Advanced Conceptual Models for Unsaturated and Two-Phase Flow in Fractured Rock

Project 87003
2002-2005

Environmental Management Science Program
Office of Science
US Department of Energy

Participants

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Problem Statement

- The Department of Energy faces substantial problems related to two-phase flow in fractured rock
  - Transport of dissolved contaminants in the Vadose Zone
  - DNAPL migration below the water table
- Conceptual models currently used to address these problems are diffusive in nature and do not properly include the influence of fractures
- Diffusive models predict smooth, gradual changes in concentration, whereas field and laboratory evidence suggests that fractures can facilitate rapid and widespread contamination, producing a sparse distribution of concentrated contaminants

Driving Issues

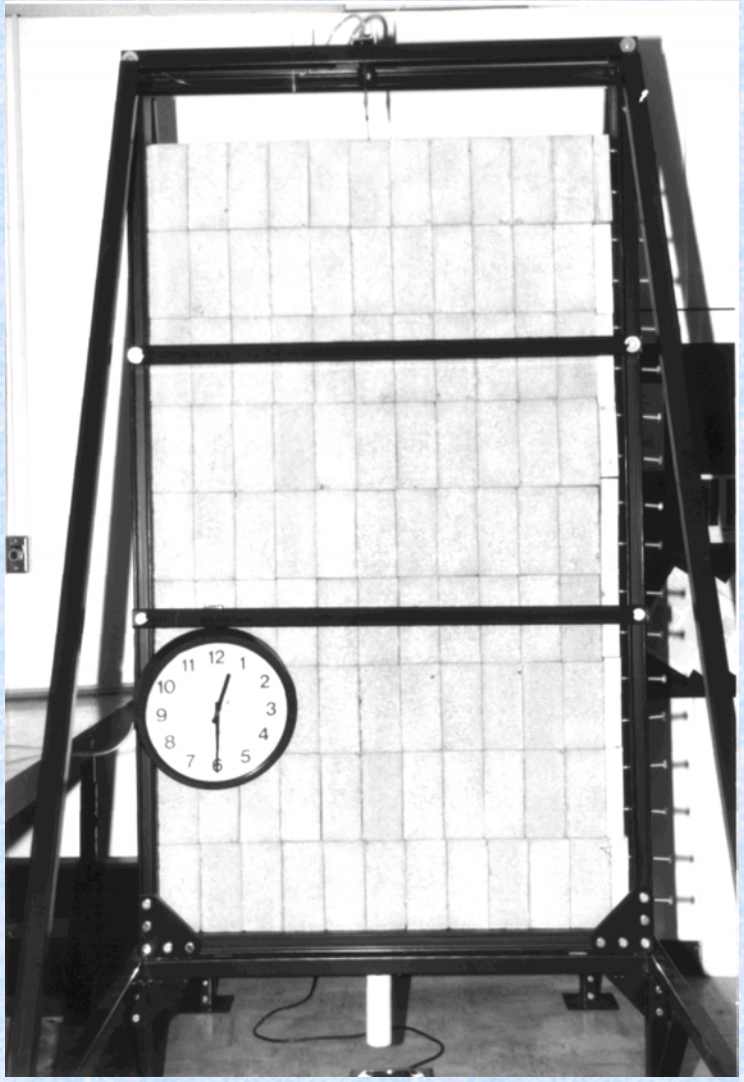
- INEEL, Subsurface Disposal Area - extremely rapid solute transport through fractured basalt, with additional complication of delayed release

- INEEL, Test Area North - unknown 3-D distribution of chlorinated solvents within fractured basalt

- Oak Ridge, Y-12 Plant - poorly understood migration of chlorinated solvents in fractured bedrock

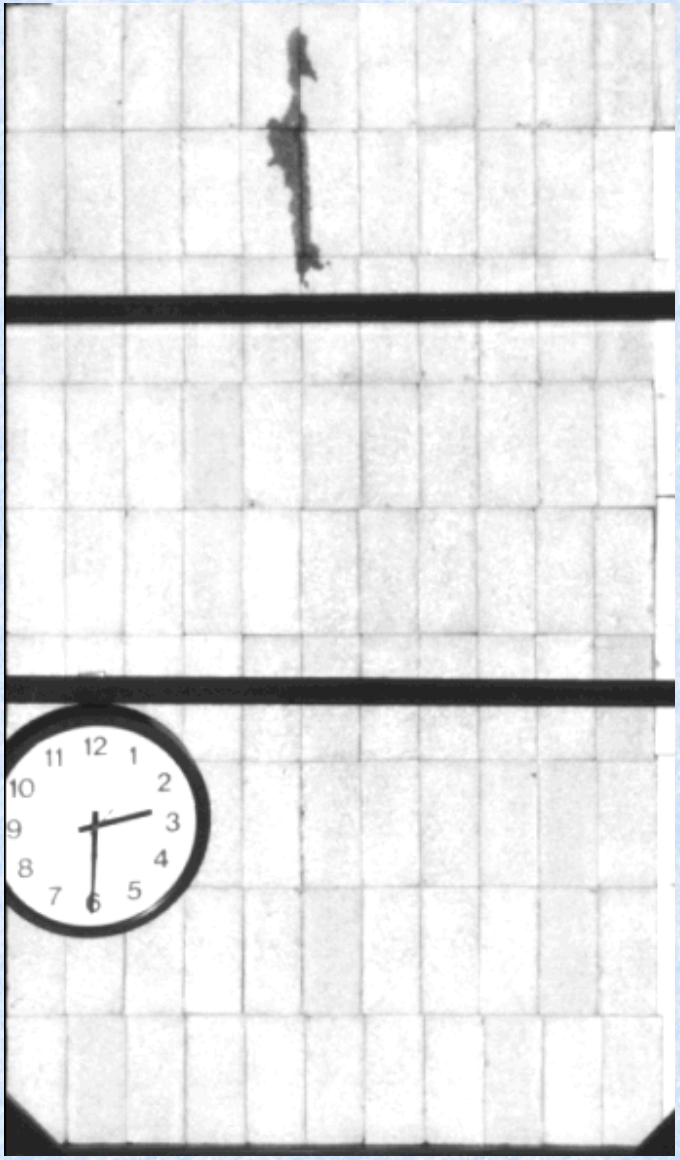
- Yucca Mountain - substantial evidence that tritium and chlorine-36 have penetrated 100's of meters below land surface through both welded and nonwelded fractured tuffaceous units

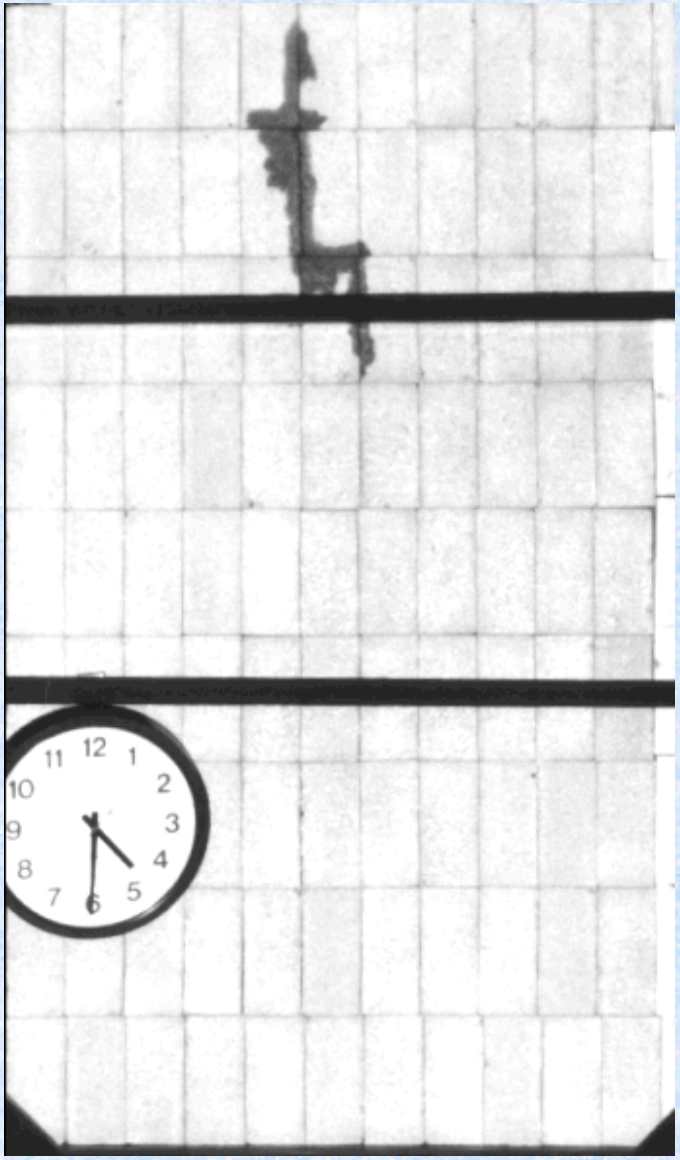
Illustrative Example



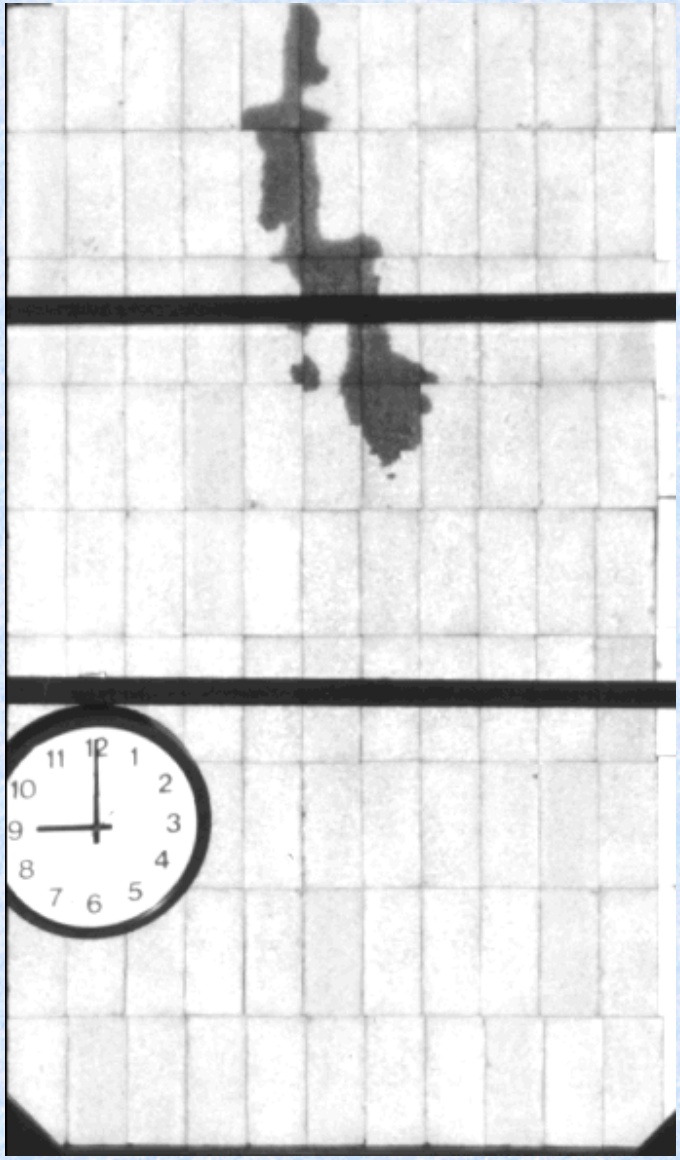
Experimental Design

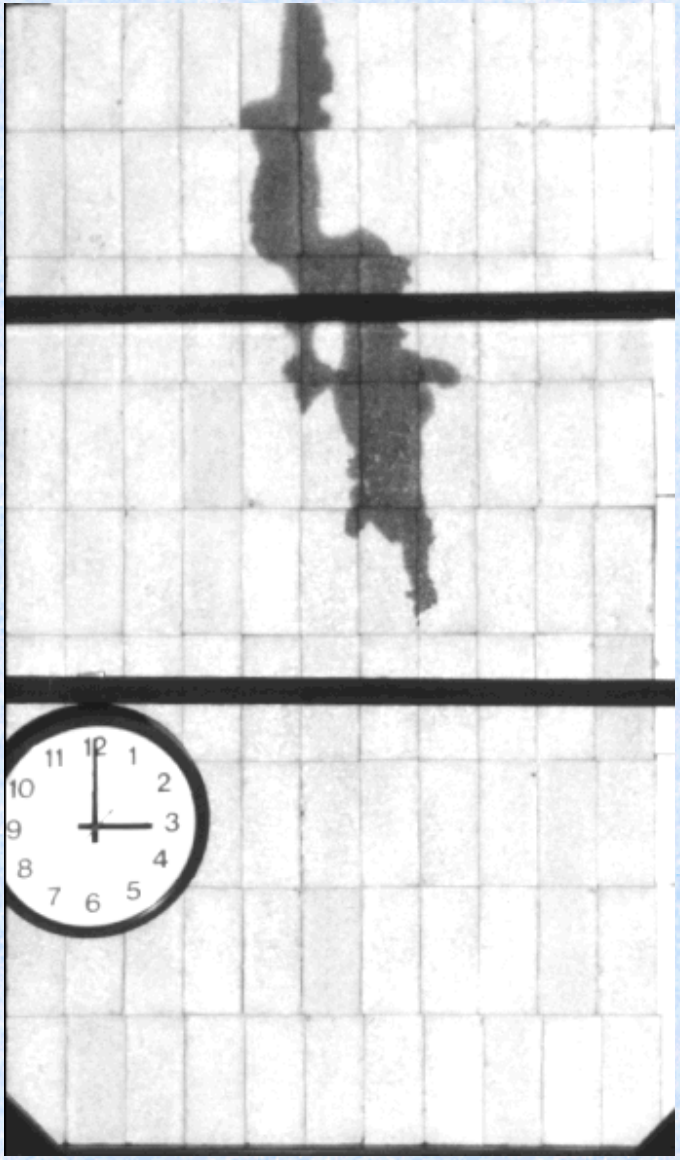
- Uncemented brick wall 1.7m high, 1m wide
- Bricks chosen to facilitate matrix interaction
  - High porosity (0.32)
  - High sorptivity
- Bricks washed and edges smoothed
- Bricks assembled within load frame
- Force applied to assure contact across fractures
- Water equilibrated to bricks
- Steady flow (1.2 ml/minute) to a central fracture at top
- Experiment ran for 71 days
- Wetted structure development recorded with photographs



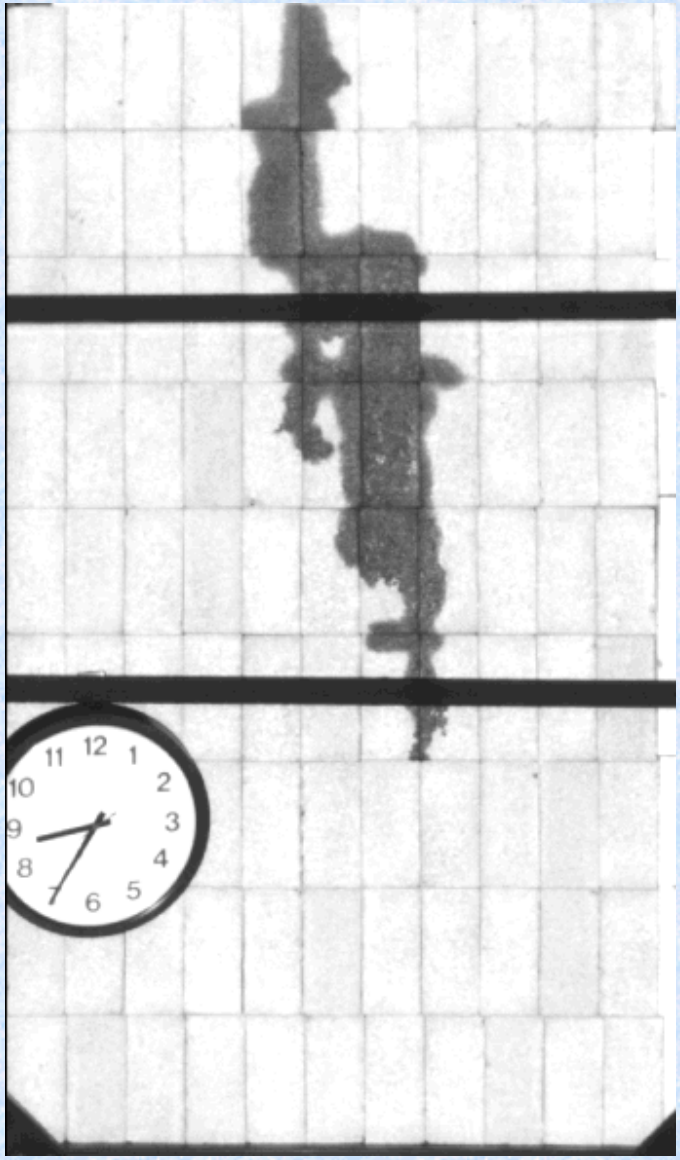


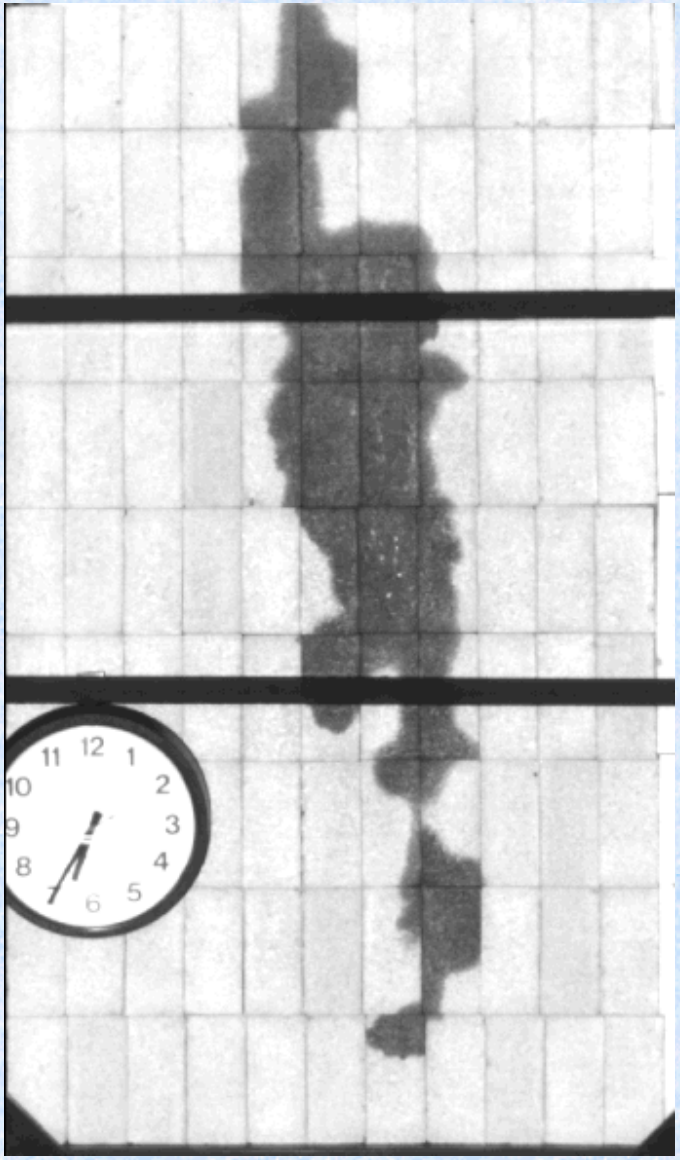
5 hours



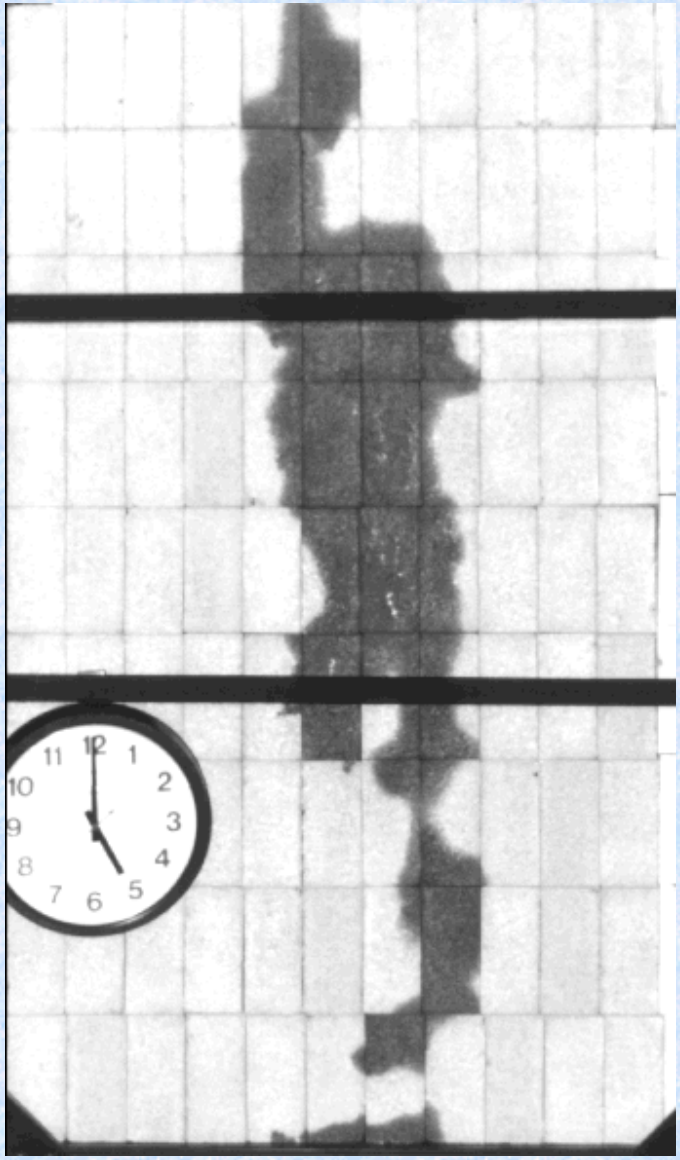


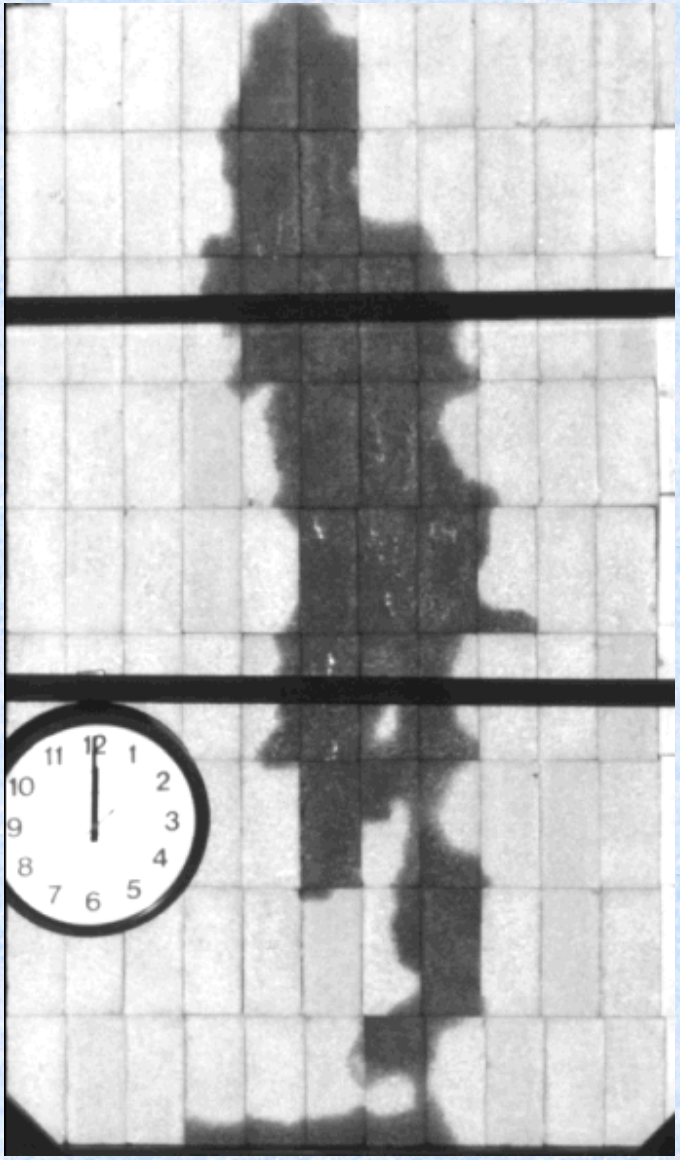
21 hours



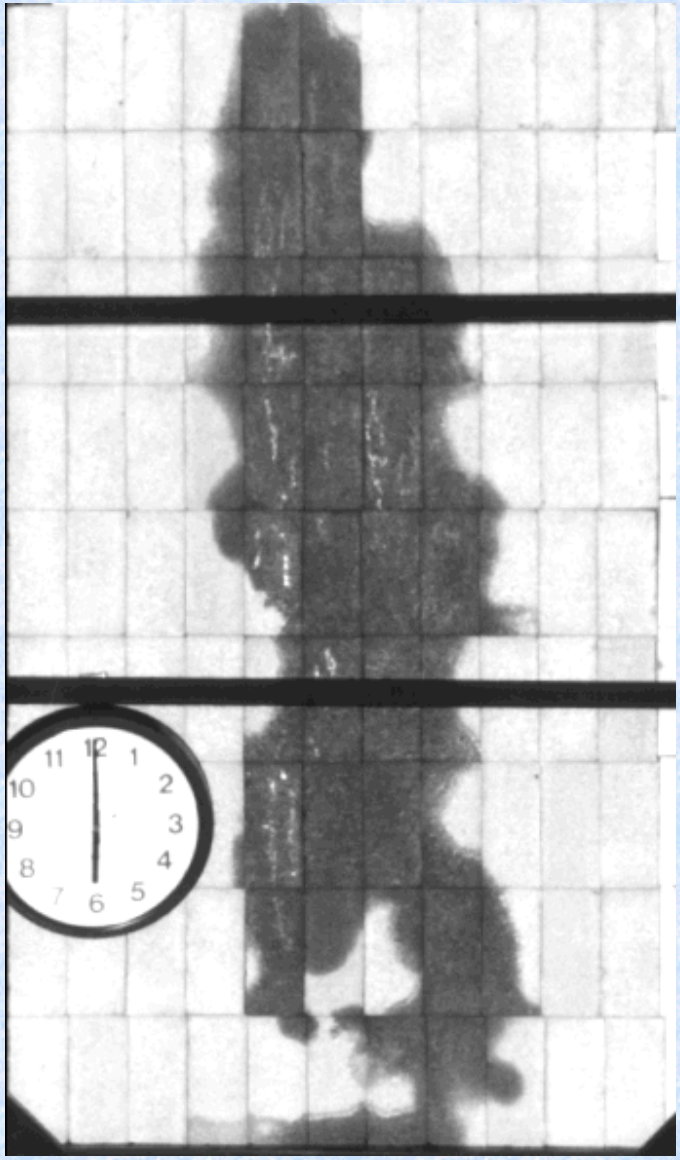


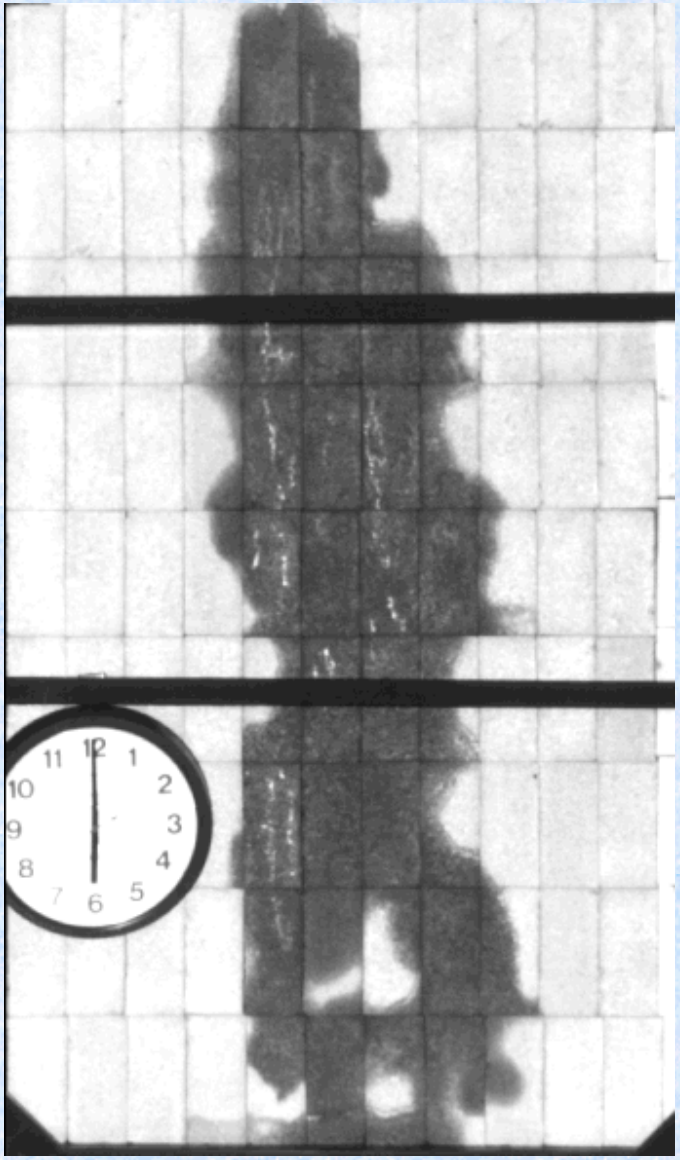
44 hours





64 hours





151 hours

Observations from the Brick Wall Experiment

- Fractures controlled system response by acting as both pathways and capillary barriers
- Fracture intersections placed a critical control on pathway development and multiple pathway formation
- Experiments exhibited unsteady behavior despite steady inflow and a reasonably quiet environment

Developing New Conceptual Models for Two-Phase Flow in Fracture Networks

- Understand processes at fracture intersections (UI, INEEL)
- Understand coupled behavior in fracture networks (SNL, UC, UI)
- Develop numerical codes for network-scale behavior (SNL, UC)
- Exercise numerical codes on realistic fracture networks and distill the fundamental behaviors (UC, SNL, INEEL, UI)

Supporting Investigations

- Two-phase flow processes within single fractures (BES)
- Processes in fracture-matrix networks (ESRA)

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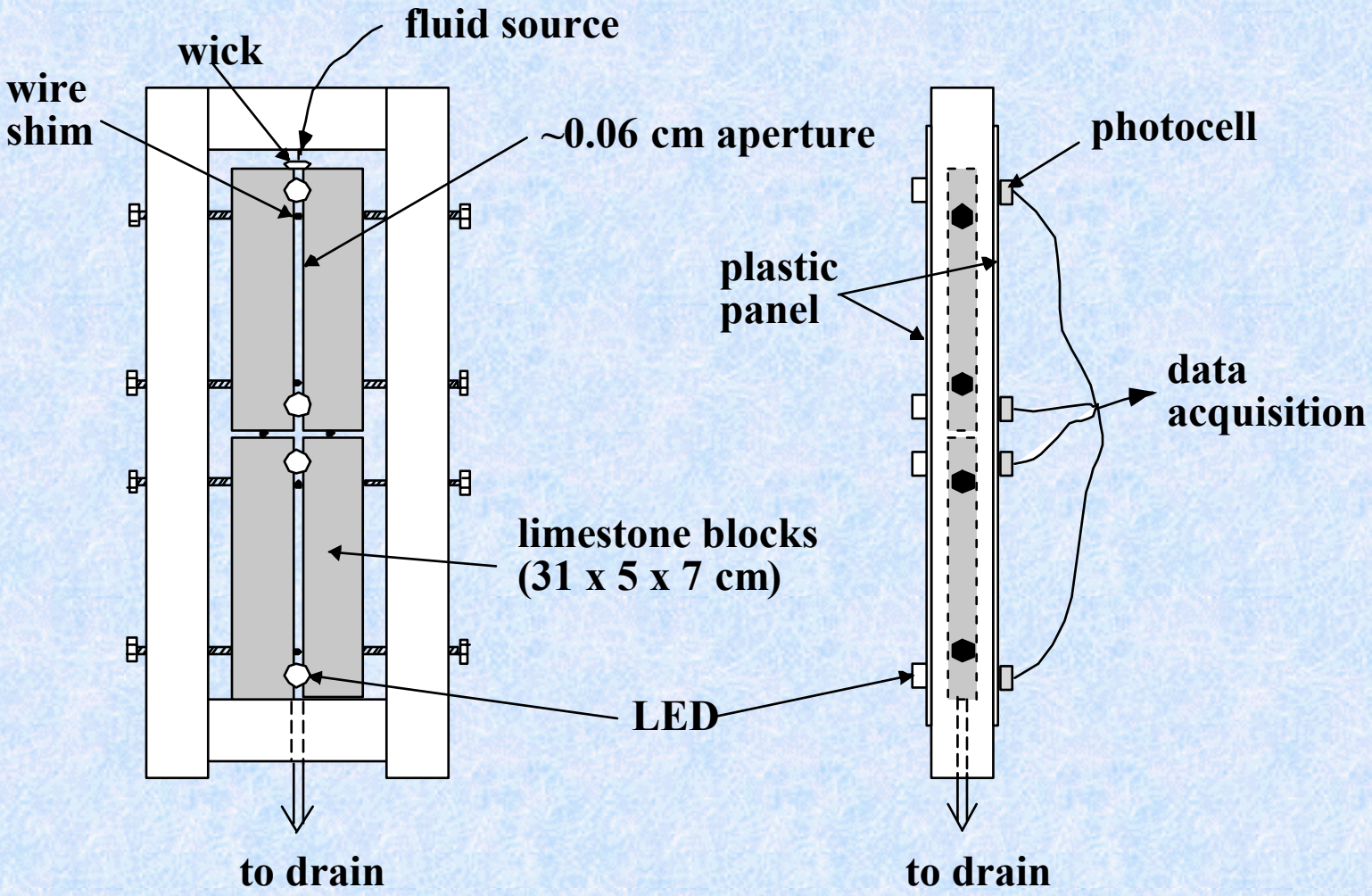
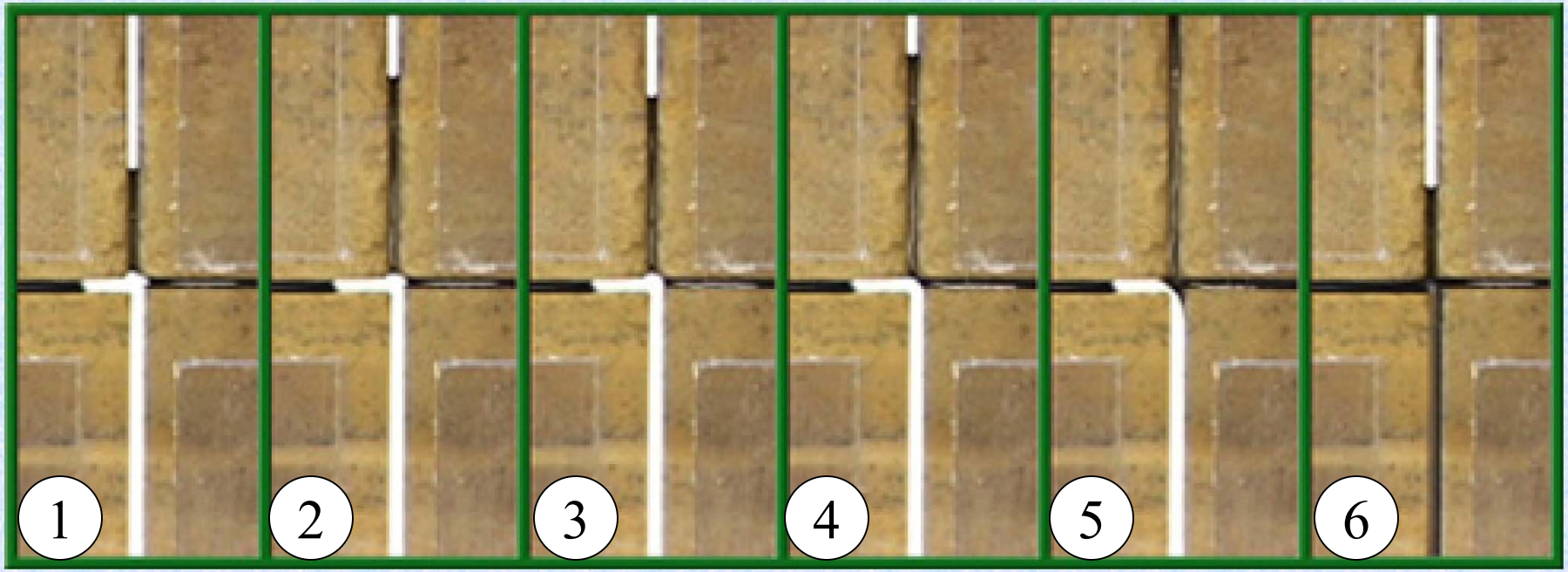
Fracture Intersections (ESRA)

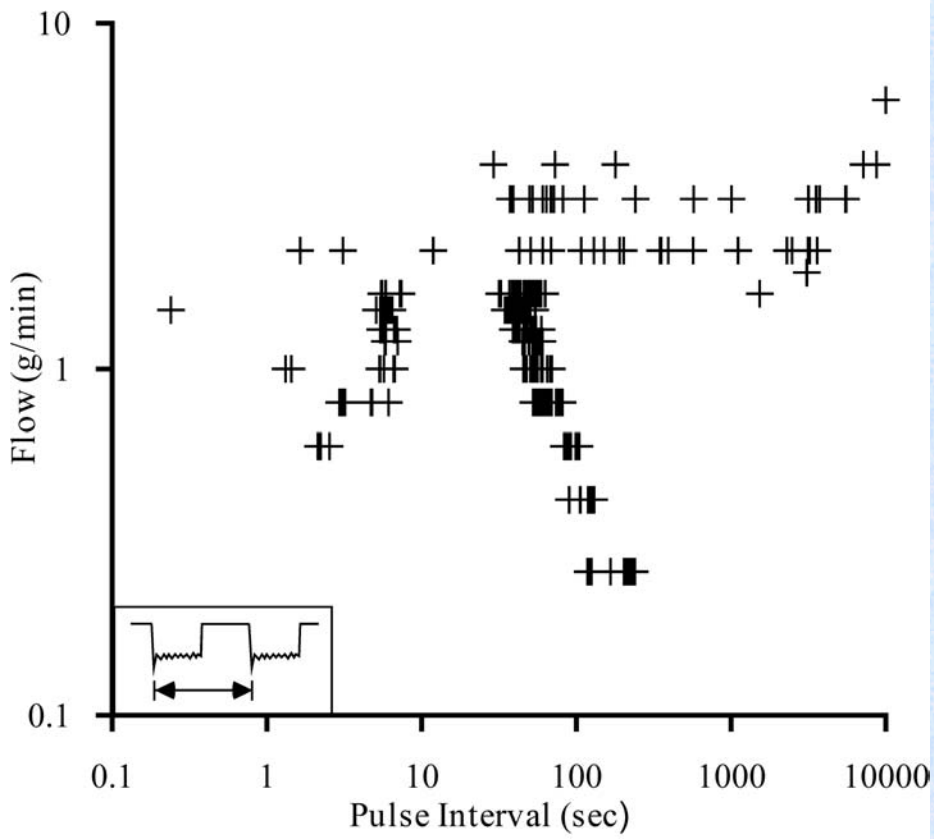


Behavior at a Simple Intersection



3.5 x 1.8 cm region about the intersection
apertures are ~0.06 cm
supply rate of ~1 ml/minute
6-step fill and drain sequence takes ~ 40 seconds
this regime is observed at flow rates <2 ml/minute

Interval between Successive Discharge Events



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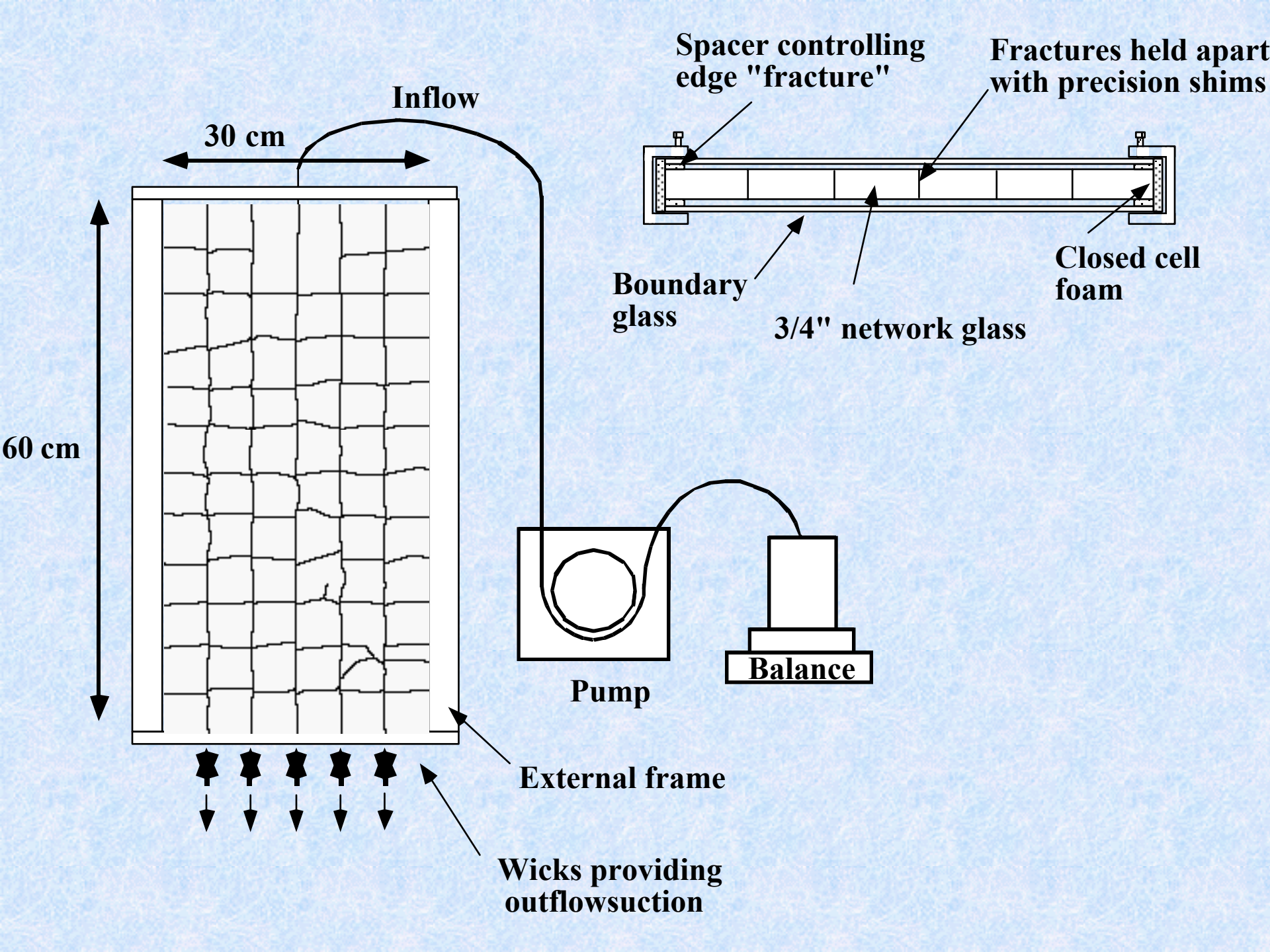
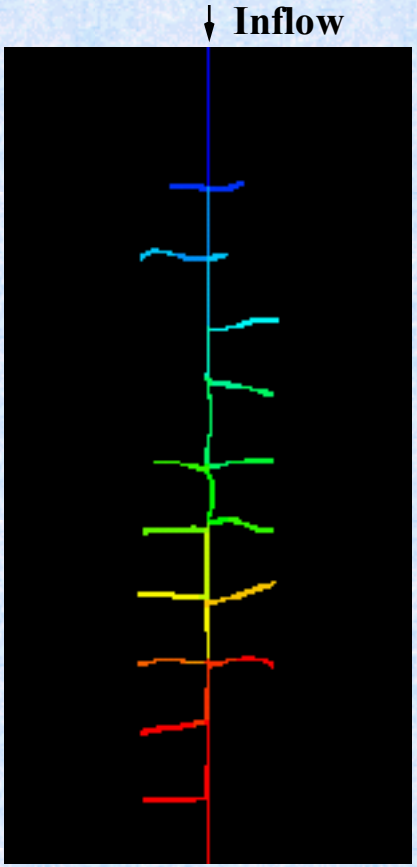
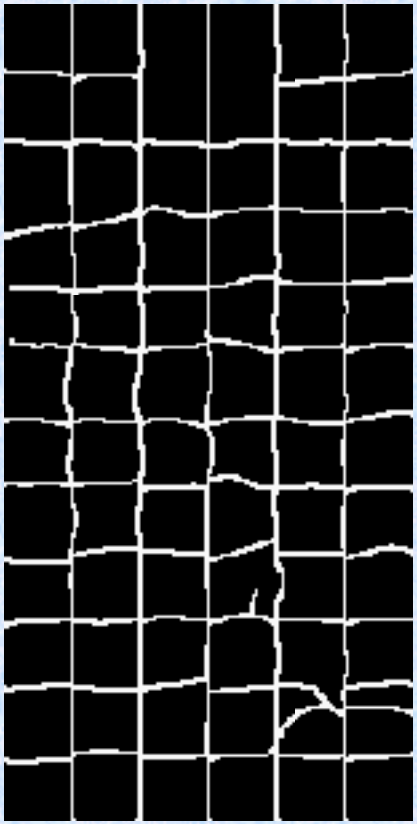

Spacer controlling edge "fracture"
Fractures held apart with precision shims
Inflow
30 cm
60 cm
Boundary glass
3/4" network glass
Closed cell foam
Pump
Balance
External frame
Wicks providing outflowsuction



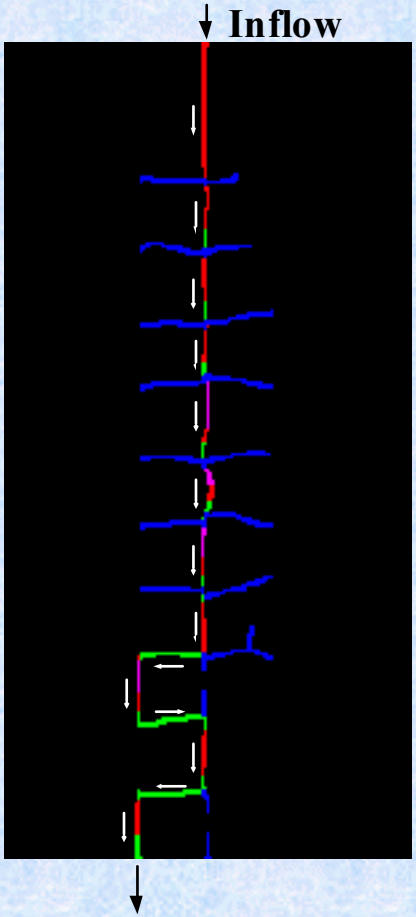
Path at Breakthrough

Early **Late**

Pore Filling Order



Fracture network



Outflow State 24hrs.

blue	stagnant
red	stable finger
green	conducting full width
purple	unstable pulsation

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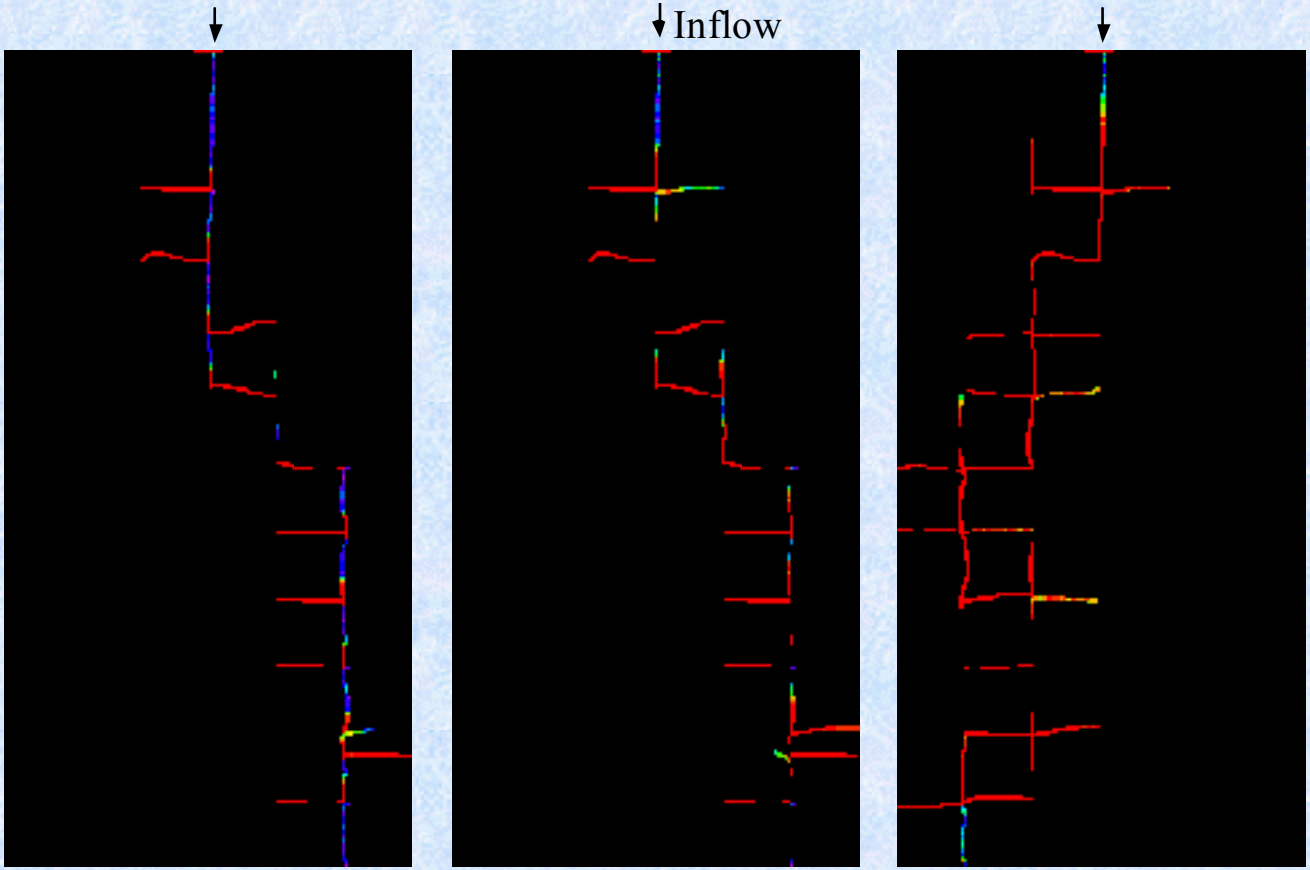
Simulation with Modified Invasion Percolation (MIP)



Base MMIP simulation MMIP, factor of 2 MMIP, factor of 4

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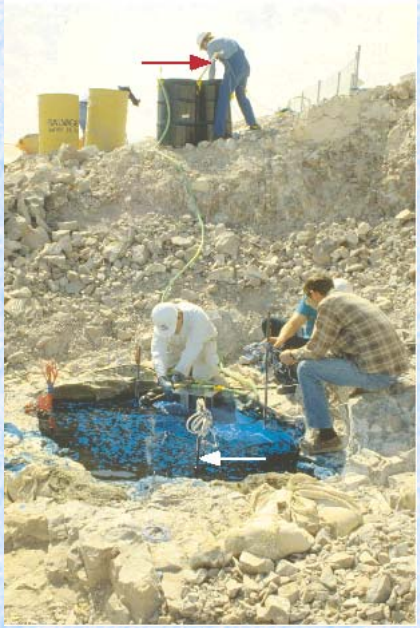
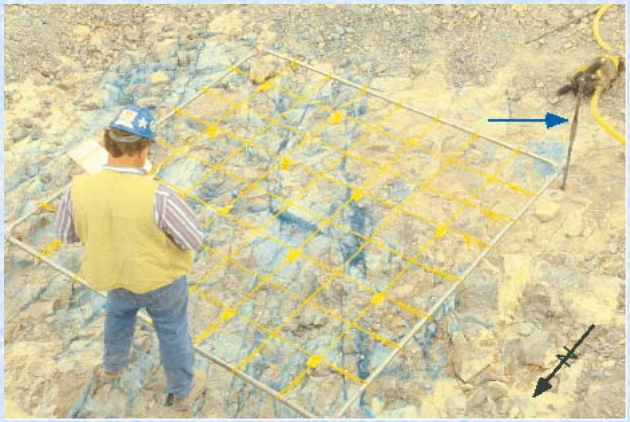
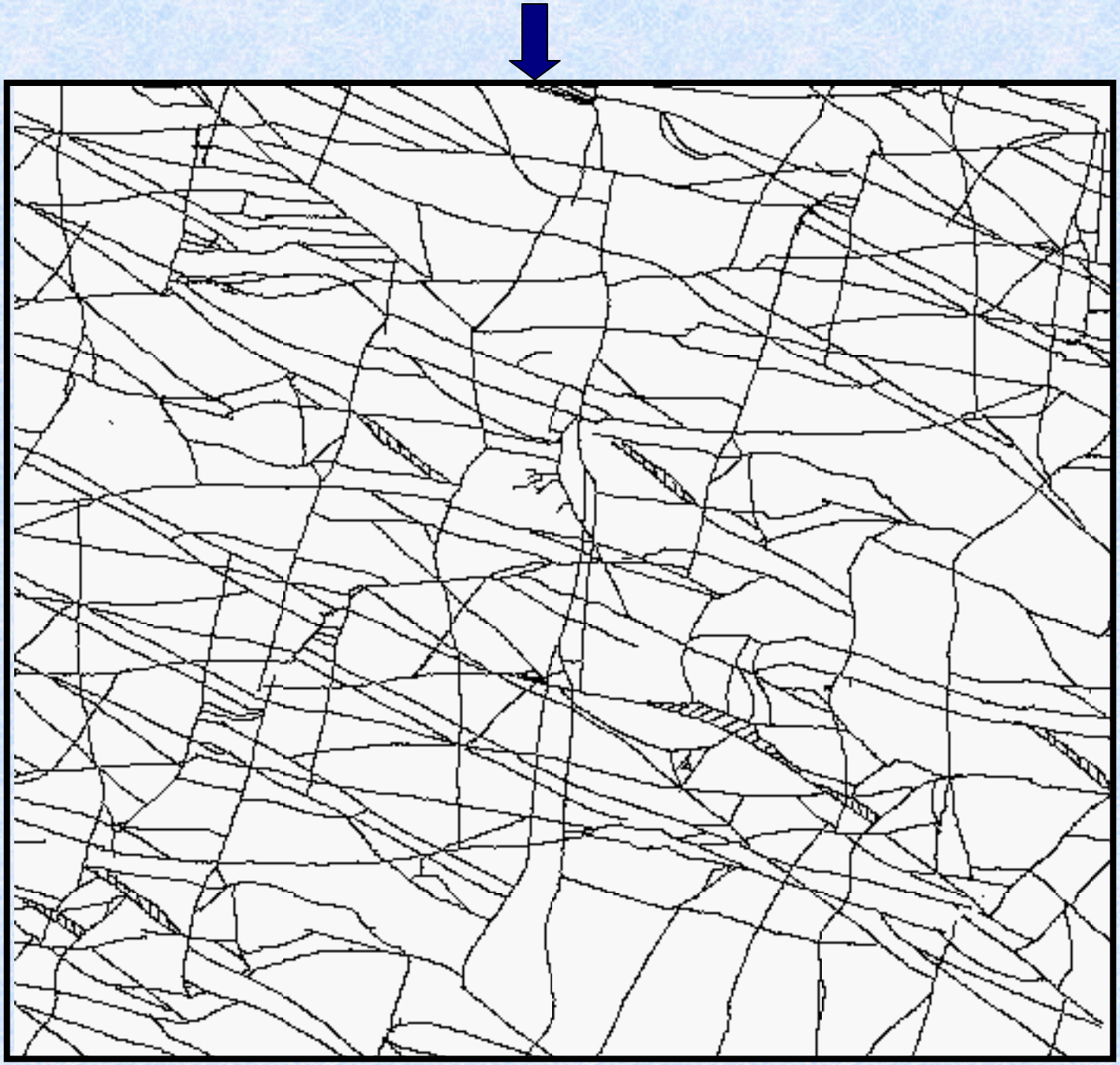
Field test at Fran Ridge Nevada, 1994

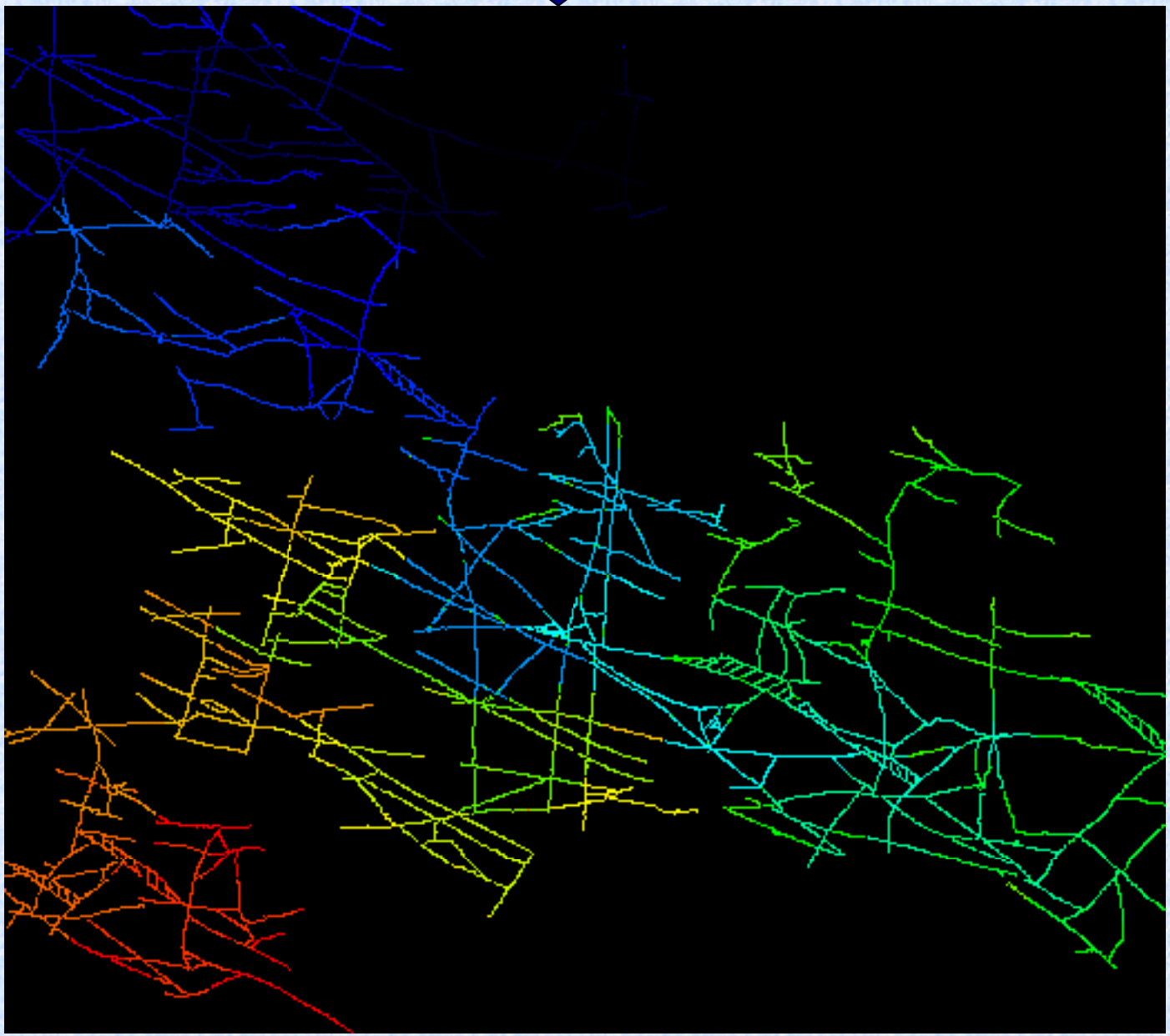


Infiltration of blue dyed water and subsequent excavation showed that liquid phase structure became quite complex, exhibiting evidence of fragmentation, preferential flow, fingers, irregular wetting patterns, and varied behavior at fracture intersection

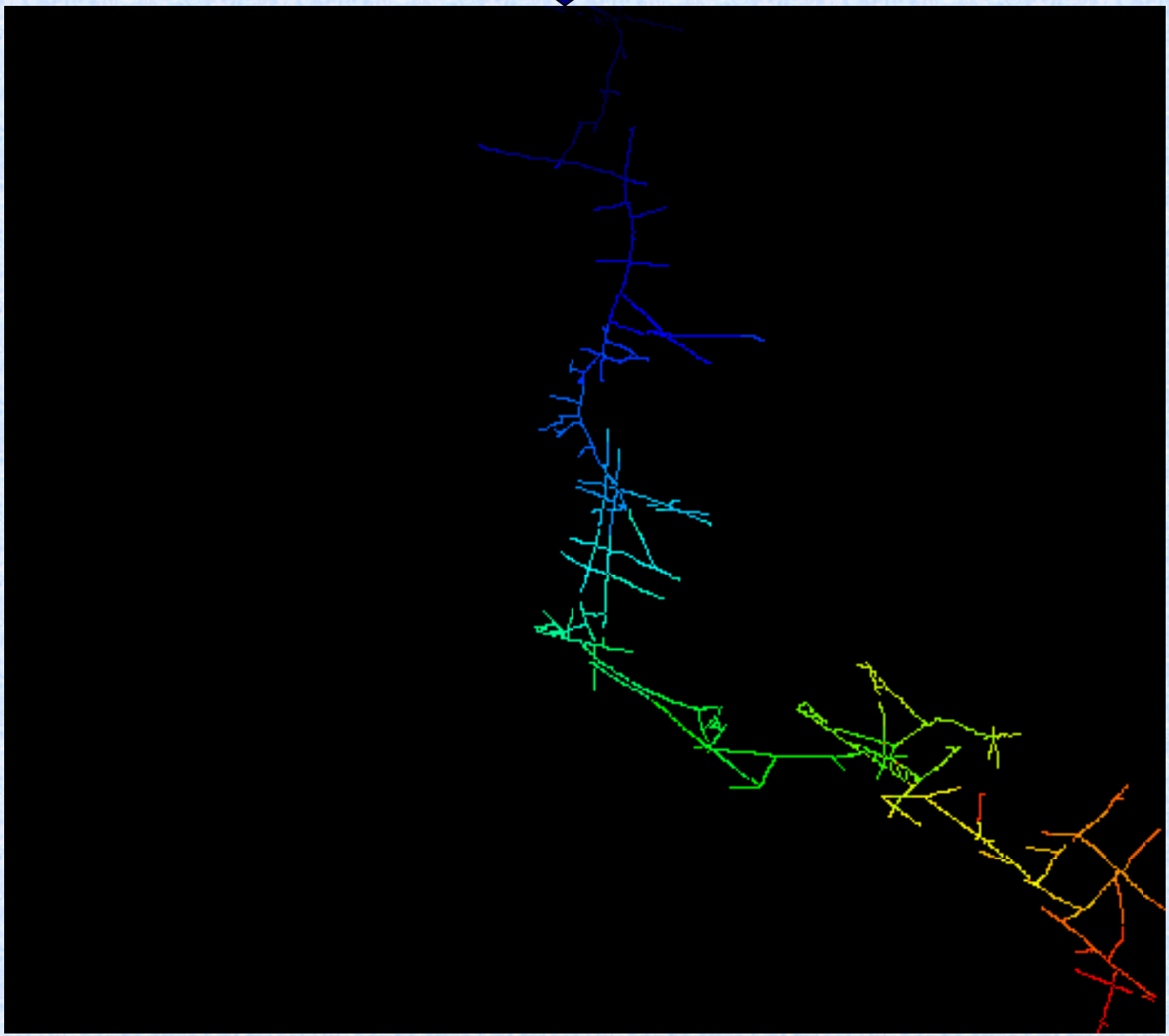




MIP, Capillary forces only



MIP, Gravity included



Fractured Basalts on the Snake River Plain

Final Thought

"Existing conceptual and predictive models have often proven ineffective for understanding and predicting contaminant movement, especially at sites that have thick vadose (unsaturated) zones or complex subsurface characteristics."

- program announcement