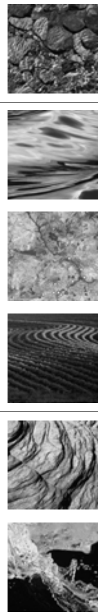

# High Resolution Site Characterization and the Triad Approach

Seth Pitkin

Triad Investigations: New Approaches and Innovative Strategies

June 2008

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A Fact-Based Fresh Look: 2” horizontal, 1.02” vertical

Needs Analysis Study: 2” horizontal, 1.97” vertical

Lesley Allen: 1.91” horizontal, 4.72” vertical

Date: 1.99” horizontal, 5.17” vertical

Images (grouped): 0.5” horizontal, 0.5” vertical

Top blue rule: 0” horizontal, 1.6” vertical

Bottom blue rule: 0” horizontal, 5.08” vertical

Logo: 6.38” horizontal, 7.42” vertical

# Contents



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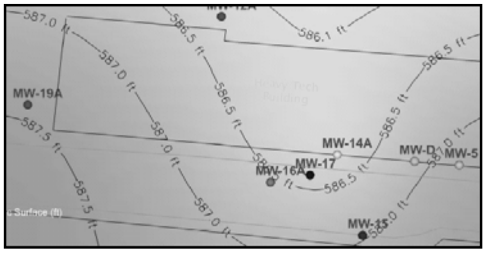
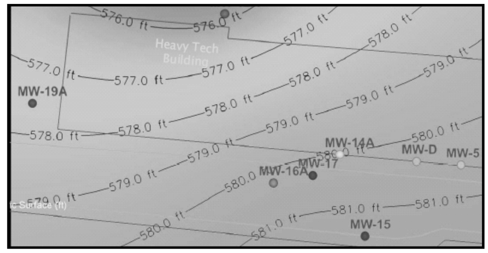
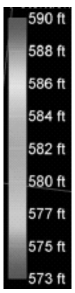
# Gasoline Plume Site in Vermont
# Variability of Hyd. Gradient w/ Depth

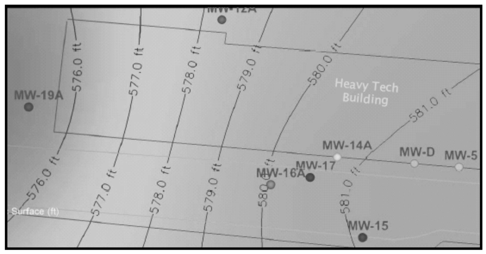



**Shallow – 585 ft amsl**




**Intermediate – 574 ft amsl**




**Deep – 557 ft amsl**

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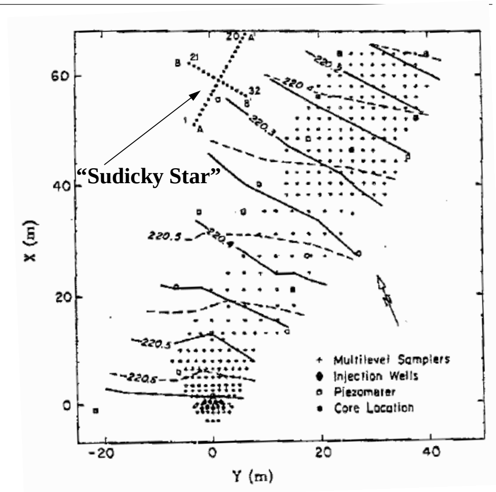
# Hydrodynamic Dispersion

- •Natural Gradient Tracer Tests
  - •Stanford/Waterloo – 1982
  - •USGS Cape Cod – 1990(?)
  - •Rivett et al 1991
- •Dispersion is scale (time/distance) dependent
- •**Transverse horizontal dispersion is weak**
- •**Transverse vertical dispersion is even weaker**
- •Longitudinal dispersion is significant




**Stanford-Waterloo Natural Gradient Tracer Test Layout**

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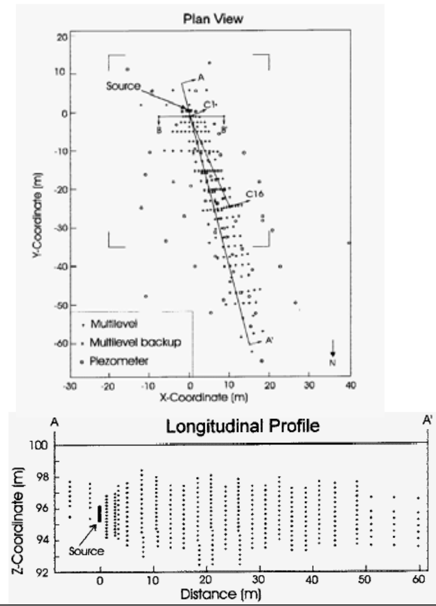
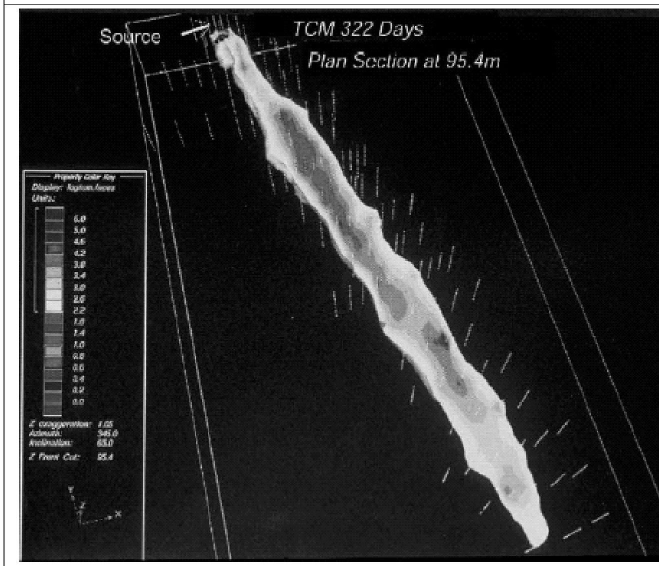
# Rivett's Experiment: The Emplaced Source Site




Rivett et al, 2000

# TCM Plume at 322 Days
*Weak Transverse Dispersion*





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Rivett et al, 2000

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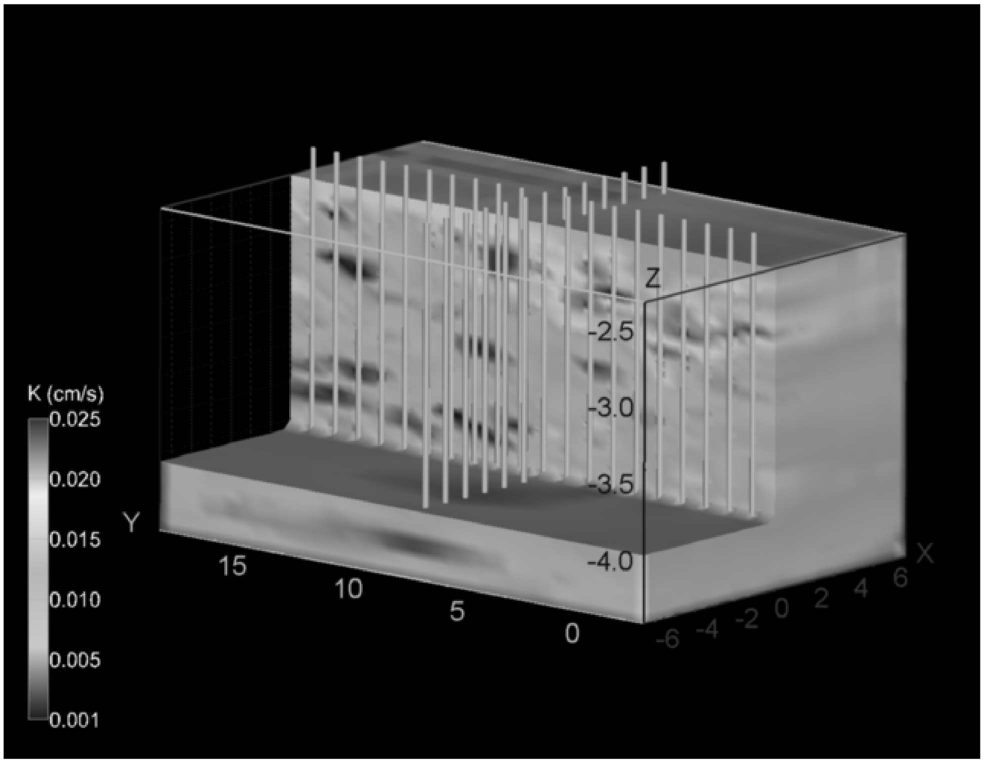
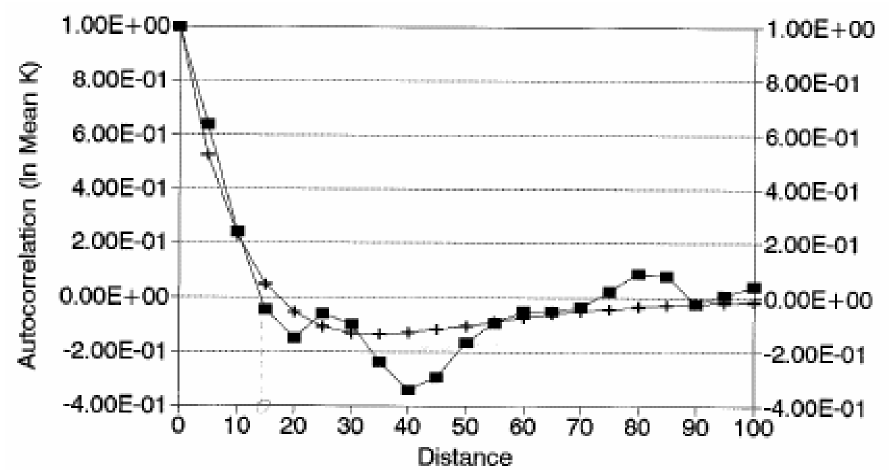

K (cm/s)
0.025
0.020
0.015
0.010
0.005
0.001
Z
-2.5
-3.0
-3.5
-4.0
Y
15
10
5
0
X
-6 -4 -2 0 2 4 6

# Autocorrelation of K
# 3 Cores in "Sudicky Star" CFB Borden

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## 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) |

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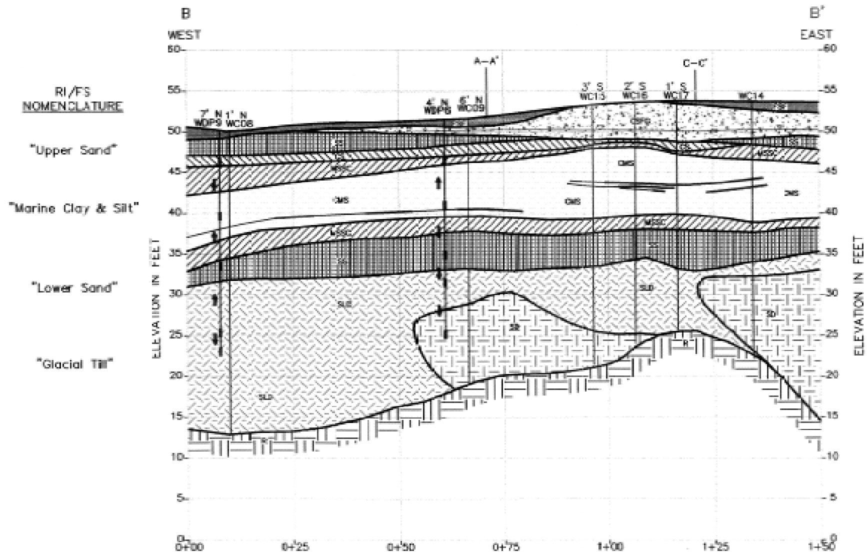
Other investigators have since performed similar studies and have found similar results.  With the exception of Columbus AFB, all of the investigators have found vertical correlation lengths  of less than 50 cm. in a given hydrostratigraphic unit. This is not a good sign for those using five foot long well screens.

# Pease AFB, NH - Site 32
# Section B – B'

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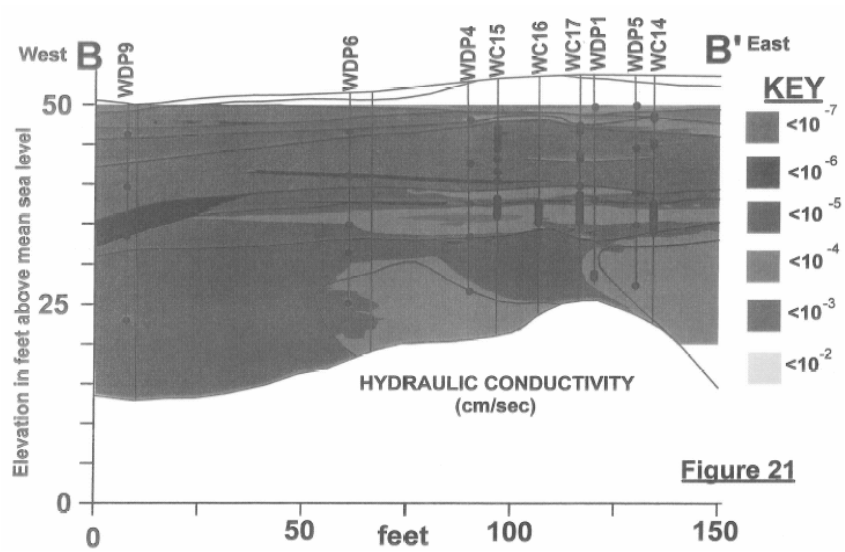
# Hydraulic Conductivity Distribution on B – B'

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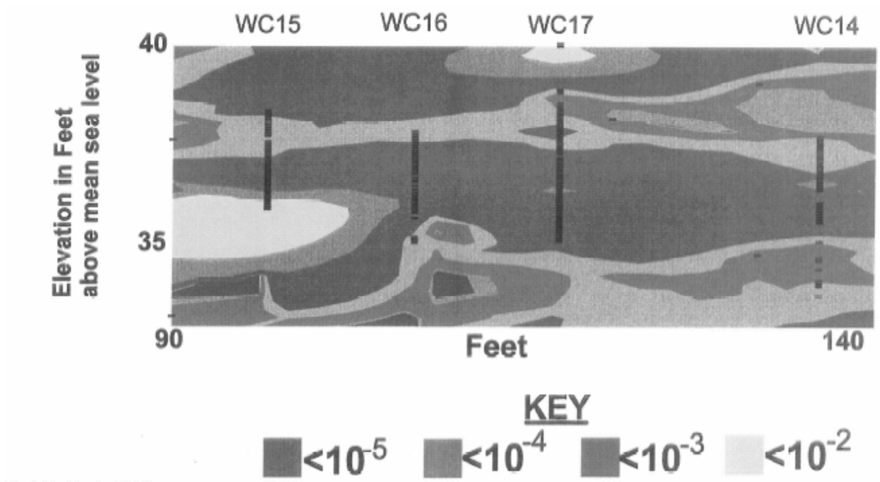
# K (cm/sec) Distribution in Lower Sand on B – B”

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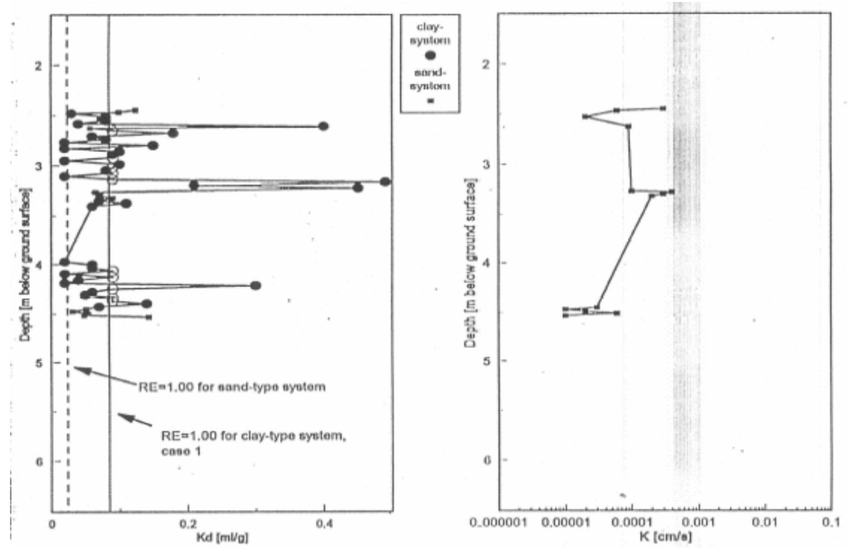
# Pease AFB Site 32
# $K_d$ and K variability with Depth

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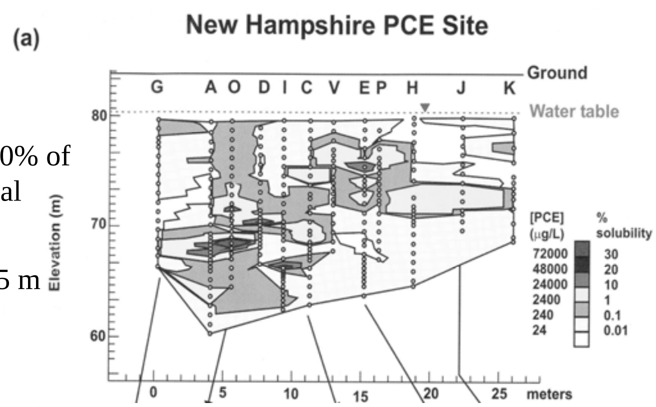
# Mass Flux Distribution

Guilbeault et. al. 2005

75% of mass discharge occurs through 5% to 10% of the plume cross sectional area.

Optimal Spacing is ~0.5 m

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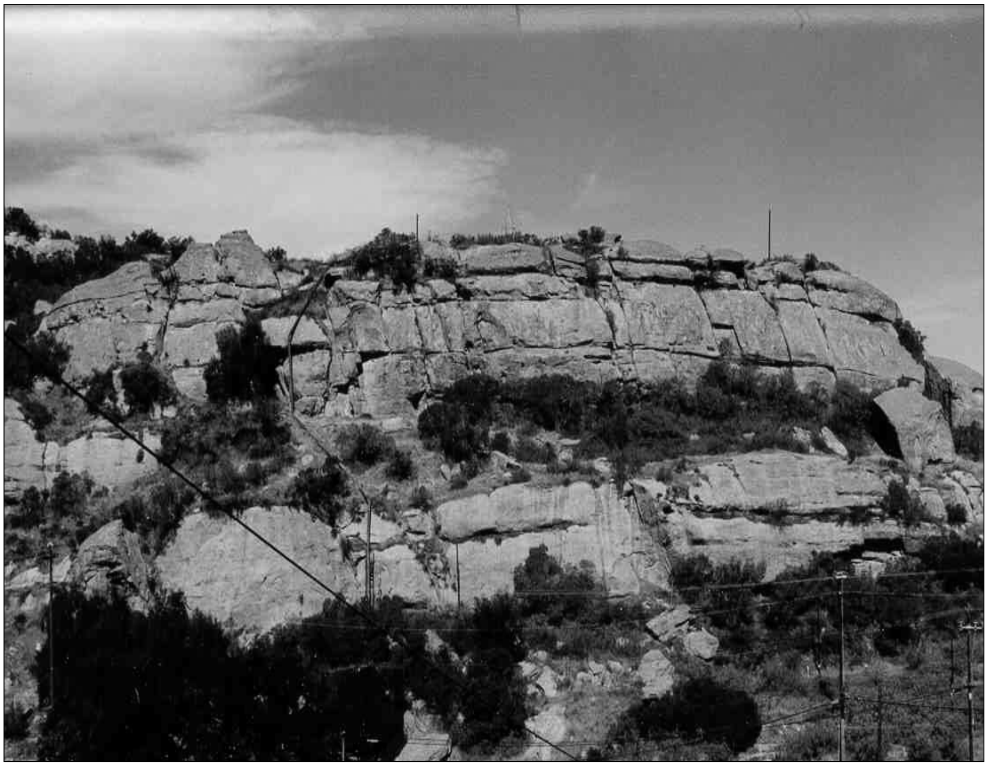
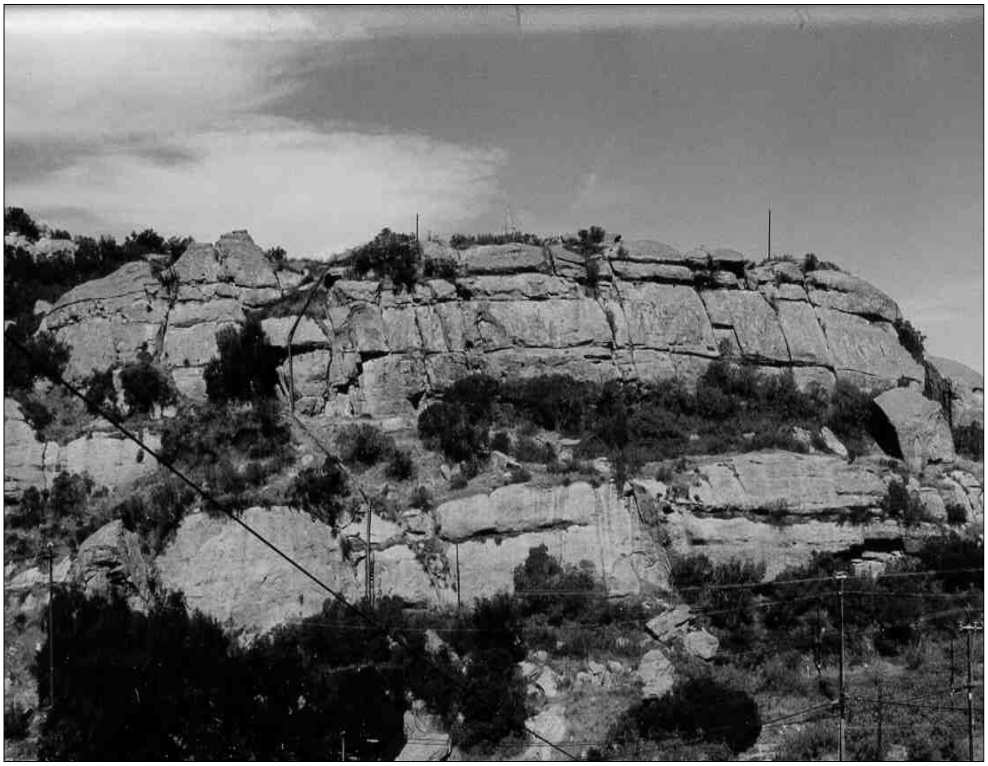
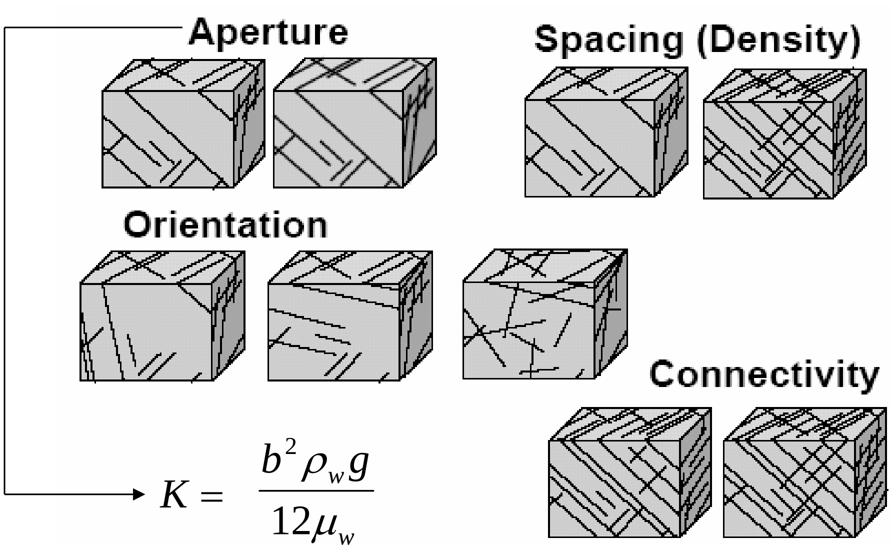




•Example of fractures exposed at outcrop.

•Fractures are orthogonal, interconnected, widely spaced, large matrix blocks.

## Factors Governing Flow in Fractured Media




$$K = \frac{b^2 \rho_w g}{12 \mu_w}$$

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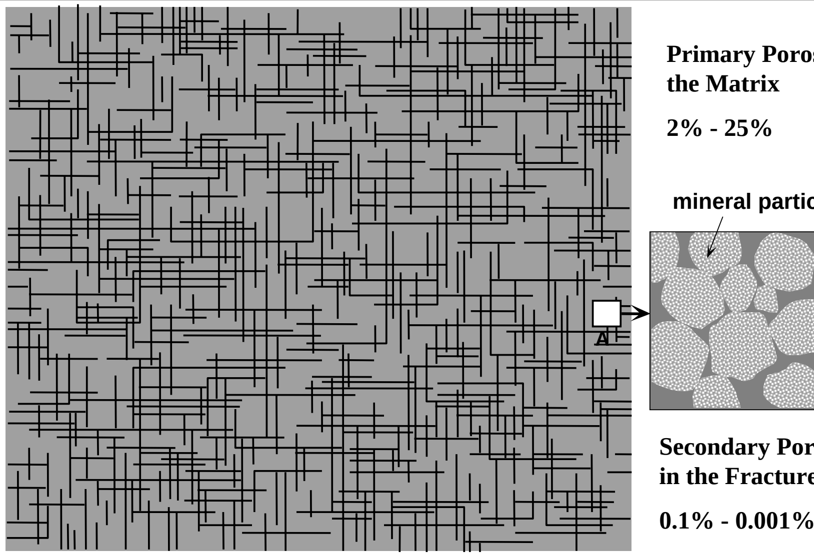
# Dual Porosity Media




**Primary Porosity in the Matrix**

**2% - 25%**

**Secondary Porosity in the Fractures**

**0.1% - 0.001%**

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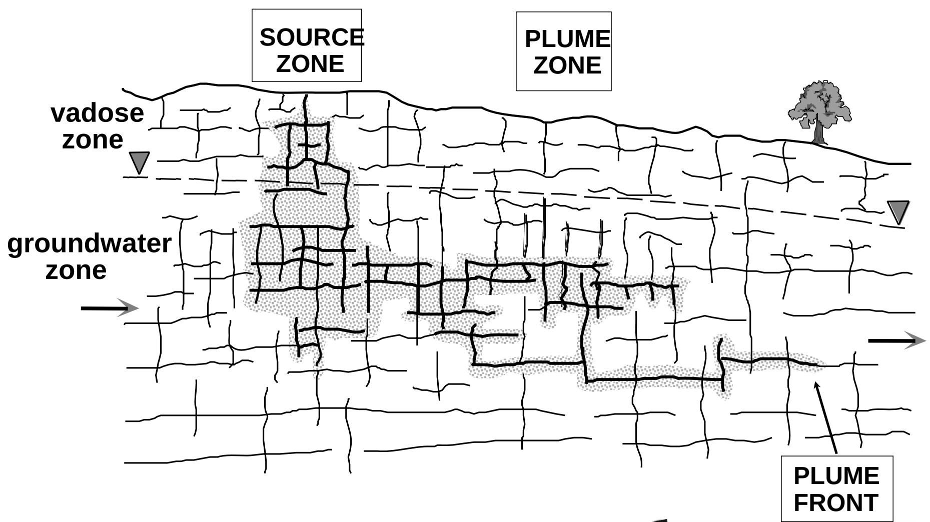
## Nature of Contamination in Fractured Porous Media

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# Contents



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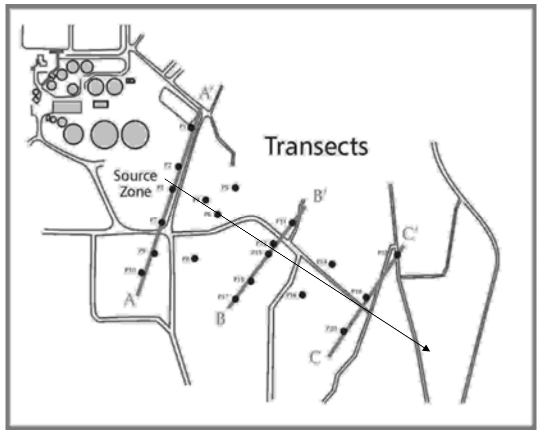
# High Resolution Approach

- **Transect**: Line of vertical profiles oriented normal to the direction of the hydraulic gradient (Horizontal spacing)
- **Short Sample Interval**: Vertical dimension of the sampled portion of the aquifer
- **Close Sample Spacing**: Vertical distance between samples
- Real-time/Near Real-time Tools
- Dynamic/ Adaptive Approach

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# High Resolution Tools

- Cone Penetrometer
- Laser Induced Fluorescence (LIF, aka UVOST, TarGOST)
- Membrane Interface Probe (MIP)
- NAPL Ribbon Sampler
- Waterloo$^{APS}$
- Soil Coring and Subsampling
- On Site Analytical
- Bedrock Toolbox
  - CORE$^{DFN}$
  - Borehole Geophysics
  - FLUTe K Profiler
  - Multilevels (Westbay, Solinst, FLUTe)

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# Collaborative Data in Porous Media:

## MIP, Wateroo$^{APS,}$ Soil Subcore Profiling and Onsite Analytical

- MIP: Rapid screening tool
  - Use to rapidly screen site and select sample locations for detailed difinitive sampling
- Waterloo$^{APS}$: Detailed definitive data in aquifers
- Soil Subcore Profiling: Detailed definitive data in aquifards
- On site analytical: Near real-time defensible data

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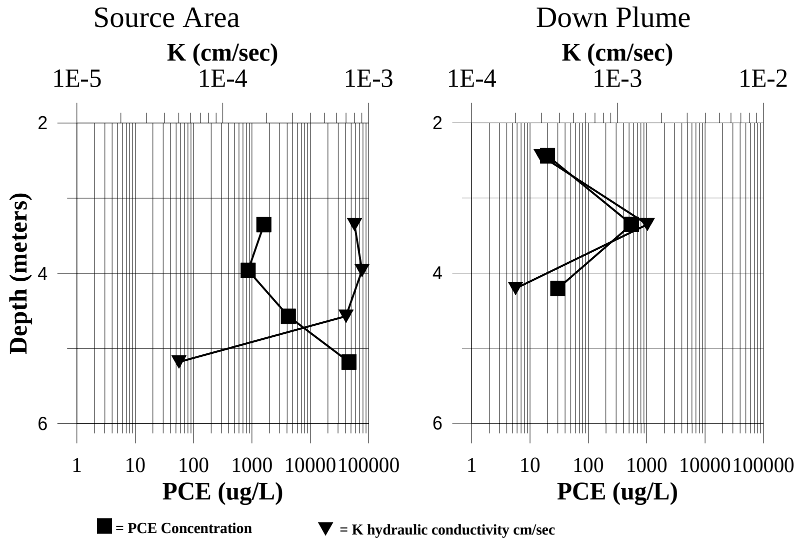
# Spatial Relationships of K and C

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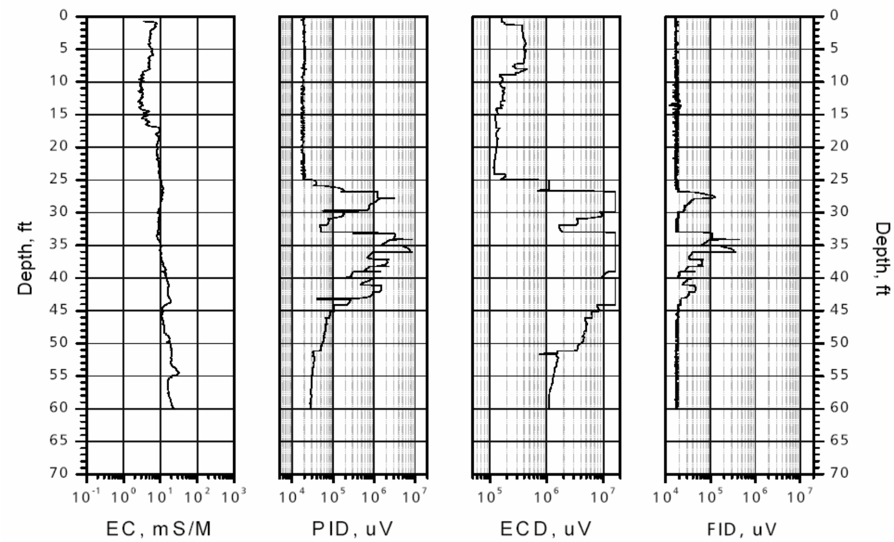
# MIP: Continuous, Real-Time Profile

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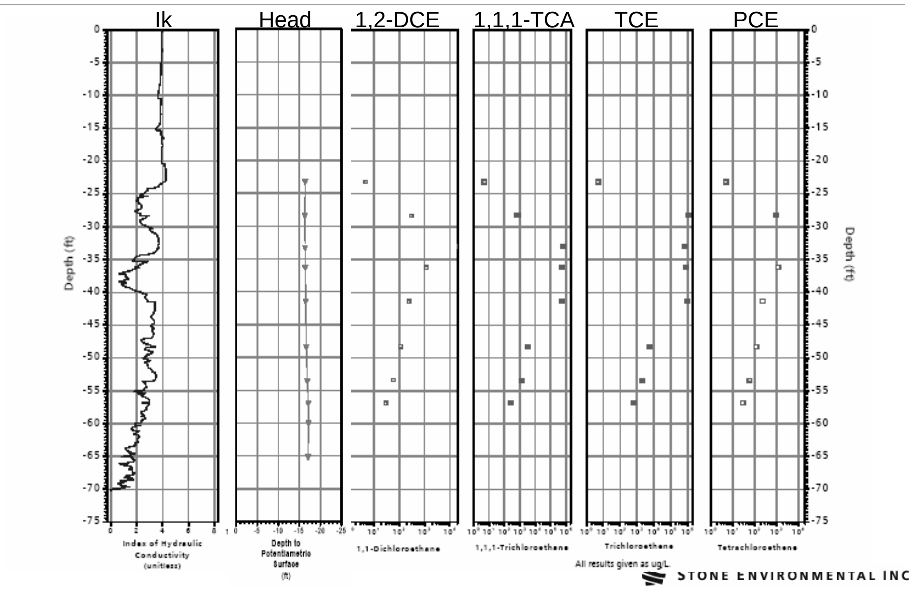
# Waterloo Profiler: Near Real-Time Closely Spaced Profile

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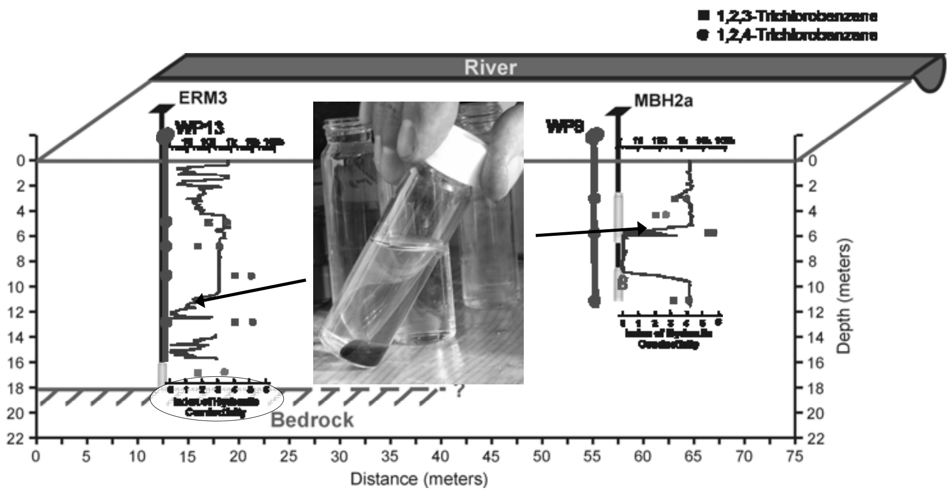
Waterloo APS™
ADVANCED PROFILING SYSTEM

# Finding What Others Missed

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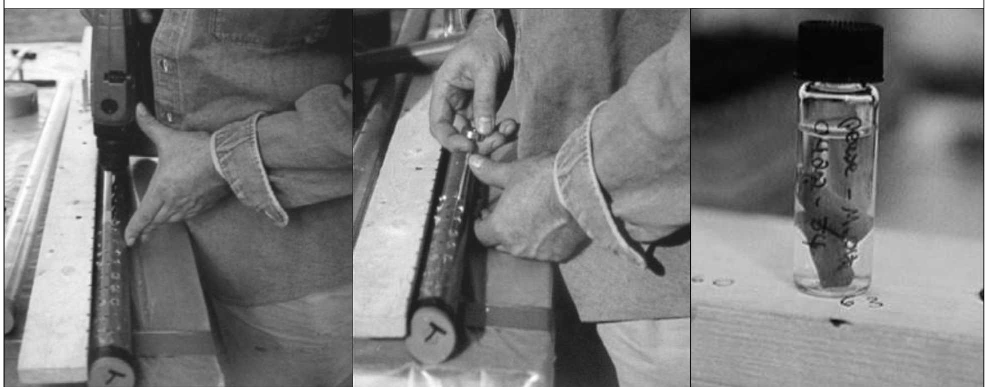
# Soil Subcore Profiling: What's in the Aquitard?



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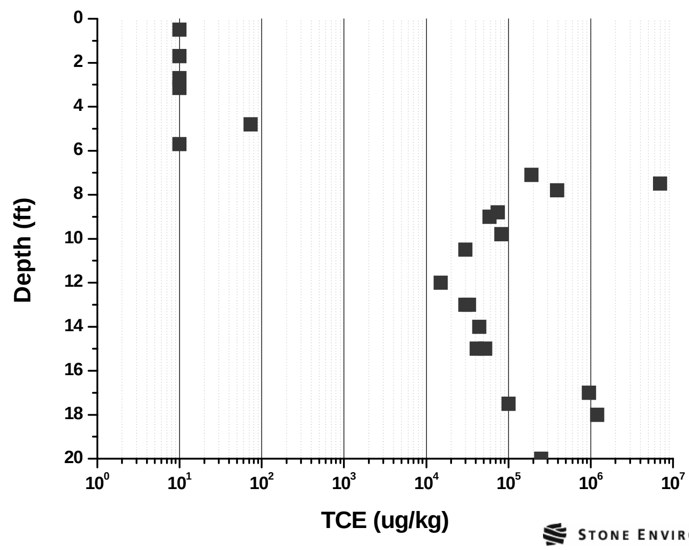
# Soil Sub-Core Sampling: Near-Real Time, Closely Spaced Profile

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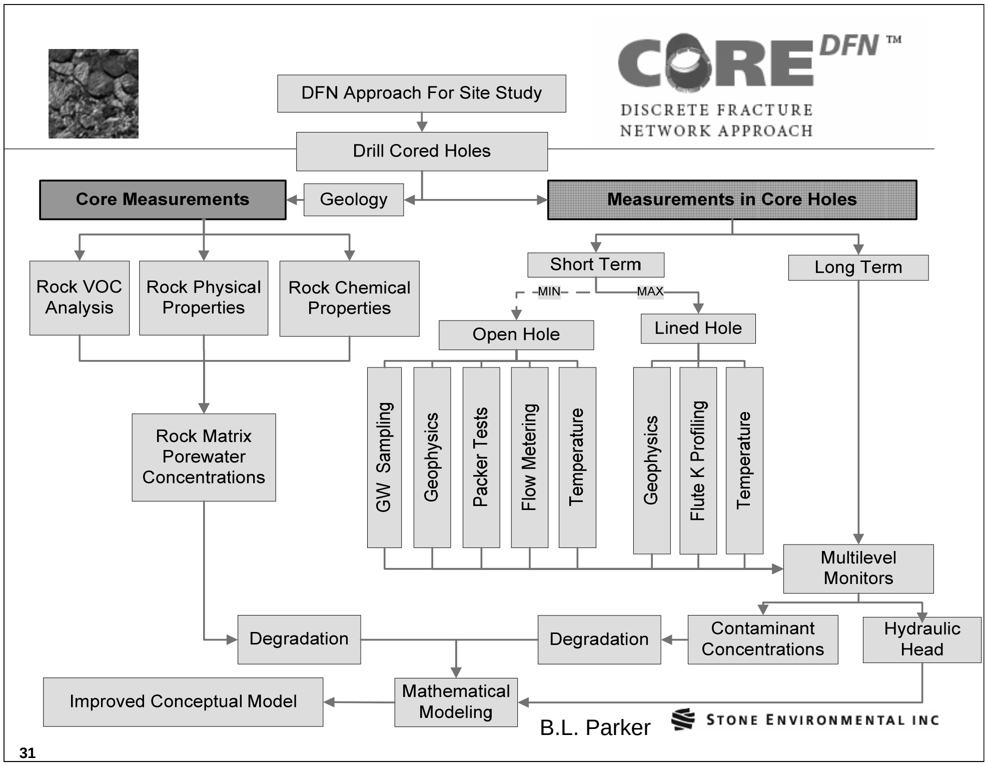
CORE DFN ™
DISCRETE FRACTURE NETWORK APPROACH
DFN Approach For Site Study
Drill Cored Holes
Core Measurements
Geology
Measurements in Core Holes
Rock VOC Analysis
Rock Physical Properties
Rock Chemical Properties
Short Term
Long Term
MIN
MAX
Open Hole
Lined Hole
GW Sampling
Geophysics
Packer Tests
Flow Metering
Temperature
Geophysics
Flute K Profiling
Temperature
Rock Matrix Porewater Concentrations
Multilevel Monitors
Degradation
Degradation
Contaminant Concentrations
Hydraulic Head
Improved Conceptual Model
Mathematical Modeling
B.L. Parker
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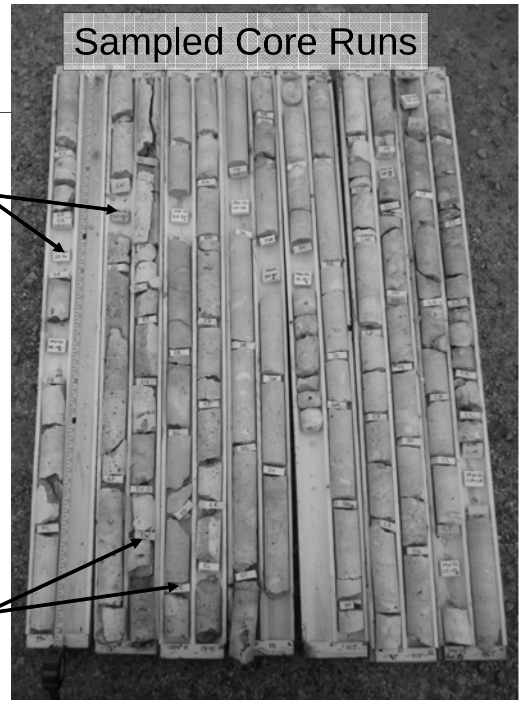
# Rock Core Sampling

Physical Property Sample

- High resolution VOC sampling
- Physical property sampling

VOC Sample

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2000 voc and 250 phys prop

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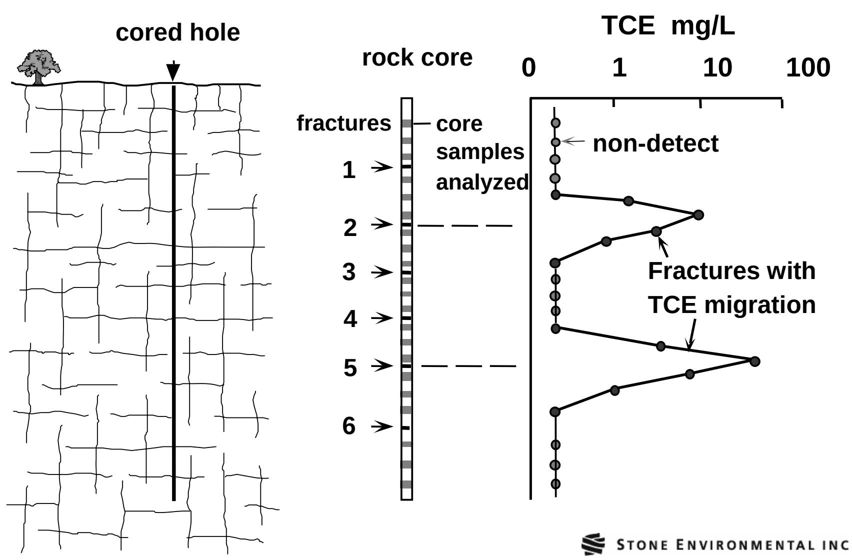
# Core Sampling for Mass Distribution & Migration Pathway Identification

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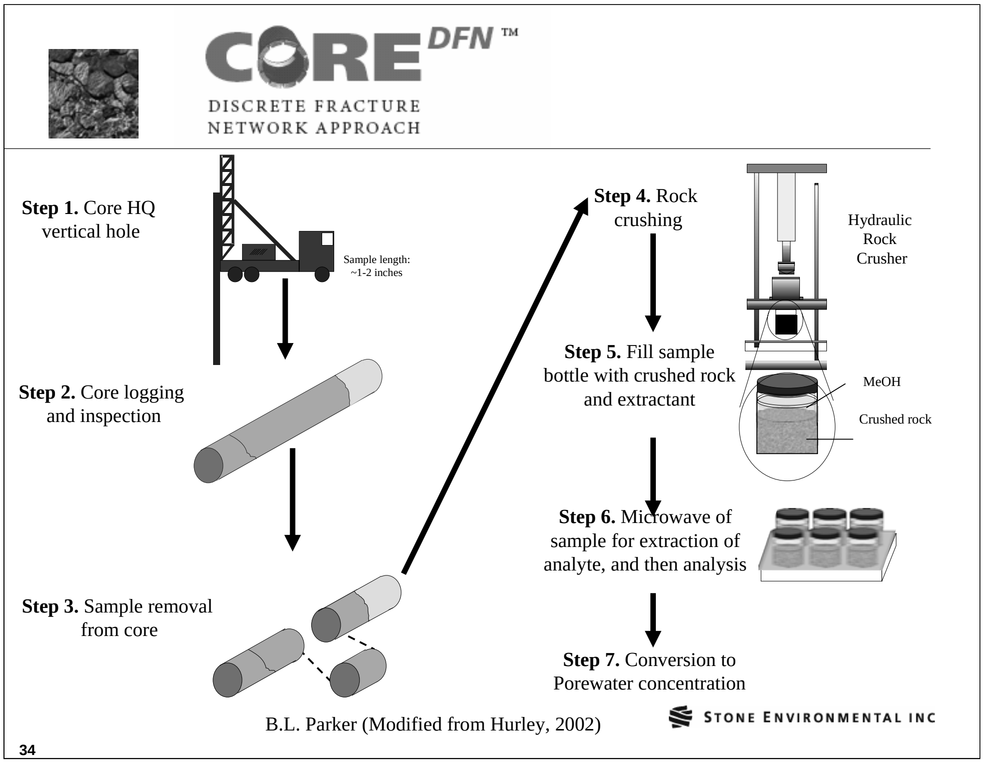
B.L. Parker


CORE DFN ™
DISCRETE FRACTURE
NETWORK APPROACH
Step 1. Core HQ vertical hole
Sample length: ~1-2 inches
Step 2. Core logging and inspection
Step 3. Sample removal from core
Step 4. Rock crushing
Hydraulic Rock Crusher
Step 5. Fill sample bottle with crushed rock and extractant
MeOH
Crushed rock
Step 6. Microwave of sample for extraction of analyte, and then analysis
Step 7. Conversion to Porewater concentration
B.L. Parker (Modified from Hurley, 2002)
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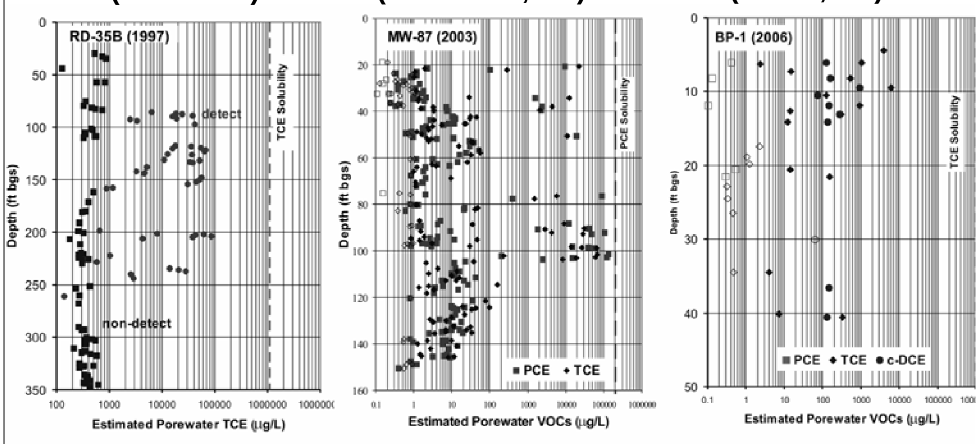
# Example Rock Core VOC Concentration Profiles

**Sandstone (California)** | **Shale (Watervliet, NY)** | **Siltstone (Union, NY)**

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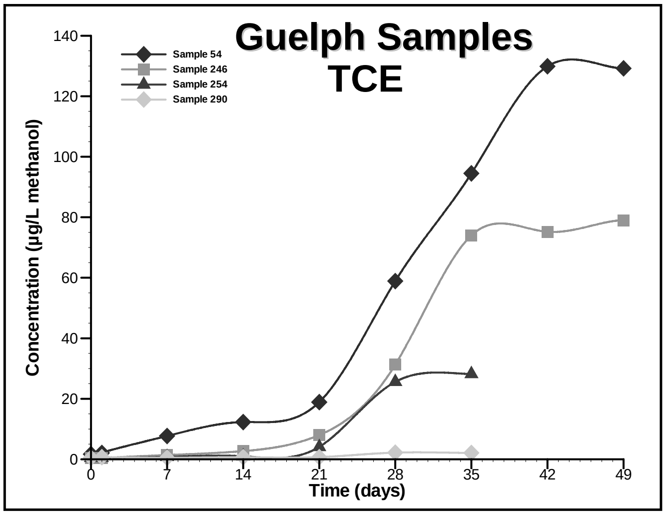
Long extraction time for shake-flask method –
Not Very Real-Time




Data from Yongdong Liu (2005)

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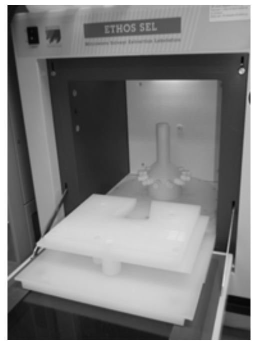
Here you can see the amount of time for TCE to reach equilibrium between the rock sample and extractant which is the flat portion of these plots

# Microwave Assisted Extraction (MAE)

- Fast - 40 min
- Extraction at higher temperature and pressure
  - Increases diffusion rate and analyte desorption rate
  - Elevated boiling point (temperatures ~ 120ºC)
  - Increased solvent penetration


B.L. Parker Photos courtesy of Dr. Tadeusz Górecki STONE ENVIRONMENTAL INC

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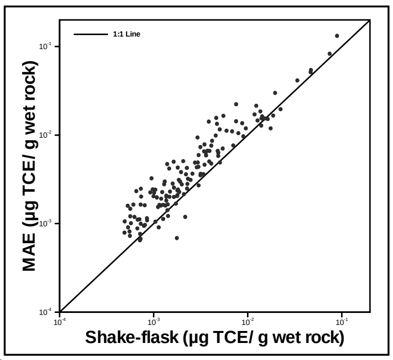
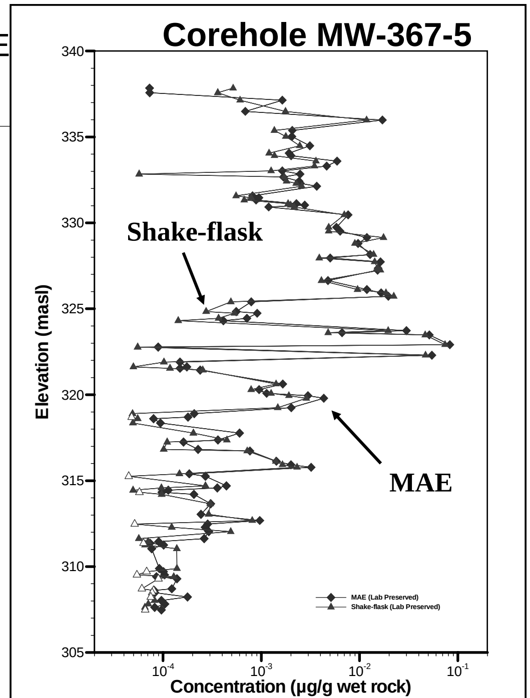
## Shake Flask vs MAE

(TCE)

- Good correlation
- More complete extraction with MAE




B.L. Parker

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# Distillation

- Contaminant hydrogeology is all about spatial variability
- High resolution site characterization is essential
- Apply Triad Approach Principles:
  - Real-time/ near real time data collection tools
  - Dynamic Work Strategy
  - Employ collaborative data using integrated tool sets
- Triad Approach in Bedrock Plumes: Coming Soon to a Fractured Rock Aquifer Near you

THE END

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# Hydraulic Parameter and Mass Flux Distribution Using the High-Resolution Piezocone and GMS

**Dr. Mark Kram, Groundswell**
**Dr. Norm Jones, BYU**
**Jessica Chau, UConn**
**Dr. Gary Robbins, UConn**
**Dr. Amvrossios Bagtzoglou, UConn**
**Thomas D. Dalzell, AMS**
**Per Ljunggren, ENVI**

EPA Clu-In Internet Seminar
13 August 2009

40 EPA Clu-In 08/13/09

## TECHNICAL OBJECTIVES

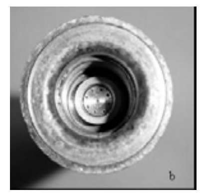
- Demonstrate Use of High-Resolution Piezocone to Determine Direction and Rate of GW Flow in 3-D
  - Compare with Traditional Methods
  - Develop Models and Predict Plume Behavior
- Integrate High-Resolution Piezocone and Concentration Data into 3-D Flux Distributions via GMS Upgrades
- Introduce New Remediation Performance Monitoring Concept

# TECHNOLOGY DESCRIPTION

High-Resolution Piezocone:

- Direct-Push (DP) Sensor Probe that Converts Pore Pressure to Water Level or Hydraulic Head
- Head Values to ± 0.08ft (to >60' below w.t.)
- Can Measure Vertical Gradients
- Simultaneously Collect Soil Type and K
- K from Pressure Dissipation, Soil Type
- Minimal Worker Exposure to Contaminants
- System Installed on PWC San Diego SCAPS
- Licensed to AMS


Custom Transducer



# SEEPAGE VELOCITY AND FLUX

## *Seepage velocity* ($\nu$):

$$\nu = \frac{Ki}{\rho} \quad \text{(length/time)}$$

where: K = hydraulic conductivity (*Piezocone*)

$i$ = hydraulic gradient (*Piezocone*)

$\rho$ = effective porosity (*Piezocone/Soil*)

## *Contaminant flux (F):*

$$F = \nu\,[X]$$

(mass/length$^2$-time; mg/m$^2$-s)

where: $\nu$ = seepage velocity (length/time; m/s)

[X] = concentration of solute (*MIP, etc.*) (mass/volume; mg/m$^3$)

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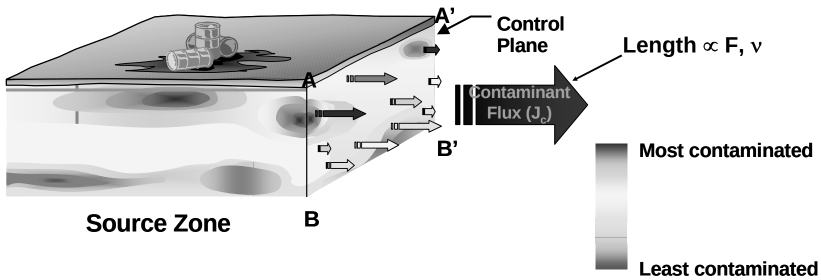
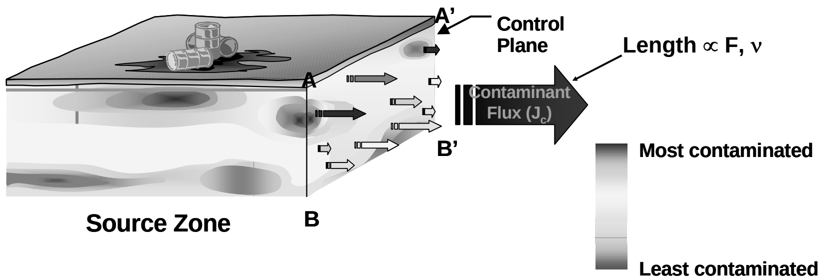
## CONCENTRATION VS. FLUX



## CONCENTRATION VS. FLUX




High Concentration ≠ High Risk!!
Hydraulic Component - Piezocone

# GMS MODIFICATIONS

**Gradient, Velocity and Flux Calculations**

- **Convert Scalar Head to Gradient [Key Step!]**

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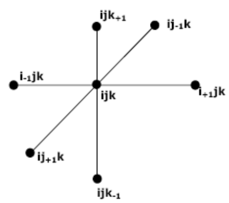
# GMS MODIFICATIONS

**Gradient, Velocity and Flux Calculations**

- **Convert Scalar Head to Gradient [Key Step!]**

## Calculating Hydraulic Gradient

For an interior node:




$$\frac{\partial h}{\partial x} = \frac{\frac{h_{i_{+1}jk} - h_{ijk}}{x_{i_{+1}jk} - x_{ijk}} + \frac{h_{ijk} - h_{i_{-1}jk}}{x_{ijk} - x_{i_{-1}jk}}}{2}$$

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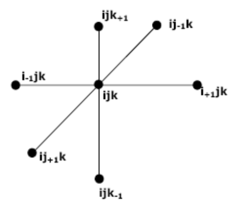
# GMS MODIFICATIONS

**Gradient, Velocity and Flux Calculations**

- **Convert Scalar Head to Gradient [Key Step!]**
  - **Merging of 3-D Distributions to Solve for Velocity**
  - **Merging of Velocity and Concentration (MIP or Samples) Distributions to Solve for Contaminant Flux**

## Calculating Hydraulic Gradient

For an interior node:




$$\frac{\partial h}{\partial x} = \frac{\dfrac{h_{i+1jk} - h_{ijk}}{x_{i+1jk} - x_{ijk}} + \dfrac{h_{ijk} - h_{i-1jk}}{x_{ijk} - x_{i-1jk}}}{2}$$

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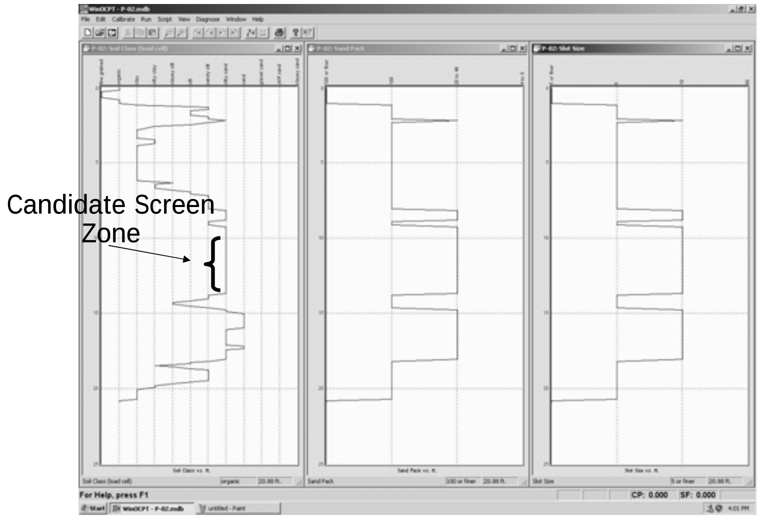
## APPROACH

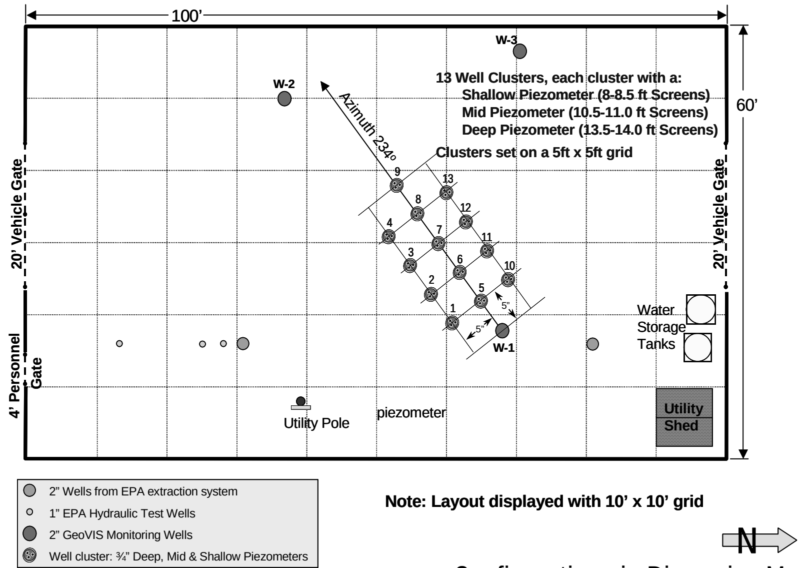
- Test Cell Orientation
  - ➢ Initial pushes for well design;
  - ➢ Well design and prelim. installations, gradient determination;
  - ➢ Initial $CaCl_2$ tracer tests with geophysics (time-lapse resistivity) to determine general flow direction
- Field Installations (Clustered Wells)
- Survey (Lat/Long/Elevation)
- Pneumatic and Conventional Slug Tests (“K – Field”)
  - ➢ Modified Geoprobe test system
- Water Levels (“Conventional” 3-D Head and Gradient)
- HR Piezocone Pushes (K, head, eff. porosity)
- GMS Interpolations ($\nu$, F), Modeling and Comparisons

# CPT-BASED WELL DESIGN




Kram and Farrar Well Design Method

# DEMONSTRATION CONFIGURATION




**Note: Layout displayed with 10' x 10' grid**

Configuration via Dispersive Model

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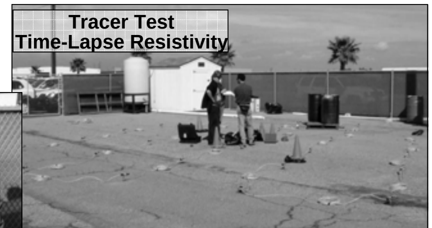
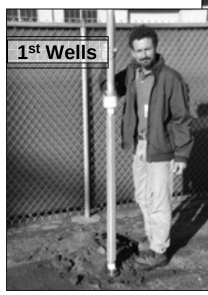
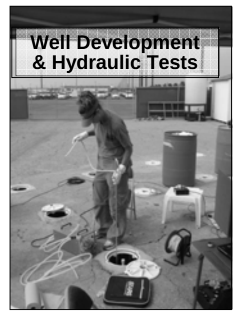
# FIELD EFFORTS



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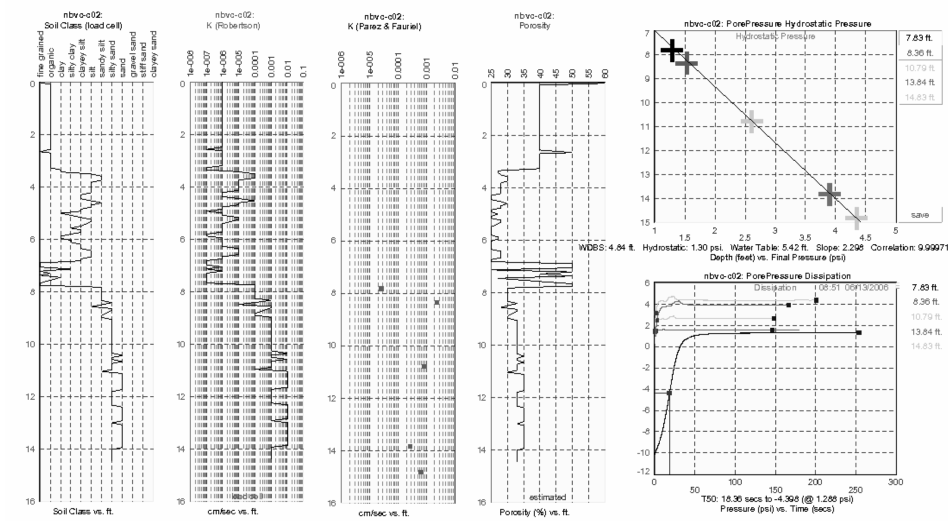
# FIELD EFFORTS



# PIEZOCONE OUTPUT

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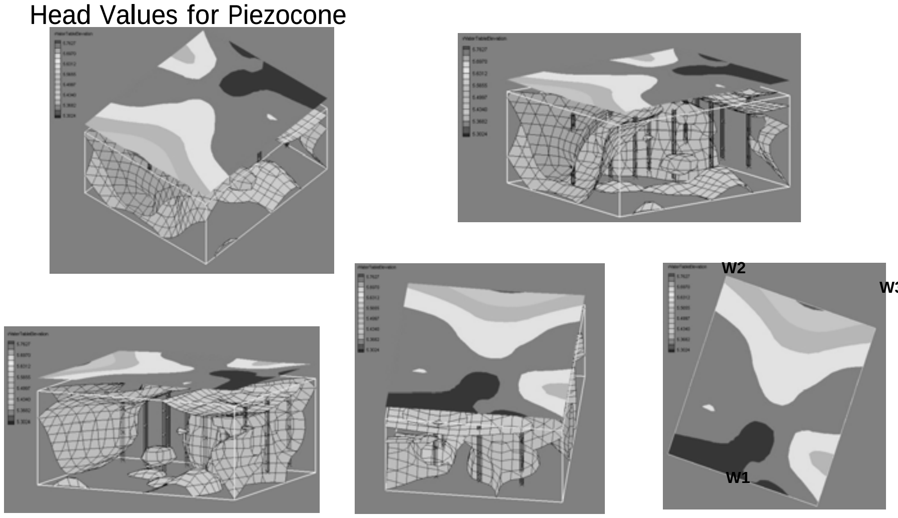
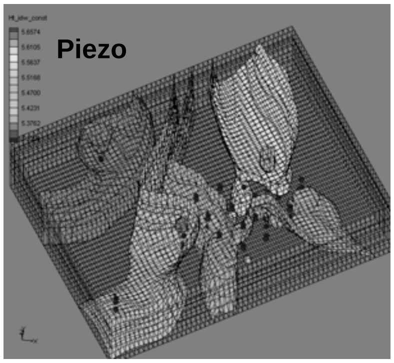
# HIGH RESOLUTION PIEZOCONE TESTS (6/13/06)

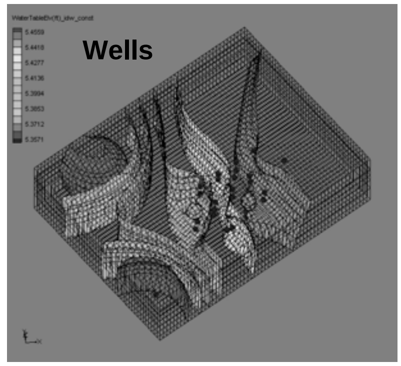
Head Values for Piezocone




Displays shallow gradient

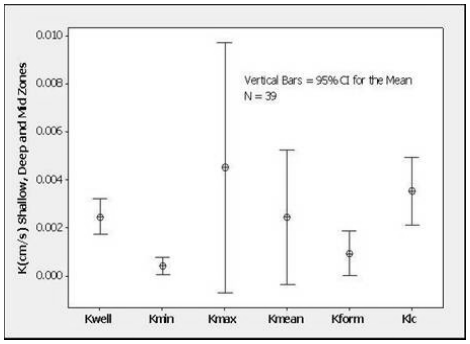
# HEAD DETERMINATION
# (3-D Interpolations)

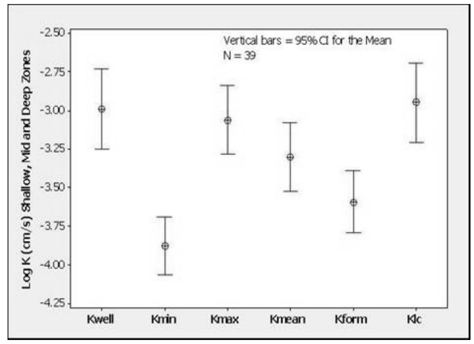



- Shallow gradient (5.49-5.41'; 5.45-5.38' range in clusters over 25')
- In practice, resolution exceptional (larger push spacing)

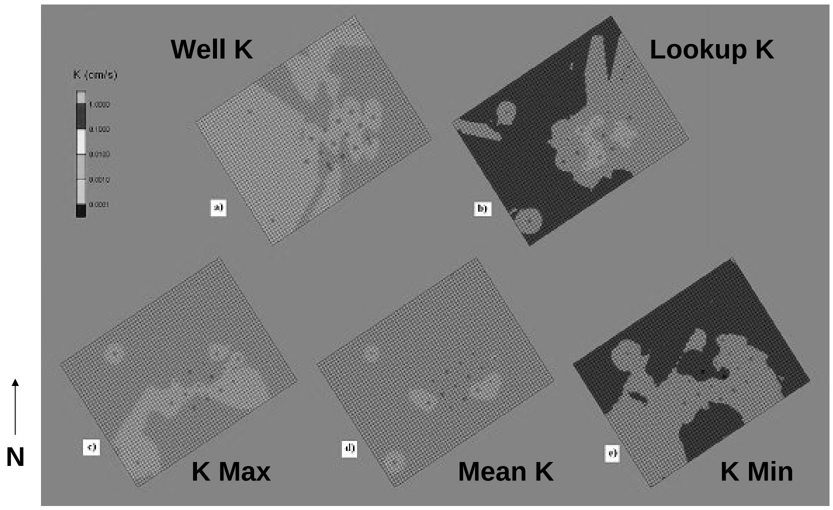
## COMPARISON OF ALL K VALUES



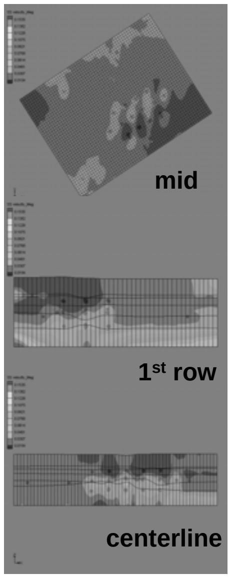

- $K_{mean}$ and $K_{lc}$ values within about a factor of 2 of $K_{well}$ values;
- $K_{min}$, $K_{max}$ and $K_{form}$ values typically fall within factor of 5 or better of the $K_{well}$ values;
- K values derived from piezocone pushes ranged much more widely than those derived from slug tests conducted in adjacent monitoring wells;
- Differences may be attributed to averaging of hydraulic conductivity values over the well screen versus more depth discrete determinations from the piezocone (e.g., more sensitive to vertical heterogeneities).

## K BASED ON WELLS AND PROBE
### (Mid Zone Interpolations)

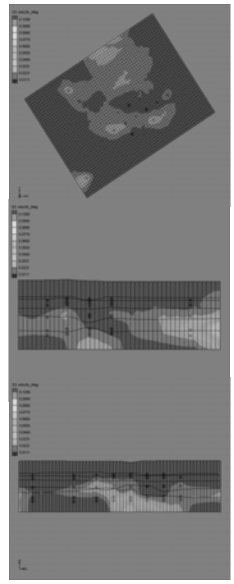


# VELOCITY DETERMINATION
**(cm/s)**

Well

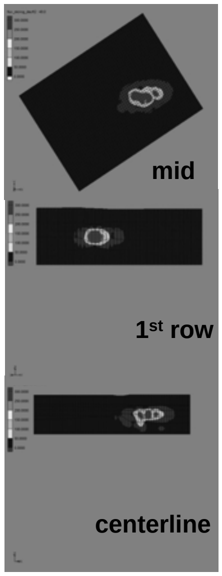



Piezo (mean K)

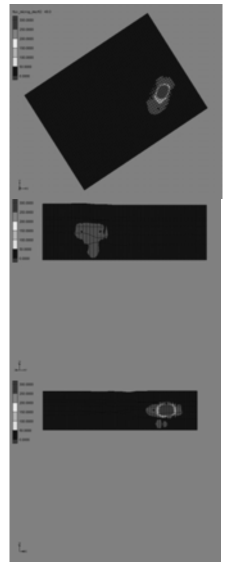


# FLUX DETERMINATION
## (Day 49 Projection)

**Well**




**Piezo (mean K)**



**ug/ft$^2$-day**

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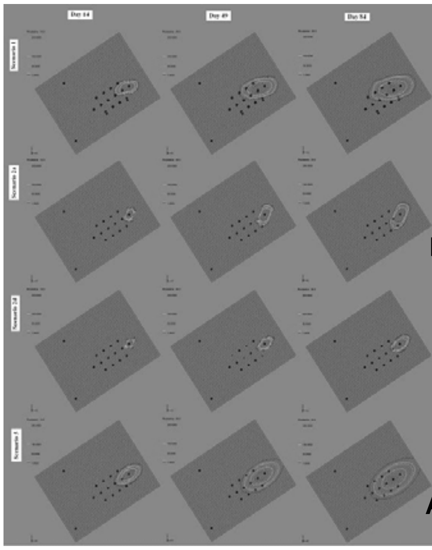
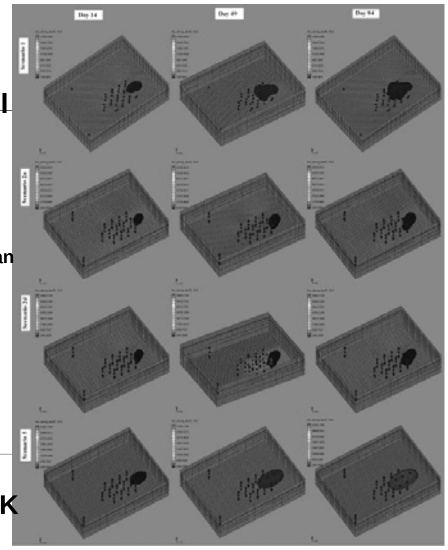
# MODELING
## Concentration and Flux

| Scenario | Head | K | Porosity |
|---|---|---|---|
| 1 | Well | Well | Average |
| 2a | SCAPS | SCAPS $K_{mean}$ | SCAPS |
| 2b | SCAPS | SCAPS $K_{min}$ | SCAPS |
| 2c | SCAPS | SCAPS $K_{max}$ | SCAPS |
| 2d | SCAPS | SCAPS $K_{lookup}$ | SCAPS |
| 3 | Well | Well | SCAPS |
| 4a | Well | SCAPS $K_{mean}$ | SCAPS |
| 4b | Well | SCAPS $K_{min}$ | SCAPS |
| 4c | Well | SCAPS $K_{max}$ | SCAPS |
| 4d | Well | SCAPS $K_{lookup}$ | SCAPS |
| 5 | Unif. grad. | Average | Average |

# MODELING
## Concentration and Flux





Well

$K_{mean}$

$K_{lc}$

Ave K

ppb

ug/ft²-day

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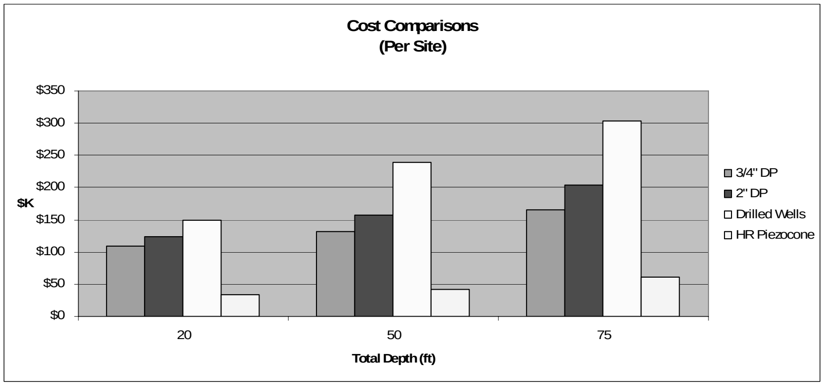
# PERFORMANCE

Performance Summary.

| *Performance Criteria* | **Expected Performance Metric** | **Results** |
|---|---|---|
| Accuracy of high-resolution piezocone for determining head values, flow direction and gradients | ± 0.08 ft head values | Met Criteria |
| Hydraulic conductivity (dissipation or soil type correlation) | ± 0.5 to 1 order of magnitude | Met Criteria |
| Transport model based on probes | Predicted breakthrough times and concentrations within one order of magnitude; probe based model efficiency accounts for more than 15% of the variance associated with well based models | Met Criteria |
| Time required for generation of 3-D conceptual and transport models | At least 50% reduction in time | Met Criteria |

# FLUX CHARACTERIZATION
## Cost Comparisons




"Apples to Apples" – HR Piez. with MIP vs. Wells, Aq. Tests, Samples
10 Locations/30 Wells

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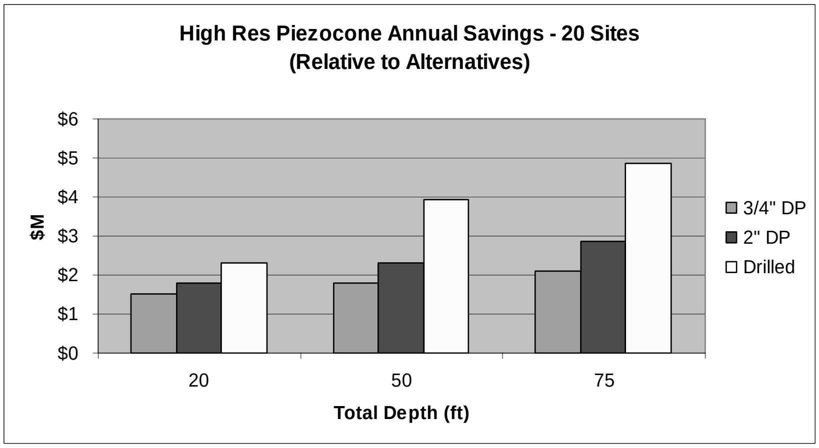
# FLUX CHARACTERIZATION
## Cost Comparisons




**Early Savings of ~$1.5M to $4.8M**

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# FLUX CHARACTERIZATION
## Time Comparisons

| | Days to Complete | | |
|---|---|---|---|
| Depth (ft) | Direct-Push Wells | Drilled Wells | HR Piezocone |
| 20 | 90 | 104 | 13 |
| 50 | 99 | 137 | 15 |
| 75 | 111 | 151 | 19 |

"Apples to Apples" – HR Piez. with MIP vs. Wells, Aq. Tests, Samples
10 Locations/30 Wells

# FUTURE PLANS

Tech Transfer
- Industry Licensing (AMS/ENVI - Market Ready by September '09)
- ITRC Guidance (Flux Methods – First Draft by September '09)
- ASTM D6067

Final Reports
- Final:
  (*http://www.clu-in.org/s.focus/c/pub/i/1558/*)
- Cost and Performance:
  (*http://costperformance.org/monitoring/pdf/Char_Hyd_Assess_Piezocone_ESTCP.pdf)*

"Single Mobilization Solution" Integration
- Expedited Chem/Hydro Characterization/Modeling
- Expedited LTM Network Design
- Sensor Deployment
- Automated Remediation Performance via Flux

## CONTAMINANT FLUX MONITORING STEPS

(Remediation Design/Effectiveness)

- Generate Initial Model (Seepage Velocity, Concentration Distributions)
  - Conventional Approaches
  - High-Resolution Piezocone/MIP
- Install Customized 3D Monitoring Well Network
  - ASTM
  - Kram and Farrar Method
- Monitor Water Level and Concentrations (Dynamic/Automate?)
- Track Flux Distributions (3D, Transects)
- Evaluate Remediation Effectiveness
  - Plume Status (Stable, Contraction, etc.)
  - Remediation Metric
  - Regulatory Metric?

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# EXPEDITED FLUX APPROACH
"Single Mobilization Solution"

Plume Delineation
- MIP, LIF, ConeSipper, Waterloo$^{APS}$, Field Lab, etc.
- 2D/3D Concentration Representations

Hydro Assessment
- High-Res Piezocone (2D/3D Flow Field, K, head, eff. por.)

LTM Network Design
- Well Design based on CPT Data
- Field Installations (Clustered Short Screened Wells)

Surveys (Lat/Long/Elevation)

GMS Interpolations ($\nu$, F), Conceptual/Analytical Models

LTM Flux Updates via Head/Concentration
- Conventional Data
- Automated Modeling

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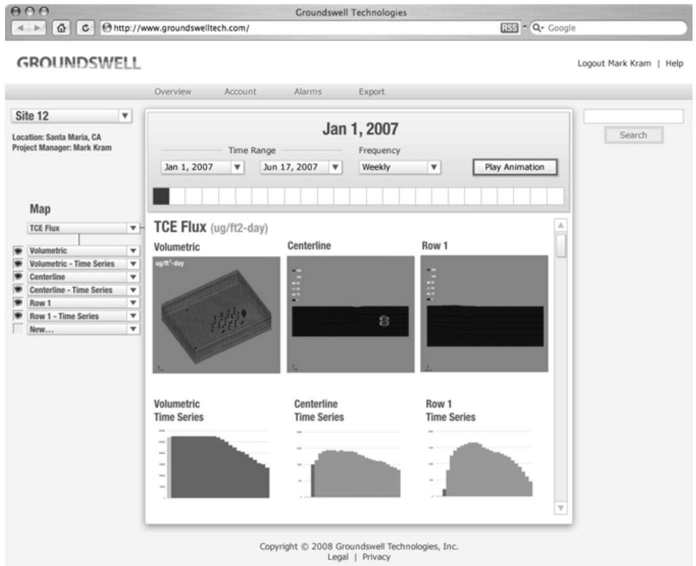
# Conceptual / Analytical Model

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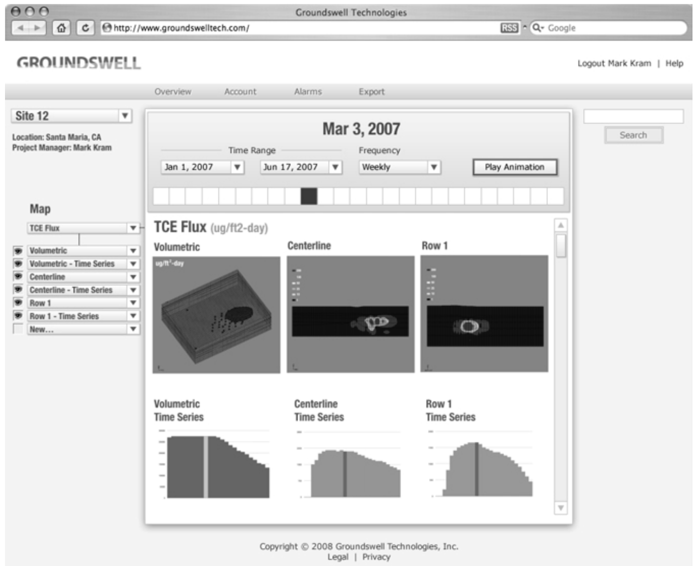
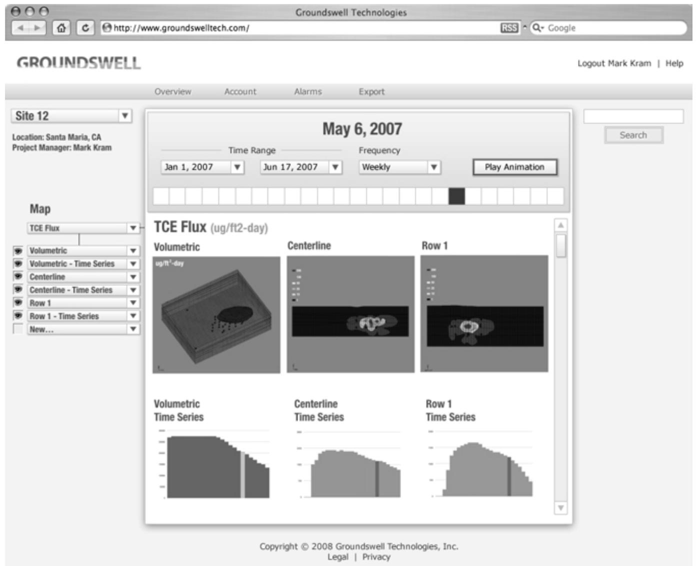
# Conceptual / Analytical Model



# Conceptual / Analytical Model

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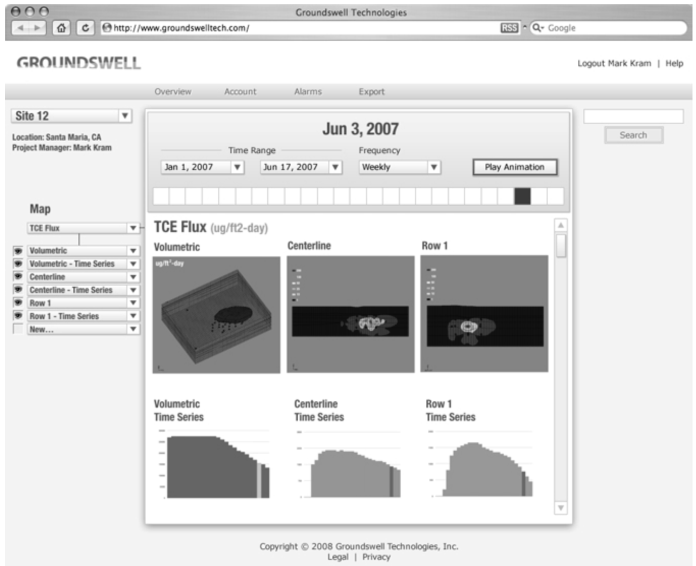
# Conceptual / Analytical Model



## CONCLUSIONS

- High-Res Piezocone Preliminary Results Demonstrate Good Agreement with Short-Screened Well Data
- Highly Resolved 2D and 3D Distributions of Head, Gradient, K, Effective Porosity, and Seepage Velocity Now Possible Using HRP and GMS
- When Know Concentration Distribution, 3D Distributions of Contaminant Flux Possible Using DP and GMS
- Single Deployment Solutions Now Possible
- Exceptional Capabilities for Plume “Architecture” and Monitoring Network Design
- Significant Cost Saving Potential
- New Paradigm - LTM and Remediation Performance Monitoring via Sensors and Automation (4D)

## ACKNOWLEDGEMENTS

SERDP – Funded Advanced Fuel Hydrocarbon Remediation National Environmental Technology Test Site (NETTS)

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- Ian Stewart (NFESC)
- Alan Vancil (SWDIV)
- Dan Eng (US Army)
- Tom Dalzell (AMS)
- Per Ljunggren (ENVI)


THANK YOU!
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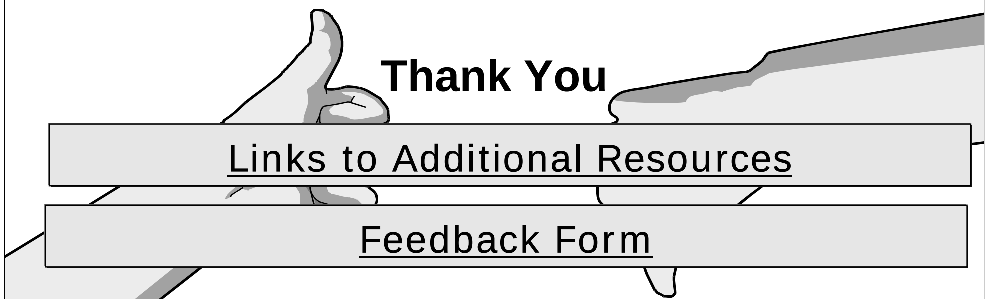
208-408-1612

# Thank You

After viewing the links to additional resources, please complete our online feedback form.




Links to Additional Resources

Feedback Form