     

Impacts of Subsurface Heterogeneity

United States
Environmental Protection
Agency

Thanks to:
Steve Dyment, U.S. EPA ORD
Seth Pitkin, Stone Environmental

Overview

- **Hydrogeology review**
  - Porosity
  - Hydraulic conductivity
  - Hydraulic gradient
- **Contaminant fate and transport review**
  - Advection-Dispersion-Dissolution-Sorption-Degradation-Density-Viscosity-Mobility-Capillary Pressure-Back Diffusion
  - Unconsolidated systems
  - Fractured rock systems
  - DNAPL

Hydrogeology Review

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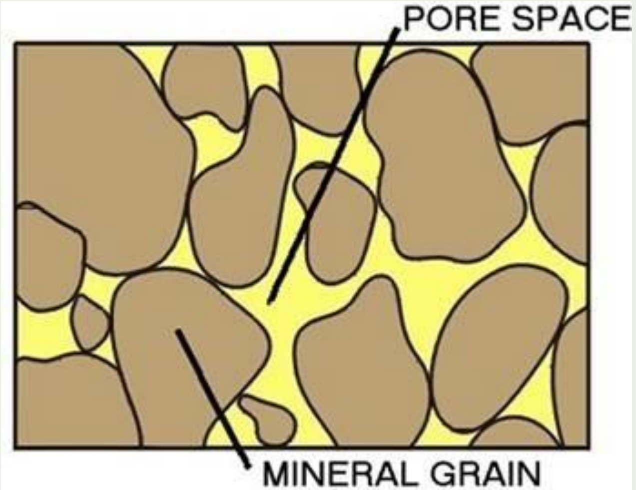
Subsurface Environments:
No Place for Low Resolution

- Porosity
- Hydraulic Conductivity
- Hydraulic Head/Hydraulic Gradient
- Capillary pressure
- Geochemistry

Porosity

- **Ratio of volume of void space to total volume of medium**
- **Where the fluids reside**
- **<u>NOT</u> the same as Permeability/Hydraulic Conductivity**
  - Clay has a very high porosity but a very low permeability
- **Particle size distribution and sorting**
  - Well sorted (poorly graded) … uniform grain size
  - Poorly sorted (well graded) variety of grain sizes



Dual Porosity Systems

- Systems in which there are (relatively) high and low permeability units
- Nearly all advective flow takes place through the pores in the high permeability materials (mobile porosity)
- Water in the saturated pore spaces in the low permeability materials (immobile porosity) is dominated by diffusive, rather than advective flux
- Pore water in the low permeability materials essentially serves as storage for solutes

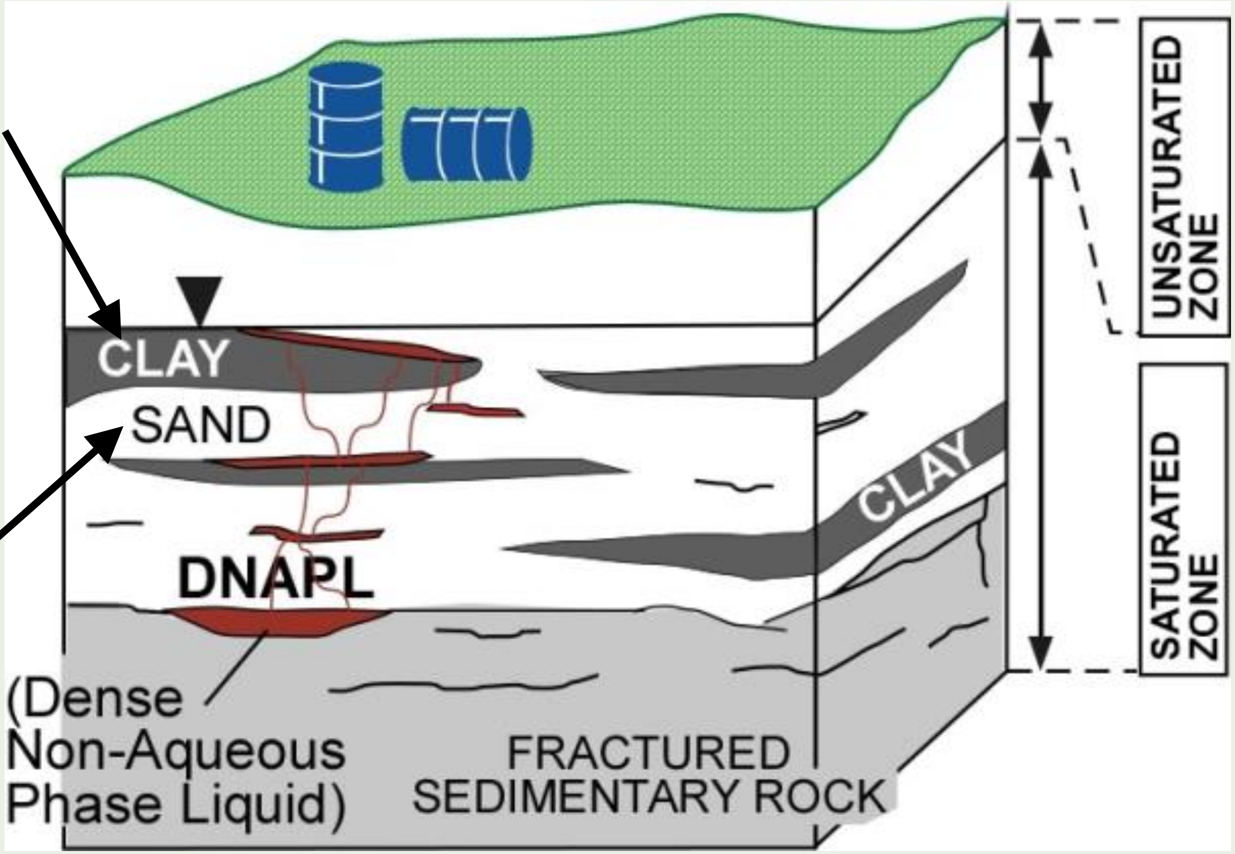
Dual Porosity in Unconsolidated Media

Immobile Porosity

Relatively low permeability bypassed by advective flow and dominated by diffusive flux

Mobile Porosity

Relatively high permeability and dominated by advective flow

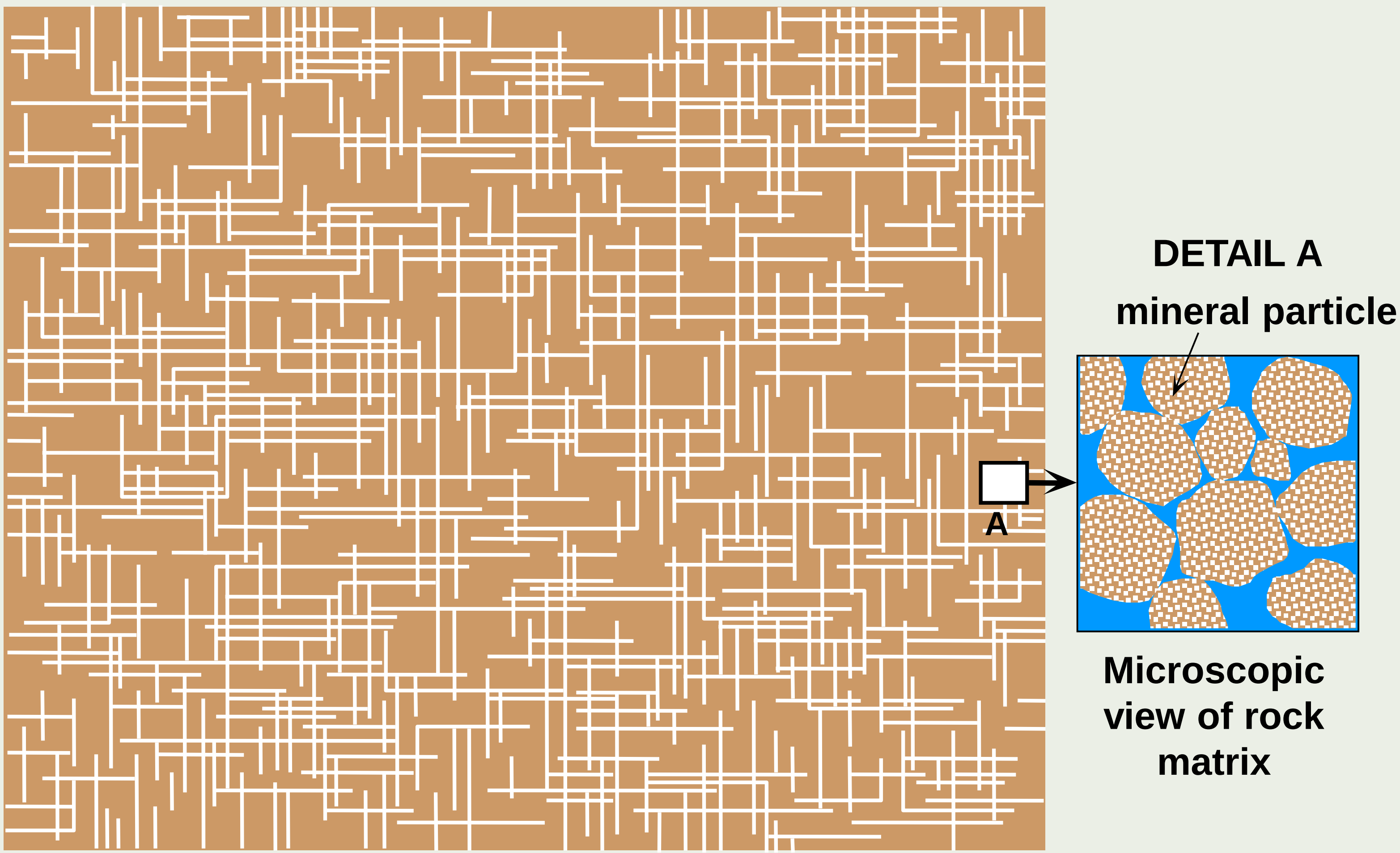


Source: Chuck Newell and Tom Sale

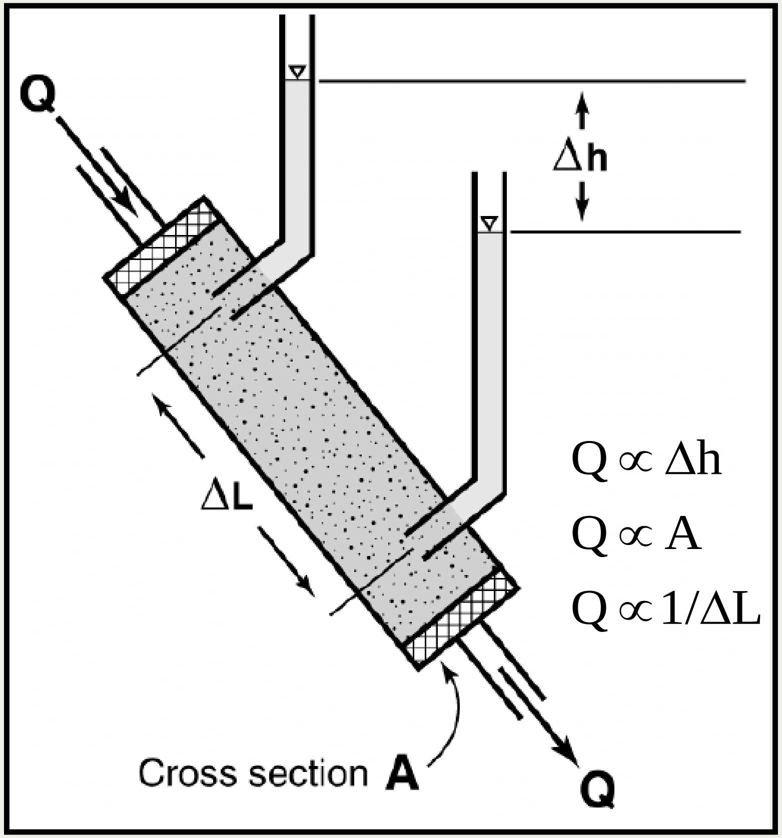
Dual Porosity in Fractured Rock

Small Fracture (secondary) Porosity and Large Matrix (primary) Porosity

0.001 to 0.1% 2 to 25%



Darcy's Law



$$Q = -KA\frac{\Delta h}{\Delta L}$$

$$q = Q/A = -K\frac{\Delta h}{\Delta L}$$

Q is the volumetric flow rate [L^3/t]

L is the length between piezometers [L]

A is the cross-sectional area [L^2] of the column

h is referred to as the hydraulic head [L]

q is the Darcy flux or specific discharge (L/t)

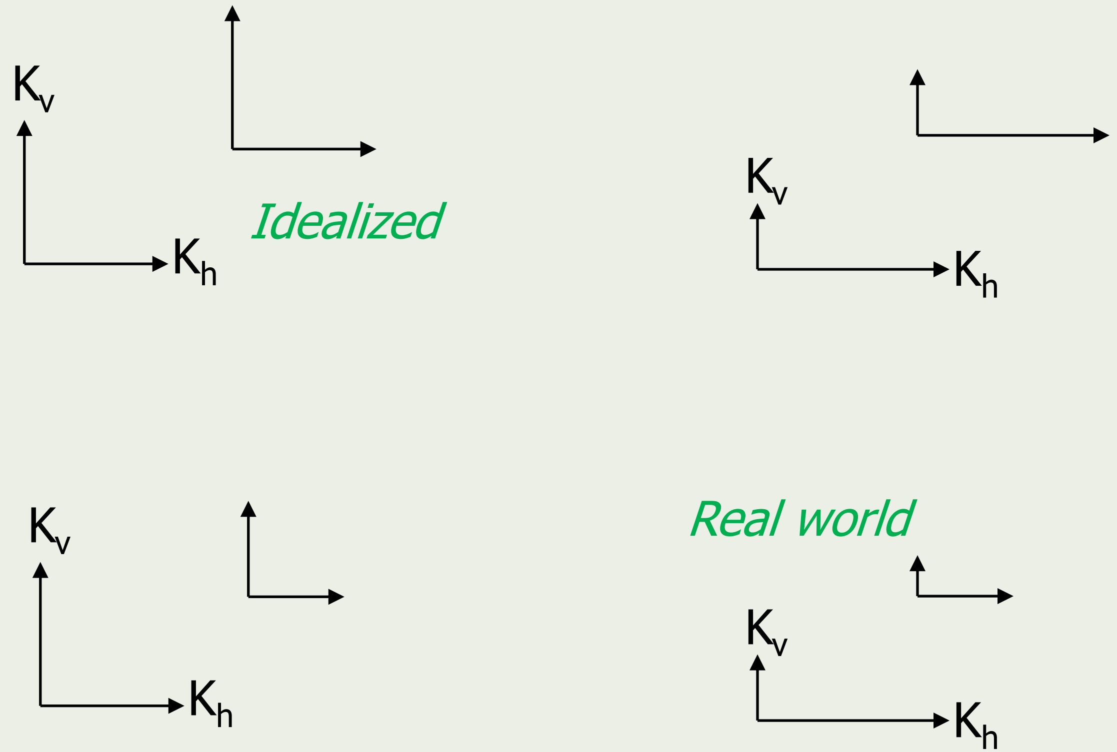
Hydraulic Conductivity

- **Empirical proportionality constant describing the ease with which water passes through a particular porous medium**
- **Permeability (k): property of the medium**
  - » $k = cd^2$; where:
    - › c = proportionality constant of the medium
    - › d = mean grain diameter. Units of area (L^2)
- **Hydraulic Conductivity (K): property of the medium <u>and</u> the fluid**
  - » $K = k(\rho g/\mu)$; units of velocity (L/t) where:
    - › ρ = density of fluid (M/L^3)
    - › g = gravitational constant (L/t^2)
    - › μ = viscosity of fluid (M/L/t)

Homogeneity & Isotropy

Homogeneous, Isotropic

Homogeneous, Anisotropic

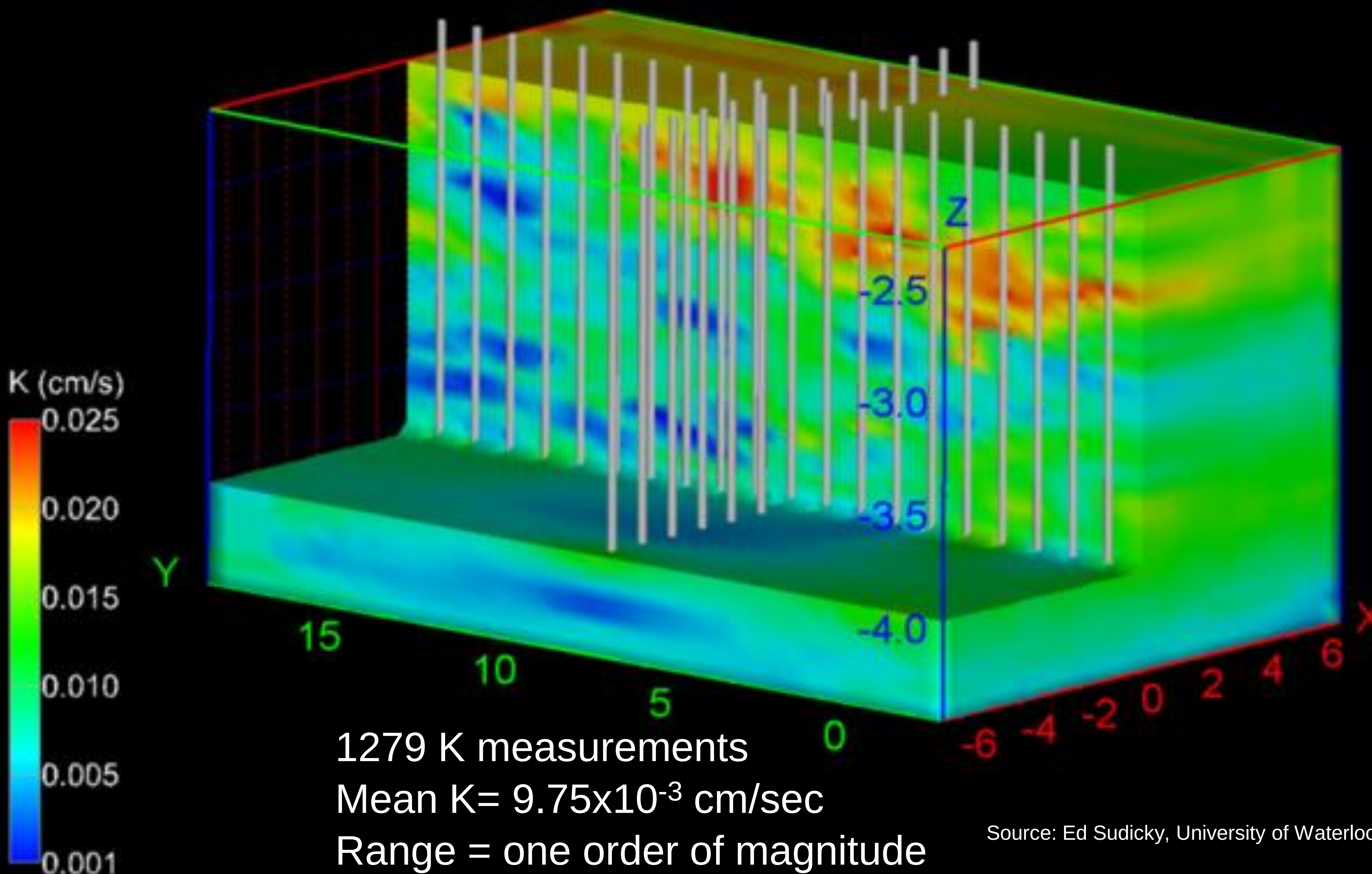


Heterogeneous, Isotropic

Heterogeneous, Anisotropic

Source: Freeze & Cherry

Distribution of K at CFB Borden – Beach Sand
(adapted from Sudicky, 1986)



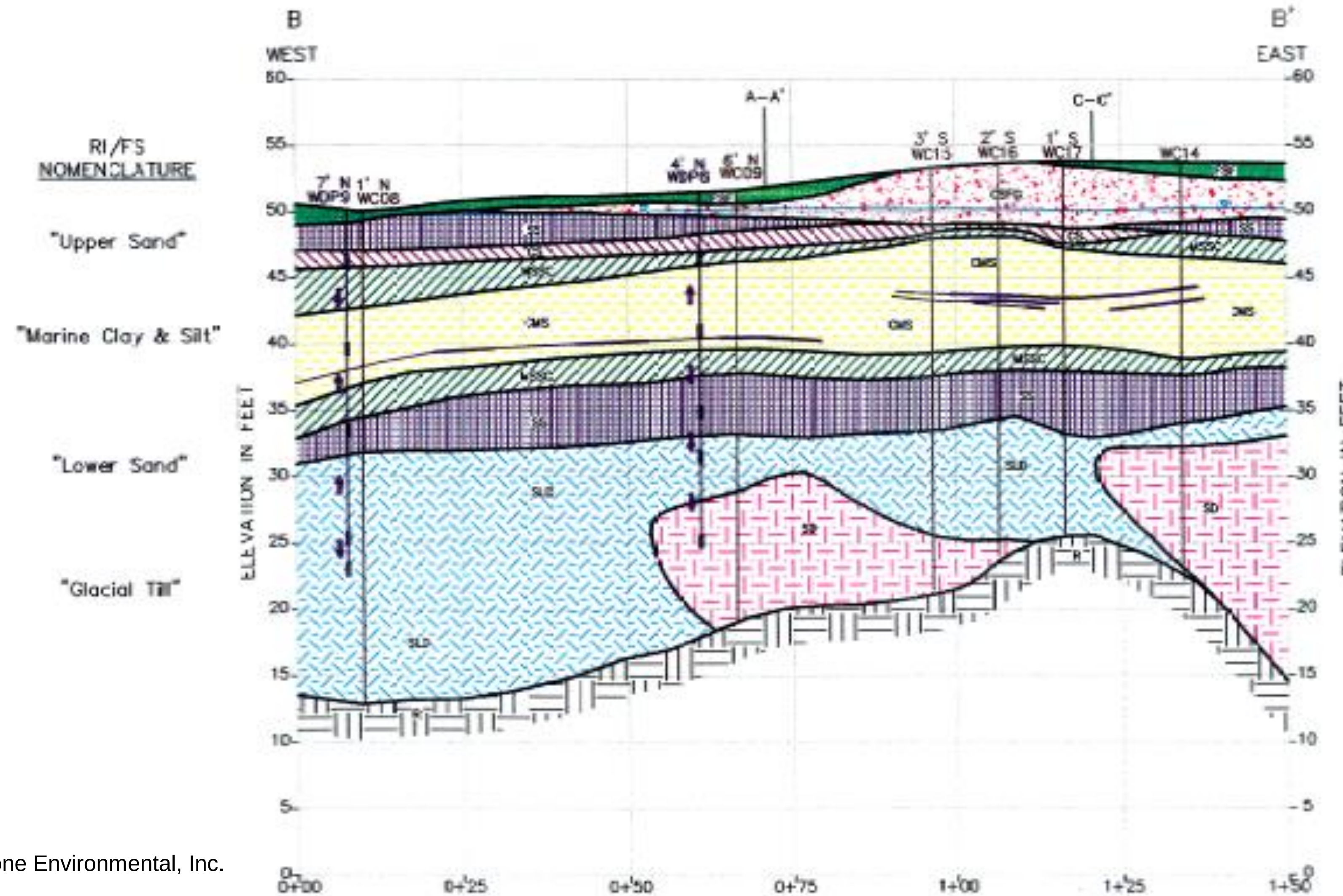
1279 K measurements
Mean K= 9.75×10^{-3} cm/sec
Range = one order of magnitude

Source: Ed Sudicky, University of Waterloo

Hydraulic Conductivity Correlation Lengths

Location	Horizontal K Correlation Length (m)	Vertical K Correlation Length (m)	Investigator
Borden, Ontario	2.8	0.12	Sudicky (1986)
Otis, ANGB	2.9 – 8	0.18 – 0.38	Hess et al. (1992)
Columbus AFB	12.7	1.6	Rehfeldt et al.
Aefligan	15 – 20	0.05	Hess et al. (1992)
Chalk River, Ontario	1.5	0.47	Indelman et al. (1999)

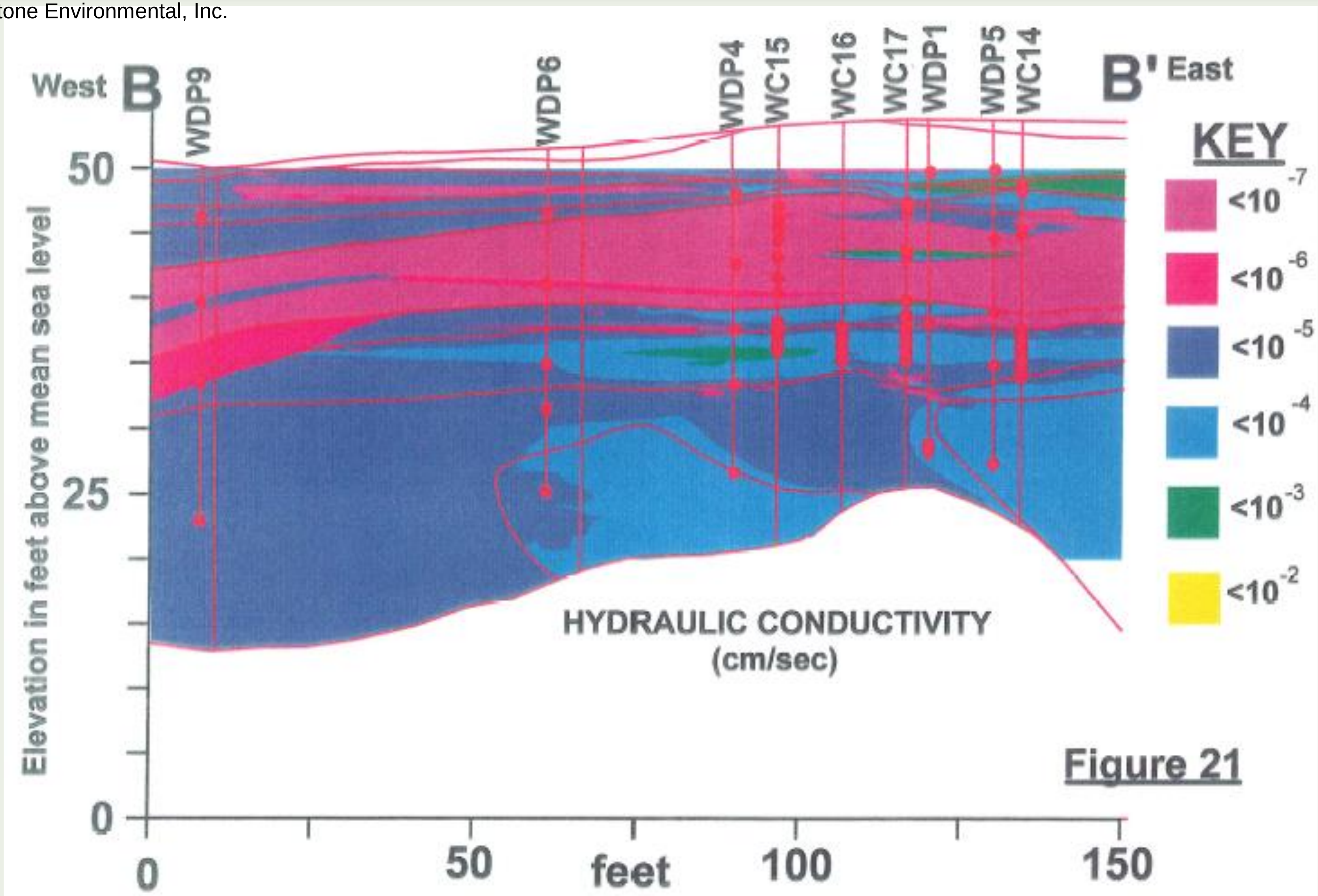
Section B – B’



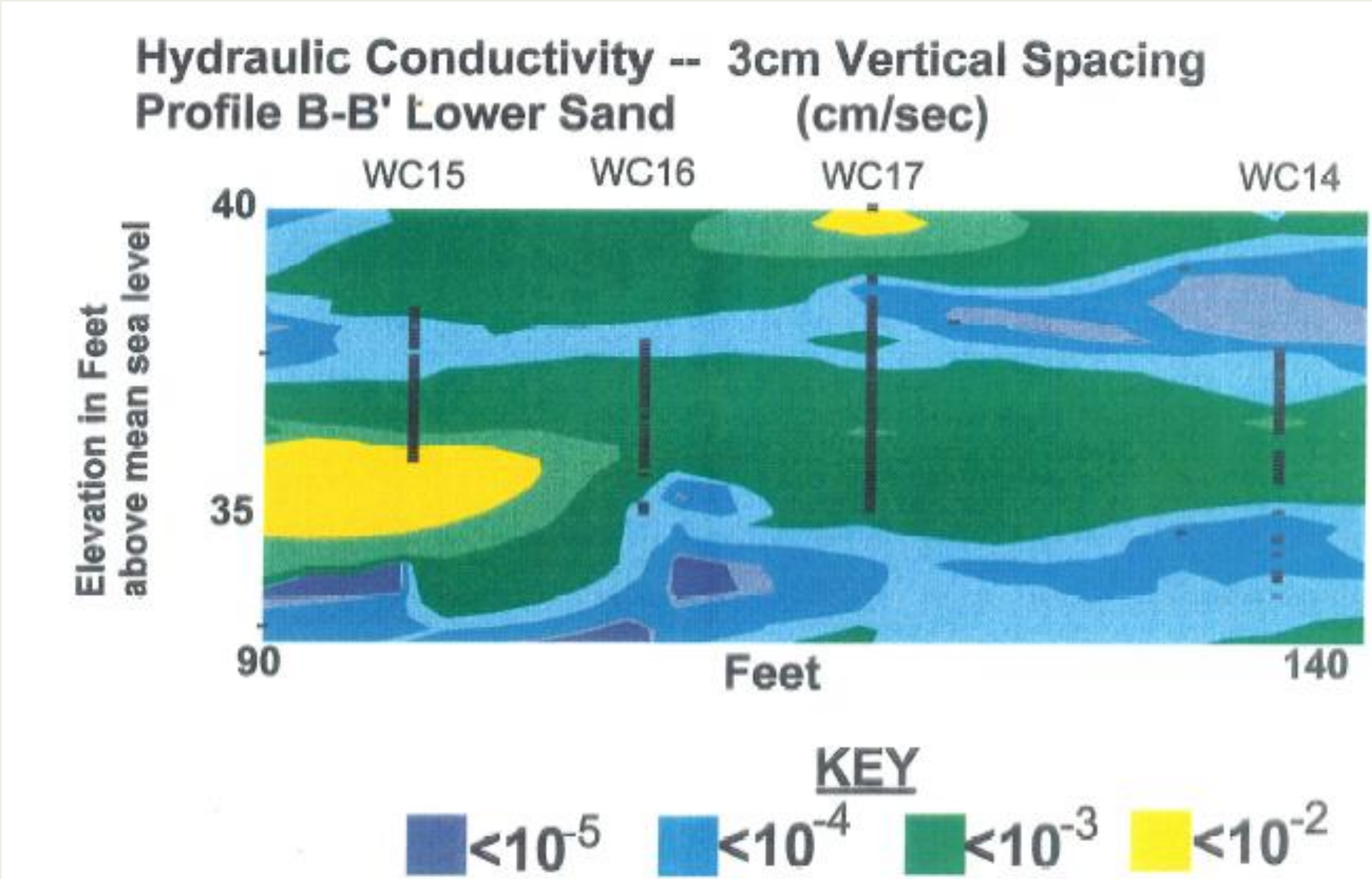
Source: Stone Environmental, Inc.

Hydraulic Conductivity Distribution on B – B’

Source: Stone Environmental, Inc.



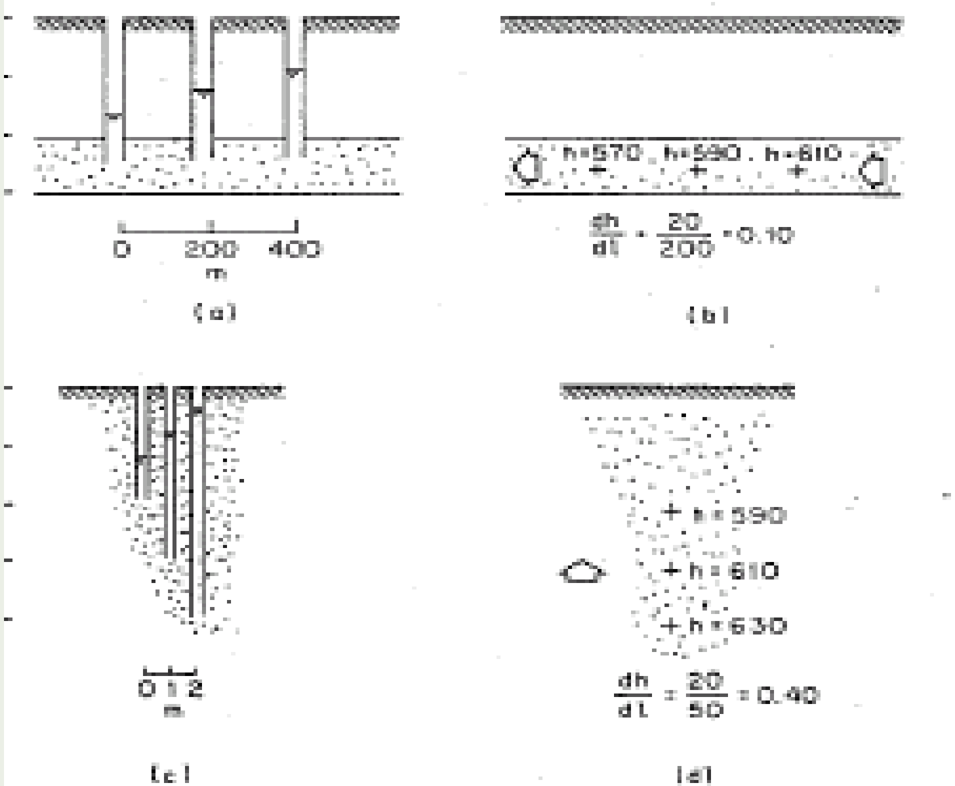
K (cm/sec) Distribution in Lower Sand on B – B’



Source: Stone Environmental, Inc.

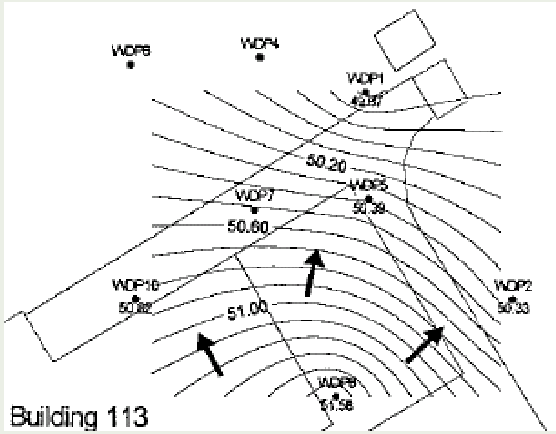
Hydraulic Gradient

- Driving Force
- Change in potential over distance
- Vector quantity (direction and magnitude)
- Three-dimensional

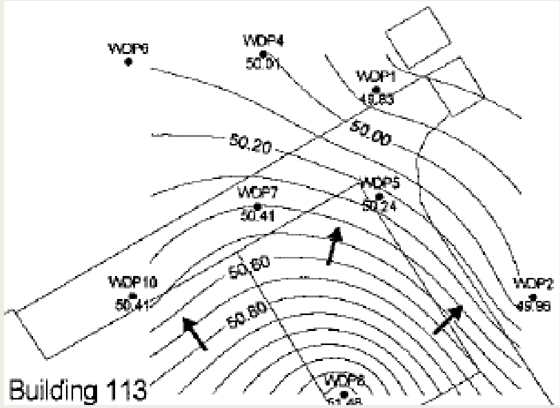


(from Freeze and Cherry, 1979)

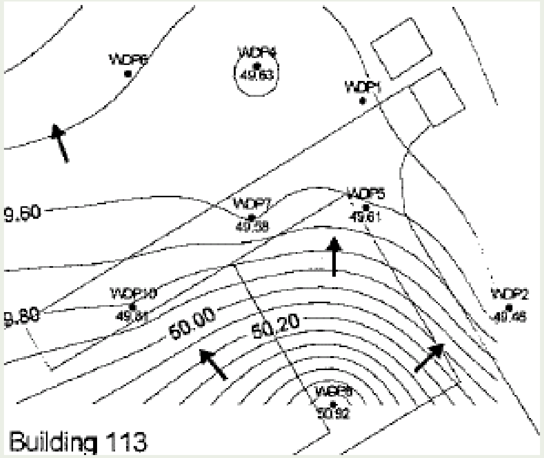
Hydraulic Gradient Variability with Depth



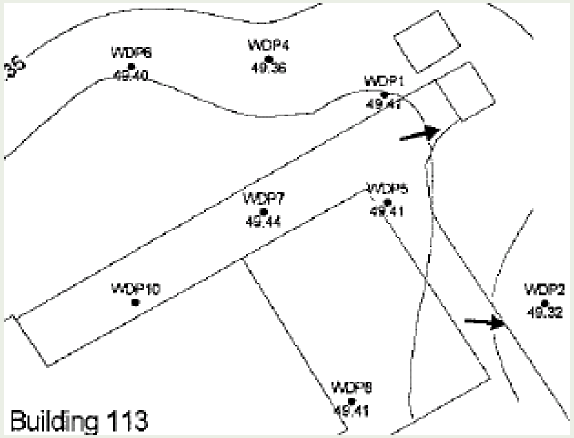
Fill/Upper Sand – 50 ft



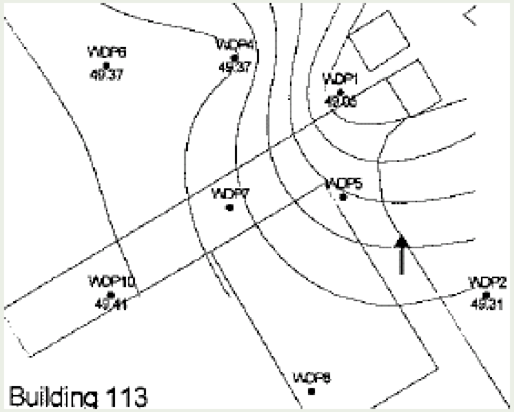
Clayey Marine Silt – 44 ft



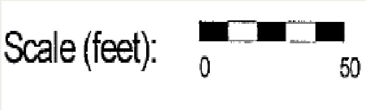
Marine S. Silt & Clay – 40 ft



Lower Sand – 35 ft



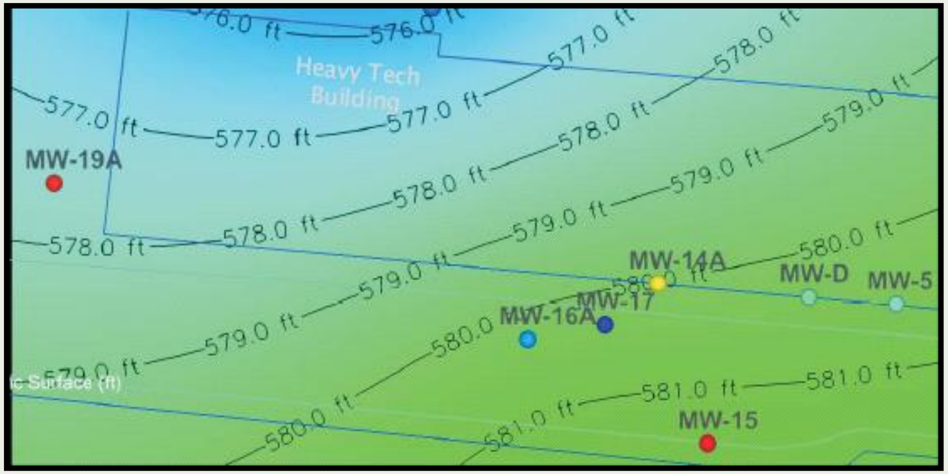
Diamicton – 30 ft



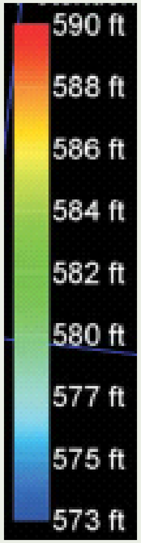
Gasoline Plume Site

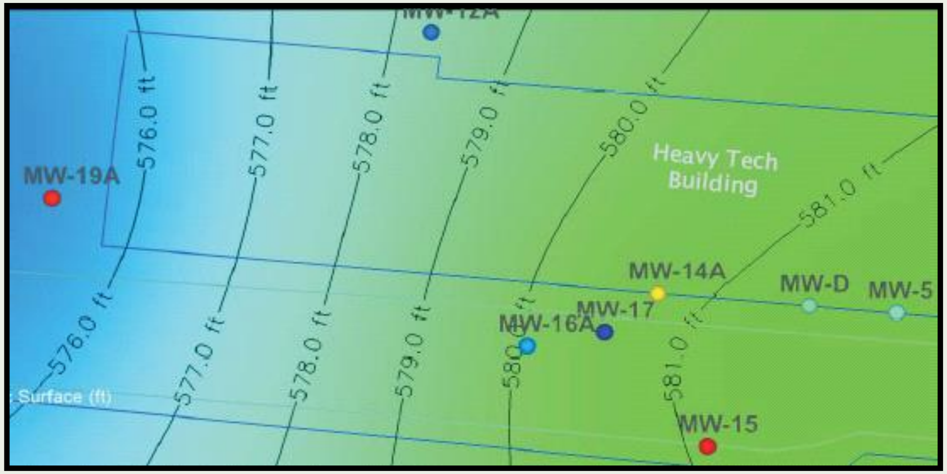
Variability of Hydraulic Gradient with Depth

Shallow – 585 ft amsl



Intermediate – 574 ft amsl





Deep – 557 ft amsl

In Review

- **Subsurface factors that affect groundwater flow vary widely over short vertical and horizontal distances**
- **Dual porosity systems**
  - Transport in the mobile porosity is dominated by advective flow
  - Transport in the immobile porosity is dominated by diffusive flux
- **'Real world' environment is far from the homogeneous and isotropic ideal**
- **Hydraulic conductivity**
  - K variability has a profound effect on groundwater flow and transport pathways
  - 2 or more orders of magnitude may be sufficient to cause flow to bypass the lower K zones and to result in those zones becoming "immobile porosity" zones
- **Hydraulic gradient**
  - The direction and magnitude can vary substantially
  - The gradient at the water table may not be representative of the hydraulic gradient throughout the vertical profile of a flow system
  - The direction of gradient does not always indicate direction of groundwater flow (anisotropy)

Questions?

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