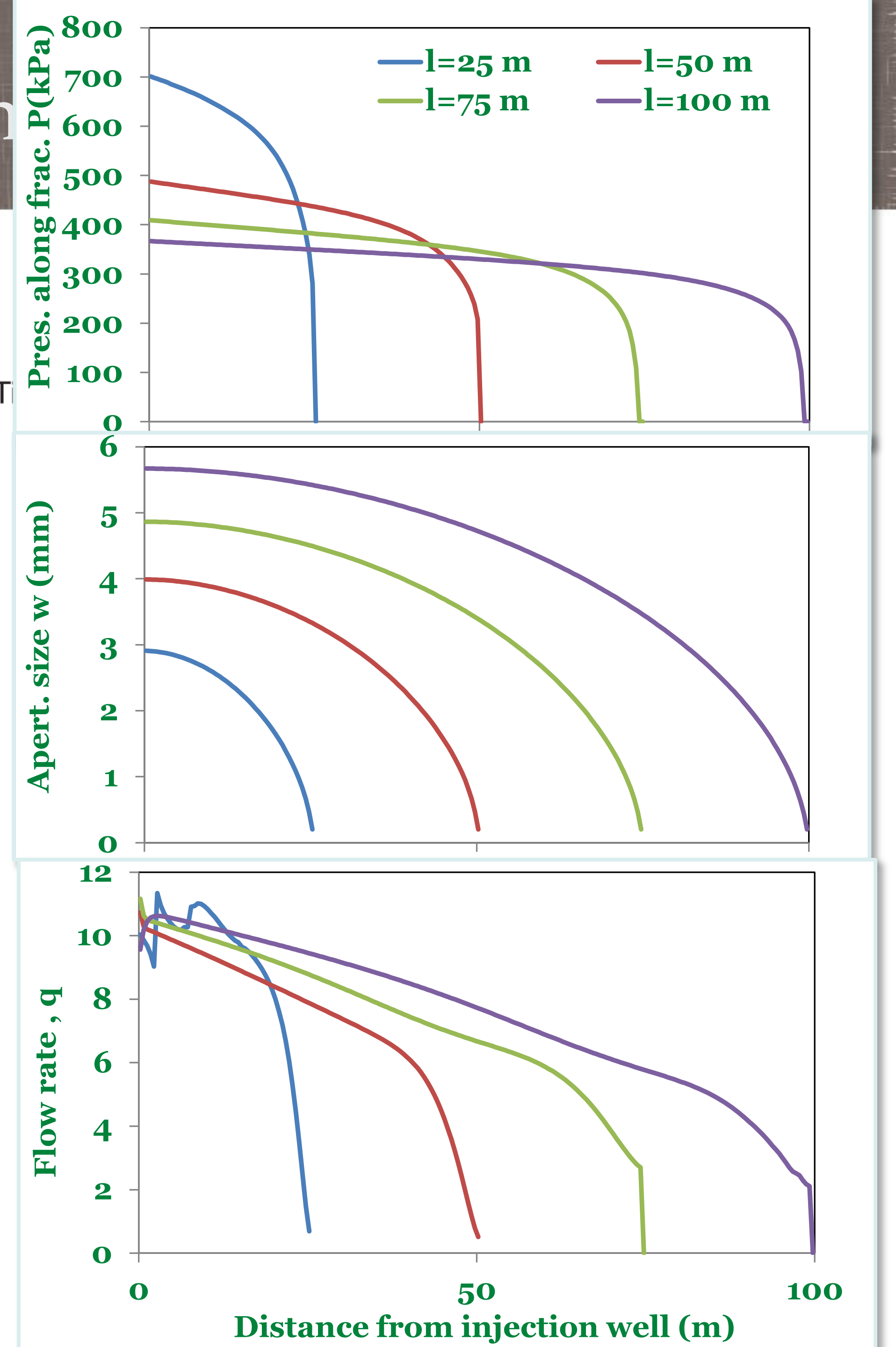

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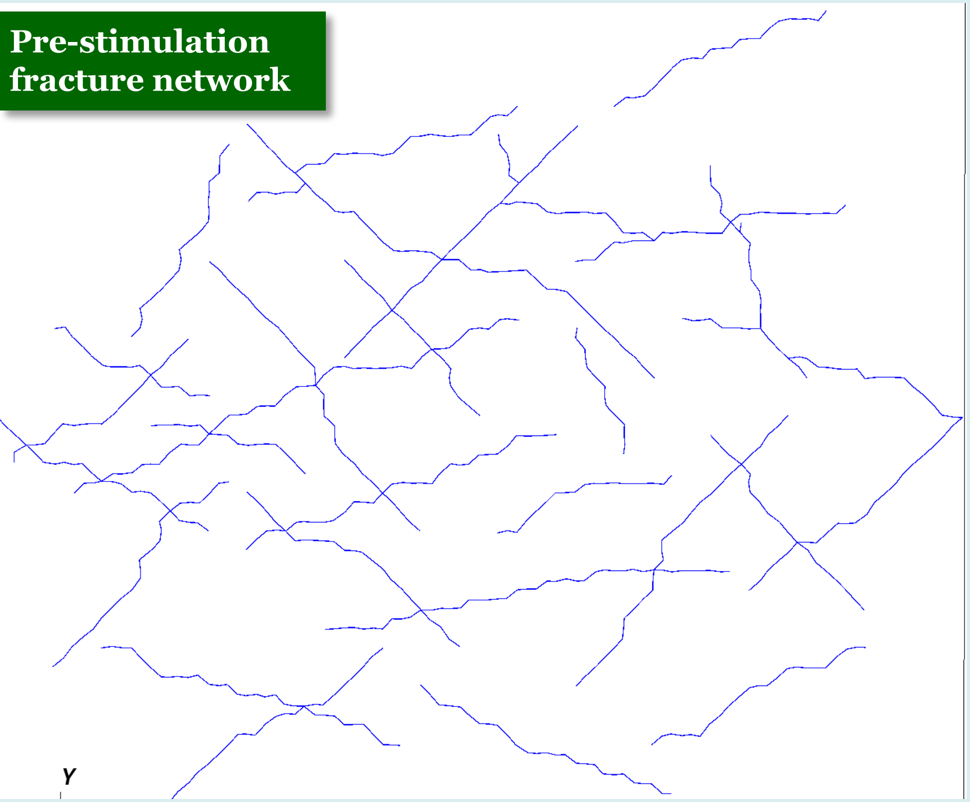

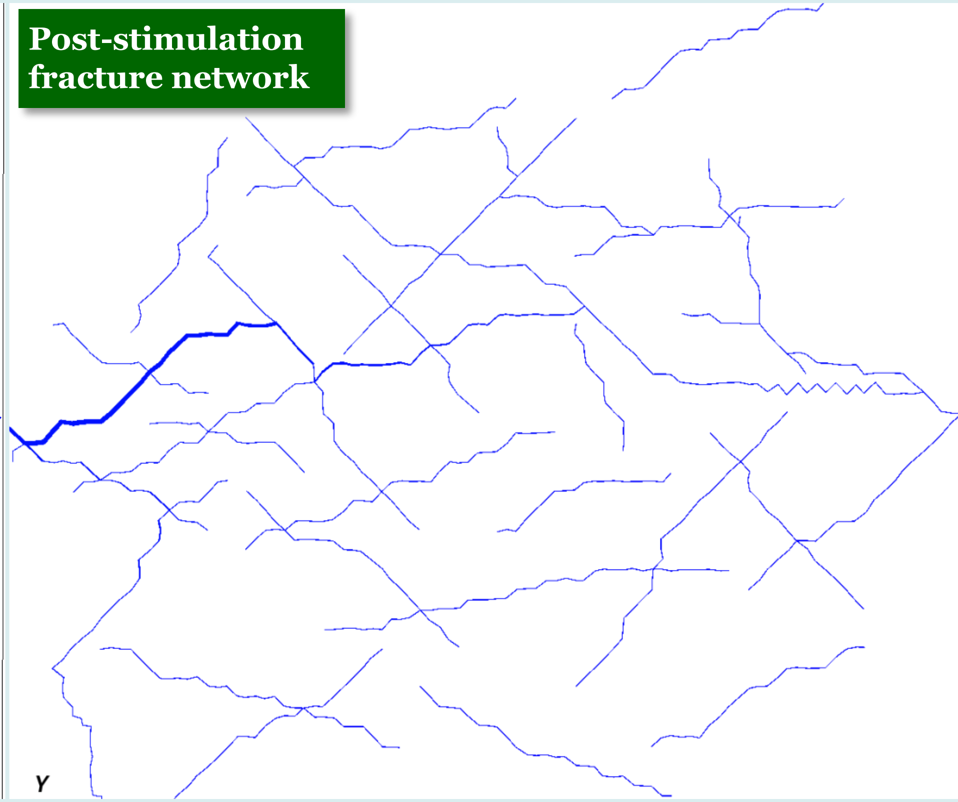

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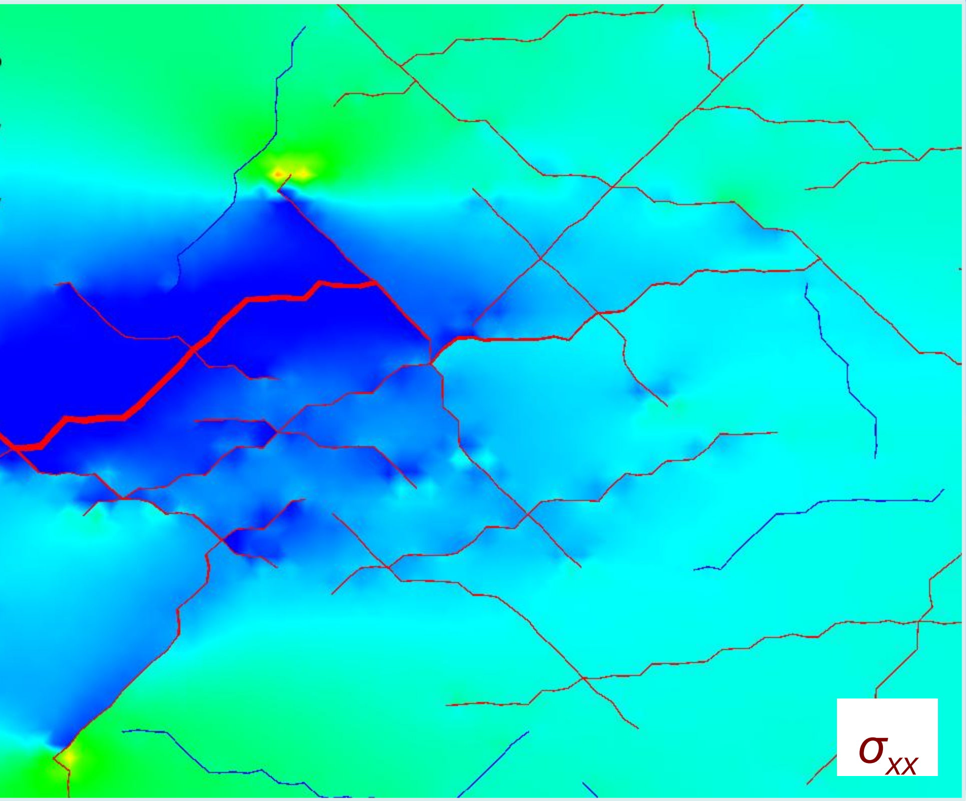

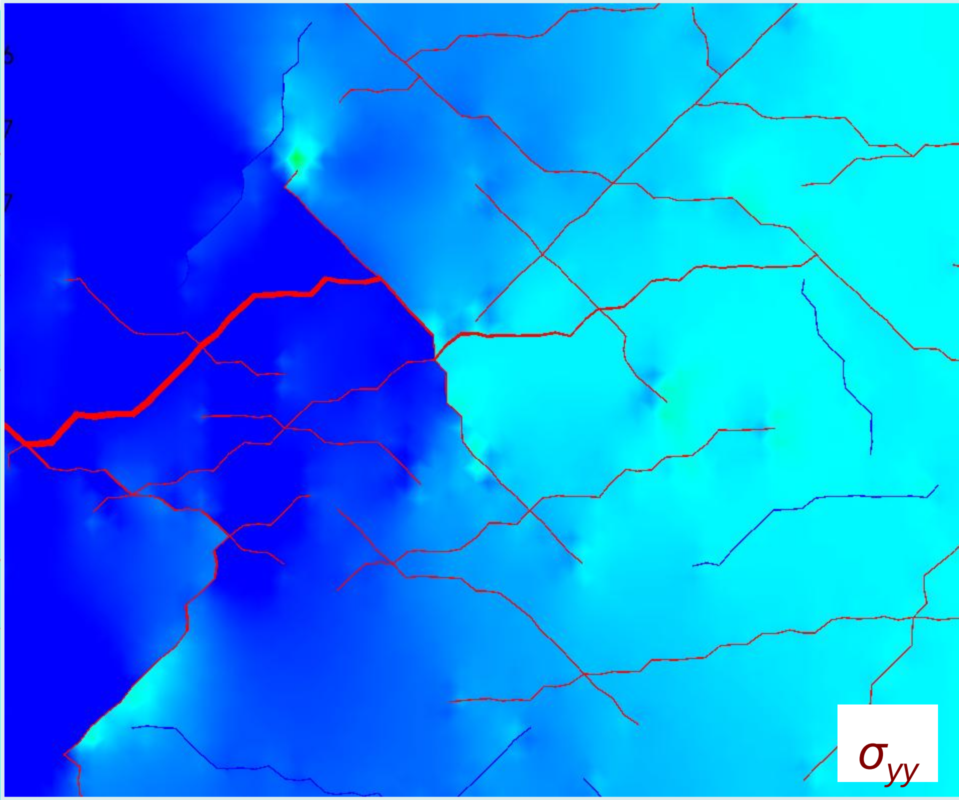

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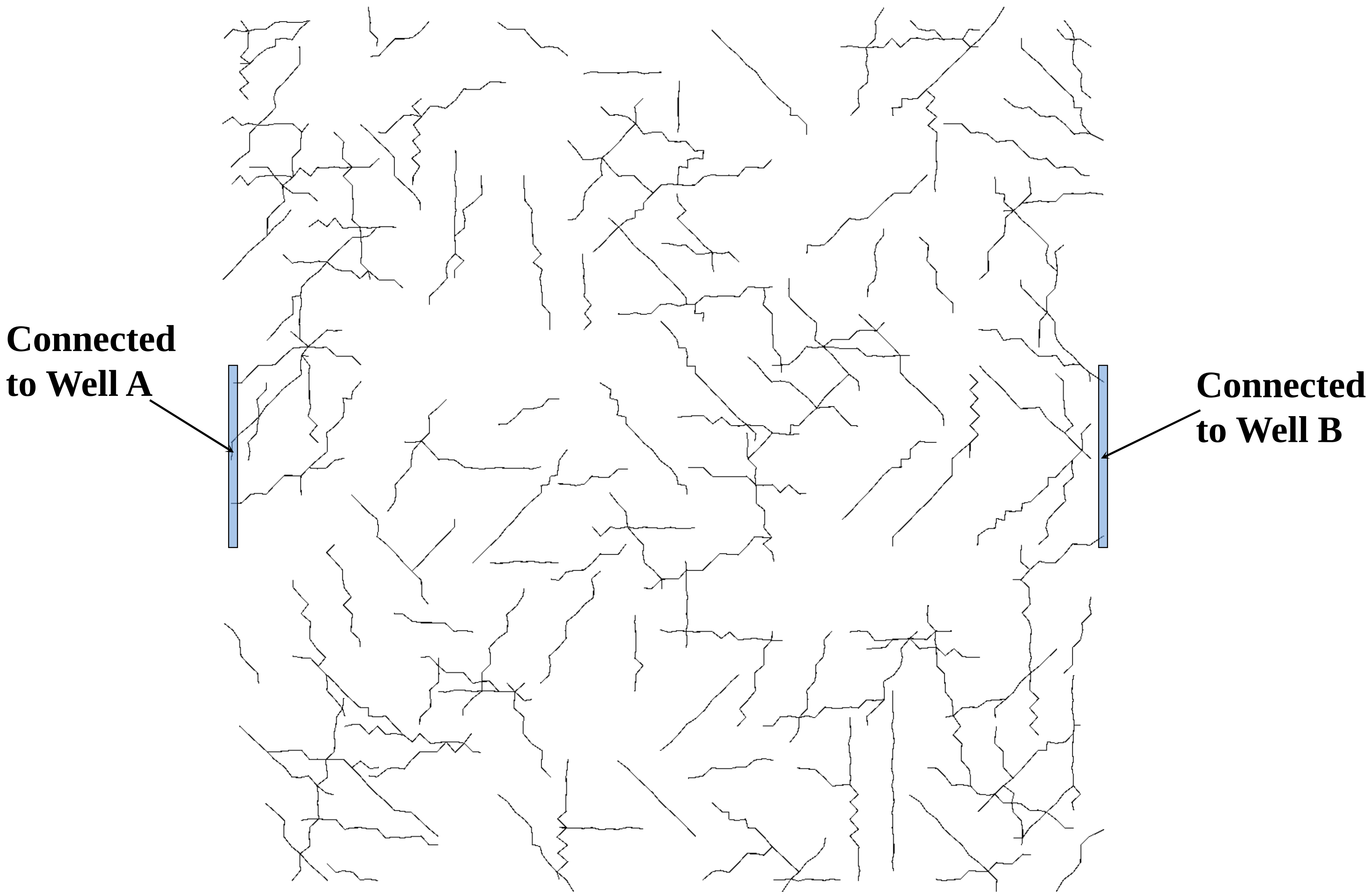
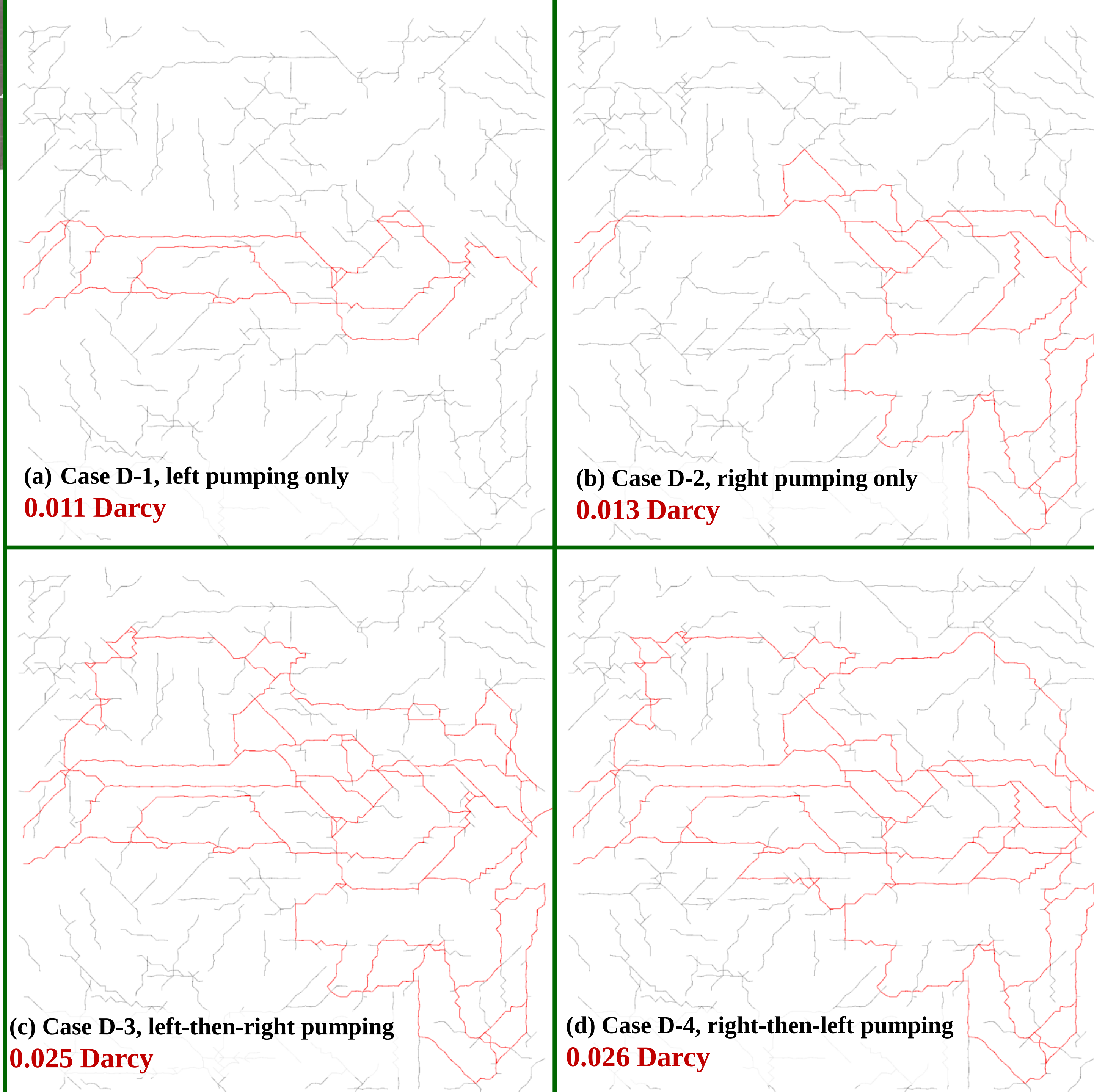
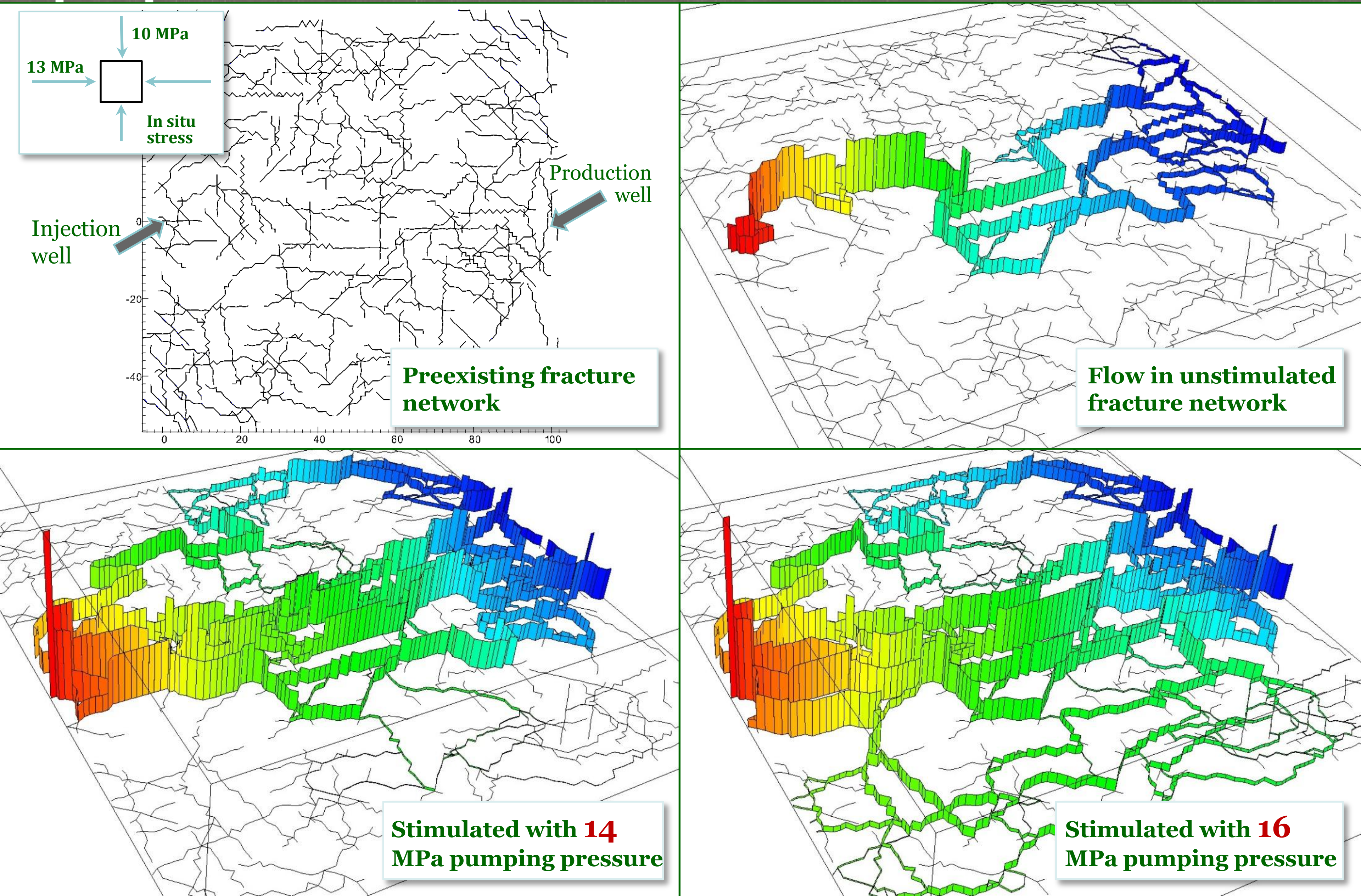



(a) Case D-1, left pumping only
0.011 Darcy
(b) Case D-2, right pumping only
0.013 Darcy
(c) Case D-3, left-then-right pumping
0.025 Darcy
(d) Case D-4, right-then-left pumping
0.026 Darcy

Application to more complex fracture networks



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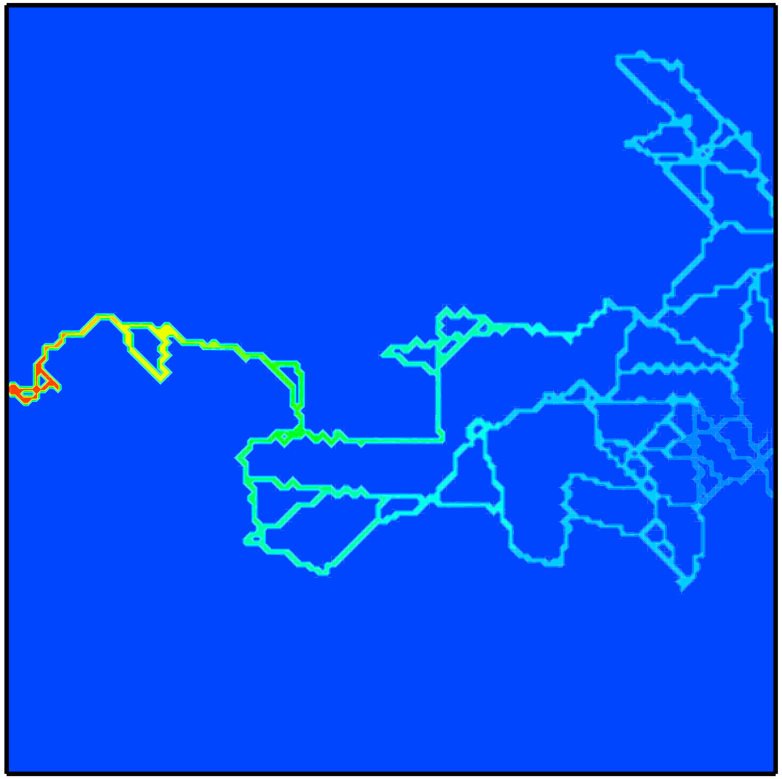
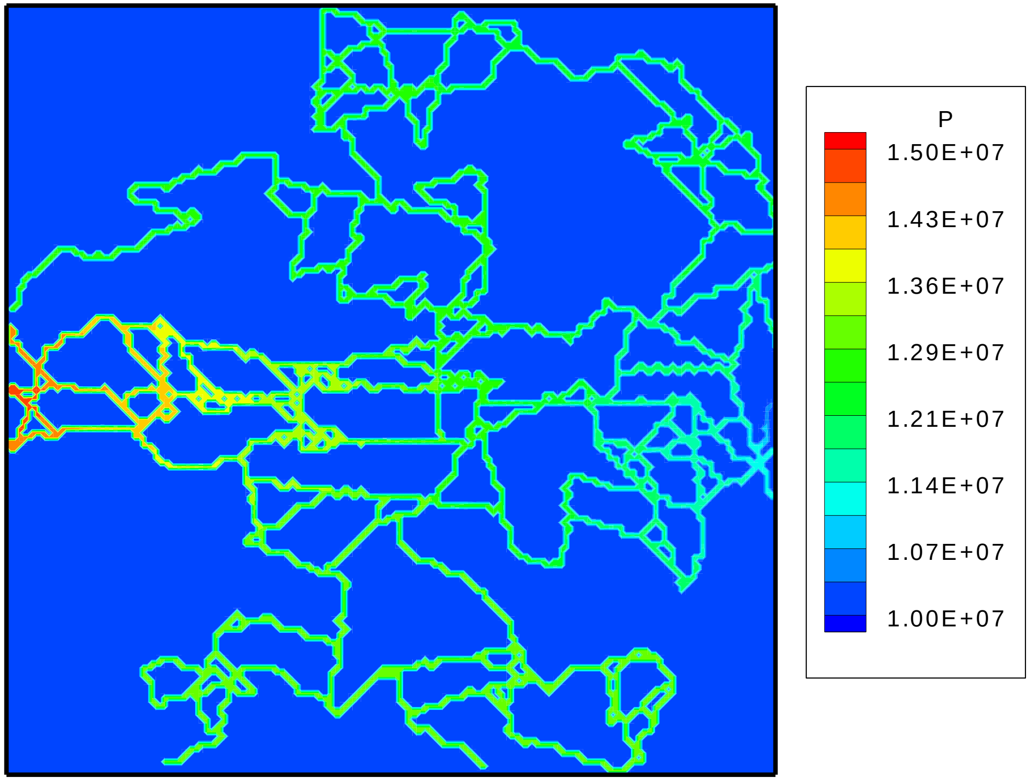
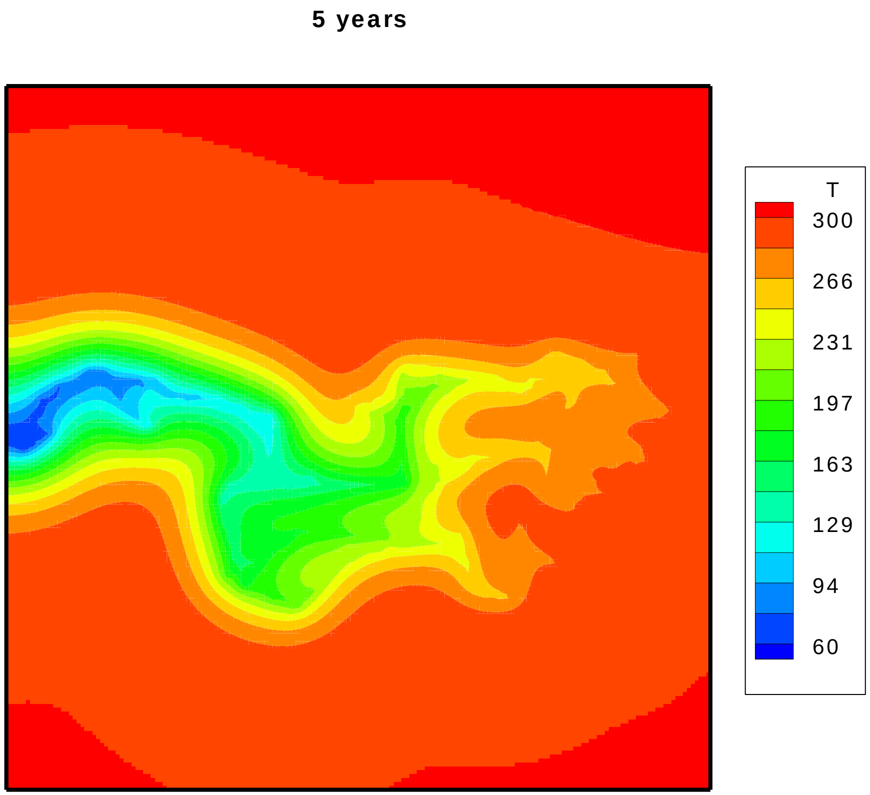


Before stimulation



After stimulation

Application to more complex fracture networks



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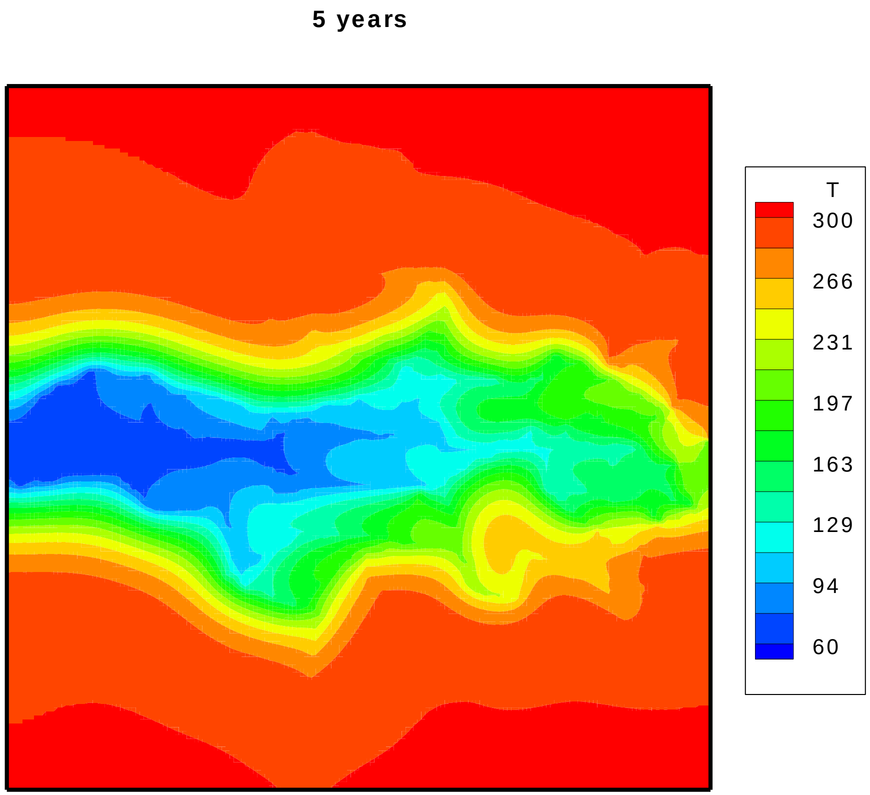

After stimulation