Visualization and Hierarchical Analysis of Flow in Discrete Fracture Network Models

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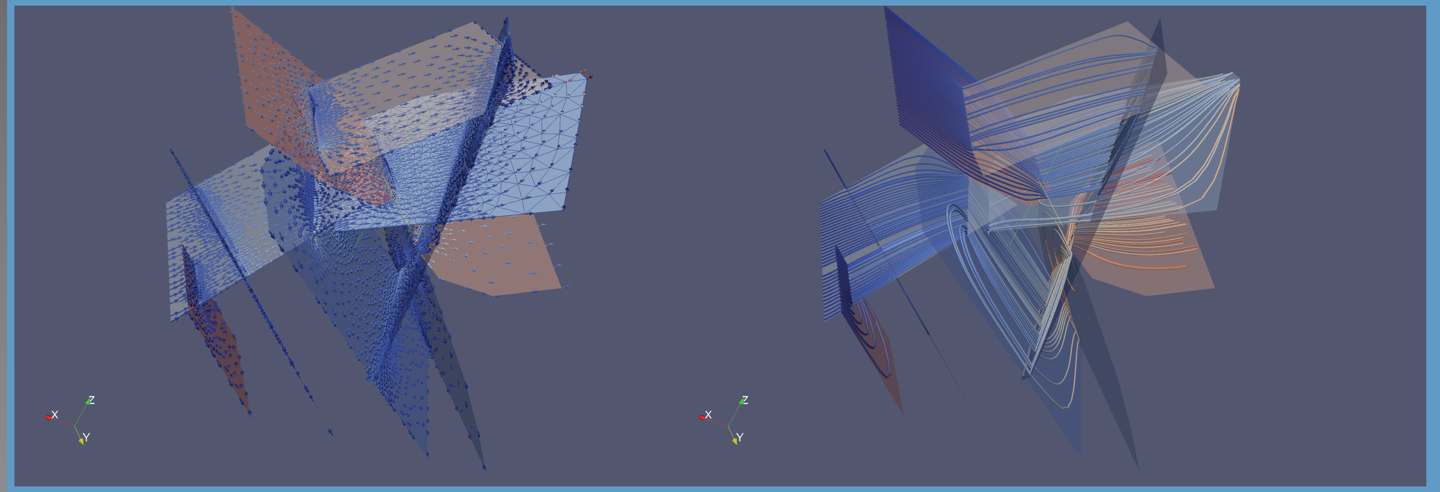
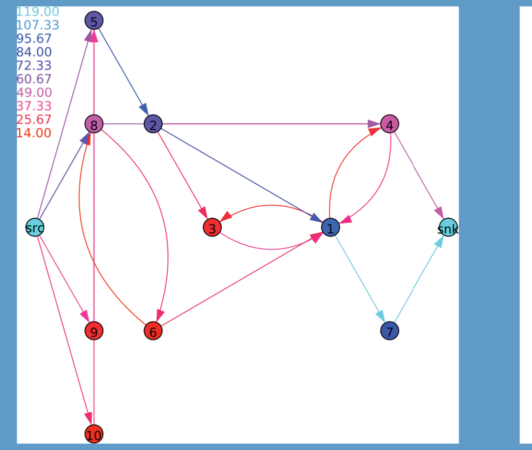
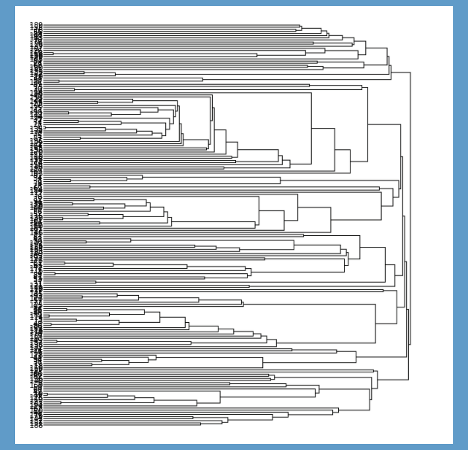
Flow and transport in low permeability fractured rock is primary in interconnected fracture networks. Prediction and characterization of flow and transport in fractured rock has important implications in underground repositories for hazardous materials (eg. nuclear and chemical waste), contaminant migration and remediation, groundwater resource management, and hydrocarbon extraction. We have developed methods to explicitly model flow in discrete fracture networks and track flow paths using passive particle tracking algorithms. Visualization and analysis of particle trajectory through the fracture network is important to understanding fracture connectivity, flow patterns, potential contaminant pathways and fast paths through the network. However, occlusion due to the large number of highly tessellated and intersecting fracture polygons preclude the effective use of traditional visualization methods. We would also like quantitative analysis methods to characterize the trajectory of a large number of particle paths. We have solved these problems by defining a hierarchal flow network representing the topology of particle flow through the fracture network. This approach allows us to analyses the flow and the dynamics of the system as a whole. We are able to easily query the flow network, and use paint-and-link style framework to filter the fracture geometry and particle traces based on the flow analytics. This allows us to greatly reduce occlusion while emphasizing salient features such as the principal transport pathways. Examples are shown that demonstrate the methodology and highlight how use of this new method allows quantitative analysis and characterization of flow and transport in a number of representative fracture networks.

BACKGROUND

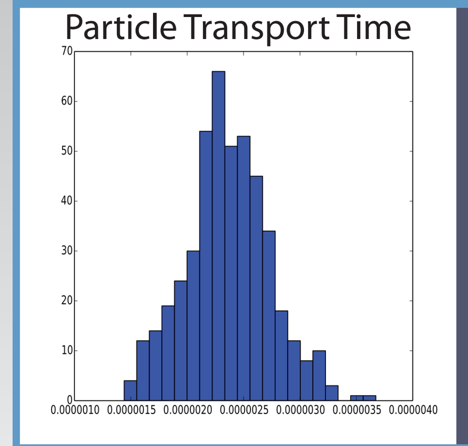


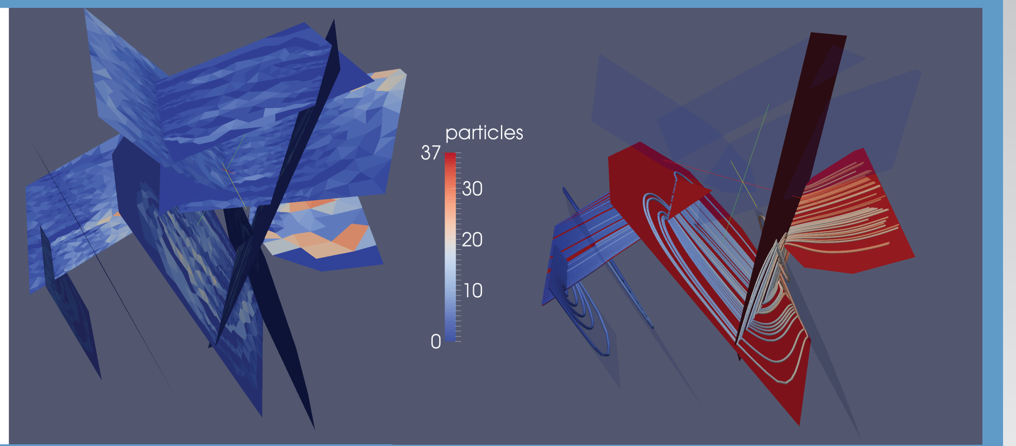
Our Discrete Fracture Networks are produced using a stochastically based using a log-normal and truncated power-law distribution for fracture sizes and Fisher distribution for the orientation. The fractures are then meshed using LAGRIT (Los Alamos Gridding Tool) which does a conforming Delaunay triangulation on the grid. A steady-state flow solution for saturated water is obtained using FEHM (Finite Element Heat and Mass Transfer code) or PFLOTRAN. Finally particles are advected on the 2D manifolds using a custom predictor-corrector based method and projected back into 3D space.





Our visualization and analysis framework uses python based scripts to generate a graph of the flow topology. Each node in the graph represents a fracture polygon in the DFN and stores attributes about the particle flow and transport within that fracture as well as links to the original geometry. Edges in the graph represent intersections between two fractures where particles traverse and also hold attribute information about the traces that pass through. For more complicated DFN (more than 1k fractures) we build cluster the graph and build a hierarchy visualized in the above dendrogram. This graph is used to run queries on the particle flow in the DFN.



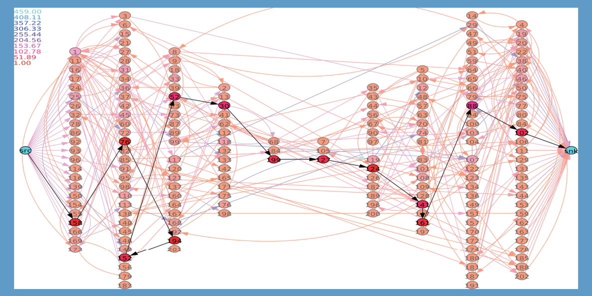


Our framework automatically produces statistics about the flow, and updates the geometry files with these statistics. For example the histogram of particle transport time for a DFN and the per-cell particle density rendered on the original fracture geometry. We also created a detailed, python based query system which allows the user to ask questions about the flow topology, the results being either statistical output such as histograms, tagged geometry files such as the above particle density, or a selection such as the fracture path with the most particles traced through it.

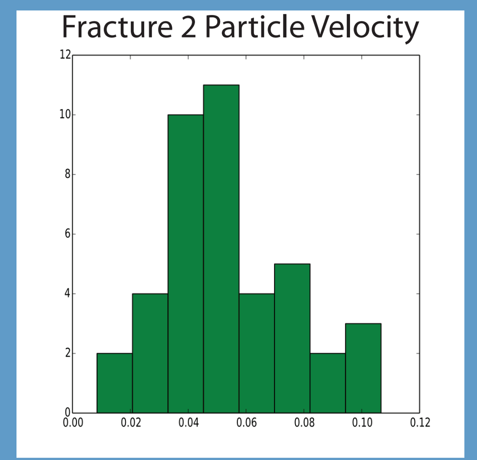
METHOD

Query Based Visualization and Analysis

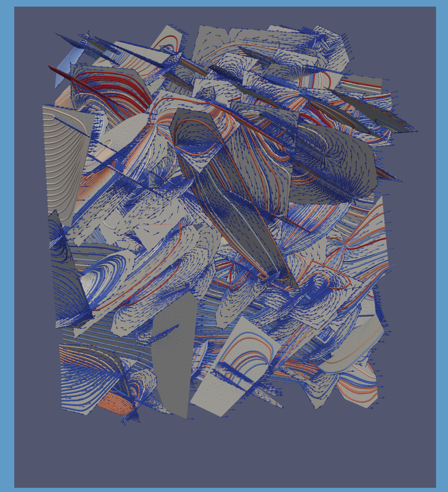
Our visualization and analysis framework is query based, meaning that we provide the user with a set of tools which can easily parse the flow graph in order to produce detailed outputs about how the system is behaving. The user is able to produce graphs and plots of the data, select specific sets of fracture polygons or particles based on a query, or add statistical information back onto the original geometry files which can then be visualized interactively. We also allow the user to manually select fractures, fracture intersections, or particle traces of interest and limit there queries to this subset. This tool allows users to easily select several metrics for analysis which help in understanding the state of the system as a whole. Our Query based system is built on python and thus is easily extendable to new types of input with very little effort by the user.



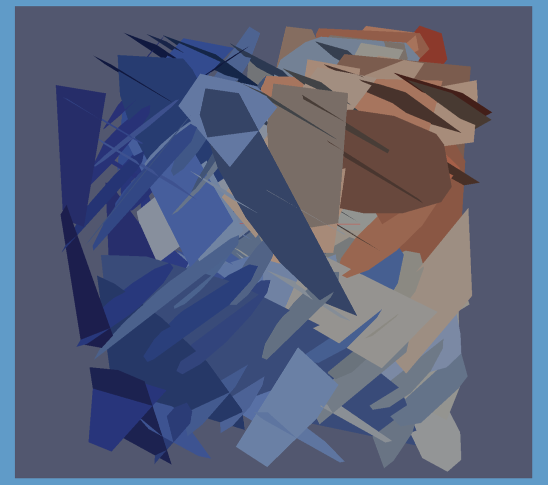
We allow users to query the among others the fastest, shortest, most concentrated paths.



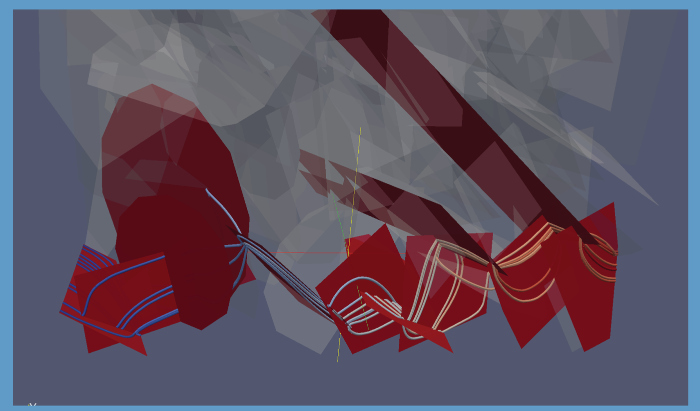
Histogram plots of transport on individual fractures



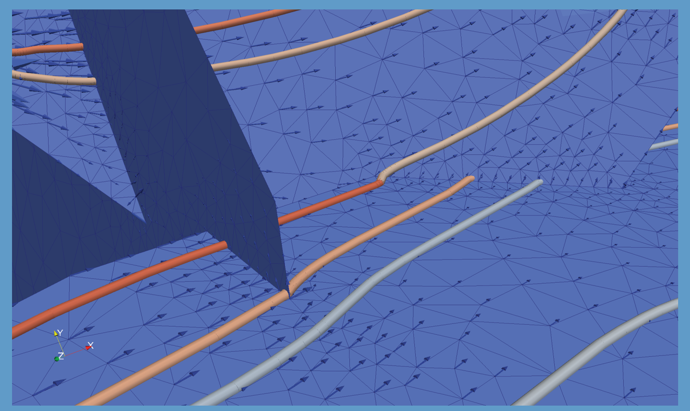
The user can interactively visualize the DFN, flow field, and Particle traces as well as query the system for details.



By tagging the geometry we can easily visualize details about the DFN, here each fracture is rendered by the average time a particle enters it.

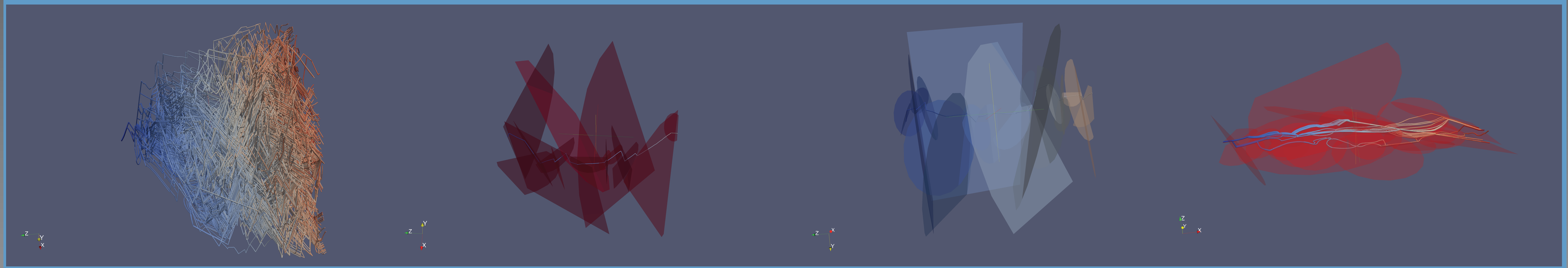


Path based queries highlight portions of the DFN, here we show the high-density path, which has the highest number of particles traversing it over the shortest number of fractures.

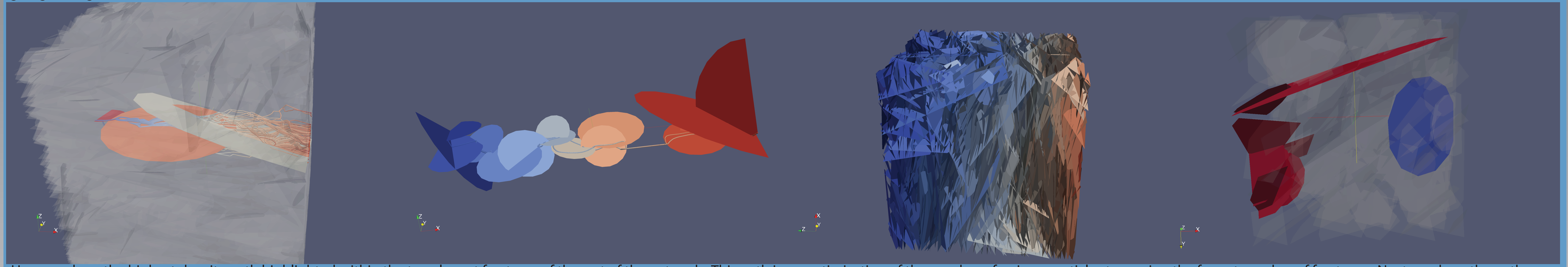


After making a selection, the user is able to more easily investigate the now subset of geometry. This allows us to better explore the dataset.

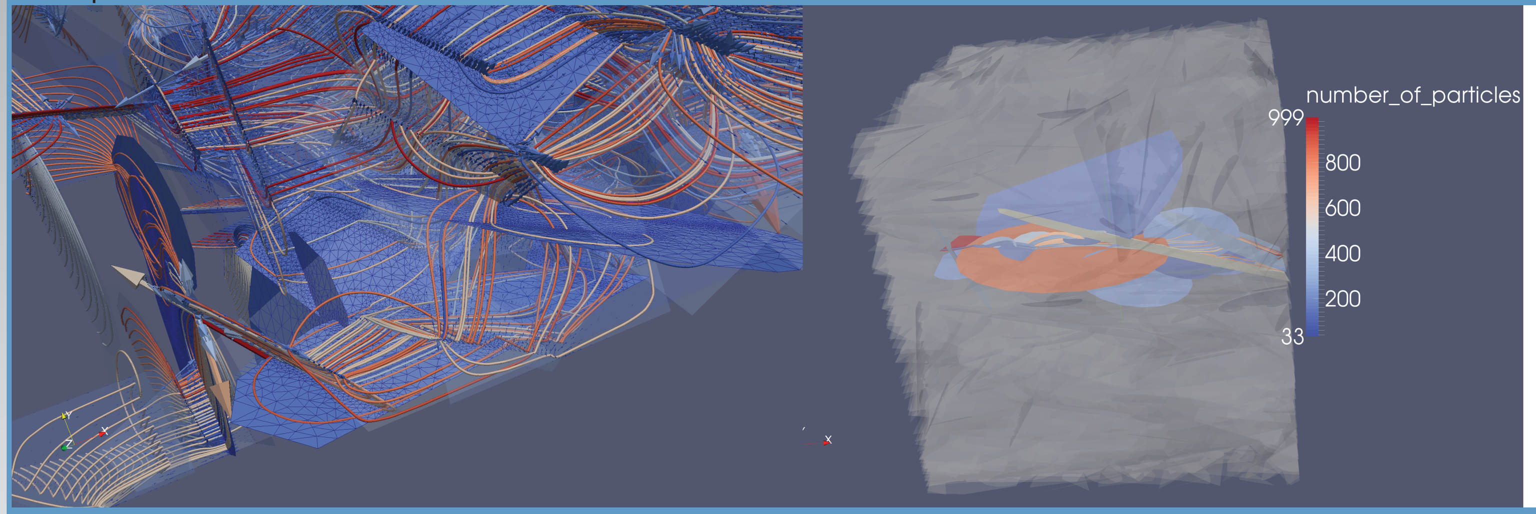
RESULTS

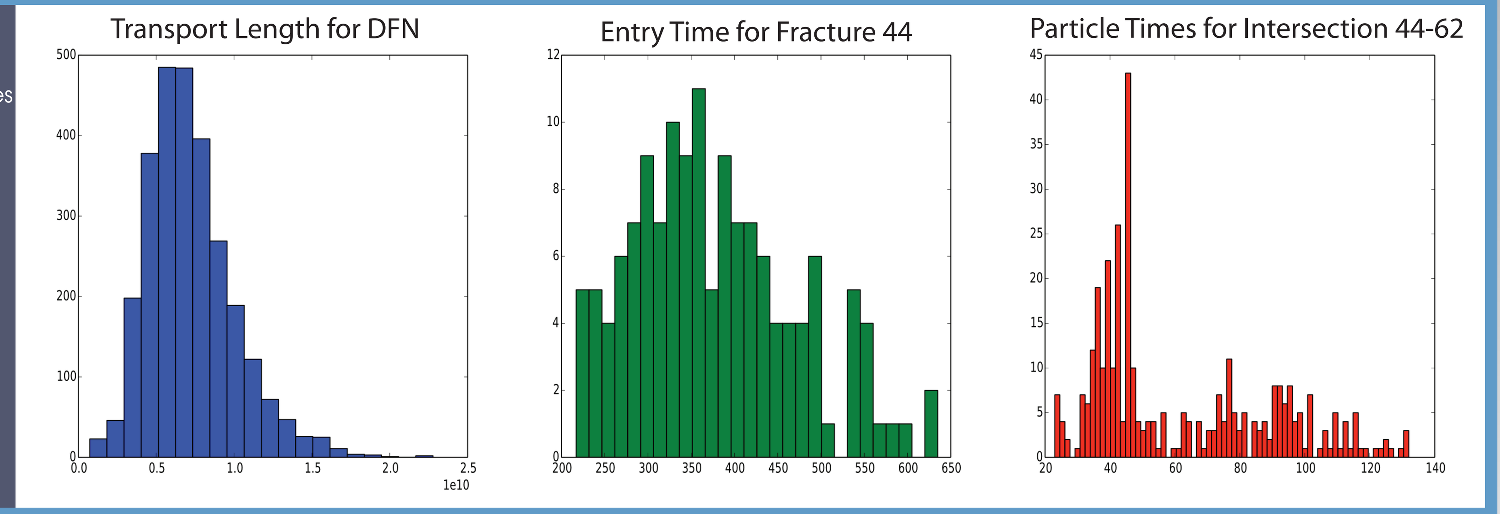


Here we show the results of our tool on a very large (over 3K Fractures) DFN. For this DFN we ran multiple realizations of the flow field, and thus have several data sets to analyze. We show here (from left to right) the particle traces rendered by there advection time, the shortest path in the DFN for a given flow field, the fastest path in the DFN with fractures rendered by the average exit time of each trace going through the network, and finally the path with the most unique particles going through it.



Here we show the highest density path highlighted within the translucent fractures of the rest of the network. This path is an optimization of the number of unique particles traversing the fewest number of fractures. Next we show the path through the DFN with the slowest transport time as in the next image, fractures are rendered by relative transport time. We also allow the user to query the DFN itself, in the last image we show all fractures (red) where particles originate which end up in the blue fracture.





Finally we allow the user to select subsets of the Fracture, Flow field, and particle traces if there is a specific are they want to investigate. We can show these selections separately, or within the rest of the fracture. We can also plot statistical details for the fracture network as a whole (blue), individual fractures (green)

In conclusion we have presented a novel framework for the visualization and analysis of flow and transport on discrete fracture networks. We have created a powerful and easily extendable tool for querying analytics on the flow topology and representing those queries visually. This tool helps give user a better intuition of how the system as a whole behaves. In the future we will investigate exact analytical metrics to better classify the differences between multiple realizations of the systems and configurations of the same system.