



*Hydrologic Characterization and
Regional Ground-Water Modeling
in Fractured Rock Aquifers:
Synthesizing Heterogeneity and Scale*

Allen M. Shapiro

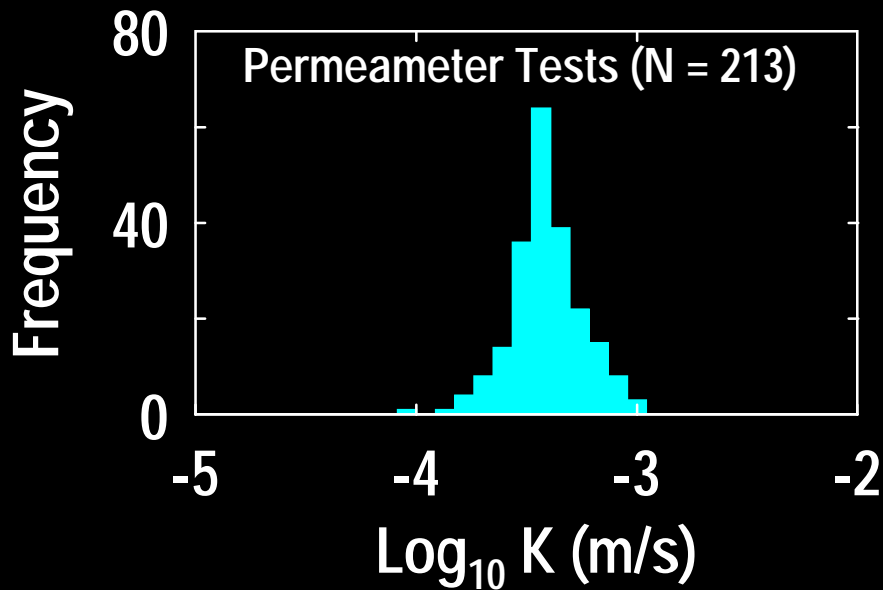
U.S. Geological Survey

Sand and Gravel Aquifer



Cape Cod, MA

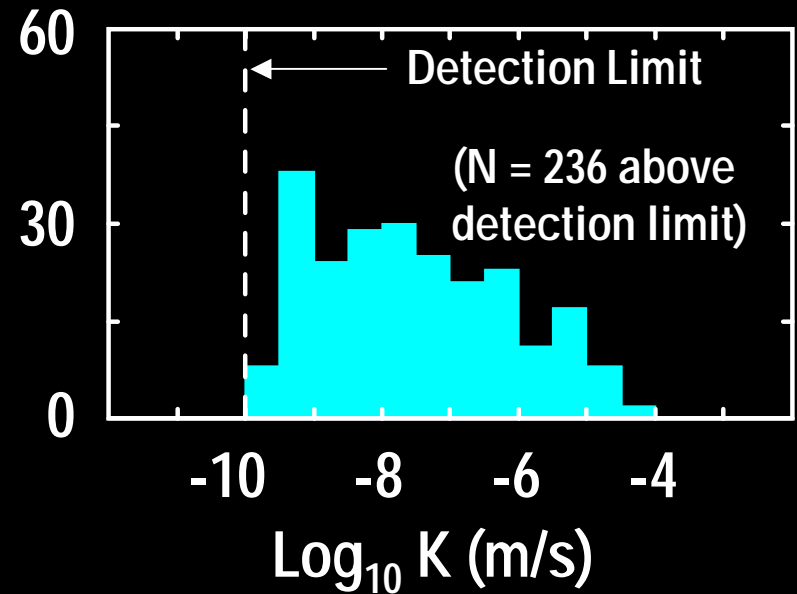
modified from Hess *et al.* (1992)



Granite and Schist



Mirror Lake Watershed, NH



Hydrologic Characterization & Modeling In Bedrock Aquifers ~ 100 meters ?



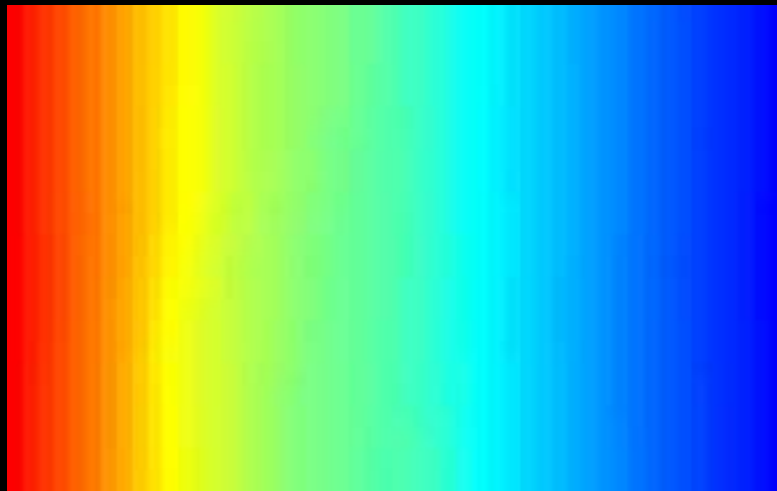
What degree of *detail* is required
and can we *characterize* the details?

Objectives of the Investigation?

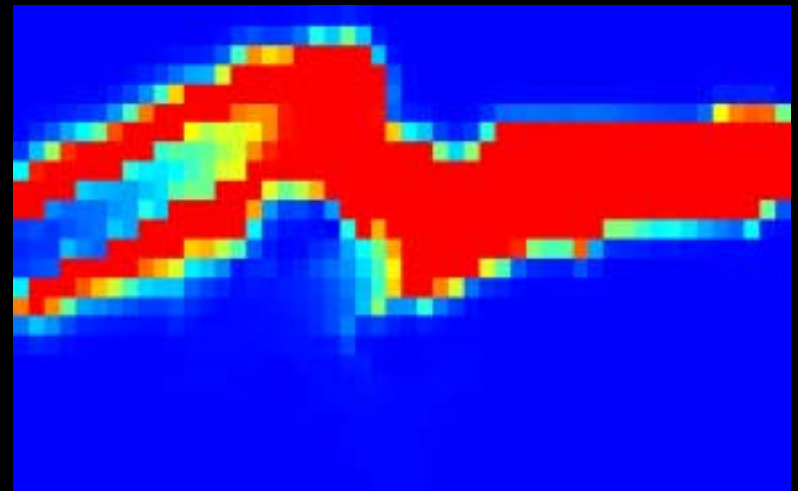


Distribution of Hydraulic Conductivity

Steady-State Hydraulic Head



Concentration at $t = t_1$



Hydrologic Characterization ~ 100 meters ?



Yes, we can!

Characterizing Fractured Rock over Dimensions ~ 100 meters



Fracture Mapping

Coupling Hydrologic Testing & Geophysics



Seismic & Radar Tomography



Surface Geophysics



Ground-Water Modeling



Drilling & Coring



Borehole Geophysics



Hydrologic Testing

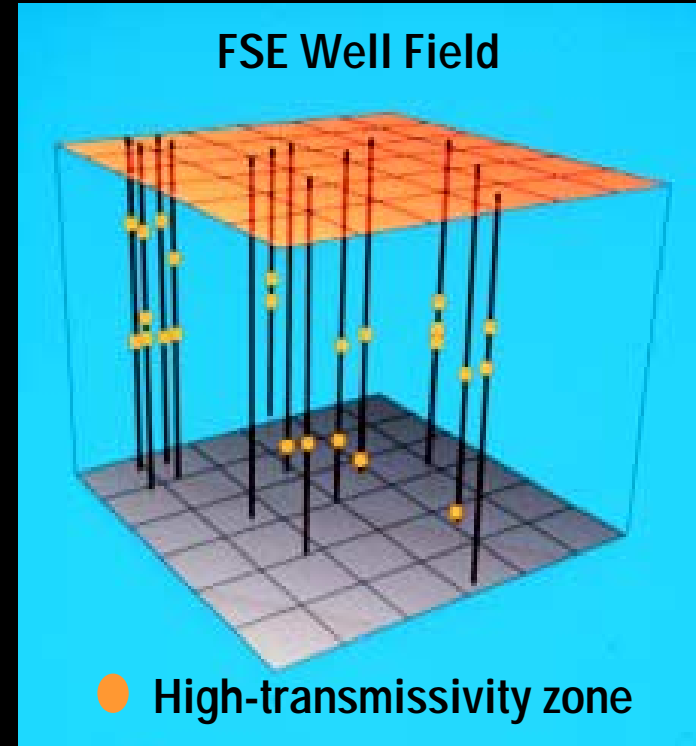
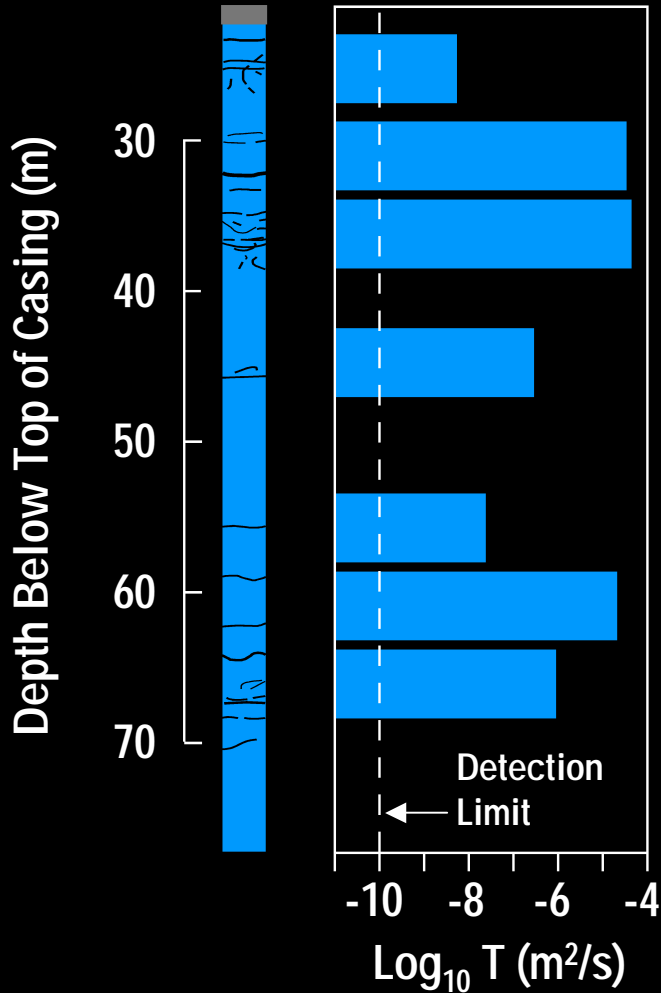


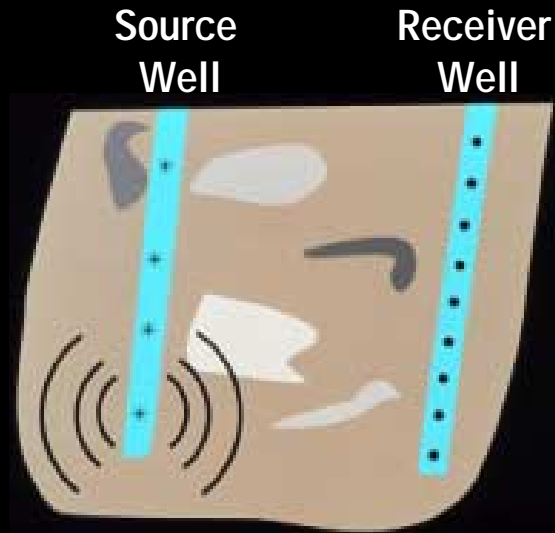
Borehole Scanning



Single-Hole Methods of Characterization

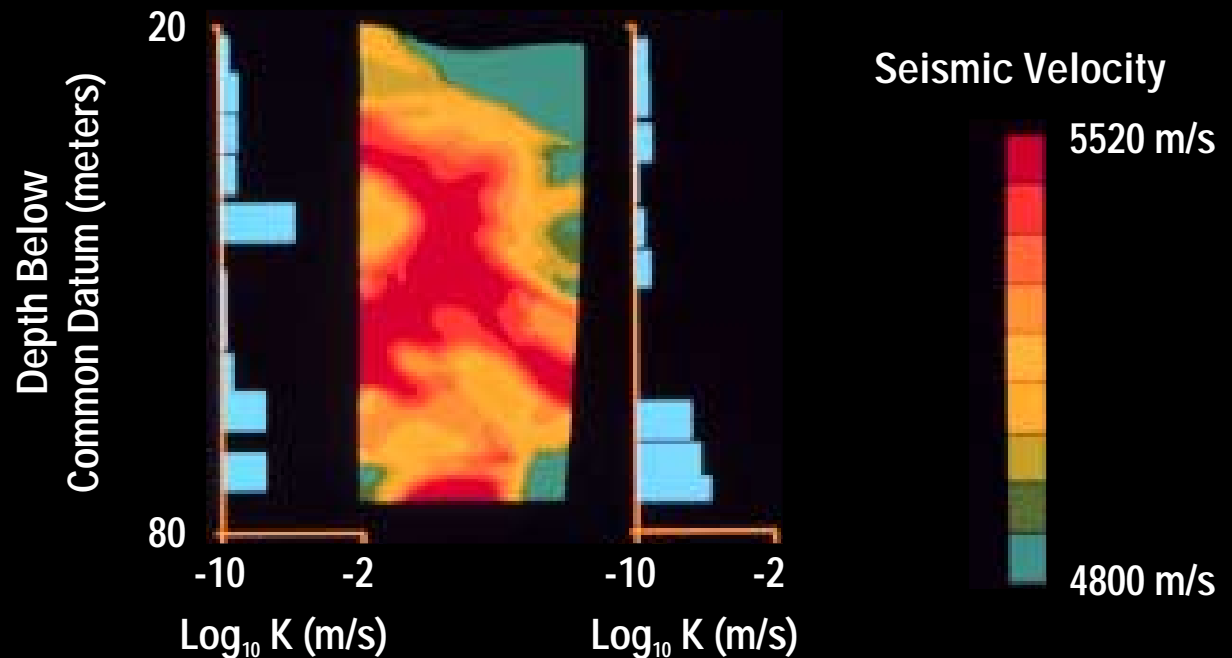
FSE-6



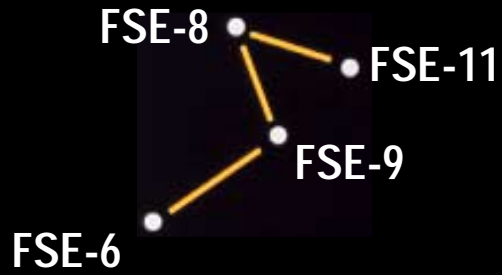


Cross-Hole Methods of Characterization

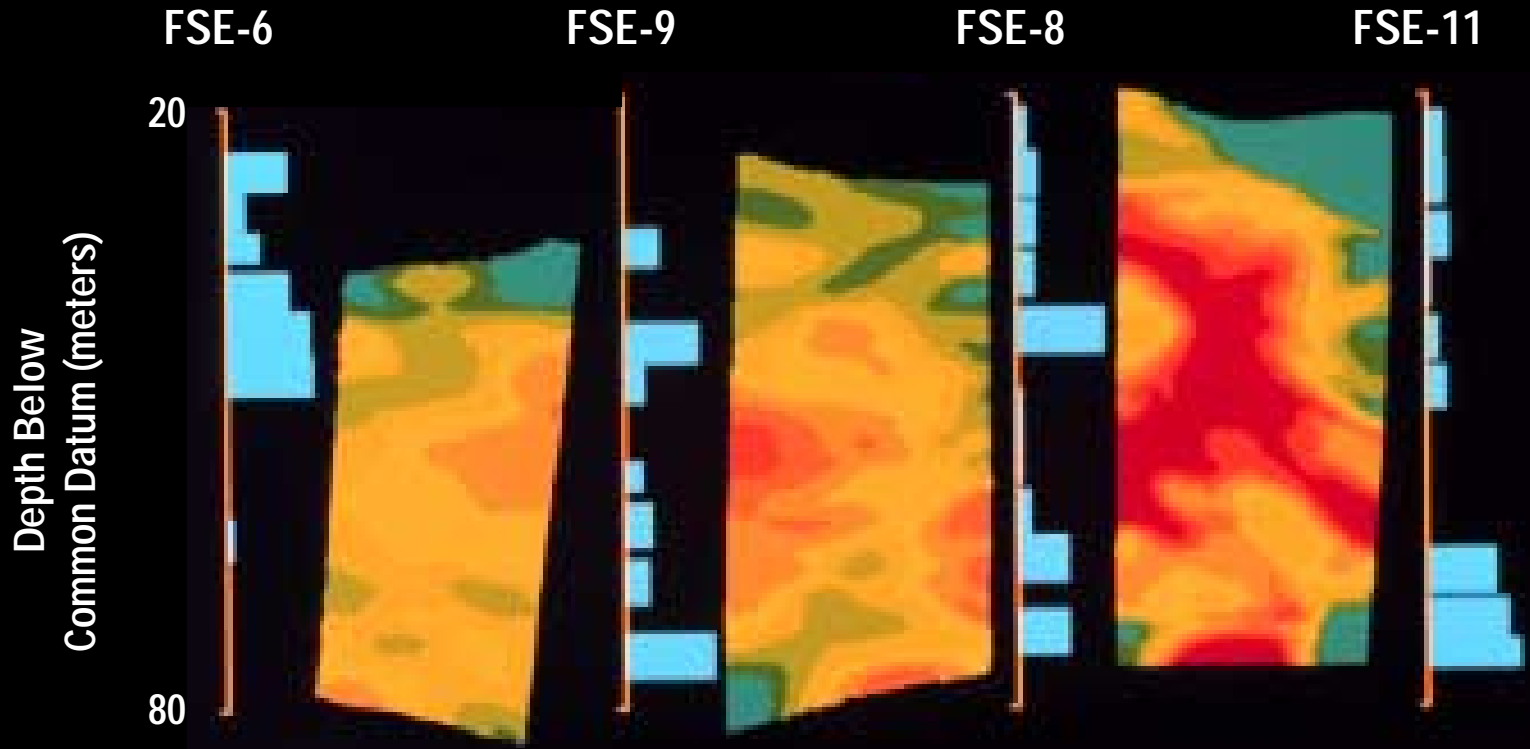
Seismic Tomography



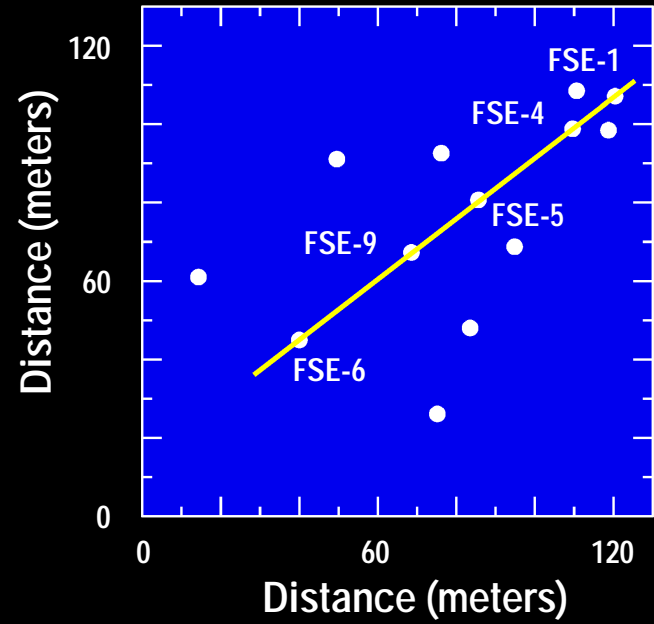
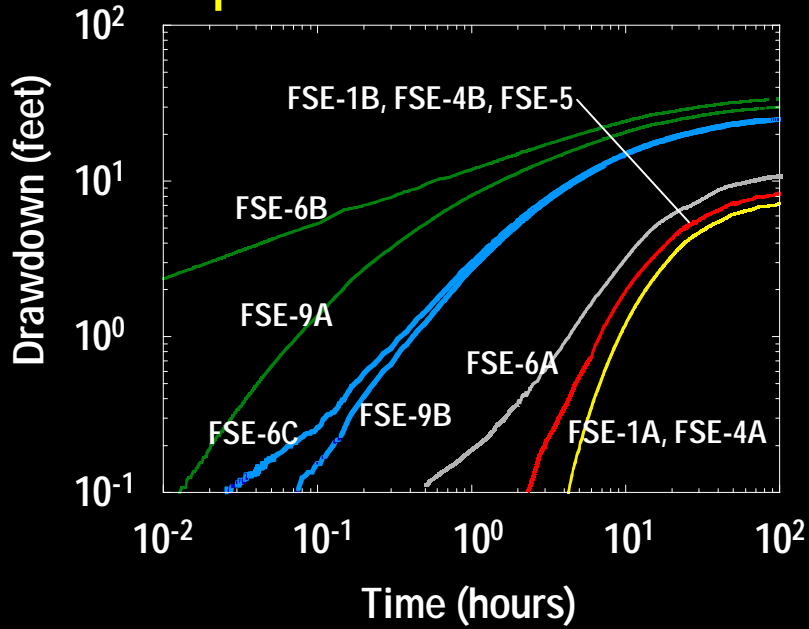
Well Locations - FSE Well Field



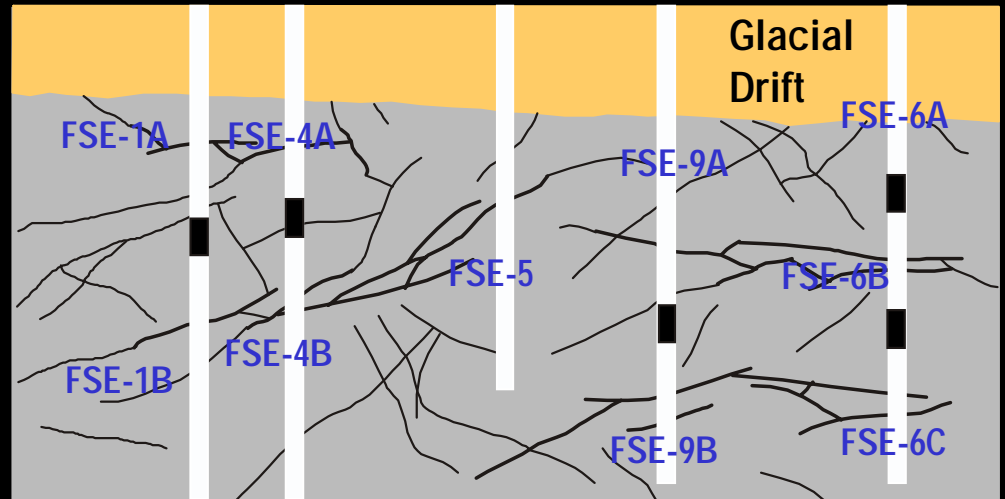
Seismic Tomography



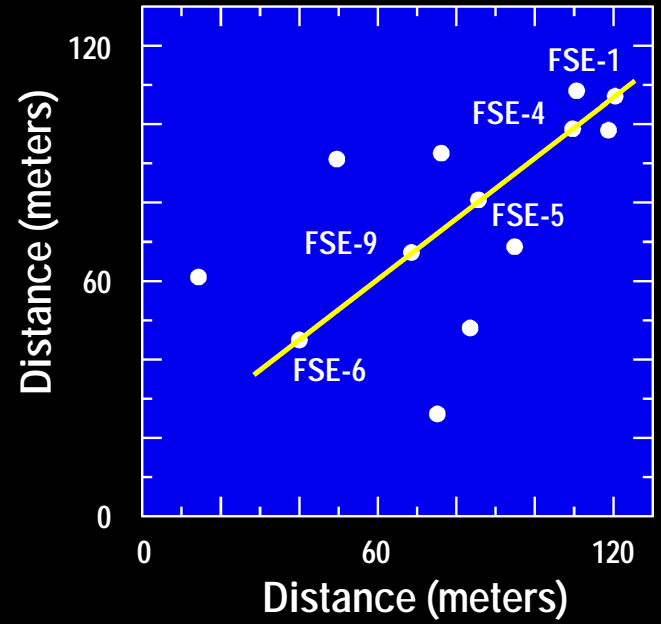
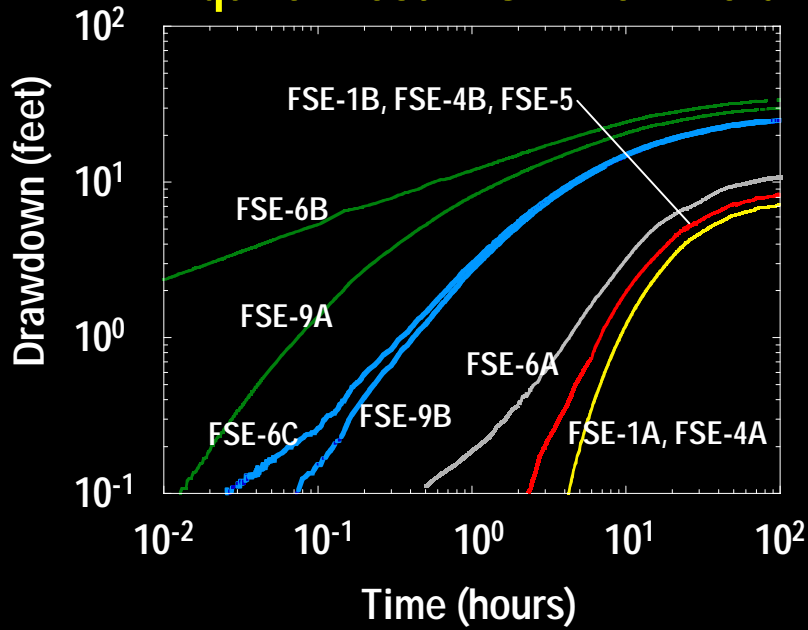
Aquifer Test - FSE Well Field



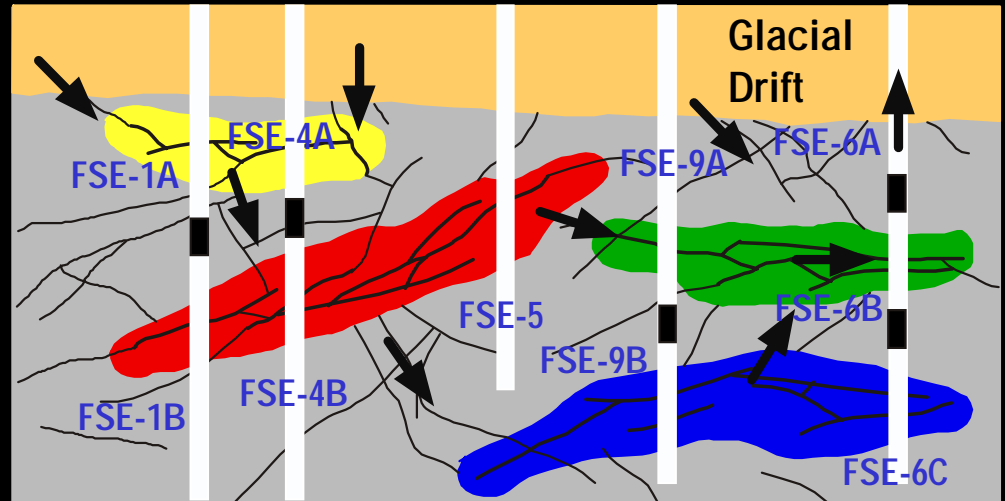
FSE-1 FSE-4 FSE-5 FSE-9 FSE-6



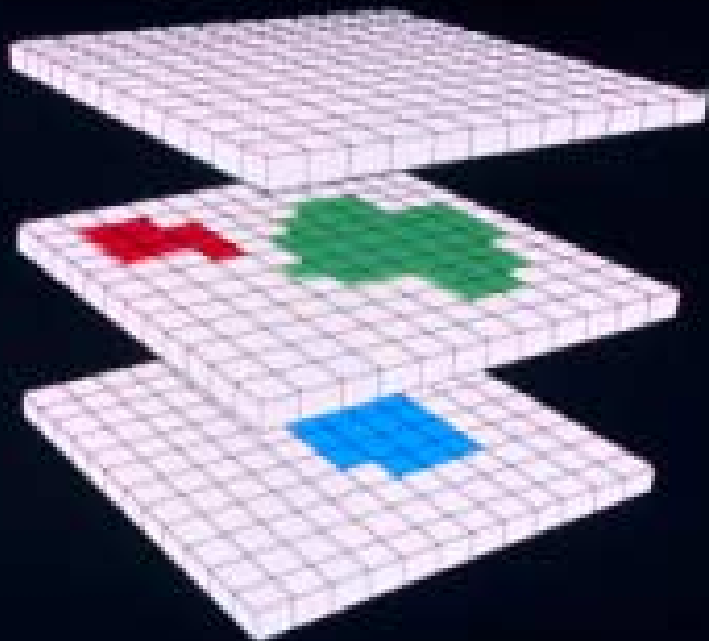
Aquifer Test - FSE Well Field



FSE-1 FSE-4 FSE-5 FSE-9 FSE-6

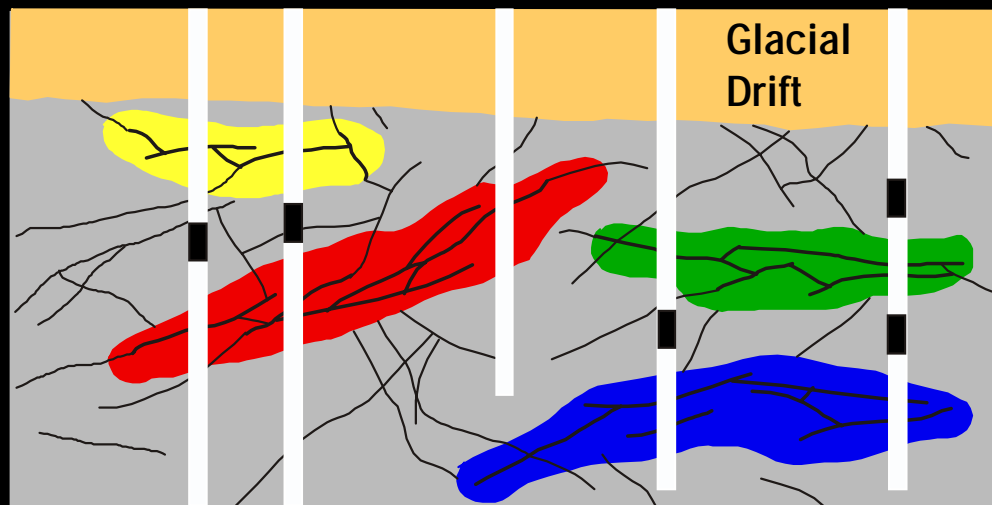


30 meters



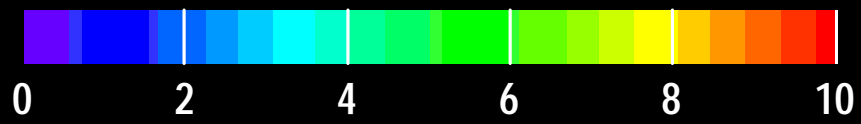
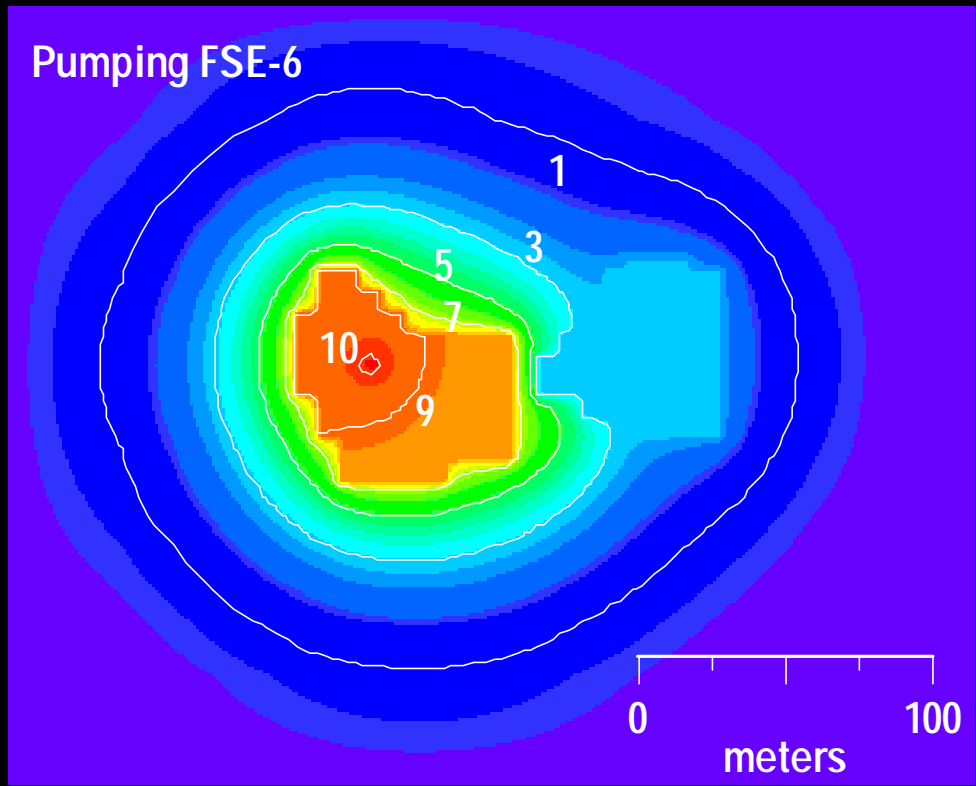
Finite-Difference Model for Ground-Water Flow

FSE-1 FSE-4 FSE-5 FSE-9 FSE-6



30 meters

Simulated Drawdown



Drawdown (meters)

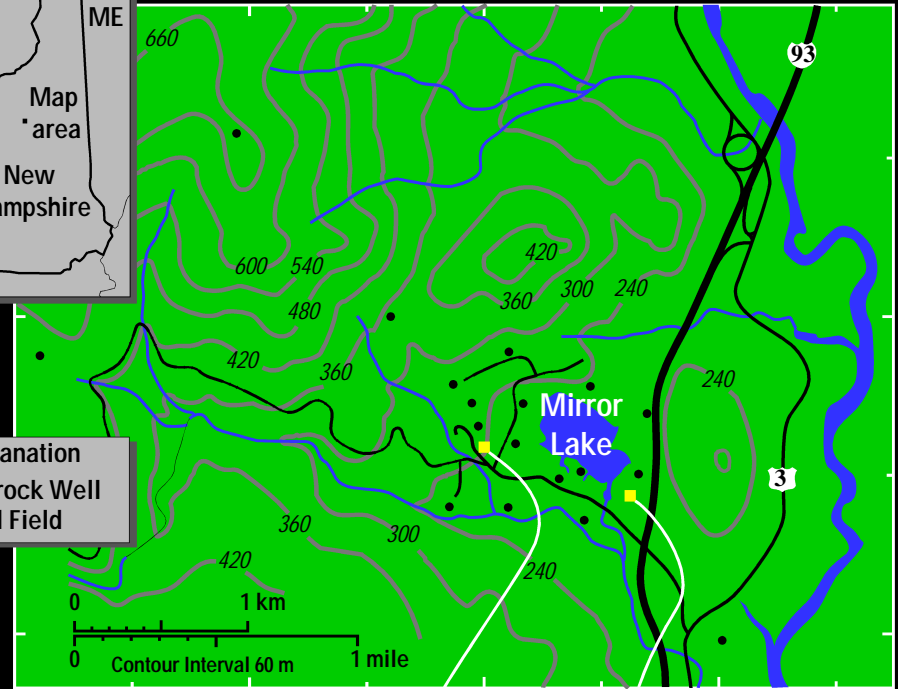
Hydrologic Characterization ~ 100 meters ?



Don't forget the obvious!

USGS Fractured-Rock Field Research Site

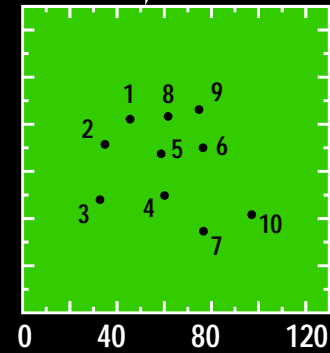
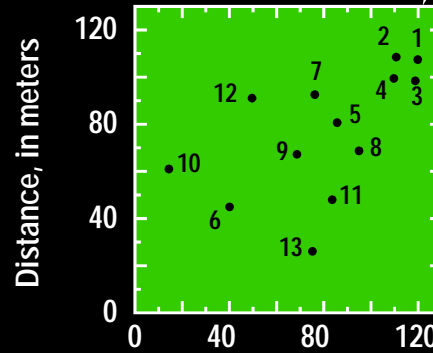
Mirror Lake Watershed, Hubbard Brook Experimental Forest, Grafton County, NH



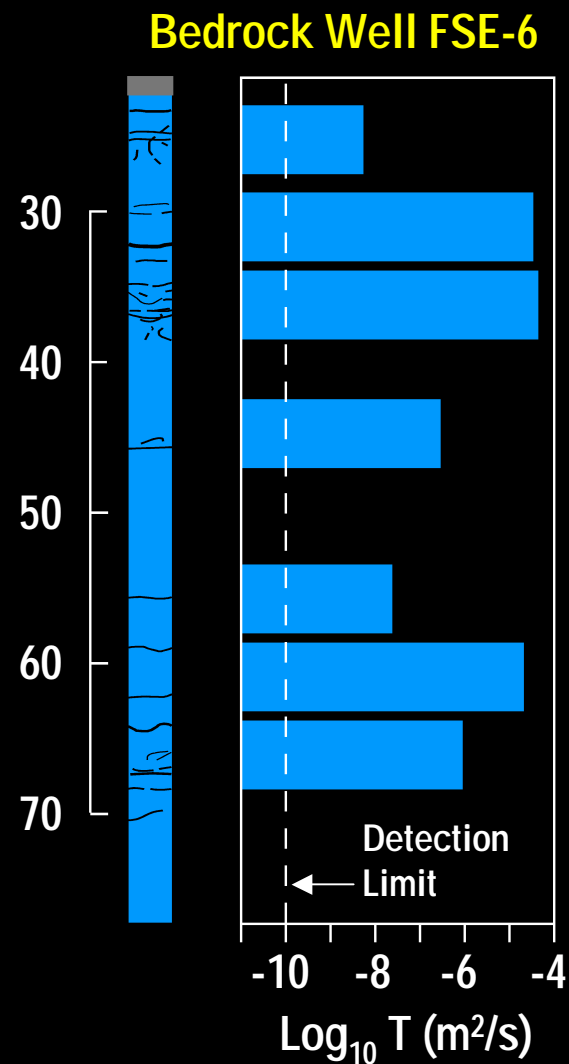
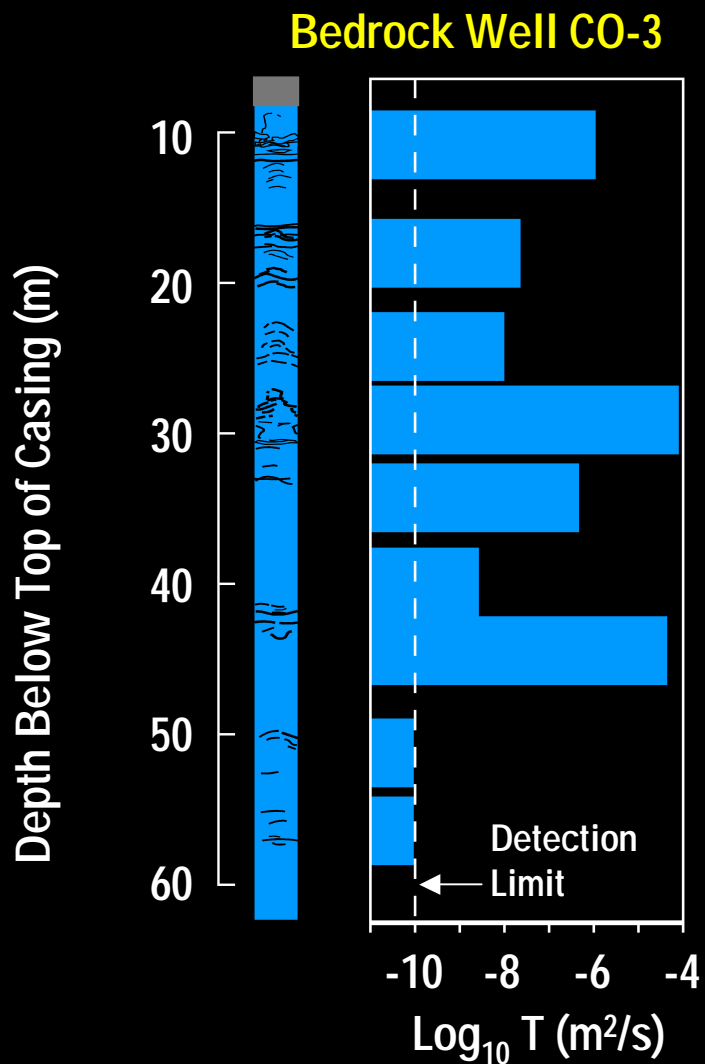
- Explanation
- Bedrock Well
 - Well Field

FSE Well Field

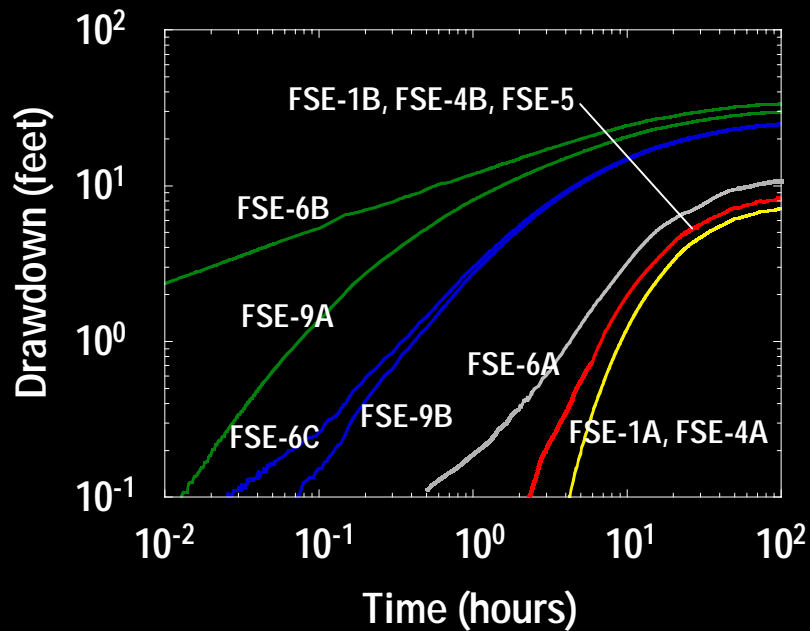
CO Well Field



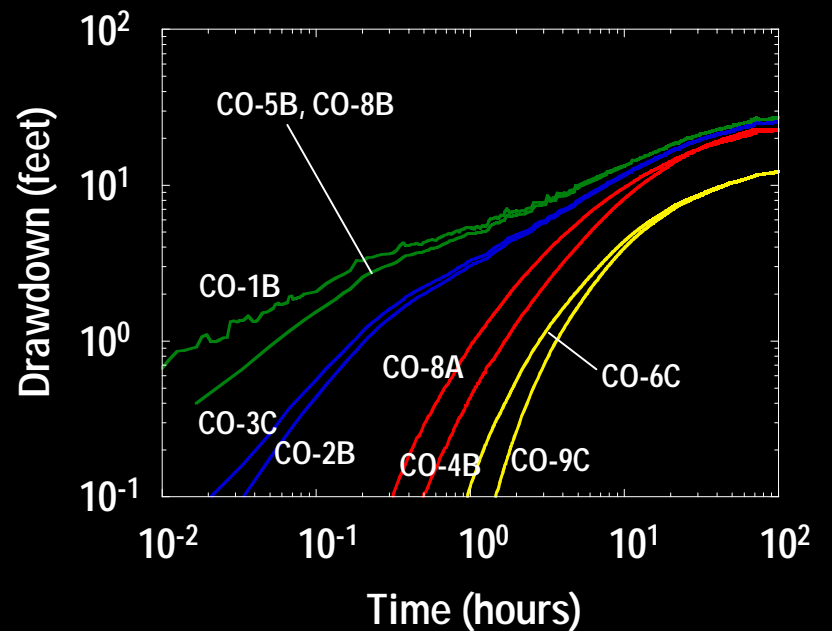
Hydraulic Conductivity and Fractures versus Depth



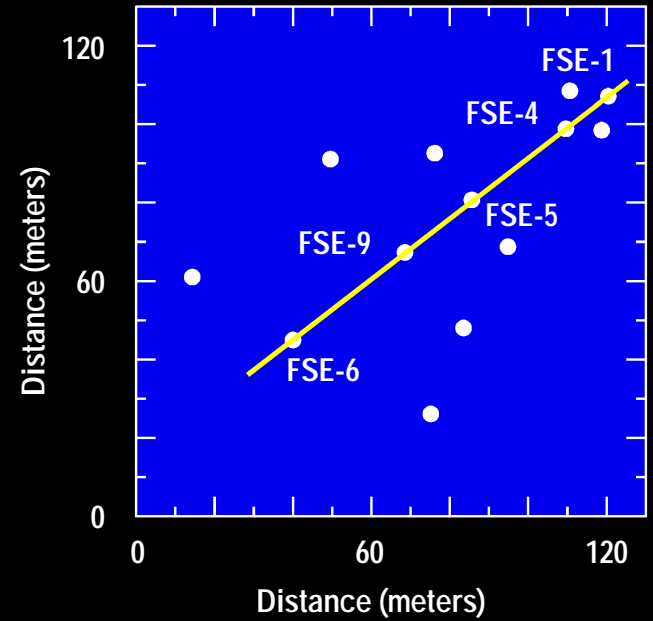
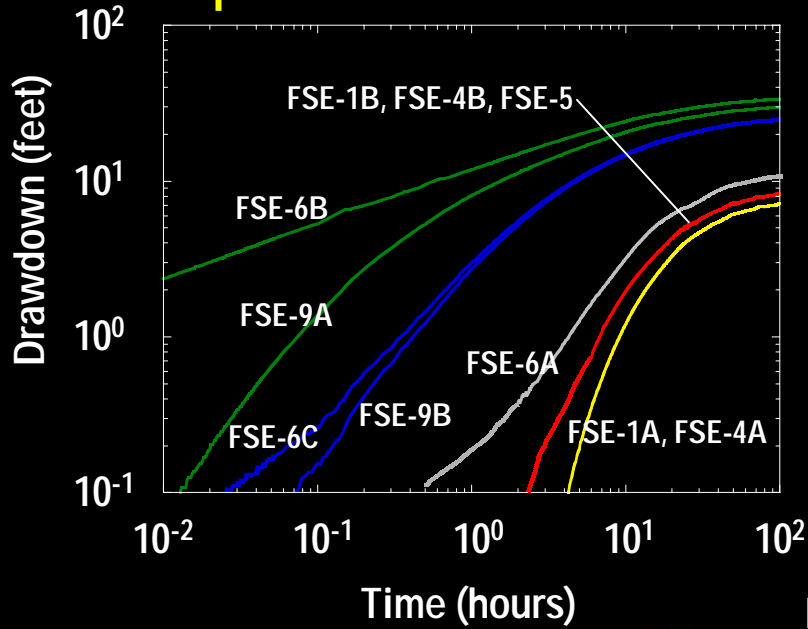
Aquifer Test - FSE Well Field



Aquifer Test - CO Well Field



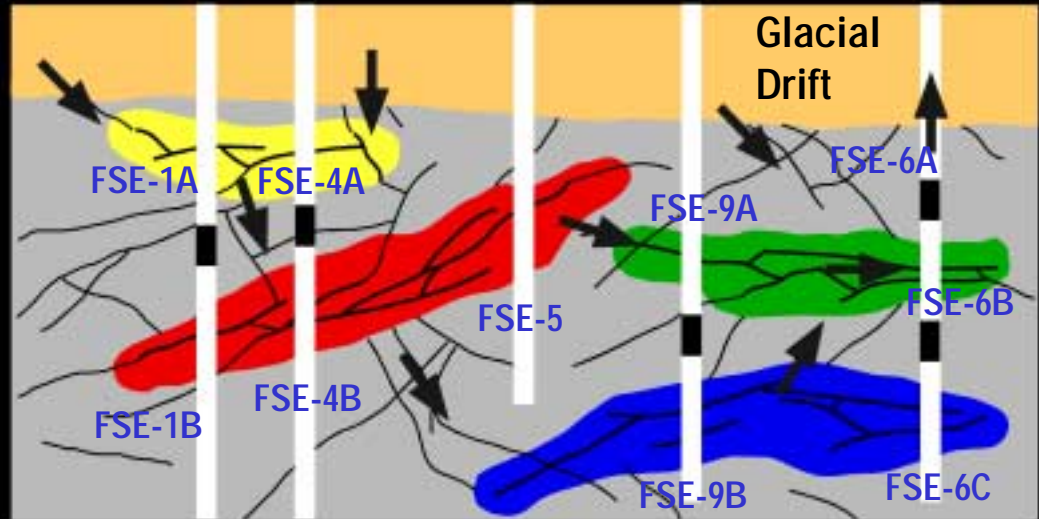
Aquifer Test - FSE Well Field



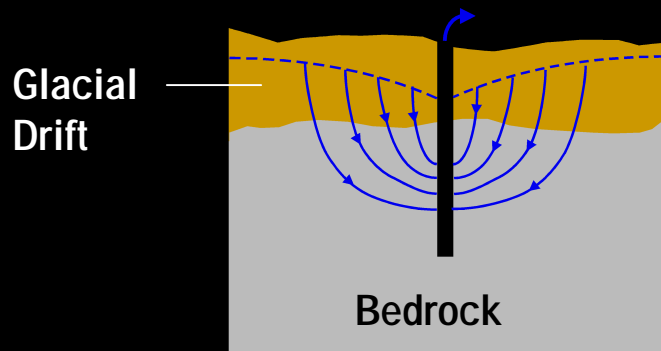
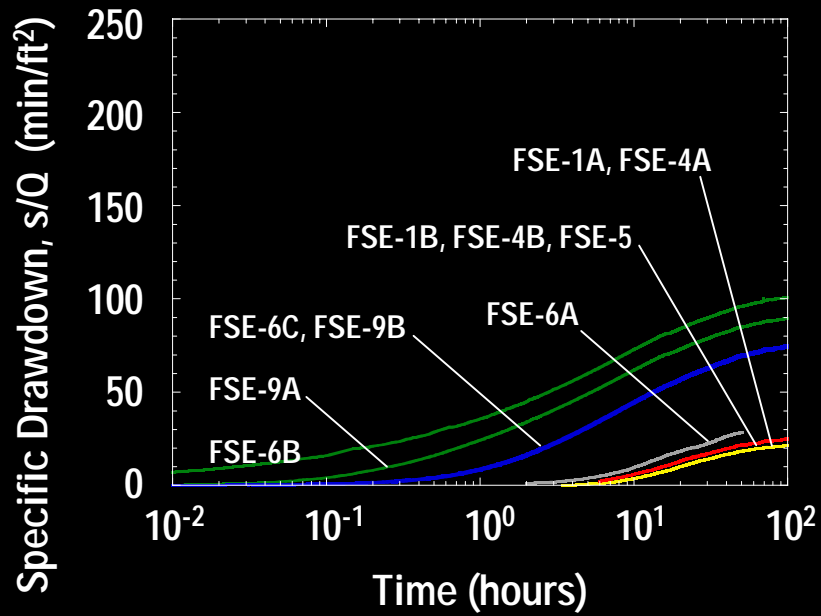
FSE-1 FSE-4 FSE-5 FSE-9 FSE-6

Conceptual Model of Aquifer Heterogeneity

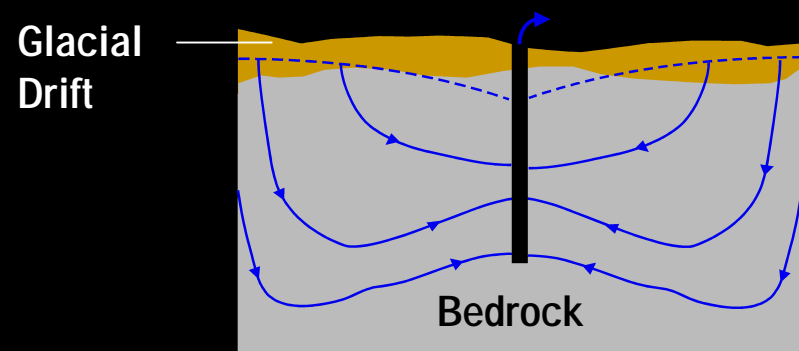
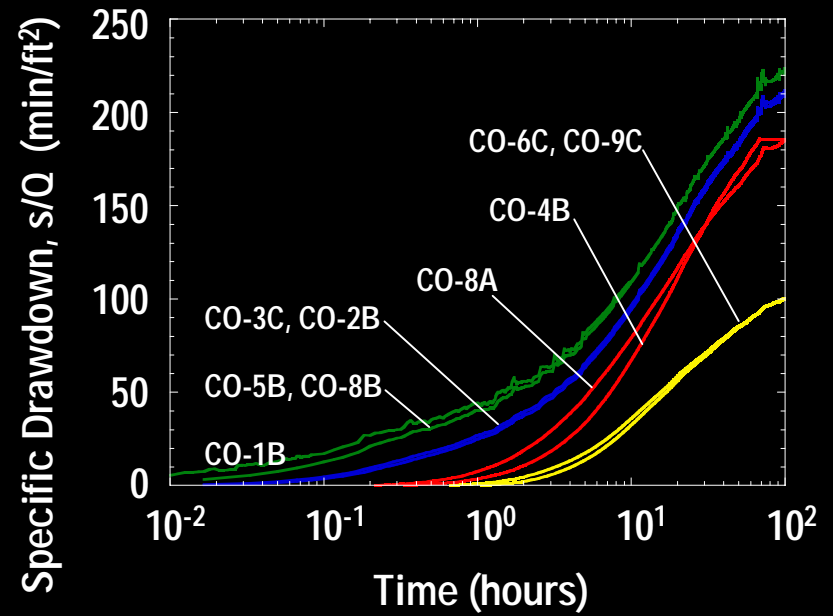
0 30
meters



Aquifer Test - FSE Well Field



Aquifer Test - CO Well Field



Hydrologic Characterization ~ kilometers ?



Objectives, degree of detail, and capabilities?

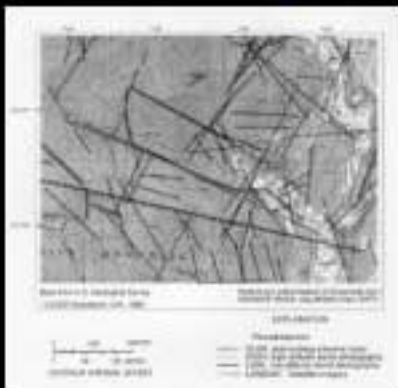
Hydrologic Characterization ~ kilometers ?



Can we (with confidence) ?

Characterizing Fractured Rock over Kilometers

Remote Sensing



Regional Hydrology



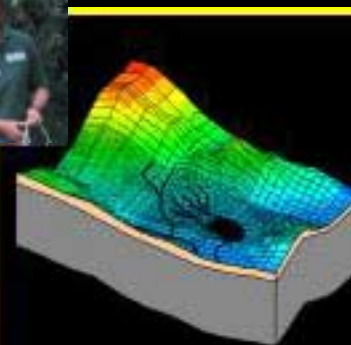
Geologic Mapping



Geochemistry



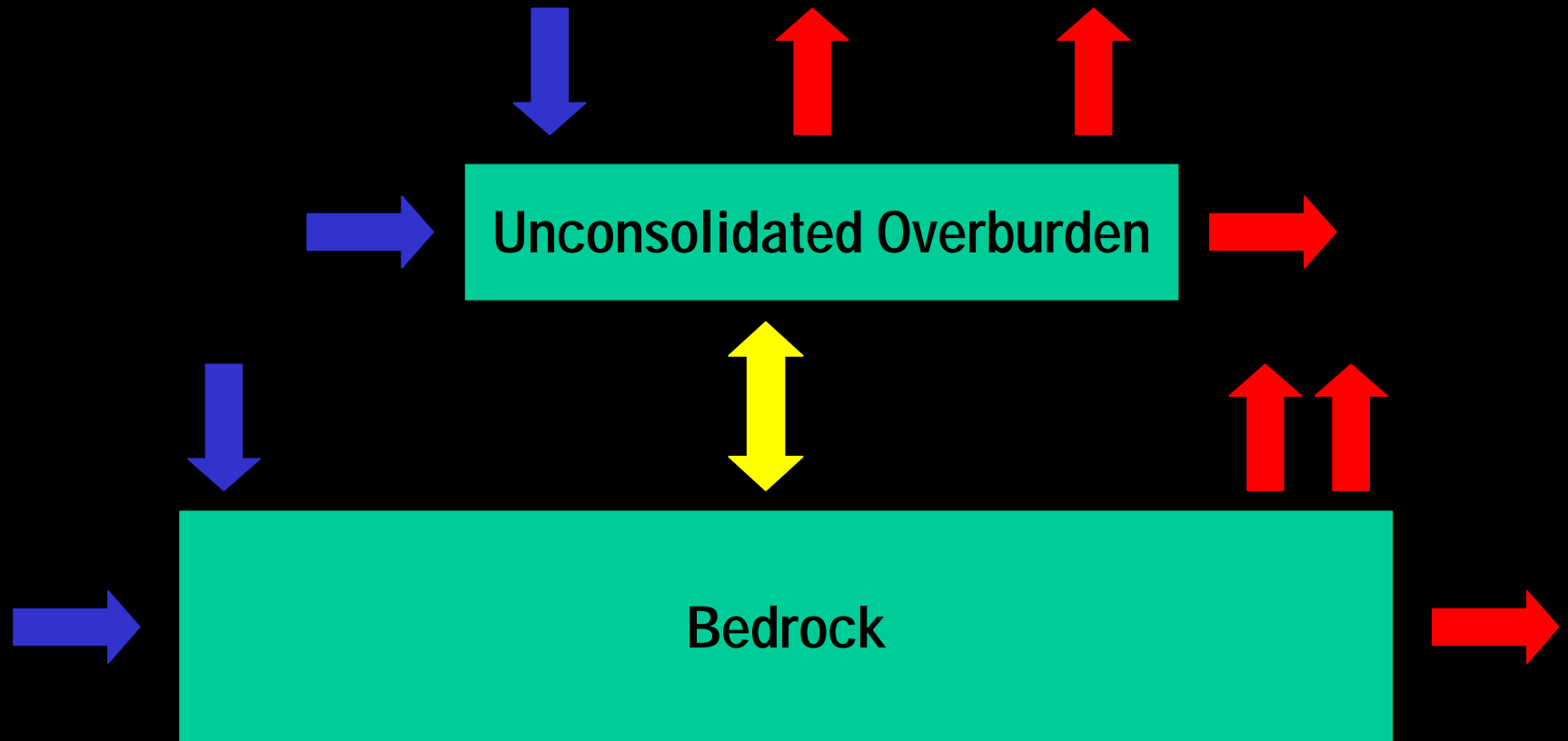
Ground-Water Flow and Transport Modeling



Surface Geophysics

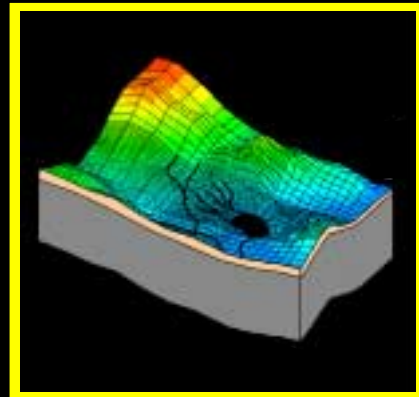


Lumped-Parameter Model: (a good place to start)

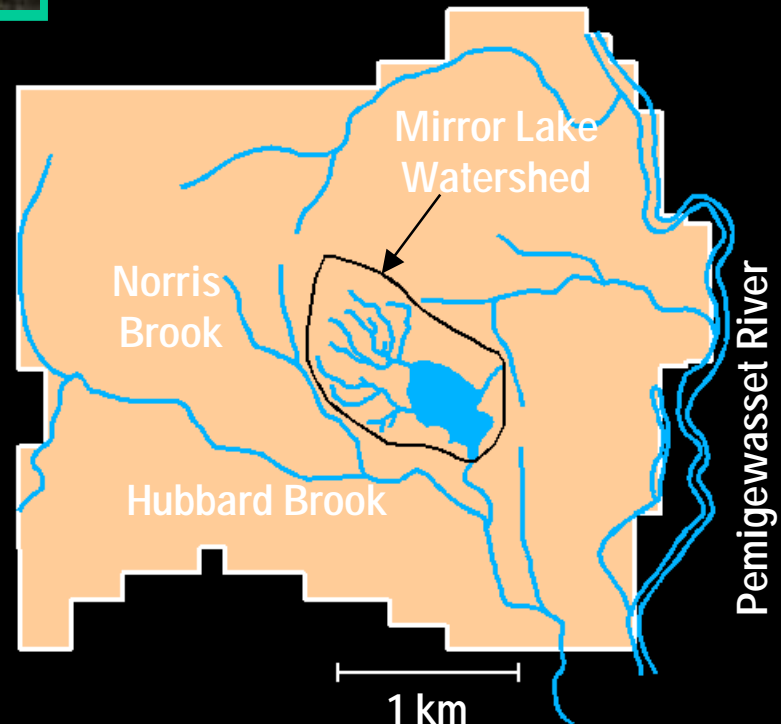


Distributed-Parameter Model:

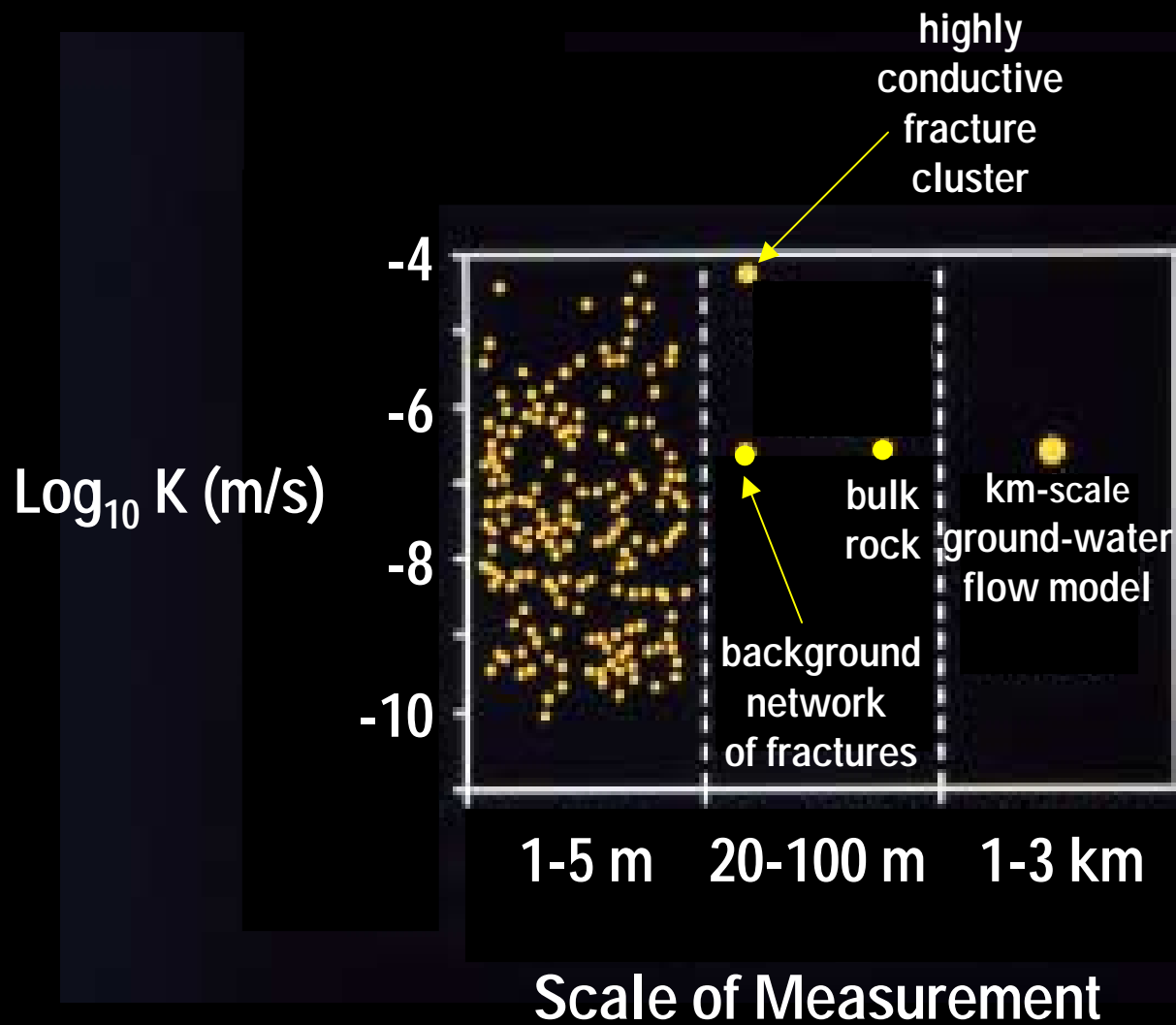
(to define a better understanding of physical processes)



N
↑

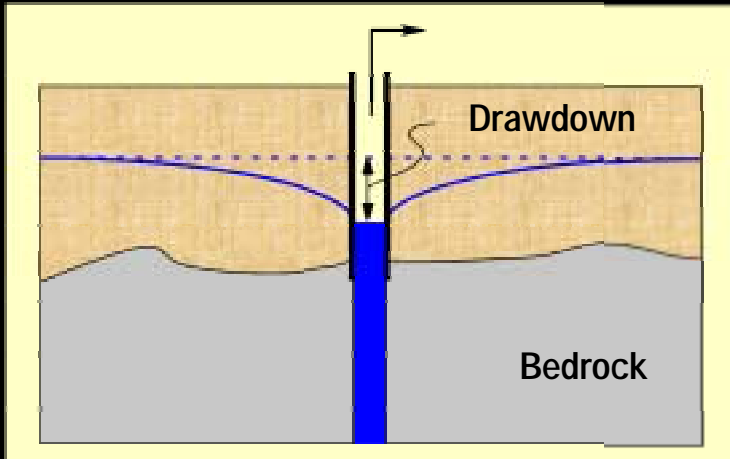


Hydraulic Conductivity Measurements at Mirror Lake



Confidence in estimates of bedrock properties. . .

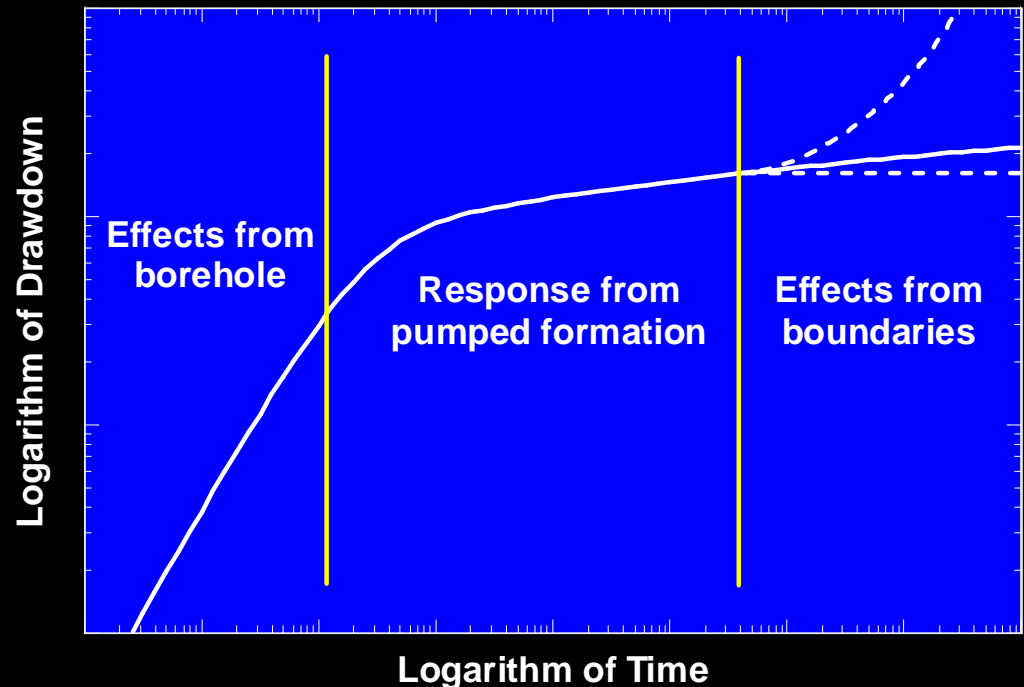
Hydraulic and chemical stresses applied in the bedrock



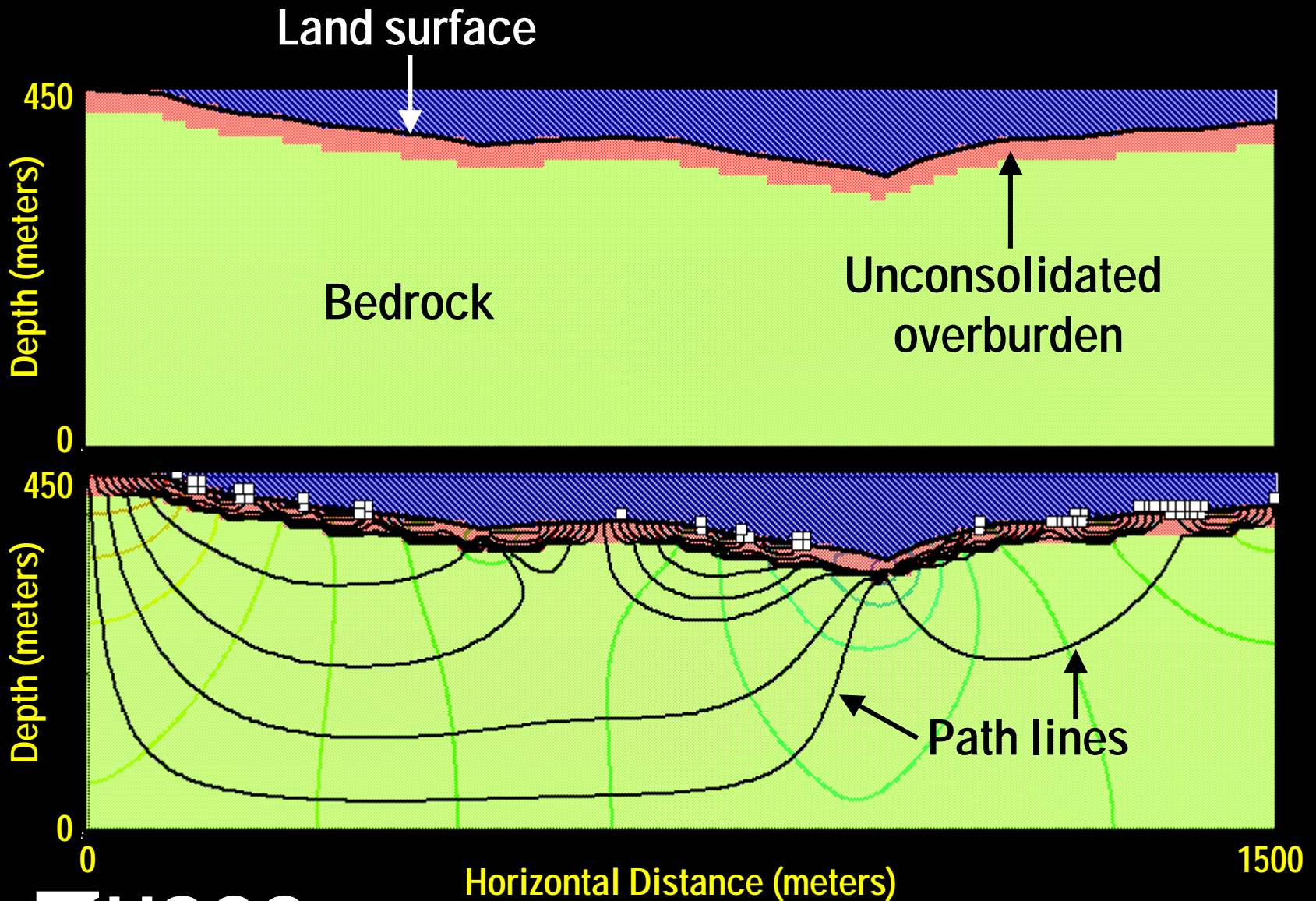
Estimating "Bulk" Properties of the Bedrock (10's meters)

Hydraulic/Aquifer Testing:

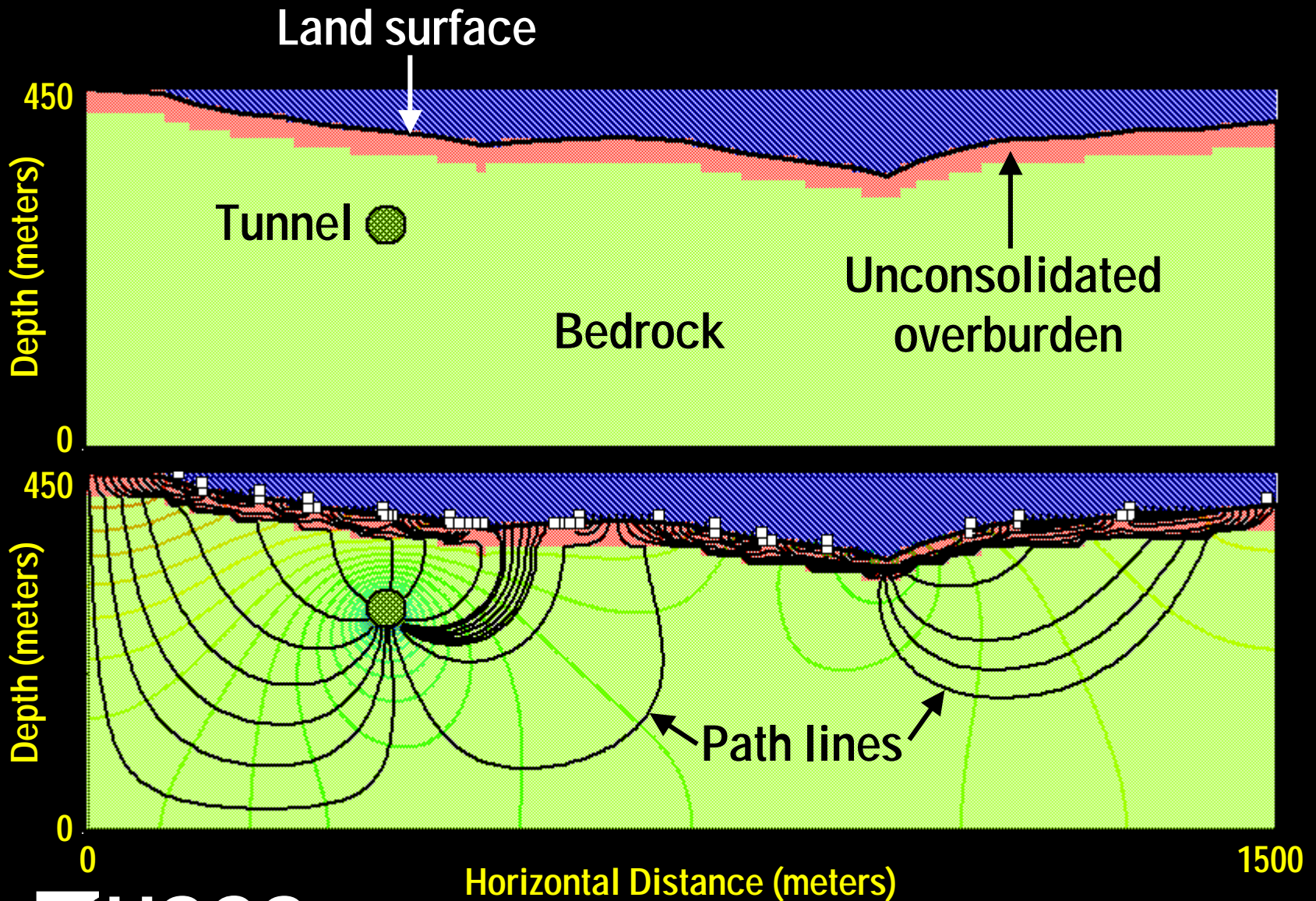
Generic Description of Time-Varying Drawdown in a Pumped Well



Regional Ground-Water Flow



Regional Ground-Water Flow – Impact of Tunnels



Washington Metro Tunnel Leakage Bethesda, Maryland



The Metro's new tunnels in Bethesda and Silver Spring show the results of water seeping in.

Water in Metro's Basement

Seepage Ruining Rail Equipment in Most Tunnels

By Lawrence Kaplan
Washington Post Staff Writer

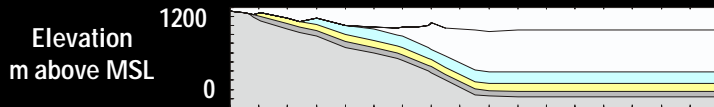
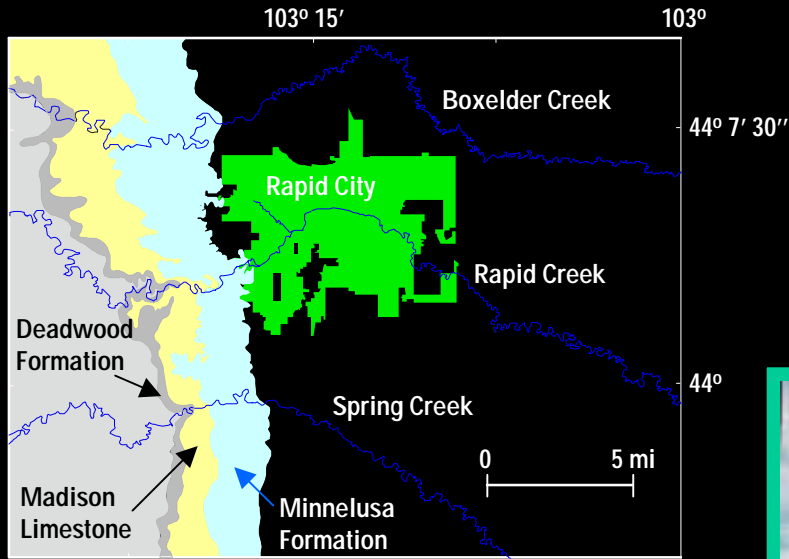
It's a dry night in Washington, but the Metro's new tunnels in Bethesda and Silver Spring are not. In fact, they are so wet that the water is dripping from the ceiling. The water is so thick that it is dripping from the ceiling. The water is so thick that it is dripping from the ceiling. The water is so thick that it is dripping from the ceiling.



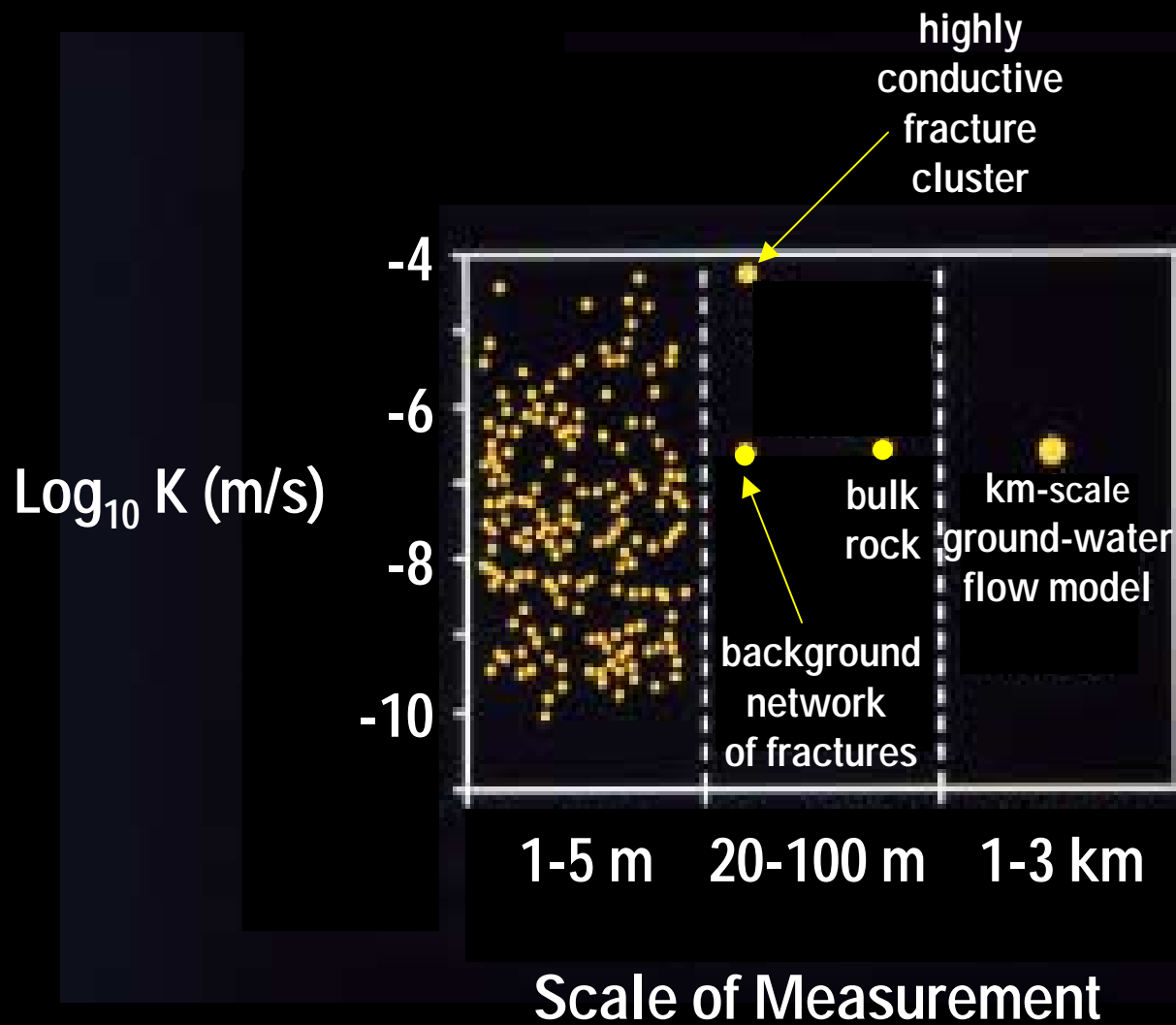
The map shows the Metro's new tunnels in Bethesda and Silver Spring. The tunnels are highlighted in red and orange. The map also shows the locations of the new tunnels in Bethesda and Silver Spring.

The Metro's new tunnels in Bethesda and Silver Spring are not dry. In fact, they are so wet that the water is dripping from the ceiling. The water is so thick that it is dripping from the ceiling. The water is so thick that it is dripping from the ceiling.

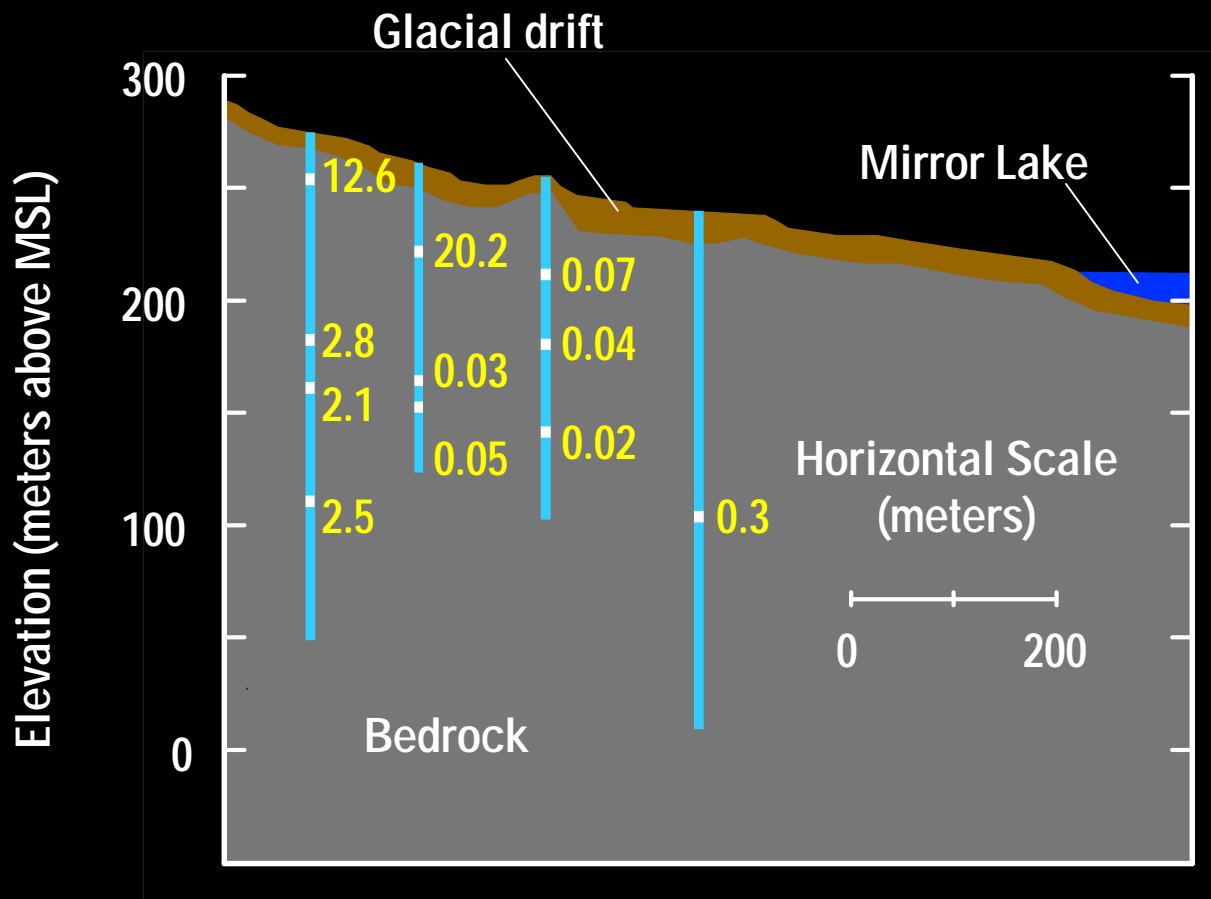
Madison Limestone Rapid City, South Dakota



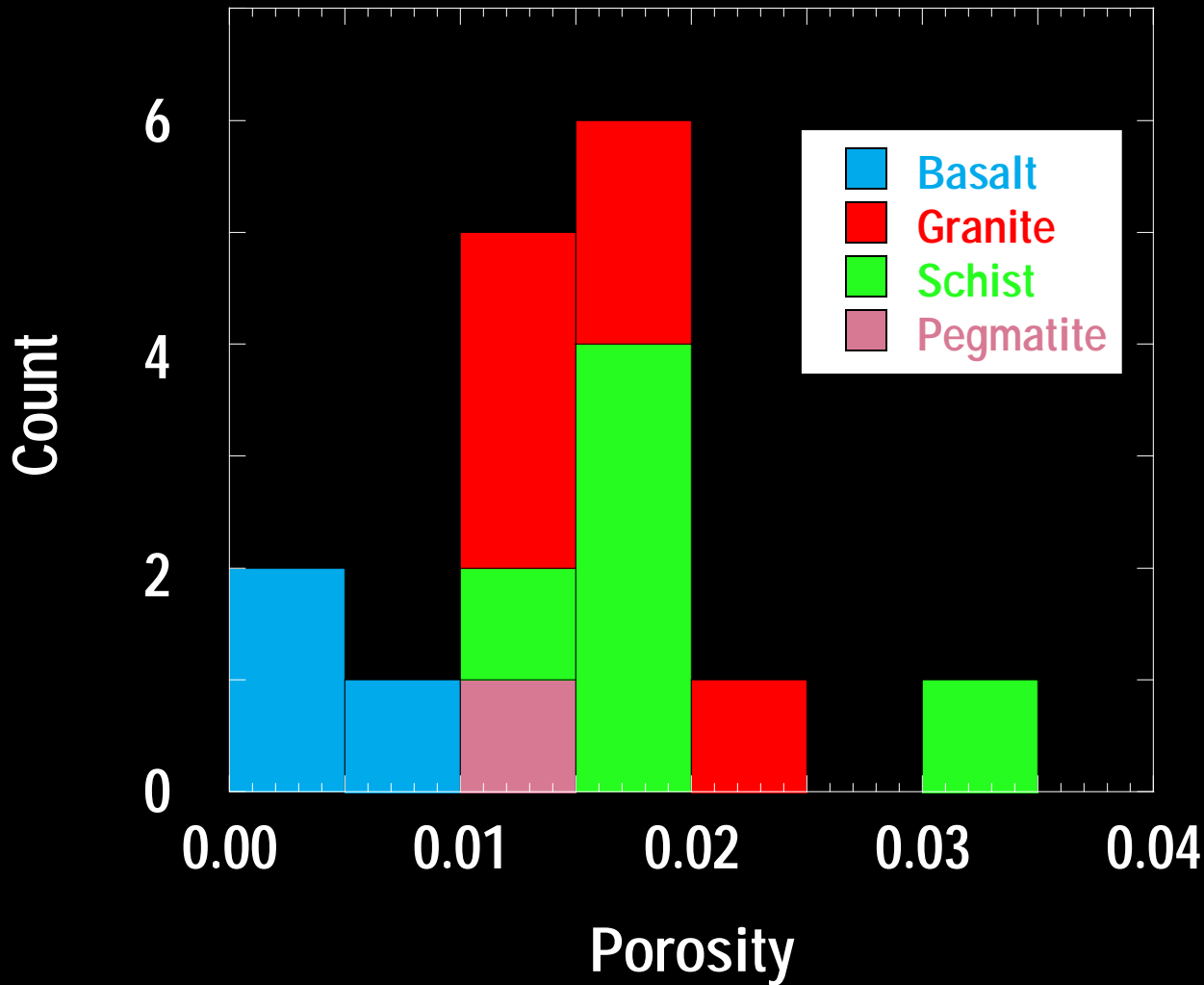
Hydraulic Conductivity Measurements at Mirror Lake



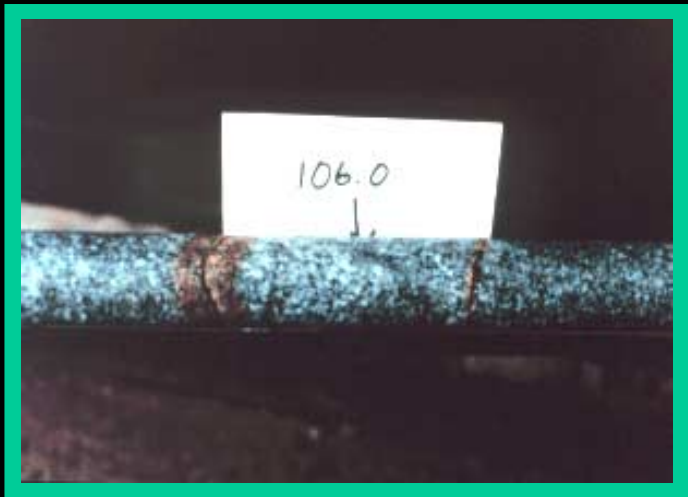
Tritium Concentrations - 1992



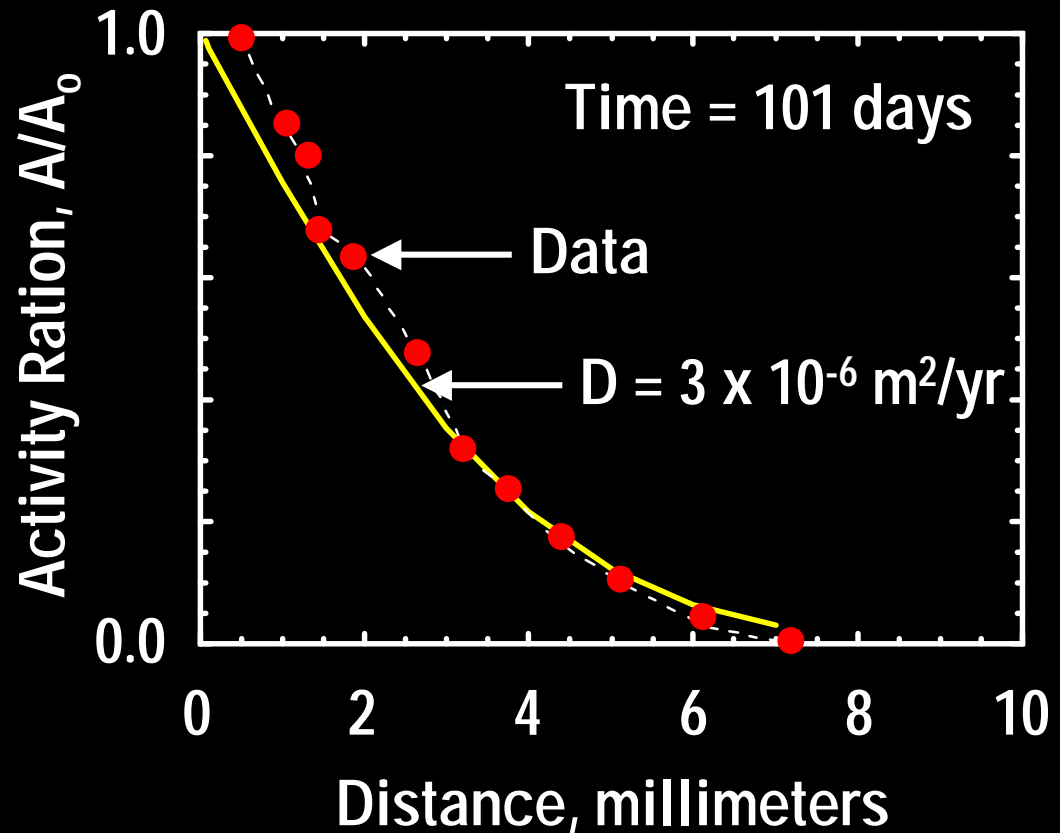
Mirror Lake Watershed, New Hampshire



Laboratory-Scale Experiments

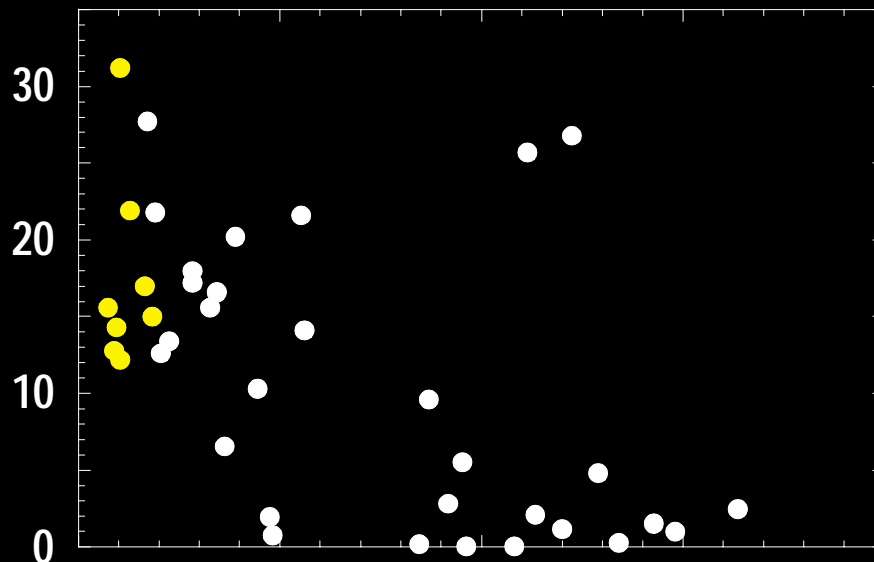


Diffusion of ^{137}Cs in a Granite Core



$$D = n_{\text{rm}} \alpha D_{\text{w}} = n_{\text{rm}} D_{\text{rm}}$$

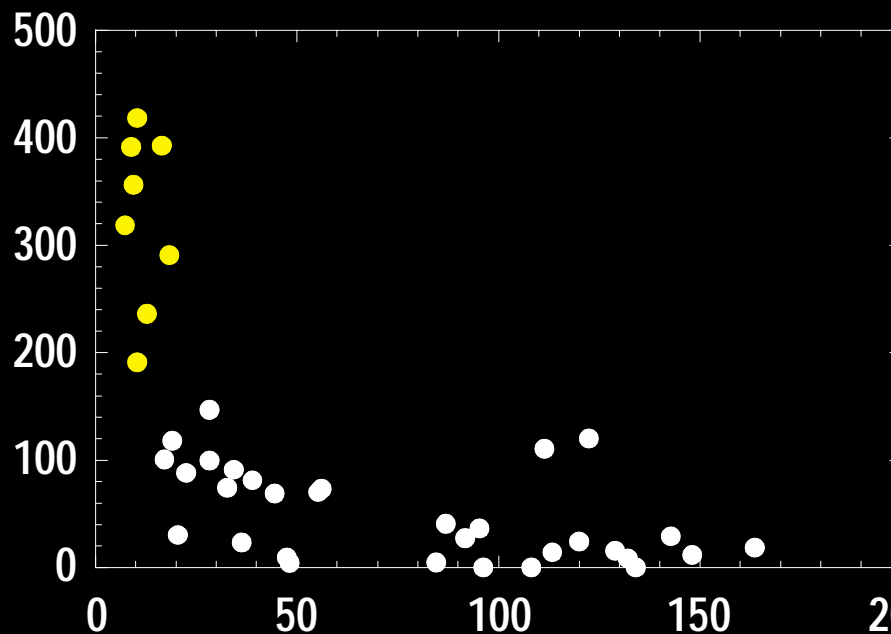
Tritium (TU)



● Bedrock

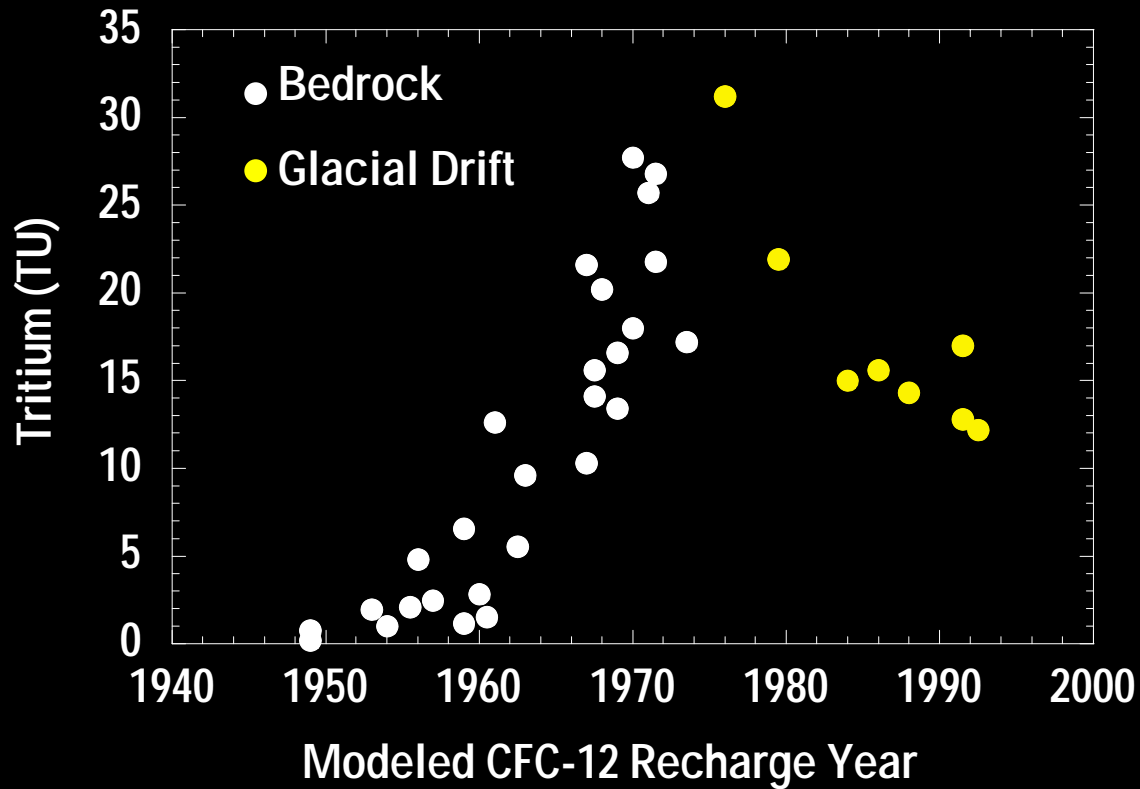
● Glacial Drift

CFC-12 Concentration
(picograms per kg H₂O)

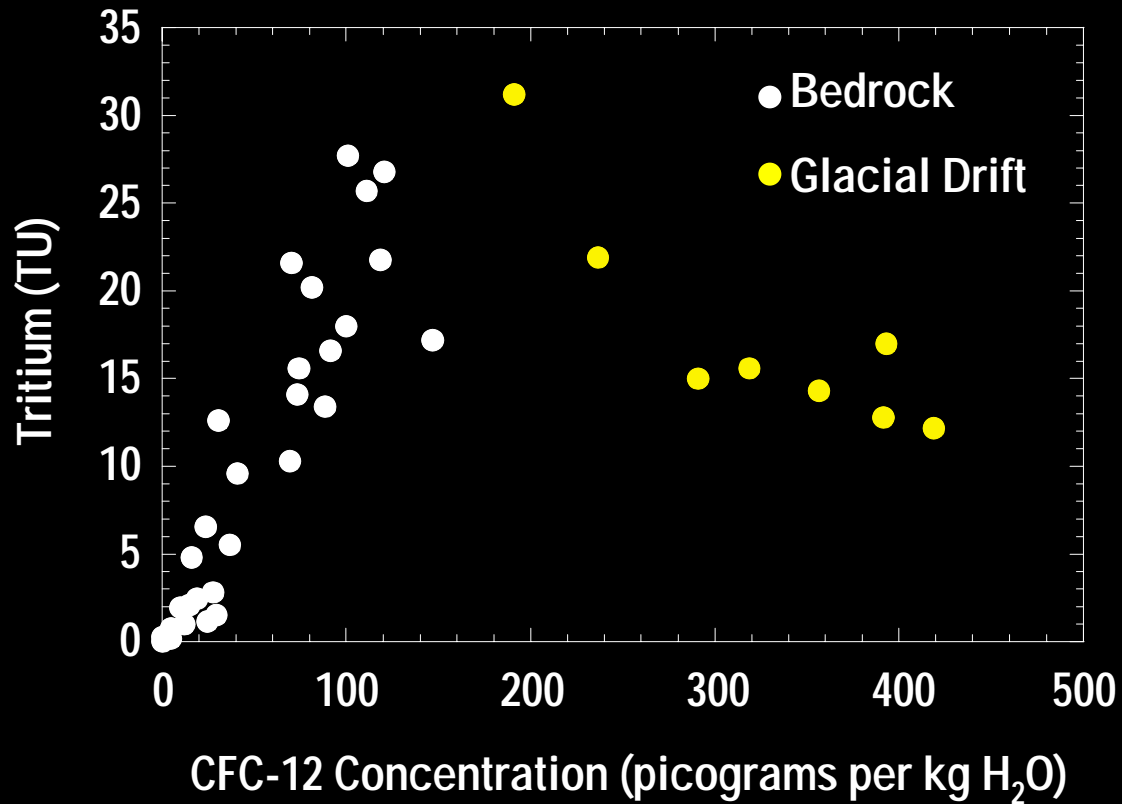


Depth Below Land Surface (m)

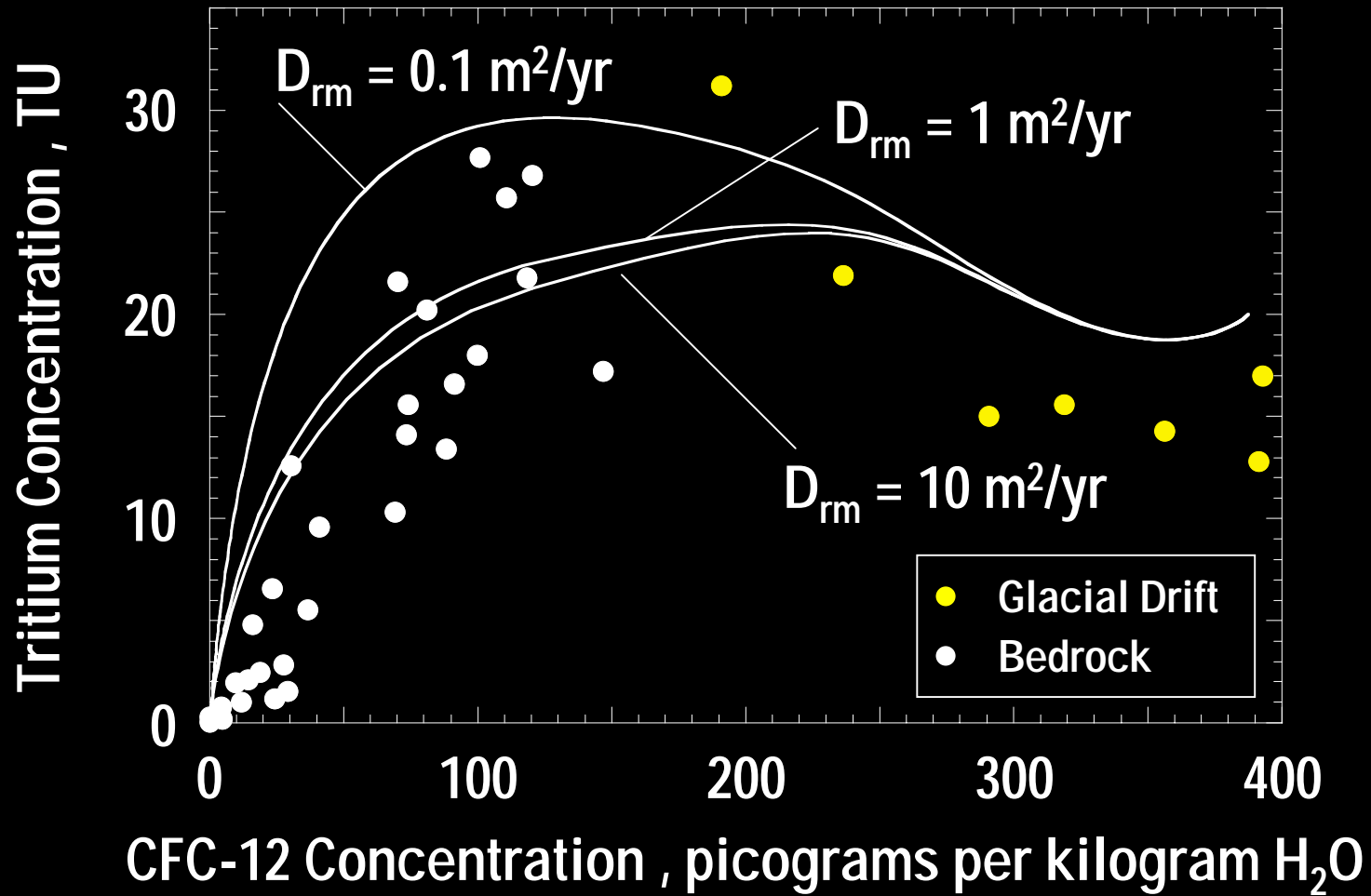
Tritium Versus Modeled CFC-12 Recharge Year



Tritium Versus CFC-12 Concentration



Model Results Versus ^3H and CFC-12 Data



Effective Matrix Diffusion at Different Scales



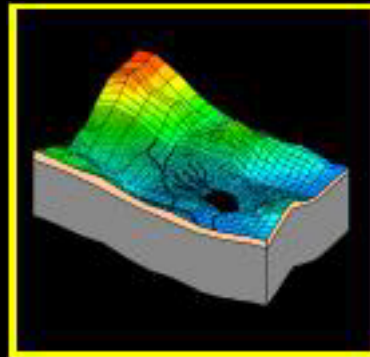
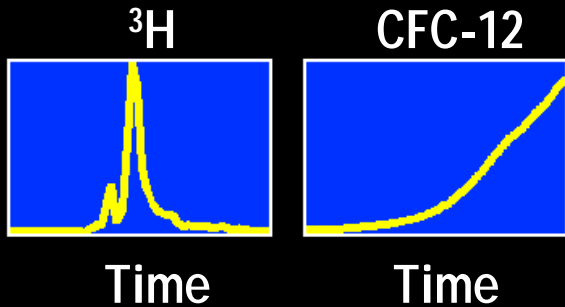
0.1 m

$$D_{\text{eff}} \ll D_w$$



10's m

$$D_{\text{eff}} > D_w$$



100's m

$$D_{\text{eff}} \gg D_w$$

Some closing thoughts...

1. Objectives, degree of detail, and capabilities
2. Synthesis (modeling) starting on day 1 → data collection
3. Don't forget the obvious (recharge, water balance, stream flow, geologic structure, surficial geology, . . .)
4. Can we characterize regional ground-water flow in bedrock aquifers with confidence?