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Photos placed in horizontal position with even amount of white space between photos and header

FLOW AND TRANSPORT SIMULATIONS IN FRACTURED CRYSTALLINE ROCK

October 26, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

- Part I: Introduction, Yifeng Wang
- Part II: Fracture Networks, Elena Kalinina
- Part III: Flow and Transport Simulations, Teklu Hadgu

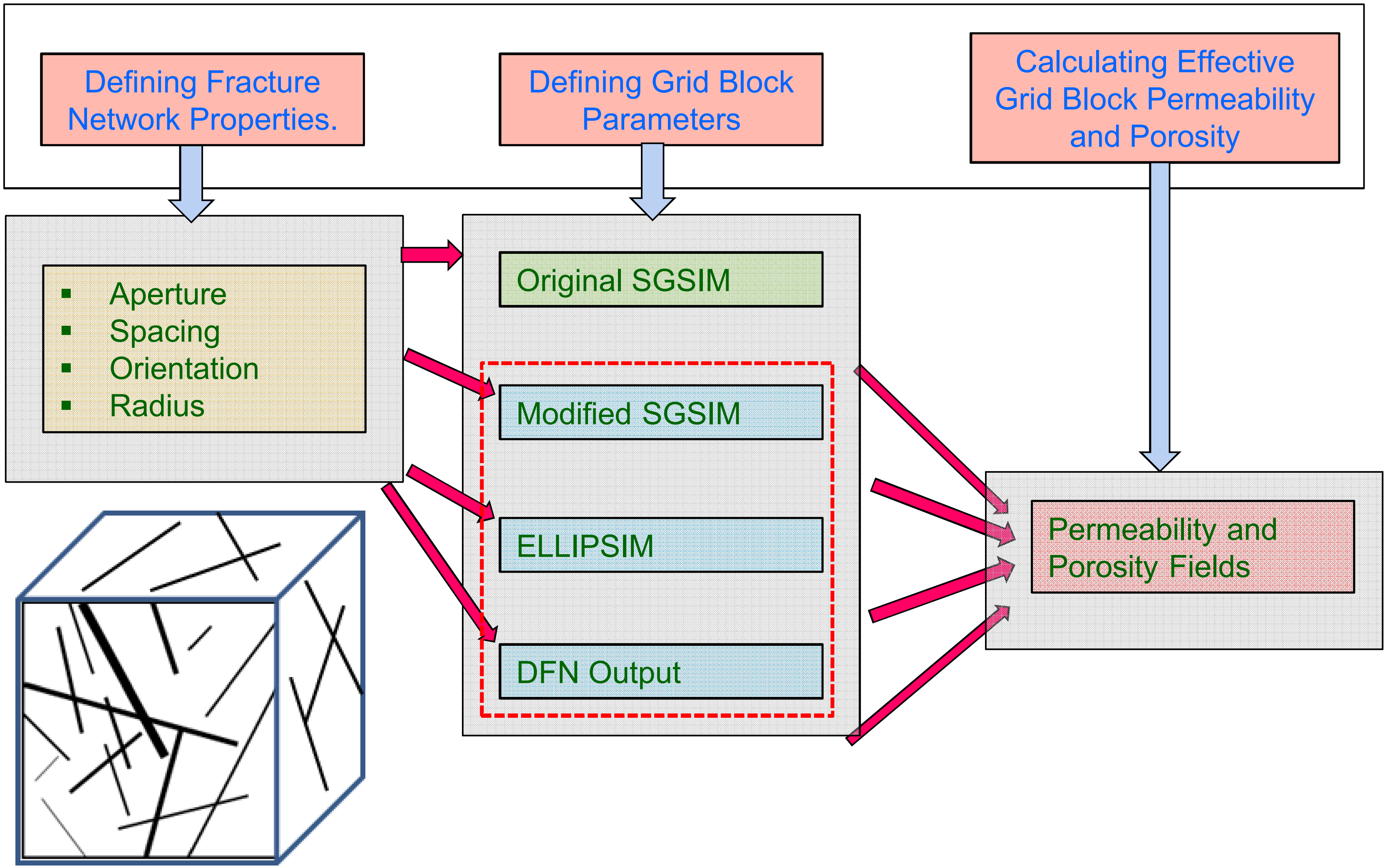
Fracture Continuum Model (FCM)

- The Fractured Continuum Model (FCM) incorporates fully three-dimensional representations of multiple independent fracture sets.
- Based on discrete fracture and effective continuum approaches (McKenna and Reeves, 2005, Kalinina et al. 2012, and Hadgu et al. 2016).
- FCM applications:
  - Multiple sets of natural and induced fractures with different orientations.
  - Different fracture spacing and aperture in different fracture sets.
  - Different fracture density with depth

FCM Approach

- Uses method developed by Chen et al. (1999) to compute permeability tensors as a function of fracture parameters
- Fracture parameters are: strike, dip, aperture and spacing of each fracture set (defined as probability distributions)
- Fracture parameters are defined for each block of uniform orthogonal mesh using 3 different methods:
  - Sequential Gaussian Simulation SGSIM
  - Ellipsim
  - DFN generated output

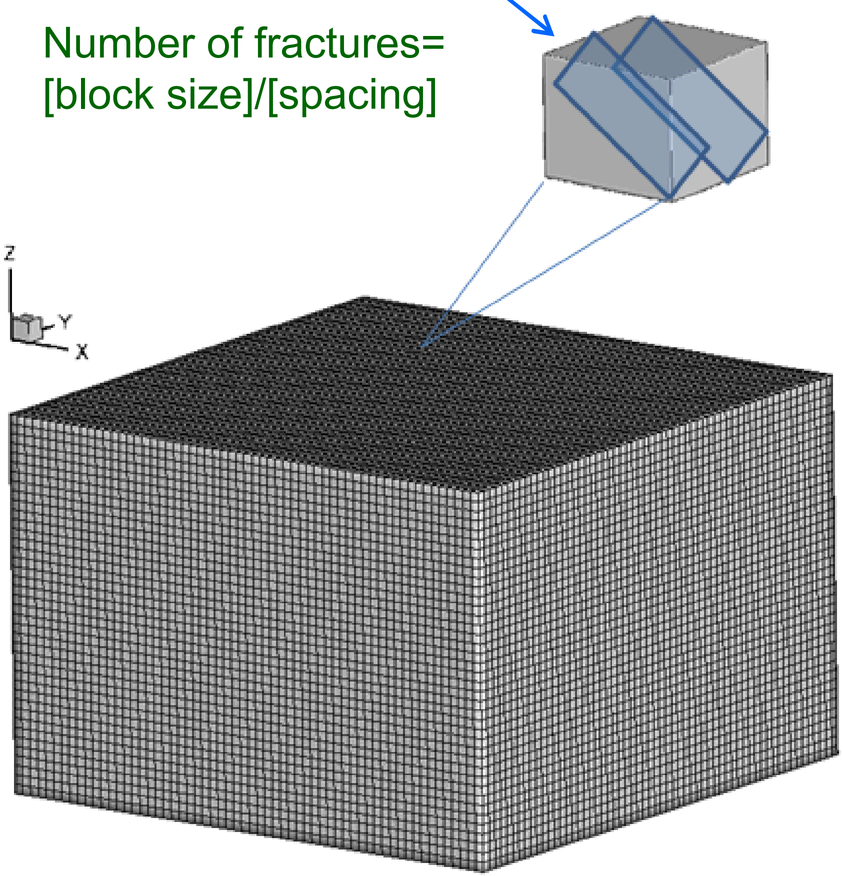
Evolution of FCM Approach



Definition of Grid Block Permeability Tensor (same for all methods)

Kxx, Kyy, Kzz

Number of fractures= [block size]/[spacing]



Permeability of grid block with one fracture set

$$k_{ij} = \frac{b^3}{12d}\begin{bmatrix} (n_2)^2 + (n_3)^2 & -n_1 n_2 & -n_3 n_1 \\ -n_1 n_2 & (n_3)^2 + (n_1)^2 & -n_2 n_3 \\ -n_3 n_1 & -n_2 n_3 & (n_1)^2 + (n_2)^2 \end{bmatrix}$$

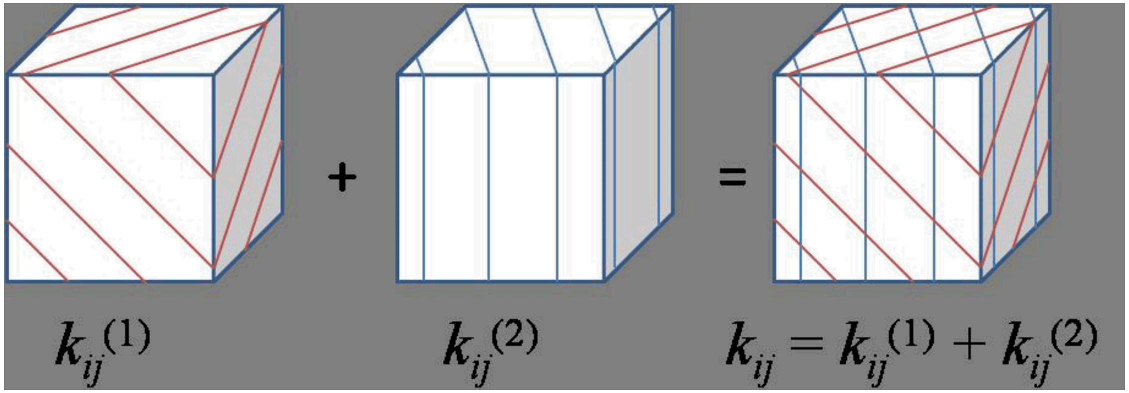
$$n_1 = Cos\left(\alpha \frac{\pi}{180}\right) x Sin(\omega \frac{\pi}{180})$$

$$n_2 = Cos\left(\alpha \frac{\pi}{180}\right) x Cos(\omega \frac{\pi}{180})$$

$$n_3 = -Sin(\alpha \frac{\pi}{180})$$

b - fracture aperture
d - fracture spacing
α - fracture plunge (90^0 - dip)
ω - fracture trend (strike - 90^0)

Permeability of Grid Block with Multiple Fracture Sets



$$k_{ij}^{*} = \sum_{m=1}^{N} k_{ij}^{m}$$

k_{ij}^{m} is permeability tensor of fracture set m

Assumption: The summation assumes that the total porosity within a grid-cell changes very little.

Definition of Fracture Parameters in a Grid Block: I. Sequential Gaussian Simulation (SGSIM)

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Original SGSIM Method

SGSIM:
- Correlation Ranges in x, y, z
- Correlation angles in x, y, z

→

Spatially Correlated Number $P_{x,y,z}$

→

Fracture Parameters:
$Spacing_{x,y,z}(P_{x,y,z})$
$Aperture_{x,y,z}(P_{x,y,z})$
$Strike_{x,y,z}(P_{x,y,z})$
$Dip_{x,y,z}(P_{x,y,z})$

↑ Any distribution can be defined.

Modifications

Number of fractures k in a grid block is calculated using Poison distribution f(k,λ).

Probability f(k,λ) is assigned to each grid block using spatially correlated number P_{xyz}

Correlation Ranges in x, y, z – based on fracture radius
Correlation angles in x, y, z – based on fracture orientation

Fracture aperture (b) is calculated as: $b = \gamma \cdot R^{\omega}$

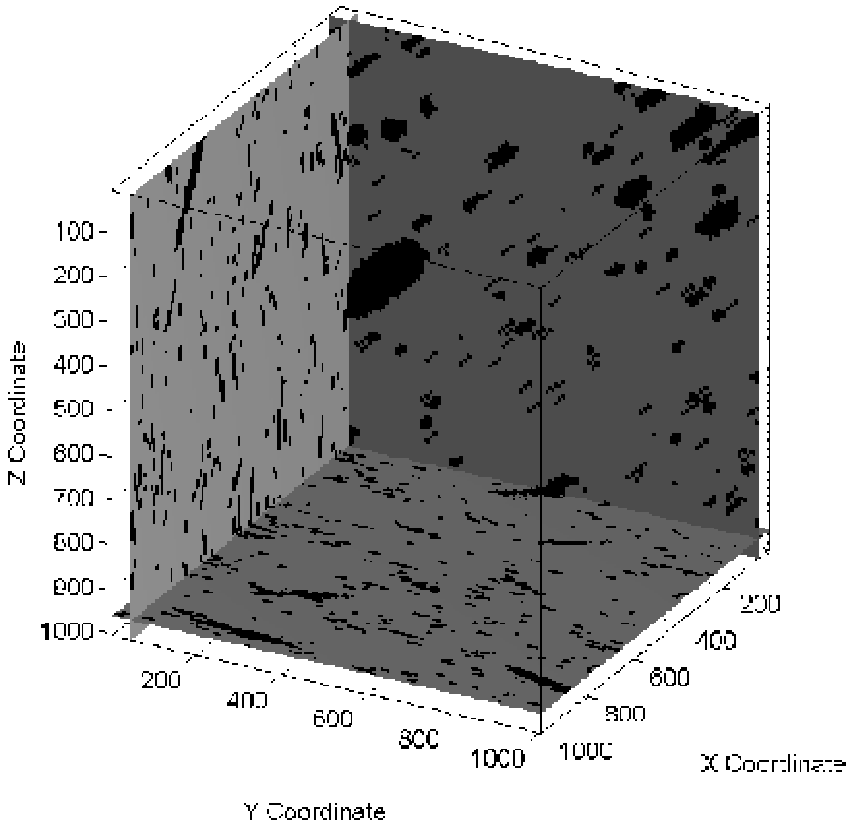
where R is fracture radius distribution and γ and ω are parameters.

Fracture Plunge (α) and Trend (Θ) are defined with univariate Fisher distribution.

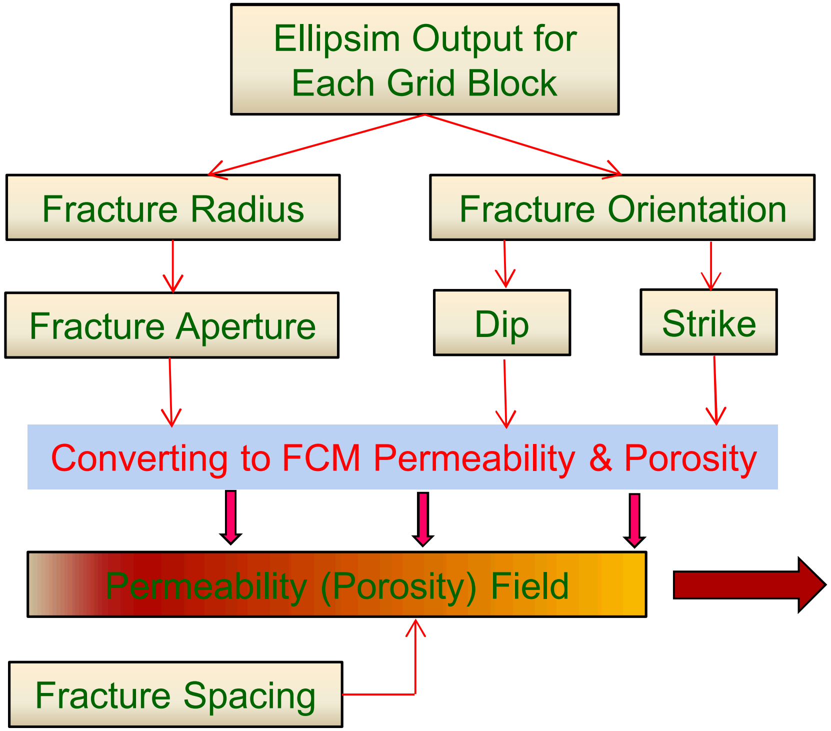
Definition of Fracture Parameters in a Grid Block: II. Boolean Simulation of Ellipsoids (Ellipsim)

- Ellipsim generates a specified number of ellipses.
- Each ellipse set represents a specific fracture set.
- Ellipse centers are randomly placed within the modeling domain.
- The ellipse radius is drawn from the power-law distribution.
- The ellipse orientation is drawn from the triangular distribution approximating Fisher distribution.
- The grid blocks located within a specific ellipse are assigned its radius and orientation.

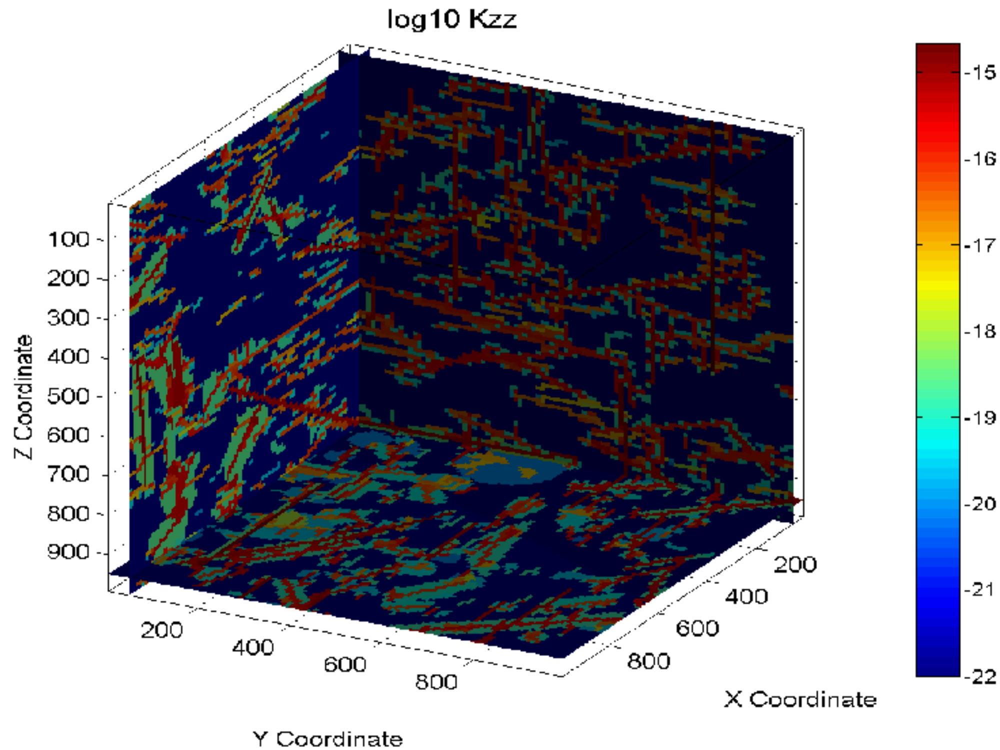
Example of One Fracture Set with 2,300 E-W Trending Fractures



Converting Ellipsim Output to FCM Permeability (continued)



Example of Permeability Field with 3 Fracture Sets (6,500 fractures)



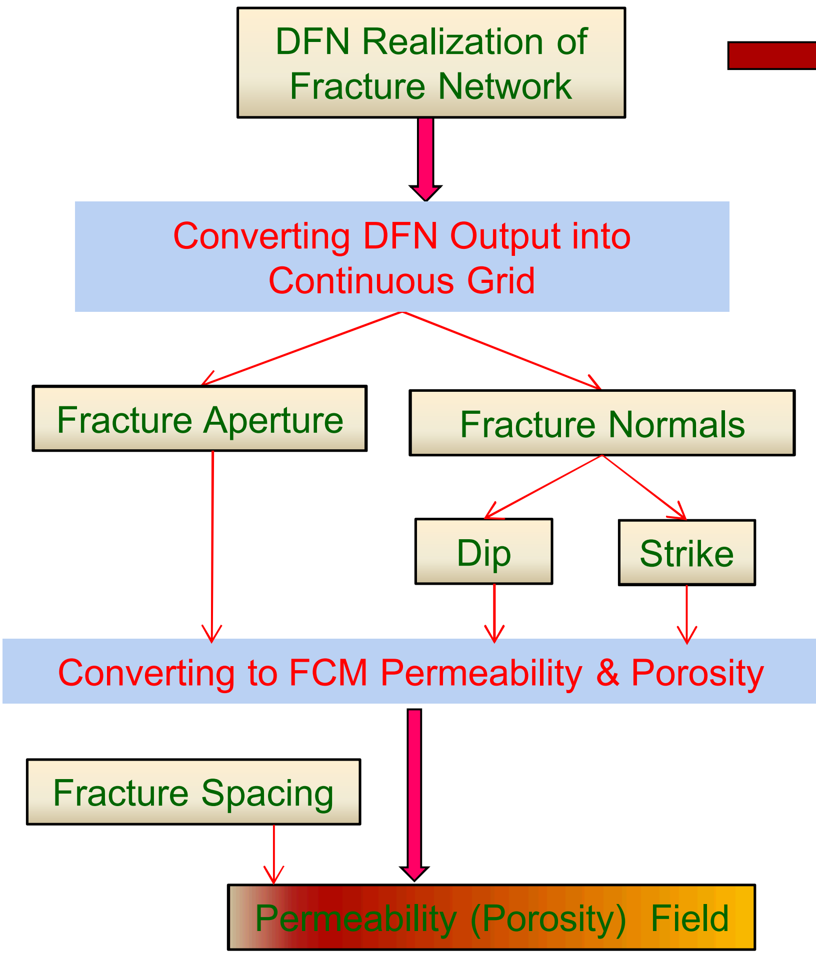
Aperture (b) is calculated from radius R as:

$$\log(\sigma) = \log(\gamma \cdot R^{\omega}), \qquad \sigma = \frac{b^3}{12}\frac{\rho g}{\mu}$$

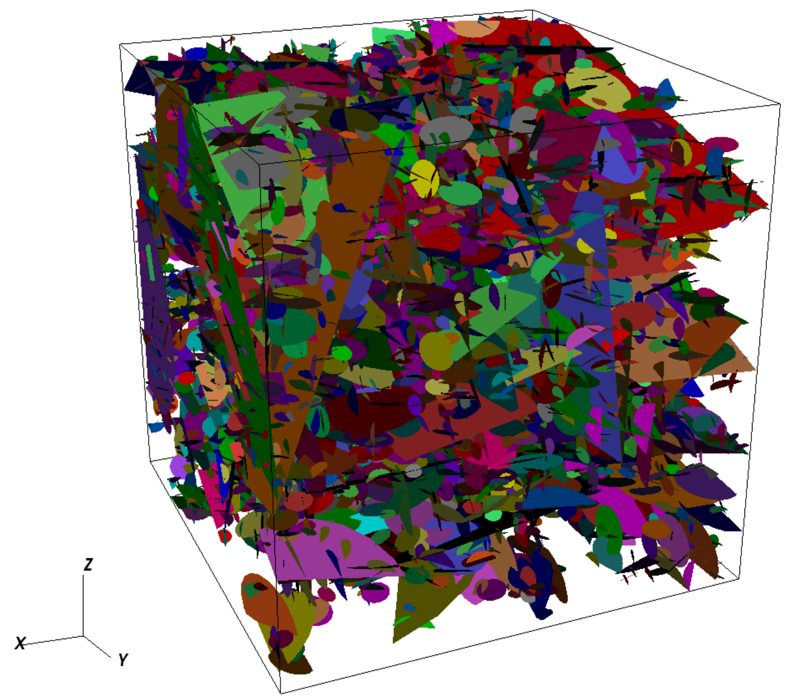
σ is fracture transmissivity, γ and ω are parameters, ρ is fluid density, g is gravity acceleration and μ is a fluid viscosity

Fracture Spacing=Grid Block Size (one fracture per grid block)

Definition of Fracture Parameters in a Grid Block: III. Converting DFN Output to FCM Permeability

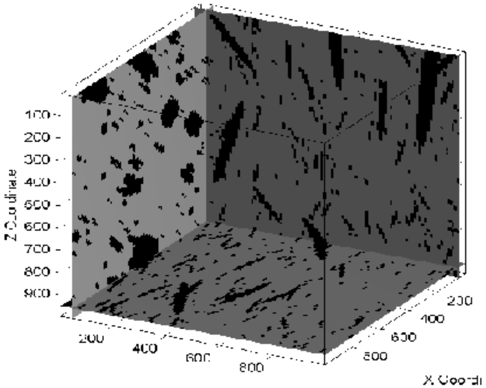


Example of DFN Realization of Fracture Network with 3 Fracture Sets

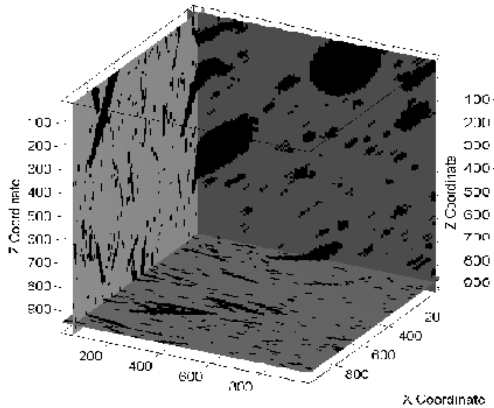


Example of Three Fracture Sets Generated with ELLIPSIM

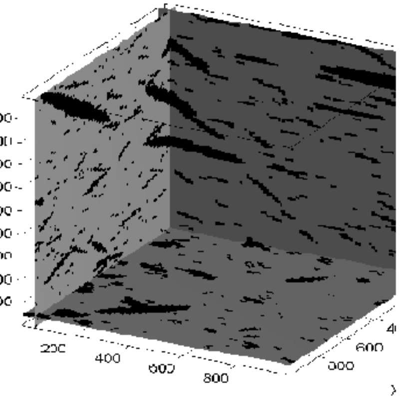
Vertical Fractures N-S



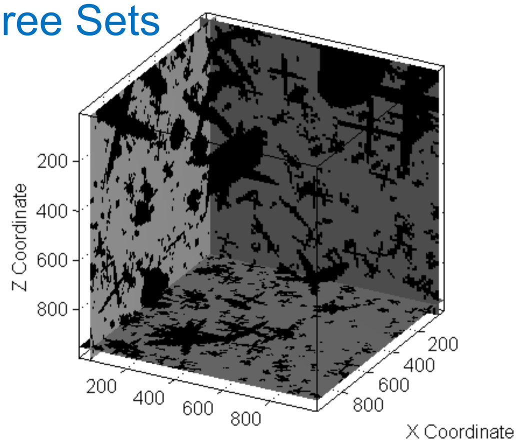
Vertical Fractures E-W



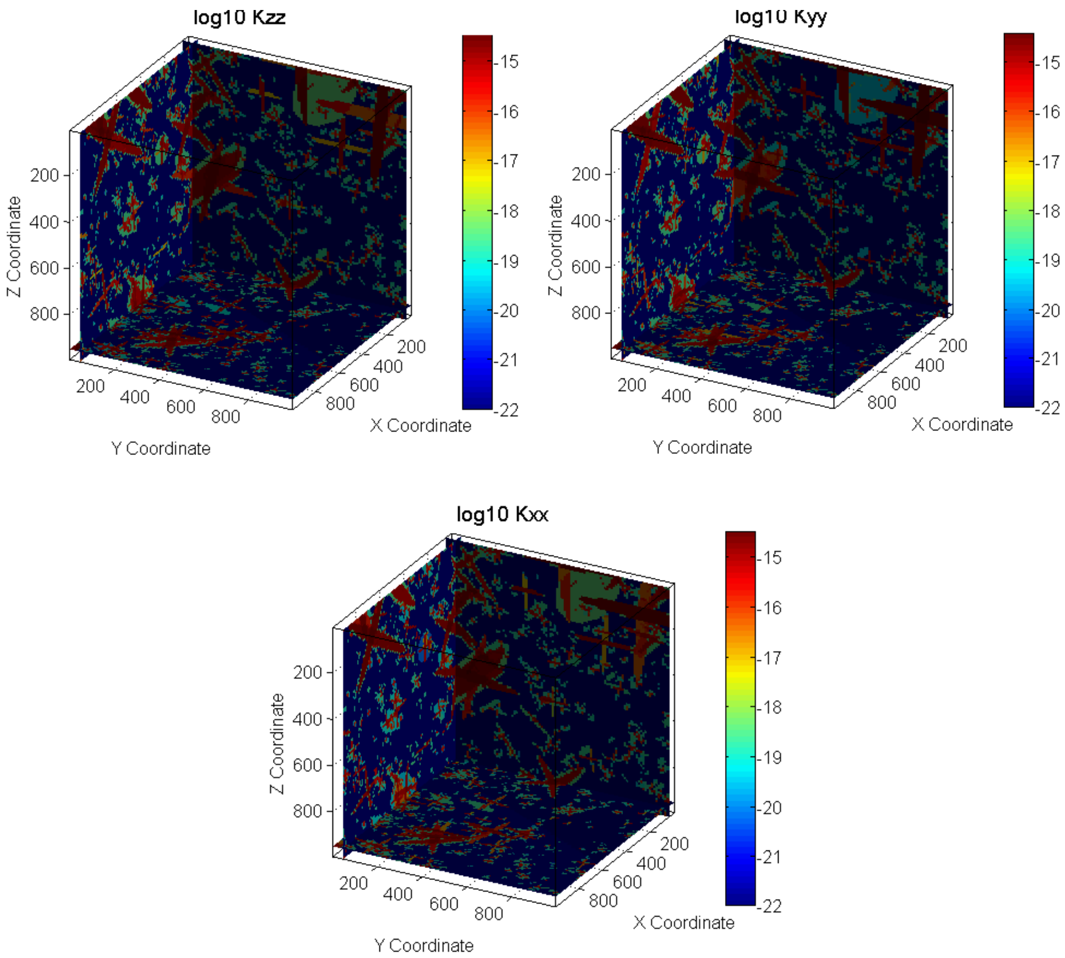
Horizontal Fractures W-E



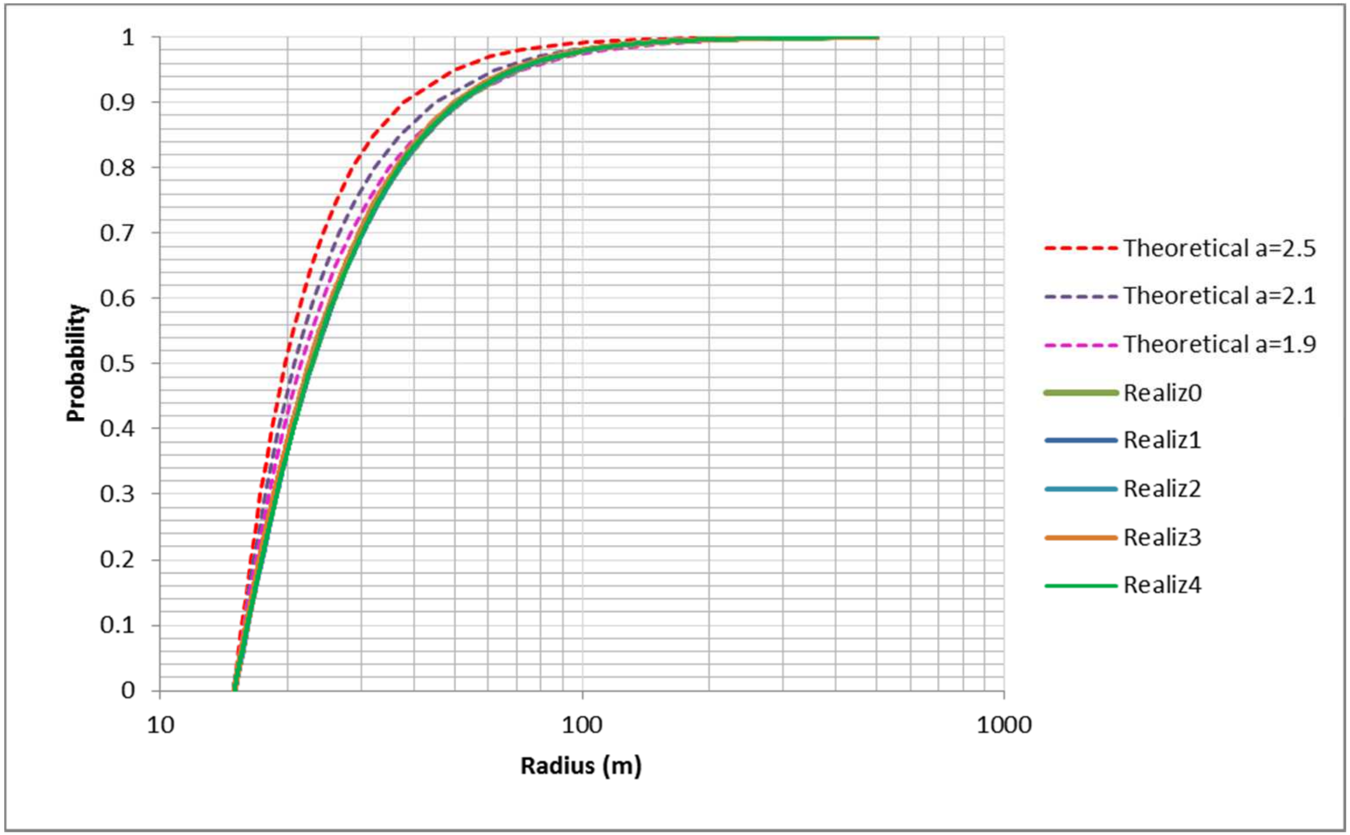
All Three Sets



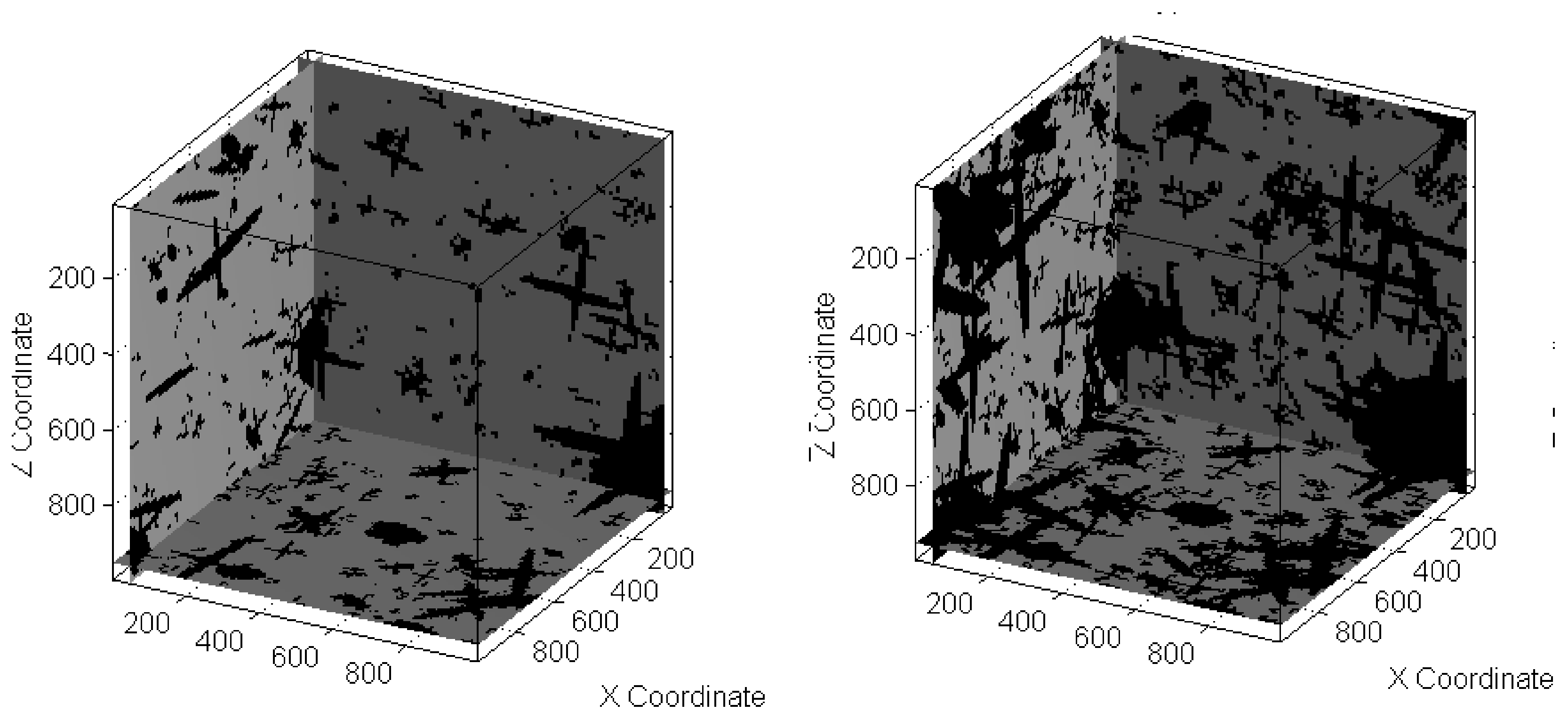
k_{xx}, k_{yy}, and k_{zz} Permeability Fields for the Fracture Network with Three Fracture Sets



Theoretical Power-Law Distributions with Different Parameter and Sampled by DFN Distributions of Fracture Radius



Fracture Network with Original (Left) and Modified (Right) Fracture Parameters



Summary of Methods: FCM (SGSIM)

- No assumption regarding fracture shape is required.
- Aperture, spacing, and orientation are defined based on distributions of field observations (not calculations).
- The fracture parameter distributions are not altered.
- The number of fractures can be very large.
- An exact number of fractures cannot be generated.
- Fractures are not explicitly modeled.
- Minimum fracture size is limited by the grid block size.
- Uniform orthogonal mesh is required.

16

Summary of Methods: FCM (ELLIPSIM)

- An exact number of fractures can be generated.
- The fracture parameter distributions are not altered.
- The number of fractures can be very large.
- Ability for flow and transport through fractures and rock matrix
- Fractures are not explicitly modeled.
- Fractures are ellipses with fixed distribution of radius.
- Minimum fracture size is limited by the grid block size.
- Uniform orthogonal mesh is required.

DFN-FCM Comparison

- Direct Comparison: DFN versus FCM (DFN output)
  - *DFN realization is converted to FCM realization - eliminates uncertainty in generating fracture network.*
  - *The only difference is between explicit (DFN) and effective (FCM) representation of fracture network.*
  - *Effective permeability of the modeling domain and breakthrough curves can be compared for each realization.*
- Indirect Comparison: DFN versus FCM ELLIPSIM
  - *Evaluates the difference in conceptual models – flow and transport through fractures (DFN) versus flow and transport through fractures and matrix (FCM).*
  - *Effective permeability of the modeling domain and breakthrough curves have to be compared based on statistics from multiple realizations.*

Test Case Fracture Parameters

Fracture Set	Mean trend (degrees)	Mean plunge (degrees)	κ	α	R_u (m)	R_0 (m)	Number of fractures
North-South Vertical	90	0	22	2.5	500	15	2,100
East-West Vertical	0	0	22	2.7	500	15	2,000
West-East Horizontal	360	90	10	2.4	500	15	2,300

Fracture radius R follows a truncated power law distribution:

$$R = R_0 \cdot \left[1 - u + u \cdot \left(\frac{R_0}{R_u}\right)^{\alpha}\right]^{-1/\alpha},$$

Fracture orientation ϴ follows Fisher distribution:

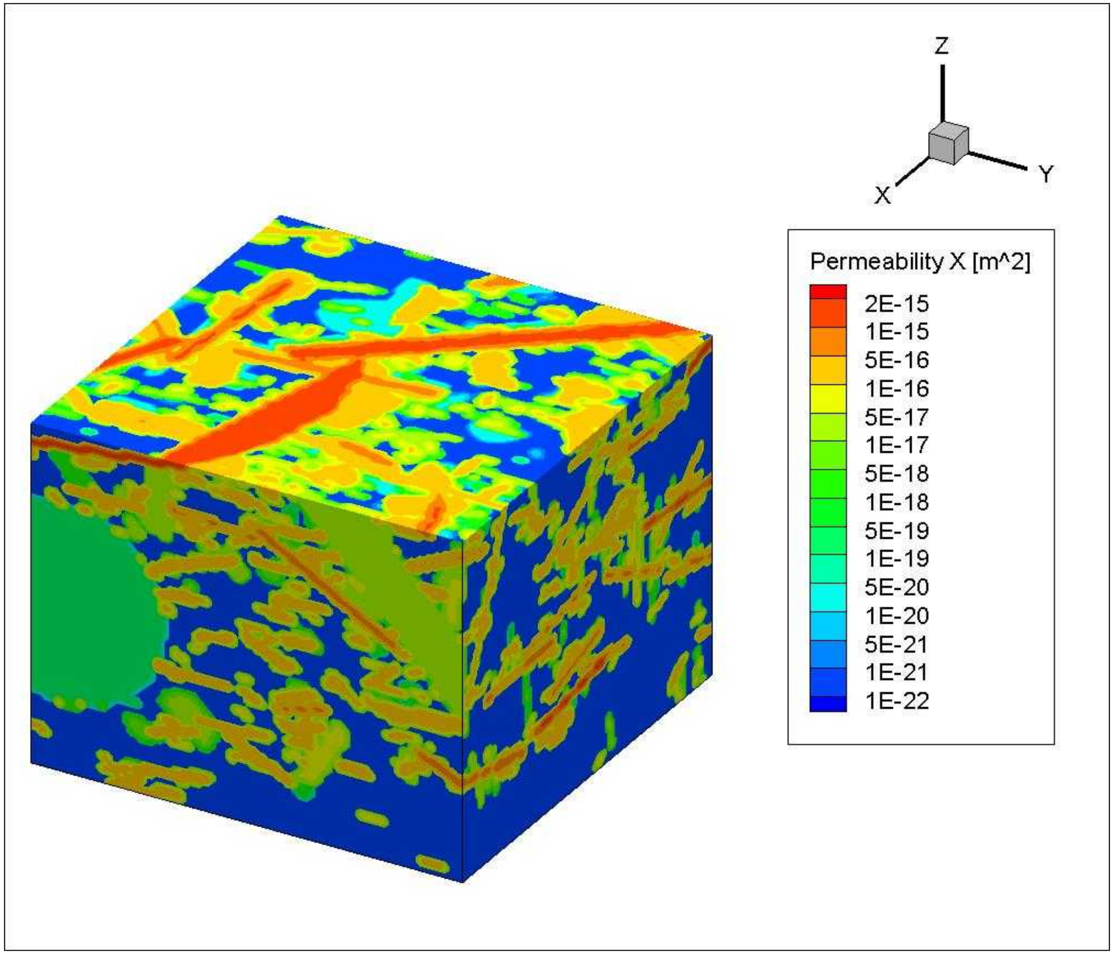
$$f(\theta) = \frac{\kappa \cdot sin\theta \cdot e^{\kappa \cdot cos\theta}}{e^{\kappa} - e^{-\kappa}},$$

Benchmark Simulations - Model Setup

- Domain: 1000 m x 1000 m x 1000 m with cell size of: 10 m x 10 m x 10 m
- No. of Elements: 1,000,000
- Porosity: Anisotropic
- Permeability: Anisotropic
- Initial Conditions: Hydrostatic pressure
- Boundary Conditions:
  - Pressure at West Face: 1.001 MPa
  - Pressure at East Face: 1.0 MPa

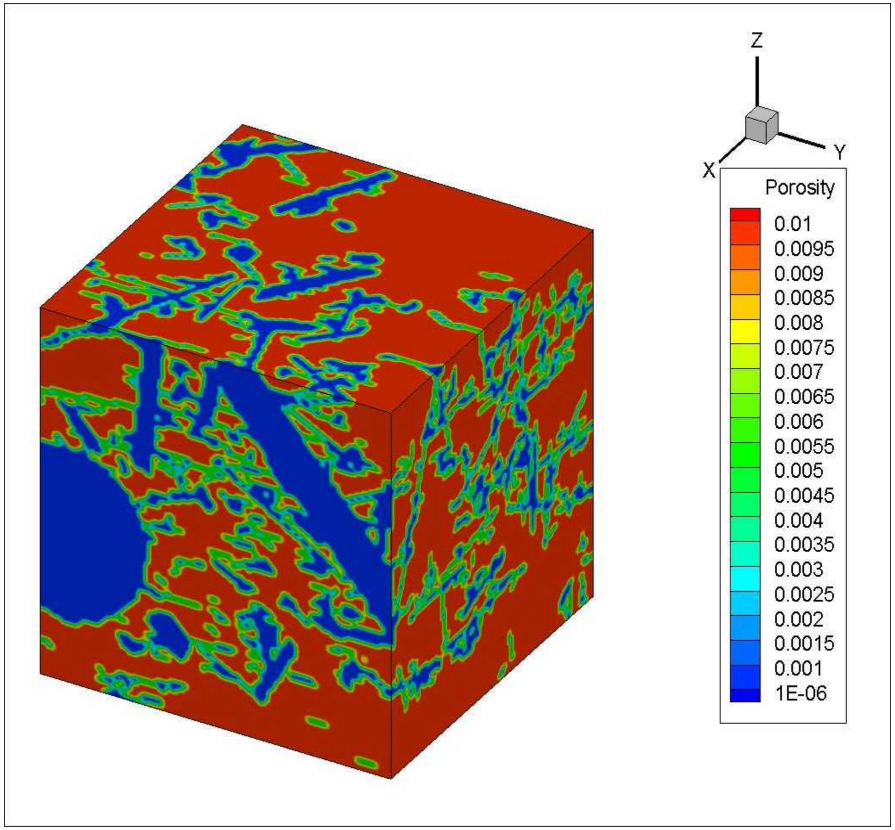
Anisotropic Permeability Field
Based on DFN Works Fracture Output Data

- 5 Realizations (Permeability fields)
  - Permeability field of Realization 1 shown



Anisotropic Porosity Field
Based on DFN Works Fracture Output Data

- 5 Realizations (Porosity fields)
  - Porosity field of a Realization



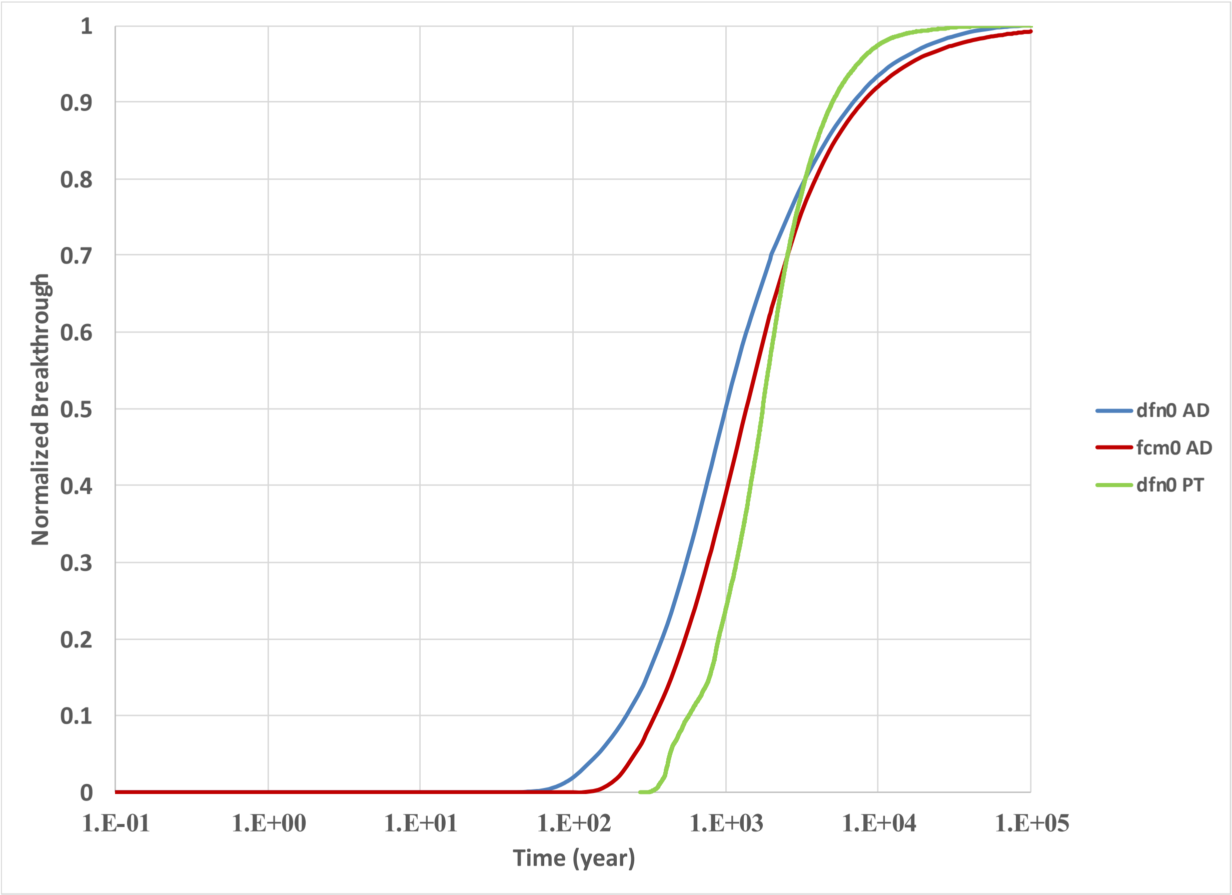
Effective Permeability Evaluation: DFN Works Fracture Output Data

- PFLOTRAN numerical simulator used
- Steady state flow utilized to estimate effective permeability for each realization
- Darcy's law and east face flux used to calculate effective permeability

Realization	Pressure Difference (Pa)	East Face Flux (kg/s)	Effective Permeability (m^2)
1	1000	4.57E-05	4.67E-17
2	1000	3.88E-05	3.97E-17
3	1000	4.15E-05	4.24E-17
4	1000	3.60E-05	3.68E-17
5	1000	3.79E-05	3.87E-17

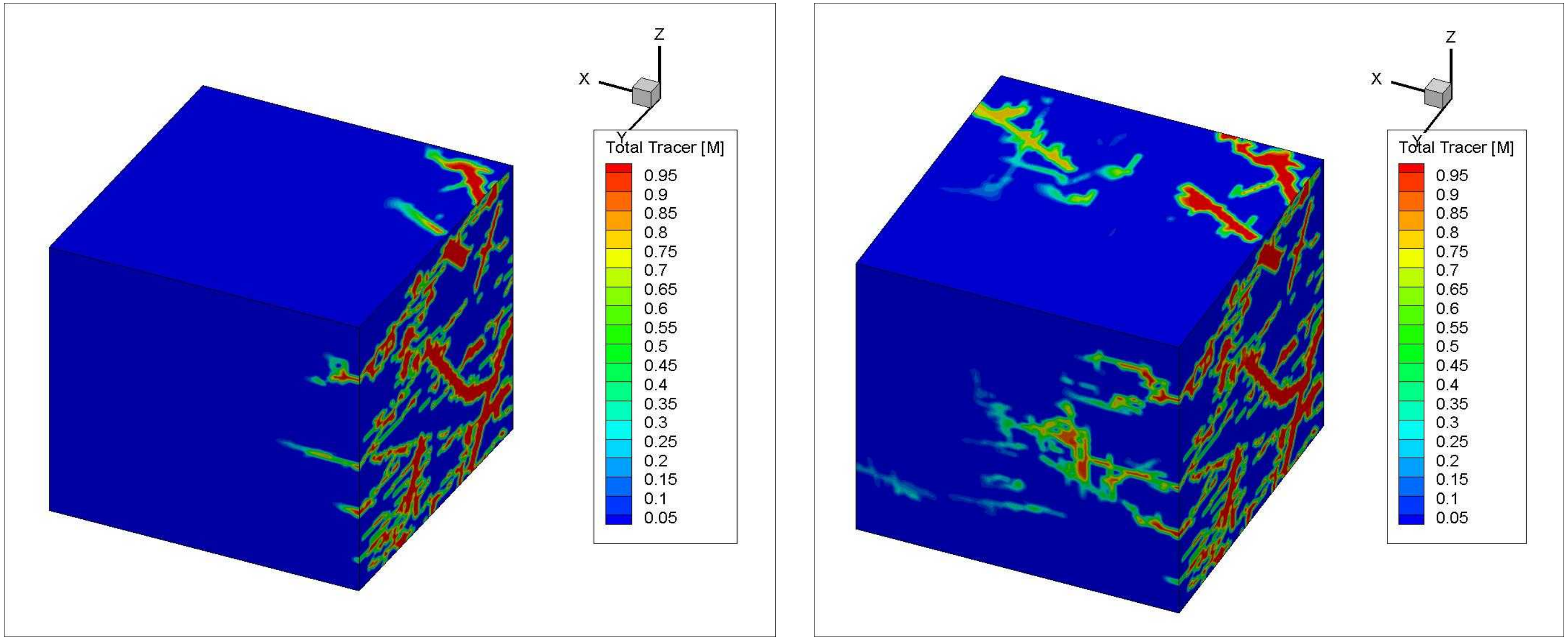
Comparison of Tracer Breakthrough Curves: DFN Works Fracture Output Data

- Tracer breakthrough curves using DFN (Particle Tracking), DFN (Advection-Diffusion) and FCM (Advection-Diffusion) for Realization 0



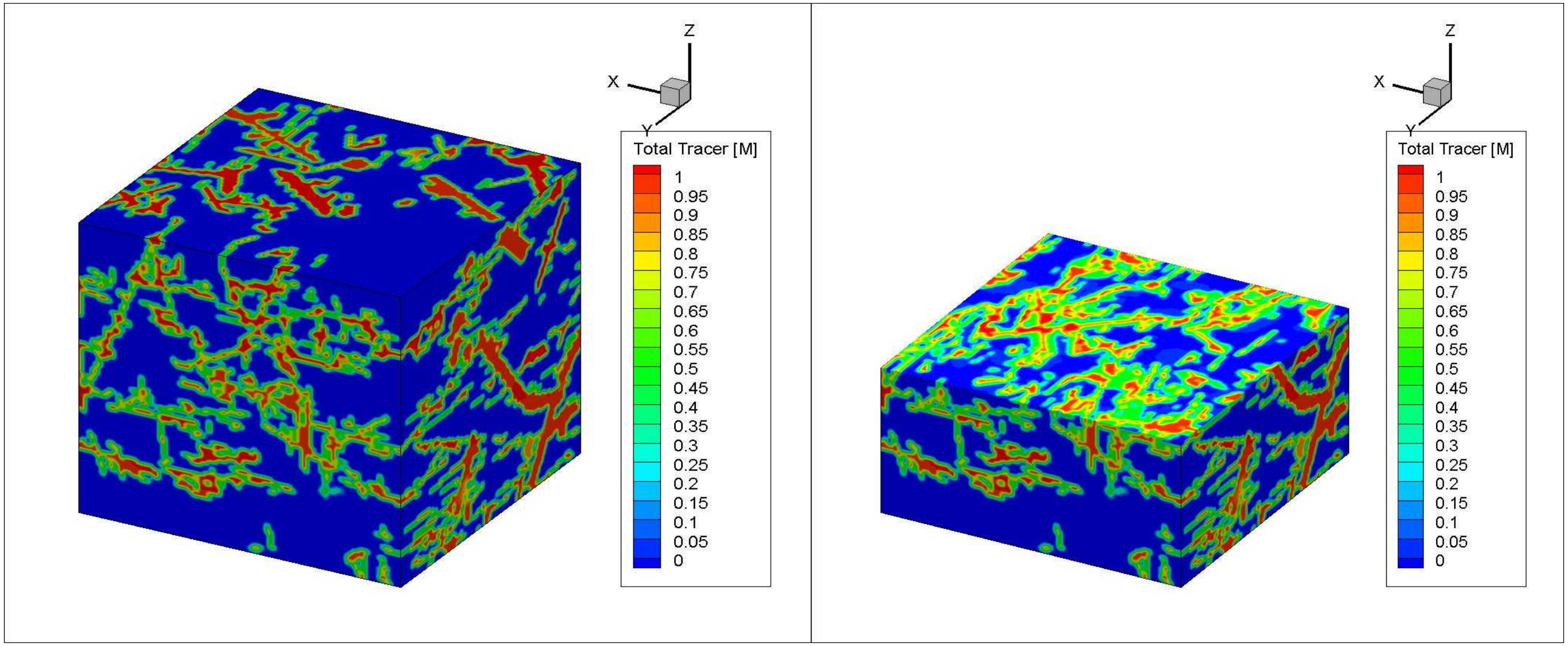
Tracer Distributions: DFN Works Output Data

- FCM Tracer Transport Results (after 70 and 400 years simulation time) for Realization 0



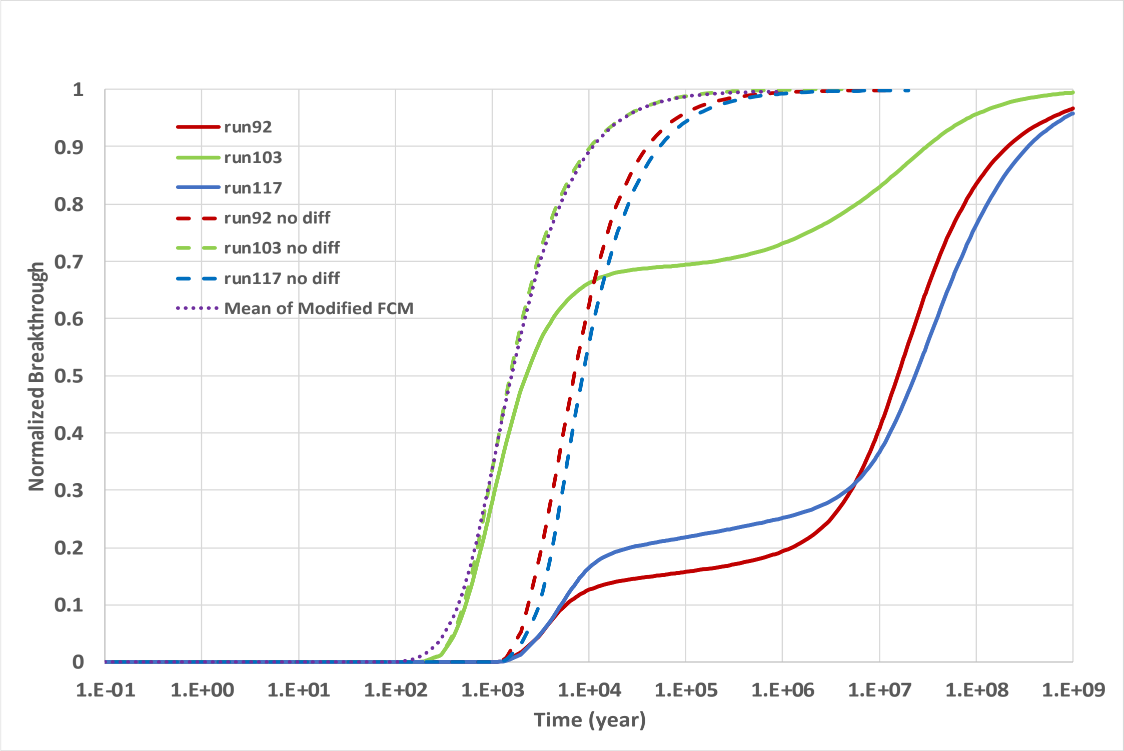
Tracer Distributions:
DFN Works Output Data (Contd.)

- FCM Tracer Transport Results (after 1.0E05 years simulation time) for Realization 0



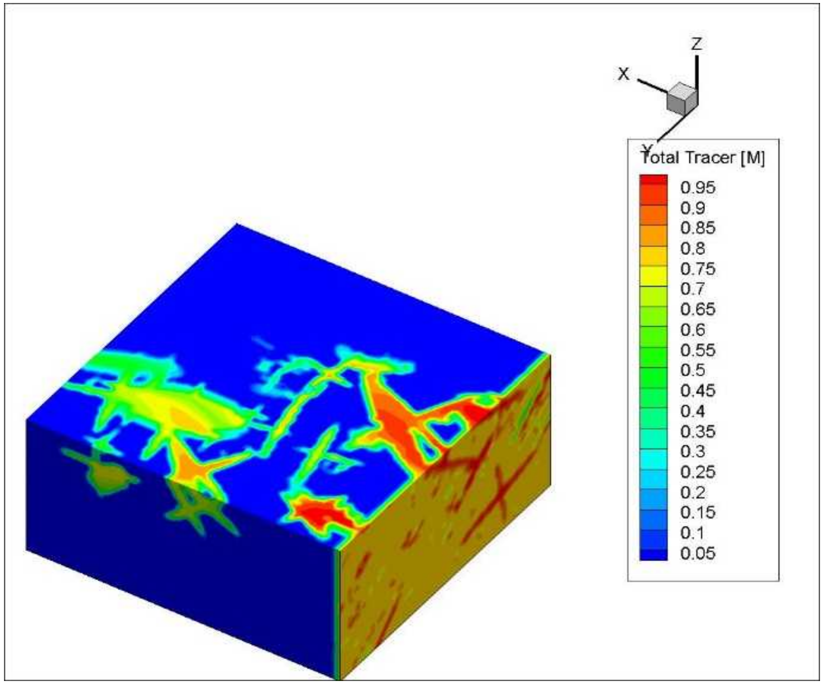
Tracer Breakthrough Curves: FCM with Original Parameter Distributions

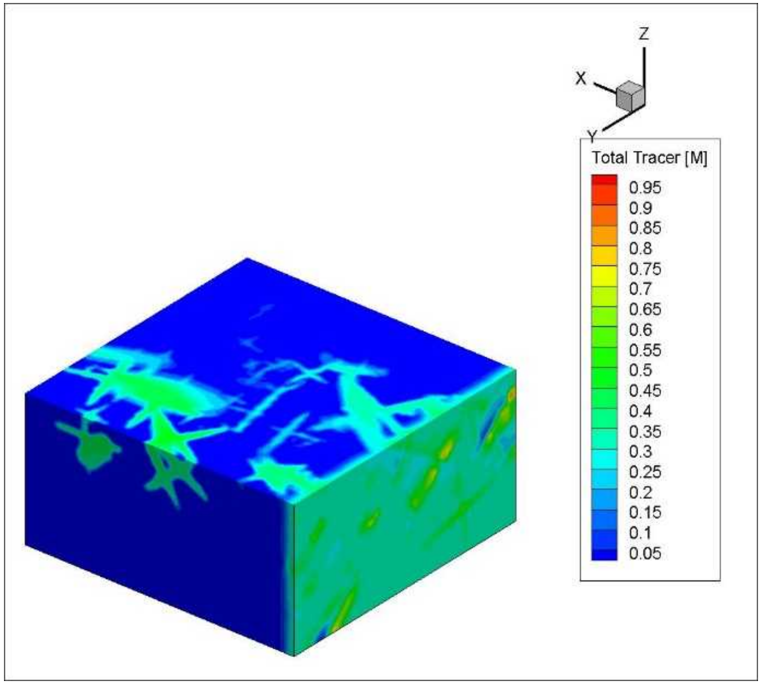
- FCM Tracer Transport Results (after 70 and 400 years simulation time)



Tracer Distributions:
FCM with Original Parameter Distributions

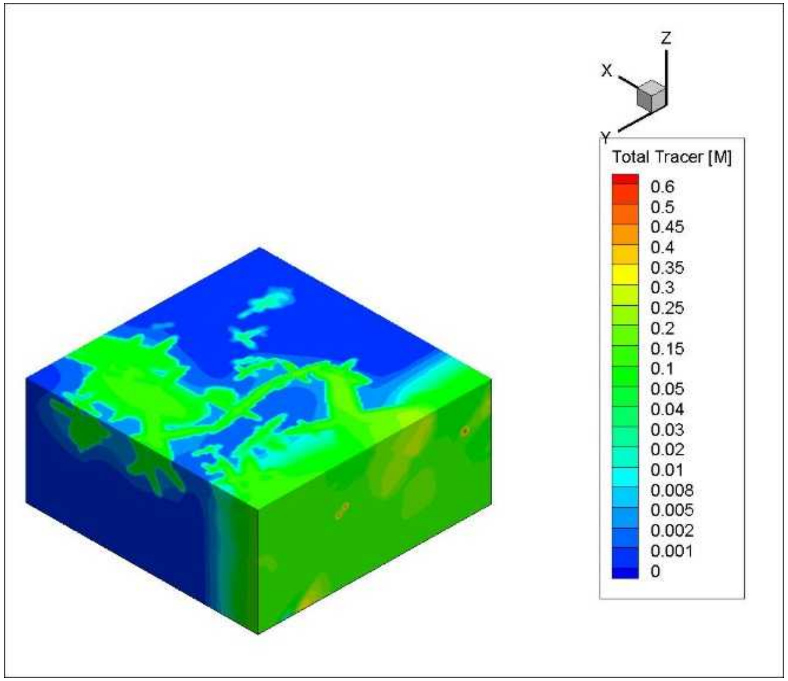
- FCM Tracer Transport Results (after 1.E03 and 1.E04 years simulation time)

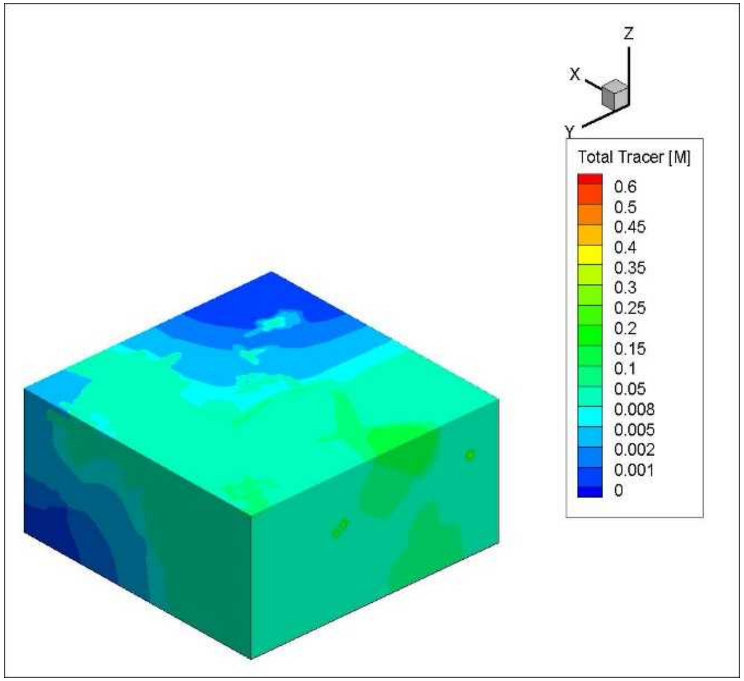




Tracer Distributions:
FCM with Original Parameter Distributions (Contd.)

- FCM Tracer Transport Results (after 1.E05 and 1.E06 years simulation time)





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