Towards Taming the Complexities of Fractured Rock Aquifers

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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
Geologic Complexities of Fractured Rock Aquifers

Granite and schist
Mirror Lake, NH

Complex fracture connectivity
Enormous range of hydraulic properties

Elevation (ft above msl)

Acoustic TelevIEWER Log

Transmissivity ($ft^2$/day)

$10^{-4}$ $10^{-2}$ $10^0$

Detection limit

USGS
Fractured rock aquifers are characterized by a hierarchy of void space

Granite and schist, Mirror Lake, NH
Primary porosity

Lockatong Mudstone, West Trenton, NJ
Fractures
Fault zone
Fractures parallel and perpendicular to bedding
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

Elevation (ft above msl) Acoustic Televiewer Log Transmissivity (ft²/day)

 Detection limit

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

Fracture

Rock Matrix

x = 0 m

x = 50 m

v = 1 m/day

Injection at x = 0 m

C/C₀

Time (days)

0 1 2 3 4

C/C₀

(x = 50 m)

Advection, dispersion

Elapsed Time (days)

10⁻²

10⁻⁴

10⁻⁶

10¹ 10² 10³ 10⁴

USGS
Significance of the primary porosity

Fracture

Rock Matrix

x = 0 m

x = 50 m

v = 1 m/day

Injection at x = 0 m

C/C_0

Time (days)

0

1

2

3

4

C/C_0 (x = 50 m)

Advection, dispersion

Advection, dispersion, matrix diffusion

Elapsed Time (days)

10^1

10^2

10^3

10^4
Significance of the primary porosity

Fracture
Rock Matrix

x = 0 m  x = 50 m

v = 1 m/day

Injection at x = 0 m

C/C₀

Time (days)

0 1 2 3 4

C/C₀

(x = 50 m)

Advection, dispersion

Advection, dispersion, matrix diffusion (D₂ > D₁)

D₁

D₂

Elapsed Time (days)

10¹ 10² 10³ 10⁴
Significance of the primary porosity

Fracture

Rock Matrix

x = 0 m

x = 50 m

v = 1 m/day

Injection at x = 0 m

C/C₀

Time (days)

0 1 2 3 4

C/C₀ (x = 50 m)

Advection, dispersion

Advection, dispersion, matrix diffusion (D₂ > D₁)

D₁

D₂

Trend line slope = -1.5

Elapsed Time (days)

10¹ 10² 10³ 10⁴
Significance of the primary porosity in fractured rock

15BR - Pumping since 1995
Naval Air Warfare Center, West Trenton, NJ

Concentration (micrograms per liter)

Year


TCE
DCE
VC
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...
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
Advances in the characterization of fractured rock aquifers
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
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
Processes affecting the fate and transport of contaminants

Fracture
Rock Matrix

\[ x = 0 \text{ m} \quad x = 50 \text{ m} \]

\[ v = 1 \text{ m/day} \]

Injection at \( x = 0 \text{ m} \)

\[ C/C_0 \]

Time (days)

\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \]

\[ C/C_0 \]

(\( x = 50 \text{ m} \))

Advection, dispersion

Advection, dispersion, matrix diffusion (\( D_2 > D_1 \))

\[ D_1 \quad D_2 \]

Trend line slope = -1.5

Elapsed Time (days)

\[ 10^1 \quad 10^2 \quad 10^3 \quad 10^4 \]
Tracer test:
Bromide injection into BRP3
Bromide recovery 15BR (pumping)

Naval Air Warfare Center
West Trenton, New Jersey

Trend line slope = -1.5
Tracer test:
Bromide injection into 36BR
Bromide recovery 15BR (pumping)
Granite and schist, Mirror Lake, NH

Multiple tracers (with different free water diffusion coefficients) injected

Trend line slope = -2

Free-water diffusion coefficient

PFBA
(2.1 x 10^{-2} m^2/yr)

Bromide
(6.3 x 10^{-2} m^2/yr)

Deuterium
(7.2 x 10^{-2} m^2/yr)
Granite and schist, Mirror Lake, NH

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

Trend line slope = -2

Pumping rate (L/min)
9.8
8.3
5.2
4.5
2.9

Concentration per mass injected

Pumped volume (liters)

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

Highly permeable (fast) fluid pathway

Low permeability (slow) fluid pathway

Time 1

Time 2
Breakthrough curves from a tracer test as the summation of transport along multiple pathways.

- Trend line slope = -2
- Sum of breakthrough from all pathways
- Breakthrough from an individual pathway

Pulse Injection

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

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

Transmissivity of fractures in granite and schist

Breakthrough curves for tracer test

- Detection limit: N = 236 above detection limit
- Trend line slope = -2
- Bromide
- Deuterium
- PFA

Concentration per injected mass vs. Pumped volume (liters)
there is no inconsistency between the results of these two tests.

A continuum of responses can exist between "diffusion" dominance and "advection" dominance.
This is truly a remarkable result. . .

. . .a consistency between disparate geologic settings over dimensions from 10’s of meters to kilometers. . .
...but there are significant challenges... 

• Are there geologic controls that will \textit{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 . . .