# Matrix Diffusion-Derived Plume Attenuation and Implications for Remediation in Crystalline Bedrock

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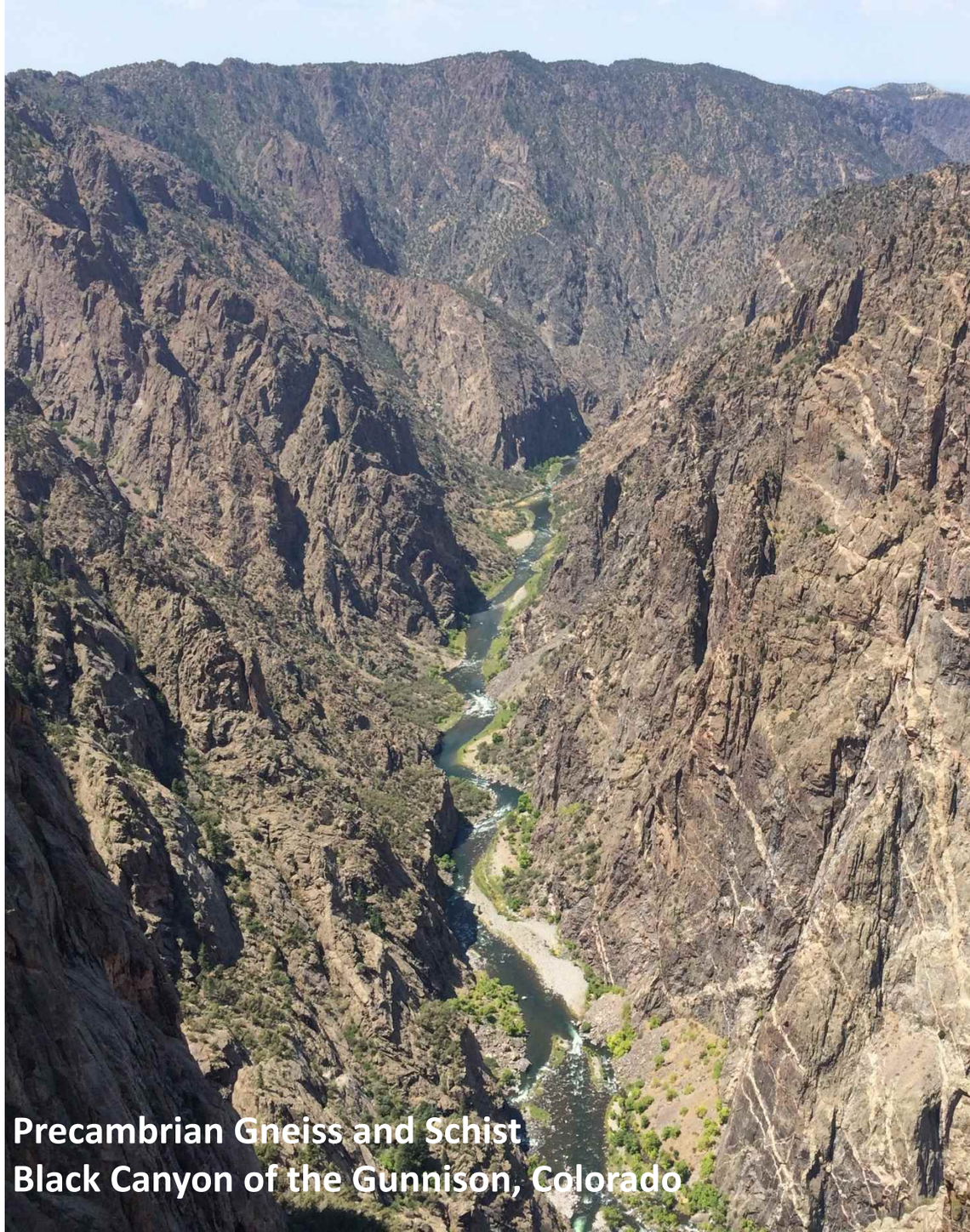

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# Main Message

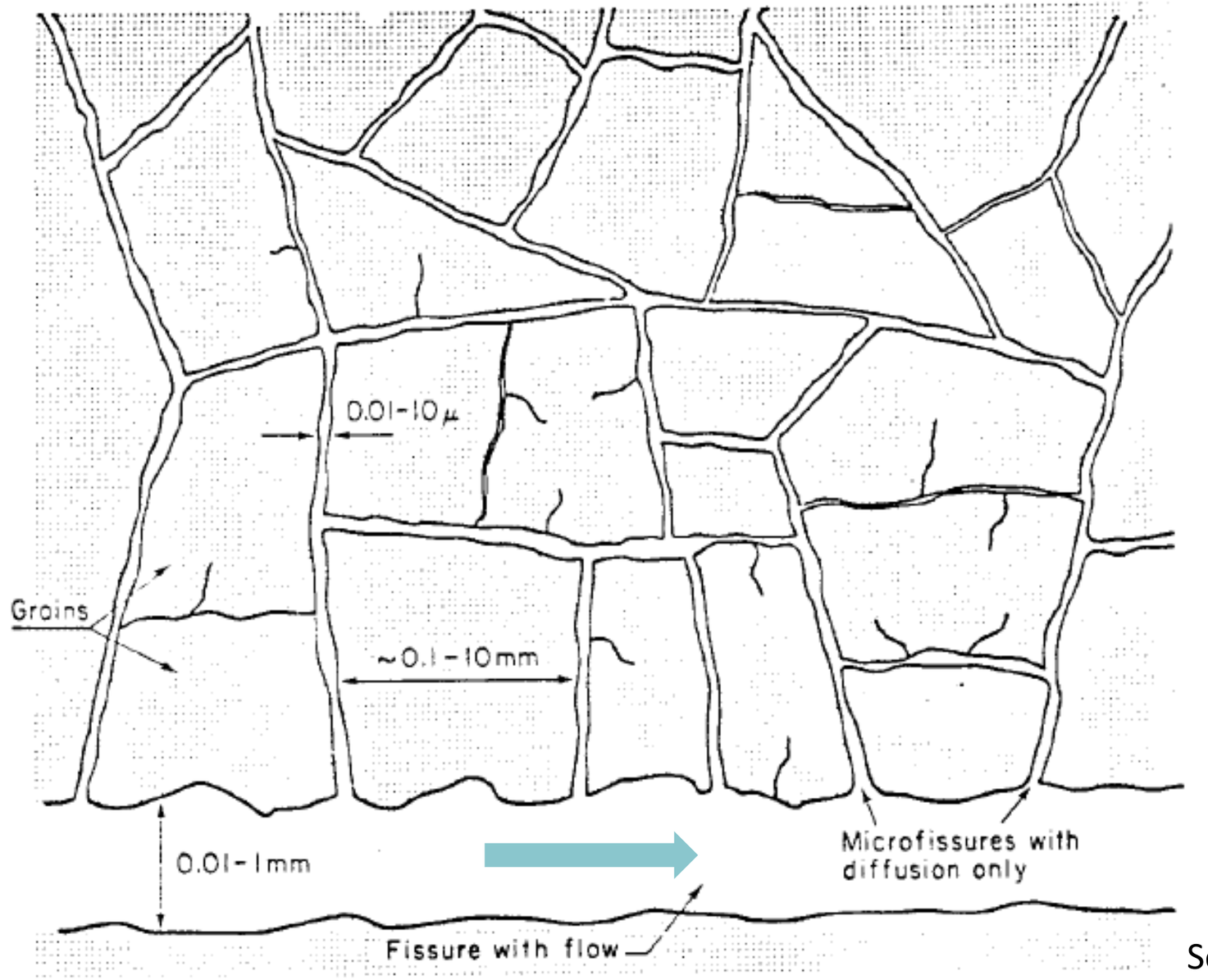
- Crystalline rock can have significant matrix porosity
- Contaminant transport in crystalline rock can be strongly influenced by matrix diffusion
- Matrix diffusion must be considered when evaluating fate, transport, and remediation in crystalline rock

**El Capitan Granite**
**Yosemite National Park, California**

# Crystalline Rock Has Significant Matrix Porosity

# Conceptual Model of Matrix Porosity in Crystalline Rock

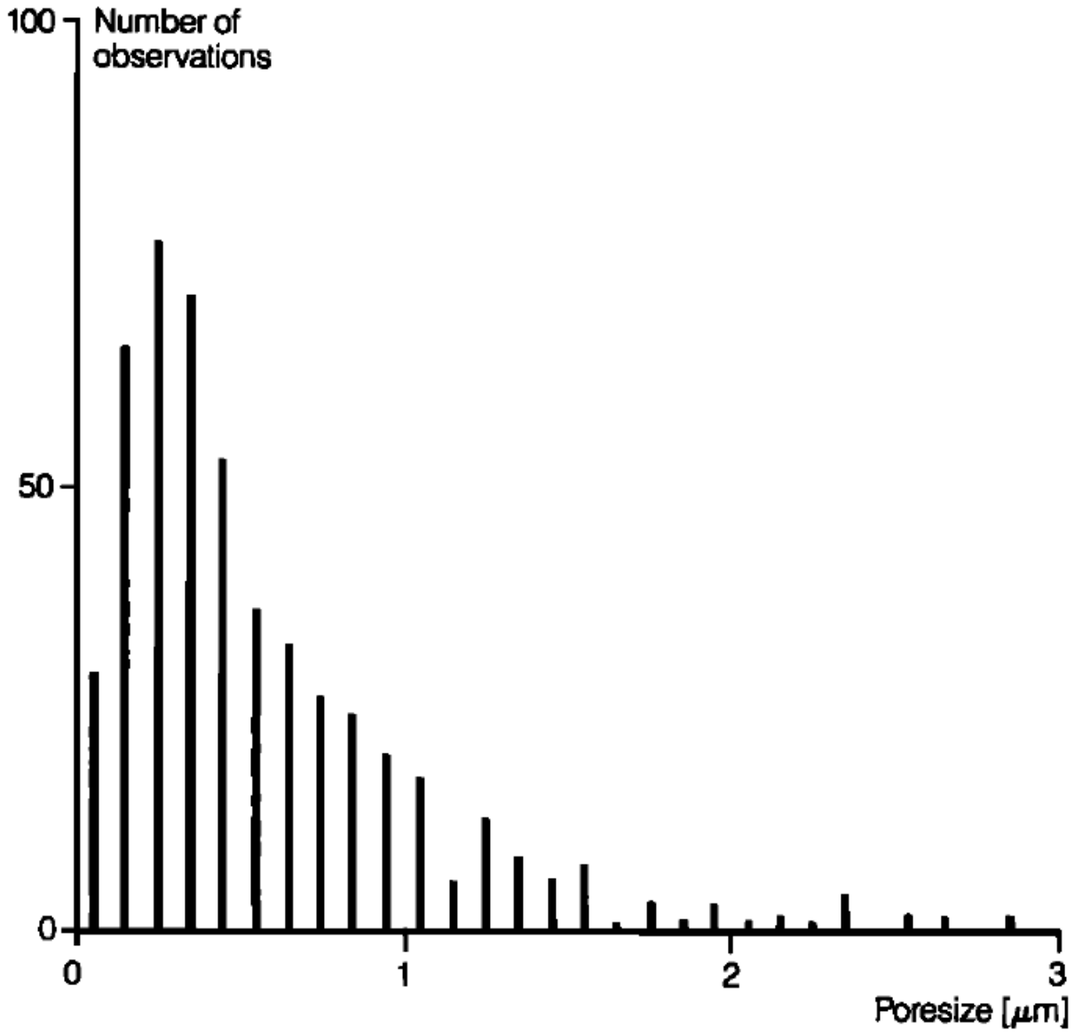
**Matrix (diffusive transport)**



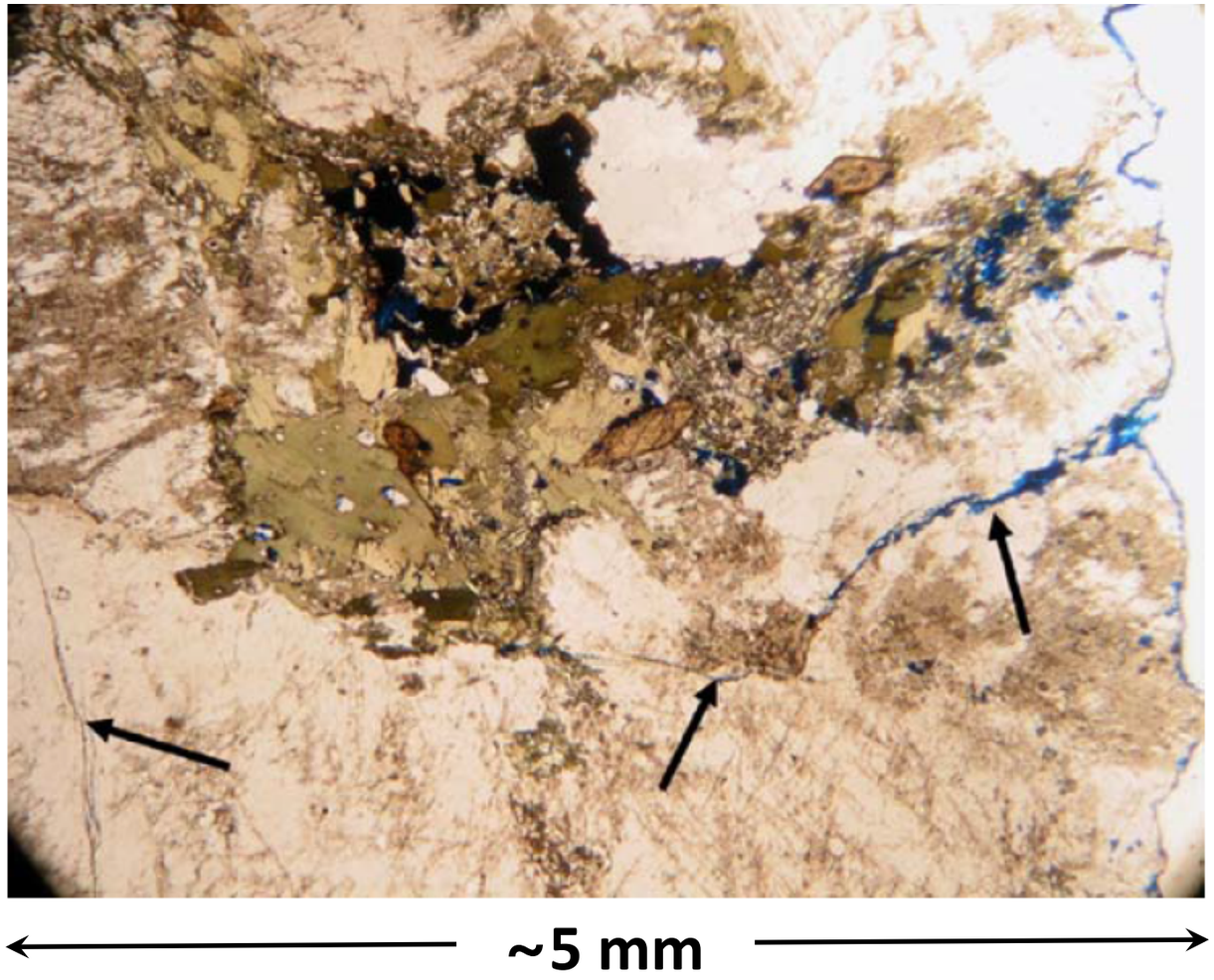

**Fracture (flow)**

Source: Neretnieks (1980)

# Microfracture Sizes in Crystalline Rock Matrix

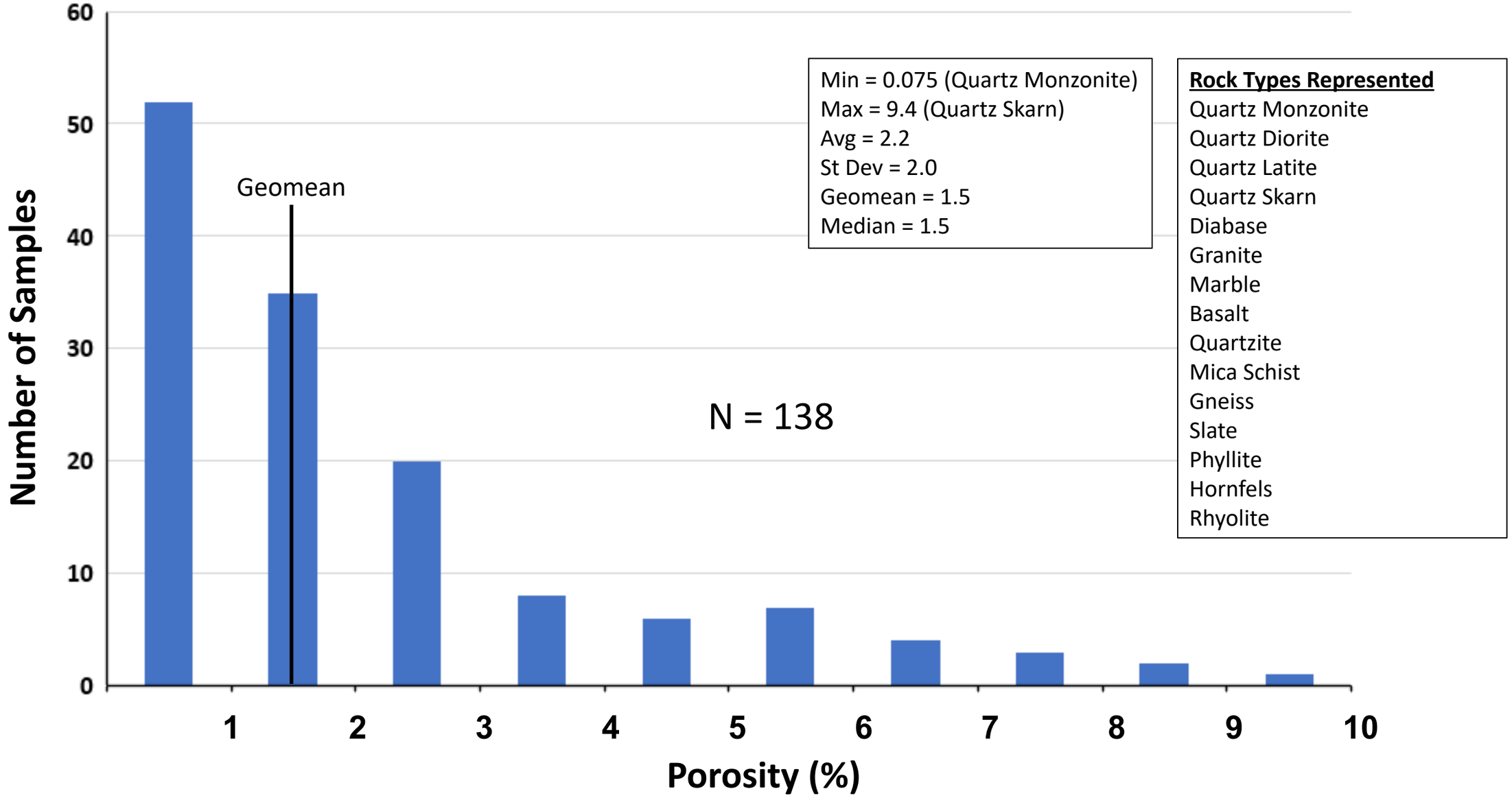



Source: Birgersson and Neretnieks (1990)




Source: Tullborg and Larson (2006)

# Literature Summary: Matrix Porosity Values in Crystalline Rocks



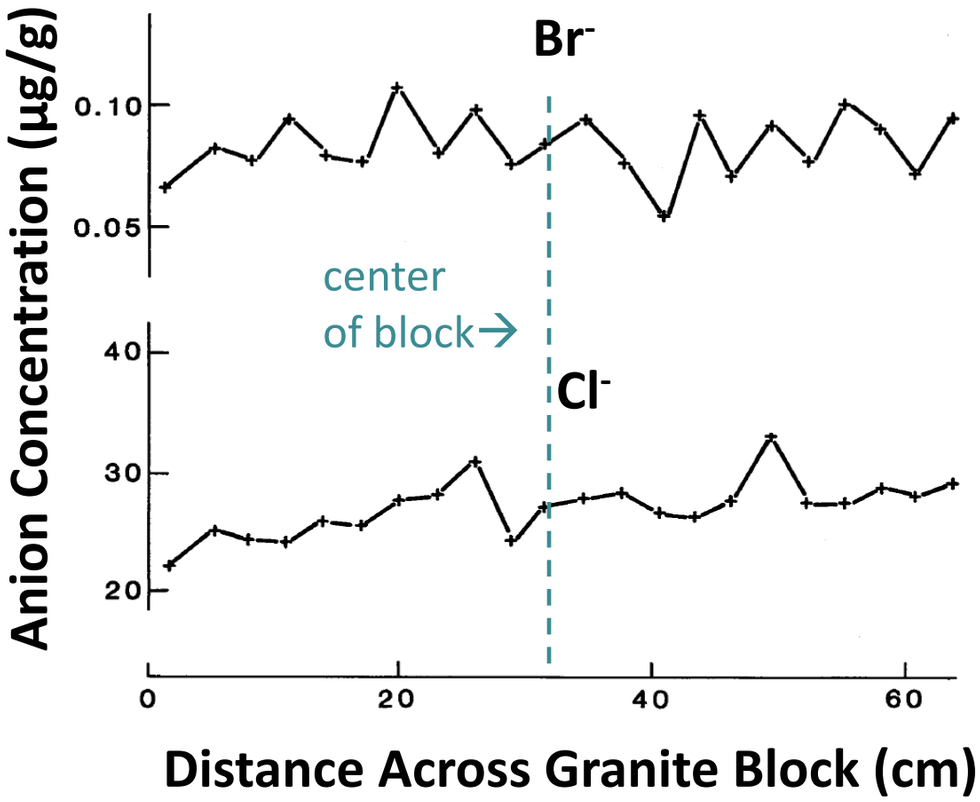
# Empirical Evidence of Solute Diffusion into Granite

# Granite Block Immersed in Sea Water for 31 Years

## (Jeffries 1988)

| Anion | Fresh Granite | Immersed Granite |
|---|---|---|
| $Cl^-$ | 1.2 – 2.6 | 28 |
| $Br^-$ | <0.002 | 0.08 |

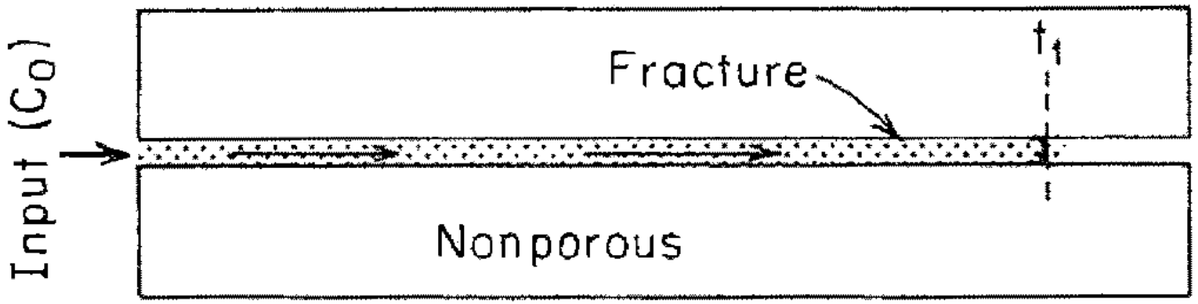
Note: Concentrations in µg/g



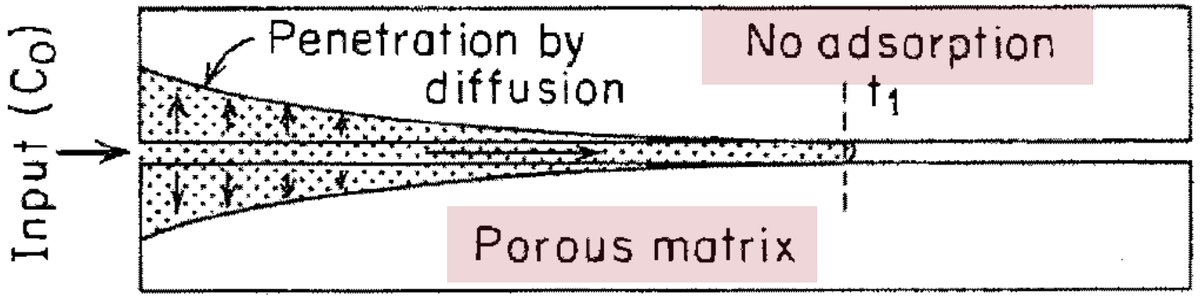

**Conclusion:** "Diffusion of $Cl^-$ and $Br^-$ from the sea water into the block has gone to equilibrium, indicating a higher diffusivity for the granite than previously expected."

# Influence of Diffusion on Contaminant Fate and Transport

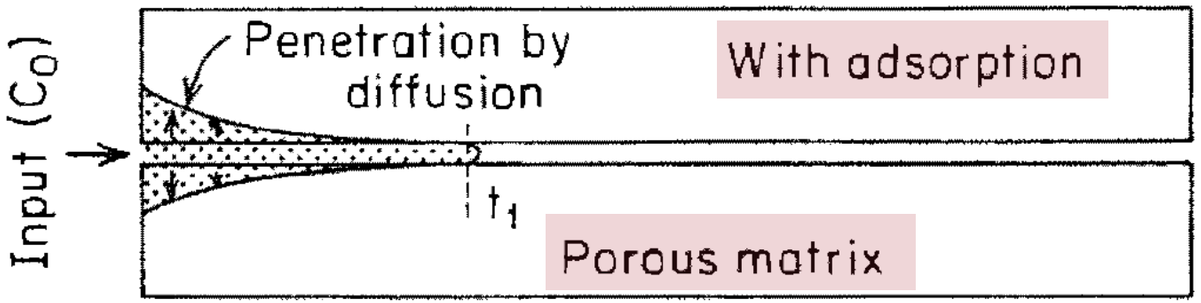
# Attenuation During Plume Advance (Freeze and Cherry 1979)




e.g., chloride or TCE in obsidian

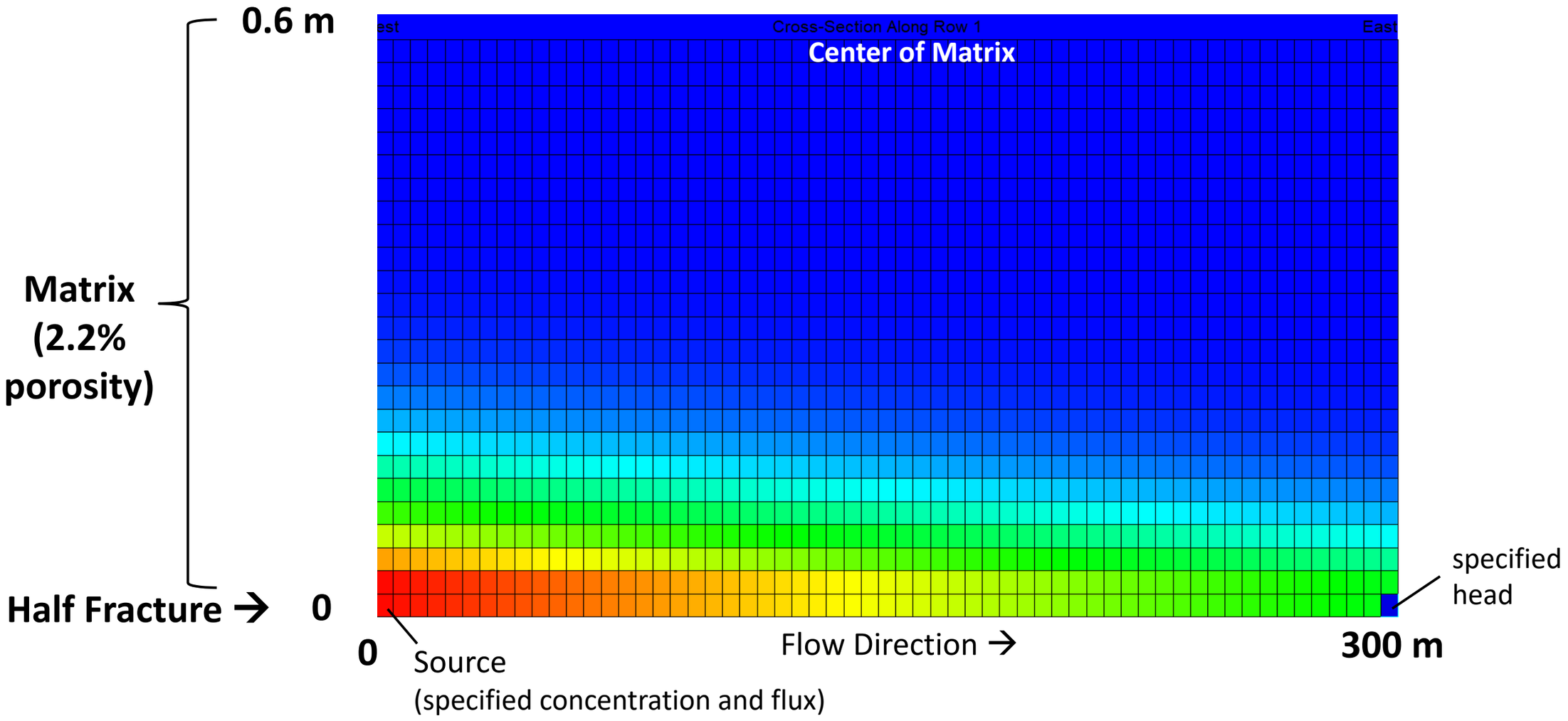



e.g., chloride in typical crystalline or sedimentary rock

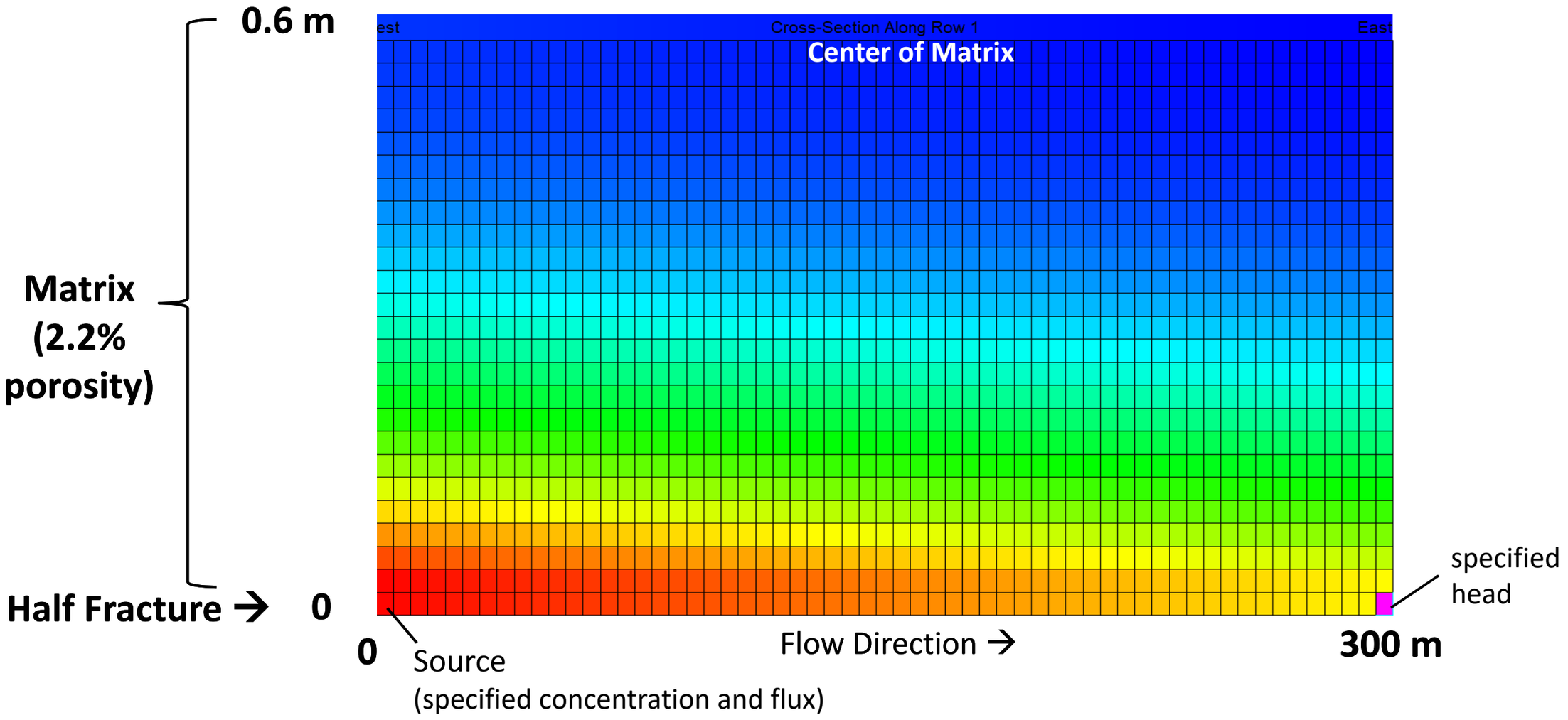



e.g., TCE in clastic sedimentary rock

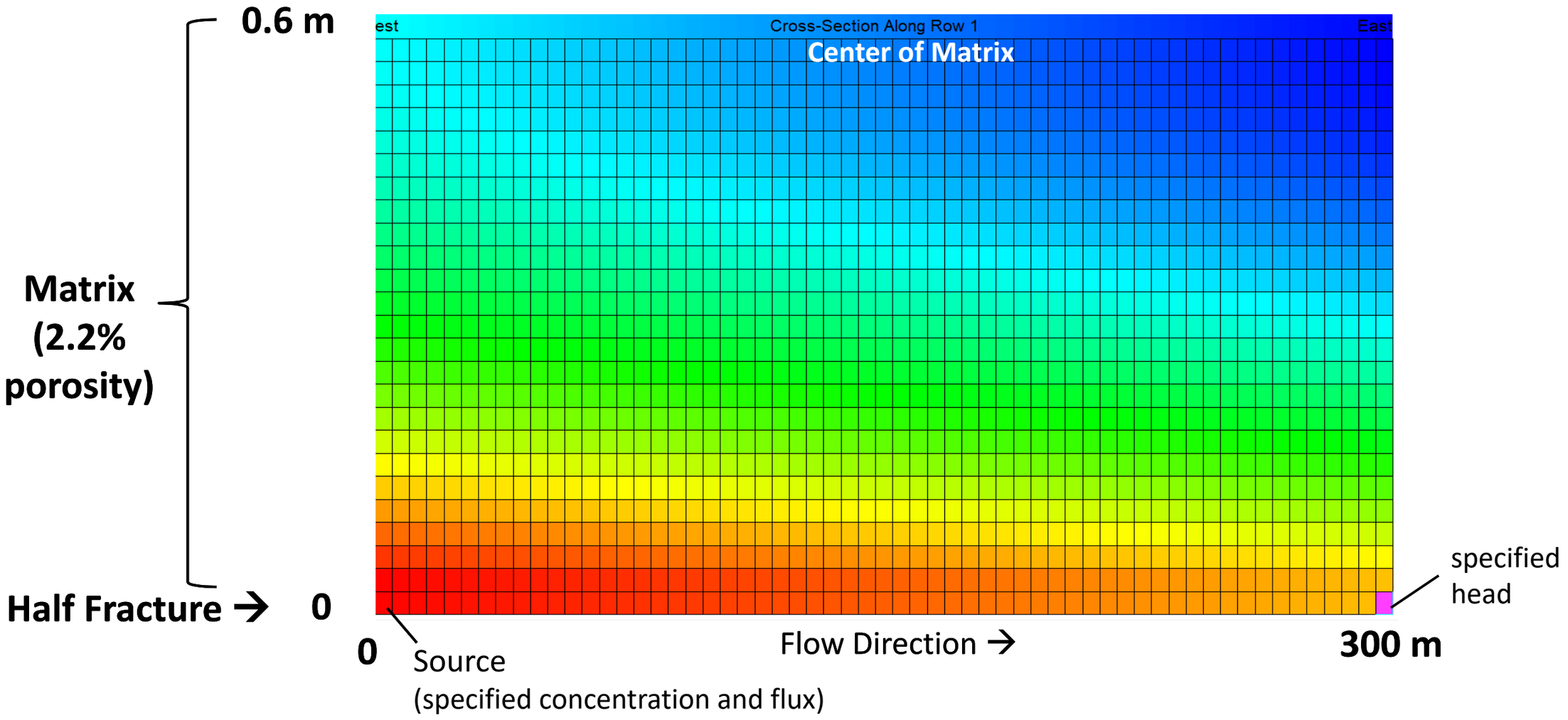
# Numerical Model of Non-Reactive Plume Advance: 1 Year



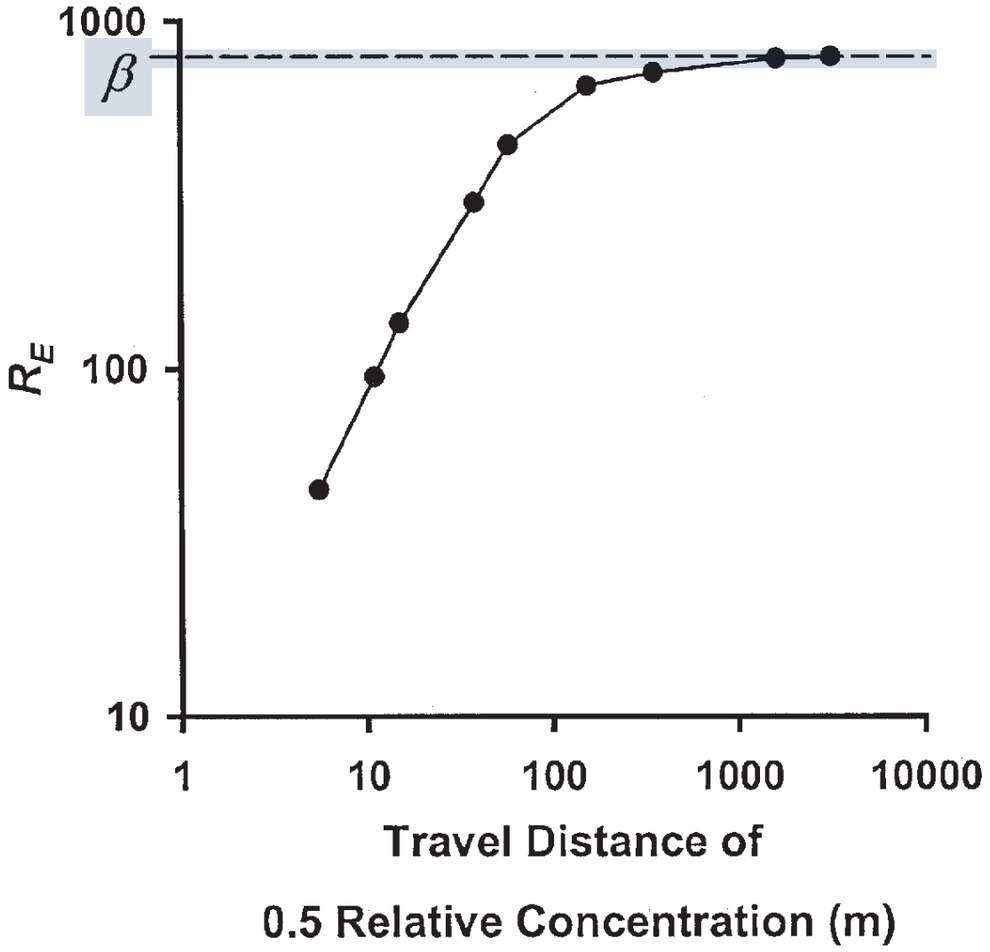
# Numerical Model of Non-Reactive Plume Advance: 5 Years



# Numerical Model of Non-Reactive Plume Advance: 20 Years



# Steady-State Plume Attenuation Factor: β




$$\beta = \phi_m / \phi_f$$

Where:

$\Phi_m$ = Matrix porosity

$\Phi_f$ = Fracture porosity = $e/S$

$e$ = Fracture aperture (hydraulic)

$S$ = Fracture spacing

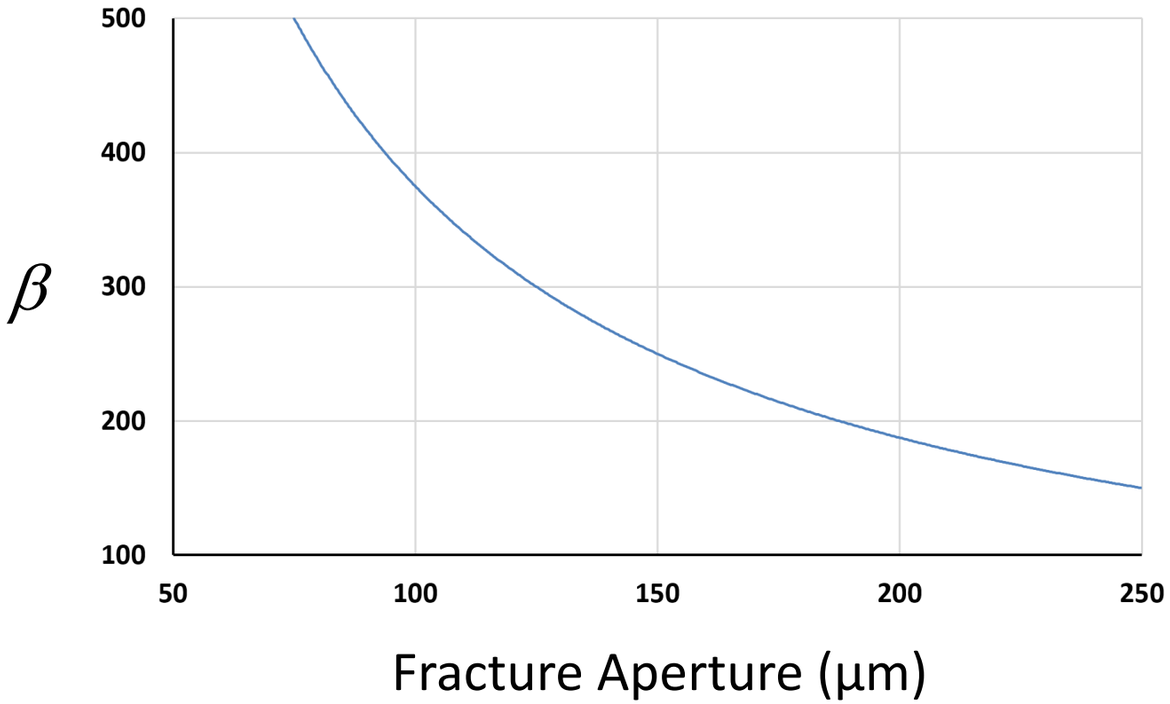
Source: Lipson et al. (2005)

# Steady-State Plume Attenuation Factor: β (cont.)

## Influence of Fracture Aperture

Fracture Spacing = 250 cm

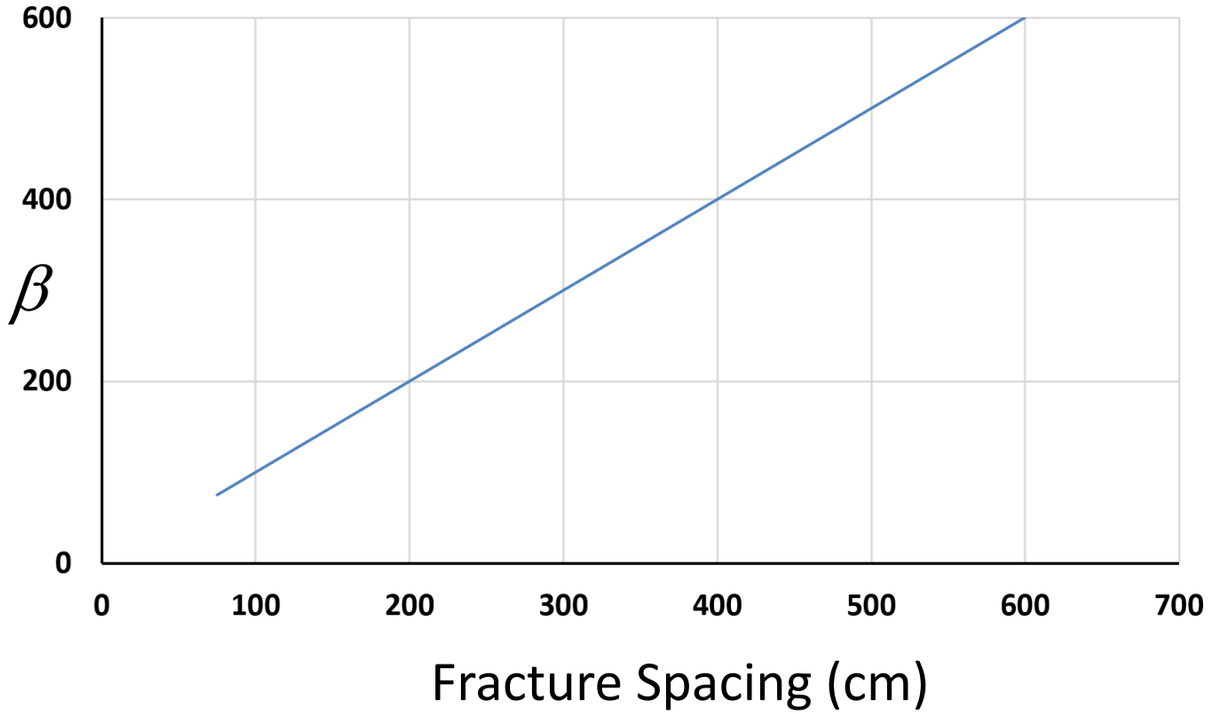
Matrix Porosity = 1.5%




## Influence of Fracture Spacing

Fracture Aperture = 150 µm

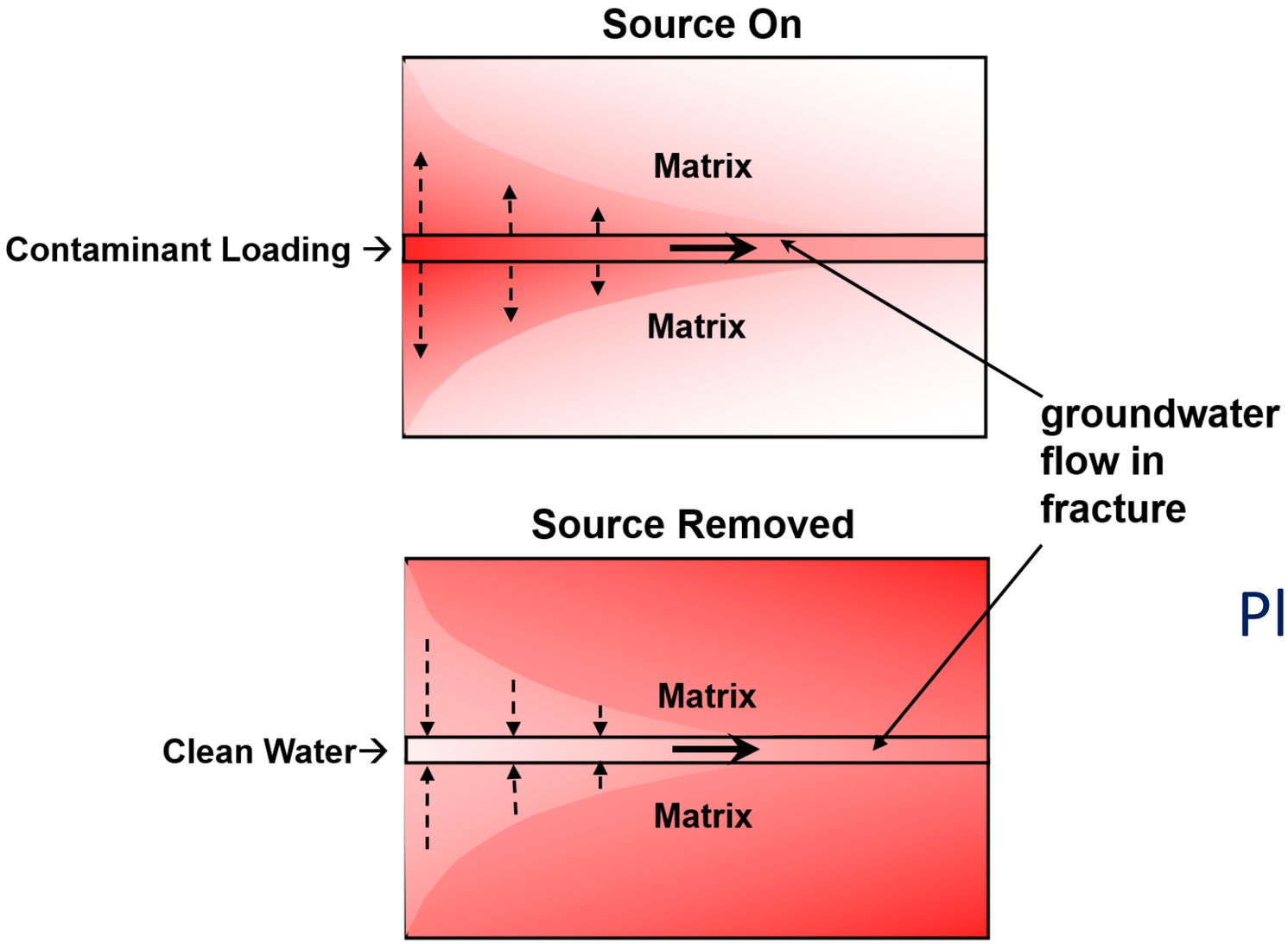
Matrix Porosity = 1.5%




*β values typically range from 100 to 600 in crystalline rock*

# Implications for Remediation

# Diffusion Reverses After Source Removal

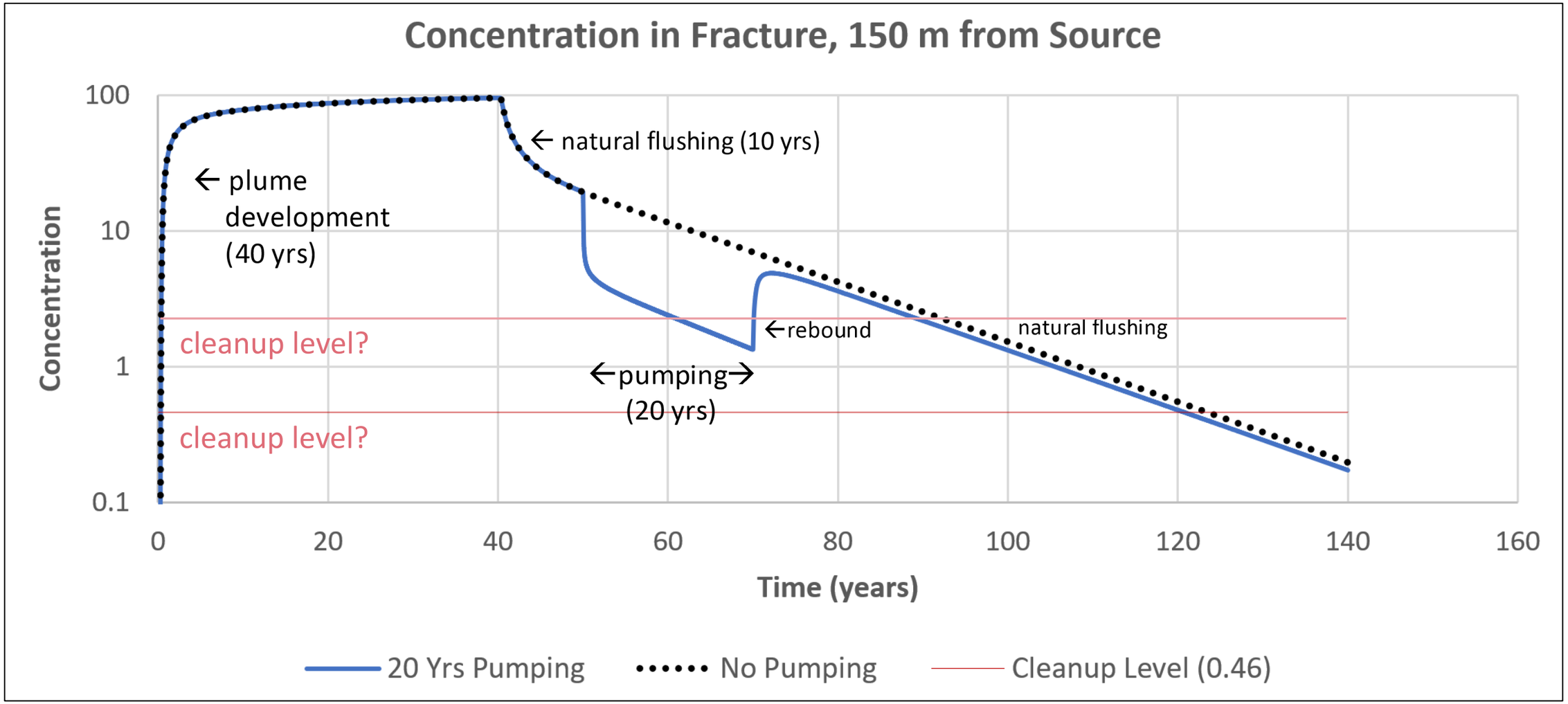



Plume advance:
Diffusion into matrix slows plume down

Plume flushing/remediation:
Diffusion out of matrix hinders groundwater cleanup

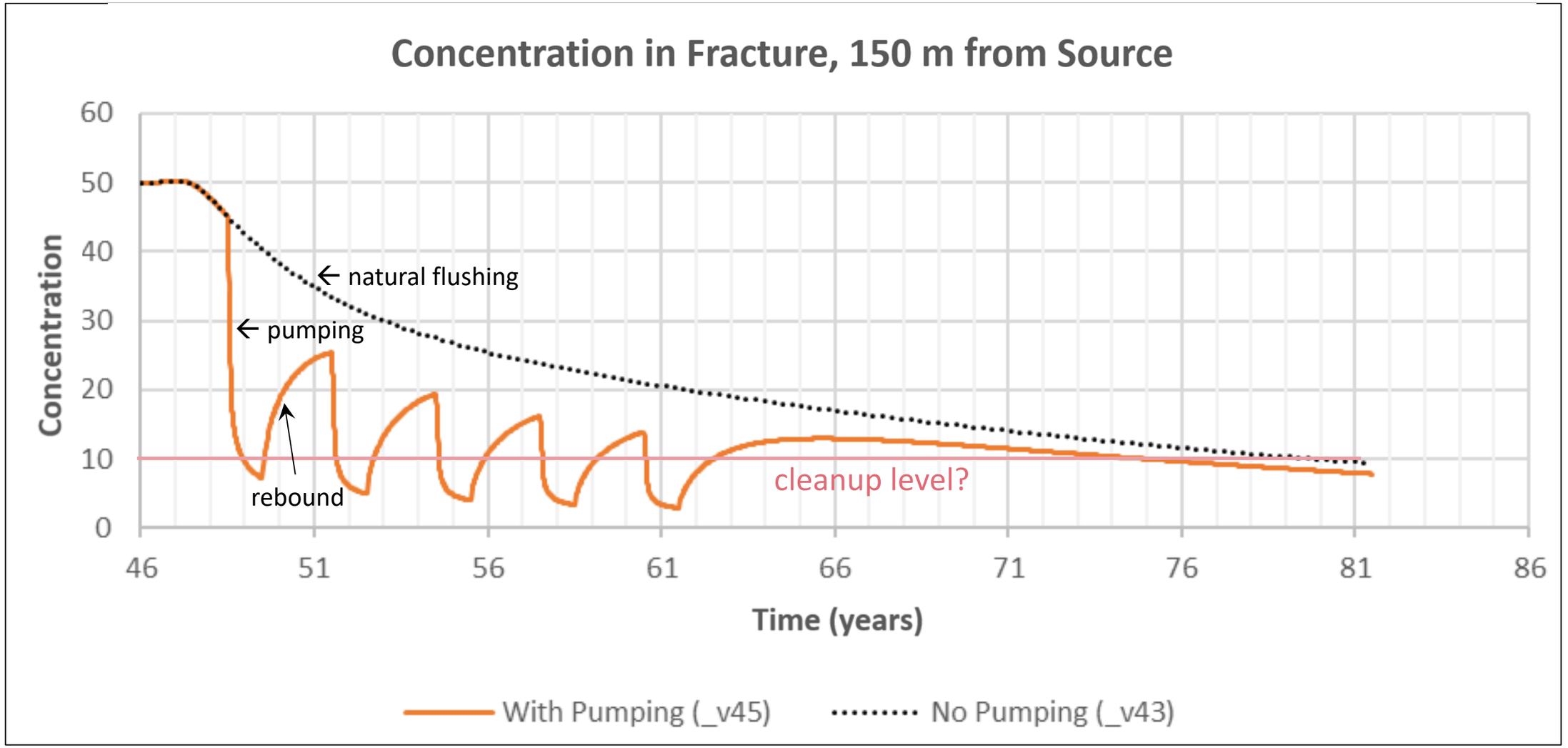
# Numerical Model: Natural Flushing versus Pump and Treat

## $e = 120\ \mu m,\ S = 1.2\ m,\ \phi_m = 2.2\%$



# Numerical Model: Natural Flushing versus Pulsed Pumping

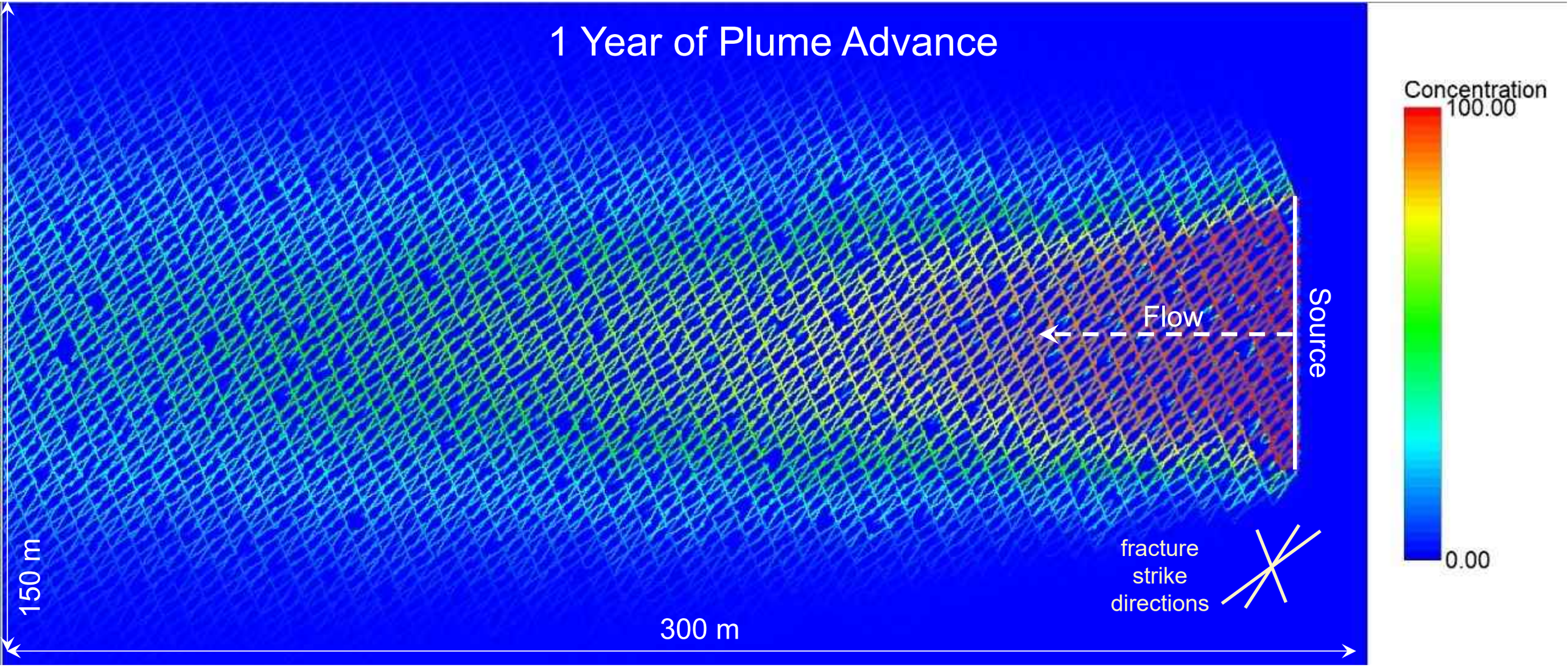
## *Same Parameters, Five 1-year Pumping Periods*



# Preliminary
# Fracture Network Simulations

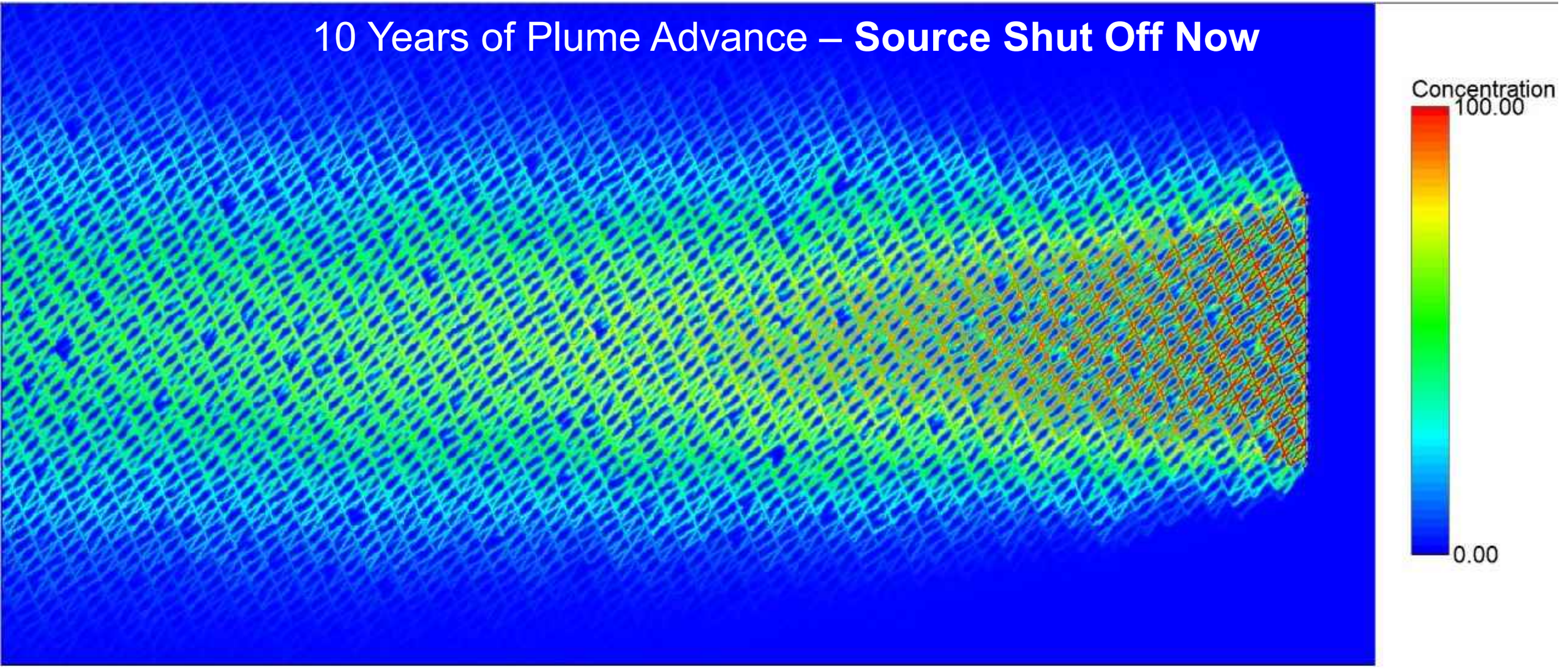
# Numerical Model: Fracture Network

## *Same Transport Parameters, Three Fracture Sets*



# Numerical Model: Fracture Network

## *Same Transport Parameters, Three Fracture Sets*



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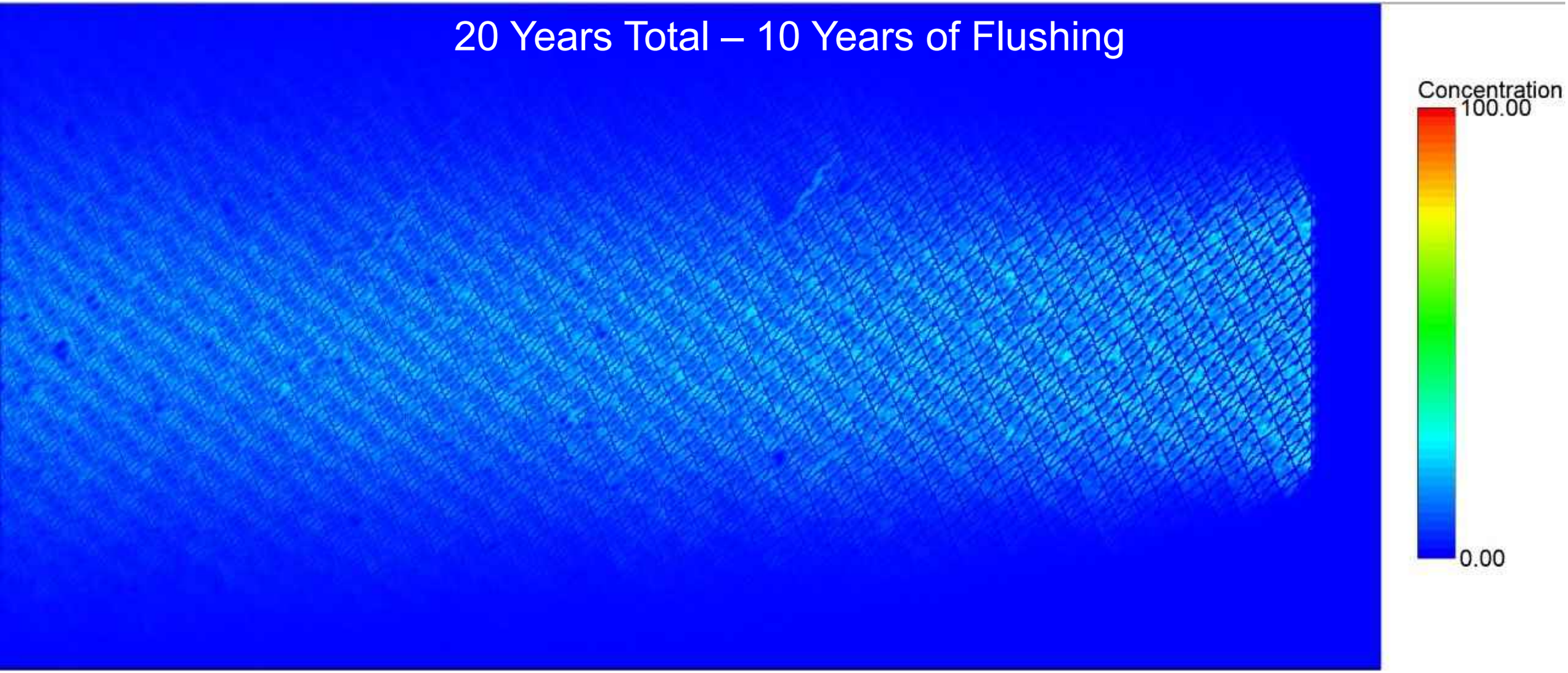
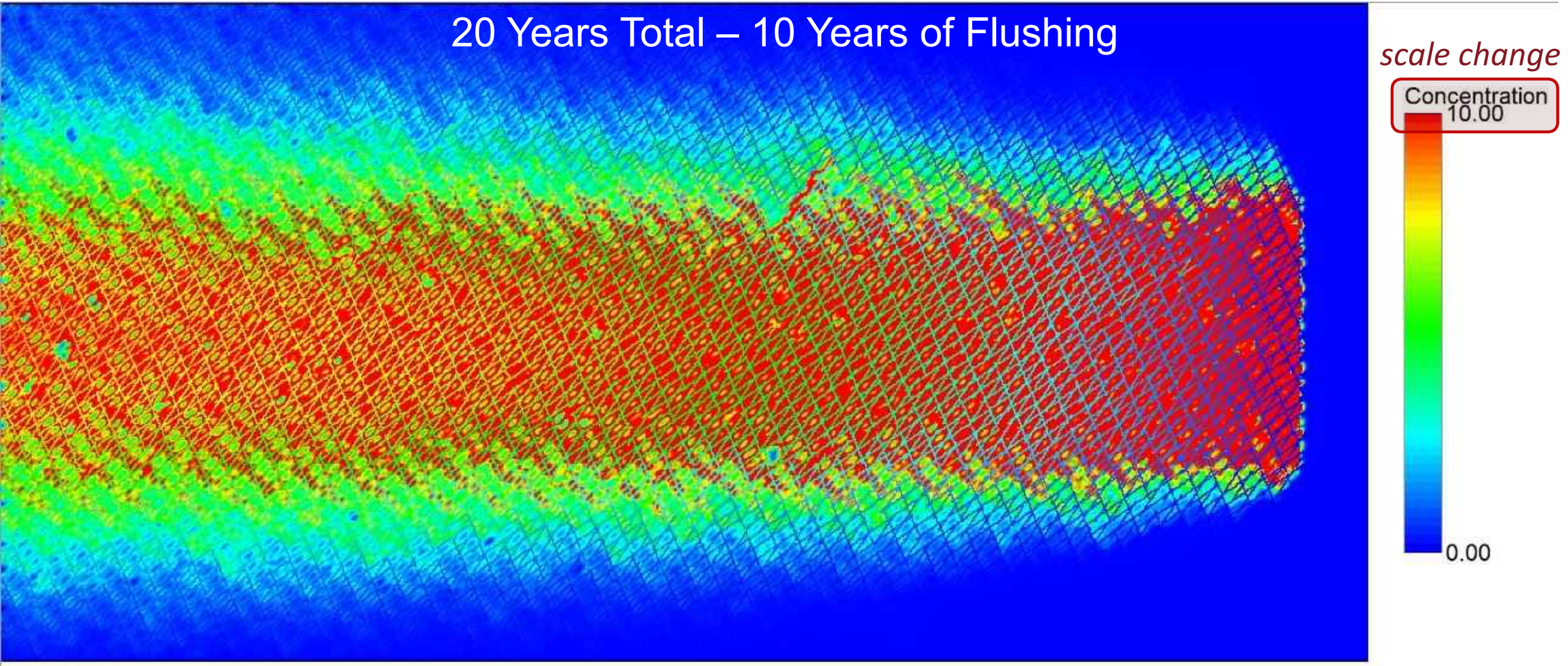


# Numerical Model: Fracture Network

## *Same Transport Parameters, Three Fracture Sets*



# Take-Aways

- Published and unpublished data indicate matrix porosity in crystalline bedrock:
  - ranges from approximately 0.08% to 9%
  - has a geometric mean of approximately 1.5%
- Plume velocities may be 100 to 600 times less than groundwater velocity in fractures
- Due to reverse diffusion:
  - natural flushing, pump-and-treat, and pulsed pumping may take many years to reach remedial goals
  - expect rebound after pumping stops

# Questions/Discussion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