Groundwater Flow over Larger Volumes of Rock: Cross-Hole Hydraulic Testing

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USEPA-USGS Fractured Rock Workshop

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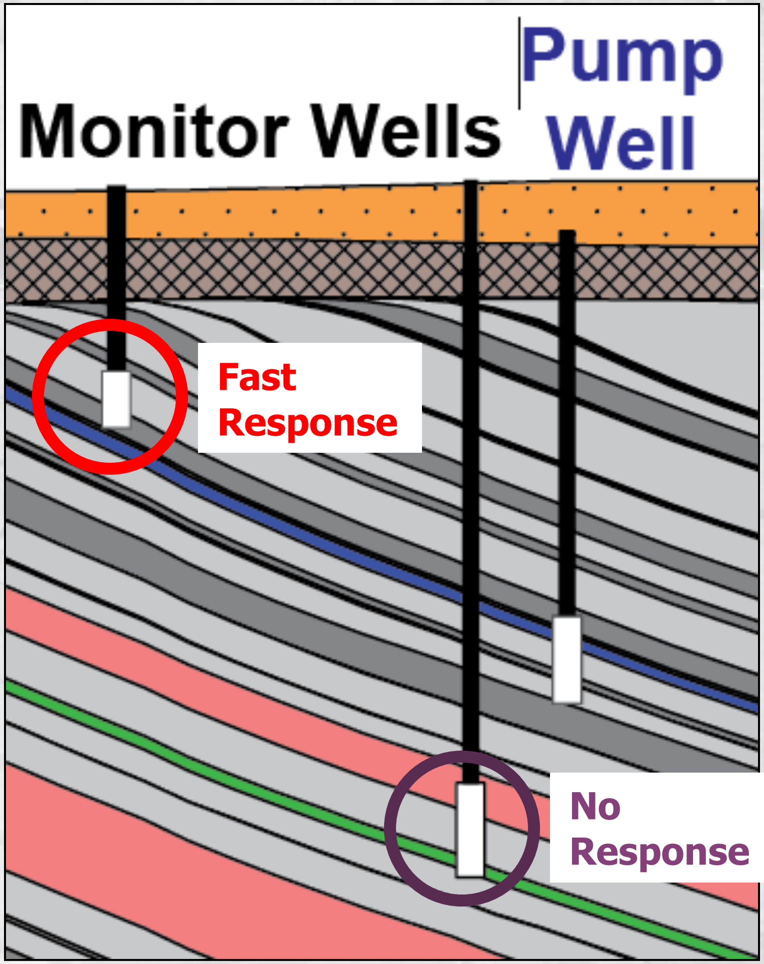
Purpose of Cross-Hole Hydraulic Testing

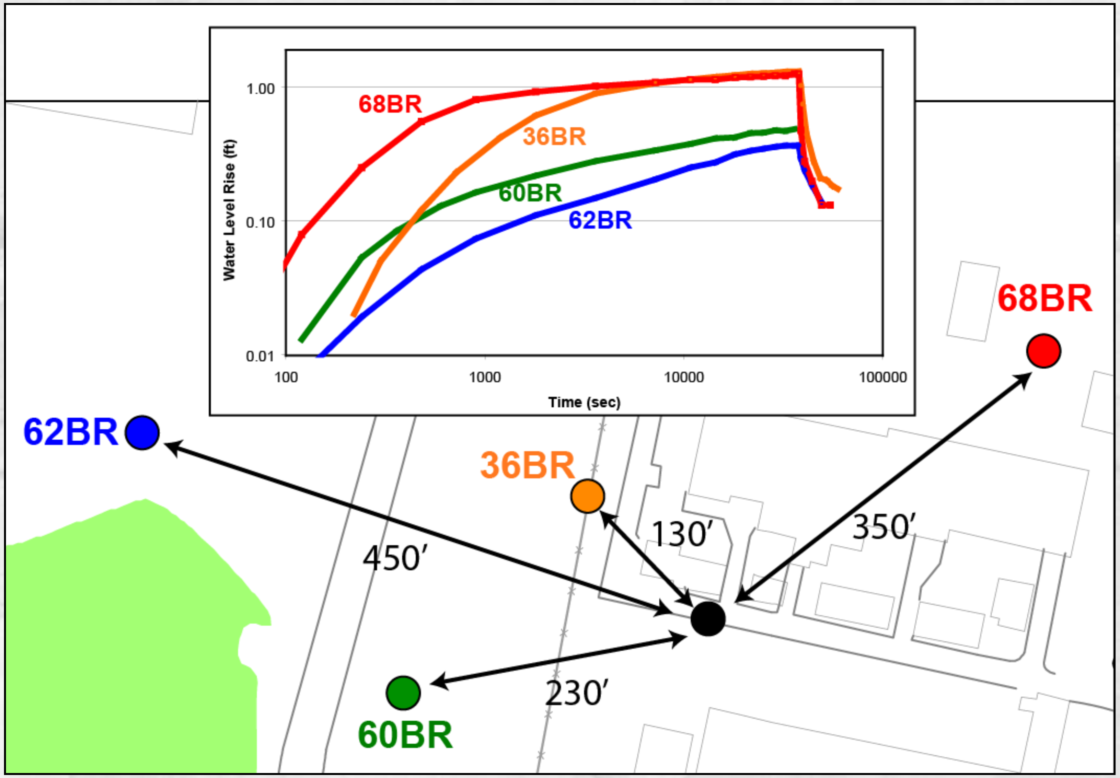
(also called aquifer testing, pump testing)

- Identify hydraulic connections and barriers between boreholes.
- Use of this info with geologic framework helps identify locations of permeable high-K fractures and lower-K rocks.
- This characterization data is critical to developing the site conceptual model.
- Quantitative analysis of test data helps refine the conceptual model and reduce its uncertainty.



Expectations: Cross-Hole Hydraulic Tests

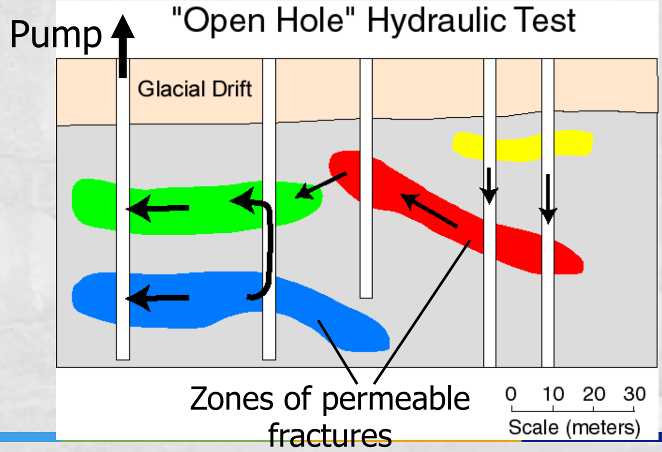
- In fractured rocks, hydraulic responses can travel long distances in short times.
- Drawdown will not necessarily decrease with distance from pumped well.



Designing Hydraulic Tests

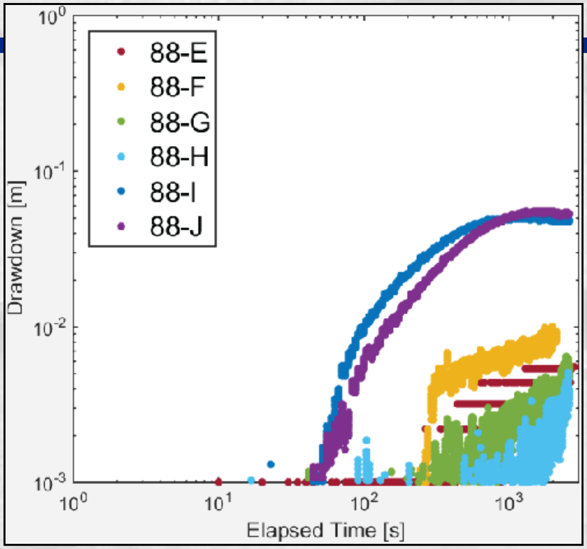
- **Borehole locations**
  - Difficult to predict distances over which permeable fractures are connected, prior to drilling wells.
  - → Use multiple criteria when selecting locations of new wells – e.g., value for characterizing contaminant distribution and chemical transport as well as groundwater hydraulics.

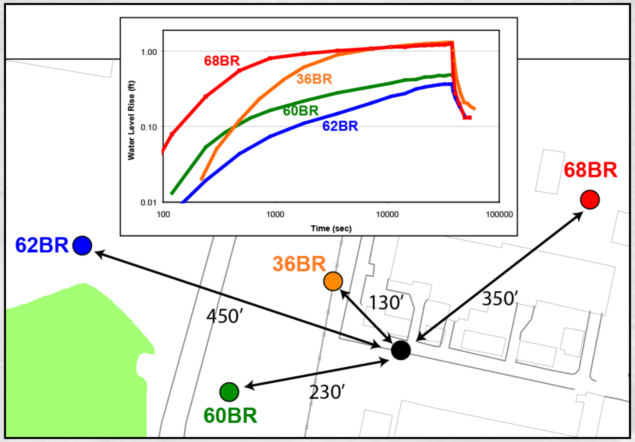
- **Creating separate vertical borehole intervals**
  - For long open boreholes, important to install packers, or liner, to isolate permeable fractures from each other.
  - Use borehole geophysics & T profiling results to guide design of monitoring intervals.



Designing Hydraulic Tests

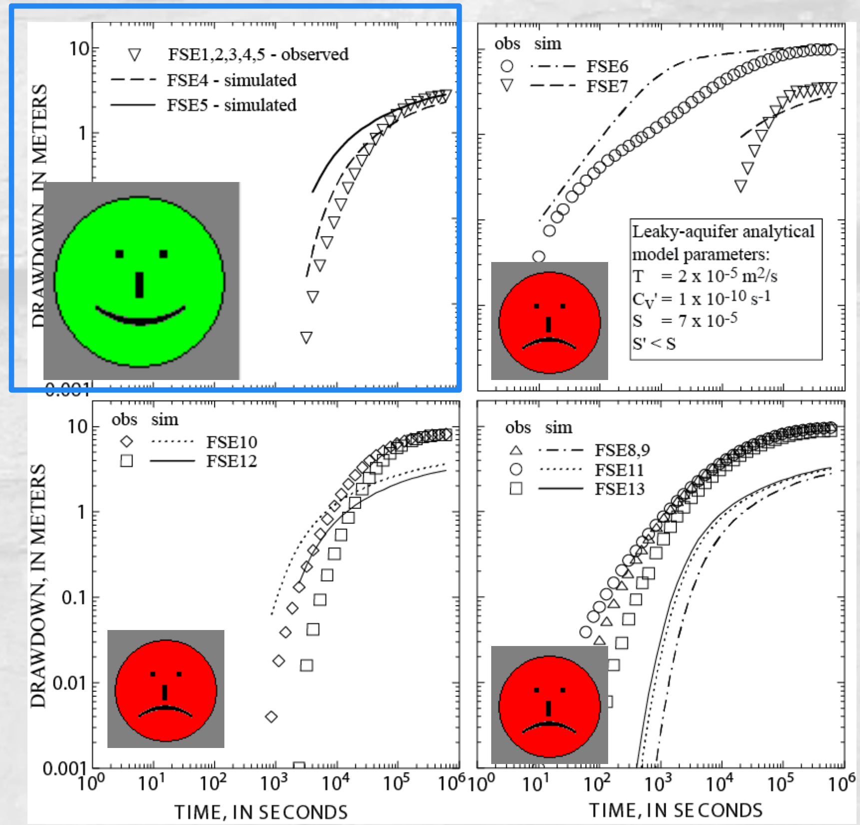
- **Considerations:**
  - Pump at a large enough rate to produce a high signal to noise ratio at observation locations.
  - But: pumping rates may be limited by fracture permeability in pumped interval.
  - Monitor water levels in as many wells and intervals as possible.
  - Detection of water-level responses in the connected, high-permeability fracture network may occur rapidly (seconds) after onset of test.





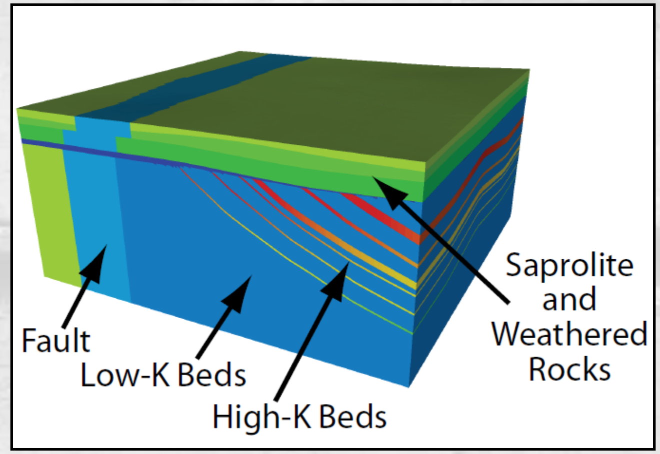
Analyzing Cross-Hole Hydraulic Test Data

- In heterogeneous fractured rock aquifers, analytical solutions for estimating K or T from hydraulic tests have limited applicability.
- Best to use numerical model (e.g. MODFLOW) so that heterogeneity can be properly represented.

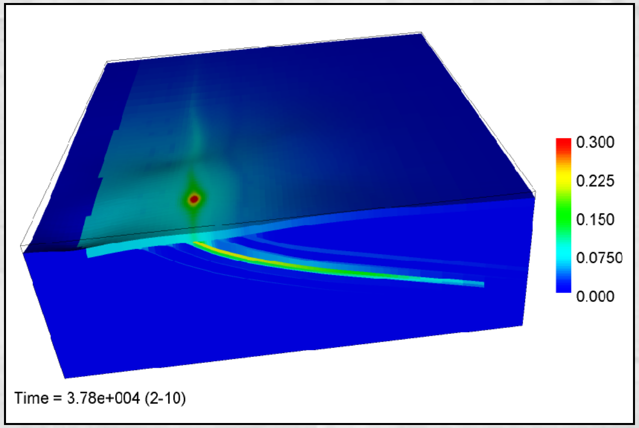


Value of Modeling for Analyzing Hydraulic Test Data

- Enables consistent synthesis of site characterization data – geology, geophysics, hydraulics.
- Process of developing and calibrating gw flow model helps advance the 3D hydrogeologic conceptual model – e.g., identifying the network of permeable fractures.
- Model can be refined as new data are collected.
- Model for analyzing hydraulic tests can then be used to design and evaluate remedies, e.g.:
  - Design well locations and pumping rates for achieving hydraulic containment.
  - Analyze capture zones of wells
  - Design strategies for injecting amendments for bioremediation
  - Evaluate contaminant mass fluxes, using groundwater fluxes quantified by the model



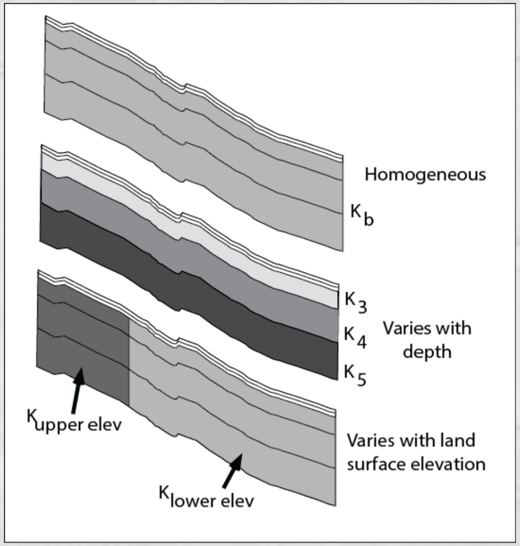
Hydraulic Conductivity Representation



Simulated Drawdown

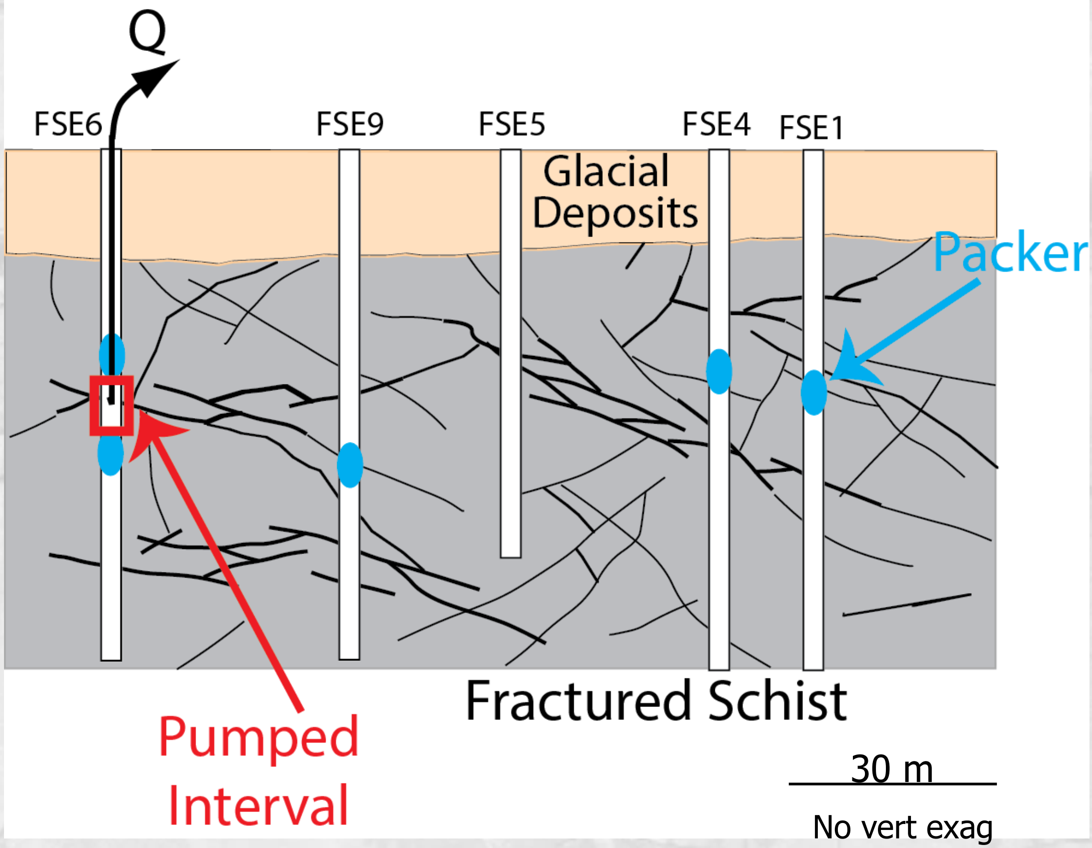
Limitations / Difficulties of Cross-Hole Hydraulic Testing in Fractured Rocks

- **Compared to unconsolidated aquifers:**
  - **Lower density of boreholes and of depth-discrete monitoring locations**
  - **More complex field equipment needed– e.g. packers for dividing open-hole wells.**
- **Low permeabilities may limit spatial extent of measurable drawdowns.**
- **Interpretations will likely be non-unique. Consider:**
  - **Alternative conceptual models.**
  - **Estimating uncertainty in model parameters.**
  - **Carrying uncertainties/alternative models through in any predictive analyses.**



Cross-Hole Test in Fractured Schist

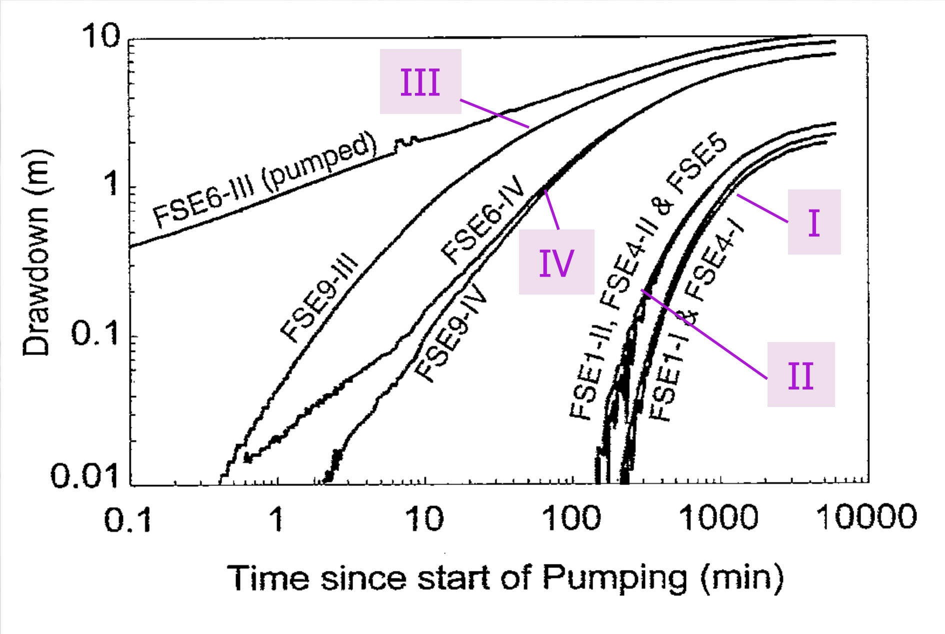
- Packers divide boreholes into 2 or 3 intervals.
- Packer placement guided by T profiling results.
- Pump 10 L/min for 3.3 days.

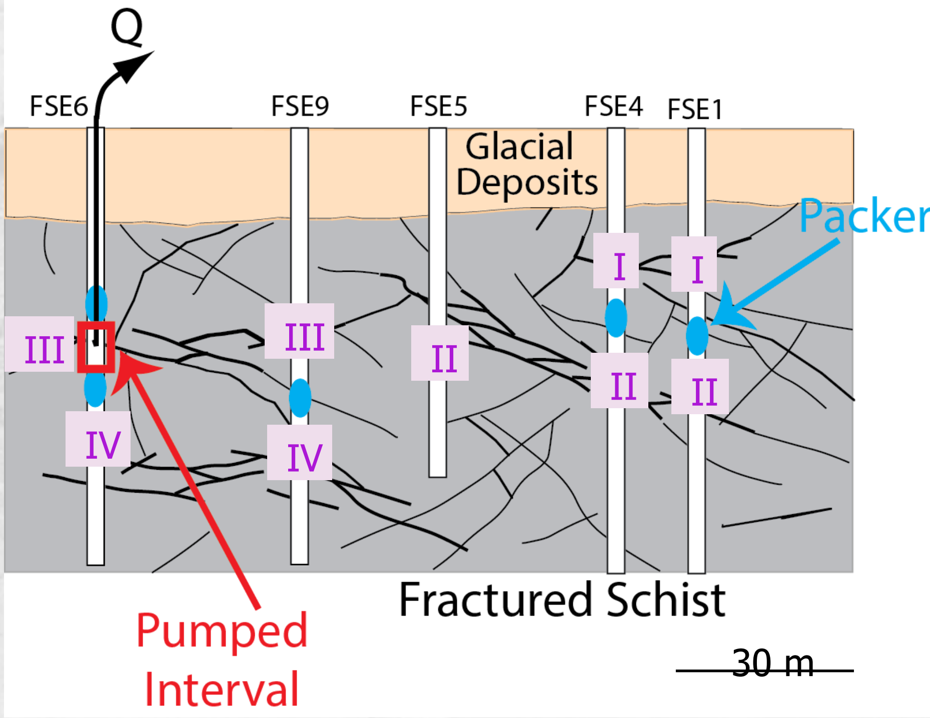


(Hsieh et al. 1999; Hsieh 2000)

Cross-Hole Test in Fractured Schist

- **Observed Drawdown:**





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Cross-Hole Test in Fractured Schist

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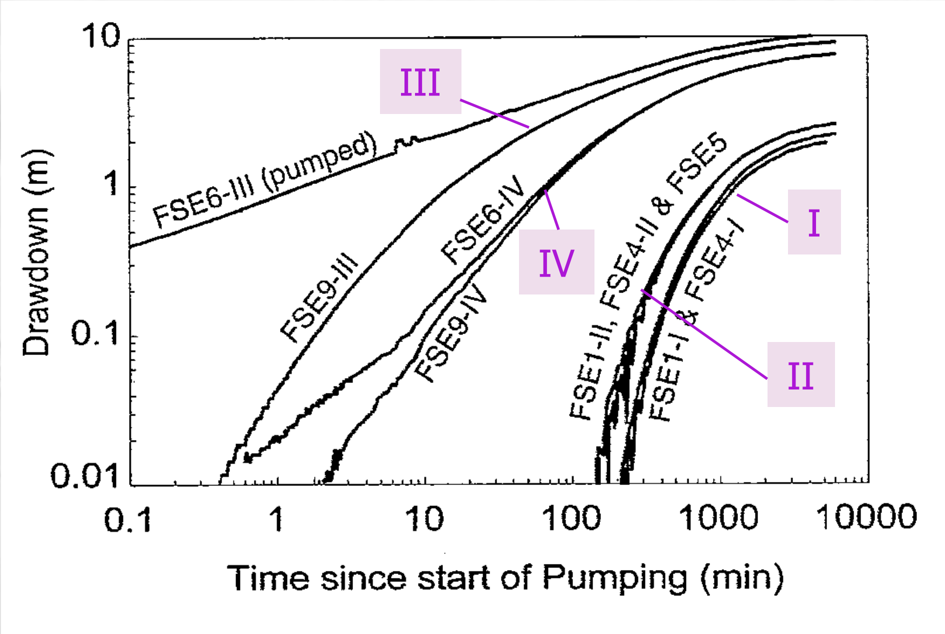
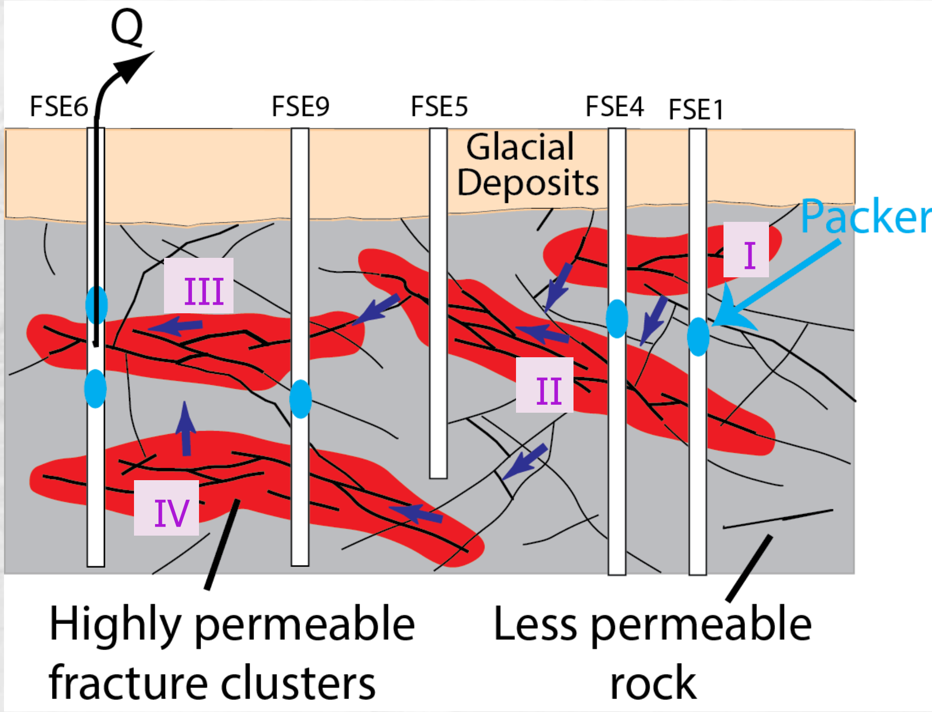
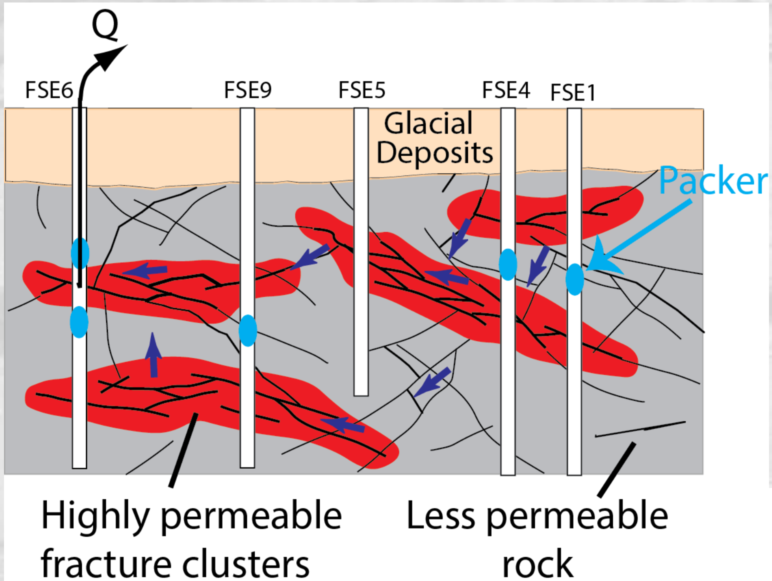


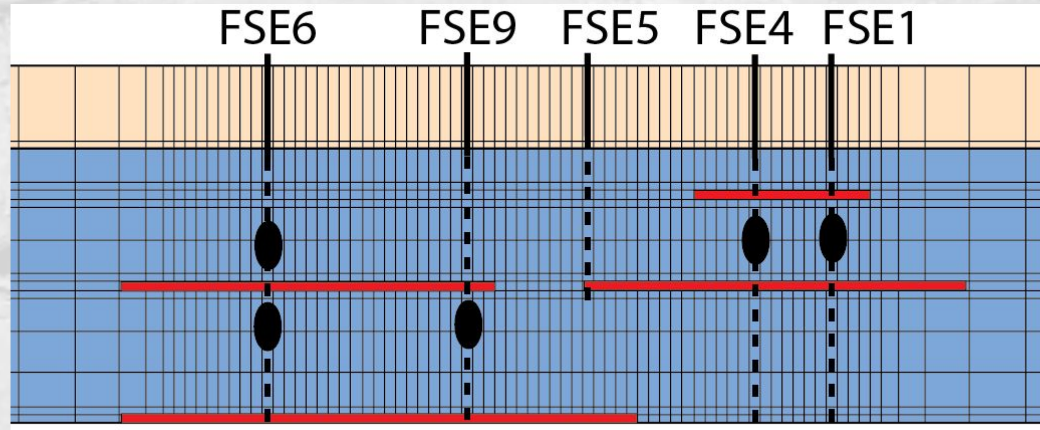
- **Conceptual Model:**



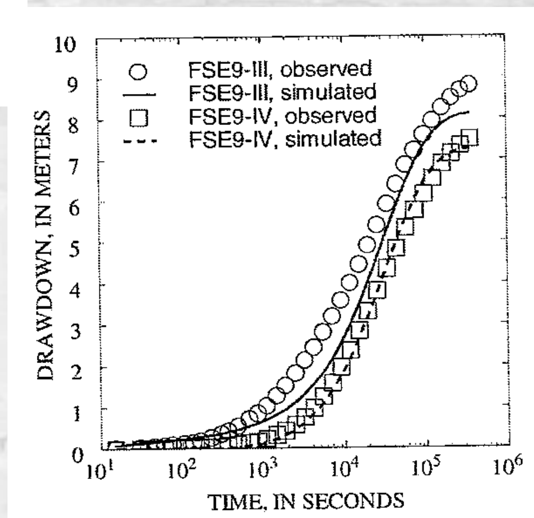
(Hsieh et al. 1999; Hsieh 2000)

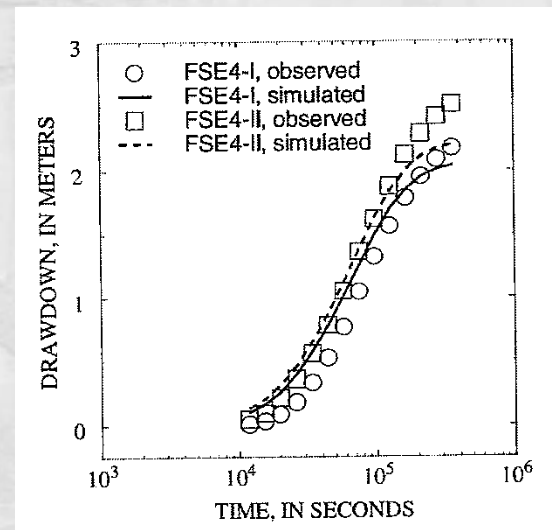
Analysis With Simple Numerical Model





- **Simple numerical model:**
  - Confirms conceptual model
  - Captures primary heterogeneities
  - Is basis for transport model
  - Not unique
  - Has uncertainties





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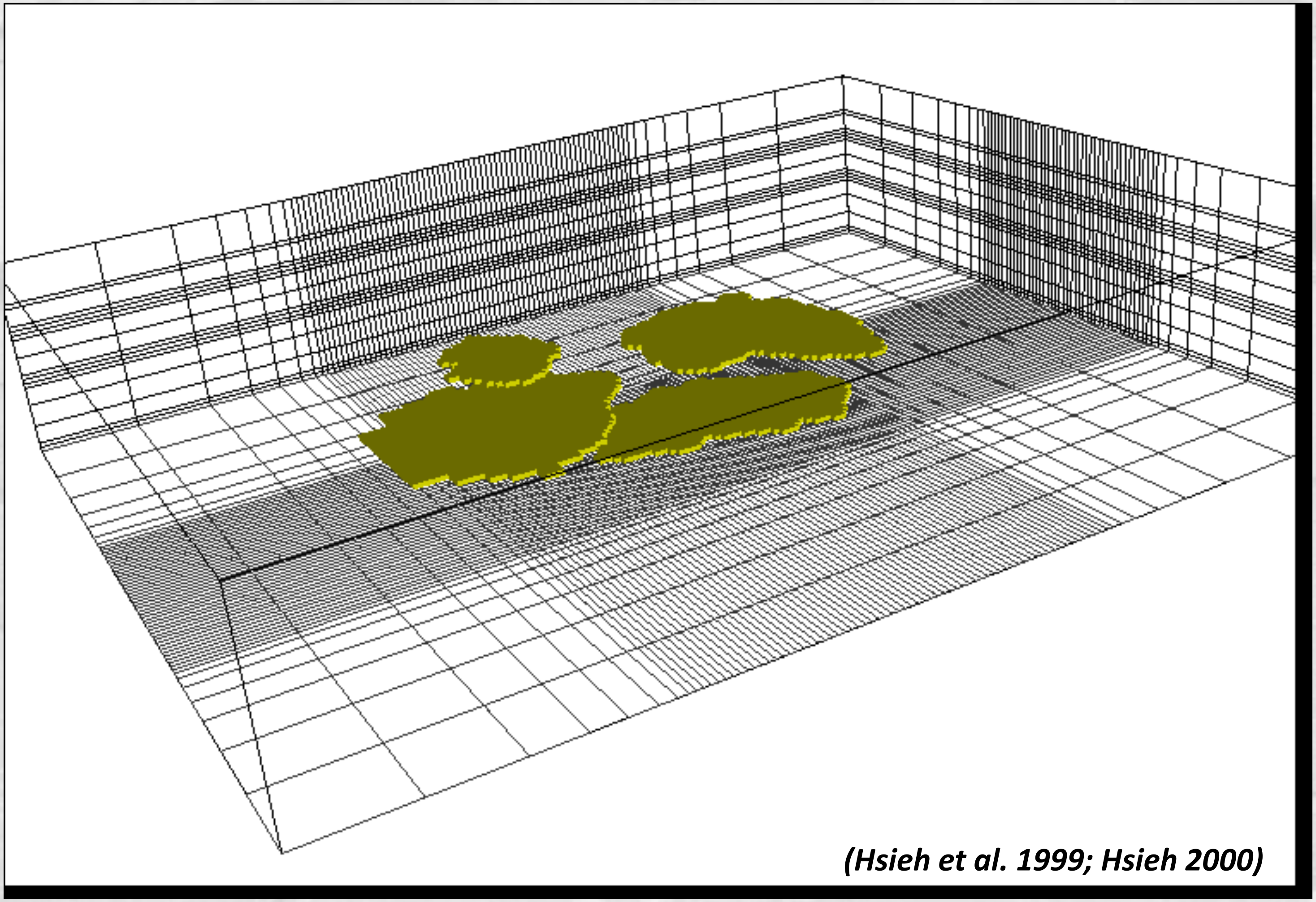
Analysis With Simple Numerical Model

- 3D view of model

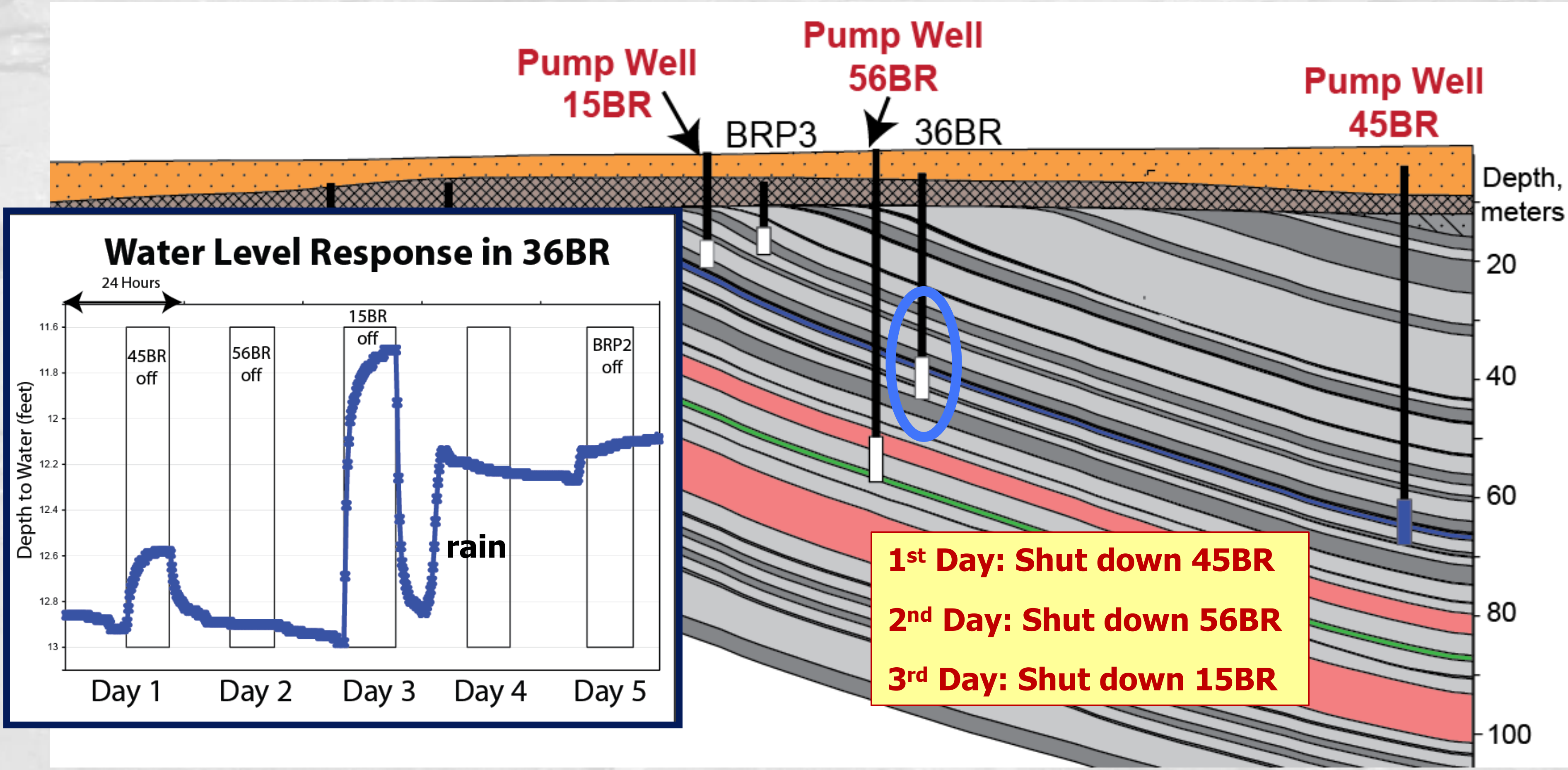


(Hsieh et al. 1999; Hsieh 2000)

Using Existing Pump & Treat System for Cross-Hole Hydraulic Testing

- **Procedure:**
  - Shut down pump in one well of the P&T system.
  - Monitor water-level rises in obs wells.
  - Conduct relatively short tests (run test during the day, with overnight recovery)
  - Repeat for all pumping wells of system
- **Advantages**
  - No additional contaminated water withdrawn
  - Short tests limit effect of shutdown on offsite contaminant migration

Well Shutdown Testing in Sedimentary Rocks

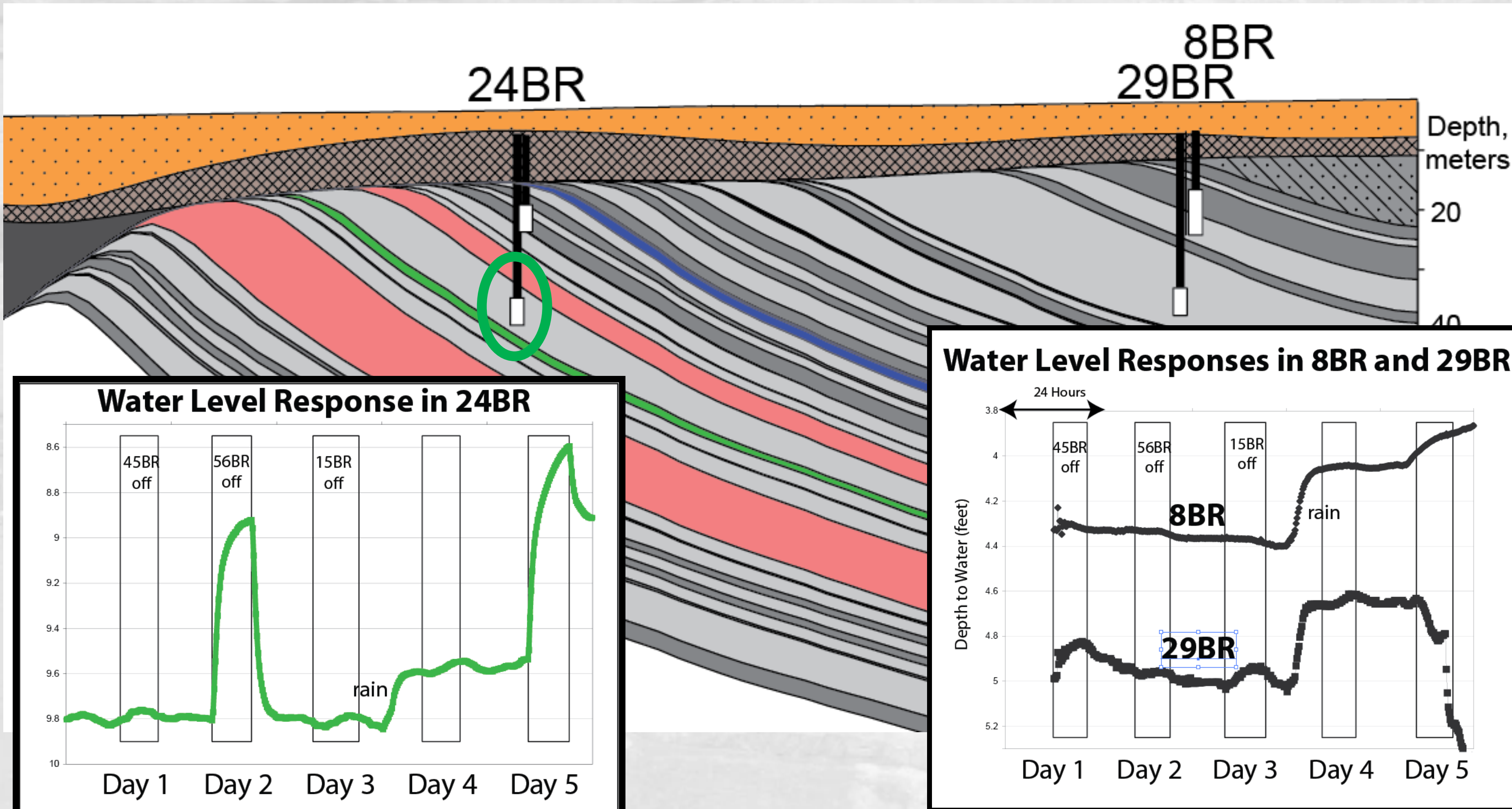


1st Day: Shut down 45BR

2nd Day: Shut down 56BR

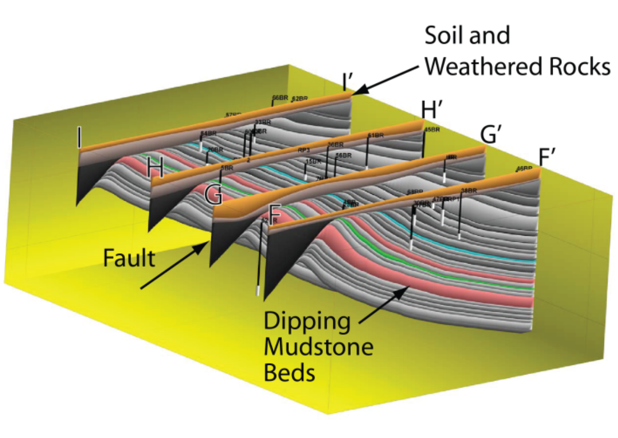
3rd Day: Shut down 15BR

Well Shutdown Testing in Sedimentary Rocks

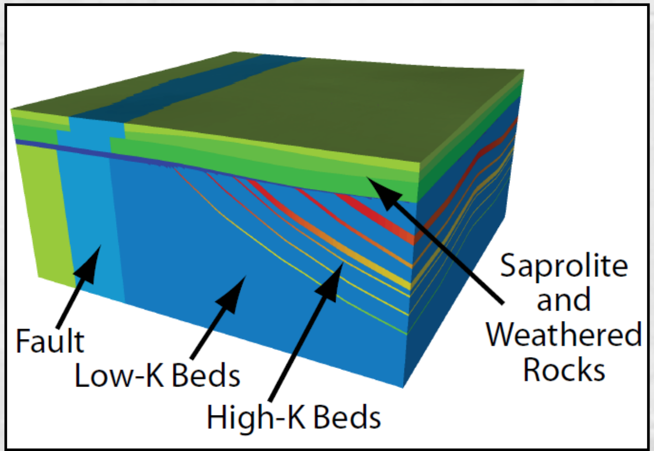


Well Shutdown Testing in Sedimentary Rocks: Analysis

- Use geologic framework and qualitative analysis of shutdown tests to guide model construction.
- Hydraulic connections and barriers evident from the data help identify which mudstone beds are high-K and which are low-K.



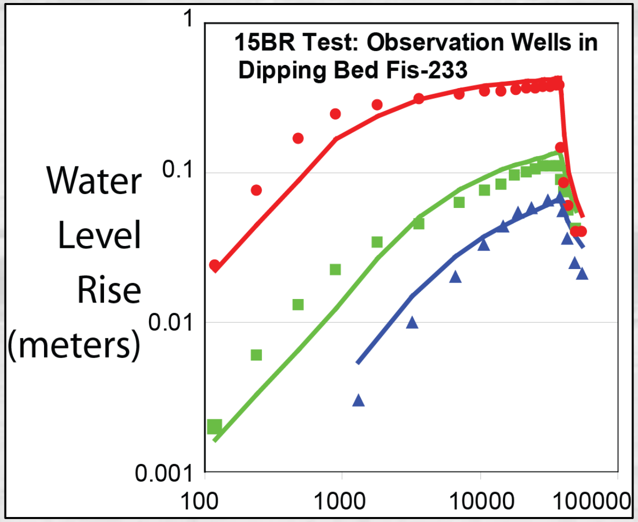
Geologic Framework

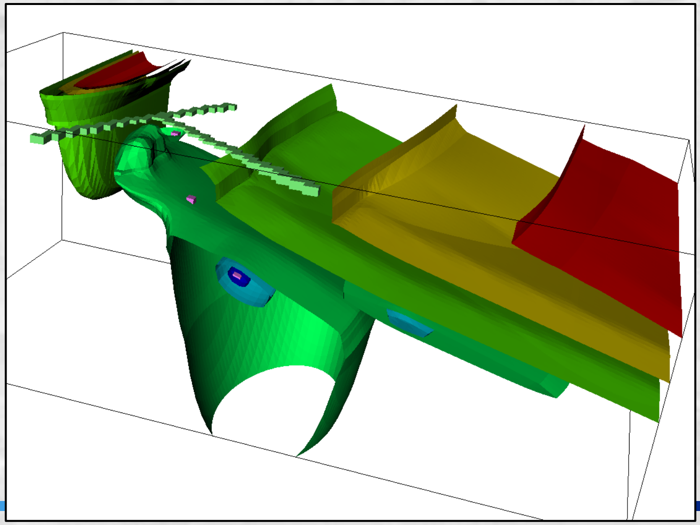


Hydraulic Conductivity Representation

Well Shutdown Testing in Sedimentary Rocks: Analysis

- Calibrate model to water-level rise data
- Use model to simulate:
  - GW flow in system with all P&T wells pumping
  - Pumping well capture regions
- Simulated GW fluxes and flow paths important for:
  - Simulating contaminant transport
  - Designing & evaluating remediation





Cross-Hole Hydraulic Tests in Fractured Rocks: Final Thoughts

- **Valuable for identifying:**
  - **Possible paths for relatively rapid contaminant transport**
  - **Less permeable volumes of rock where slow advection and diffusion likely dominate transport**
- **Interpreting hydraulic test data:**
  - **Apply models! Use geology! Incorporate heterogeneity!**
  - **Presence of permeable high-angle fractures might be inferred from data, but can be difficult to identify their locations**
  - **Be aware of limitations – nonuniqueness, uncertainty**
- **Tracer testing provides more definitive characterization of transport paths and processes**