Towards Taming the Complexities of Fractured Rock Aquifers

Allen M. Shapiro

U.S. Geological Survey
Reston, VA

Paul Hsieh

Claire Tiedeman

John Lane

Bill Burton

Matt Becker

Pete Haeni

Dan Goode

Carole Johnson

USGS
science for a changing world

The challenge of characterizing ground water flow and contaminant transport

Granite and schist
Mirror Lake, NH

Mudstone, Lockatong Formation
West Trenton, NJ

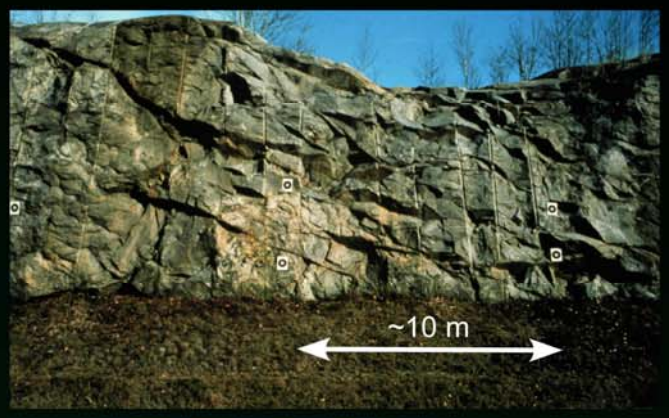
Madison limestone
Rapid City, SD

Silurian dolomite
Argonne, IL

Gneiss, Sykesville Formation
Washington, DC

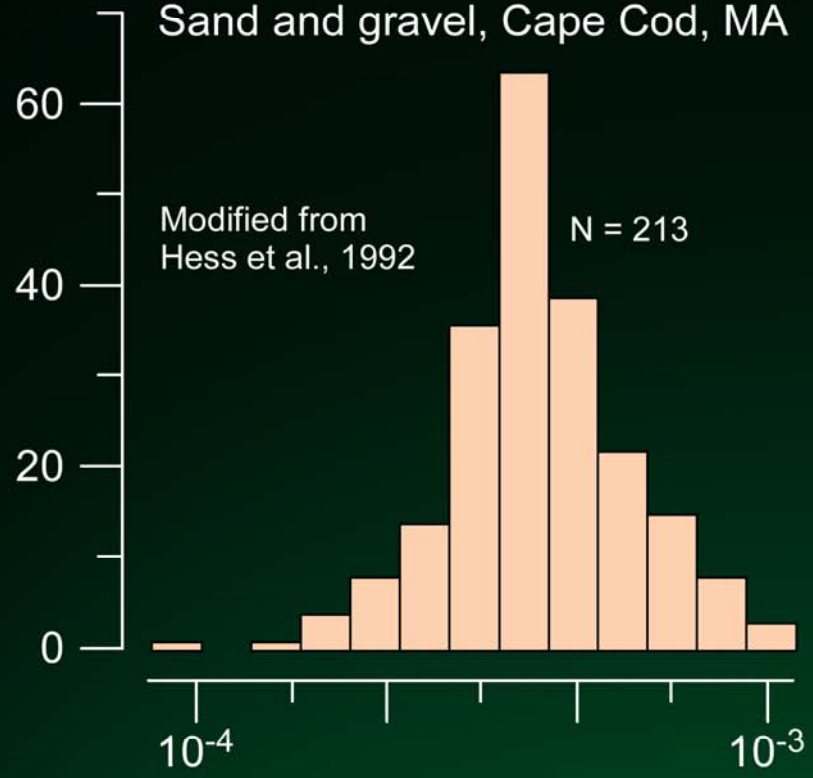
Tonalite, Georgetown Intrusive Suite
Washington, DC

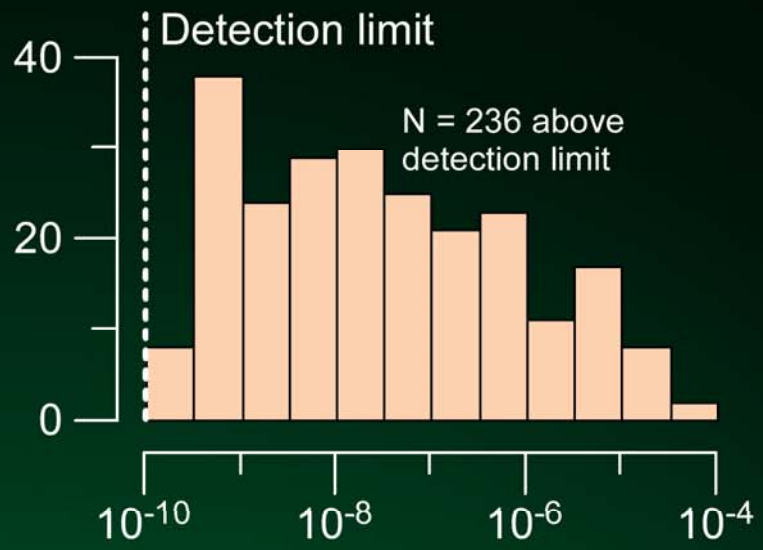
USGS



Sand and gravel, Cape Cod, MA

Granite and schist, Mirror Lake, NH





Hydraulic conductivity

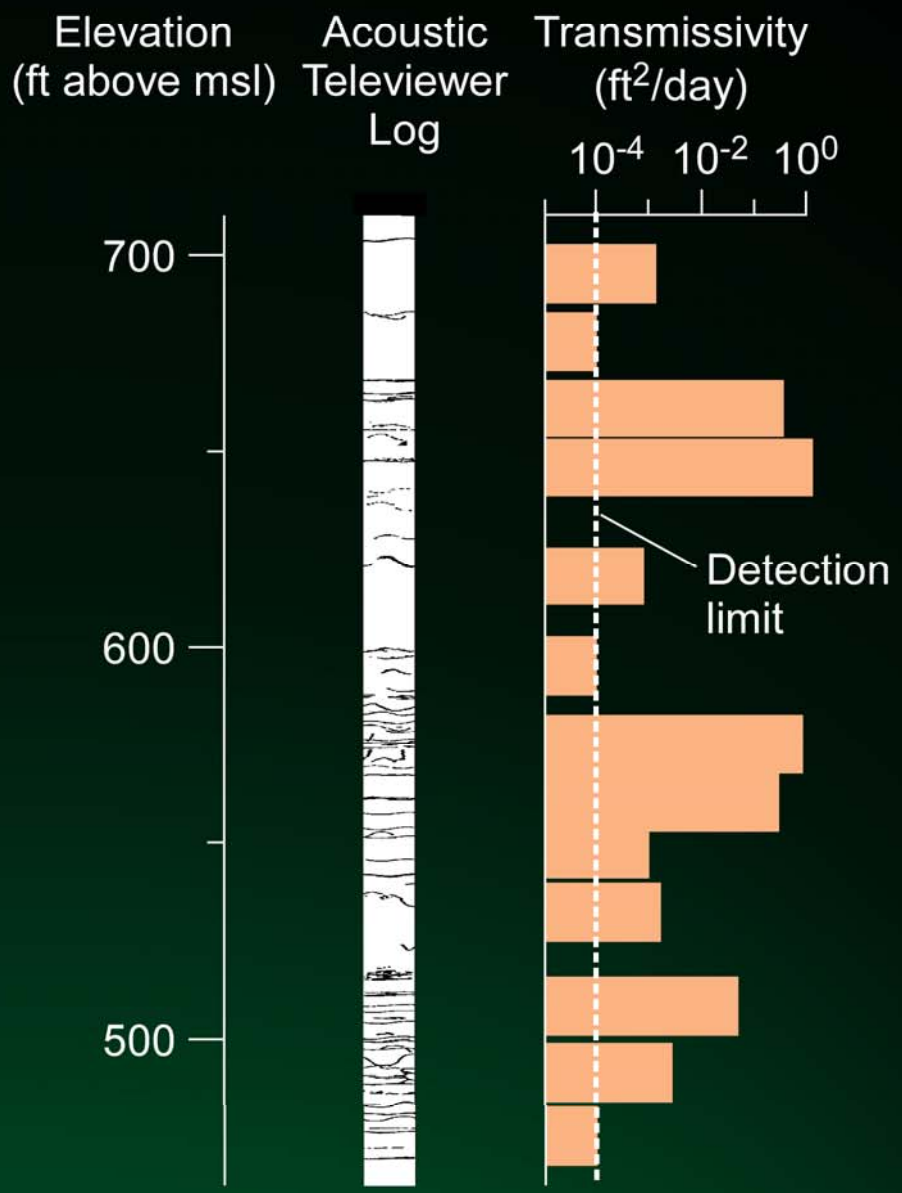
USGS

Geologic Complexities of Fractured Rock Aquifers

Granite and schist
Mirror Lake, NH

Complex fracture connectivity

Enormous range of hydraulic properties



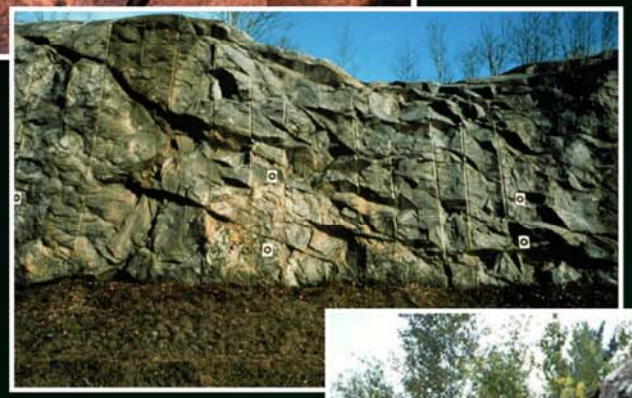
USGS

Fractured rock aquifers are characterized by a hierarchy of void space

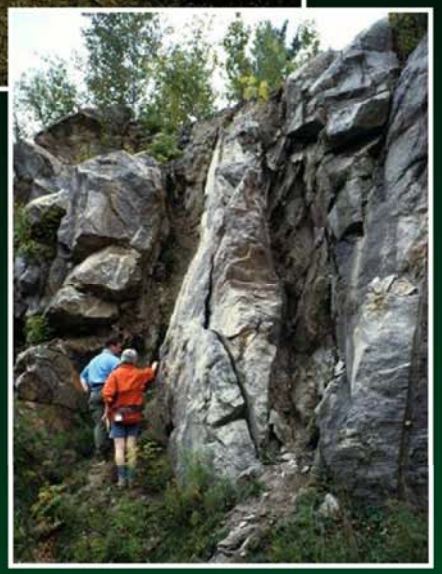
Granite and schist, Mirror Lake, NH

Lockatong Mudstone, West Trenton, NJ

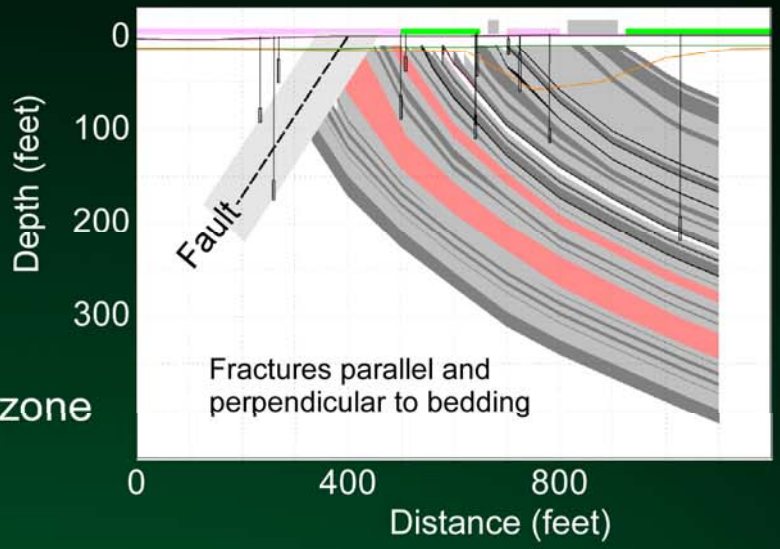
Primary porosity



Fractures



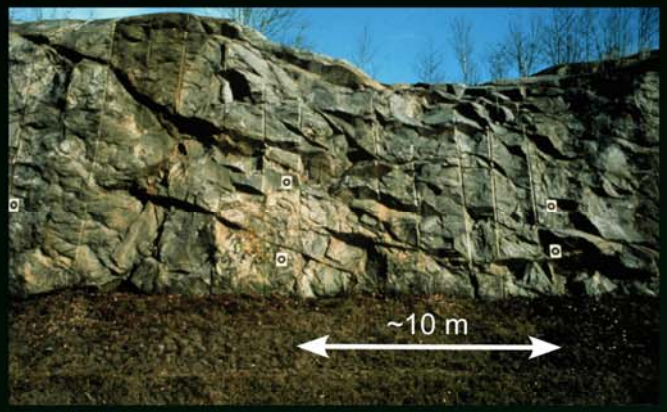
Fault zone



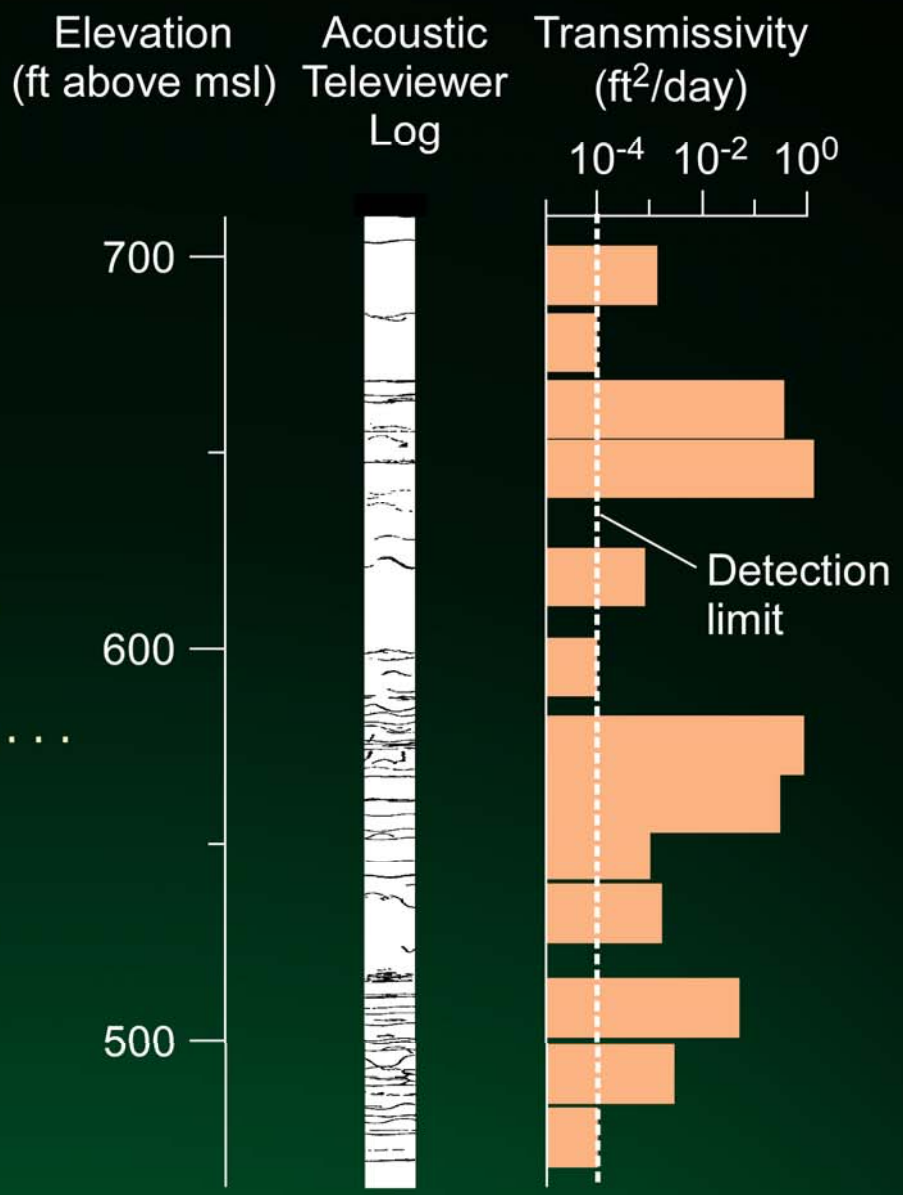
USGS

. . .for characterizing ground water flow and chemical transport,
it is essential to identify the most permeable fractures and their connectivity . . .

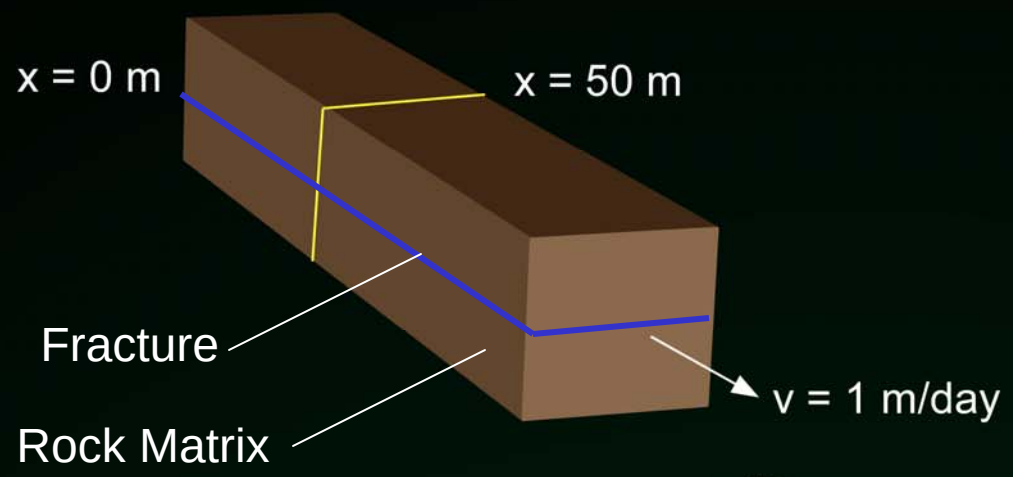
Granite and schist, Mirror Lake, NH

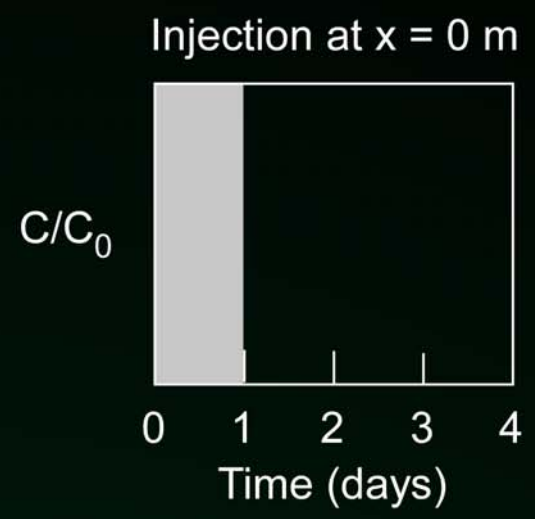


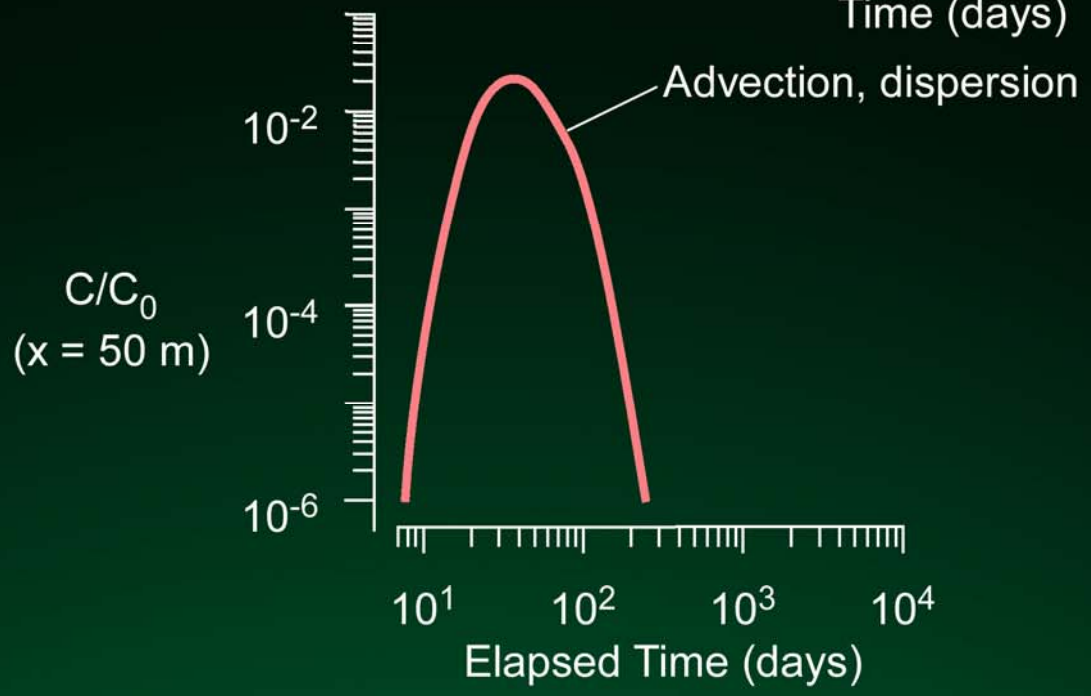
. . .for characterizing chemical transport,
it is essential to account for the
fluid in the rock matrix (primary porosity) . . .



Significance of the primary porosity

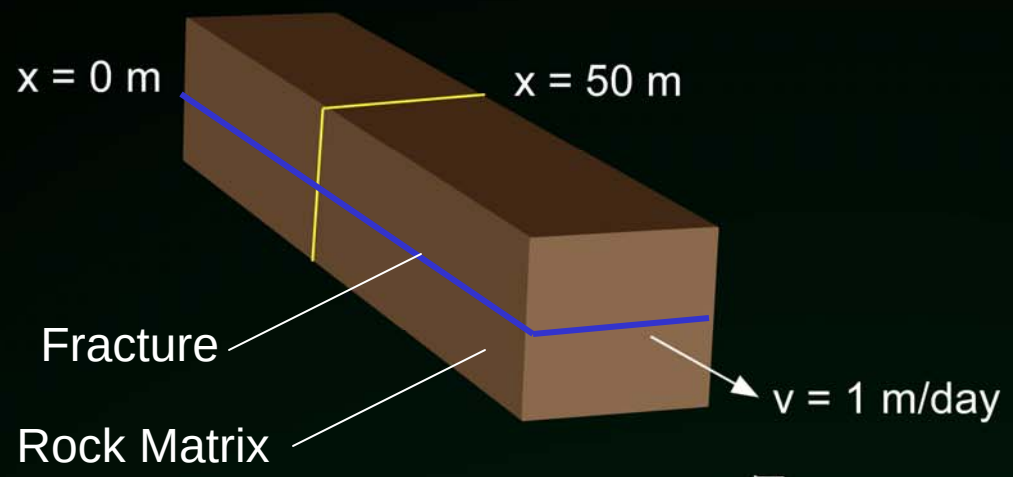


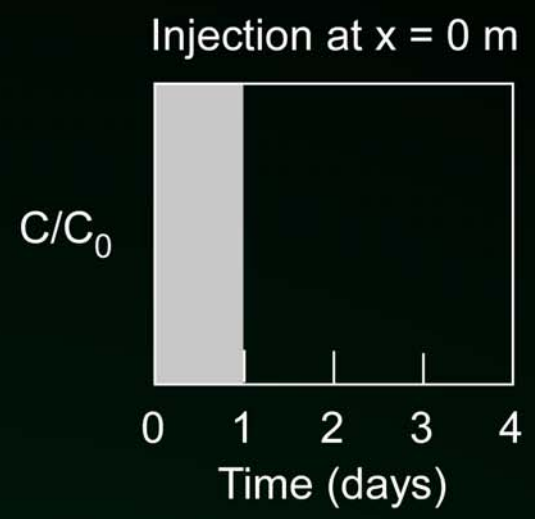


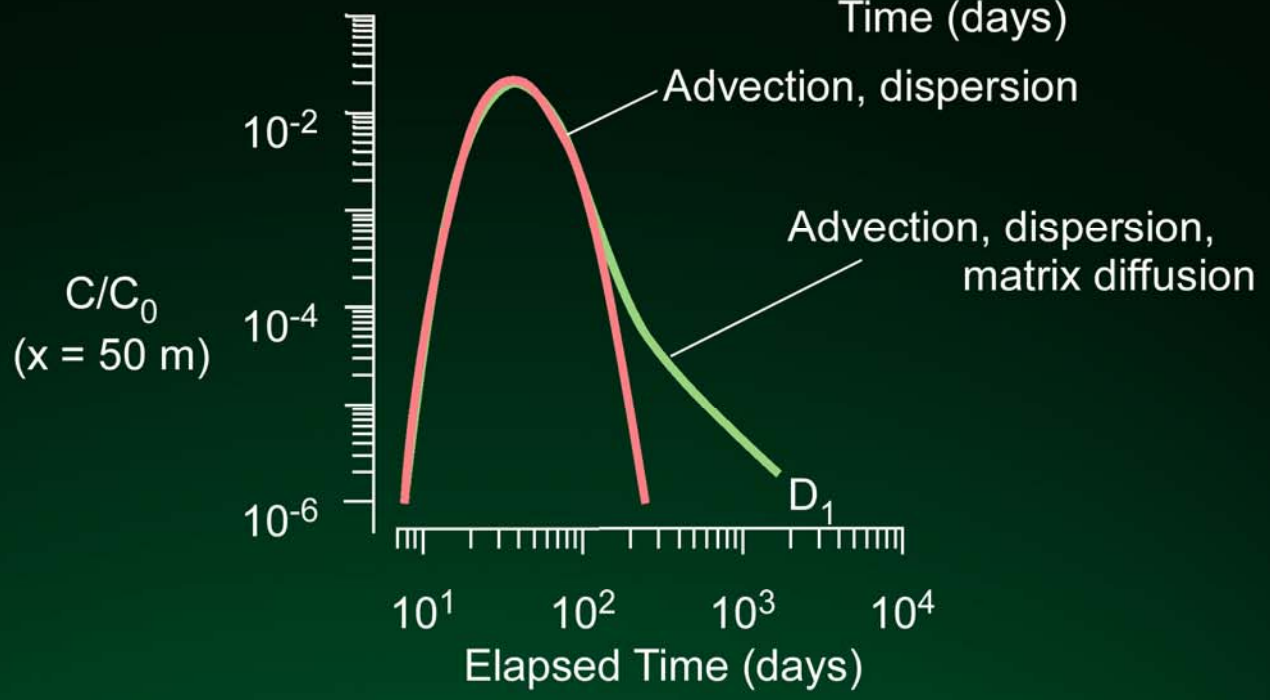


USGS

Significance of the primary porosity

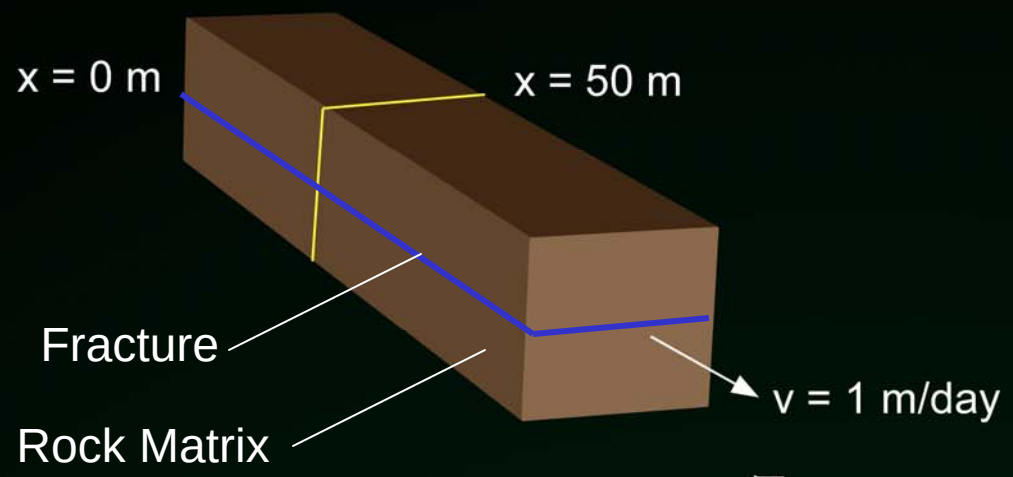


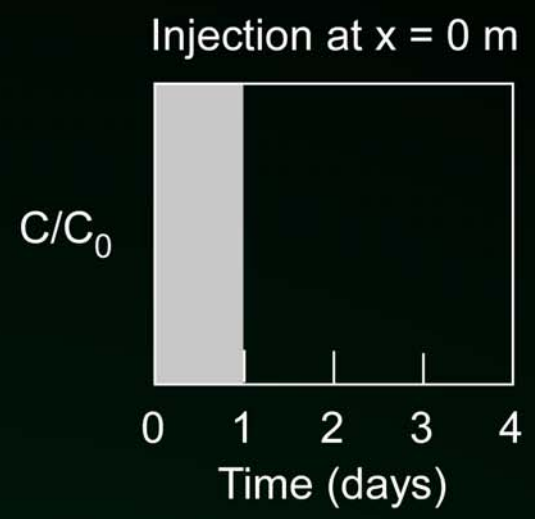


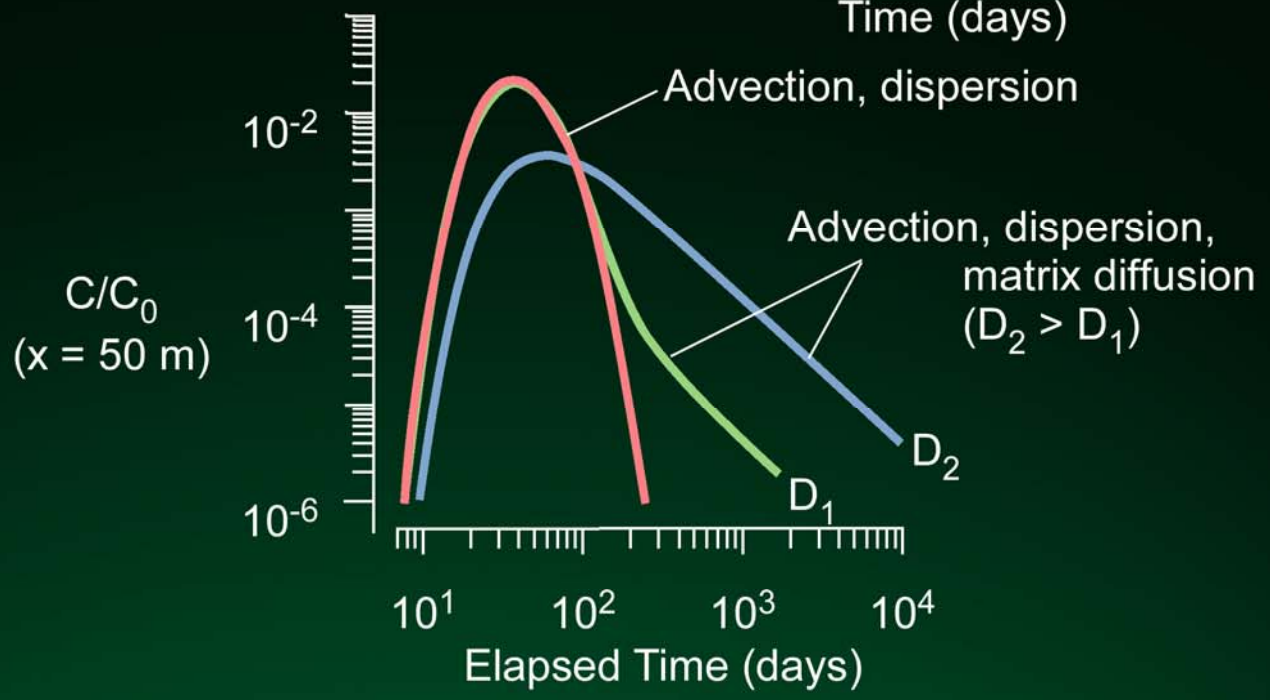


USGS

Significance of the primary porosity

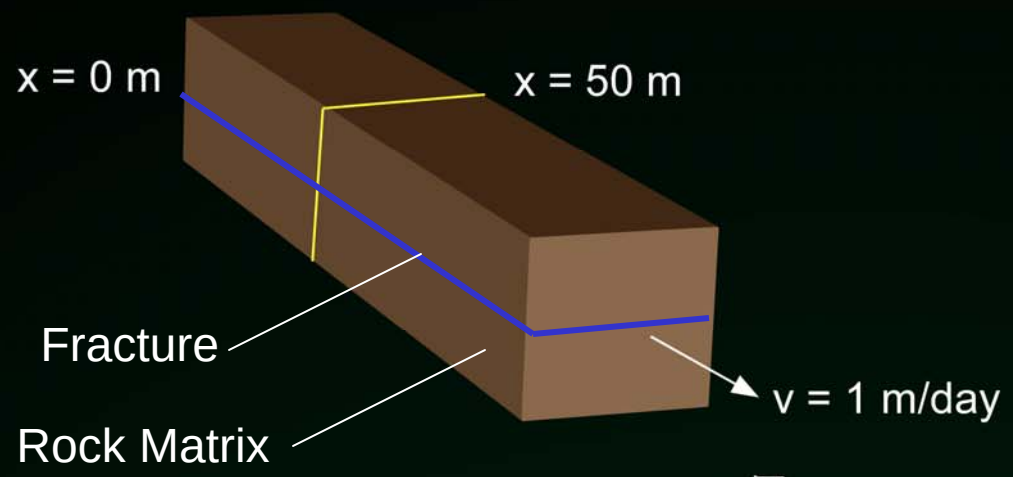


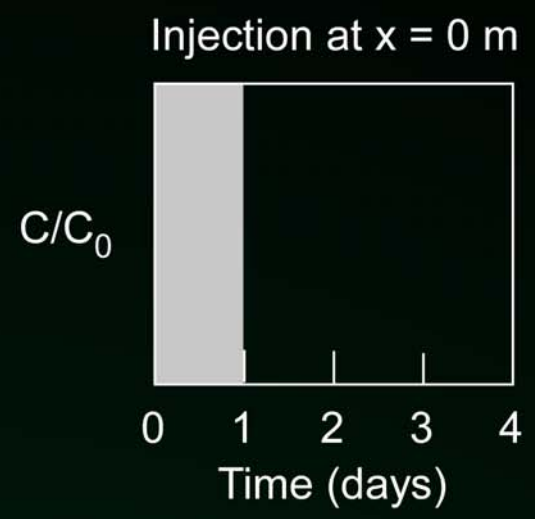


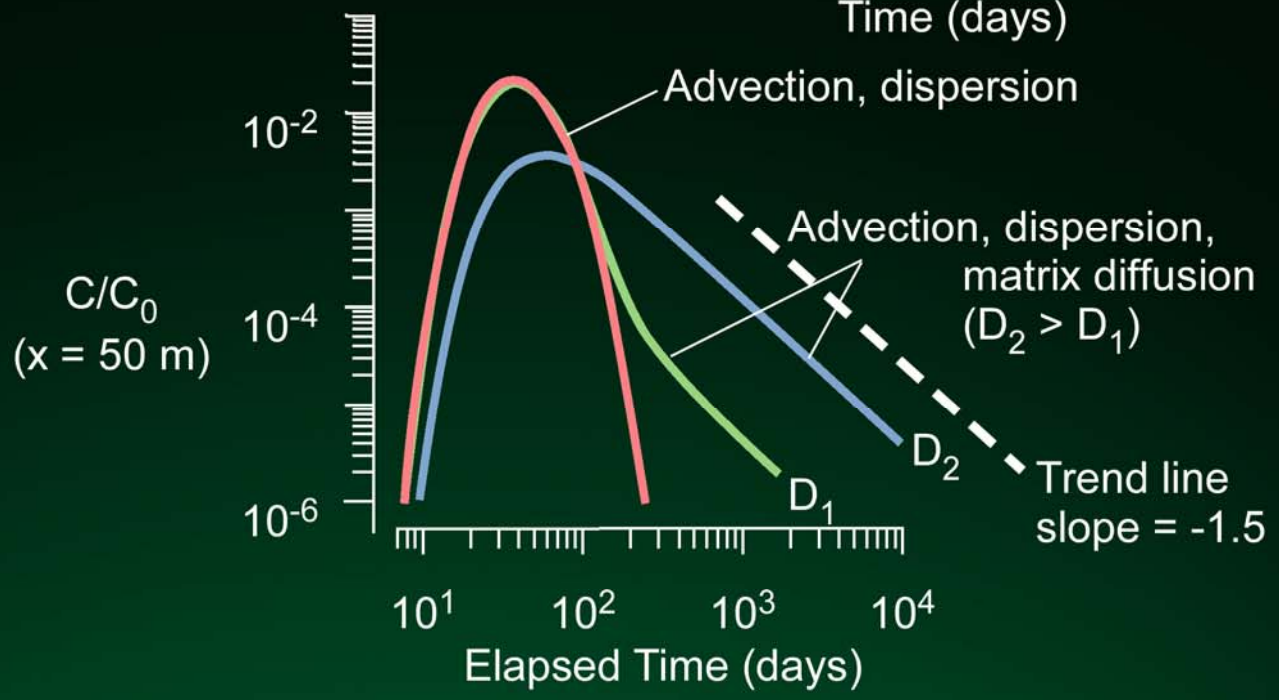


USGS

Significance of the primary porosity

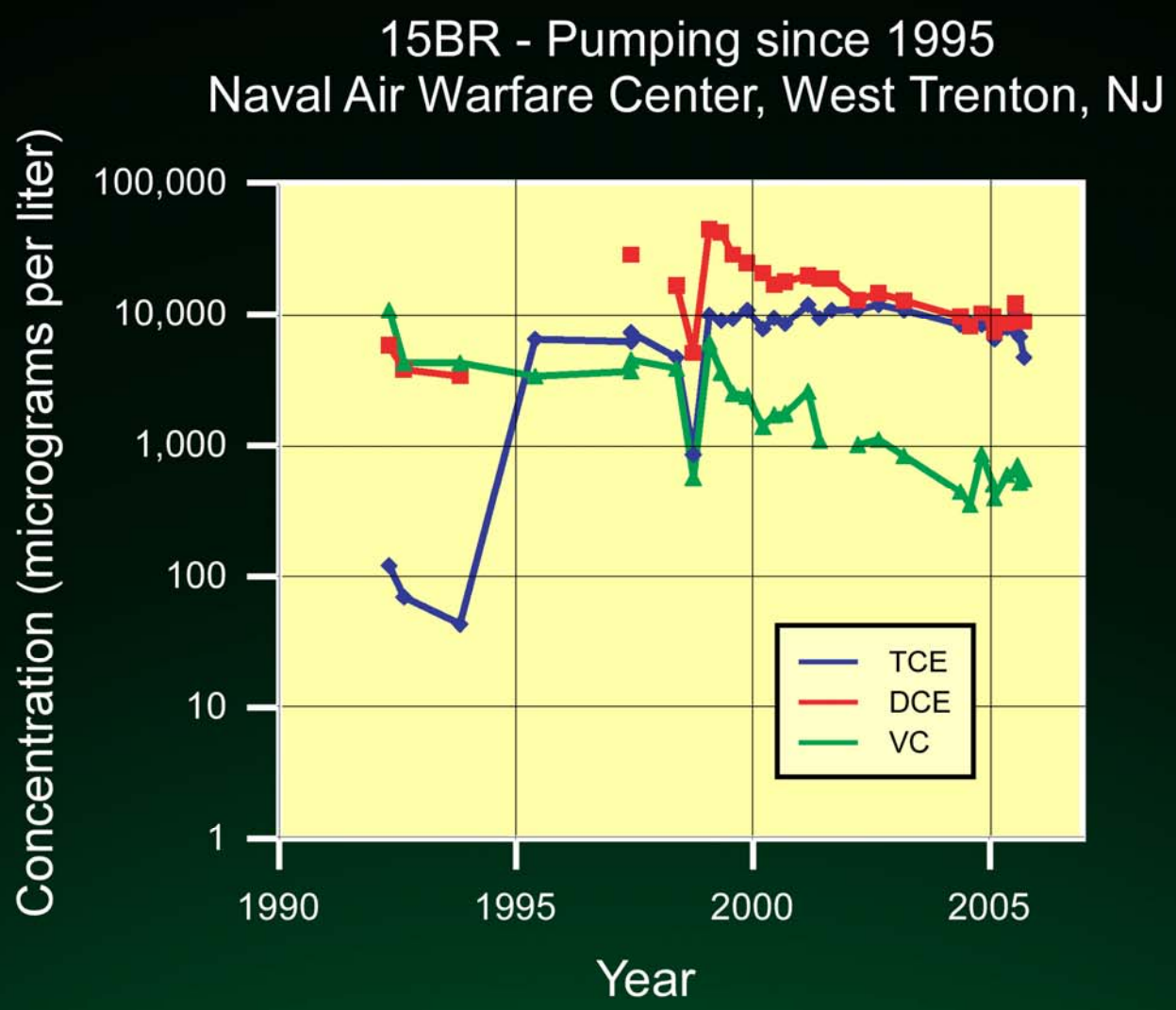






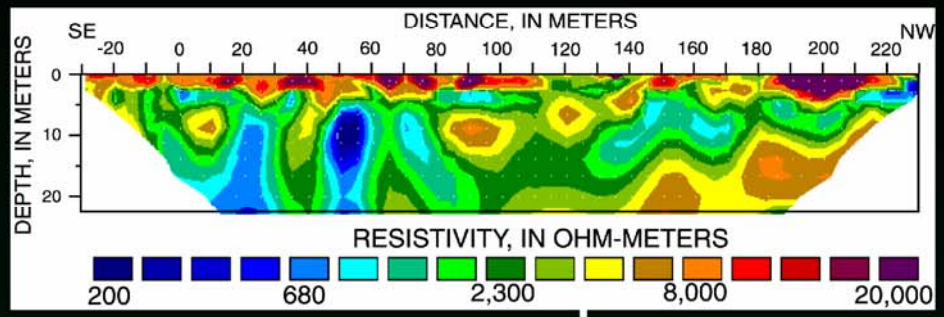
USGS

Significance of the primary porosity in fractured rock



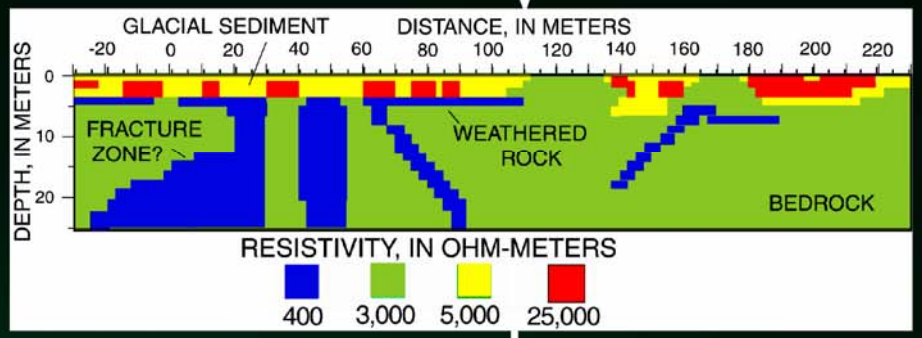
USGS

Advances in the characterization of fractured rock aquifers

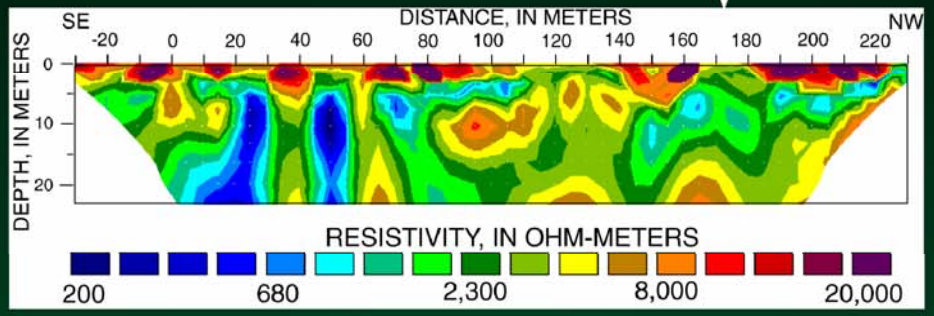


Surface Geophysical Surveys

2-D and 3-D resistivity surveys are used to develop conceptual models of subsurface structures. . .



Hypothesized model resistivity



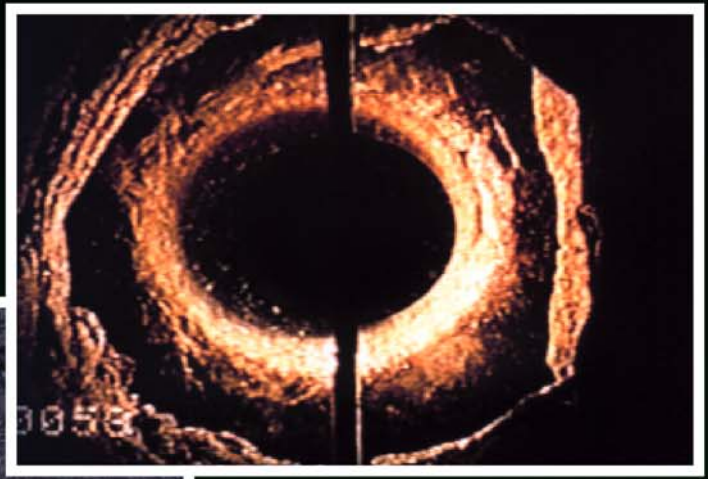
USGS

Advances in the characterization of fractured rock aquifers

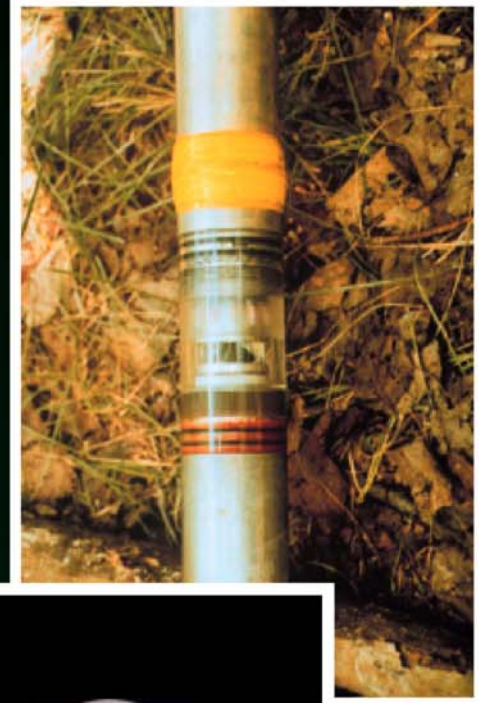
Optical-digital borehole camera

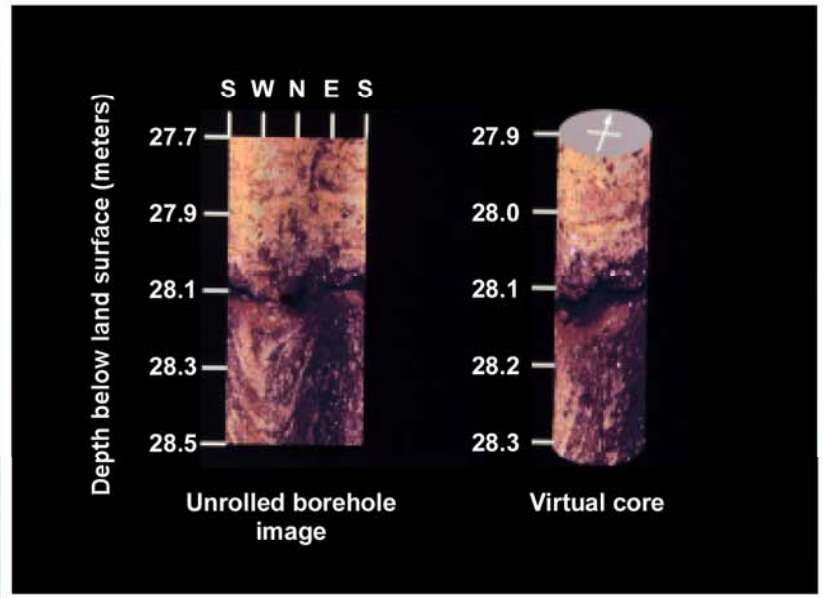
Analog borehole video camera

1980's



1990's



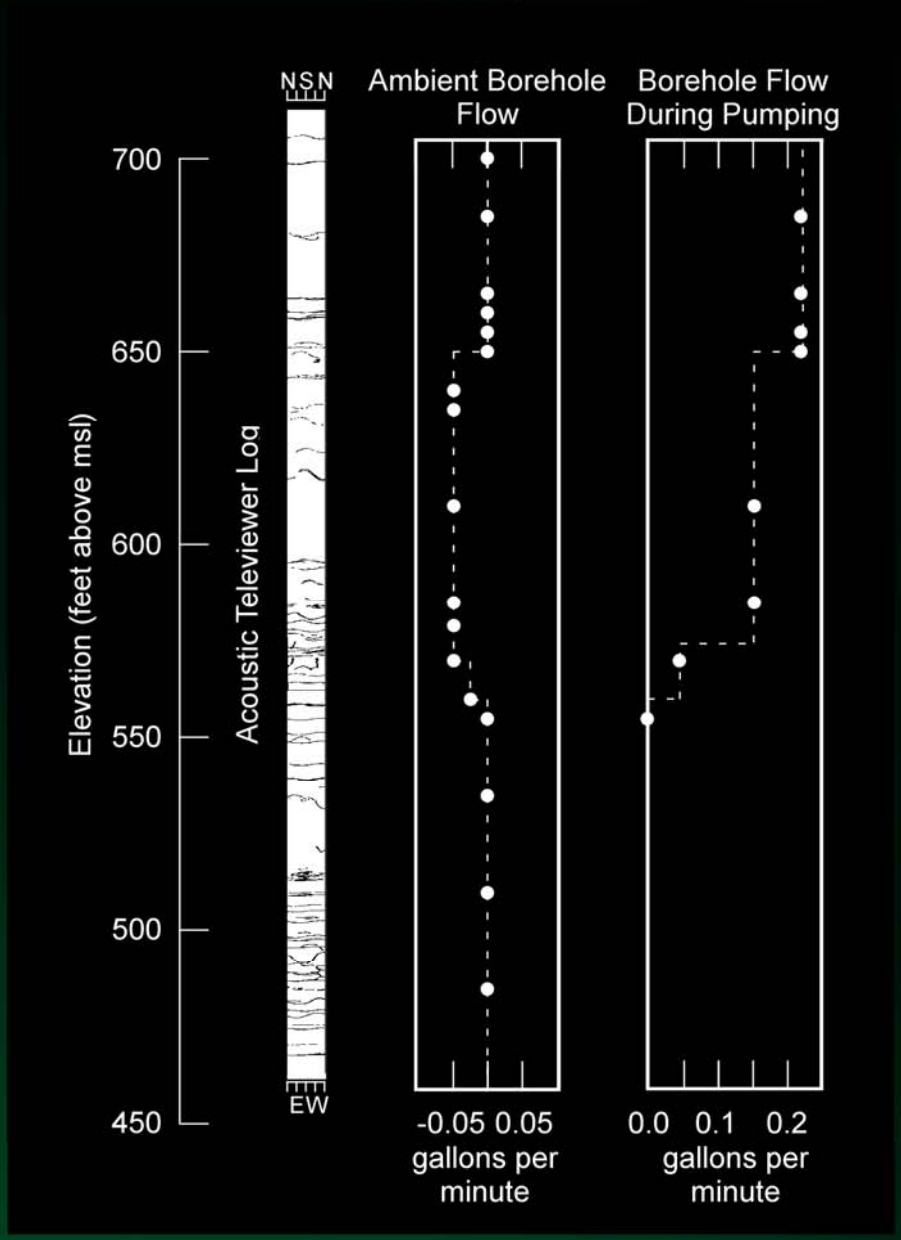


USGS

Advances in the characterization of fractured rock aquifers

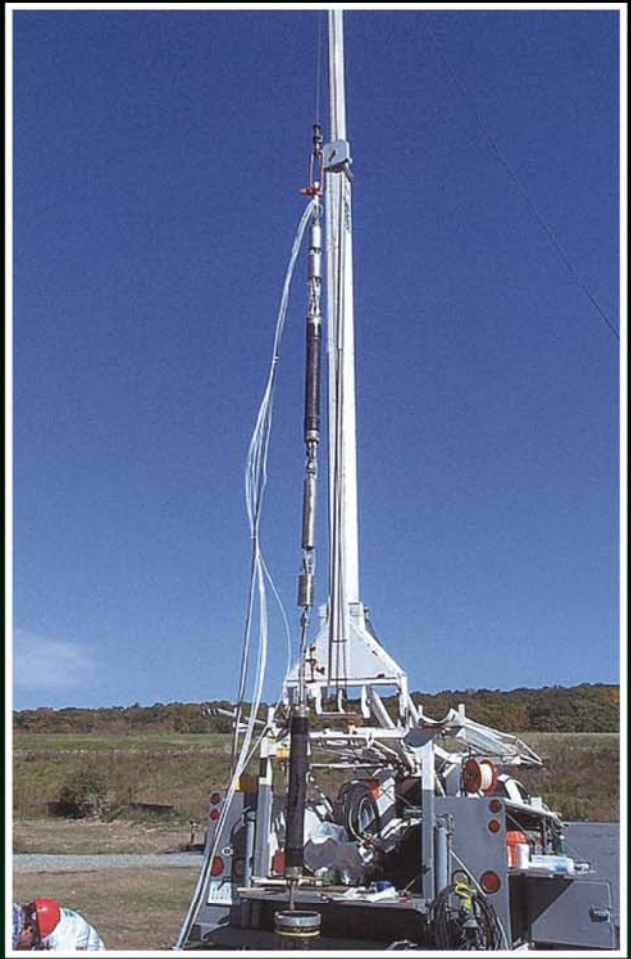
Identifying hydraulically significant features

Heat-pulse borehole flowmeter

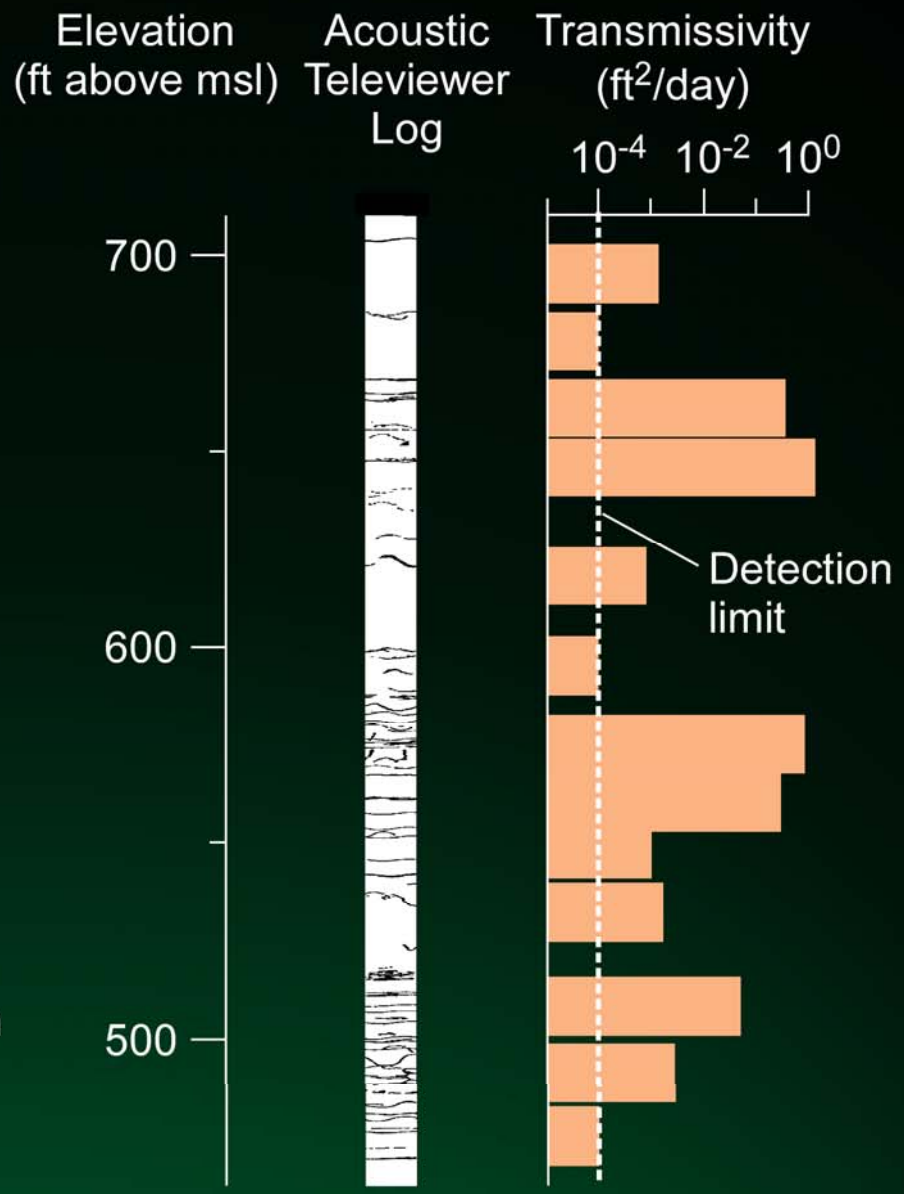


USGS

Advances in the characterization of fractured rock aquifers

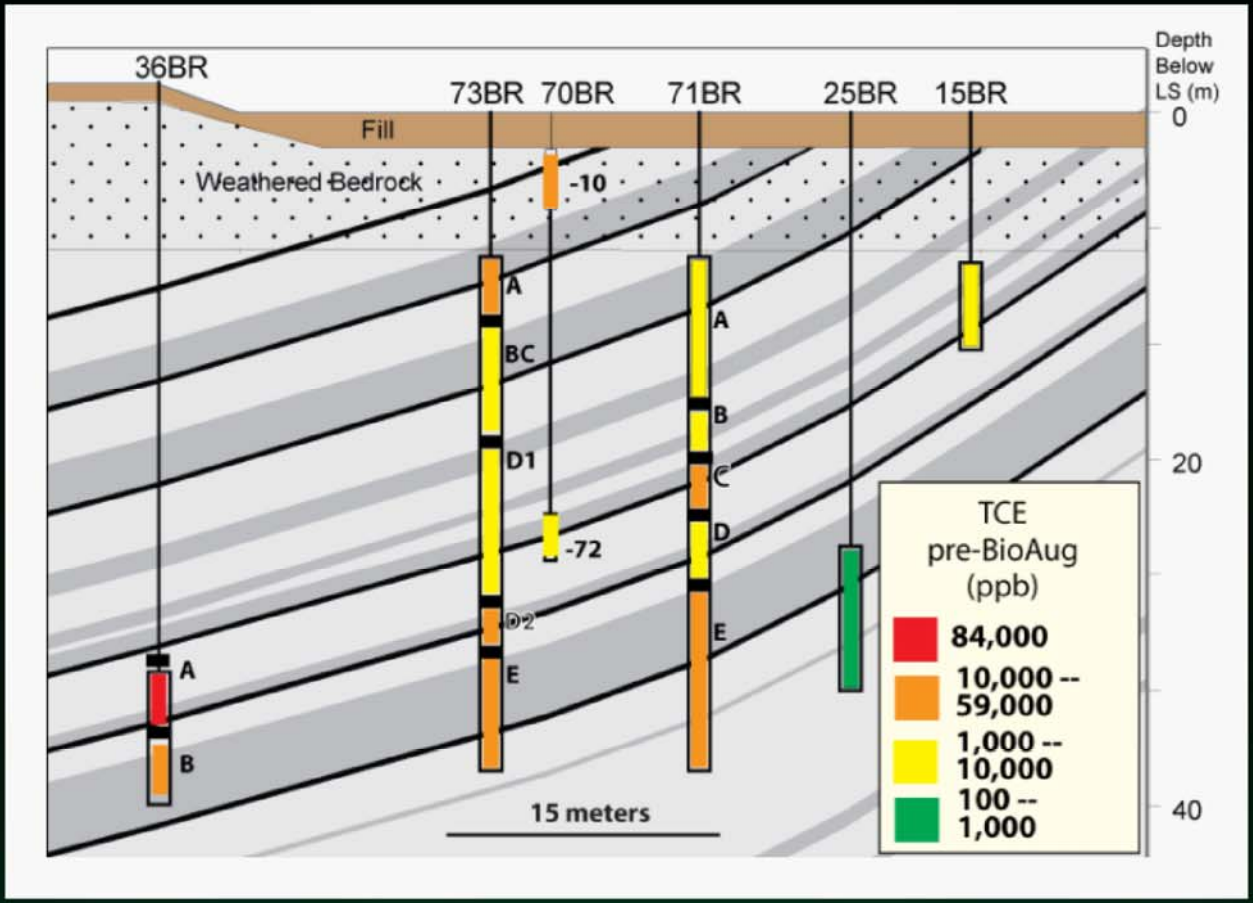


Hydraulic and geochemical characterization



USGS

Advances in the characterization of fractured rock aquifers



Application of packers, borehole liners, or "short" screened wells to identify chemical stratification, and conduct *in situ* chemical tracing experiments

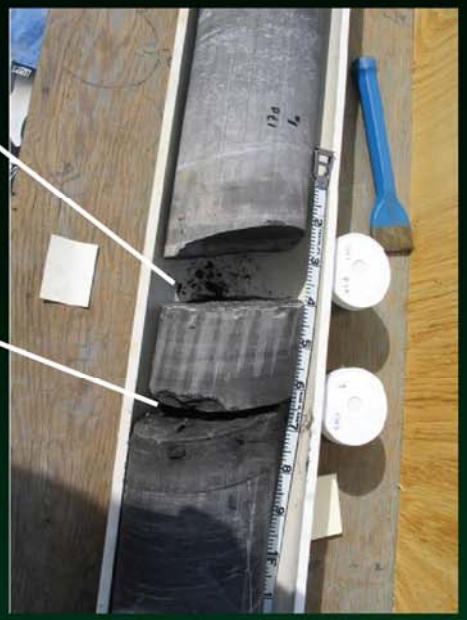
USGS

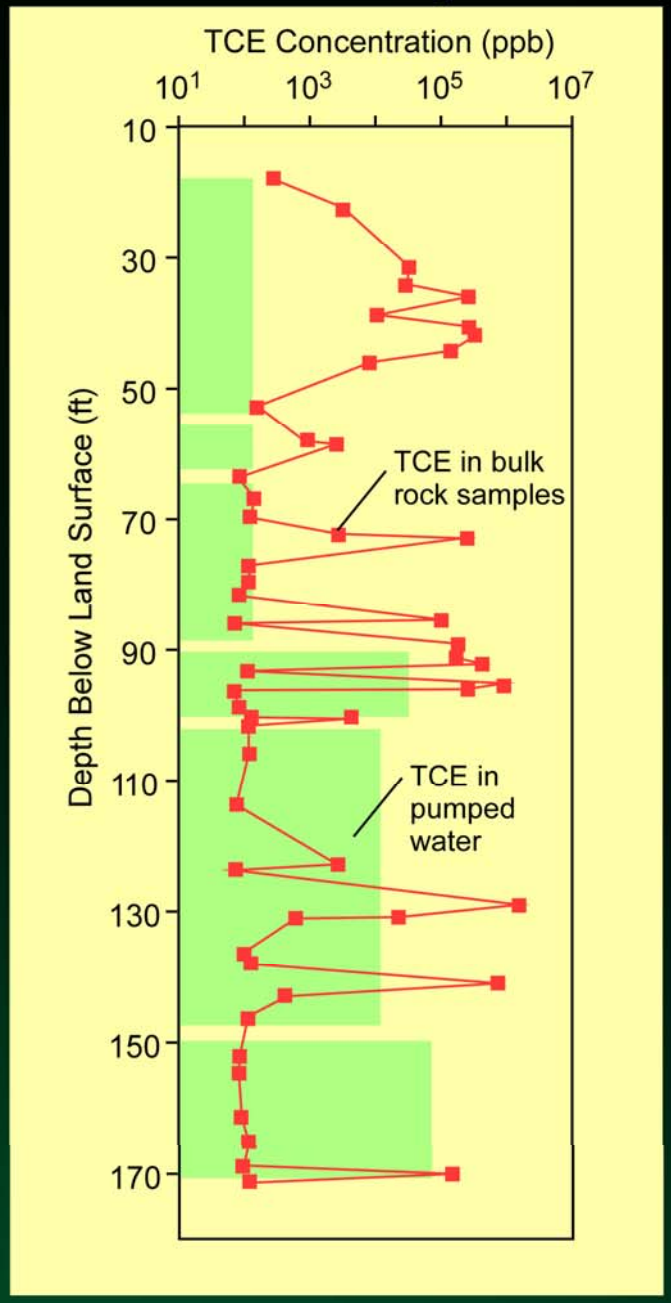
Advances in the characterization of fractured rock aquifers

Characterizing the geochemistry of the fluid in the rock matrix

170.3 ft
71,000 ppb TCE

170.7 ft
171 ppb TCE



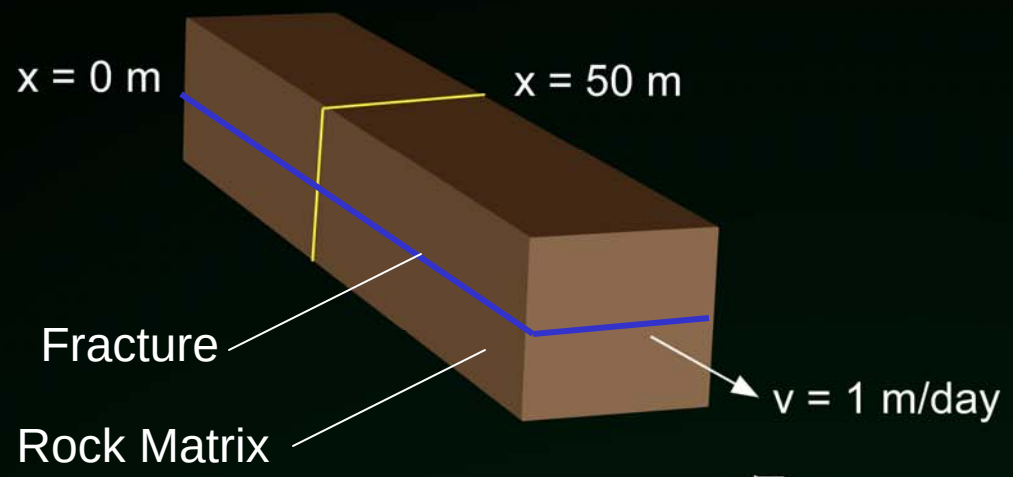


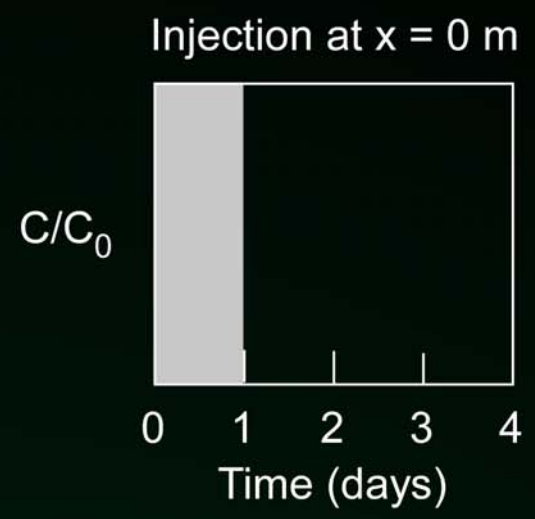
Borehole 68BR

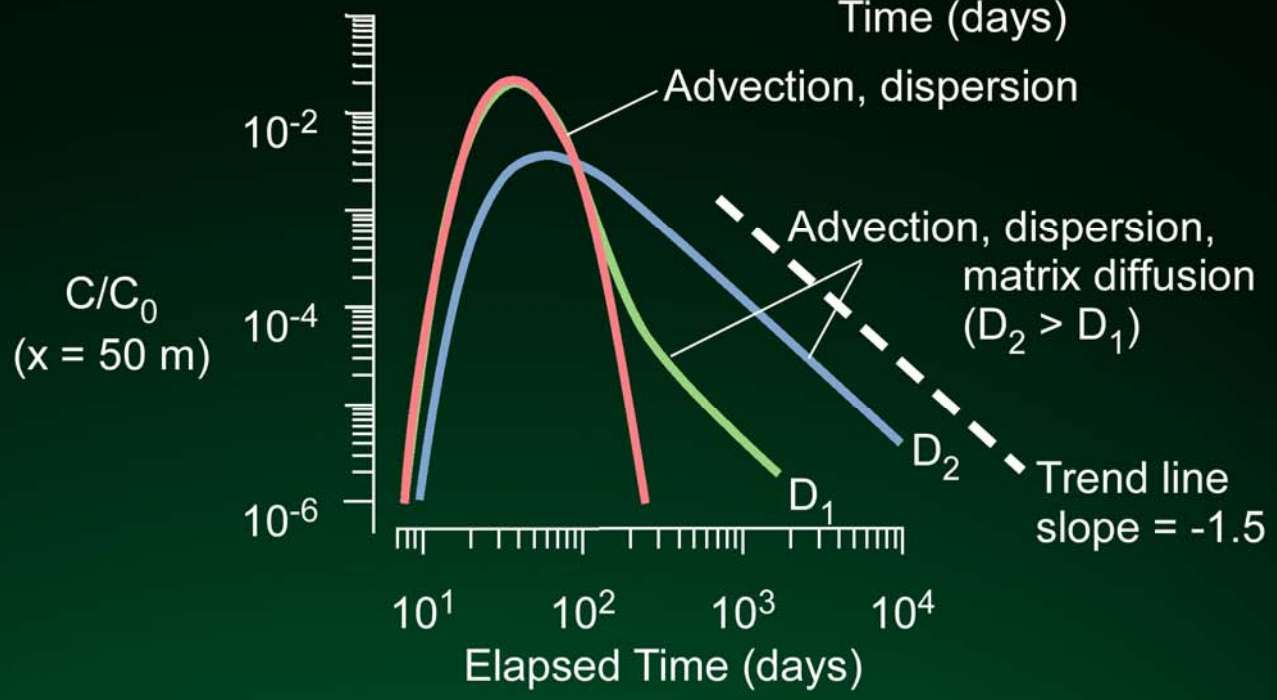
Naval Air Warfare Center,
West Trenton, NJ

USGS

Processes affecting the fate and transport of contaminants

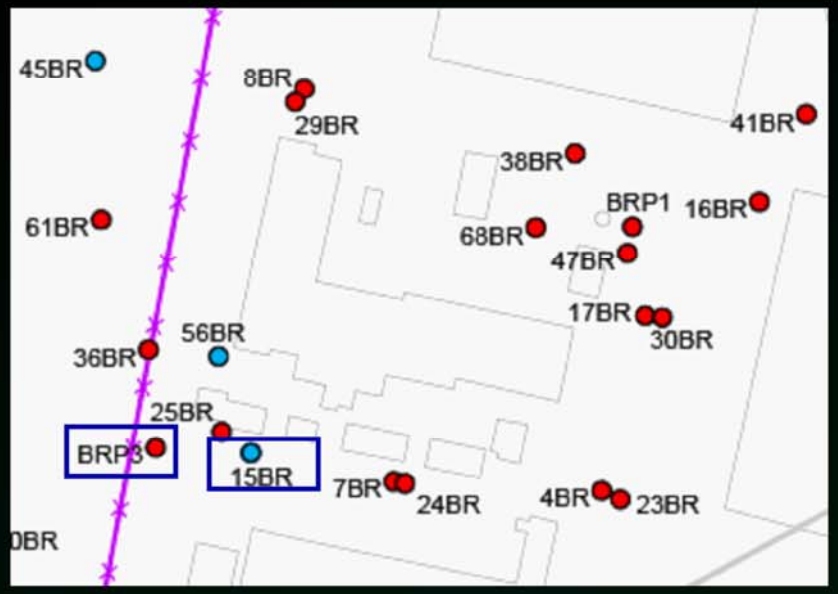




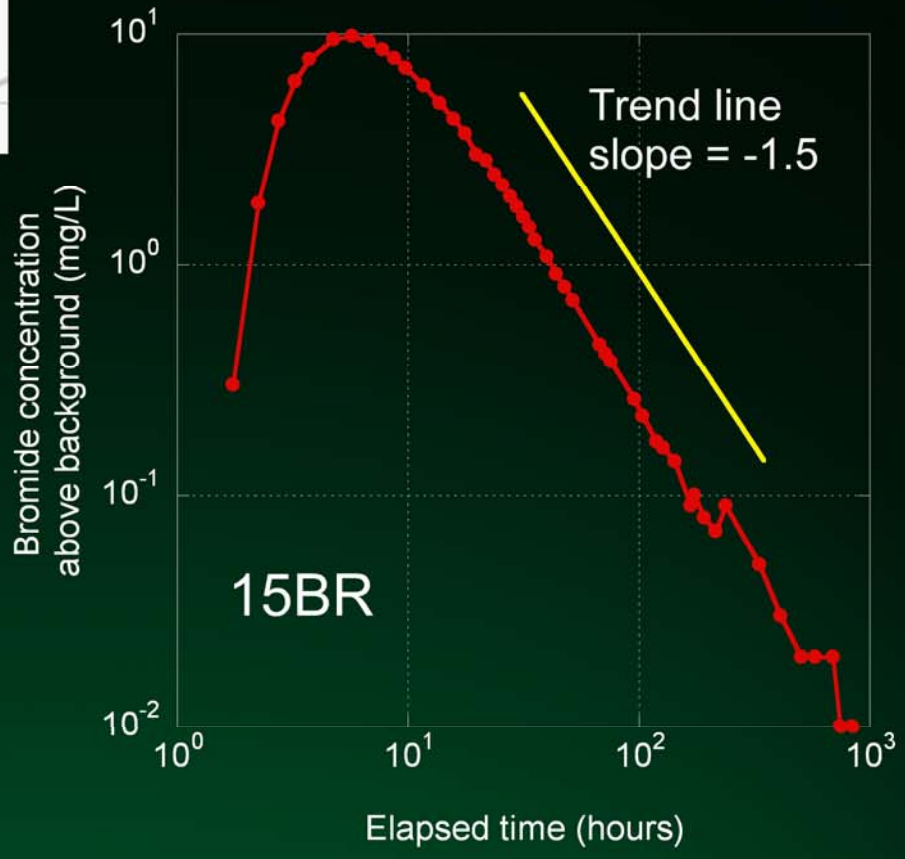


USGS

Naval Air Warfare Center
West Trenton, New Jersey

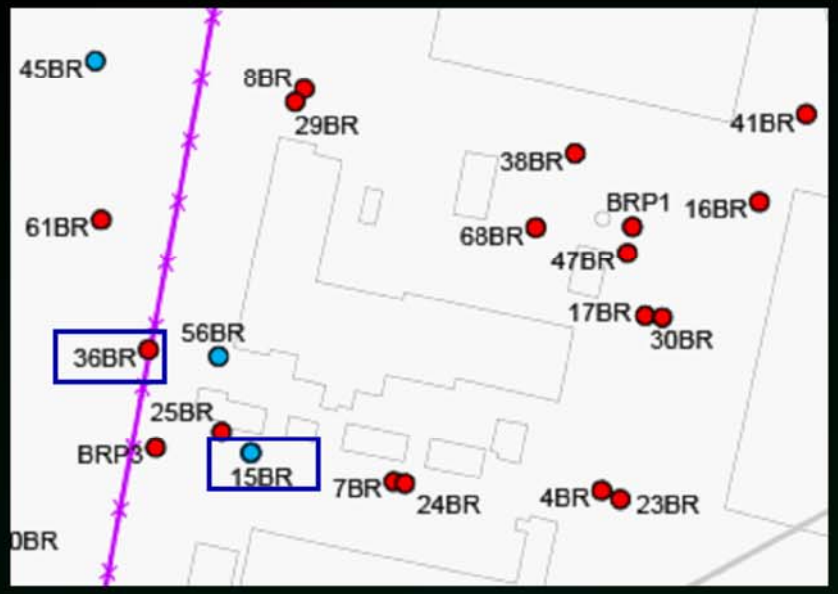


Tracer test:
Bromide injection into BRP3
Bromide recovery 15BR (pumping)

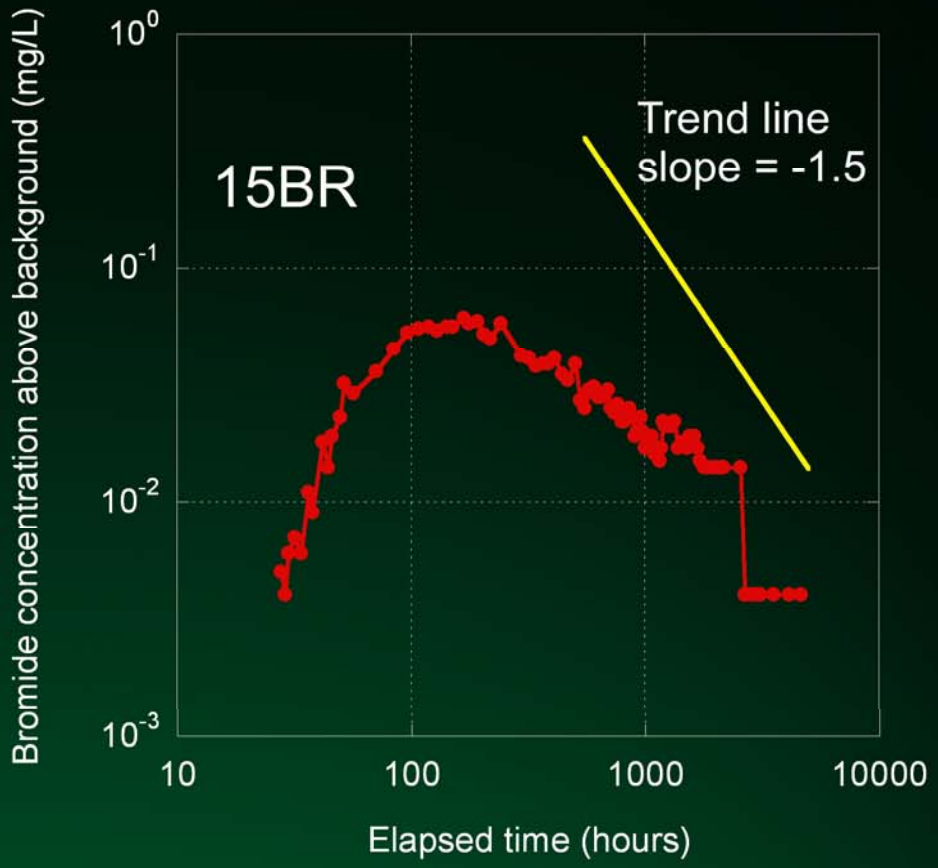


USGS

Naval Air Warfare Center
West Trenton, New Jersey



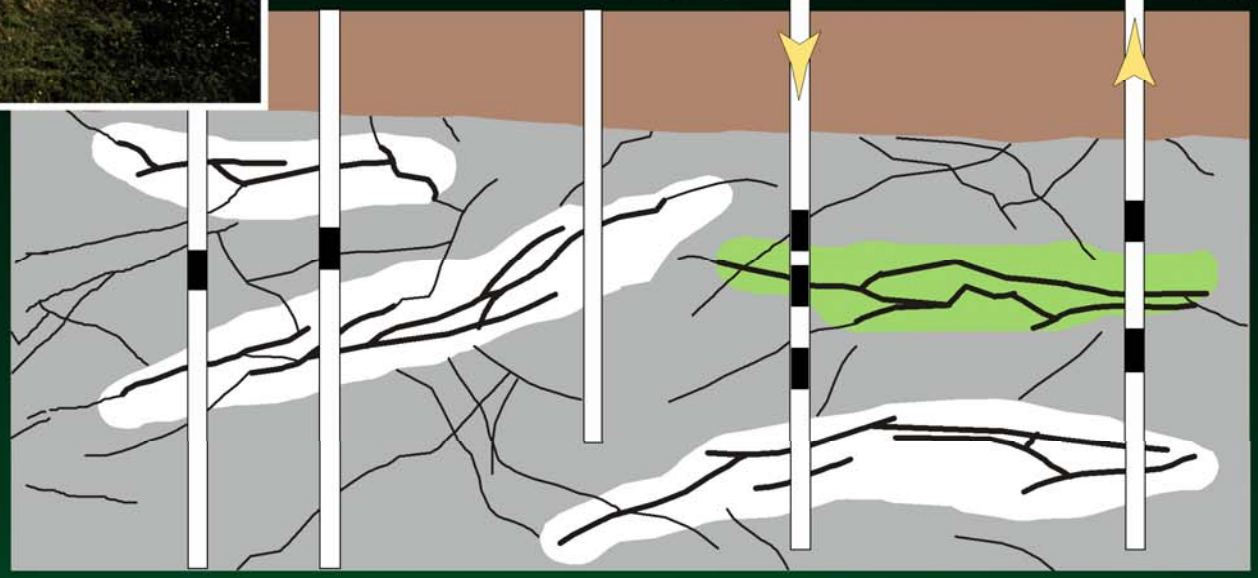
Tracer test:
Bromide injection into 36BR
Bromide recovery 15BR (pumping)



USGS

Granite and schist, Mirror Lake, NH

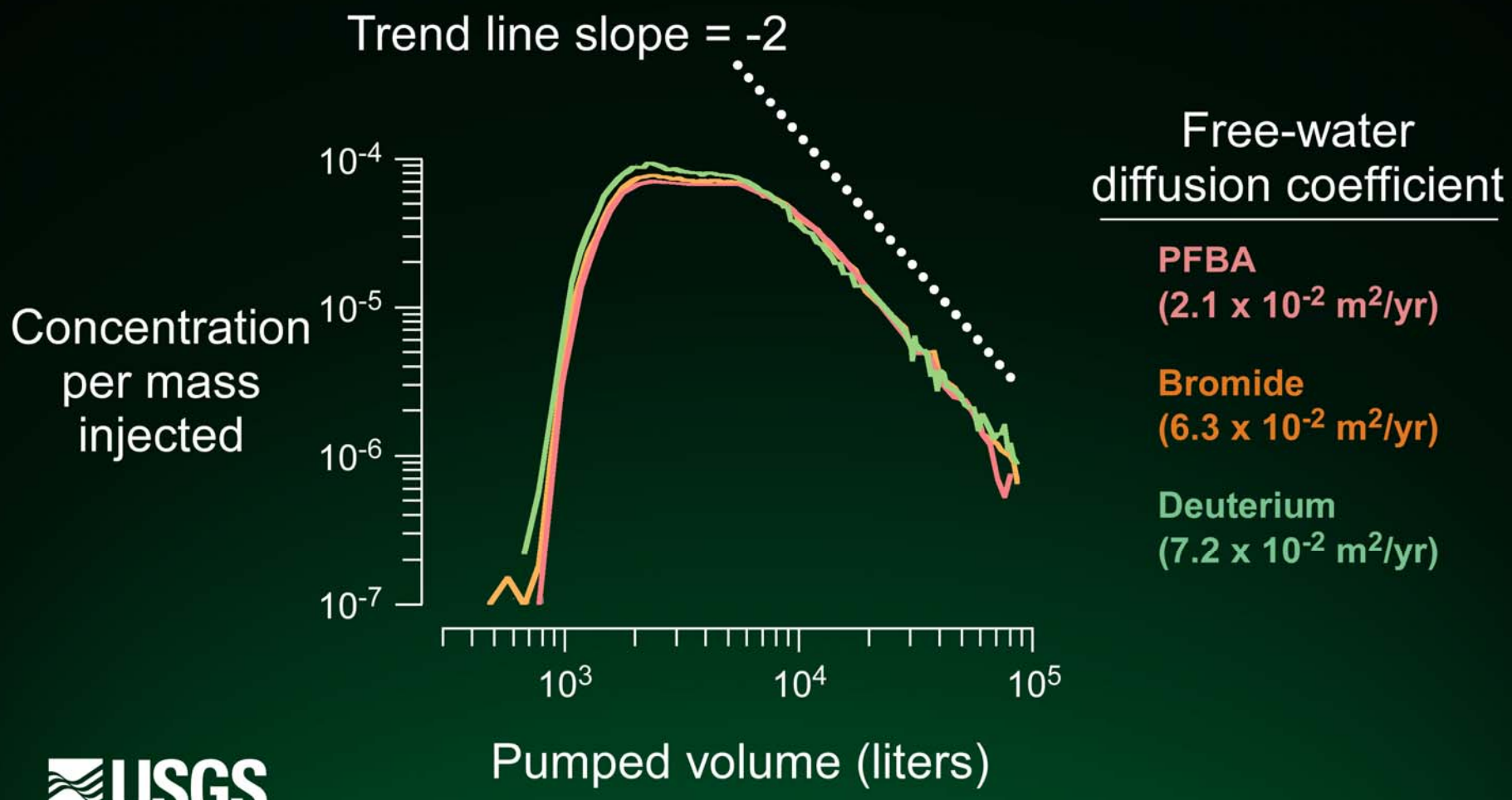
FSE well field
Mirror Lake,
New Hampshire



USGS

Granite and schist, Mirror Lake, NH

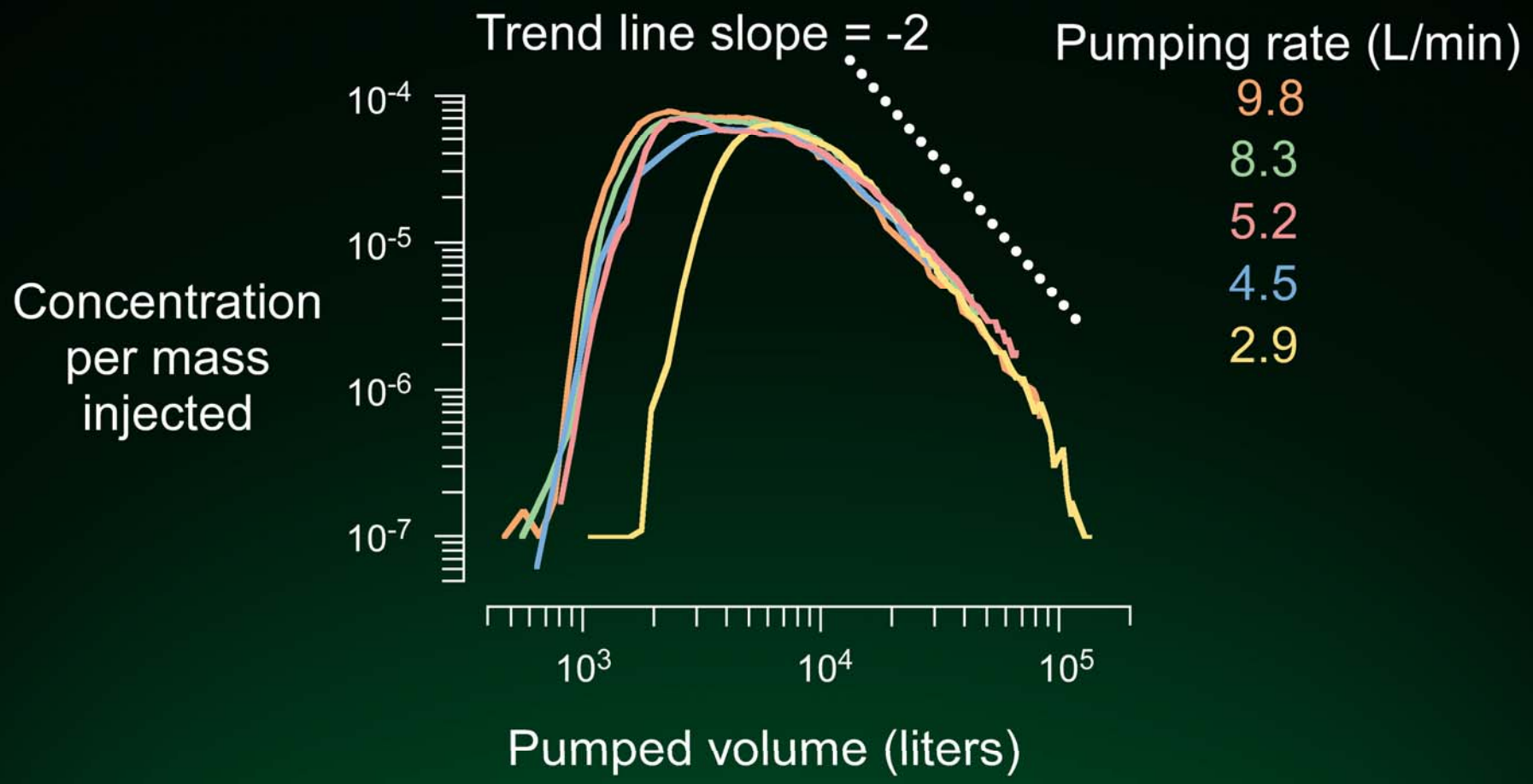
Multiple tracers (with different free water diffusion coefficients) injected



USGS

Granite and schist, Mirror Lake, NH

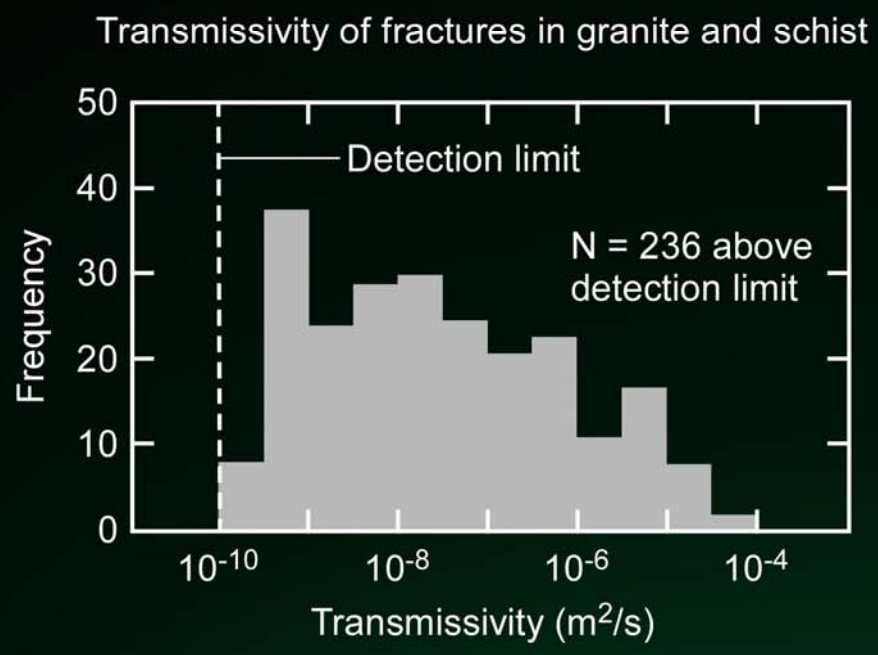
Multiple tracer tests conducted (each with a different pumping rate)

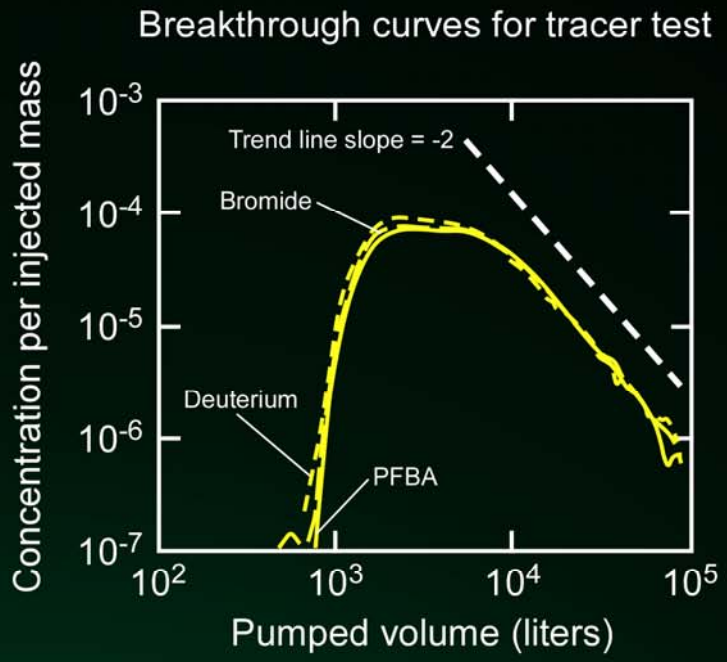


USGS

(effective diffusion coefficient > free water diffusion coefficient)

. . .large range in the transmissivity of fractures is responsible for a large range in the fluid velocity. . .

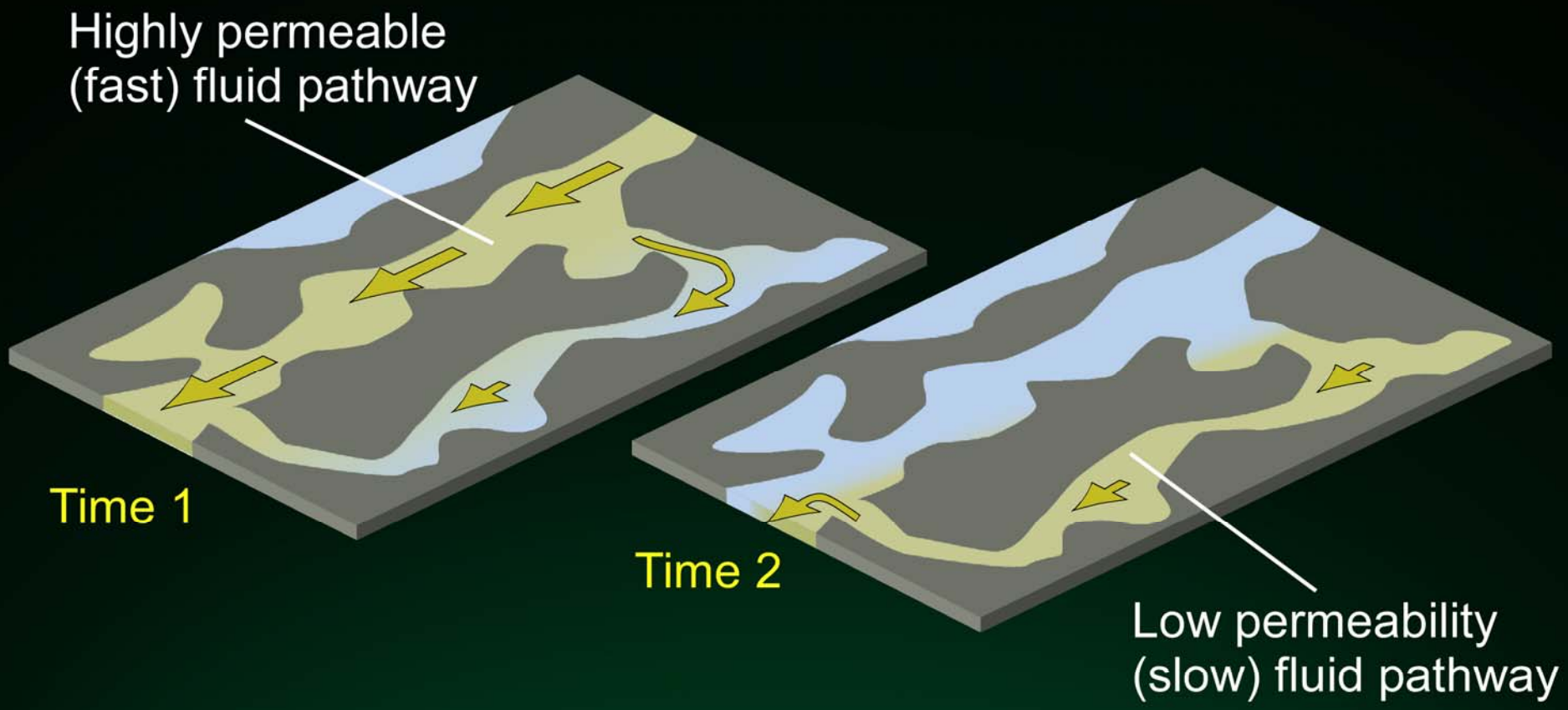




Large range of fluid velocities in fractures can yield responses similar to matrix diffusion. . .

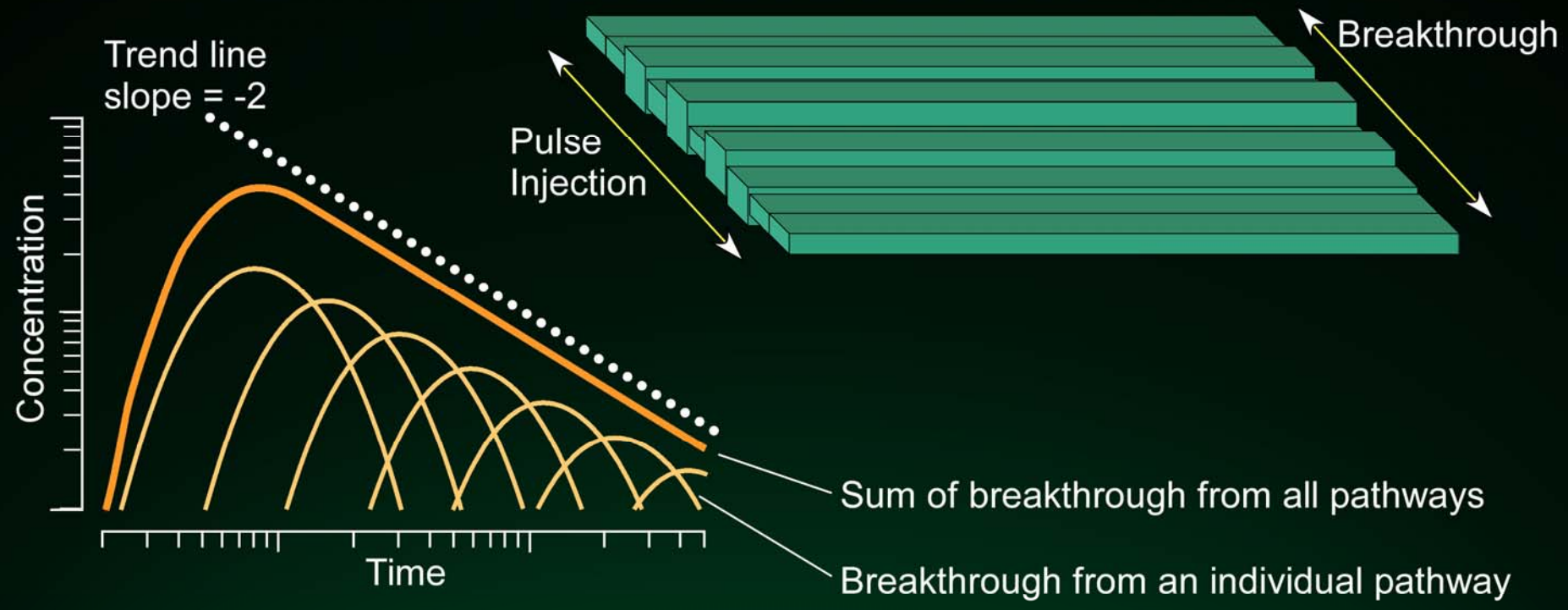
USGS

“Slow advection” gives rise to an “effective” diffusion



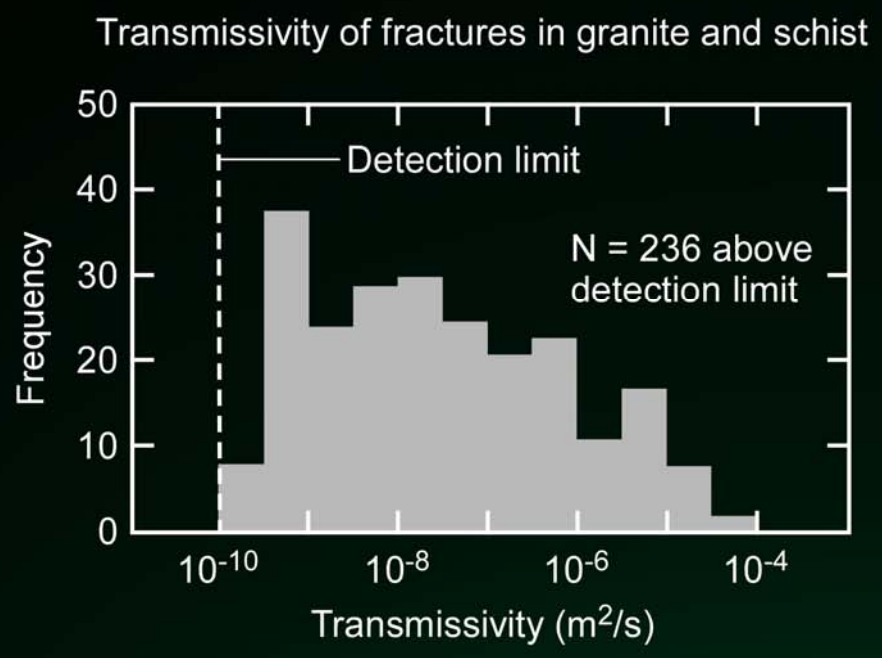
USGS

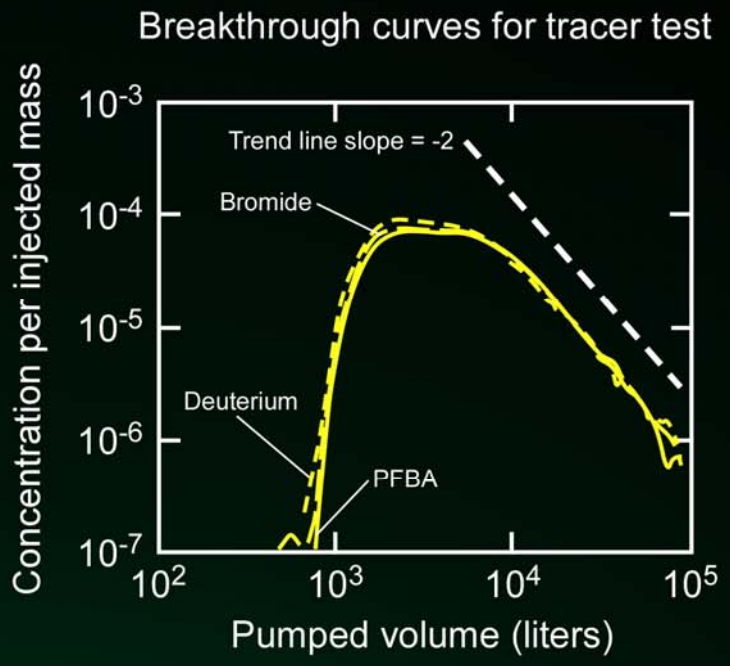
Breakthrough curves from a tracer test as the summation of transport along multiple pathways. . .



USGS

. . .the character of the breakthrough curves is telling us something



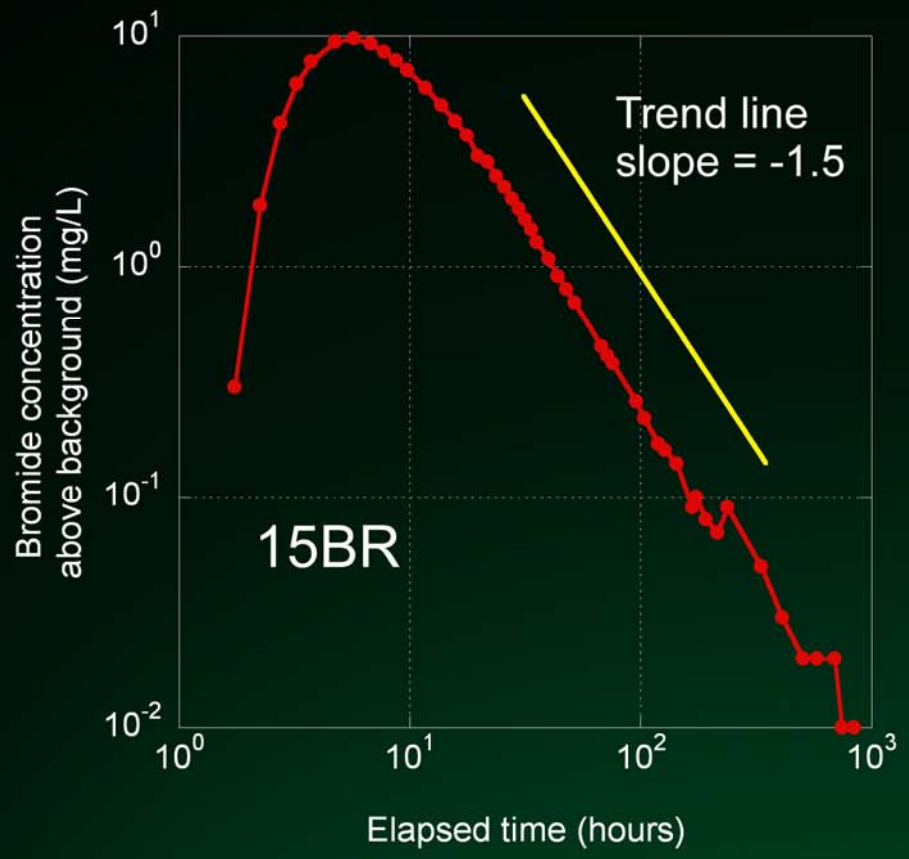


- *range of the fluid velocity*
- *residence time of the chemical constituents*
- *underlying heterogeneity*

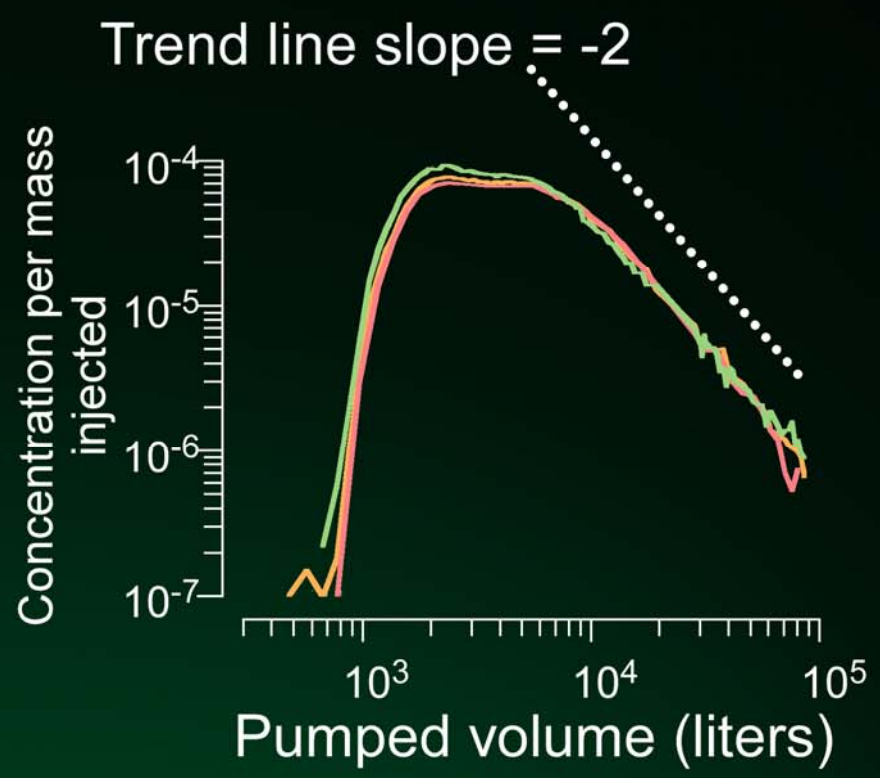
USGS

. . .there is no inconsistency between the results of these two tests. . .

Naval Air Warfare Center,
West Trenton, NJ



Mirror Lake Watershed,
Grafton County, NH



a continuum of responses can exist between "diffusion" dominance and "advection" dominance

USGS

This is truly a remarkable result. . .

. . .a consistency between disparate geologic settings over dimensions from 10's of meters to kilometers. . .

USGS

. . .but there are significant challenges. . .

• Are there geologic controls that will *a priori* indicate the dominance of diffusion over advection. . .(similar concerns exist in unconsolidated porous media) ?

• What is the structure of the heterogeneity that controls the fluid advection. . . ?

Can we apply similar characteristics to heterogeneity in disparate geologic settings and over dramatically different length dimensions. . .?

• More challenges to be raised on Wednesday morning . . .

USGS