Novel Methods for Developing Process-Based Conceptual Site Models for Bedrock Groundwater:

from Remediation to Resource Protection

Dr. Beth Parker

Professor, School of Engineering

Director, Morwick G360 Groundwater Research Institute

University of Guelph

Tage Erlander Visiting Professor, Lund University

ATV Soil and Groundwater Winter Conference

March 9, 2022

Tage Erlander Visiting Professorship
to Beth Parker 2022-23

Tage Erlander, 1949

This professorship was created in 1981 to mark the eightieth birthday of the late Mr. Tage Erlander, who was the Swedish Minister of Education 1945-1946 and then Prime Minister 1946-1969.

Awarded annually to an internationally prominent researcher in natural and engineering sciences.

The professorship is meant to contribute to the Swedish research community through visits to build lasting scientific networks.

Swedish Research Council

LUND UNIVERSITY

Tage Erlander Host Institutions

for Beth Parker, Contaminant Hydrogeology 2022-23

Lunds universitet – Charlotte Sparrenbom, Kenneth Persson/Cintia Bertacchi Uvo, Catherine Paul, Torleif Dahlin, Gerhard Barmen, Jan-Erik Rosberg, Maria Hansson

Sveriges Geologiska Undersökning – Erik Bergstedt

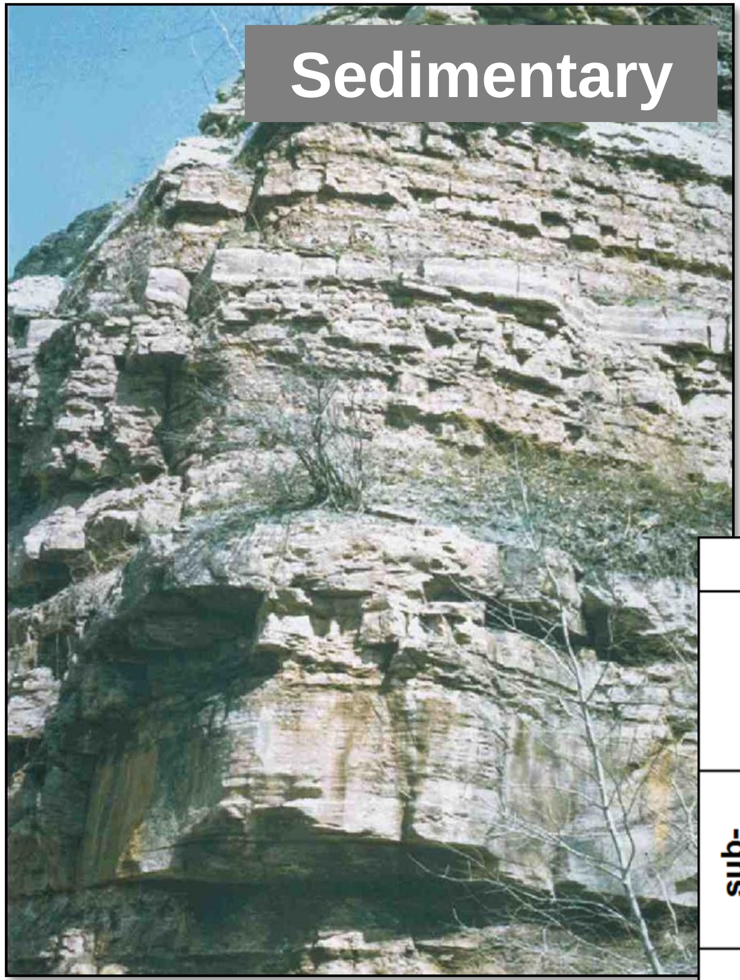
Göteborgs universitet – Philipp Wanner

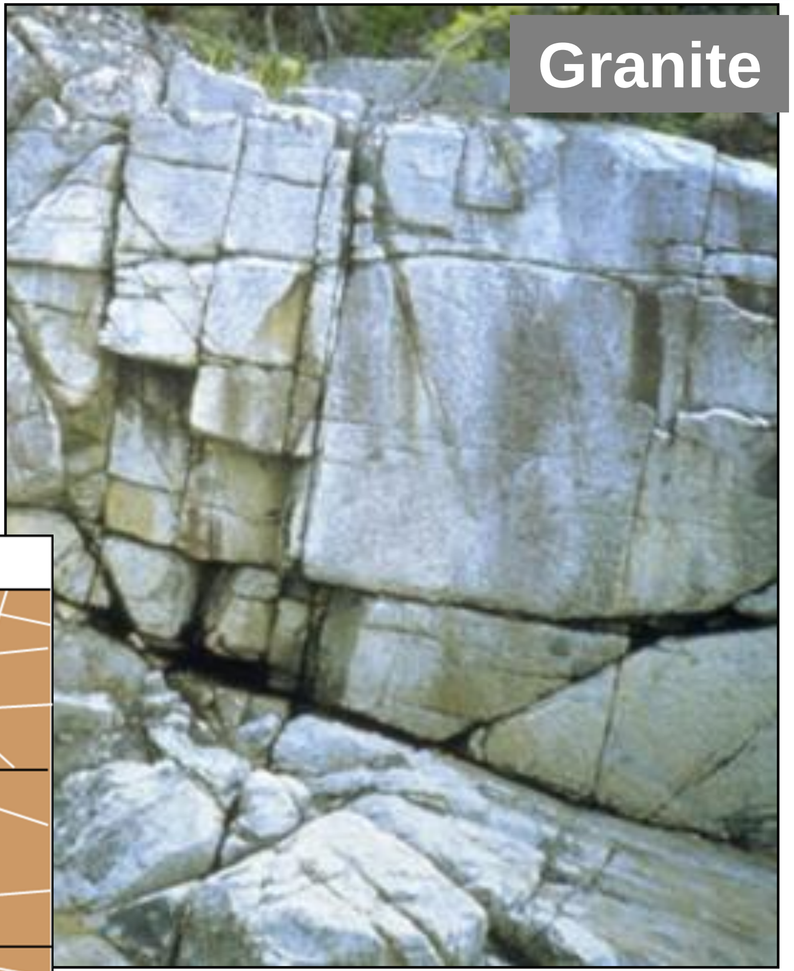
Danmarks Tekniske Universitet – Mette Broholm

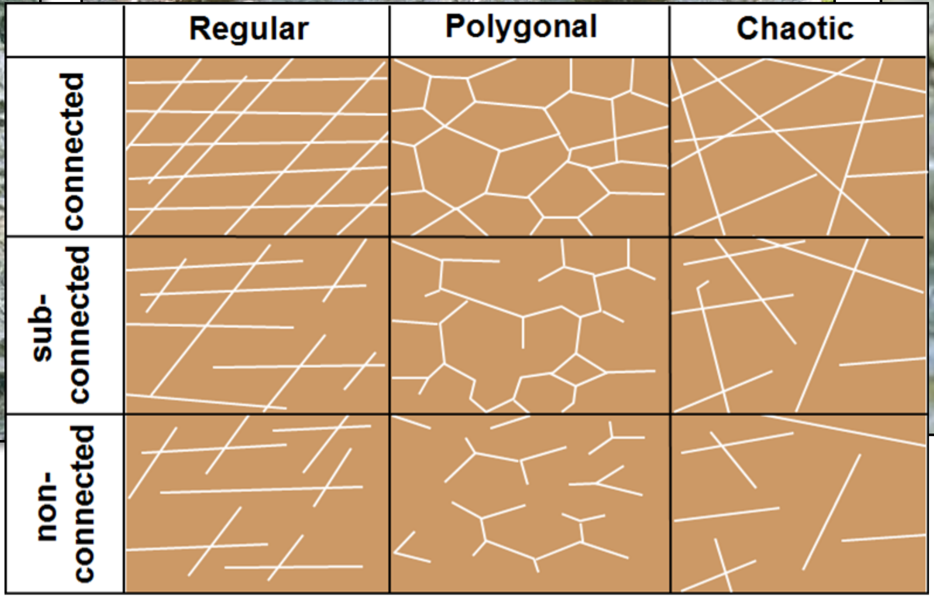
Uppsala universitet – Fritjof Fagerlund

Chalmers tekniska högskola – Jenny Norrman and Lars Rosen

Types of Fractured Rocks







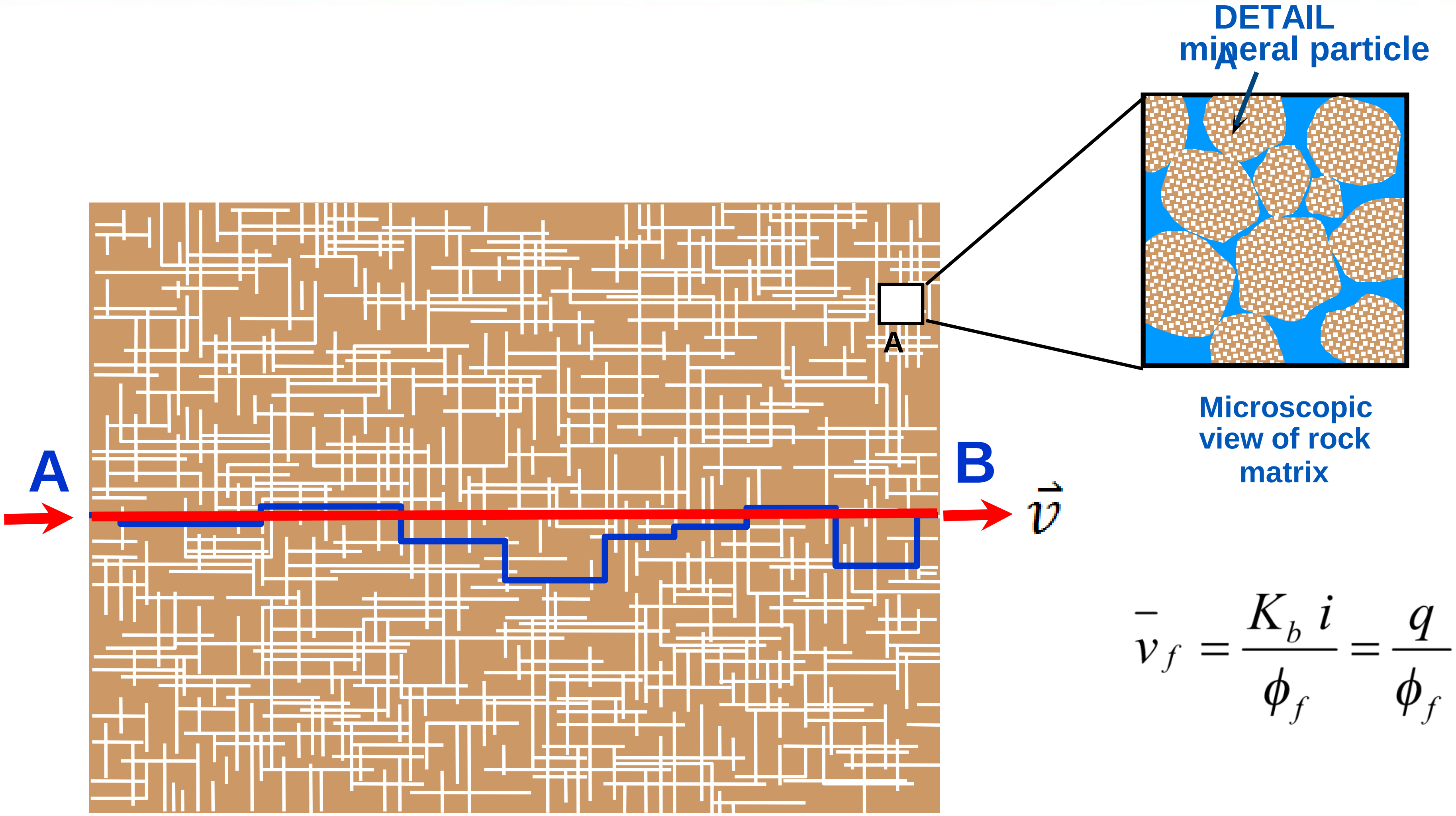
(From Chernyshev and Dearman, 1991)

Fractured Rock Hydrogeology is Challenging

"Among the current problems that hydrogeologists face, perhaps there is none as challenging as the characterization of fractured rock." – Neuman (2005)

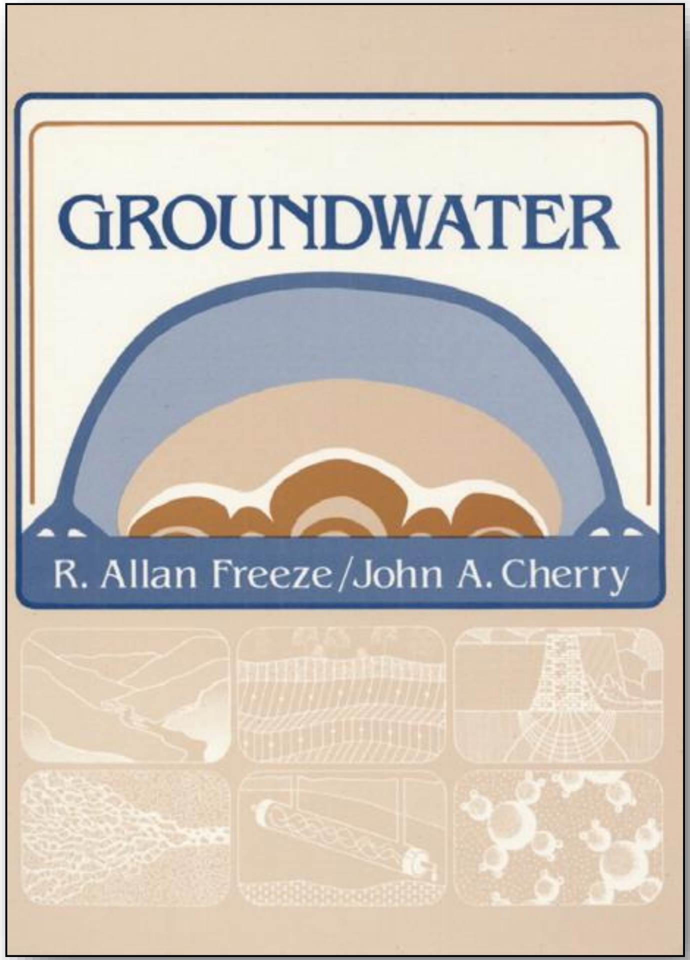
"… one must generally account for the highly erratic heterogeneity, directional dependence, dual or multi-component nature and multiscale behaviour of fractured rocks."

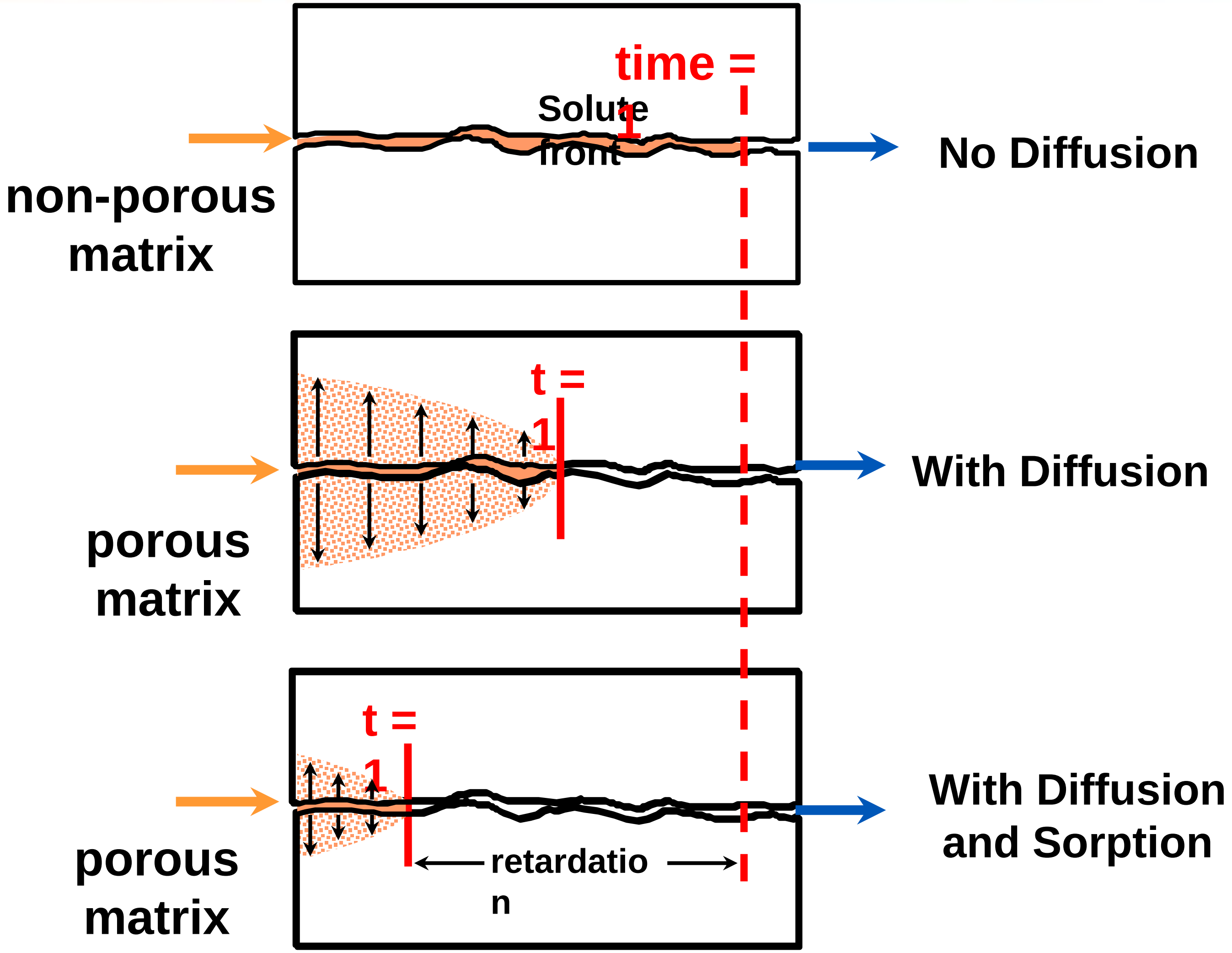
Groundwater Travel Time: Average Linear Groundwater Velocity



$$\bar{v}_f = \frac{K_b\, i}{\phi_f} = \frac{q}{\phi_f}$$

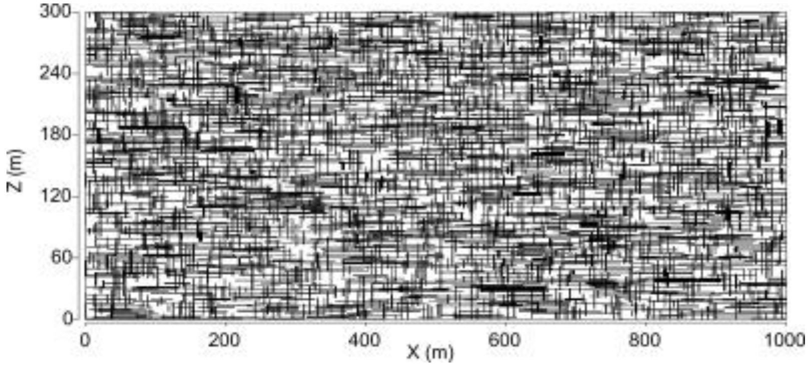
Plume Front Retardation due to Matrix Diffusion and Sorption

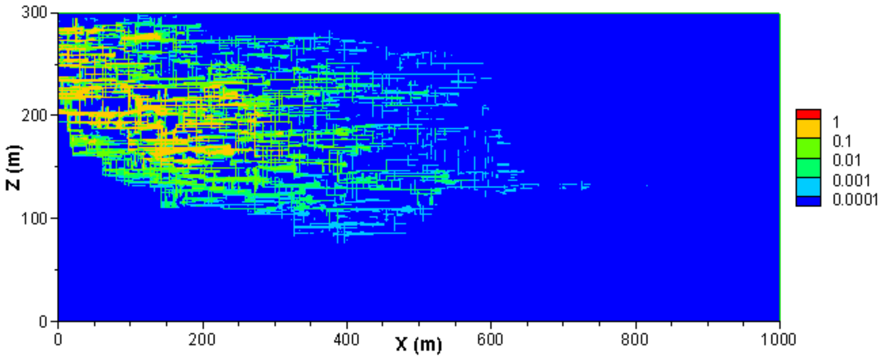




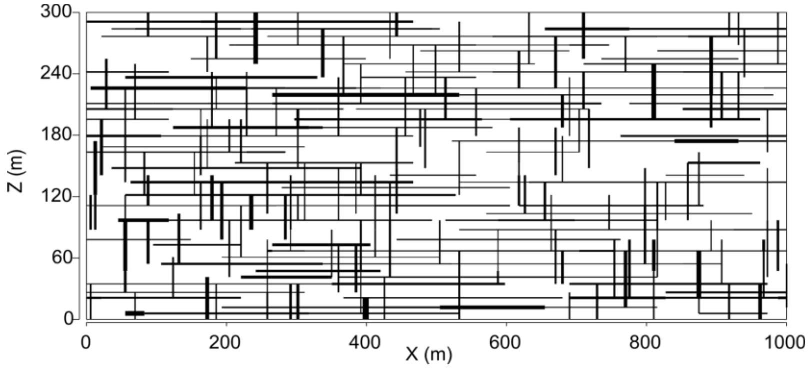
Interplay Between Matrix and Fractures Controls Plume Behavior (time of arrival & flux)

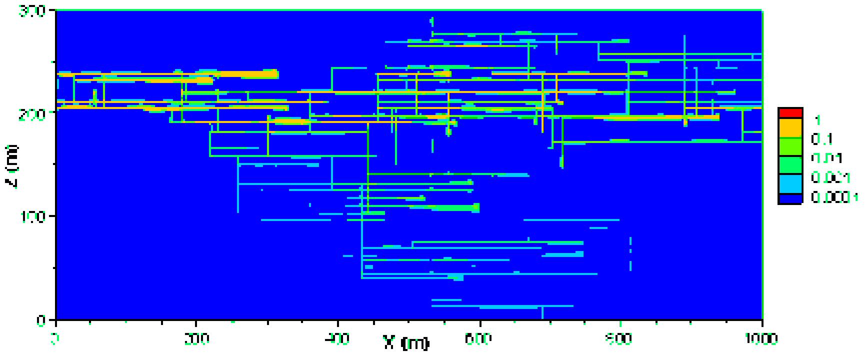
Dense Network





Sparse Network



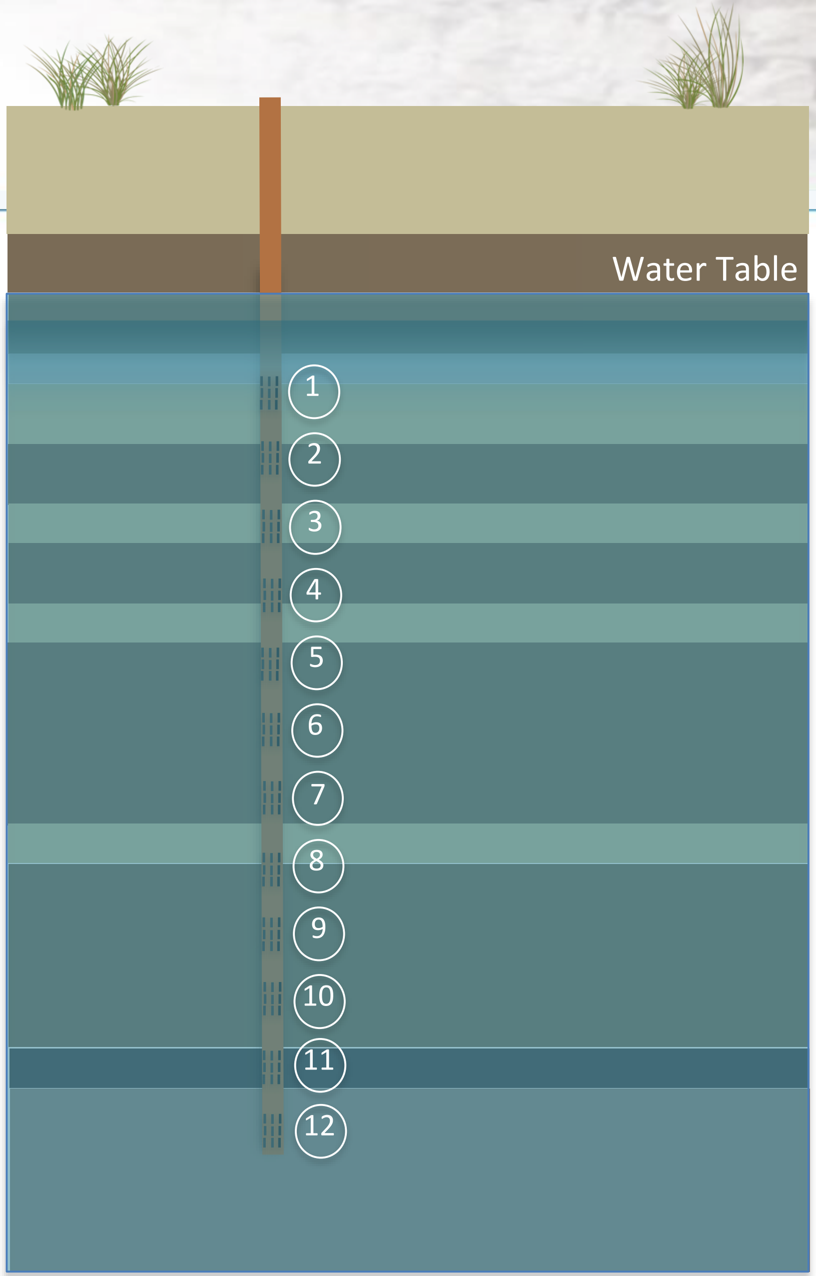


Same bulk K but very **different mass distributions**

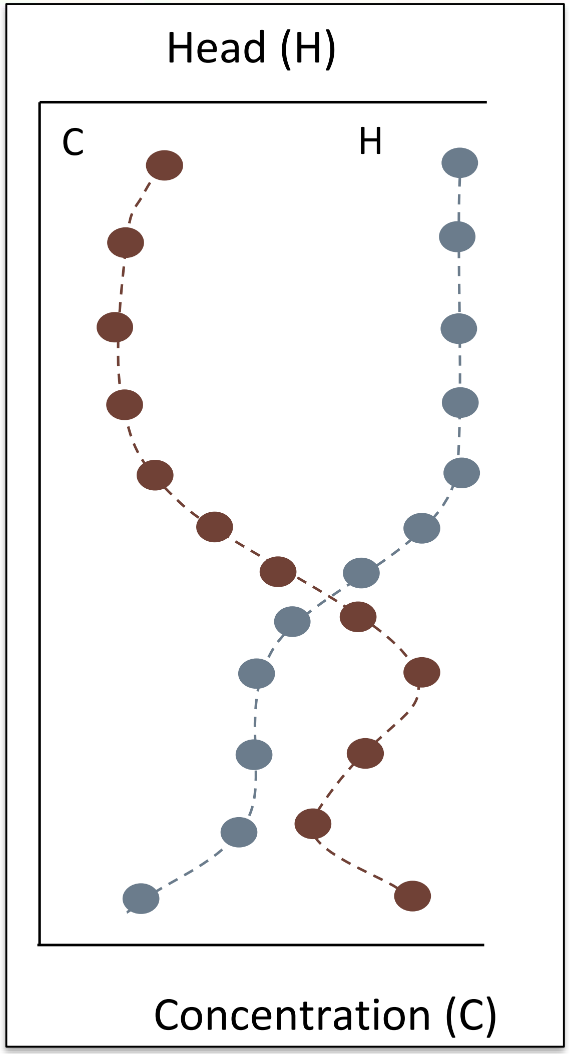
Not all Fractures are Active

- Several fracture types observed
- Some are closed, or not connected
- Different apertures, lengths, connectivity, & transmissivities

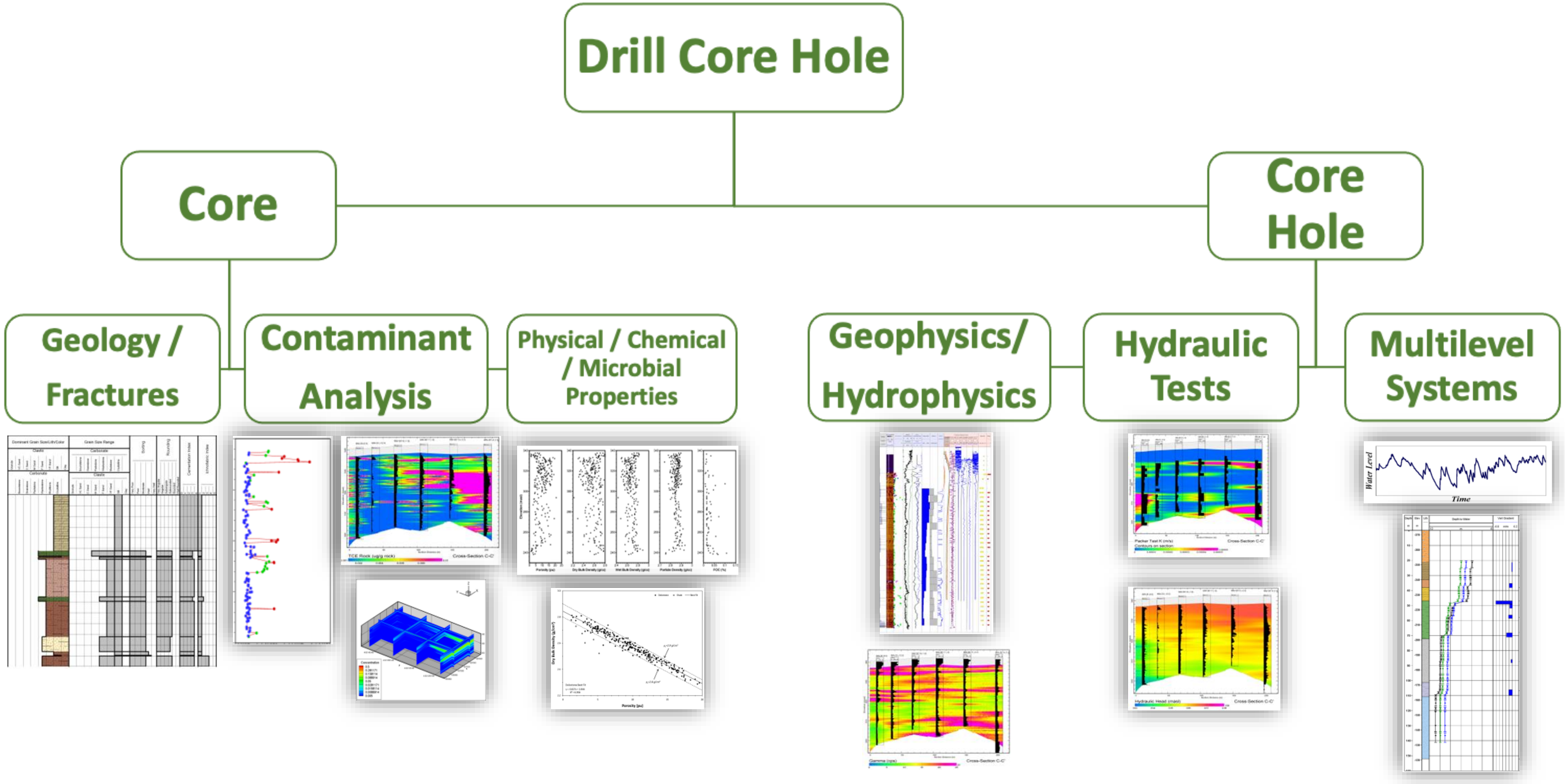
Depth-Discrete Profiles from Drilled Holes



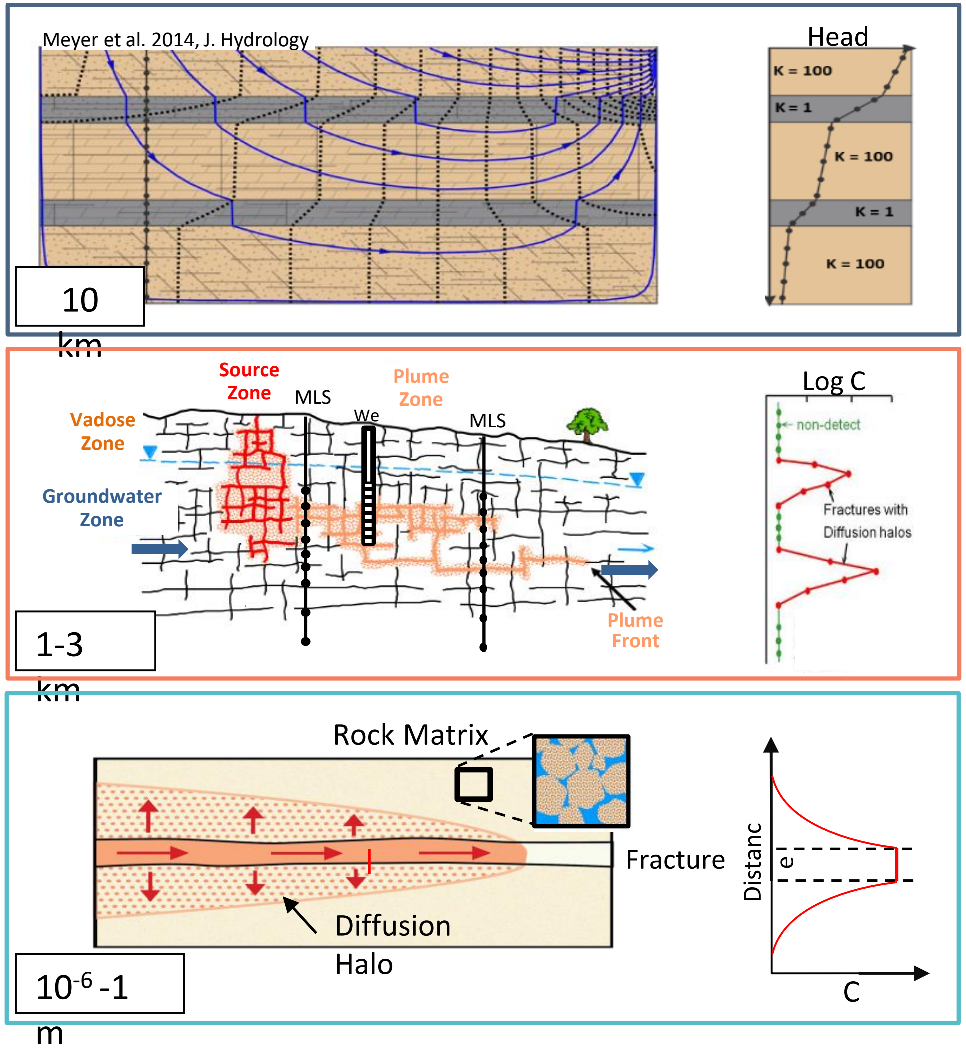
High Resolution MLS



Multi-Disciplinary Data Sets for Building Process-Based CSMs



Conceptual Site Models: A Multi-Scale Challenge



WATERSHED SCALE

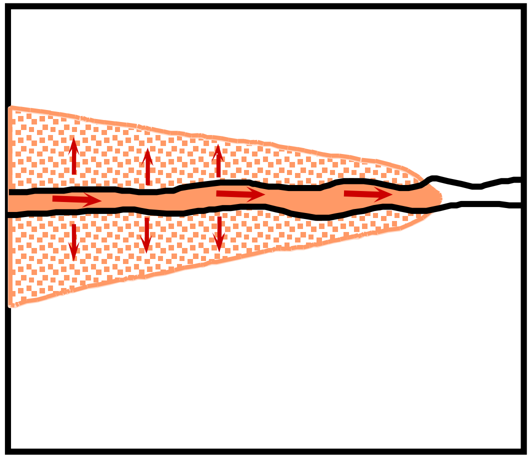
PLUME SCALE

BOREHOLE TO PORE SCALE

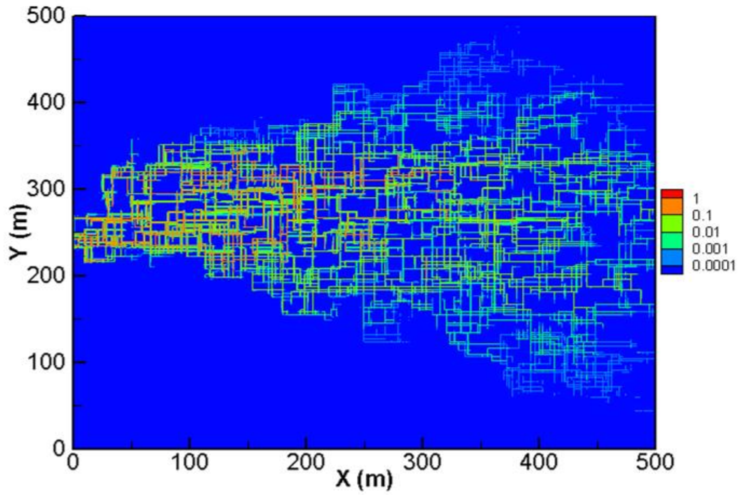
Transport & Reaction Processes in Bedrock Flow Systems:

- Advection
- Diffusion
- Apparent Dispersion
- Sorption (partitioning, reversible)
- Reactions (i.e. abiotic or biotic degradation, redox)

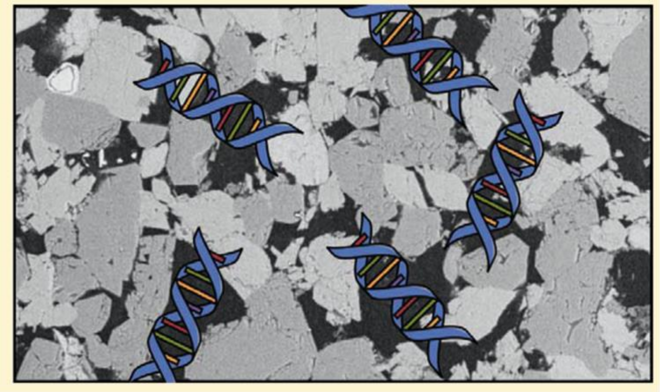
Fracture-Matrix



Plume Scale



Pore Space



What makes a CSM ‘Process-Based’?

It’s more than a simple sketch or diagram

2000

United States Environmental Protection Agency | Office of Environmental Information Washington, DC 20460 | EPA/600/R-00/007 January 2000

EPA

Data Quality Objectives Process for Hazardous Waste Site Investigations

2011

United States Environmental Protection Agency | Office of Solid Waste and Emergency Response (5102G) | EPA 542-F-11-011 July 2011

Environmental Cleanup Best Management Practices: Effective Use of the Project Life Cycle Conceptual Site Model

2014

ASTM INTERNATIONAL

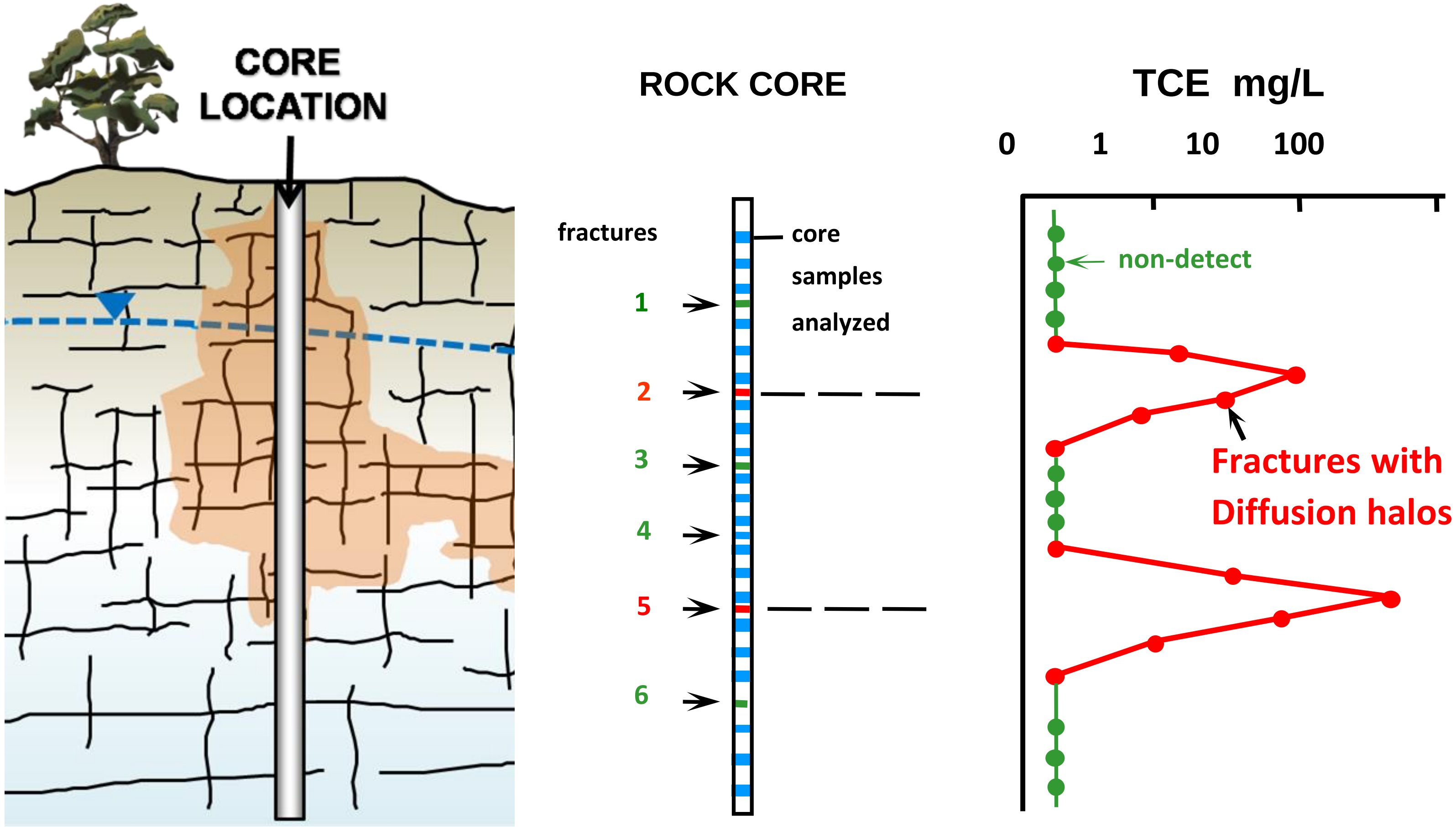
Designation: E1689 – 95 (Reapproved 2014)

Standard Guide for Developing Conceptual Site Models for Contaminated Sites[1]

This standard is issued under the fixed designation E1689; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

- **Acquire data at scale appropriate for process understanding**
- **To inform conceptual and numerical models that are <u>predictive</u>**

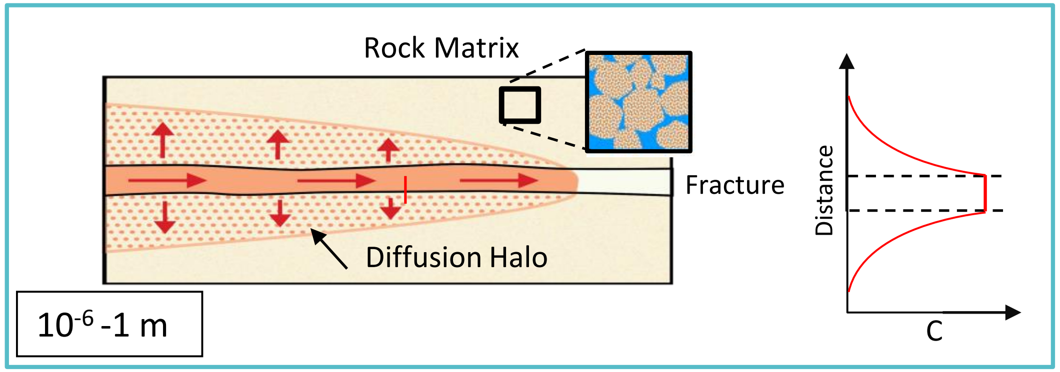
What do we mean by High Resolution?



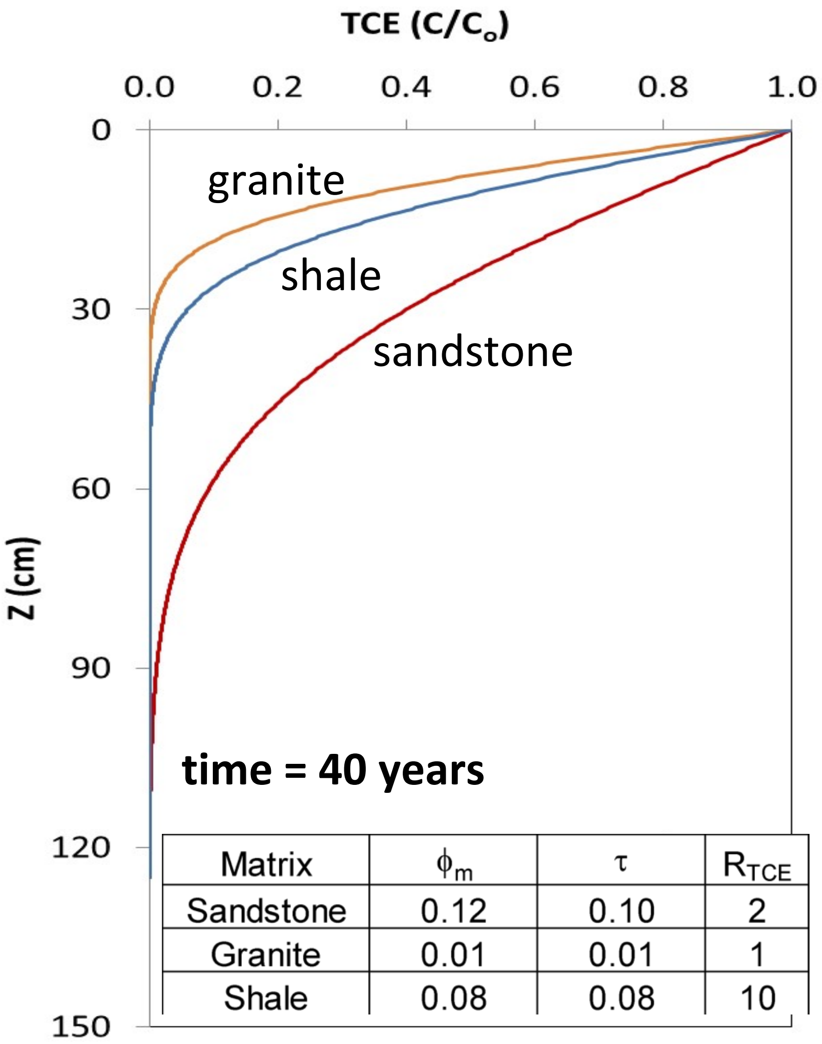
Adapted to site conditions

- Rock and matrix properties
- Contaminant and reactions
- Age of contamination

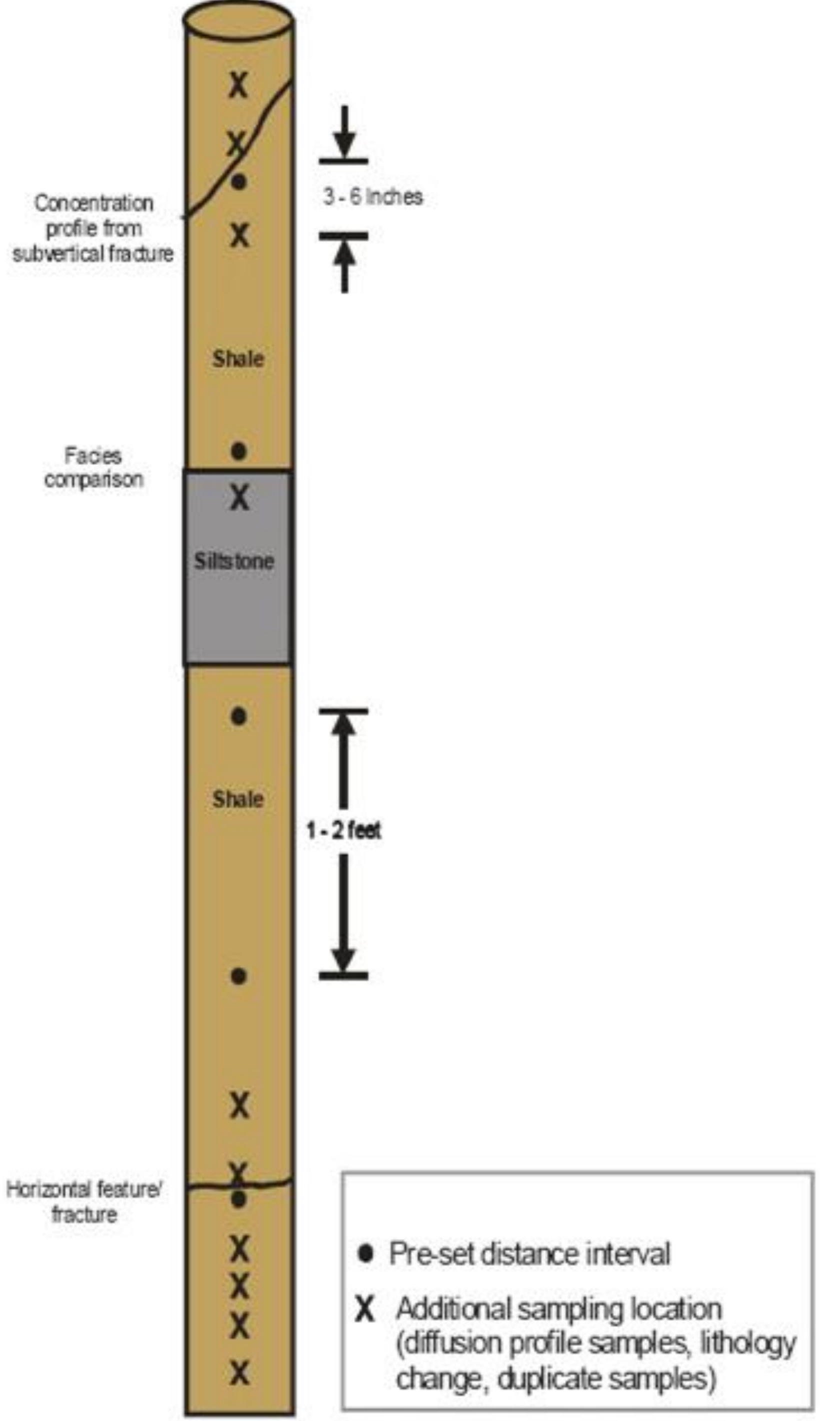
Diffusion Profiles Off Fractures



TCE, Different Lithologies



Matrix	ϕ_m	τ	R_{TCE}
Sandstone	0.12	0.10	2
Granite	0.01	0.01	1
Shale	0.08	0.08	10



Adaptive Rock Core Sampling Strategy

Contaminant Samples

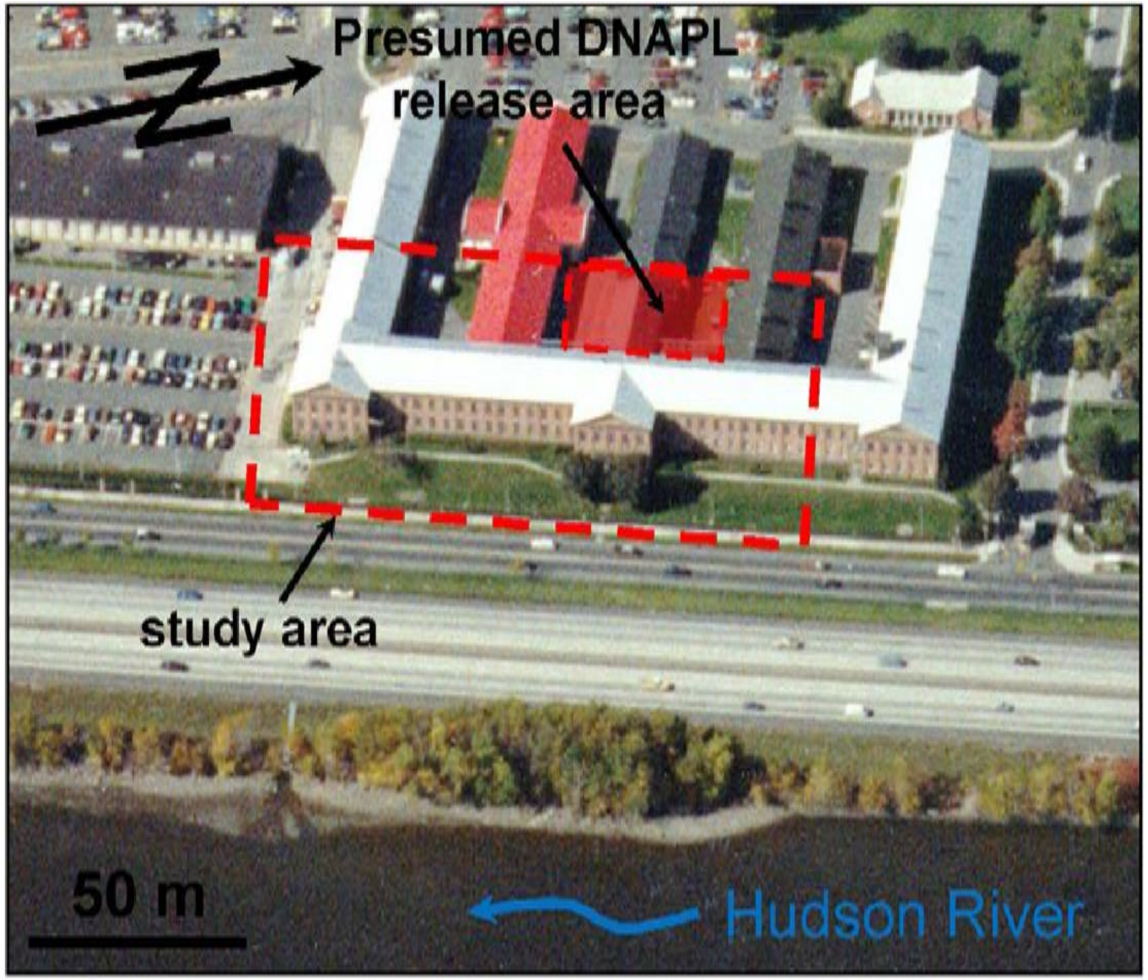
- Fracture surfaces
- Rock matrix off fractures
- Lithology changes
- Other special features

Rock properties

- φ_m, K_m, f_{oc}, mineralogy
- CSIA, DNA,
- Estimating porewater concentrations

Watervliet Arsenal,
PCE Contaminated Site near Hudson River

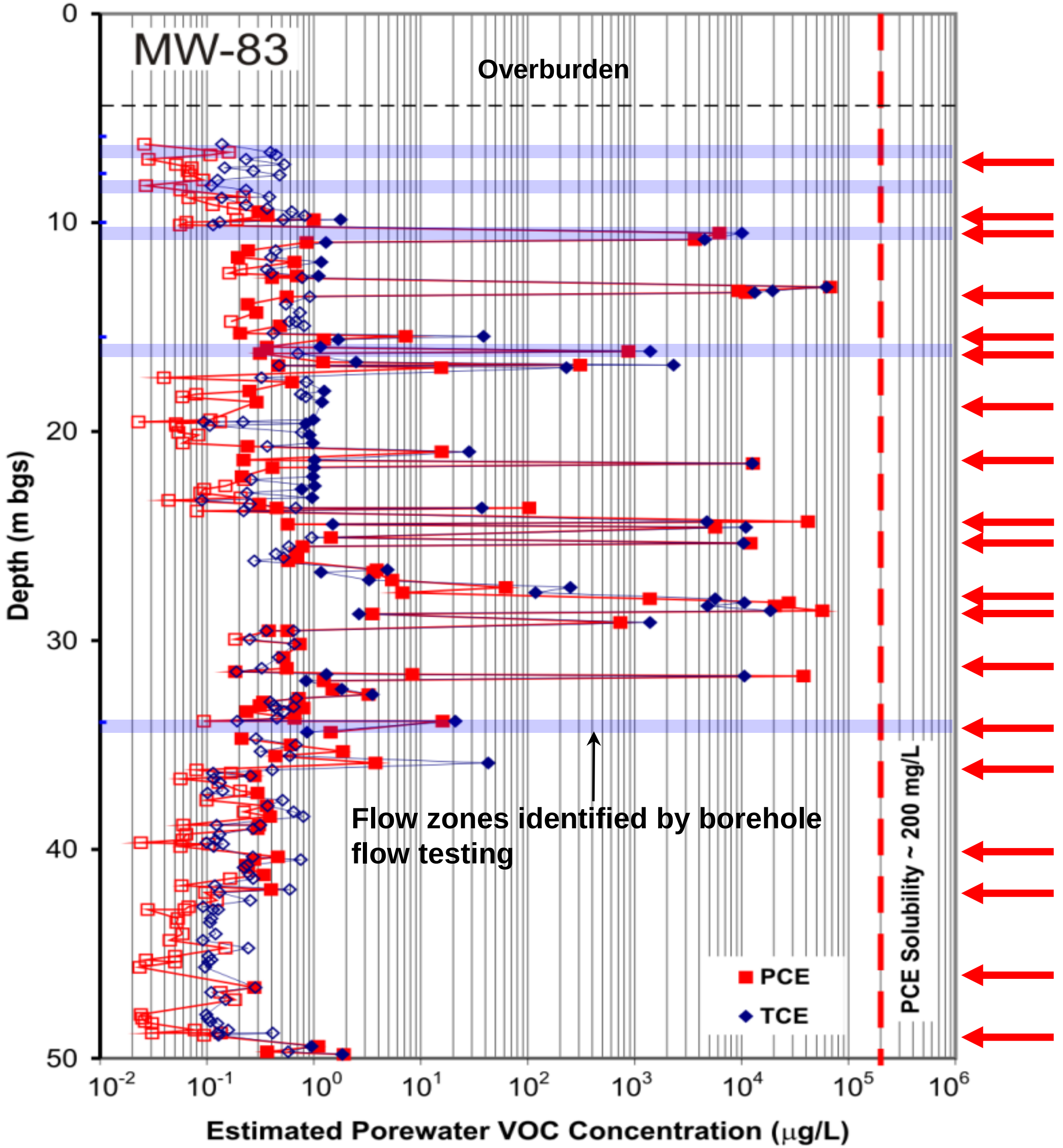
(a)



(b)

Shale

Mass Distribution in Shale (Watervliet Arsenal, NY)



Hydrogeophysical tests suggest few major flow zones

Rock core indicates many transport pathways

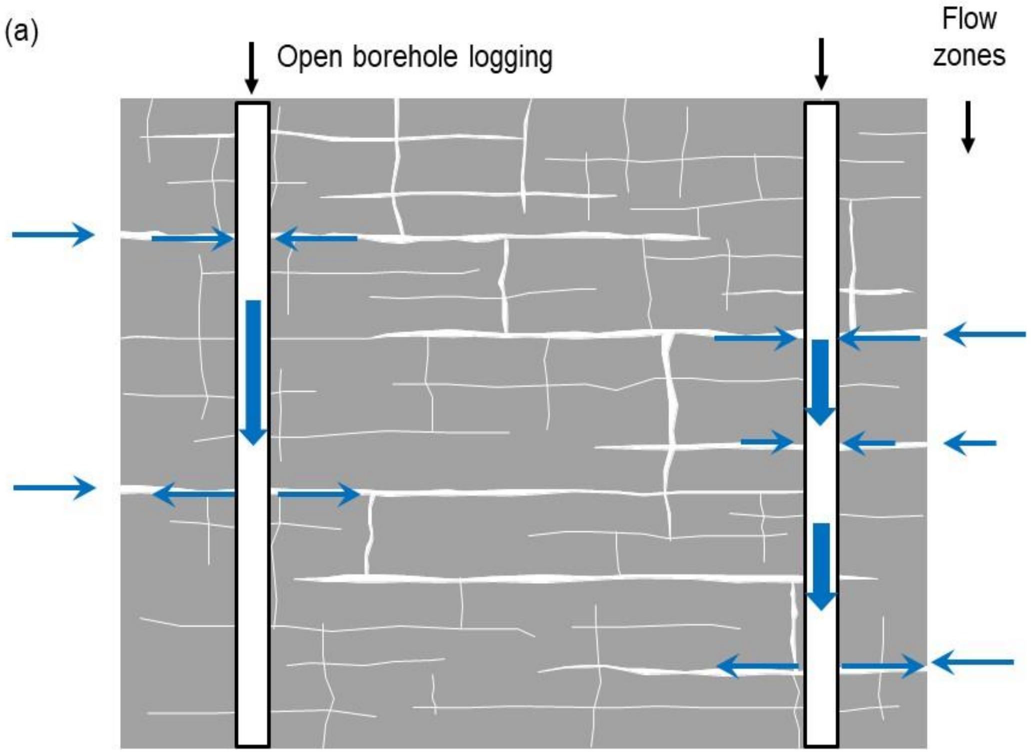
FLOW ZONE VIA OPEN HOLE FLOW LOGGING

VOC PATHWAY FROM ROCK CORE SAMPLING

Parker et al. (2018)

Two Contrasting Fracture Network Conceptual Models

Sparse Network



Journal of Hydrology

ELSEVIER

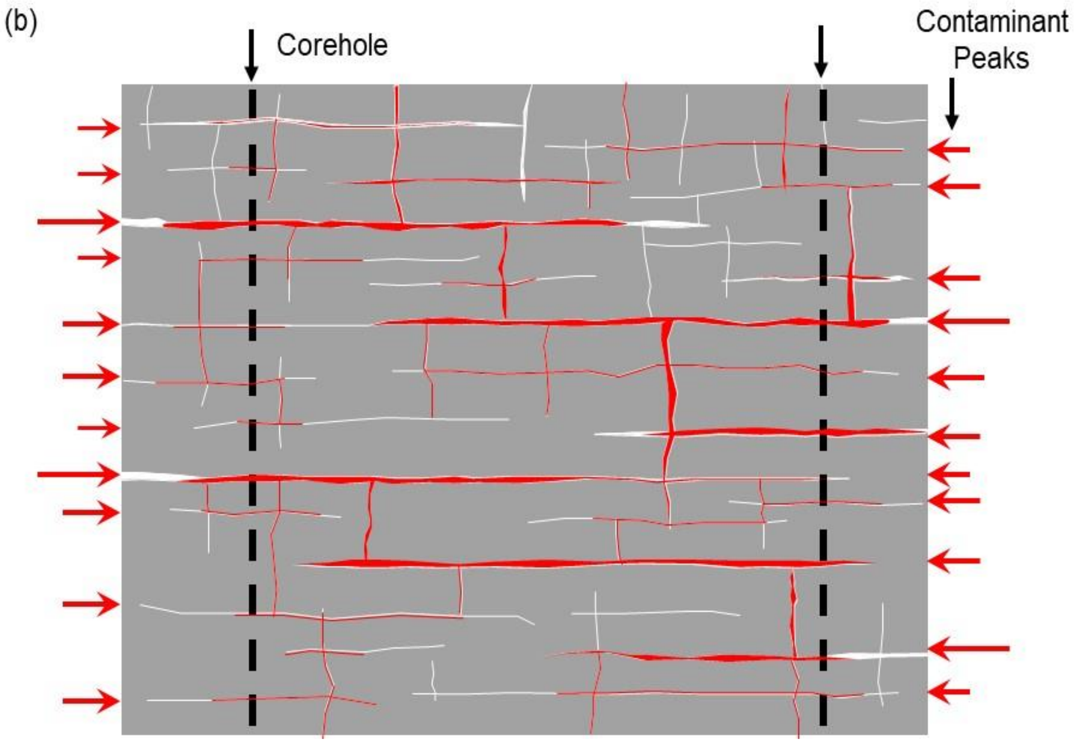
Journal of Hydrology 265 (2002) 100–117

www.elsevier.com/locate/jhydrol

Using flowmeter pulse tests to define hydraulic connections in the subsurface: a fractured shale example

J.H. Williams[a], F.L. Paillet[b,*]

Dense Network



Multiple lines of field evidence to inform fracture network connectivity at a shale site contaminated with dense non-aqueous phase liquids

Beth L. Parker, Steven W. Chapman, Kenneth J. Goldstein and John A. Cherry

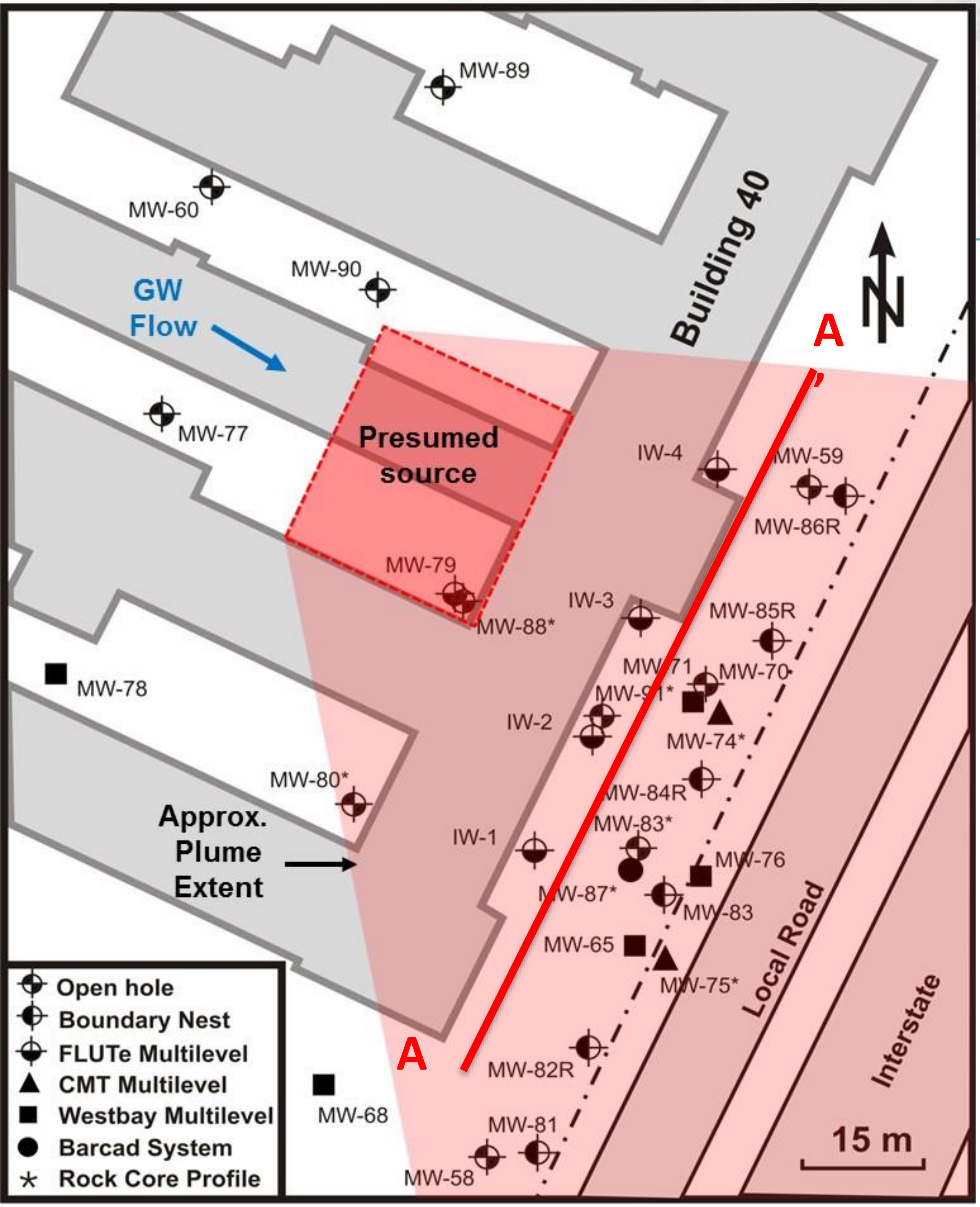
Geological Society, London, Special Publications, 479, 101-127, 17 April 2018, https://doi.org/10.1144/SP479.8

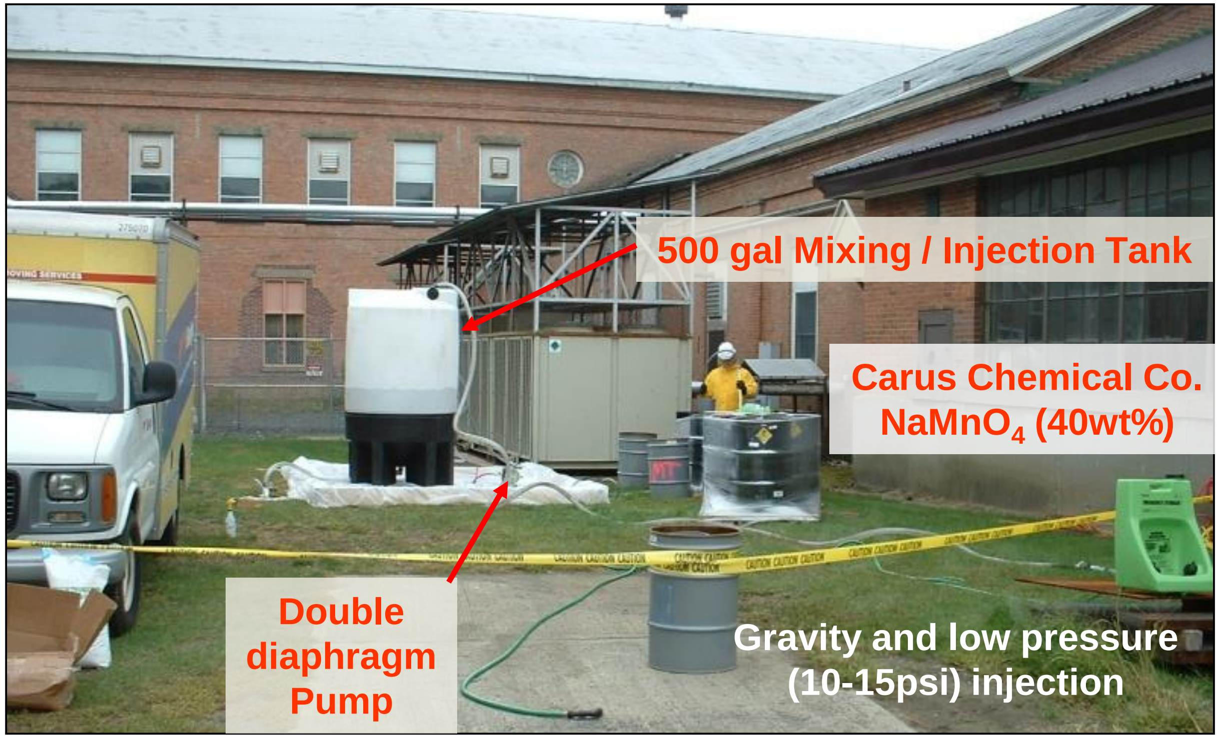
Add to Cart ($35)

The Geological Society

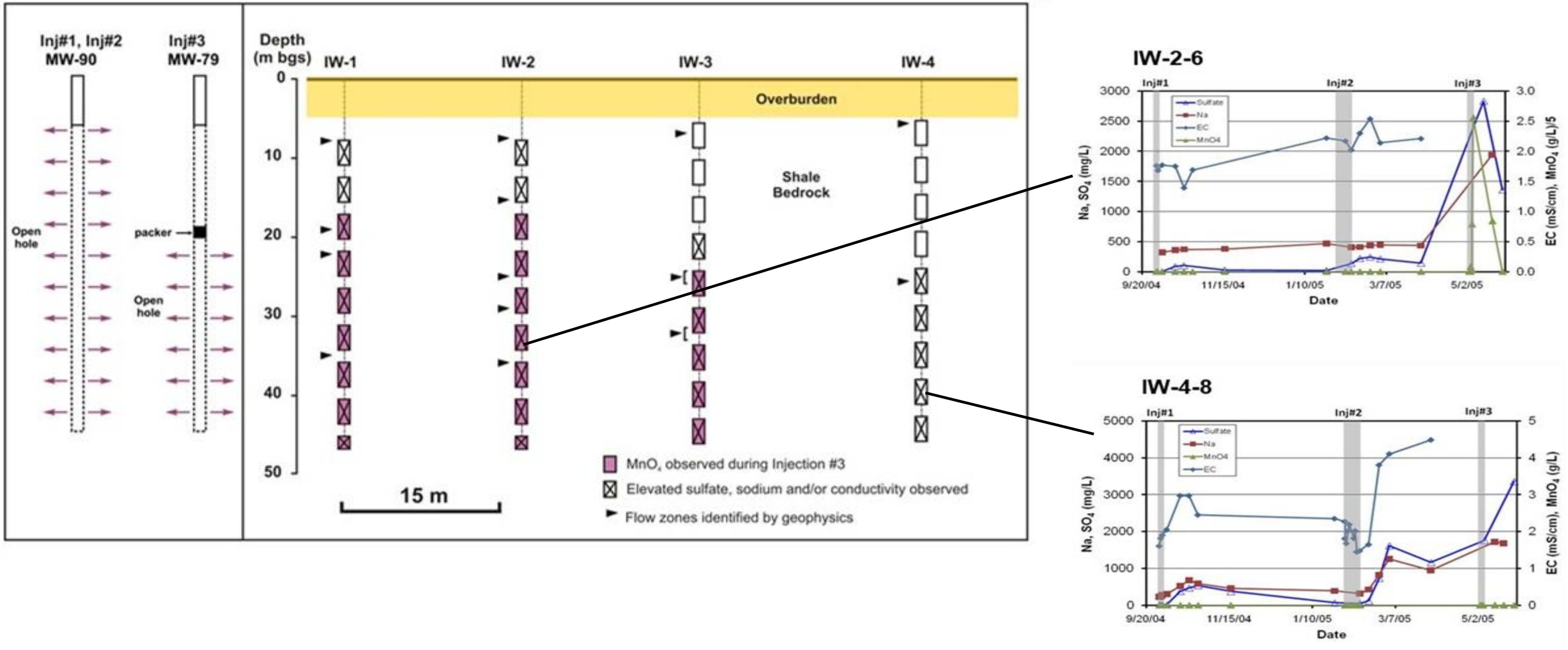
serving science & profession

High Resolution Investigation
ISCO Pilot and Full Scale Injections

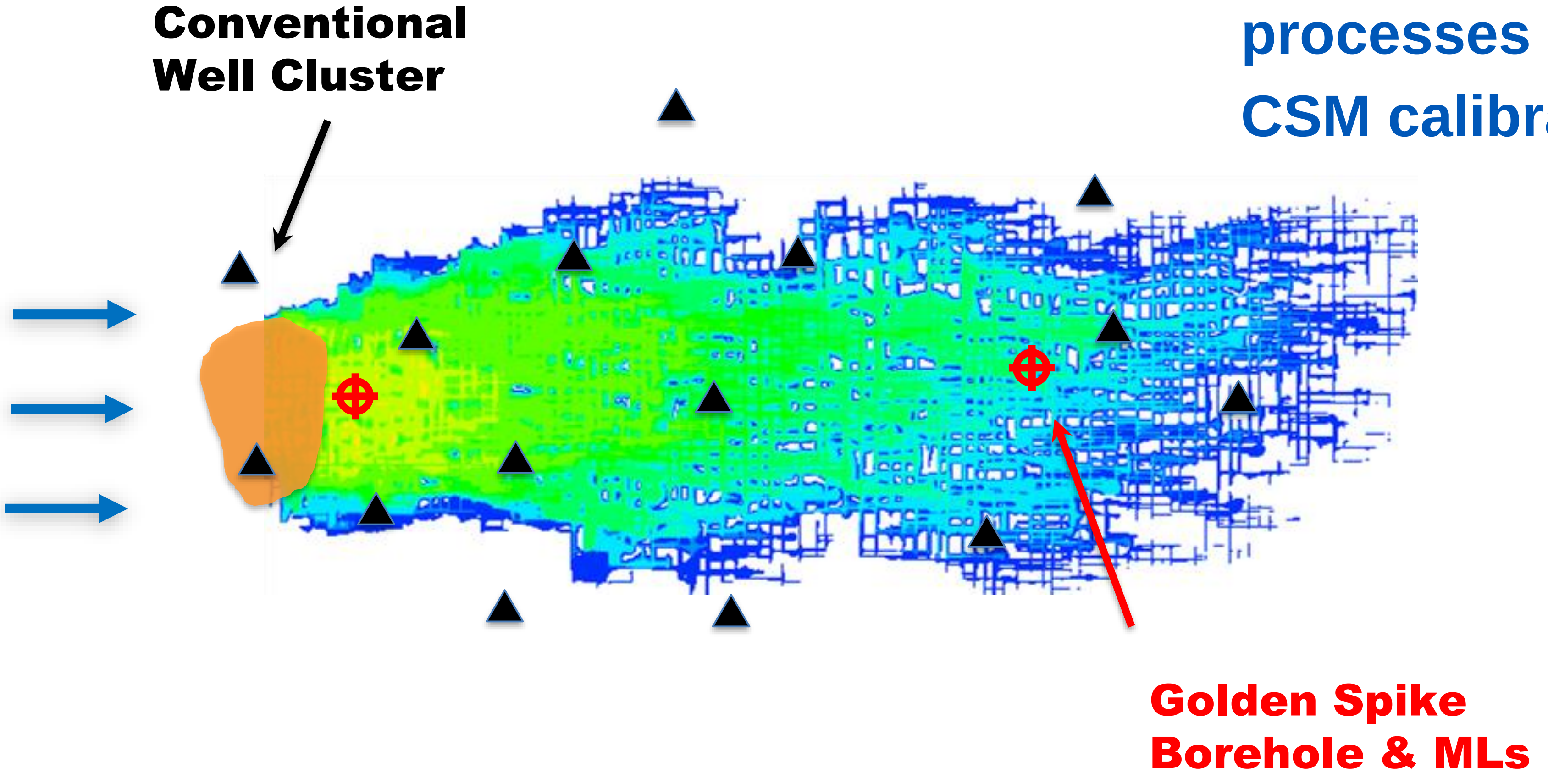




Multilevel Well Monitoring During ISCO Injections Confirm Well-Connected Dense Fracture Network



HRSC at sites with existing characterization "Golden Spike"



Generate field evidence for processes and rates:

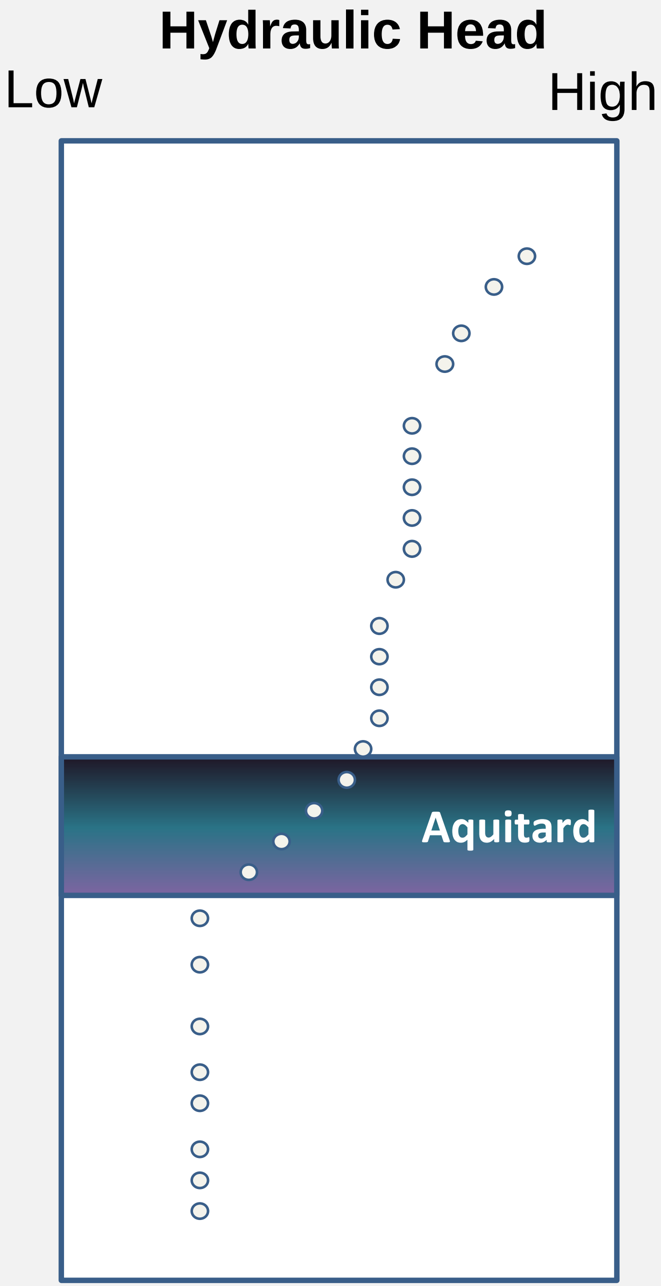
CSM calibration & validation

Basic Principle of Business Management

“You can’t manage what you don’t understand.”

Sparrius, A. (1994). You can't manage what you don't understand. *Project Management Journal, 25*(1), 25–34.

Principles that <u>should</u> underpin an effective Hydrogeology CMS & “world-class” monitoring program

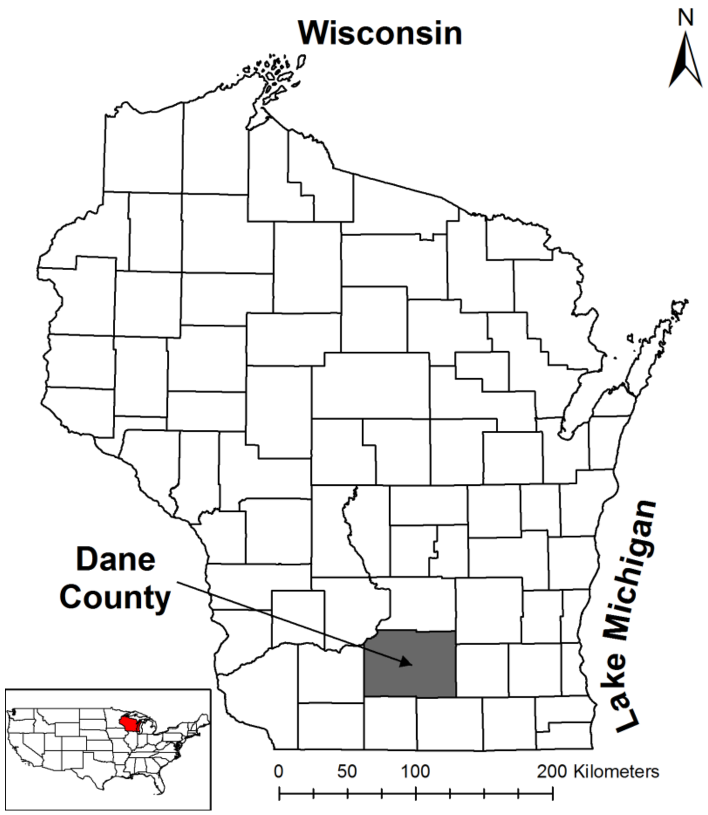


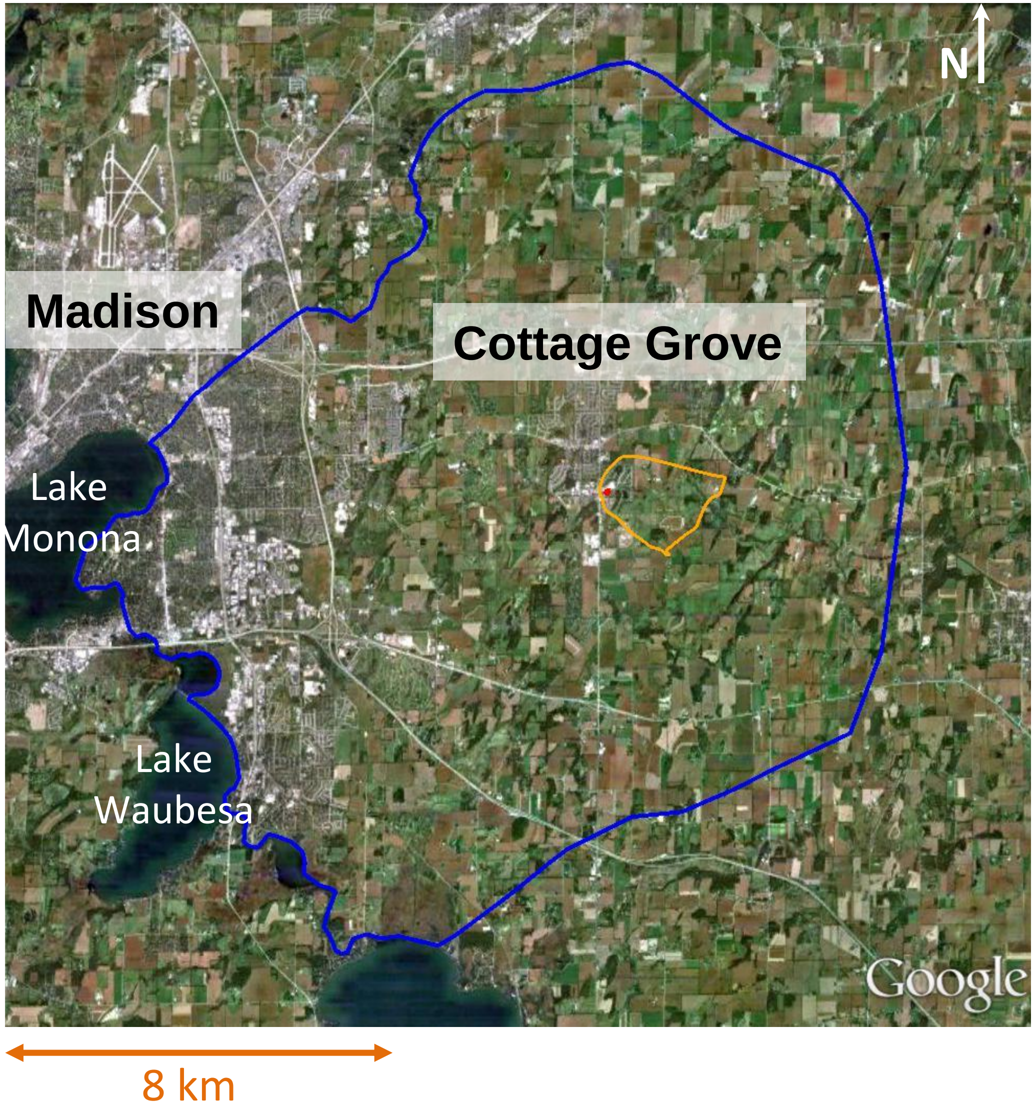
Where are your Aquitards?

Zones causing resistance

to vertical flow between aquifers

Contaminated Sedimentary Rock Site in Southern Wisconsin





DNAPL source zone

Max extent dissolved phase plume

Flow model domain

Detailed Multilevel System as an Experiment

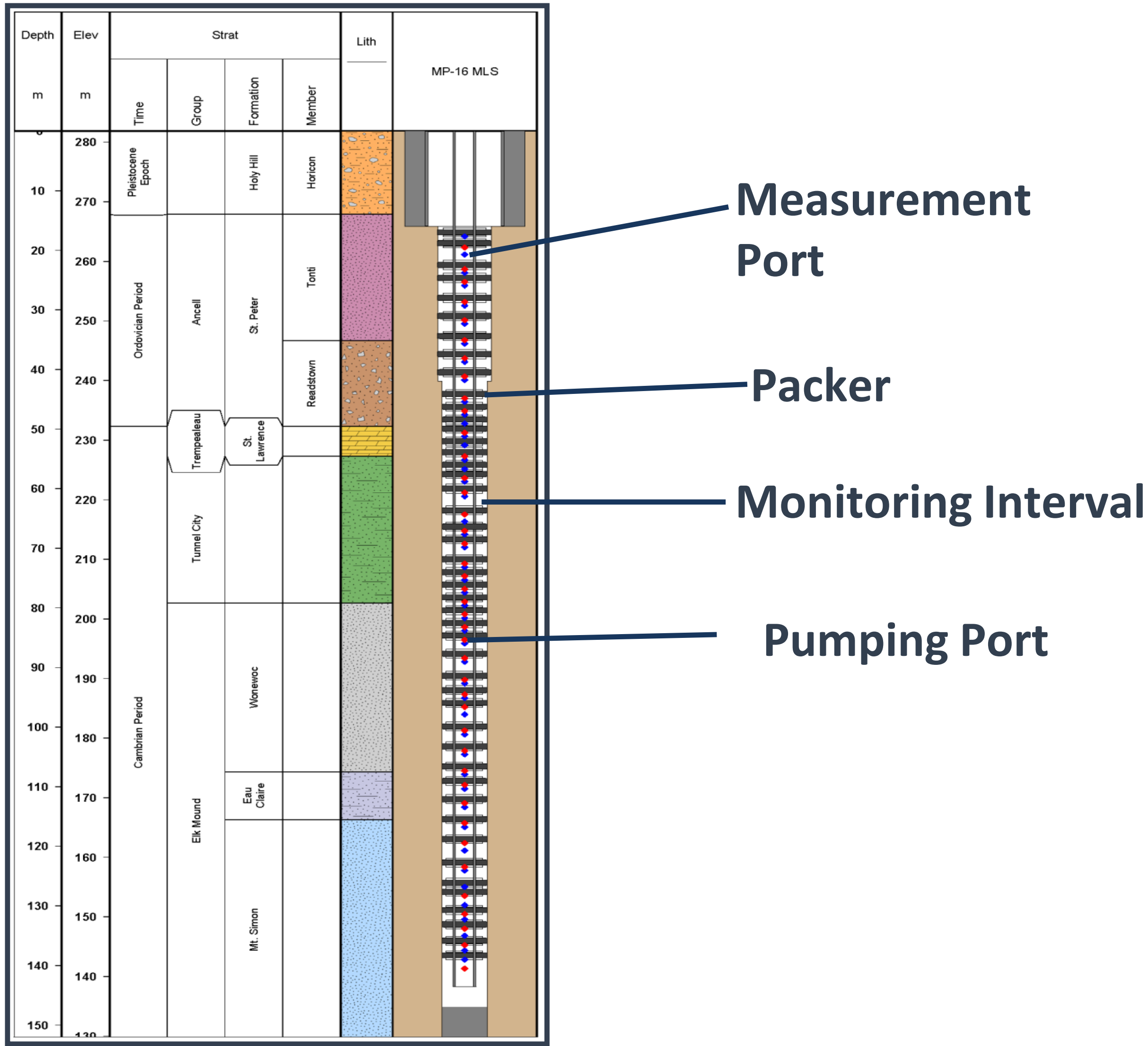
Westbay Instruments

Multilevel System

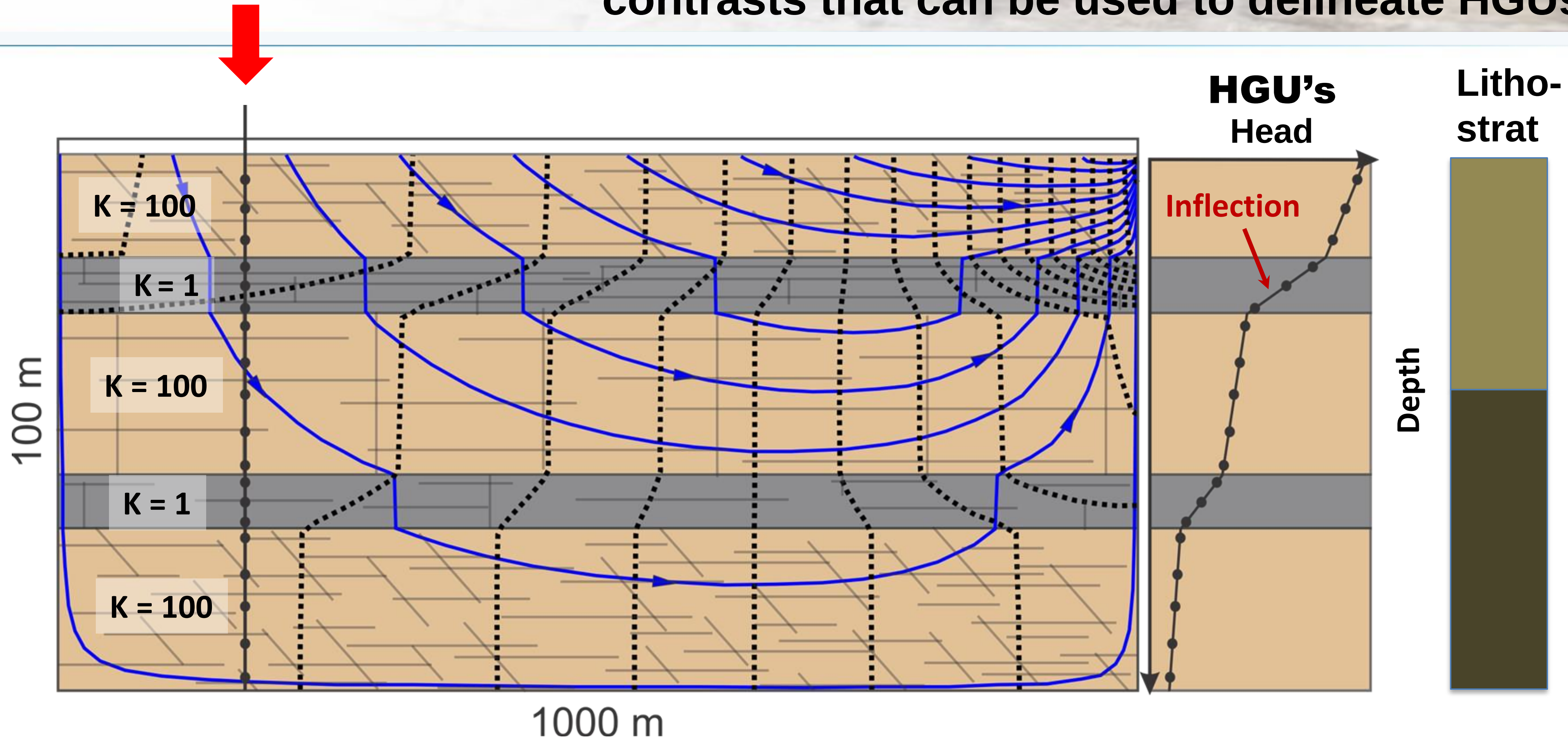
✓monitors 129.5 m of bedrock

✓46 monitoring zones

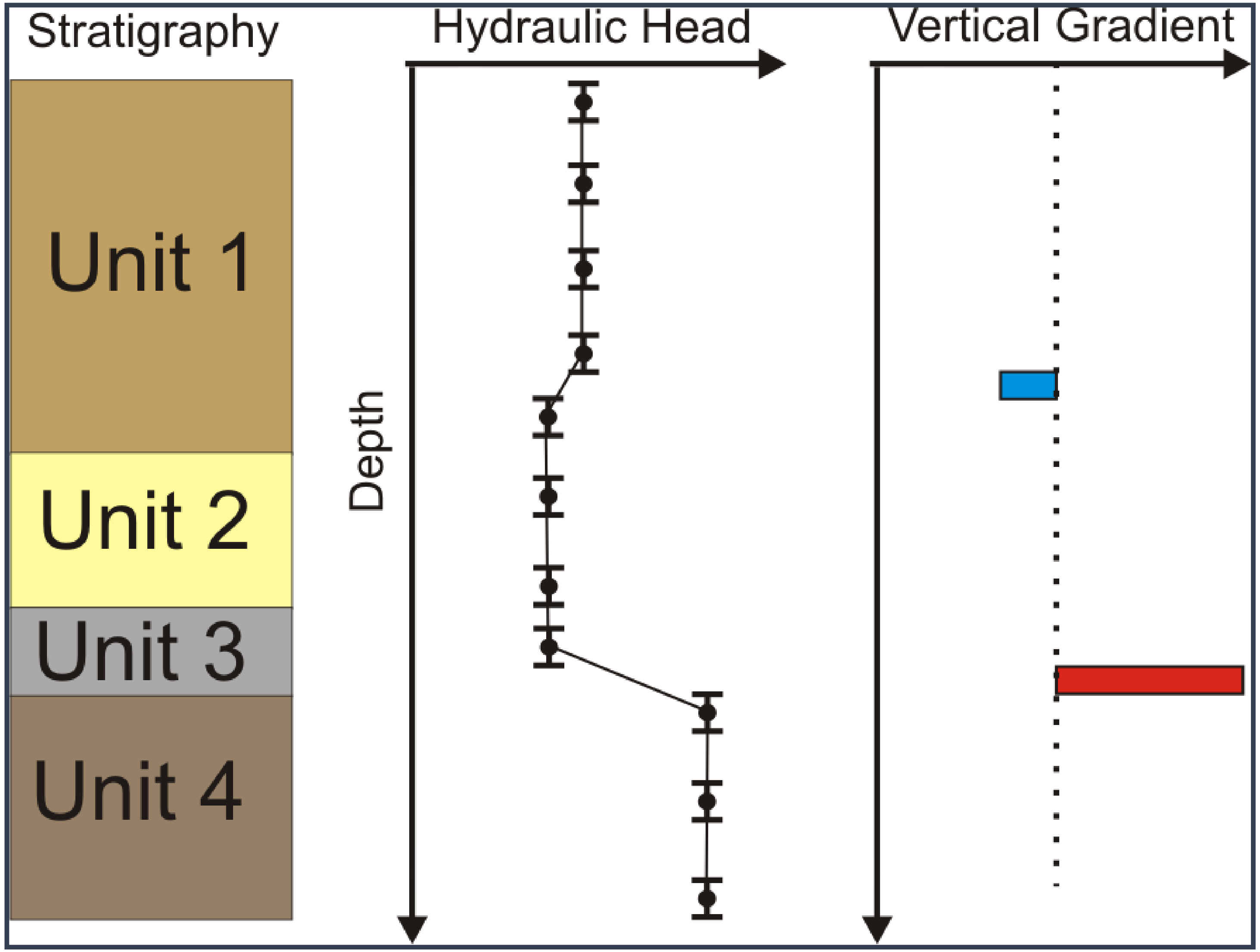
✓83% of monitoring zones are < 2.5 m long

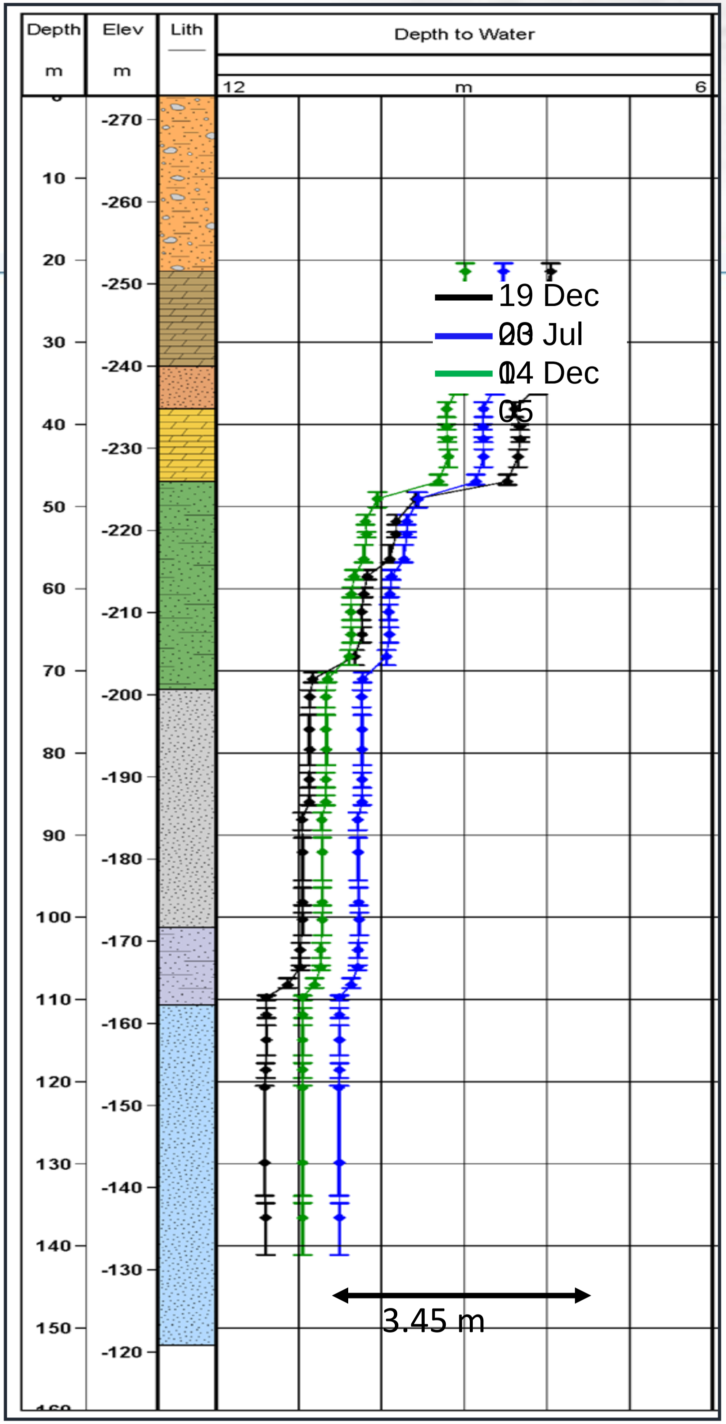


High resolution head profiles identify the position / thickness of Kv contrasts that can be used to delineate HGUs



Schematic Head Profile



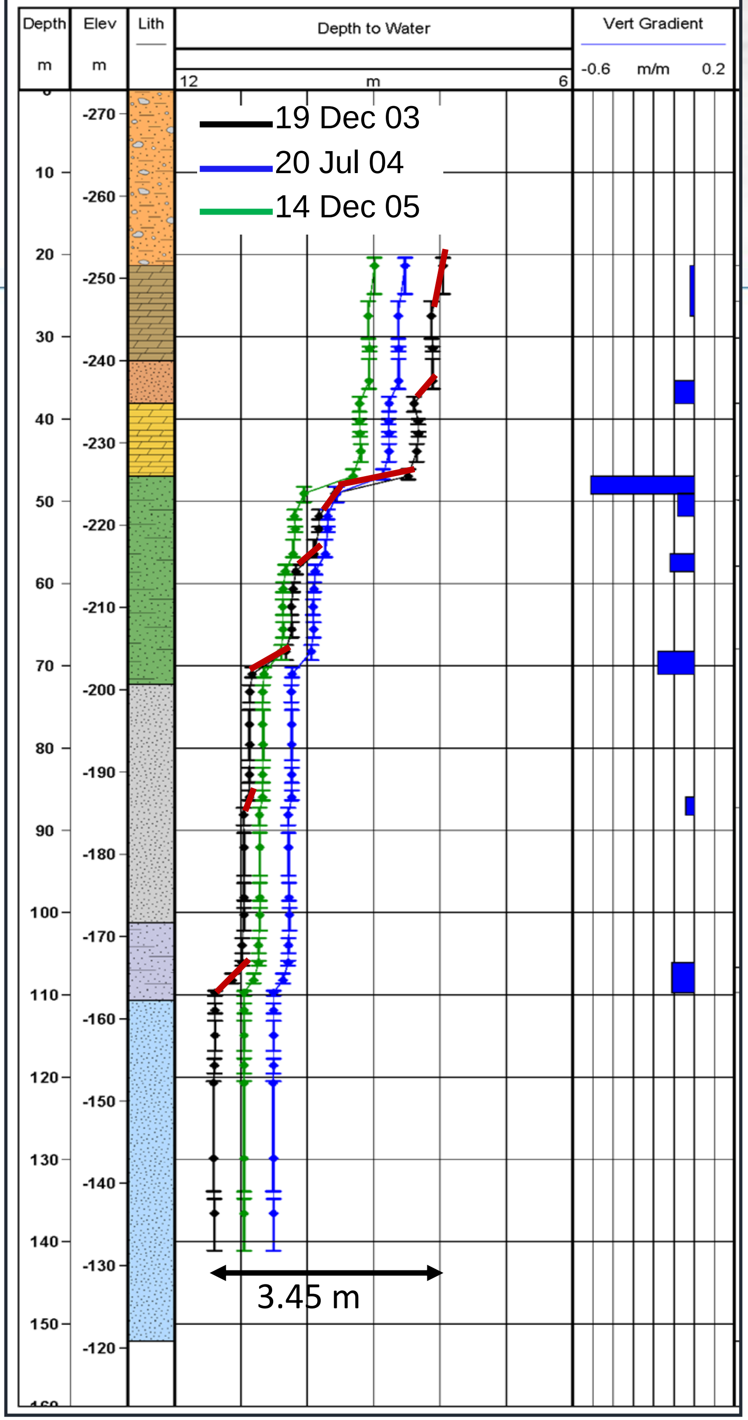


Head Profile Characteristics

- Profiles are repeatable

- Geometric head profiles; not erratic or “wiggly”

Meyer et al., 2008



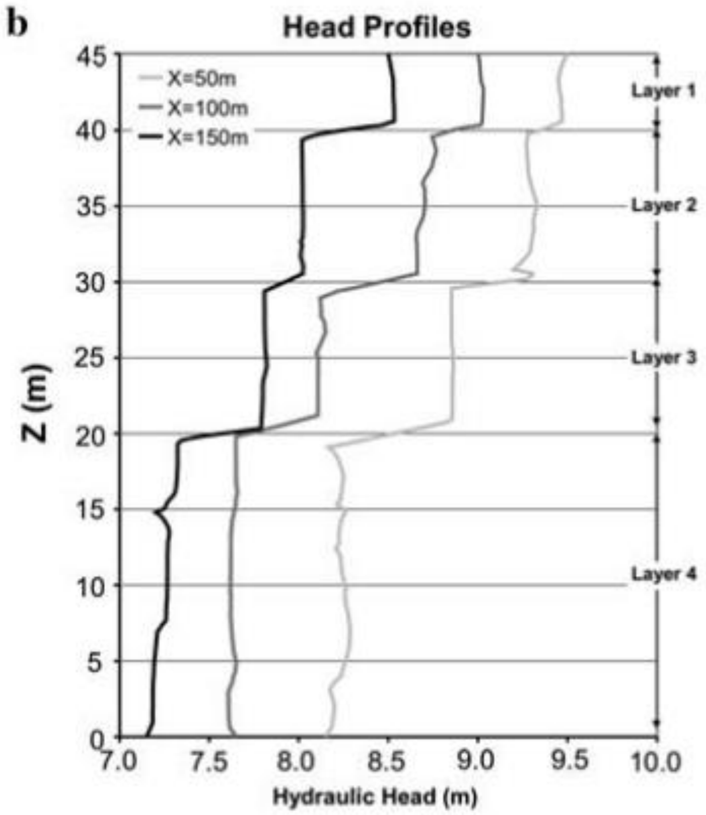
Head Profile Characteristics

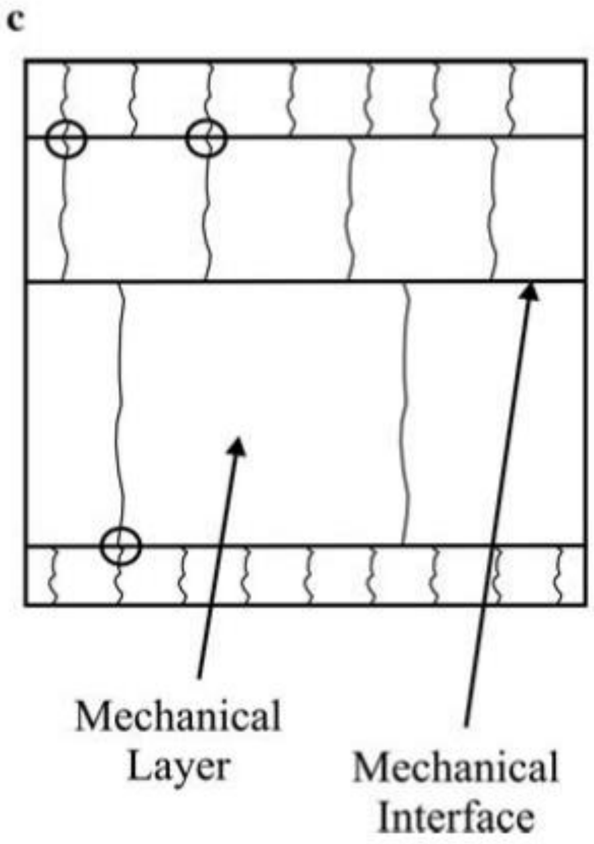
- Large vertical gradients at inflections

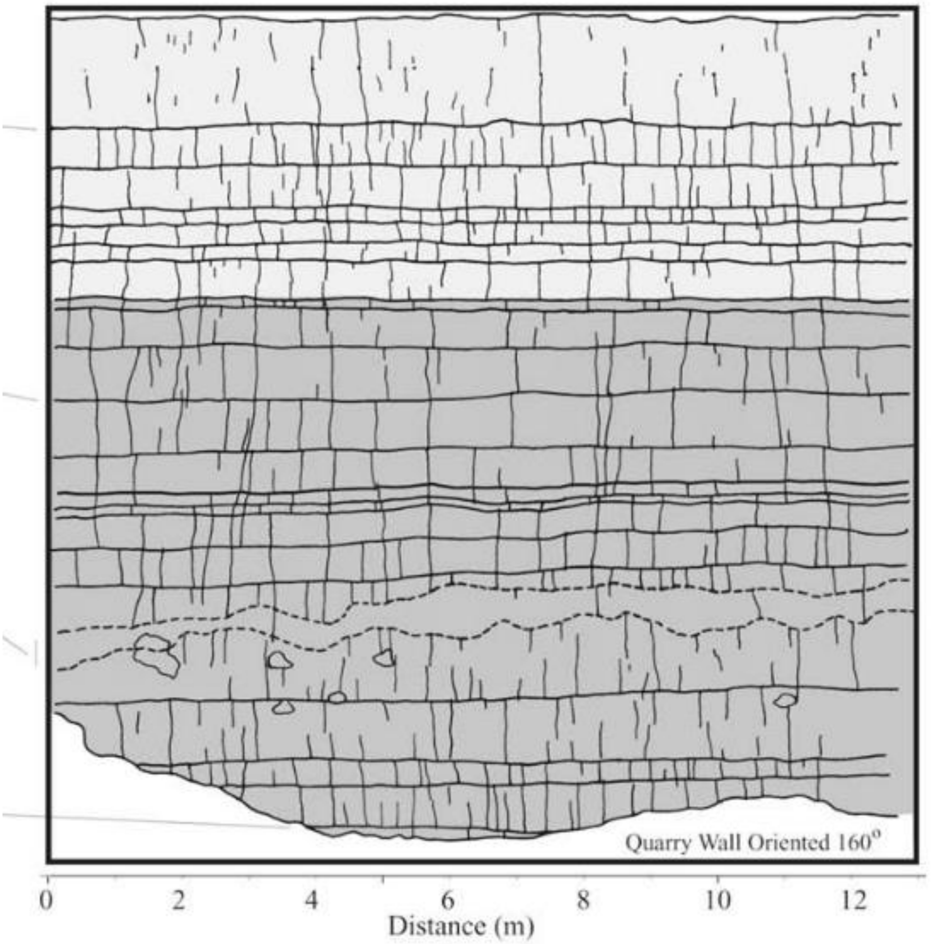
- Inflections do not always correlate with stratigraphy

Meyer et al., 2008

Meyer et al. 2008
Head Loss Related to Fracture Terminations

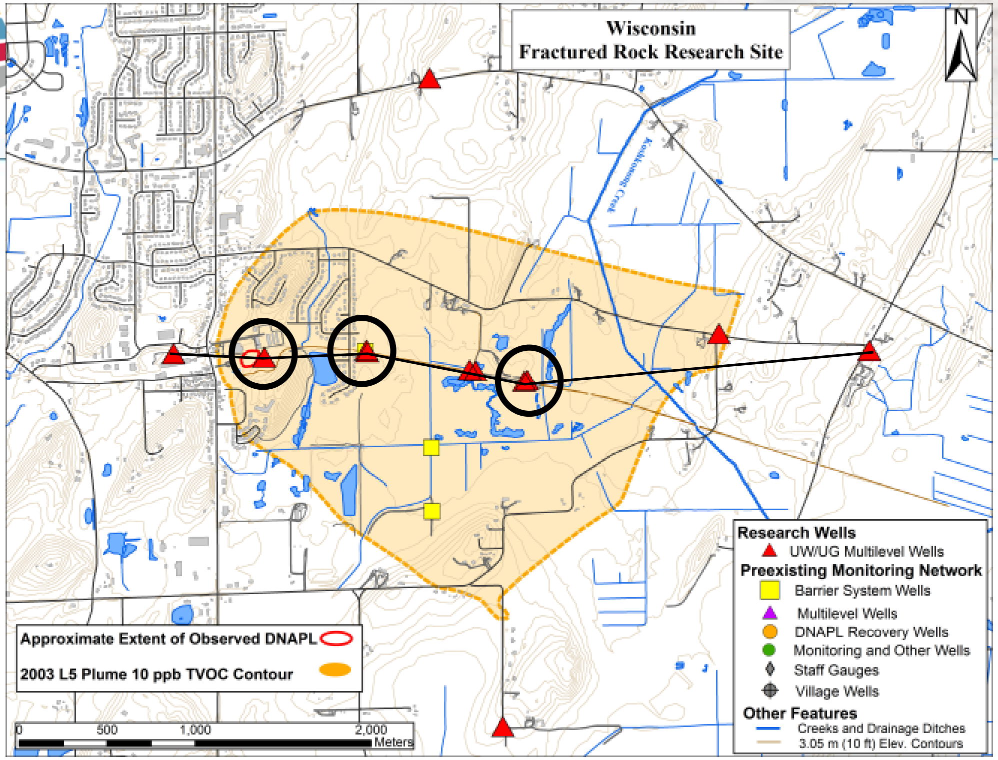






Underwood et al 2003

Rock Contaminant Profiles

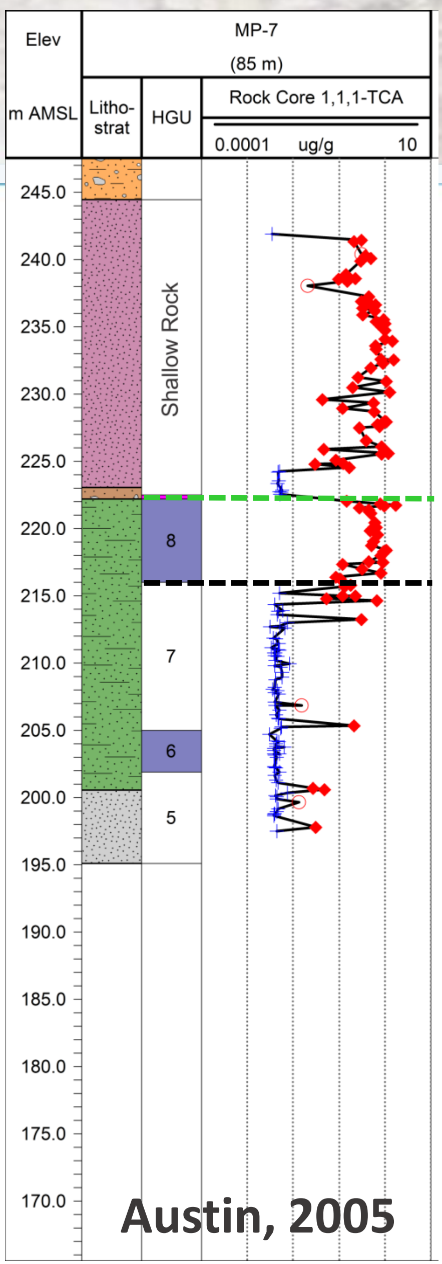


Quantifiable

Not Quantifiable

Non-Detect

Source(2003)

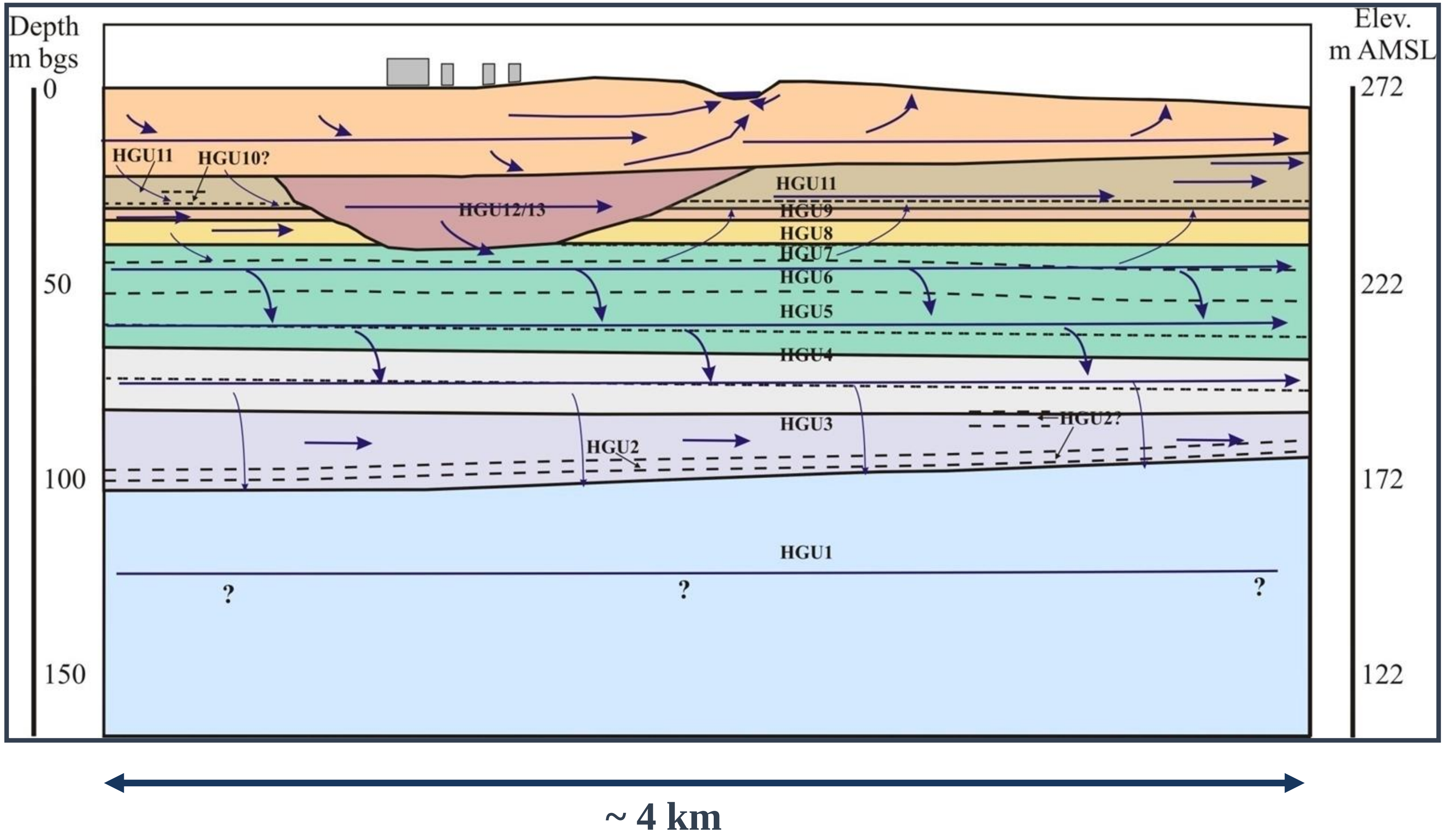


Austin, 2005

Key Observation:

Contaminant profiles show characteristics consistent with HGU boundaries

Schematic Flow System
Hydraulically Calibrated Geologic Framework



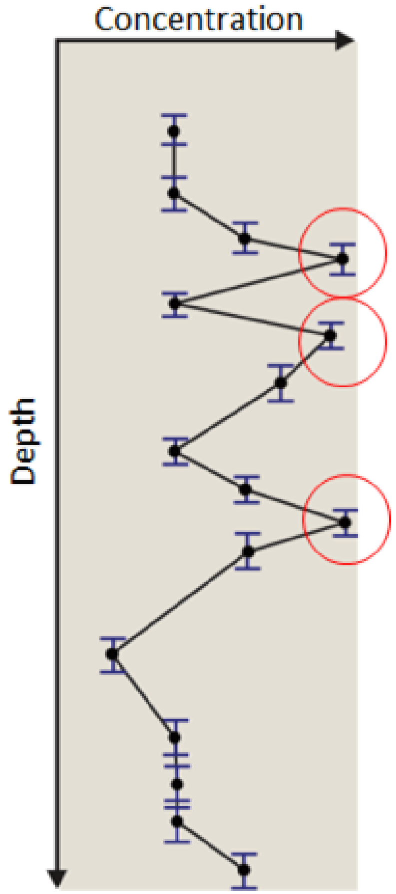
Characterization vs. Monitoring

Characterization: mass and phase distributions for transport and storage, head profiles for HGU delineation.

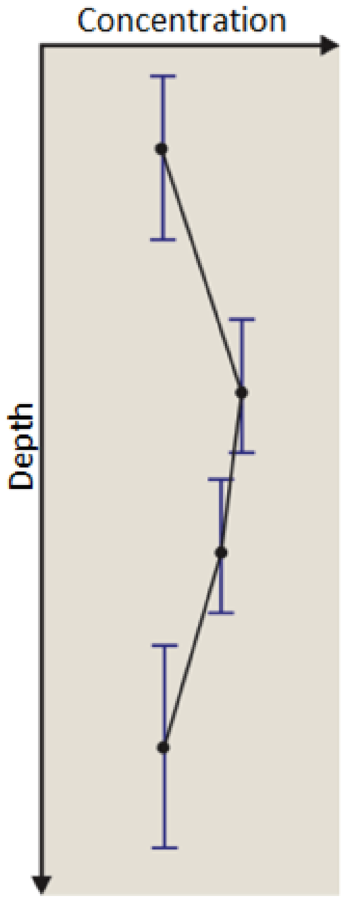
Monitoring: concentration and flux and how they change over time to assess impacts and performance.

Characterization Informs Monitoring

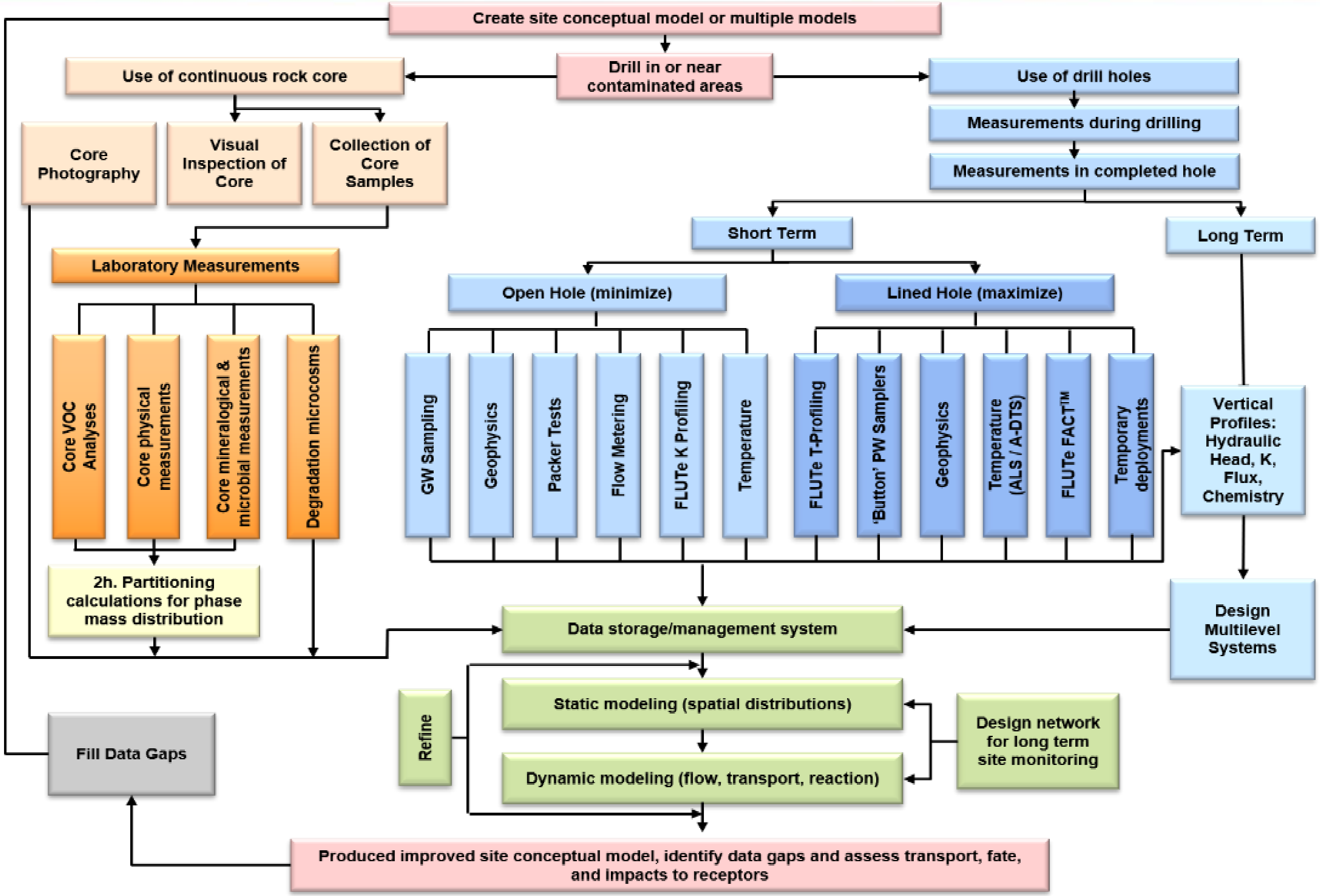
High Resolution Profiles



Monitoring Wells



DFN-M Field Approach for Studying Contaminated Bedrock Sites

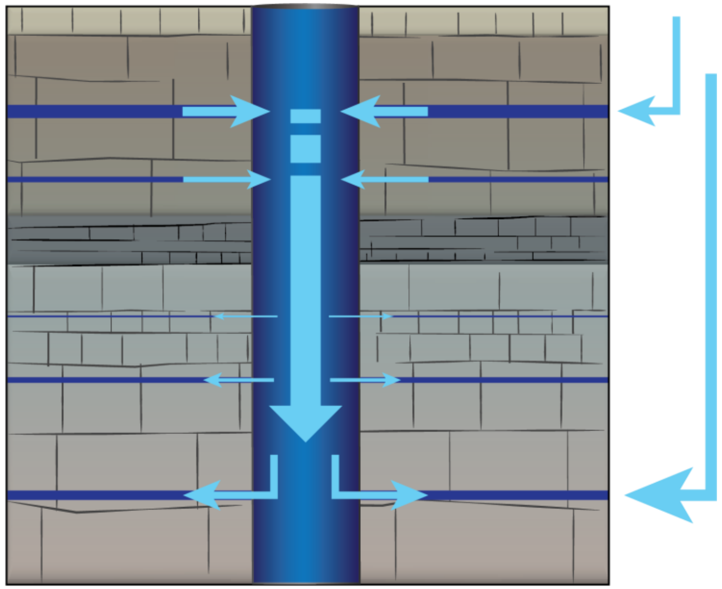


Adapted from Parker et al. 2012

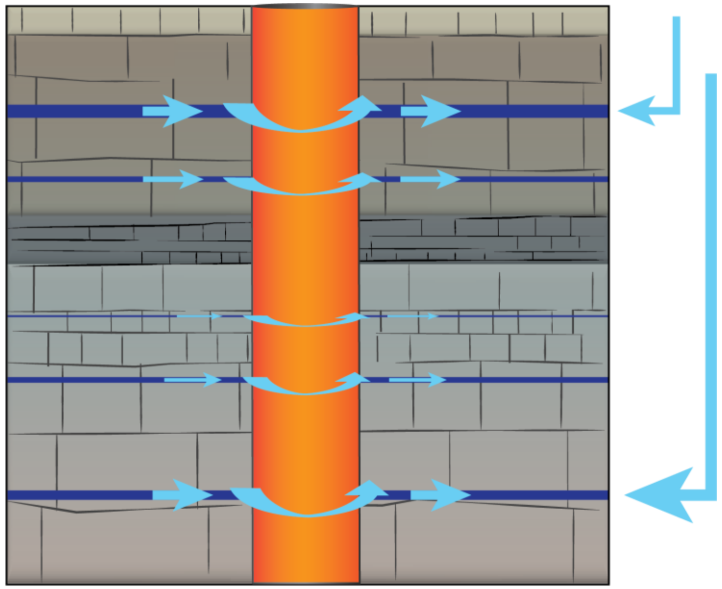
Blank FLUTe Liners to Seal Boreholes

Immediately after Drilling, Between Any Open Hole Activities, Temporary Deployed Sensors

Open Borehole (Cross-Connected)



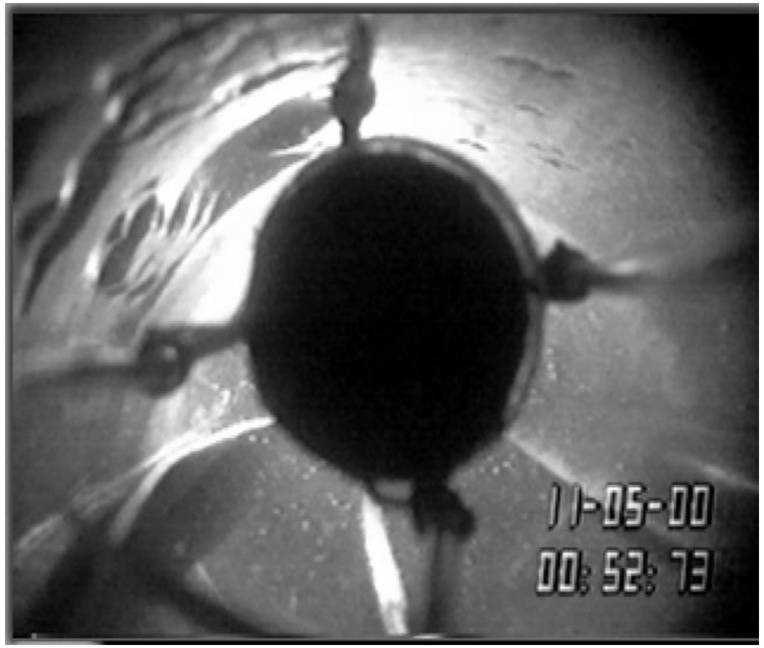
Sealed Borehole (Ambient Flow Restored)



FLUTe™

FLUTe liner compressed against borehole wall to seal

without liner

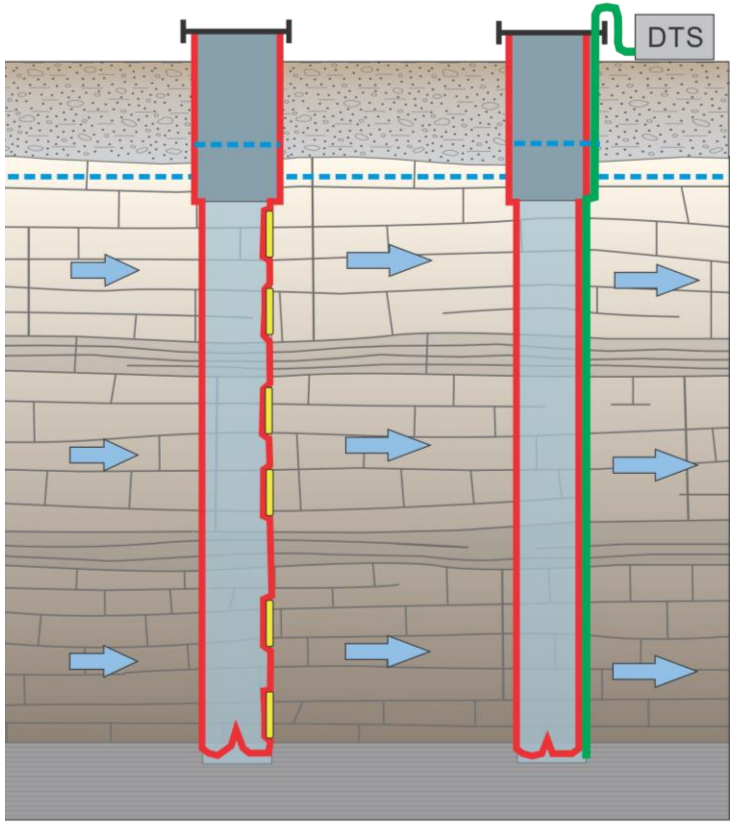


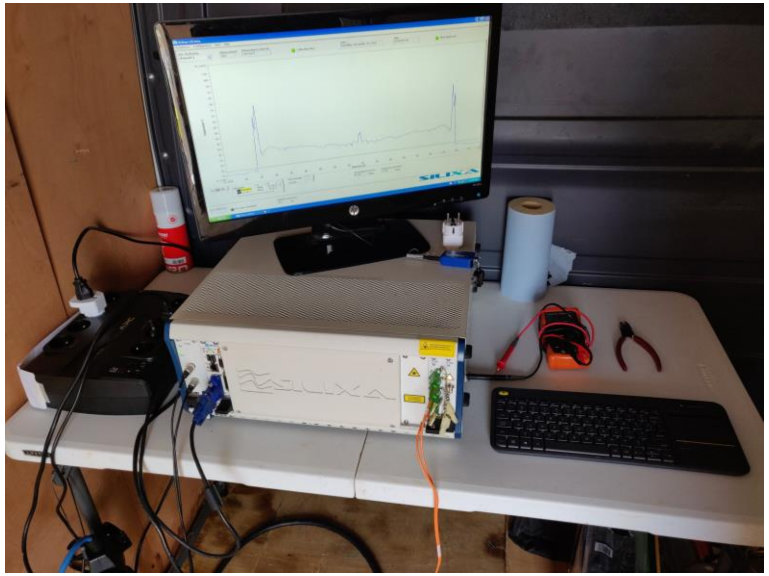
with liner

2 types of sensors

Point sensors (e.g. pressure)

Distributed Sensors
(e.g. temperature)

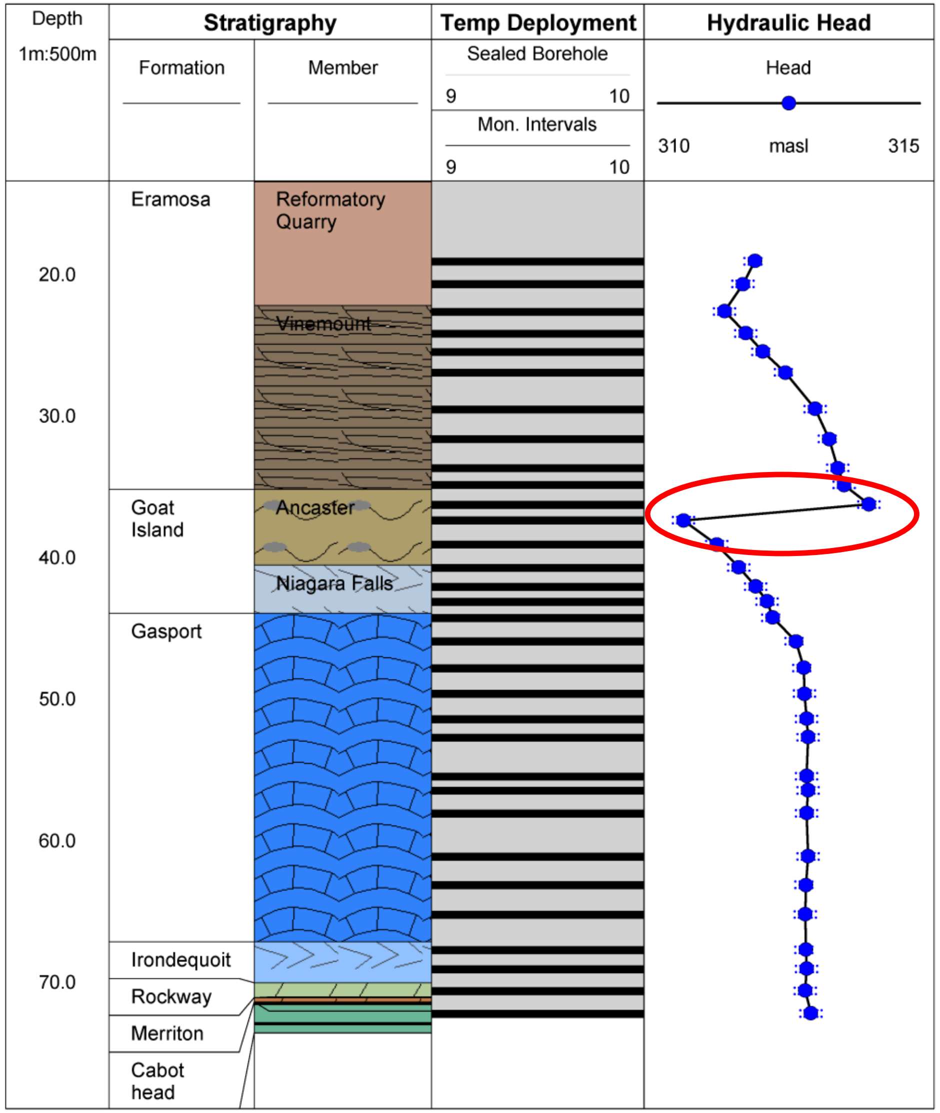




Deploy Transducer String and Install FLUTe Liner

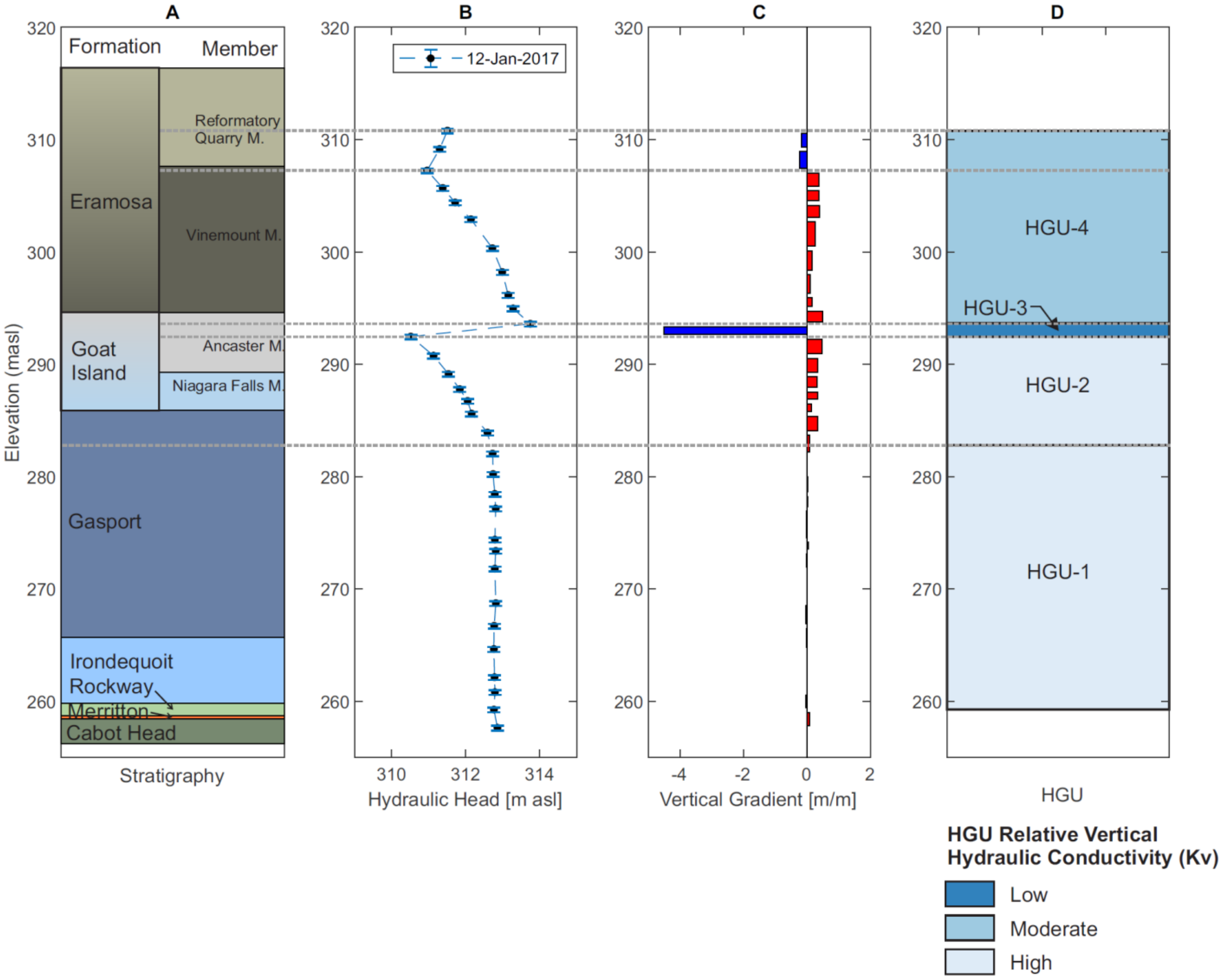
Hydraulic Head Profile from Temporary Deployment

GDC-05 at G360 Fractured Rock Observatory



- 32 discrete monitoring intervals
- Monitoring 54 m of saturated bedrock
- Average port spacing = 1.7 m

Depth-Discrete Hydraulic Head Data Used to Define 4 Hydrogeological Units (HGUs) in Dolostone

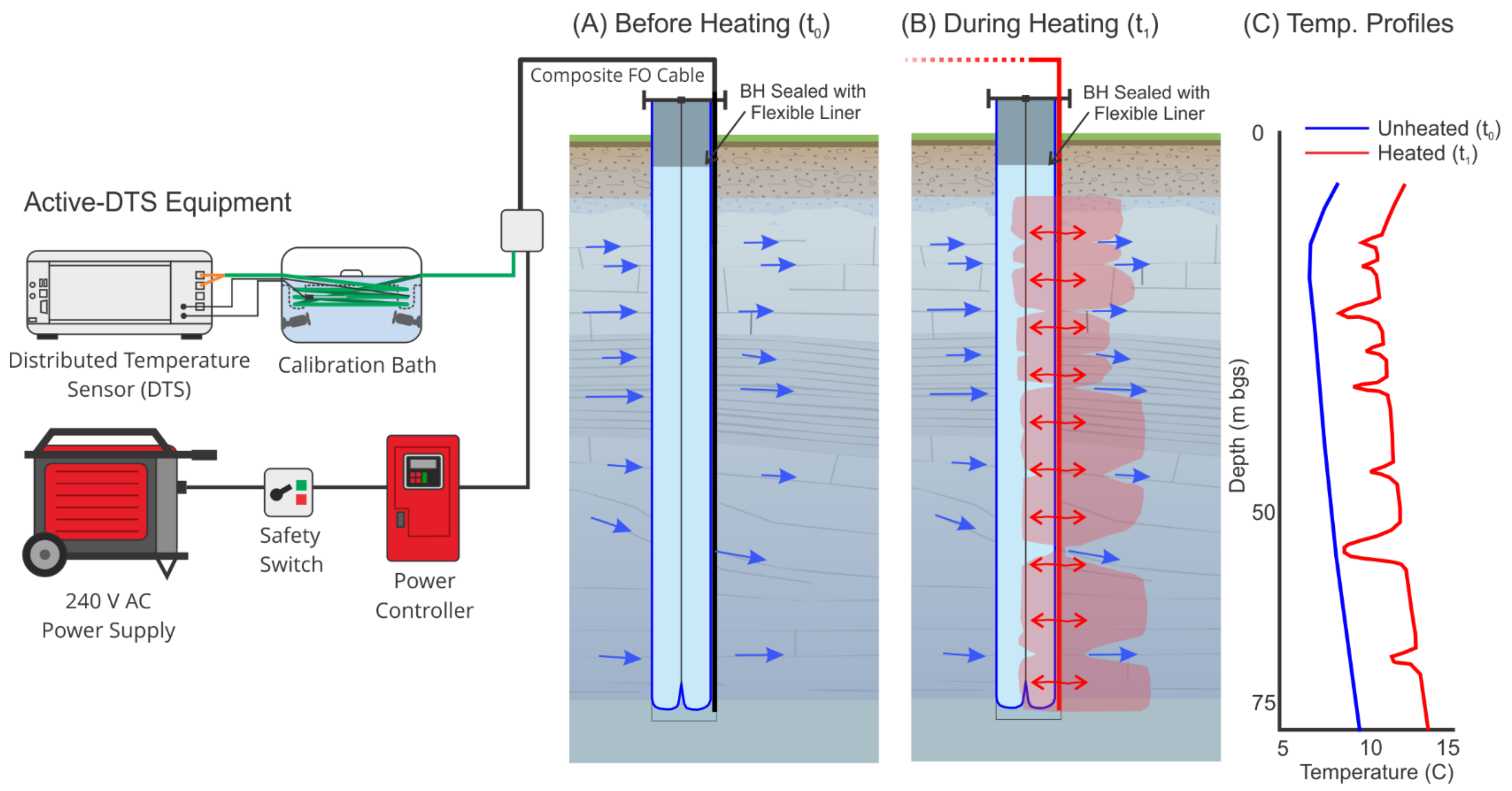


- HGUs do not correspond to lithostratigraphic boundaries
- Allows accurate placement of future multilevel packers and monitoring intervals
- Prevent cross-connection of distinct HGUs

Munn et al. 2020

Fibre Optic *Active* Distributed Temperature Sensing (A-DTS) for Active Fracture Identification

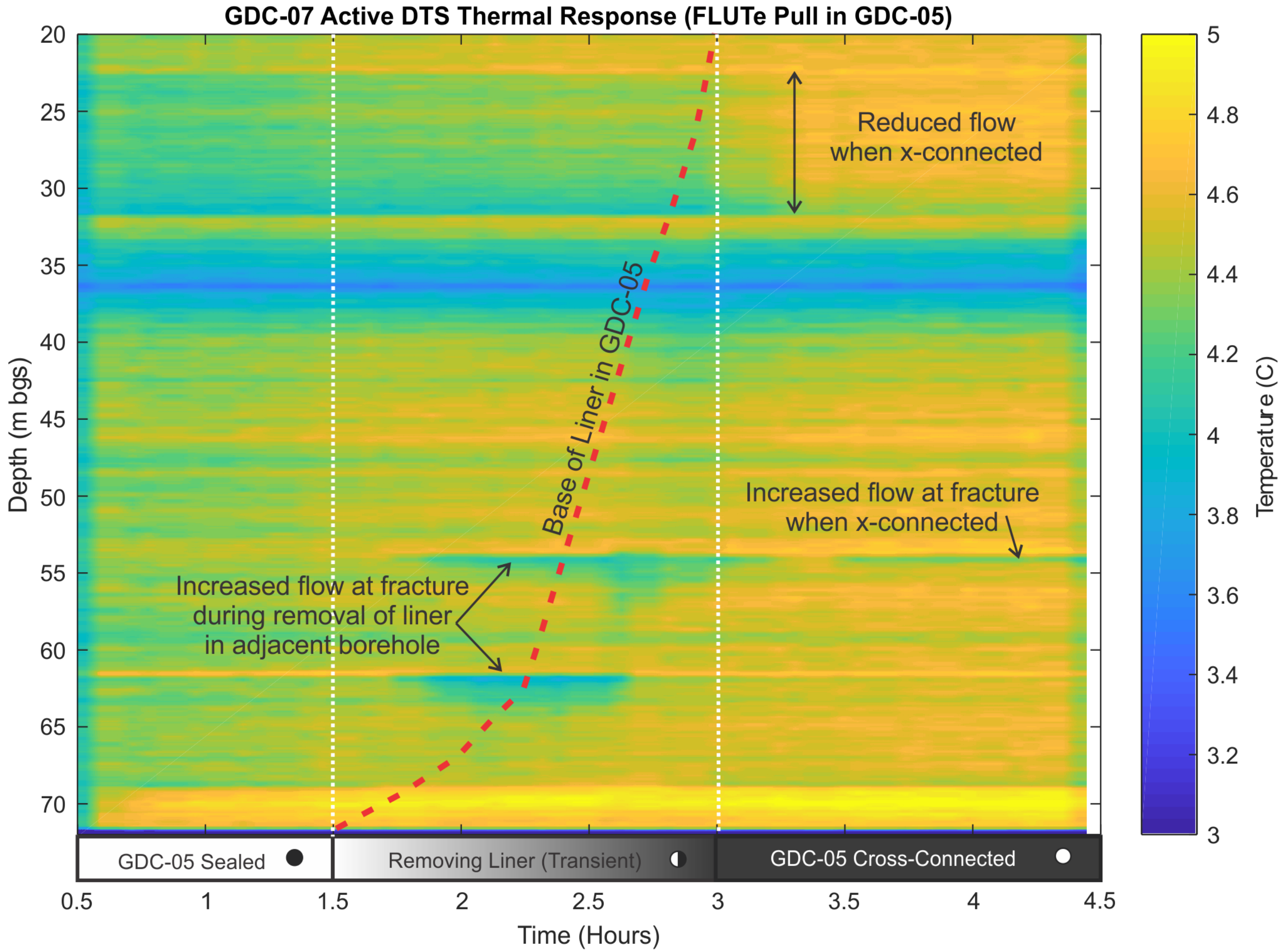
Coleman et al. 2014; Maldaner et al. 2019; Munn et al. 2020



Natural Gradient Conditions

- Custom heating cable co-deployed with Fibre Optic Cable outside liner (sealed corehole)
- Continuously record temperature during heating and thermal recovery (i.e. cooling)
- Enhanced cooling observed where groundwater flows

Changes in flow can be measured using temperature

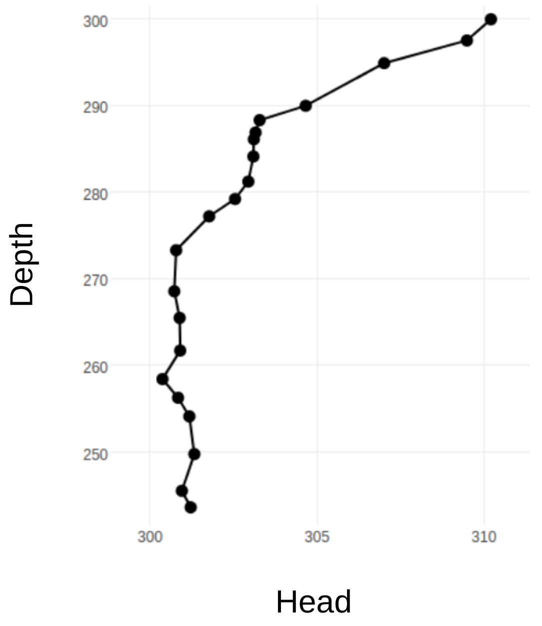


Faster Flow

Munn et al. 2020

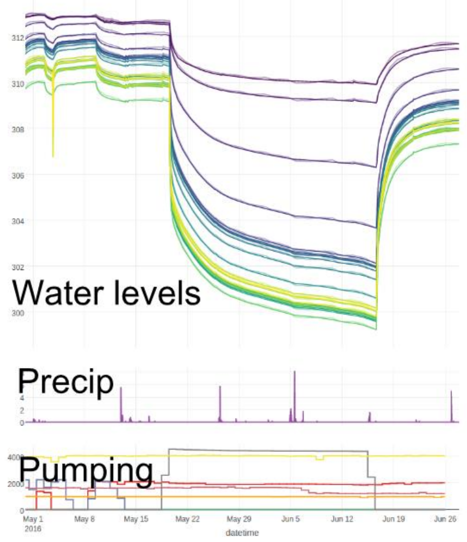
High Resolution entails…

Spatial



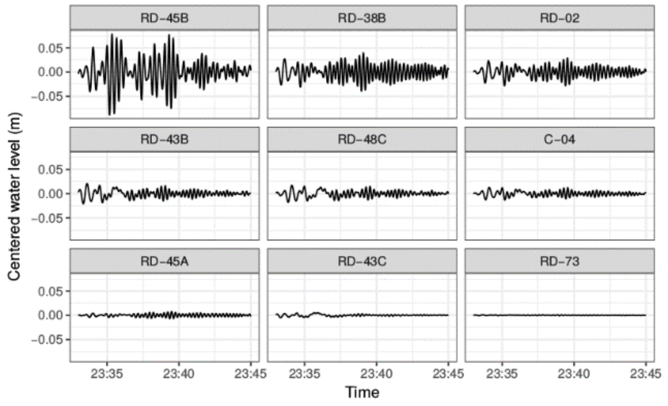
Guelph Site

Temporal



Guelph Site

Measurement Sensitivity



Chile 2015 earthquake
response in California Site well

Parker NSERC IRC, 2018

Key Message

Experience shows that data from better measurement resolution advances understanding, always.

Spatial ● Temporal ● Sensor Sensitivity

Meeting Future Challenges at Complex Sites

1. Much of the contaminant mass resides where you cannot deliver amendments directly (mass transfer rates need to be considered!).

2. Characterization should be performed at a finer scale than monitoring or remediation (monitoring wells designed and installed after characterization).

3. Wide array of field methods now exist for contaminant hydrogeology discipline, including bedrock sites (not ‘water supply’ hydrogeology). Transferable to emerging contaminants.

4. Conceptual site models <u>must be process-based </u>to be predictive.


Photo by Phil Taylor, 2021

Tak!

bparker@uoguelph.ca

ATV Jord og Grundvand

MORWICK G360 Groundwater Research Institute

University of Guelph