Technical Justification for Discrete Zone Characterization

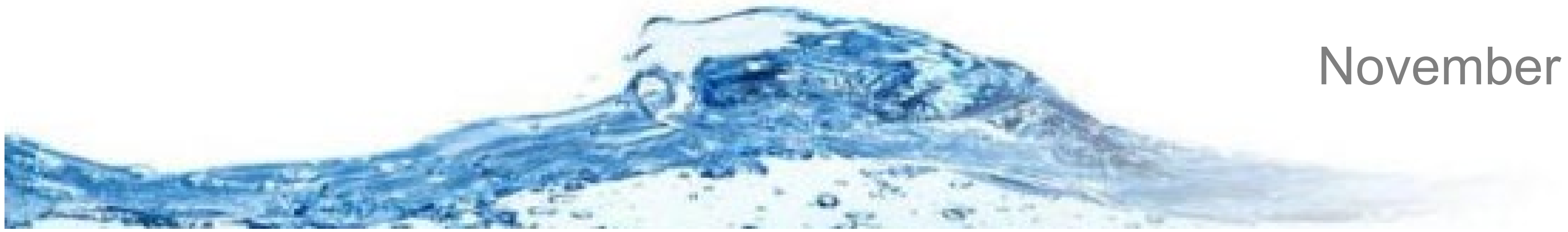
Dr. Beth Parker and Steven Chapman, M.Sc., P.Eng.

RemPlex 2025 Global Summit

"International Approaches to Discrete Aquifer / **Aquitard** Zone Characterization"

Pacific Northwest National Laboratory, Richland, Washington, USA

November 5, 2025



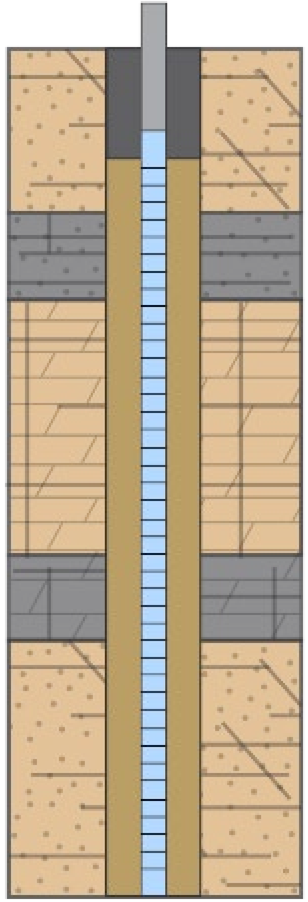
This talk shows....

- Why Discrete Interval Characterization ?

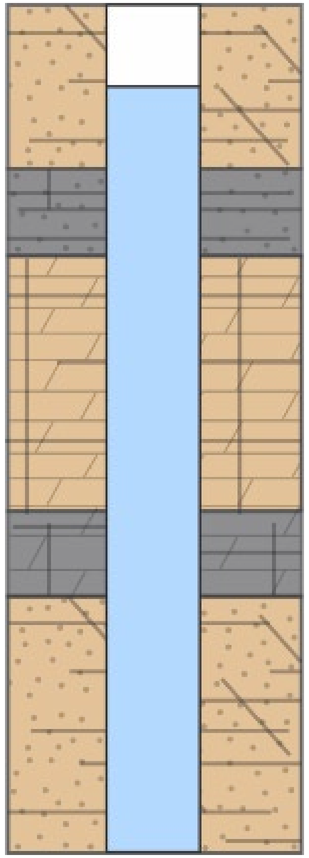
- HRSC approaches using complementary datasets in profile
  - Discrete Fracture Network–Matrix (DFN-M) approach in bedrock systems
  - Importance of CORE sampling complementing MLS groundwater datasets
    - insights from collection of data along Transects
    - use of ‘Golden Spike’ boreholes to complement existing site data

- Field case studies with examples from purpose-built MLS
  - insights on processes controlling plume attenuation and remediation

Long Screened Wells



Open Boreholes



Issues?

Long Monitoring Zones Result in Blending of Fluids and Cause Bias / Confusion

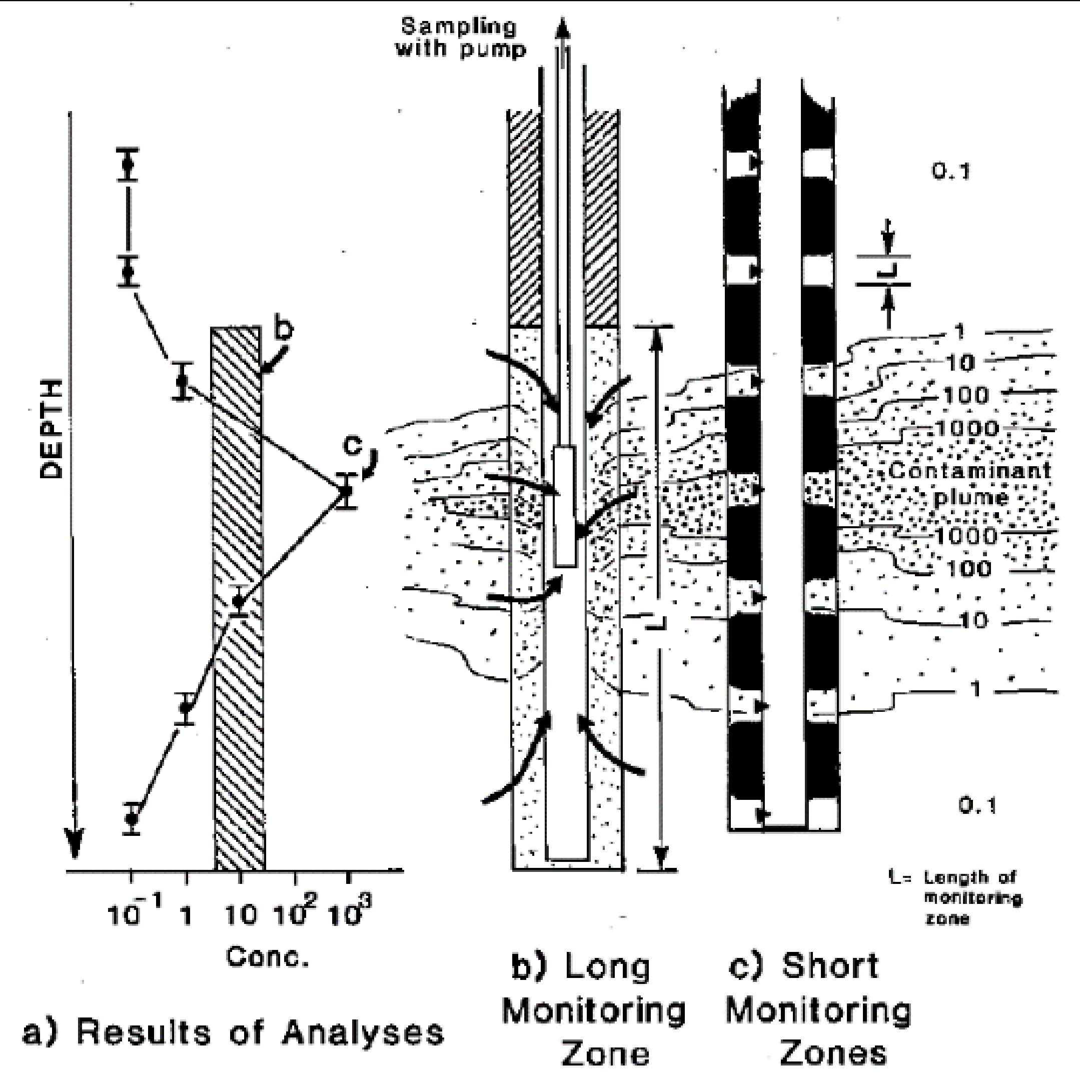


FIG. 4—*Sample degradation due to fluid mixing in the well bore annulus.*

Long Monitoring Zones
(Conventional Well / Open Hole)

versus

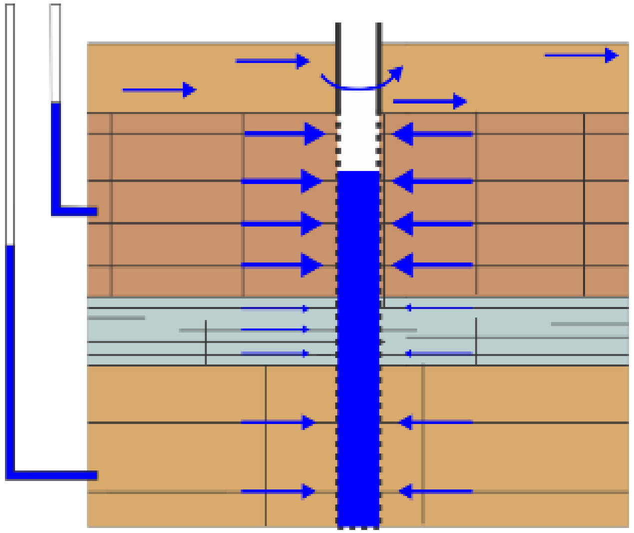
Short Monitoring Zones
(Multilevel System)

Patton & Smith, ASTM Symposium (1986)

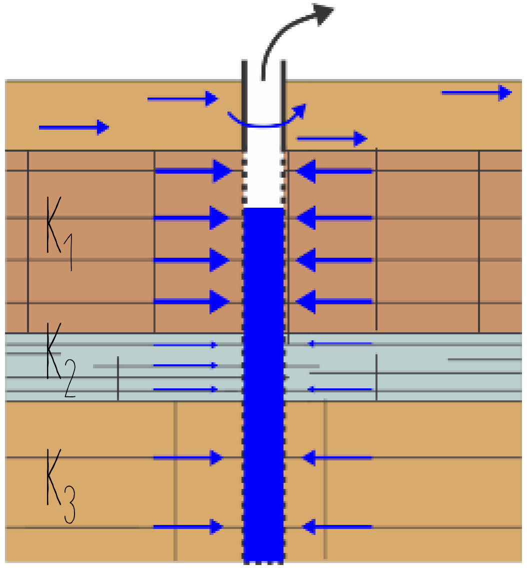
Why Multilevel Monitoring ?

- Long Screened Wells Cause Blending: 'Blunt Instruments'

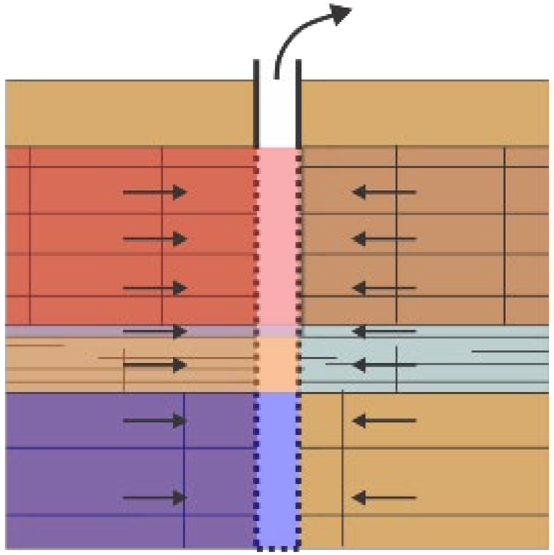
Inaccurate Head & Gradients
Missed Aquitards / HGUs



Lumped K: Poor mass discharge / capture zone estimates



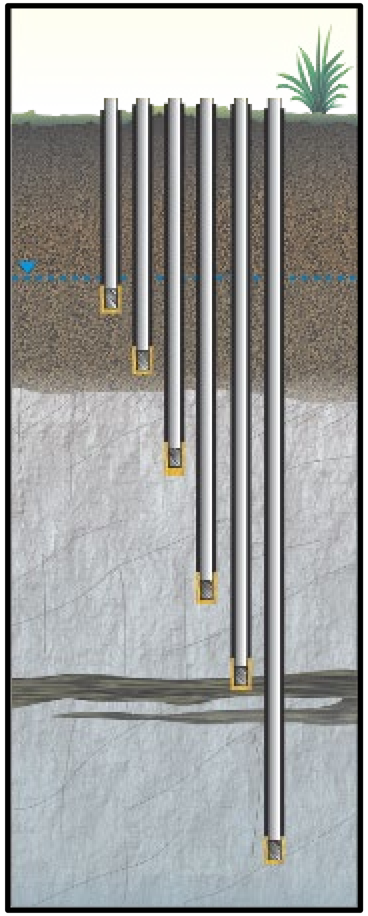
Blended Concentrations
Parent / Daughter ratios?



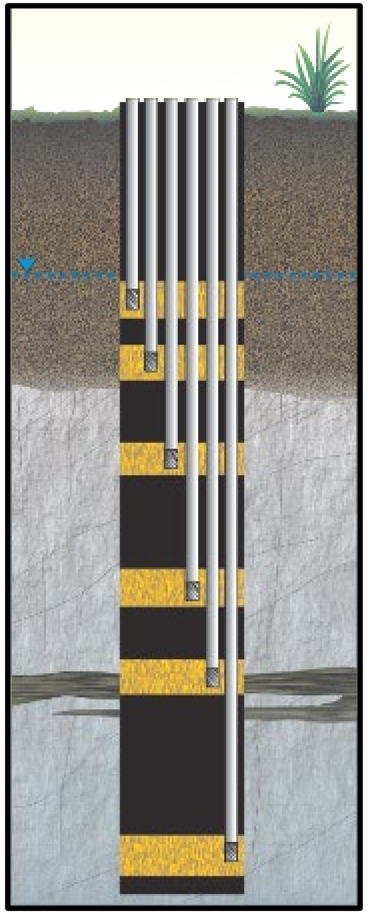
- **Minimal insight into physical system & processes**
- **Poor prediction of system behaviour**

Types of Multilevel Monitoring

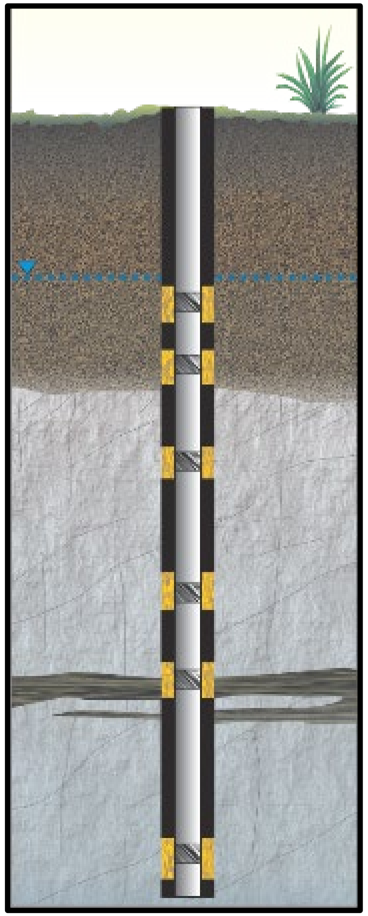
Well Cluster (good)



Well Nest (better)



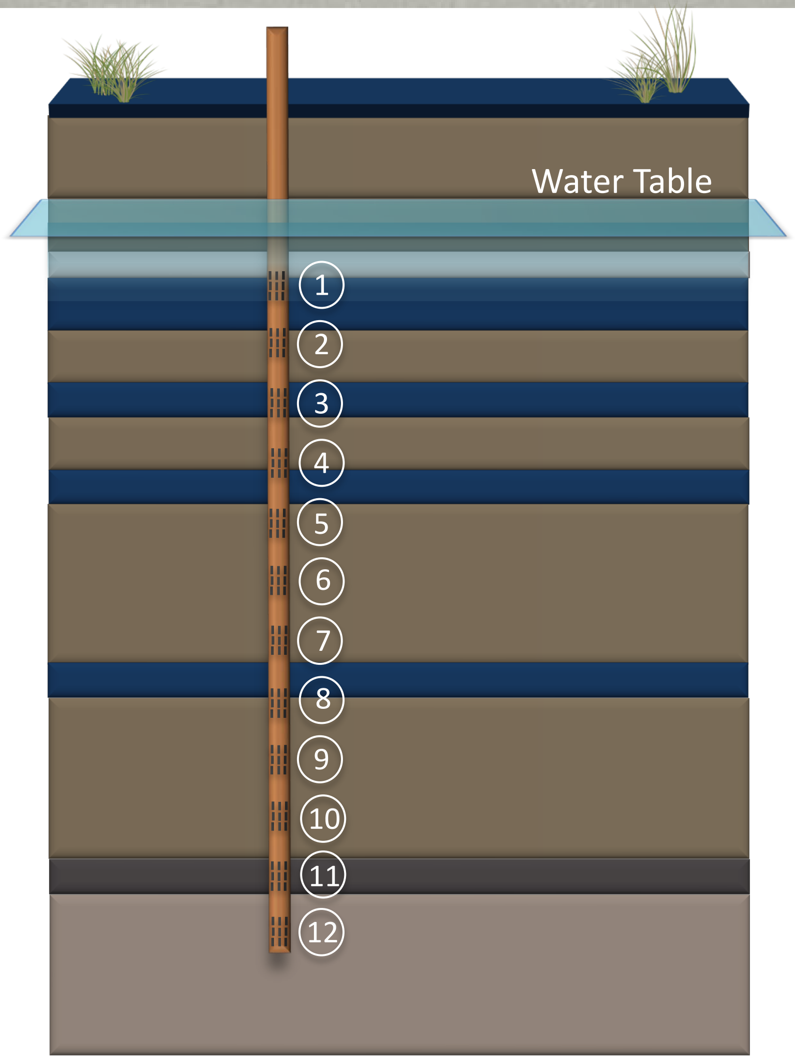
Engineered MLS (best)



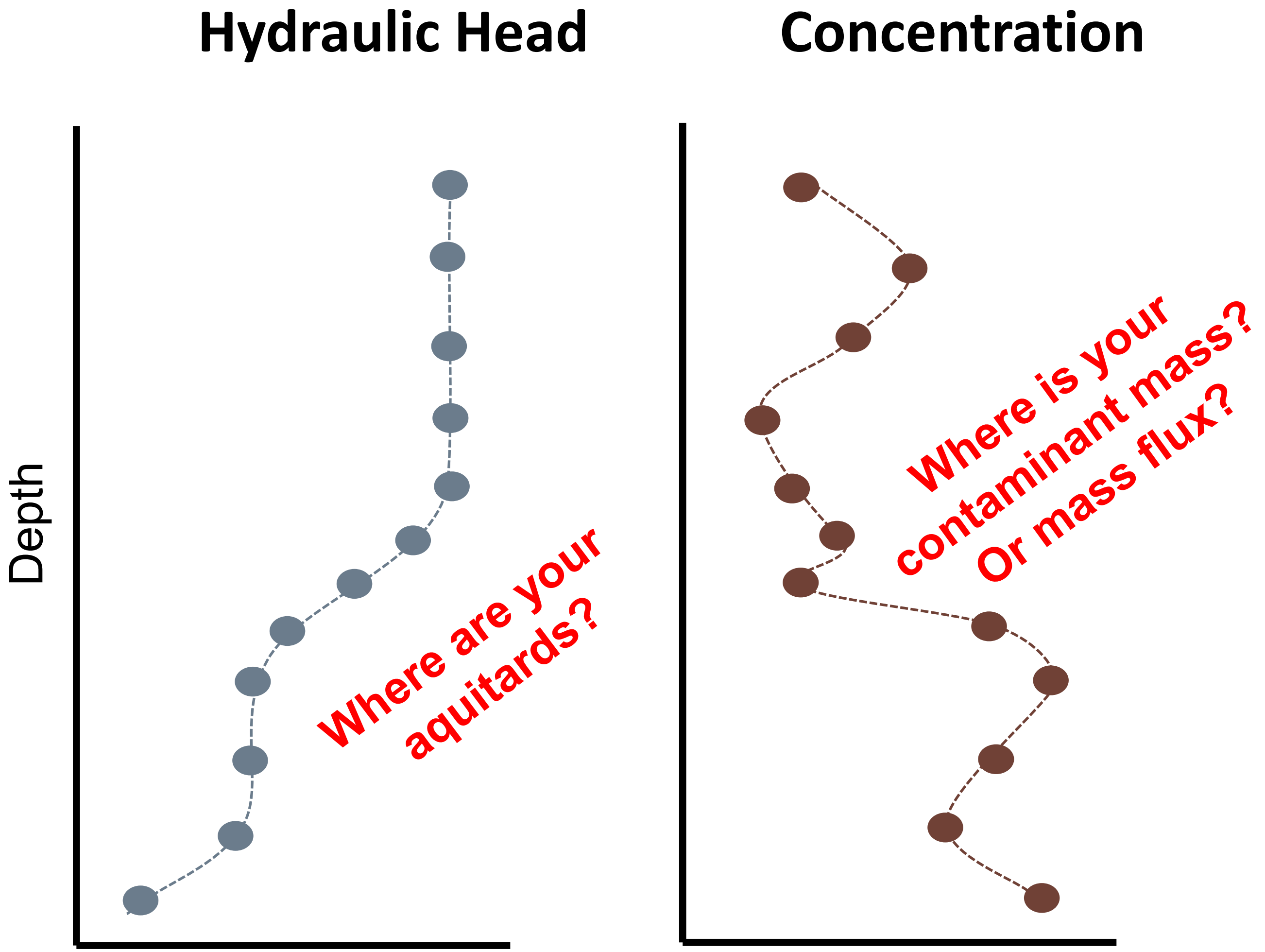
Murray Einarson Talk
(this session)

Pros and Cons of each

High Resolution Depth-Discrete Profiles from MLS in Bedrock Boreholes



High Resolution MLS



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~~3~~ 2 Companies Produce ~~4~~ 5 Different Multilevel Systems

Westbay Instruments

Westbay

Solinst

Waterloo

Solinst

CMT

CMT Multilevel
Continuous Multichannel Tubing

Water FLUTe
SWF, CHS

Solinst Flute

Solinst

G360MPS
(NEW)

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Overview of Commercially Available MLS

Multilevel System Description	Applicability / Advantages	Limitations / Difficulties	References
Westbay Systems[a] (Westbay Instruments) First used in groundwater applications in 1978. It is a modular system using PVC or stainless-steel casing with valves at the sampling point. Ports are most commonly isolated using packers that can be installed in 3.0-6.3 in. (7.6-16 cm) diameter boreholes and for holes ≥ 5 in. (≥ 13 cm) it can be installed with backfilling option.[b] To date, the maximum installation depth achieved is 4035 ft (1235 m) with the PVC version, and 7128 ft (2173 m) with the stainless-steel version. Deeper installations are feasible with the stainless-steel version.[c]	• Least chemically reactive[d] • Can be easily installed through temporary drill	• Can only monitor head in one port at a time with a single MOSDAX probe;	https://www.westbay.com/ Black et al. (1986), Patton and
Waterloo Systems[a] (Solinst) First used in groundwater applications in 1984. It is a permanent, modular system using PVC casing. Ports are isolated in 3-4.5 in. (7.6-11.4 cm) diameter boreholes using packers and in boreholes ≥ 5 in. (≥ 13 cm) by backfilling option.[b] To date, the maximum installation depth achieved is 1000 ft (305 m).[c]			

Multilevel System Description	Applicability / Advantages	Limitations / Difficulties	References
CMT Systems (Solinst) First used in groundwater applications in 1999. Polyethylene tubing with 3 or 7 chambers is used, and each chamber is converted into a depth-discrete monitoring tube in 4-8 in. (10-20 cm) diameter boreholes using backfilling option.[b] Bentonite packers can be used for 3-channel systems in boreholes from 2.5-3.5 in. (6.1-9.0 c Removable version possible using lightweight rubber packers on 7-CH system, using one of th channels for packer inflation (reducing the numb of usable ports to 6) for insertion into small-diam stable bedrock boreholes (2.5-3.5-in., 6.1-9.0 c To date, the maximum installation depth achiev 300 ft (91 m) for 7-CH and 500 ft (152 m) for 3-C	• Lowest capital cost • Simple installation procedure does not require advanced training • Can be installed through casing using all drilling techniques • Most versatile system for design modifications	• Moderately chemically reactive[d] • Maximum number of monitoring zones limited to 7 • Bentonite and sand cartridges only available for 3-CH systems; however, additional CMT packer options are being	https://www.solinst.com/instruments/multilevel-systems/403-cmt-multilevel-systems/ Einarson and Cherry (2002), Fernandes et al. (2019)
G360 MPS (Multiport System)[i] (Solinst, in progress) Adapted version of Waterloo System with increa flexibility using open-tube system (no dedicated equipment). Allows larger diameter system casi (currently 2.5-, 3.0- and 4.0-in. ID) with versatilit the number and/or diameter of internal tubes running to each port. Two versions are available: 1. Threaded version using off-the-shelf threade Sch. 40 casing in backfilled type systems in overburden or bedrock boreholes. 2. Push-fit version using double O-ring sealed push-fit Sch. 80 casing with lightweight rubbe packers, with packer inflation using pressuriz system casing and sealed manifold at surfac			

Multilevel System Description	Applicability / Advantages	Limitations / Difficulties	References
FLUTe Systems (Flexible Liner Underground Technologies)[g] **Water FLUTe** First used in groundwater applications in 1994. This system uses a continuous flexible urethane-coated nylon fabric tube (liner) to seal the borehole with spacers between the liner and the borehole wall to create monitoring zones. The entire system is pressed against the borehole wall with water or grout and can be used in 3-20 in. (7.6-50 cm) diameter boreholes. To date, the maximum Water FLUTe installation depth achieved is 1700 ft (518 m); however, deeper installations are feasible.[c]	• Most easily removable for repair/replacement or reuse of borehole[h] • Smallest sampling reservoir volume • Seals entire borehole except for monitoring intervals; general overall seal is confirmed by water level measurement inside the liner, except for zones with head larger than excess head in liner • Design is not restricted by individual component lengths • Simultaneous, rapid high-volume purging of all monitoring intervals possible • More monitoring points can be used if only measuring head • Most easily installed in artesian holes • Most convenient for angled holes and holes in karst (use heavier fabric)	• Requires lead time for fabrication and shipping to site and no field design modifications possible • Most chemically reactive[d]; however, the high-volume rapid purging system minimizes contact time for reactions to occur • A zone with significantly higher head than the blended head may result in a weak seal for this zone • Extremely low head at depth may cause liner rupture	https://www.flut.com/water-flute Cherry et al. (2007), Keller (2009), Keller (2023)
Shallow Water FLUTe (SWF) Lower cost version introduced ~2015 that uses smaller diameter open tubes running to each port within the liner that seals intervals between ports.	• Lower cost version with open tubes running to each port suited to sites with shallow water table (<25 ft) • Requires separate pumping system for sampling (e.g., peristaltic pump) • Water levels can be measured with small-diameter water level meters or FLUTe vacuum water level meter • Otherwise similar to Water FLUTe (above)	• Small-diameter tubes running to each port limit head monitoring and purging / sampling options • Otherwise similar to Water FLUTe (above)	https://www.flut.com/shallow-water-flute Keller 2023 (Section 10.5.2), MG360 experience: 10-port SWF installed at NAWC (NJ) site (2016) in a 150-ft (46-m) HQ-borehole.
FLUTe Cased Hole Sampler (CHS) Lower cost version introduced ~2018 that allows direct insertion into boreholes (no eversion) in cased holes or smooth bedrock boreholes. Uses smaller diameter open tubes running to each port within the liner that seals intervals between ports.	• Lower cost direct insertion option for installation in cased multi-screen holes or smooth open bedrock boreholes with diameters 2-4-in (5-10 cm) and shallow water table (<25 ft) • Open tubes running to each port so requires separate pumping system for sampling (e.g., peristaltic pump)	• Small-diameter tubes running to each port limit head monitoring and purging / sampling options • Requires cased multi-screen holes or stable, relatively smooth open bedrock boreholes for direct-insertion method • Can be difficult to insert system downhole, especially in rougher walled boreholes	https://www.flut.com/casedhole sampler Keller 2023 (Section 10.5.3) MG360 experience: two 6-port CHS installed at Sweden site in HQ-cored boreholes in granite (2019) to 80-90 ft (24-27 m)

Table Evolution: ITRC (2015) → LLNL / California SB4 (2015) → PNNL RemPlex Workshop (2025)

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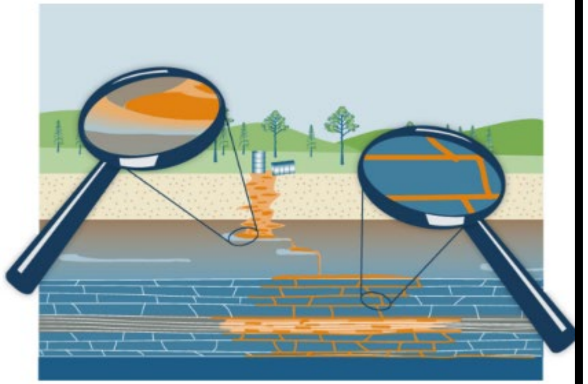
MLS Table Evolution

Guidance Document

2015

Integrated DNAPL Site Characterization and Tools Selection



May 2015

Prepared by
The Interstate Technology & Regulatory Council
DNAPL Site Characterization Team

https://projects.itrcweb.org/DNAPL-ISC_tools-selection/

LAWRENCE LIVERMORE NATIONAL LABORATORY

LLNL-TR-669645

Recommendations on Model Criteria for Groundwater Sampling, Testing, and Monitoring of Oil and Gas Development in California

Bradley K…
Carroll[1], …
Jackson[5], …
P. Morris…
Stringfell…
Avner Ve…

[1]Lawrence …
[2]Lawrence …
[3]University …
[4]California …
[5]Stanford U…
[6]Duke Univ…

June, 20…

Final Repor…
California S…

State of Calif…
LLNL Work fo…

Esser et al. (2015) *LLNL-TR-669645*

11 APPENDIX:
OVERVIEW OF DEPTH-DISCRETE MULTILEVEL GROUNDWATER MONITORING TECHNOLOGIES:
FOCUS ON GROUNDWATER MONITORING IN AREAS OF OIL AND GAS WELL STIMULATION IN CALIFORNIA

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Prepared for:

Lawrence Livermore National Laboratory

For the SB4 Groundwater Monitoring Expert Advice Project

June 29, 2015

https://water.llnl.gov/sites/water/files/2020-09/llnl_recommendations_report.pdf

Pacific Northwest NATIONAL LABORATORY

PNNL-37298

RemPlex Workshop: Vertical Delineation of Contamination in Aquifers

Hosted by Pacific Northwest National Laboratory and UK Nuclear Decommissioning Authority on October 10 and 29, 2024

January 2025

Karen P. Smith[1], Frederick D. Day-Lewis[1], John P. Heneghan[2], Nikolla P. Qafoku[1]

[1] Pacific Northwest National Laboratory
[2] Sellafield Ltd

REMPLEX CENTER FOR THE REMEDIATION OF COMPLEX SITES @PNNL

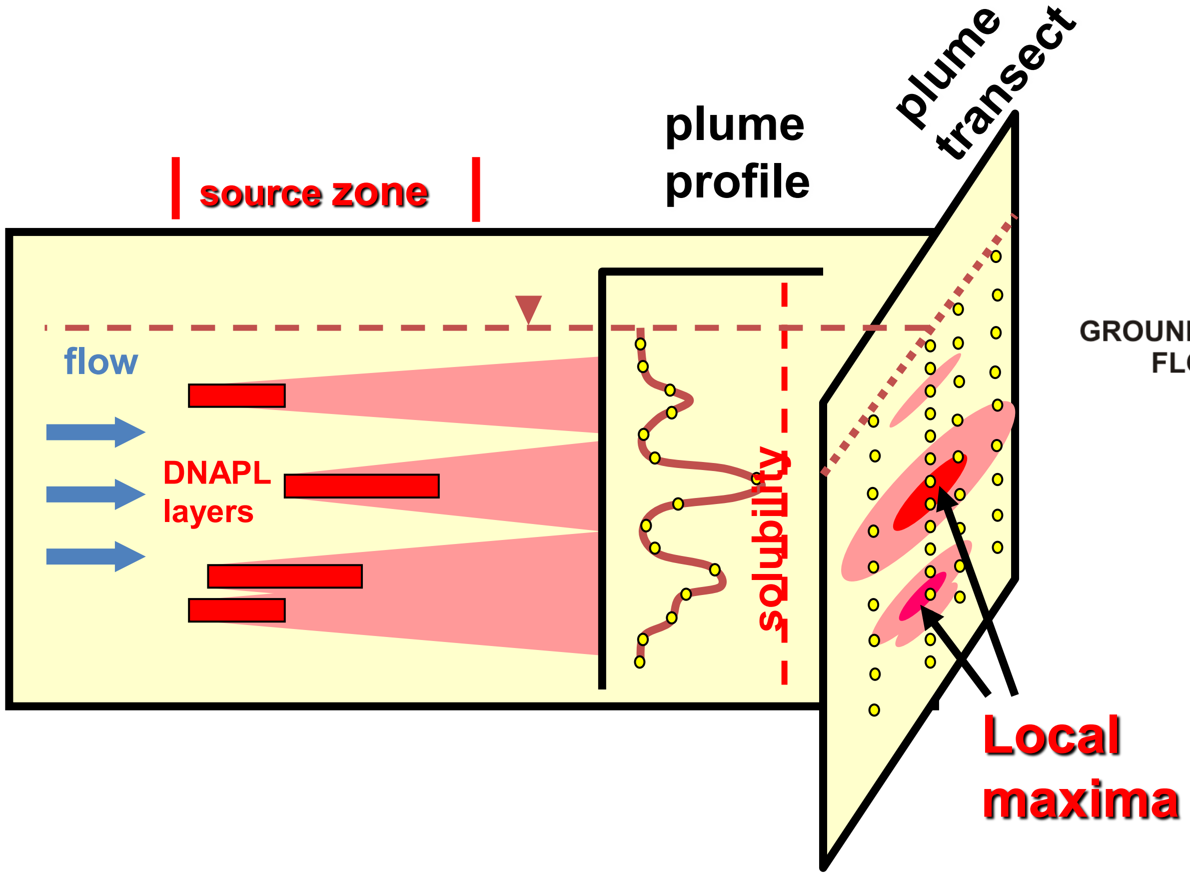
2025

ENERGY | Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

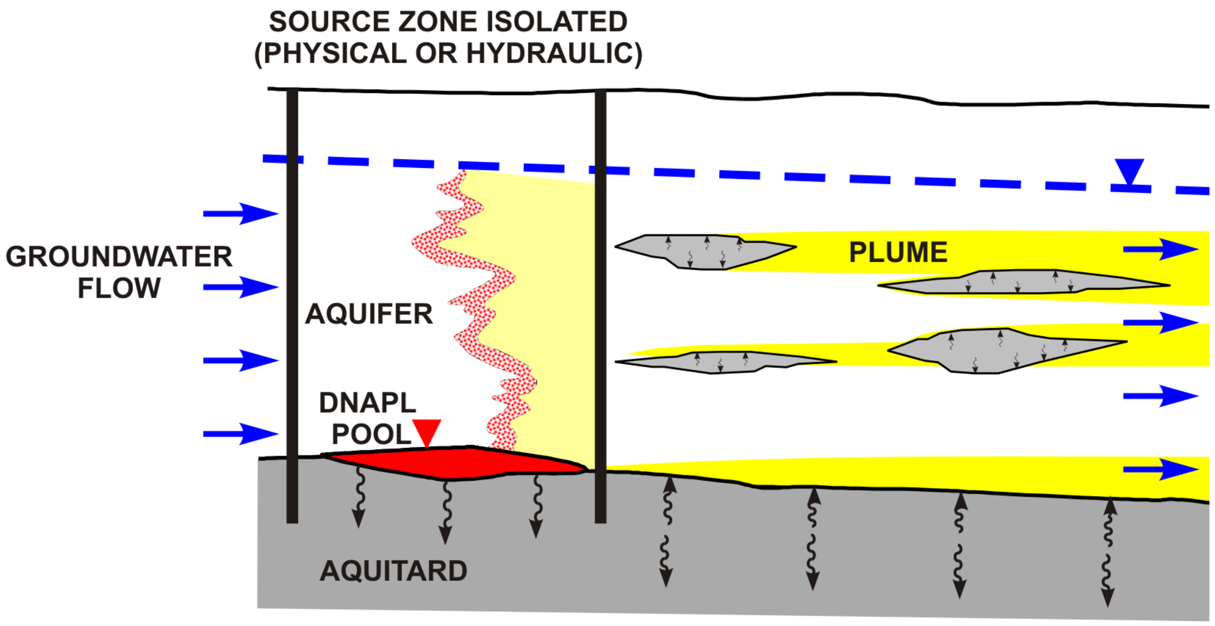
https://www.pnnl.gov/projects/remplex/workshops

In Contaminant Hydrogeology Heterogeneity is Common and Matters

Transect Approach for Plume Characterization

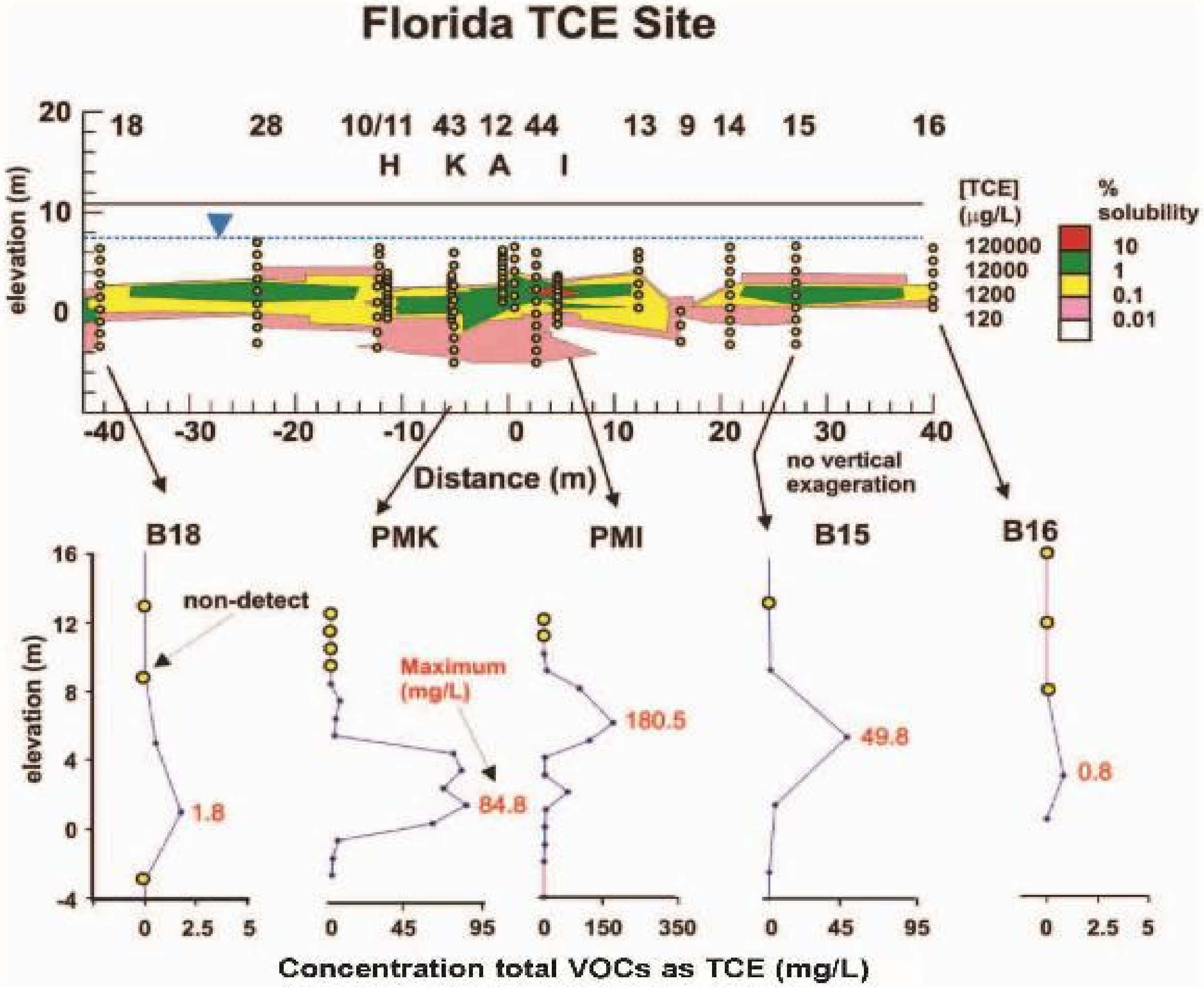


Interest in Back Diffusion Processes after Source Isolation / Remediation



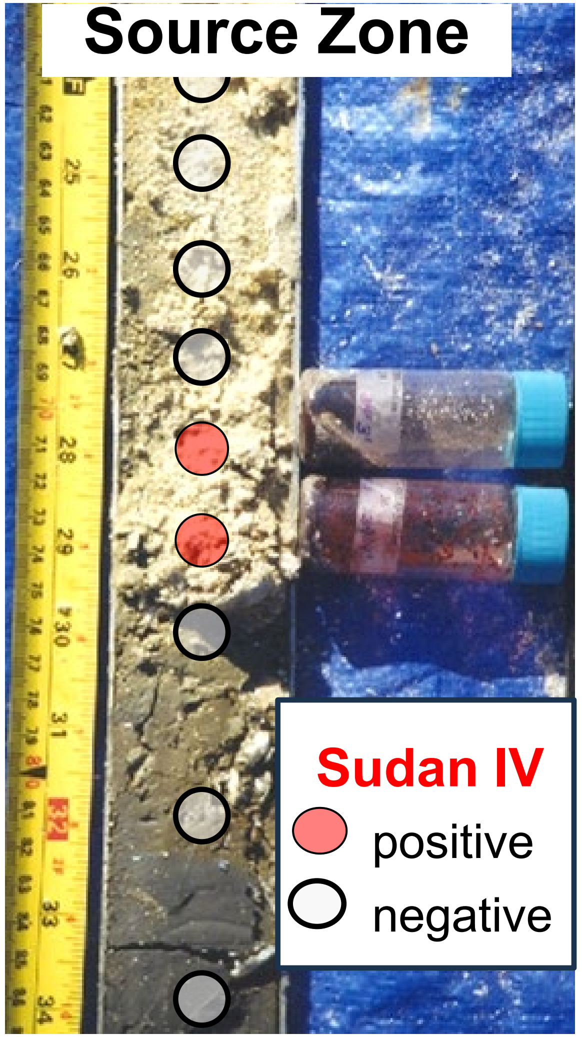
High Resolution Transect across Plume Shows Need for Multi-level Sampling

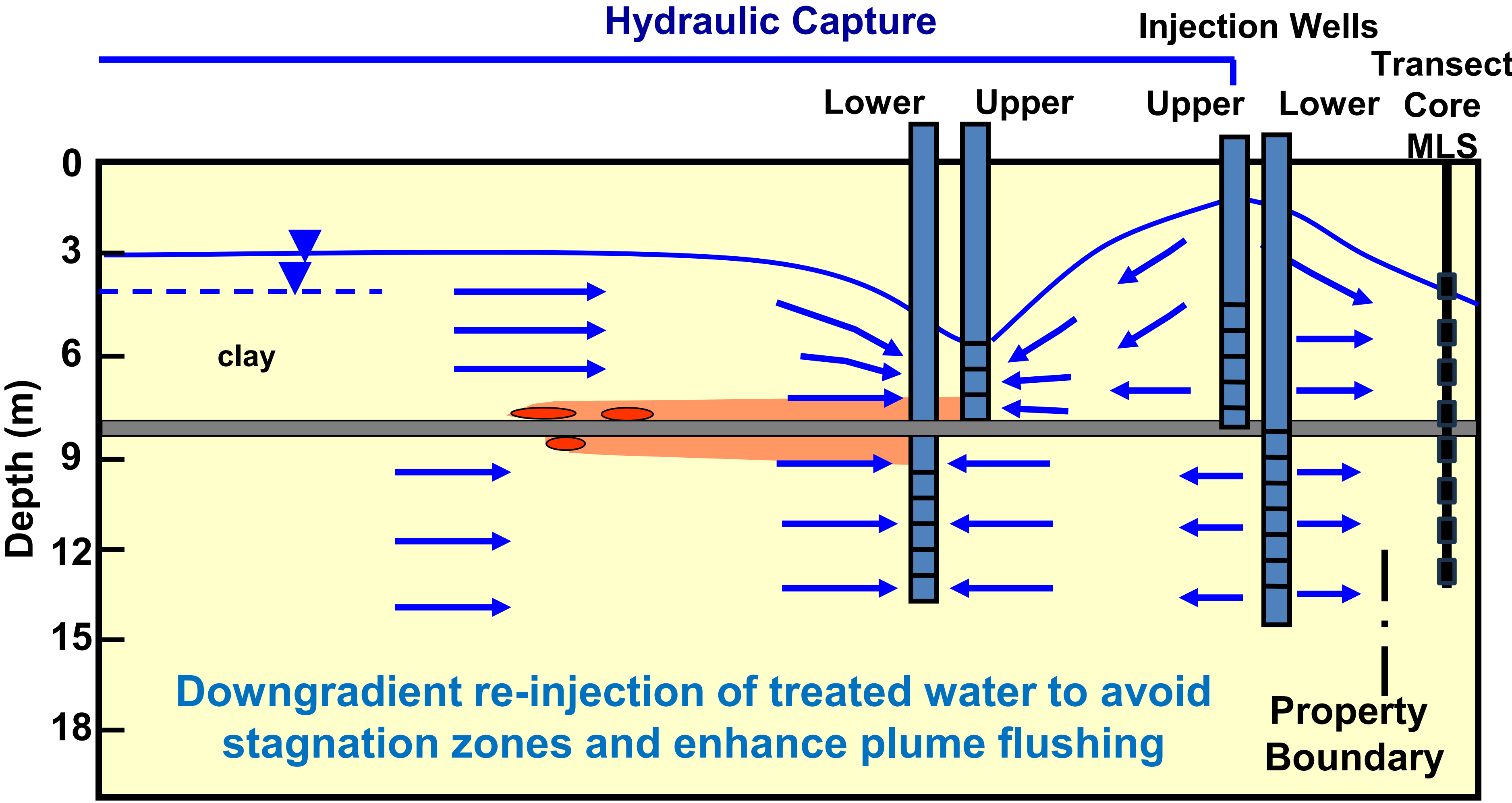
- Detailed Transects at 3 sites
- Key Findings:
  - 75% of plume mass discharge through 5-10% of plume cross-sectional areas
  - observed up to 3-4 OM variation within 0.3 m vertical intervals
  - tight vertical spacing required to delineate high conc zones
  - conventional wells provide misleading results
- Understanding plume distribution and mass discharge essential for
  - assessing natural attenuation
  - targeting remediation efforts



Guilbeault et al., Groundwater (2005)

PFC Hydraulic Capture System
Started 8/2002 → Shut down 2024





Parker et al. JCH (2008)

Core Subsampling for Mass in Low K Zones: Significant Mass in Clay Layers (Dissolved / Sorbed)

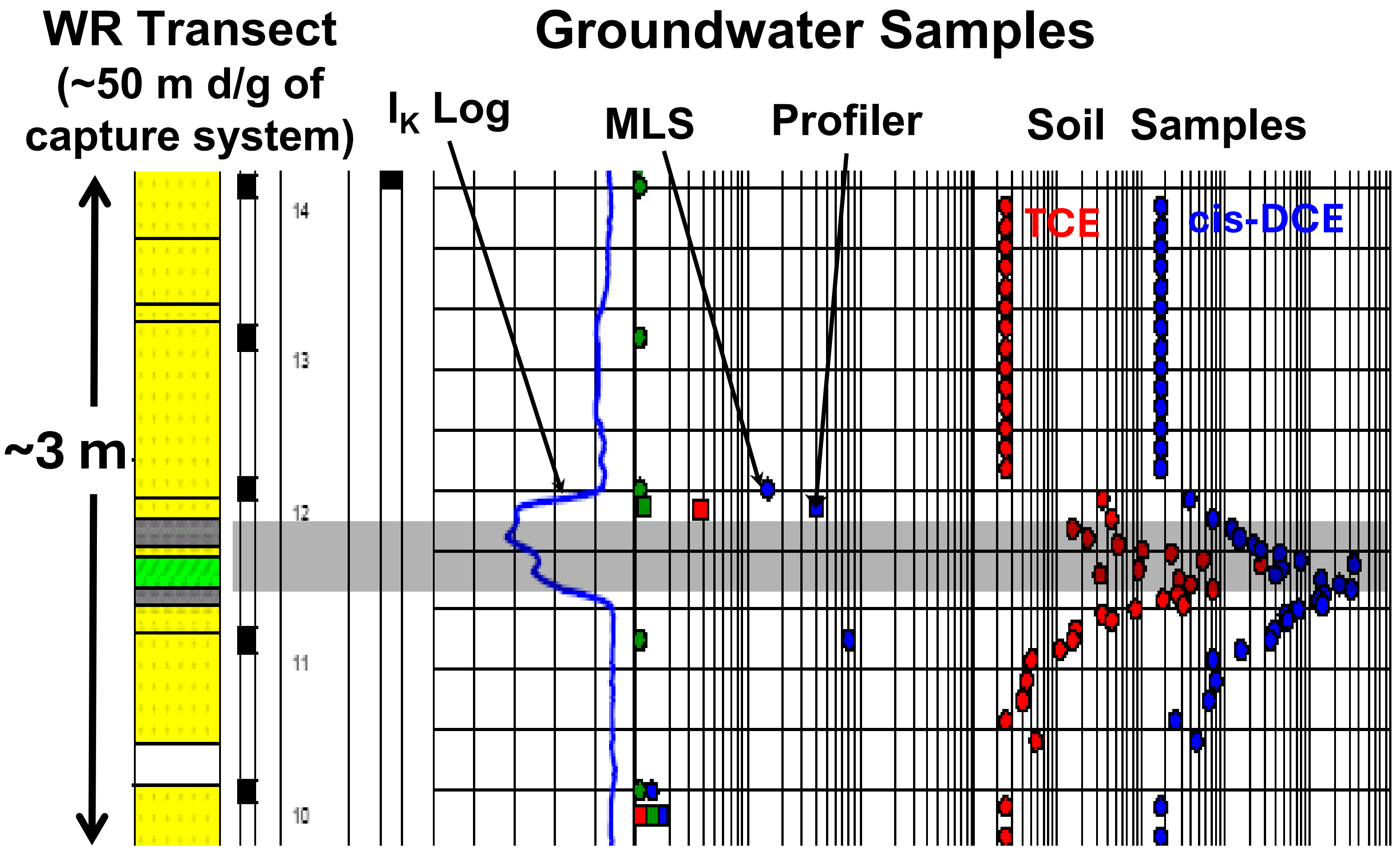
"Regulatory monitoring"
(MNA - conventional wells)

Transect monitoring
(4 d/g transects - multilevel wells)

Targeted 'Golden Spike'
profile collection ~2009
~7 years after P&T started

P&T system shut down ~2024
(successful cleanup – MNA wells)

BUT significantly delayed due to mass in clay layer(s)



Process insights (diffusion, sorption, degradation) only determined by sampling core !

DFN-M Framework for Fractured Rock Site Characterization

Multi-Disciplinary Data Sets for Building Process-Based CSMs

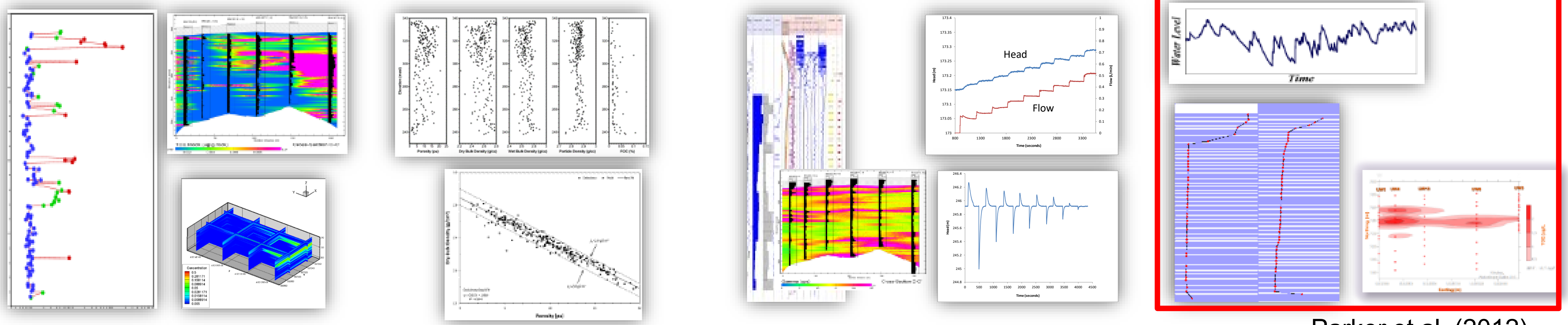
Matrix Properties & Contaminant Distribution

Drill Corehole

Flow System Characterization & Plume Distribution

- **Core**
  - **Contaminant Analyses**
  - **Physical / Chemical Properties**
- **Cored Hole**
  - **Geophysics / Hydrophysics**
  - **Hydraulic Testing**
  - **Multilevel Systems**

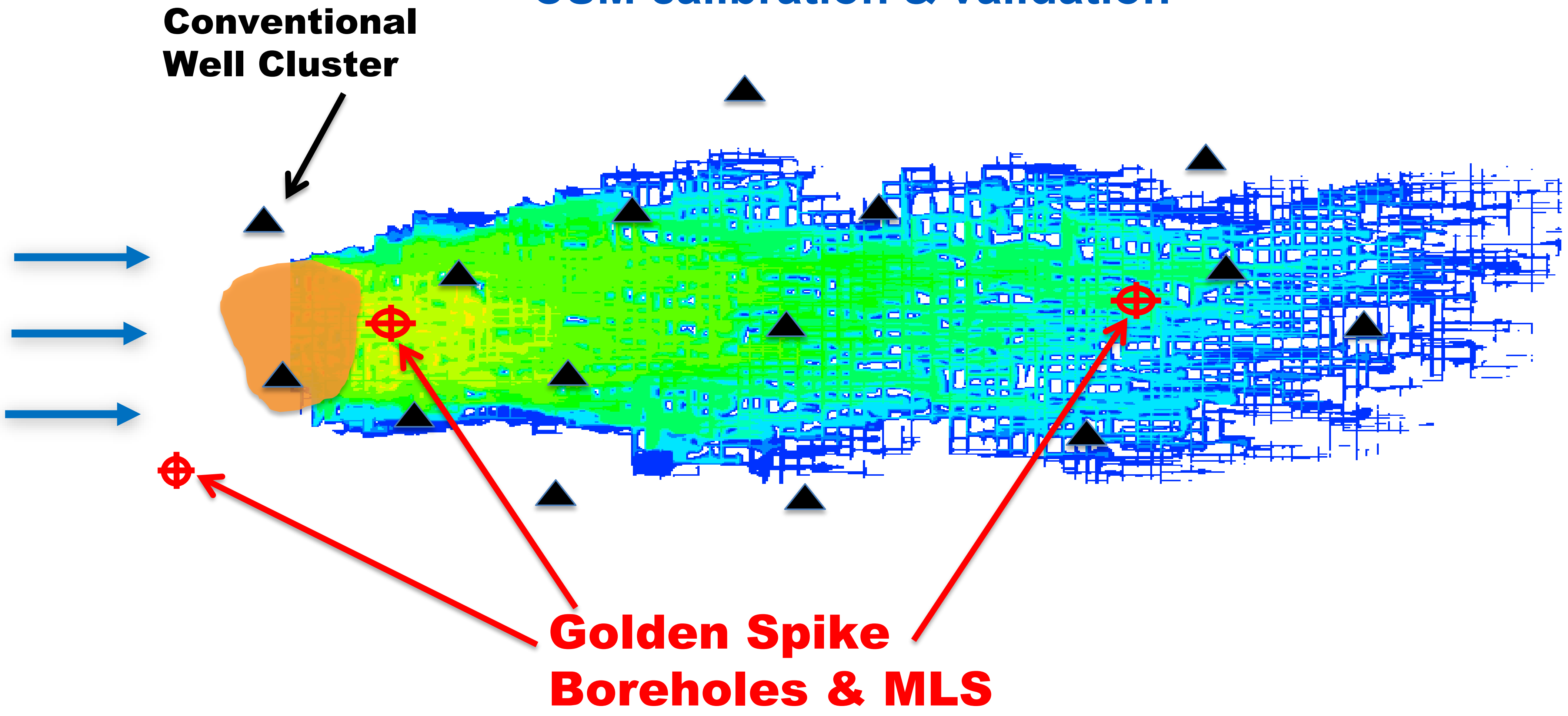
Purpose built MLS



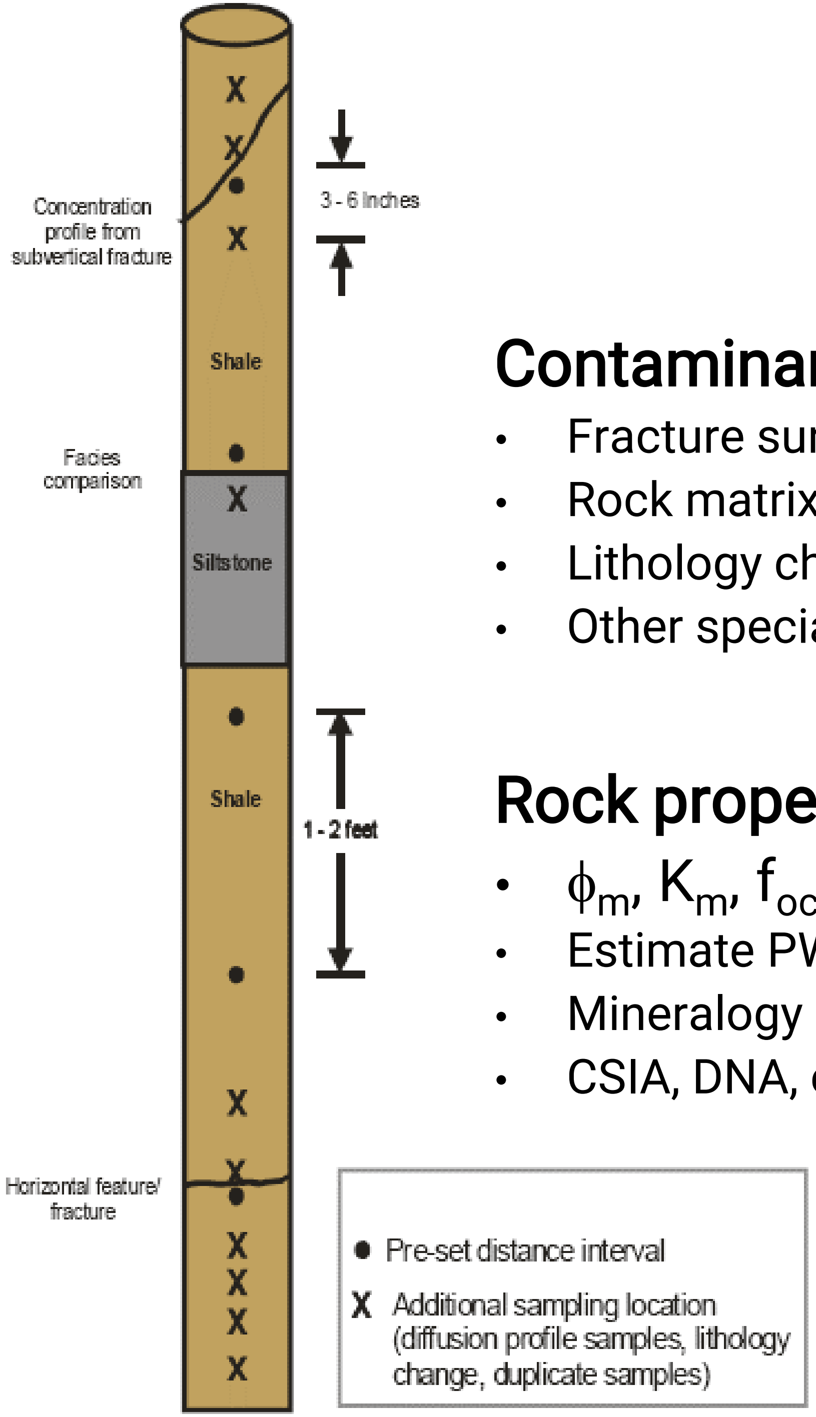
Parker et al. (2012)

HRSC at Sites with Existing Characterization: "Golden Spike" Boreholes

Generate field evidence for processes and rates: CSM calibration & validation



High Resolution Core Sampling for Mass Distribution



Contaminant Samples

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

Rock properties

- ϕ_m, K_m, f_{oc}
- Estimate PW concentrations
- Mineralogy
- CSIA, DNA, etc.

New Jersey Superfund Site (Hexavalent Cr)

Mudstone (83.5 - 98.5 ft interval)

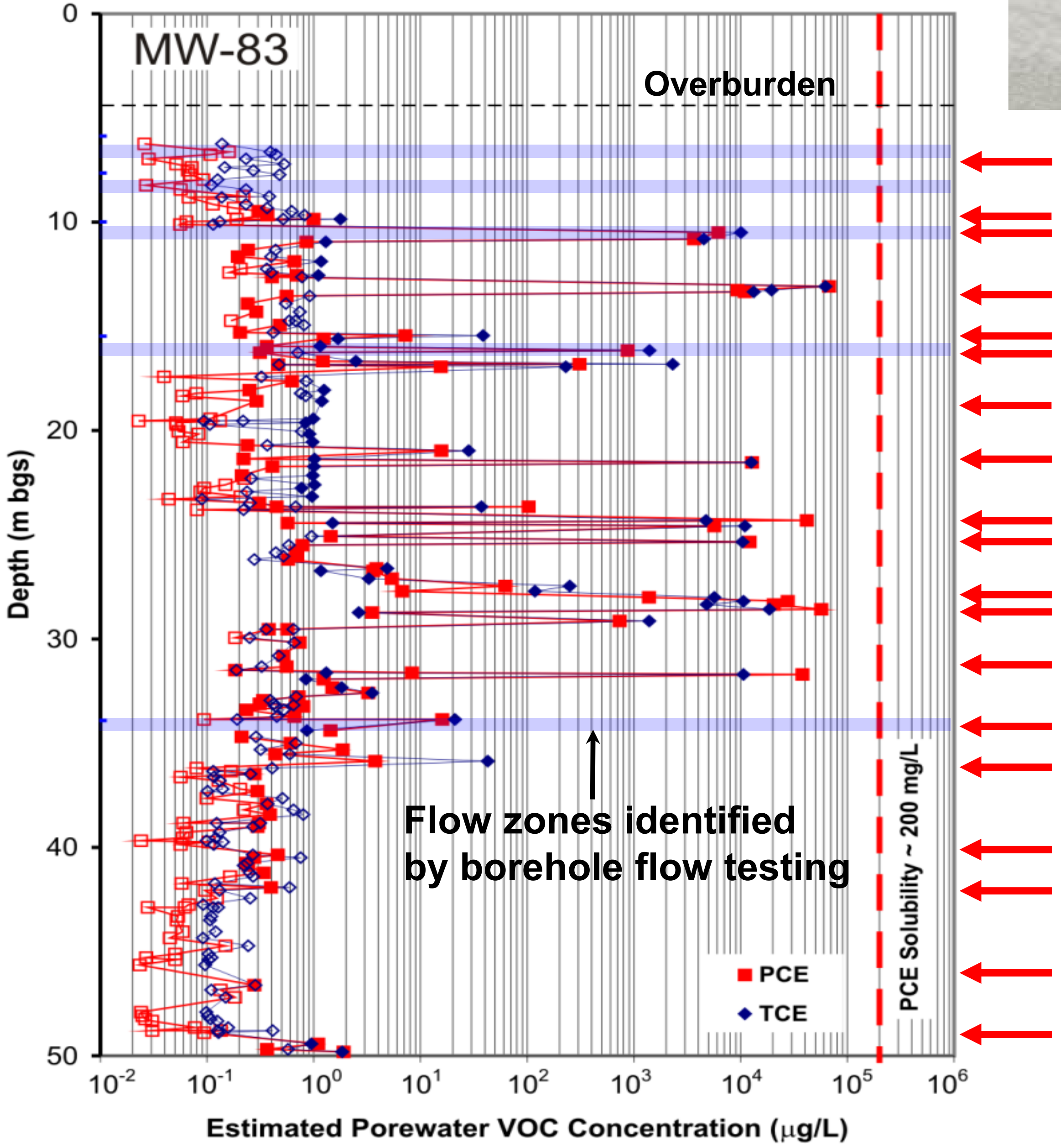
Adapt sampling to site / contaminant conditions

- Rock matrix properties
- Contaminant type(s) and sorption / reactions
- Age of contamination

<u>Commercial Application</u>

Pace® SANBORN HEAD CORE DFN™

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

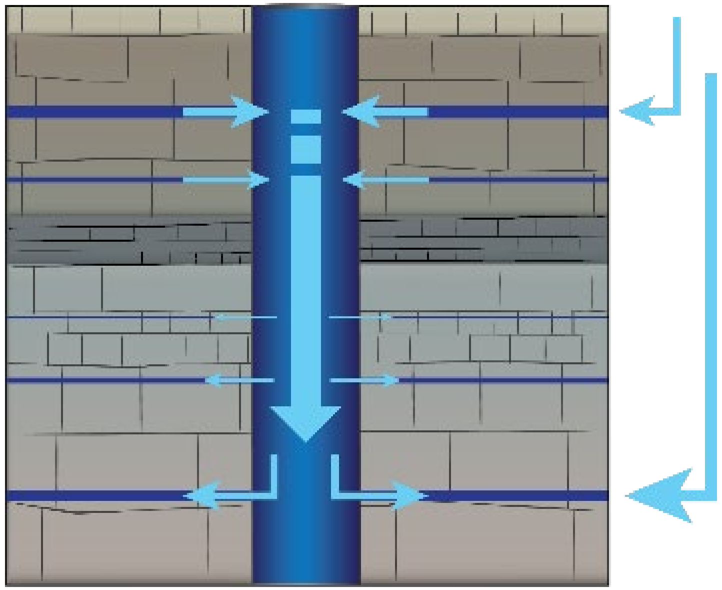
VOC PATHWAY FROM ROCK CORE SAMPLING

Parker et al. (2018)

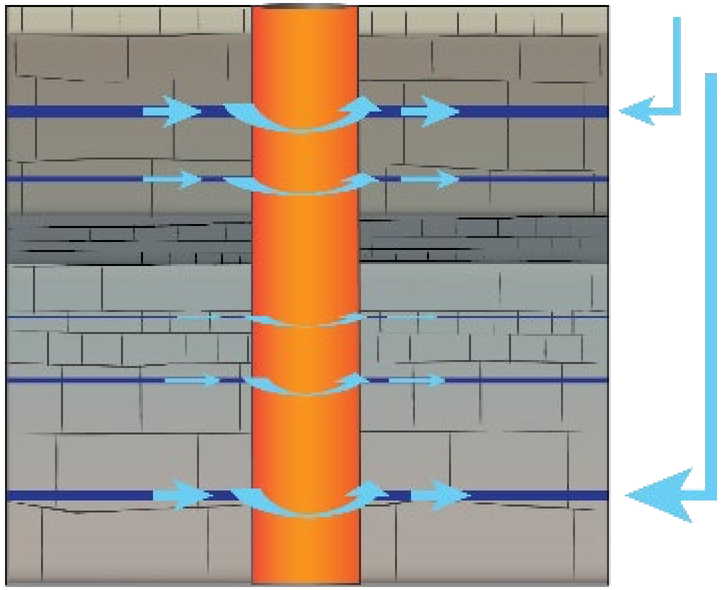
Blank FLUTe Liners to Seal Boreholes

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

Open Borehole (Cross-Connected)



Sealed Borehole (Ambient Flow Restored)



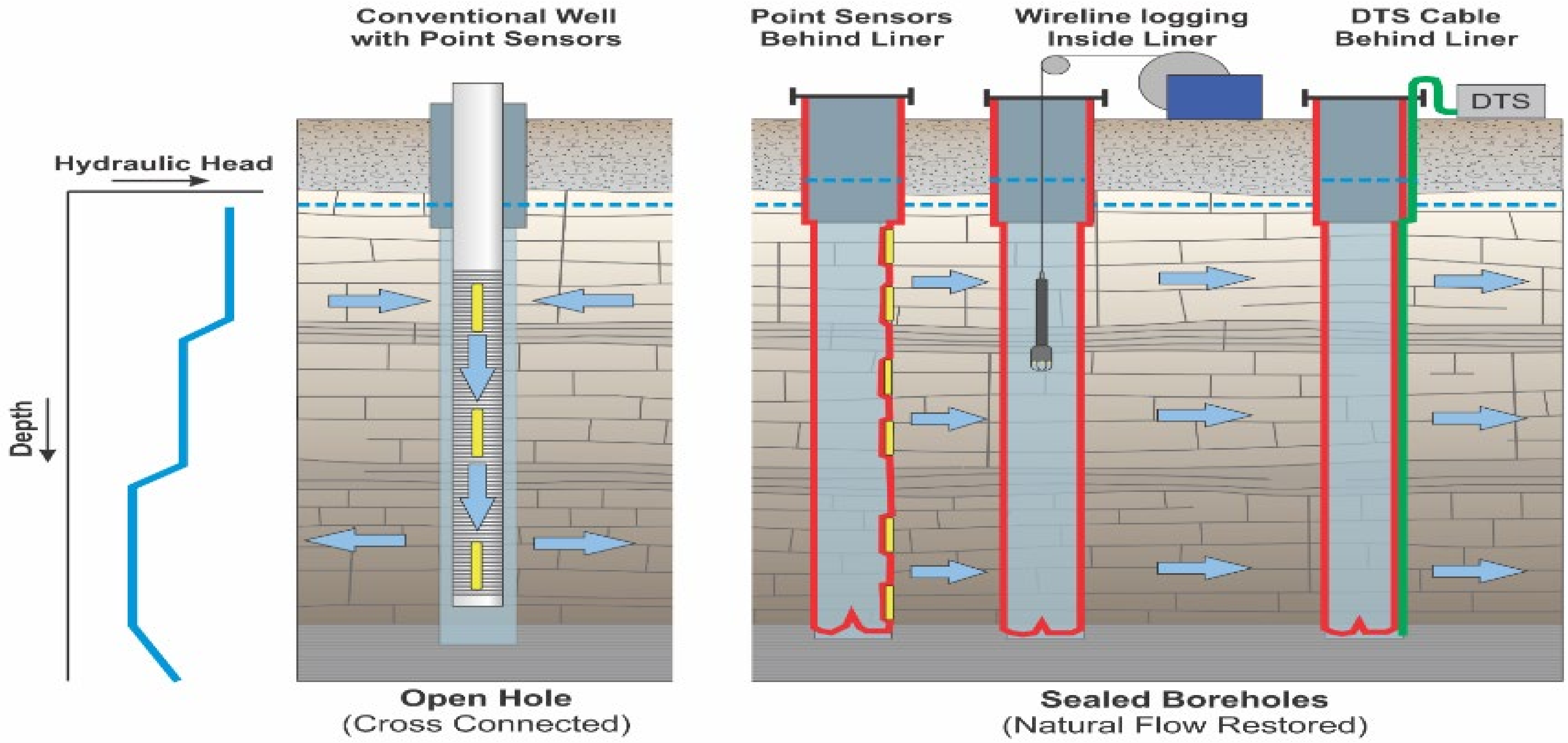
Solinst Flute

Sensor Deployment Options using Blank FLUTe™ Liners

Temporary Transducer Deployments

ALS

A-DTS



Other liner datasets:

- FLUTe T-profiling
- FLUTe RHP

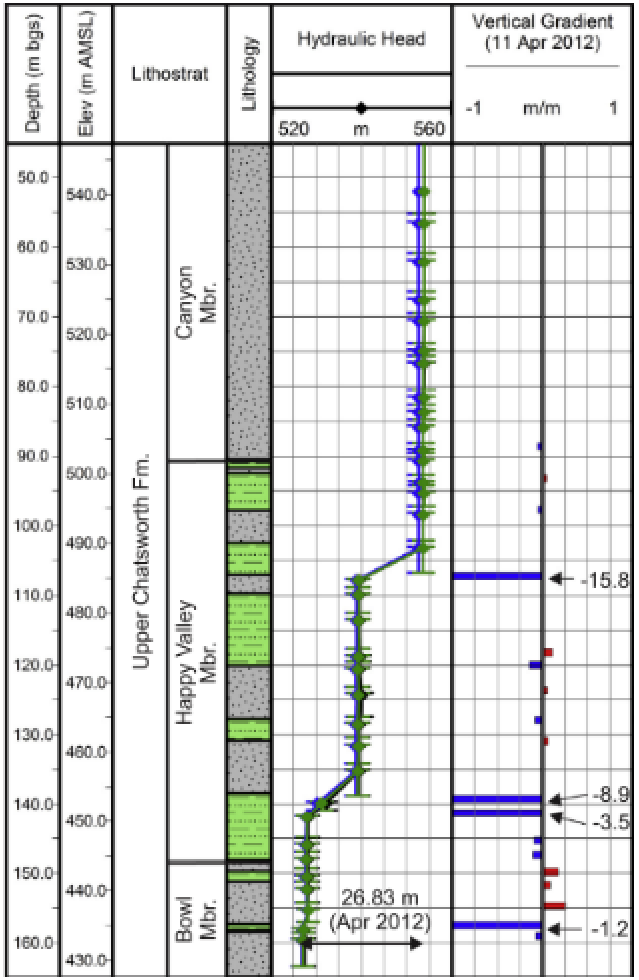
Insights on:

- Hydraulic head
- Transmissivity
- Fracture flow

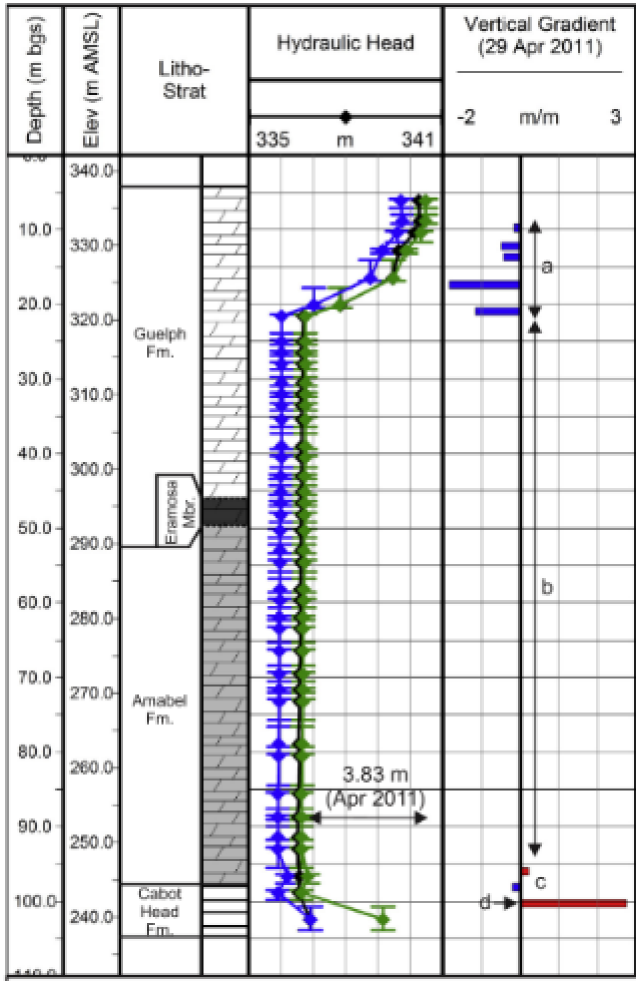
Key datasets for informed MLS design

DETAILED MLS AS 'EXPERIMENTS':
3 DIFFERENT SEDIMENTARY BEDROCK SITES

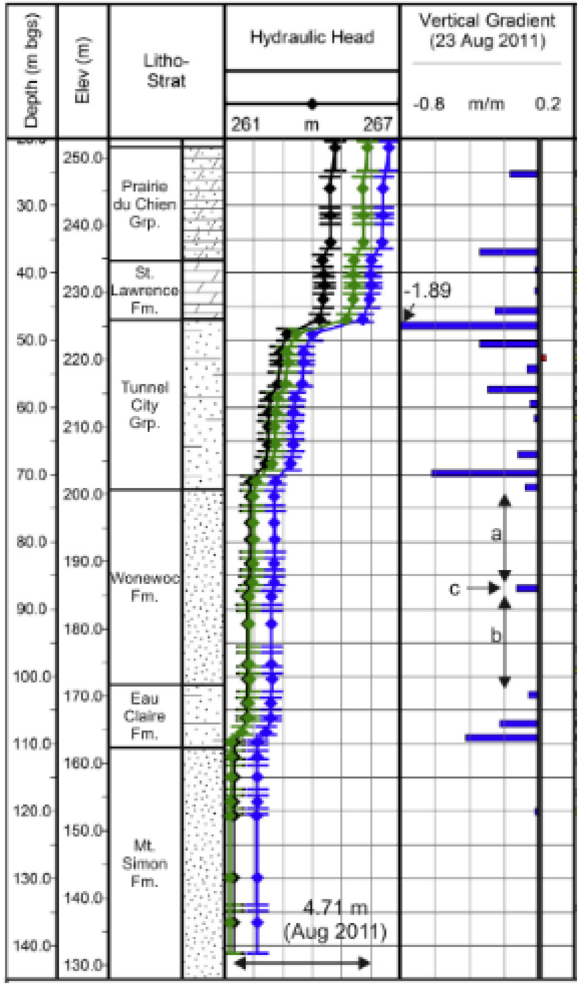
California SSFL RD-31



Guelph MW-24



Wisconsin MP-6

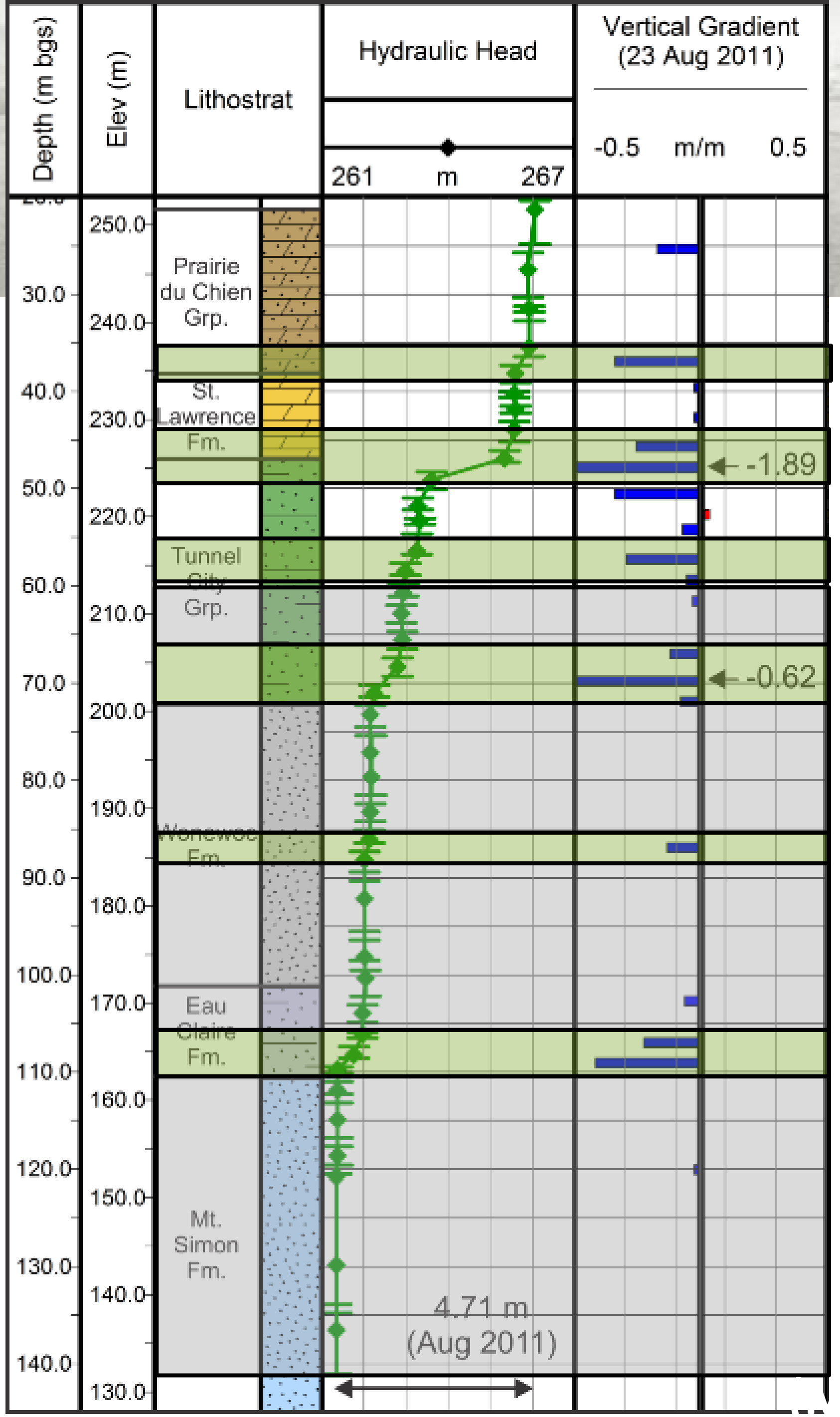


Install Summary:

- 12 systems total
- 17 – 46 ports
- Depths 90 – 260 m
- 2 – 5 zones per 10 m

Meyer et al., J. Hydrology (2014)

Head Loss Zones Do Not Always Compare to Lithostratigraphy



Wisconsin Site

Relatively low K_v

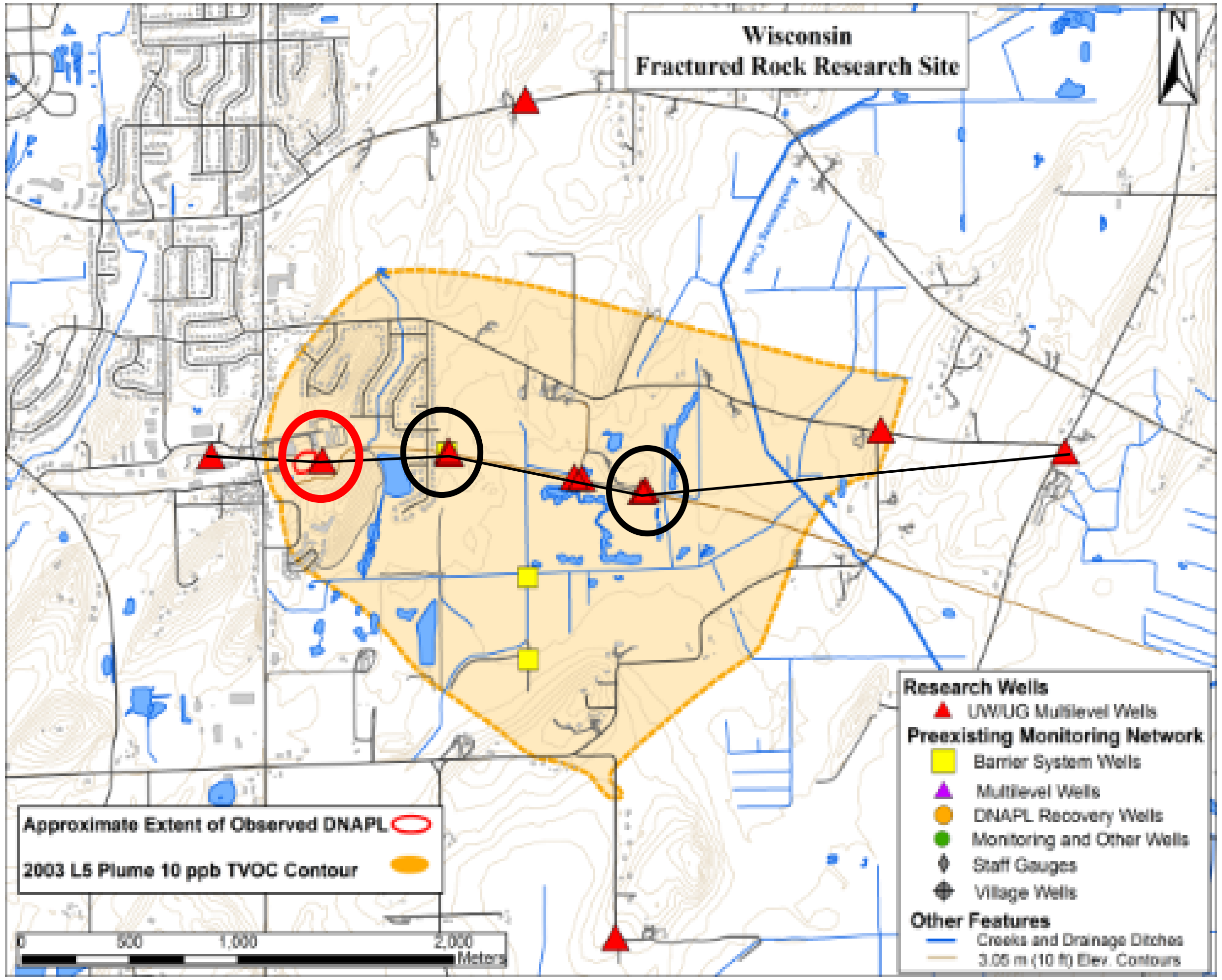
Relatively high K_v

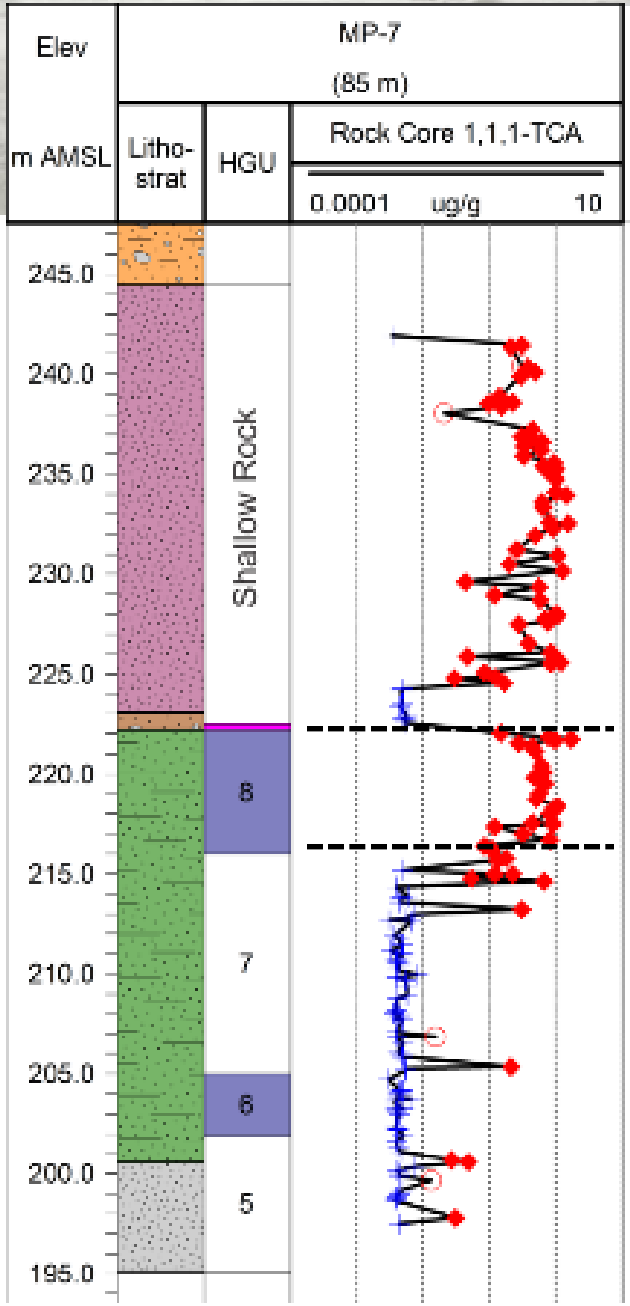
Lithostratigraphy is not always predictive of the position / thickness of K_v contrasts (aquitards)

Source Zone Core Profile

Wisconsin Site

Rock Core Contaminant Profiles





Quantifiable

Not Quantifiable

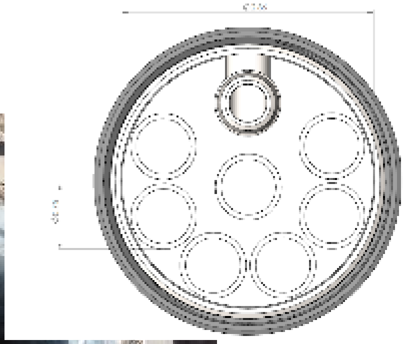
Non-Detect

Key Observation:

Contaminant profiles show characteristics consistent with HGU boundaries

Austin MASc. (2005)

G360 MPS: New Low-Cost, Versatile Multi-Port System (Adapted Versions of Modular Waterloo MLS)



Design Flexibility

- *Multiple diameter options*
- *Packer & Backfill versions*
- *Overburden & bedrock*
- *Removable (optional)*

Lower Complexity

- *Open tube systems -- lower-cost*
- *Solinst produces ports and end plugs*
- *Source casing and tubing close to site of interest*
- *Removable sensors for monitoring / sampling (non-dedicated)*

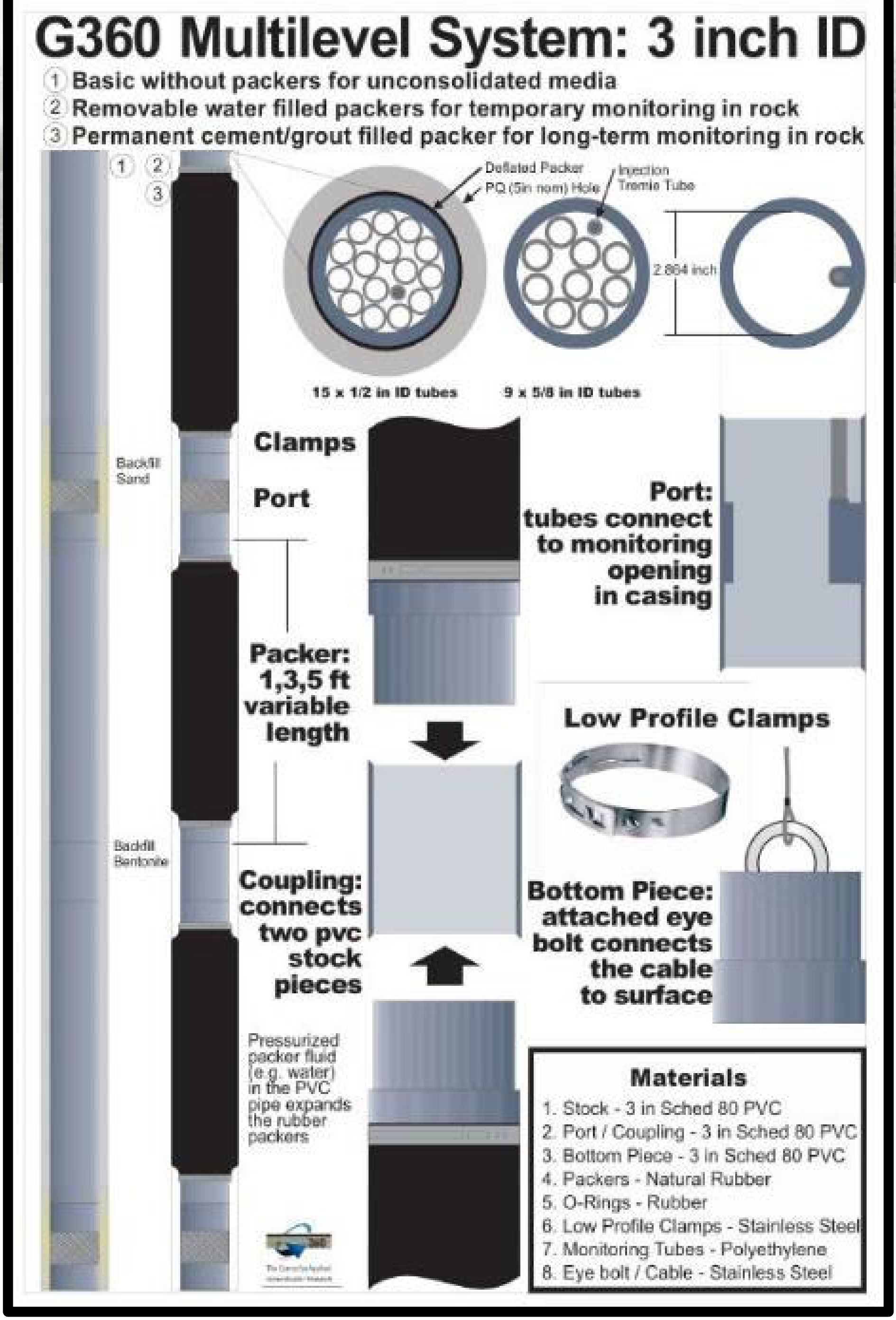
G360MPS (Multi-Port System)

Research Version

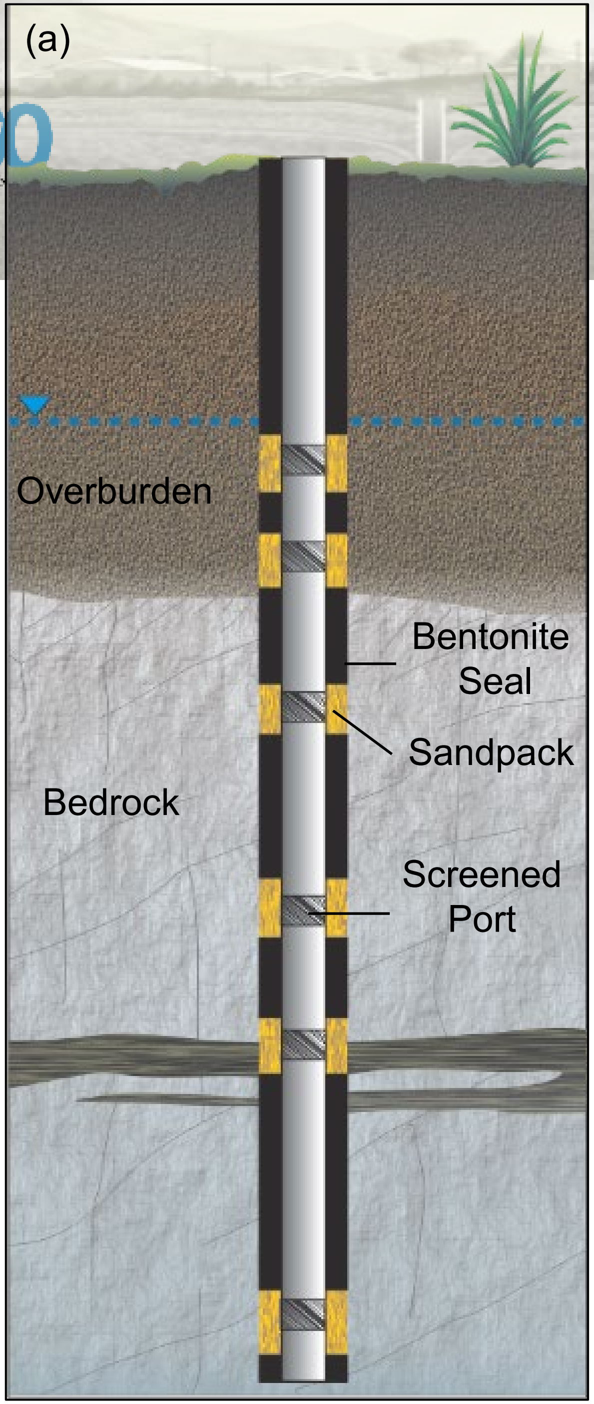
Temporary Packers (Removeable)

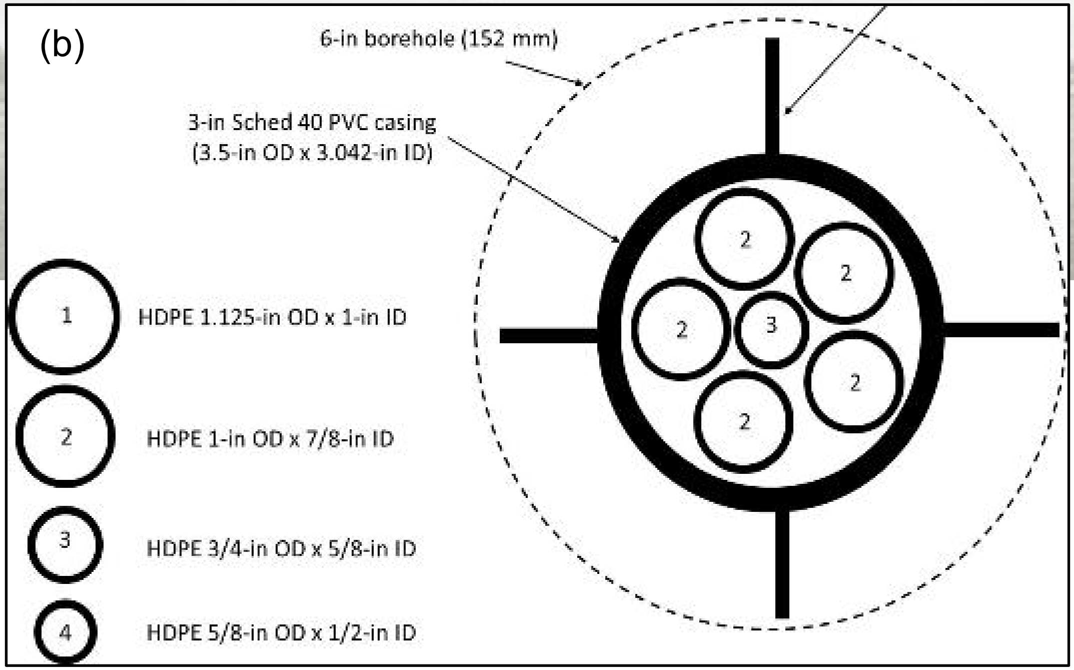
Multiple system diameter and internal tubing options

Sealed wellhead (packer inflation)



G360MPS Commercial Version





Ports, Adapters, End Plugs

Solinst

Threaded Sch.40 PVC (nominal 3-in)

Internal HDPE Tubing

(Local suppliers)

Monitoring and Sampling Options: G360MPS
All Removeable → No Dedicated Equipment

- Hydraulic monitoring
  - Small diameter WL meters
  - Self-contained pressure transducers
    - Van Essen Micro-Divers
    - Solinst Levelloggers
    - Insitu Level Troll
- Groundwater sampling
  - Waterra pumps (Standard or Low-Flow)
    - Excellent for port development
  - Peristaltic pumps (shallow WT)
  - Gas Drive pumps (deep WT)
    - Solinst Double Valve Pump (5/8-in)
    - Small Bladder Pumps
      - QED Sample Pro (0.75-in)
      - Geotech Bladder Pump (0.675-in)

UK Trial for Driller Training – Overburden / Bedrock (30m Backfilled System, 6 Ports)

MORWICK G360 Groundwater Research Institute

Sellafield Ltd

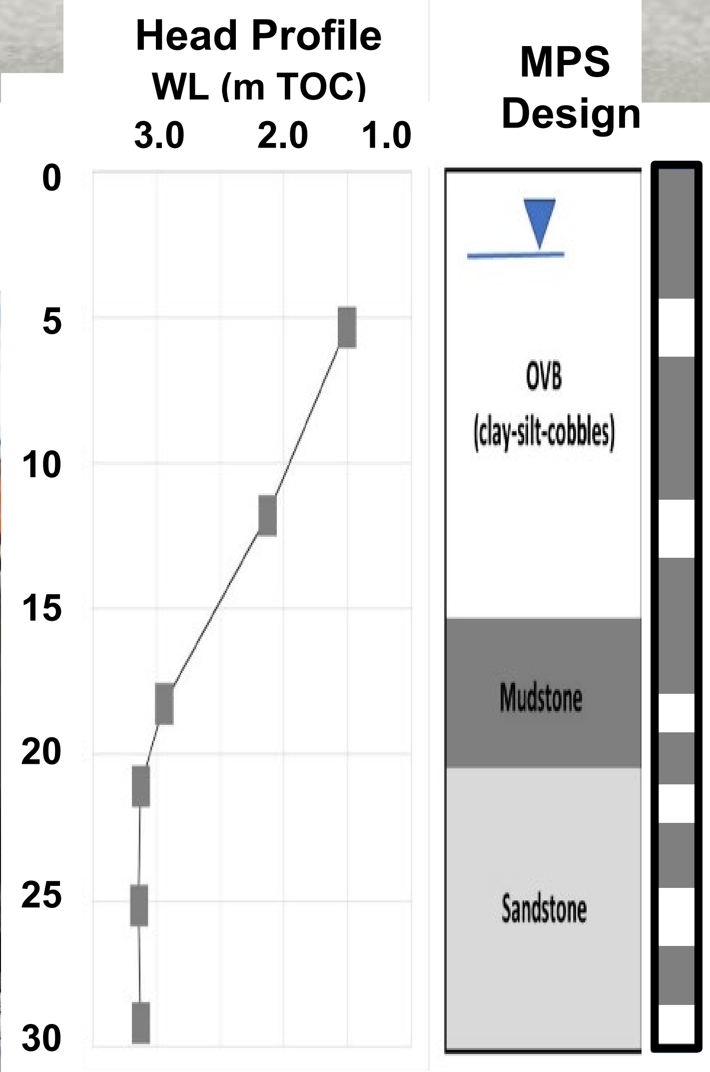
GeoSonic ON YOUR WAVELENGTH SINCE 2013

Dual Sonic / Coring Rig

Depth from (m)	Depth to (m)	Method	Diameter
GS	16.5	Sonic coring	150 mm
16.5	30.5	GeoBor-S	146 mm

Modular system
Adding casing, ports

Attaching port



Installs at Sellafield site
John Heneghan (this session)

Example Dataset: Insights from MLS Raven Site, Helsingborg, Sweden

Former dry cleaner
Historical PCE releases

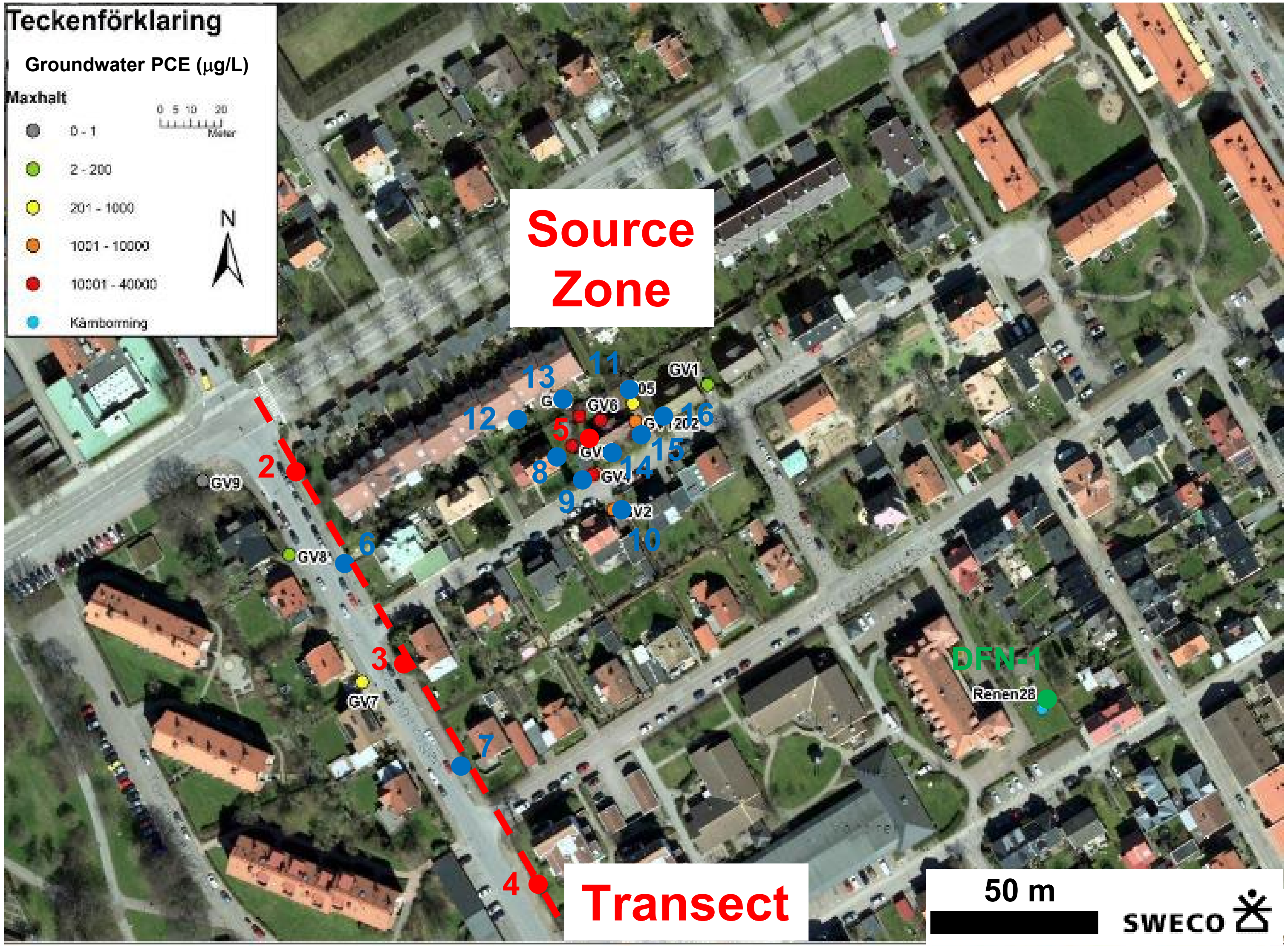
Dense mostly residential area

Building demolished prior to investigations

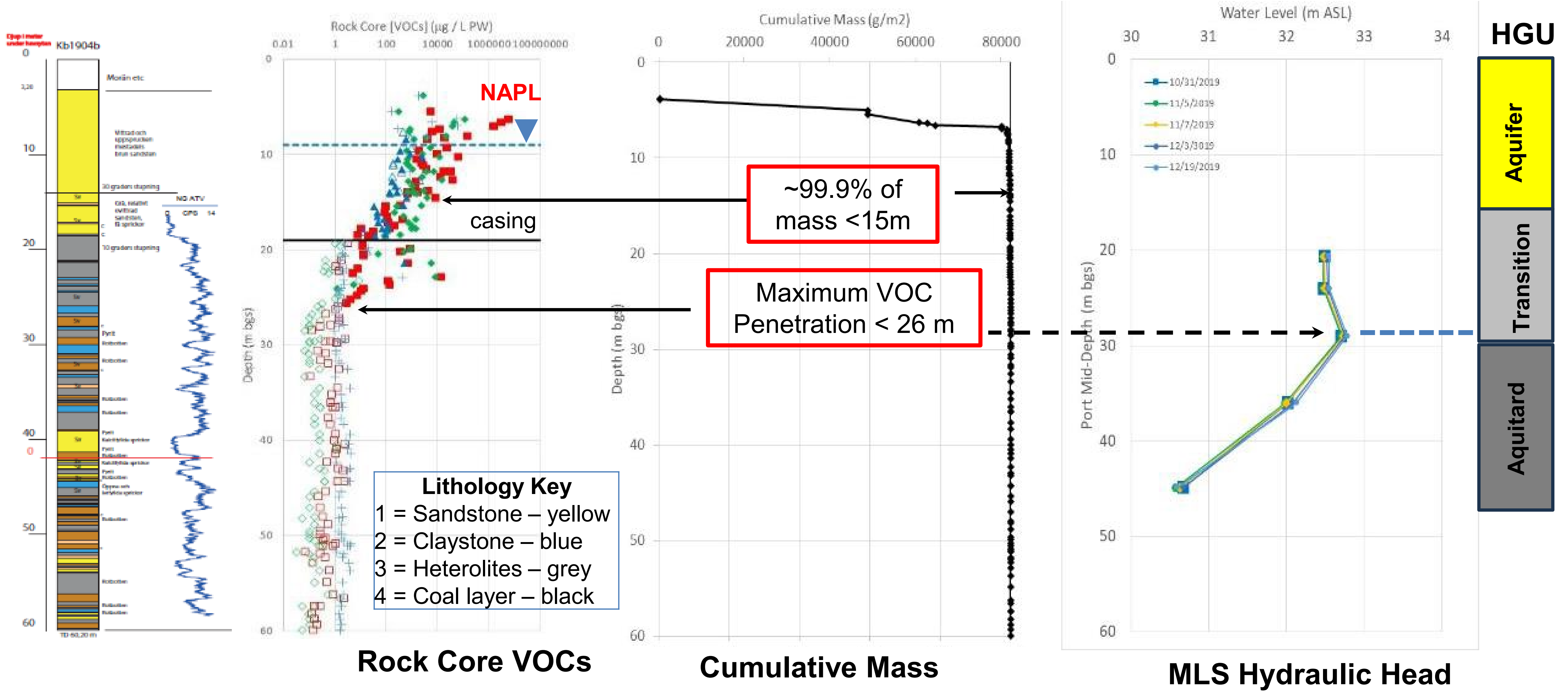
Photo credit: Erik Bergstedt, SGU

Phased DFN-M Approach at Sweden Raven Site

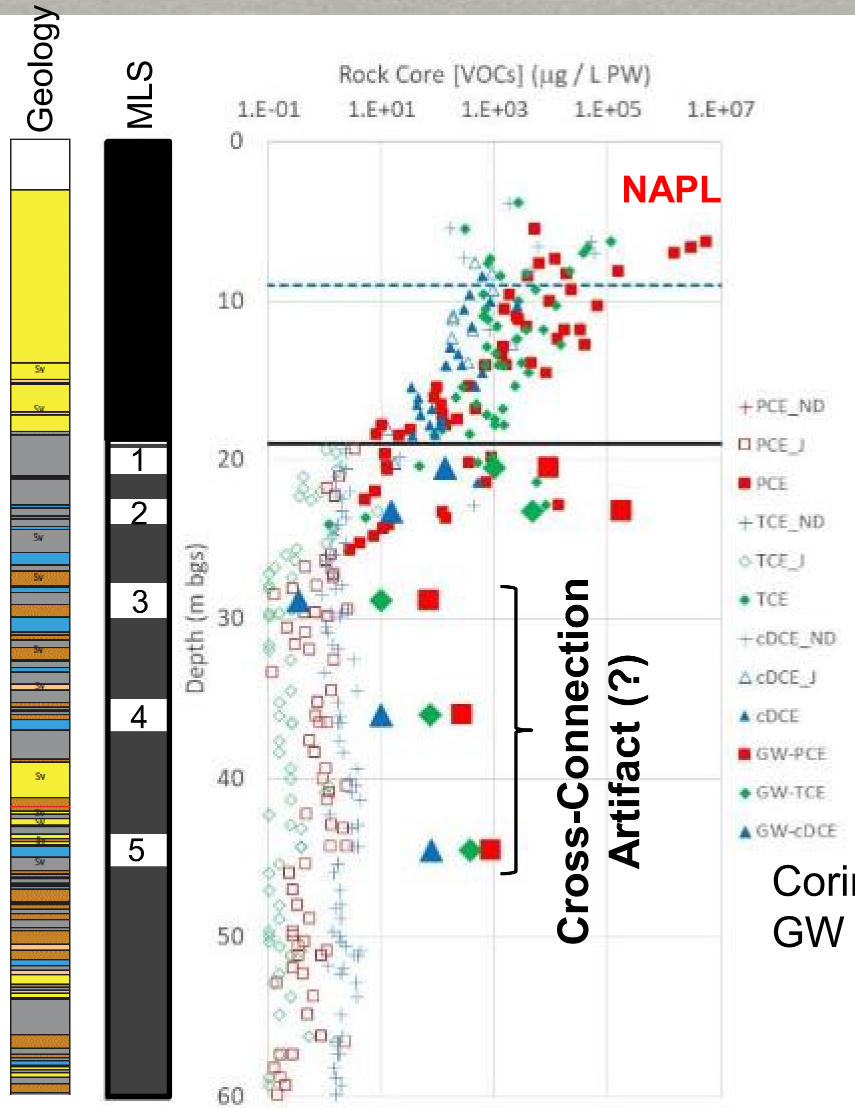
- **Phase 1 (2018)**
  - 1 corehole up- and cross-gradient (DFN-1)
  - test DFN-M methods
  - encountered buried valley (unexpected)
- **Phase 2 (2019)**
  - 3 coreholes on Transect (DFN-2, 3, 4)
  - 1 corehole in Source Area (DFN-5)
  - Depths of 60-70 m bgs
  - High resolution core sampling
  - Open hole geophysics (gamma, ATV, other)
  - Lined boreholes
    - Temporary transducer deployments
    - ALS / A-DTS flow system characterization
  - **MLS installations (G360MPS)**
- **Phase 3 (2021)**
  - 2 coreholes to fill gaps along Transect (DFN-6, 7)
  - 9 coreholes near / on-site (DFN-8 to 16)
  - Shallower depths <25 m (informed by Phase 2)
  - High resolution core sampling
  - Geophysics inside casing (gamma only)
  - **MLS installations through drill string**

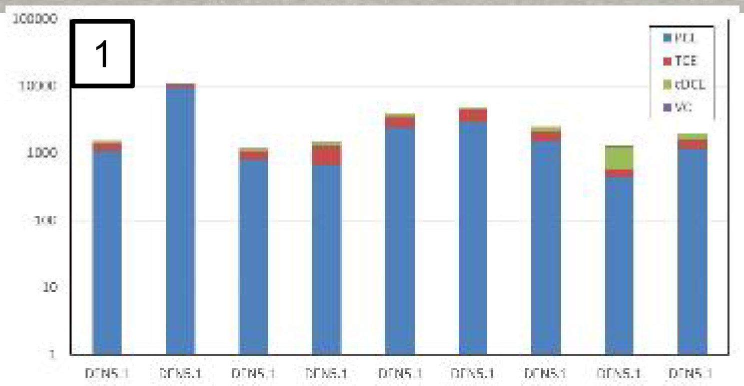


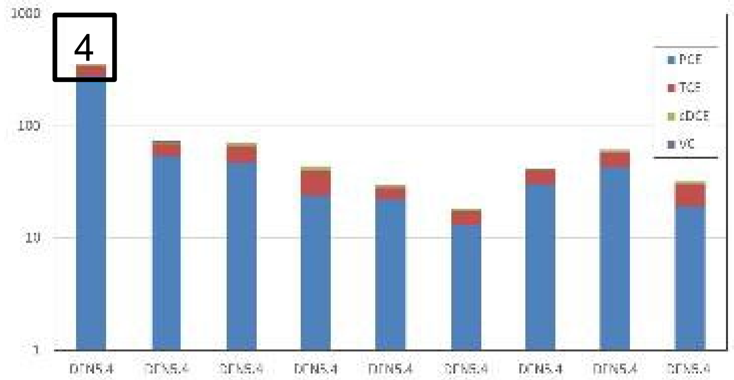
Head Profiles Indicative of Aquitard Unit(s) Preventing Deeper Contamination

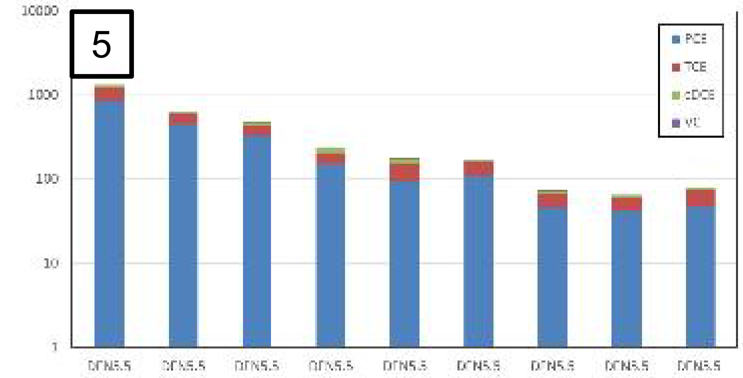


MLS Groundwater Data versus Core Porewater VOCs Source Area Borehole (DFN-5)







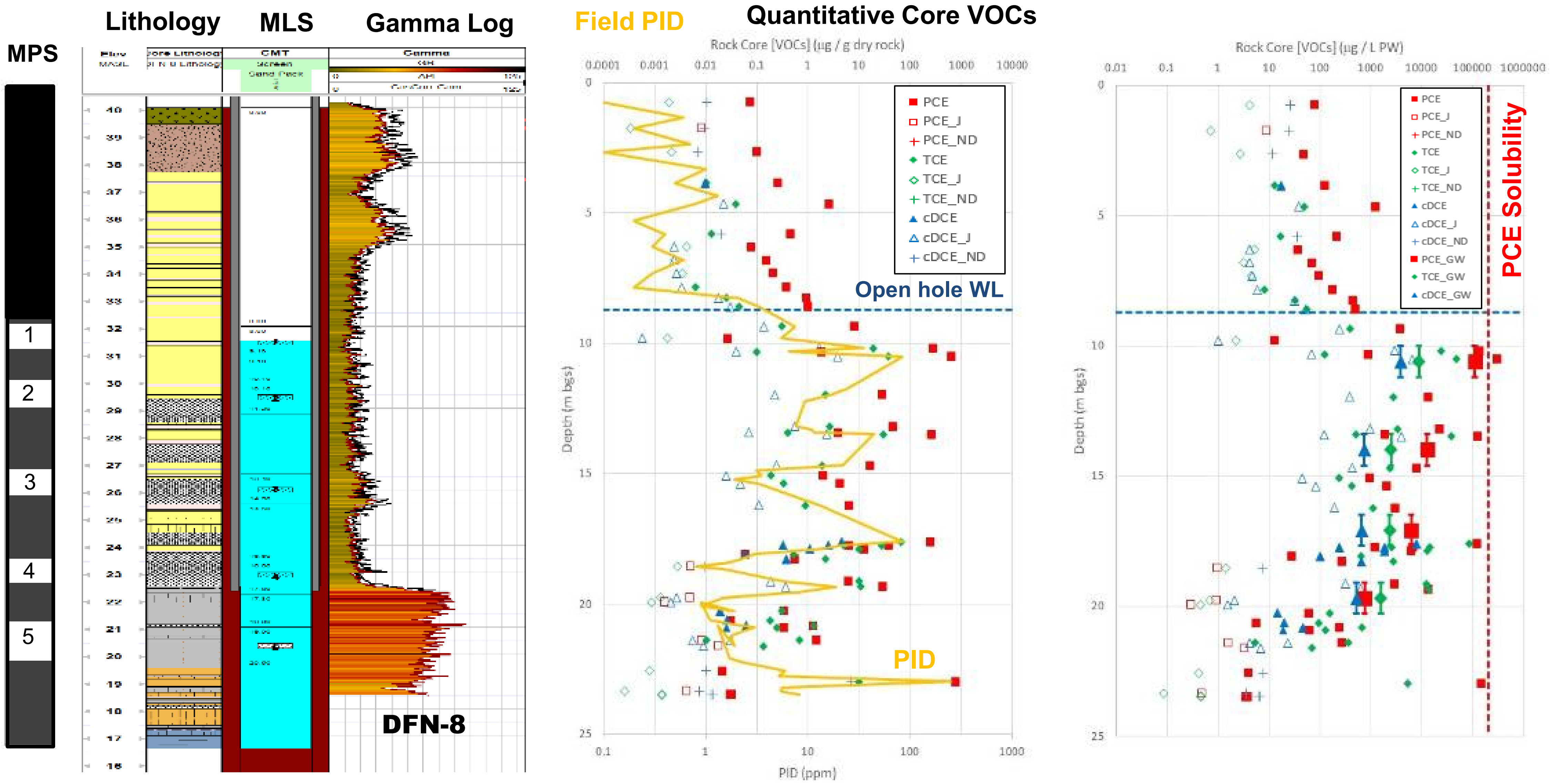


Coring ~ 5/2019; MLS Install ~ 10/2019
GW Sampling ~ 11/2019 to 3/2023

Boreholes lined except
- 1 day for open hole geophysics
- Temporary deployment removal
- A-DTS cable install / removal

Ports 3-5 → persistent cross-connection impacts

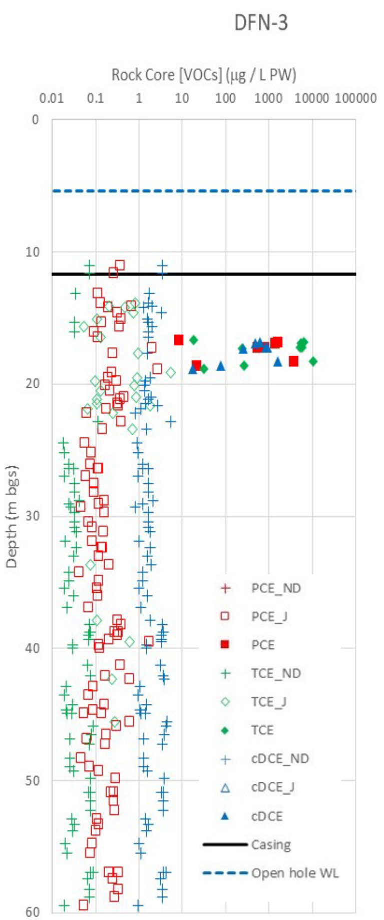
Phase 3 MPS Installations
Install through Drill String after Coring and Gamma Logging
(No Open Hole Period)

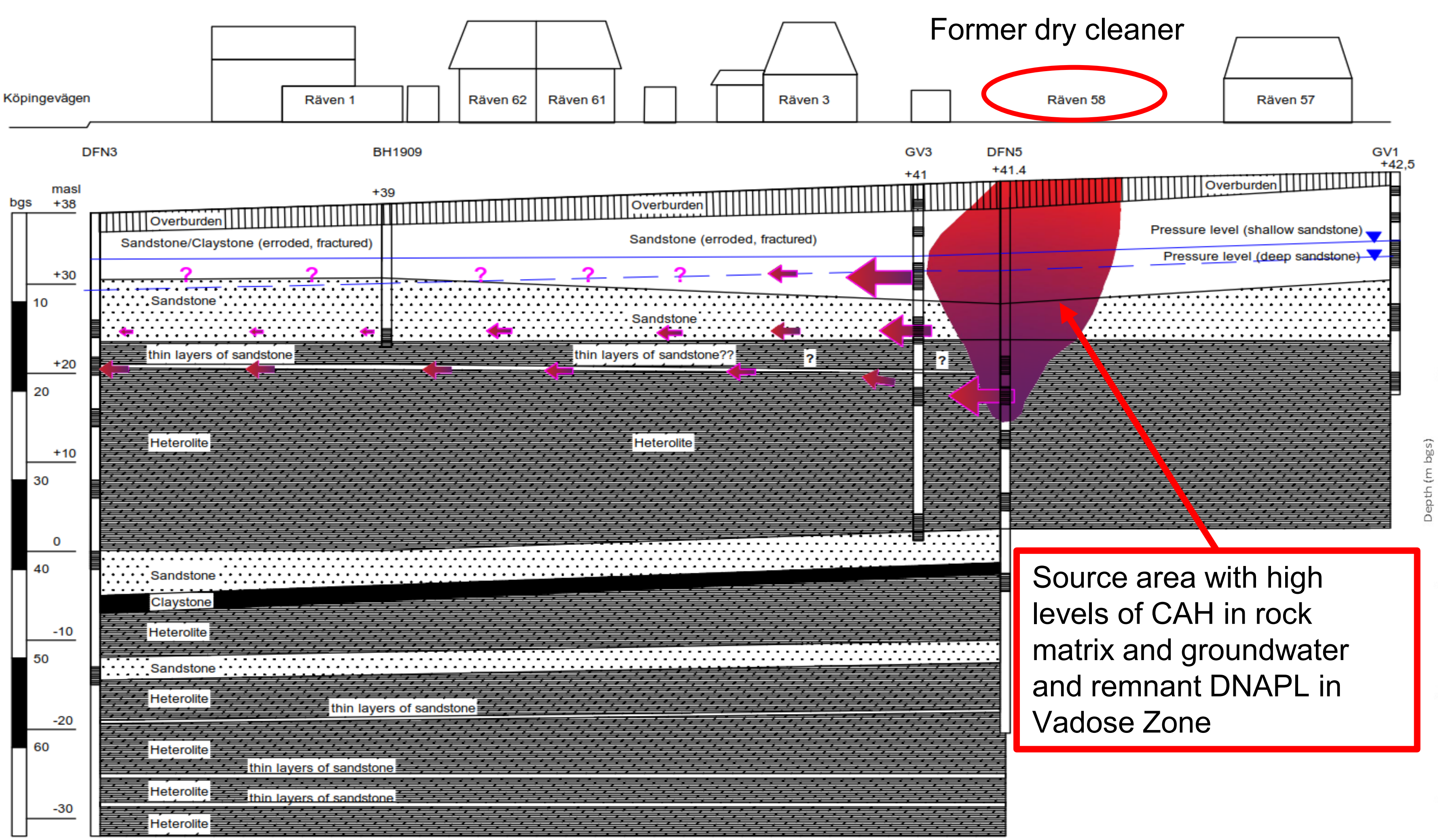


Updated Site Conceptual Model

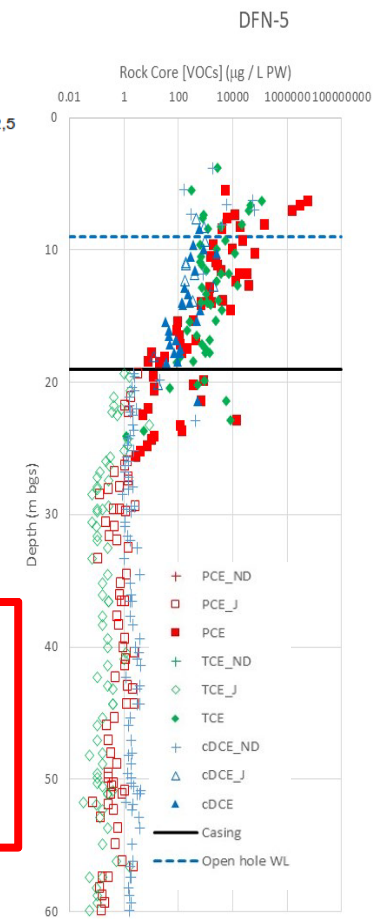
Hydrogeologic Unit Controls and Strong Plume Attenuation

Transect





Source



Key Points on MLS for Discrete Interval Characterization

1. Importance of CORE for high resolution contaminant mass distribution

2. MLS play a critical role in monitoring evolution of site conditions

3. HRSC datasets for effective MLS design (ports, seals) and results interpretation

4. Strategic MLS to complement conventional well networks
    a) Deployed along Transects
    b) Deployed at key locations ('Golden Spike' boreholes)

5. Improved SCMs (process-based) for better prediction / decision making

Thank you!
Questions?

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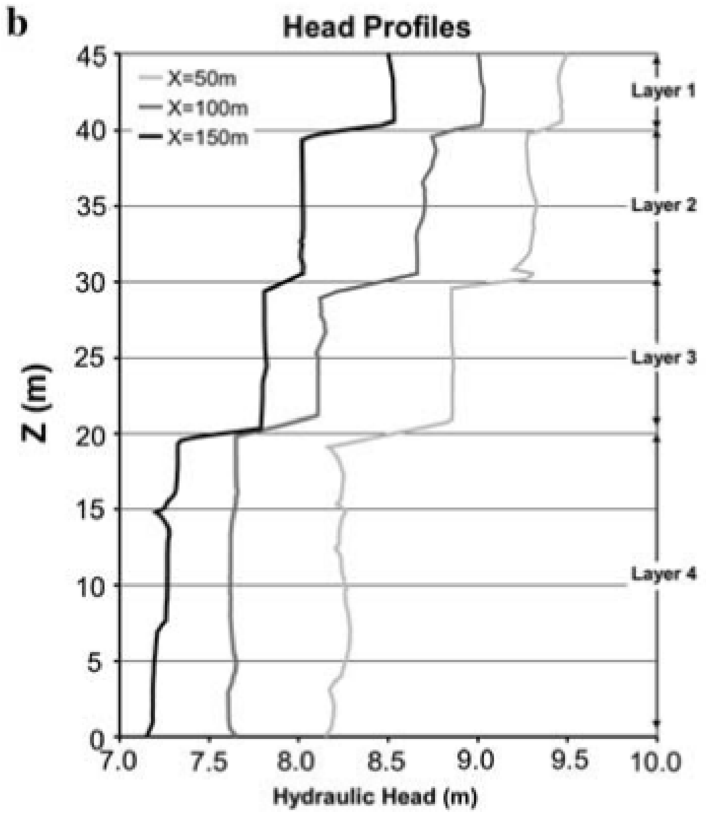
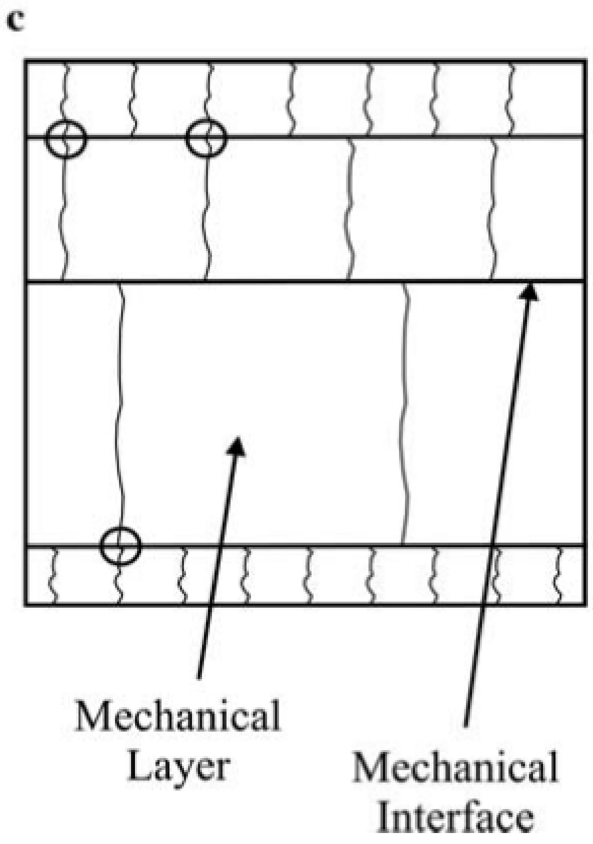
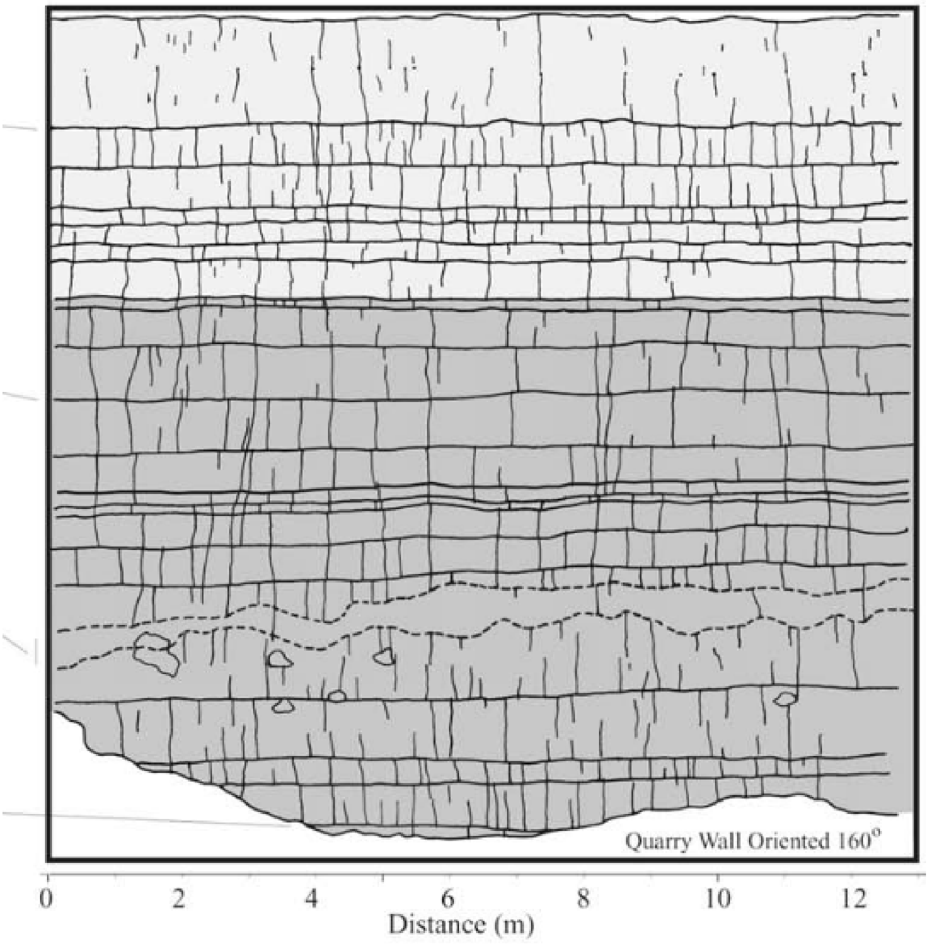
- Extra Slides

HEAD LOSS RELATED TO FRACTURE TERMINATIONS DIFFERENTIATE HYDROGEOLOGIC UNITS / AQUITARDS





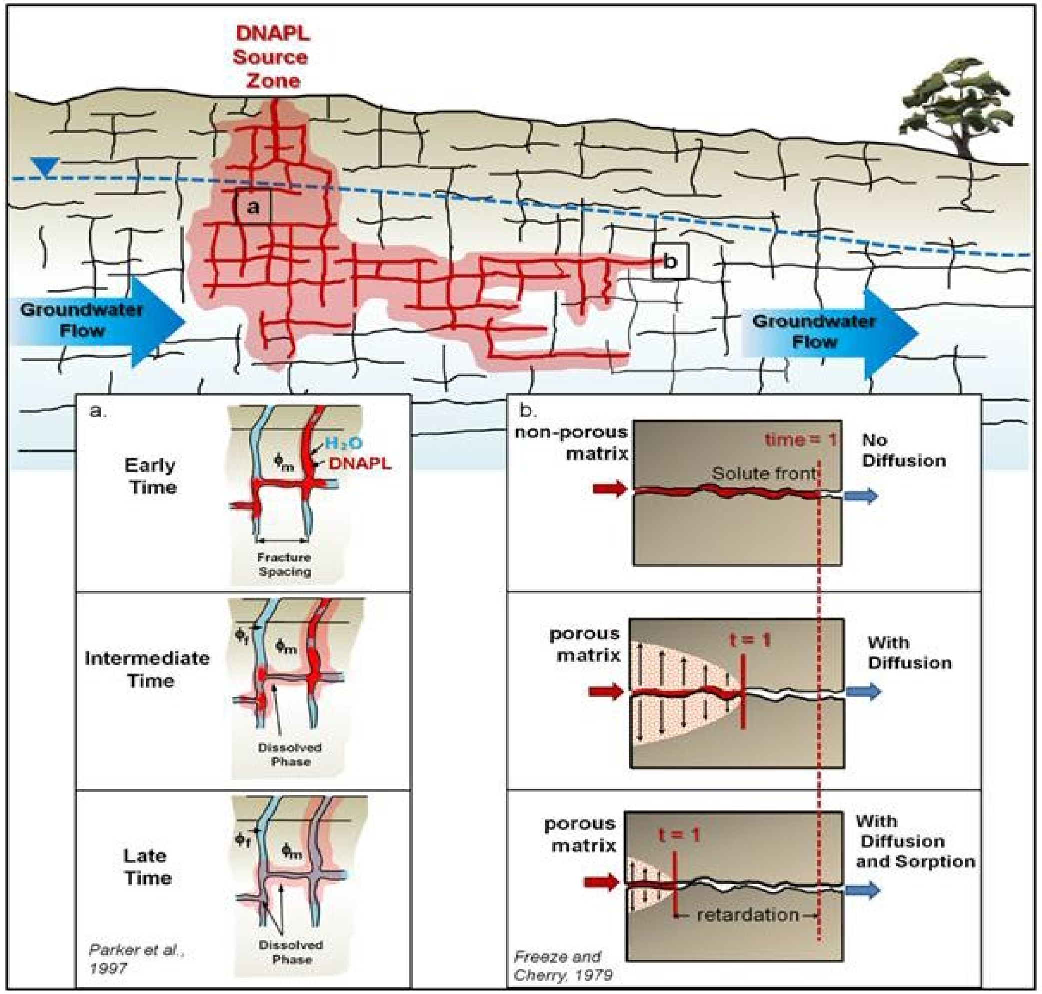


Meyer et al., Environmental Geology, 2008

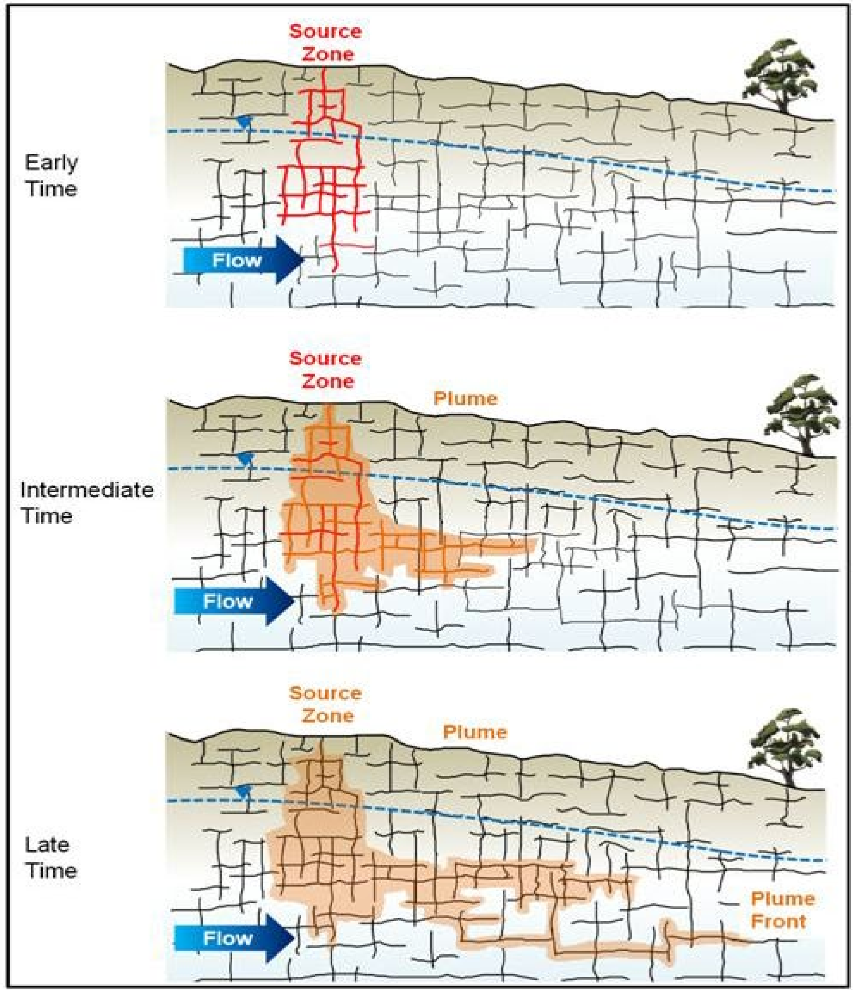
Underwood et al 2003

Source Zone and Plume Evolution Stages

Time and Distance Scales are Site Specific



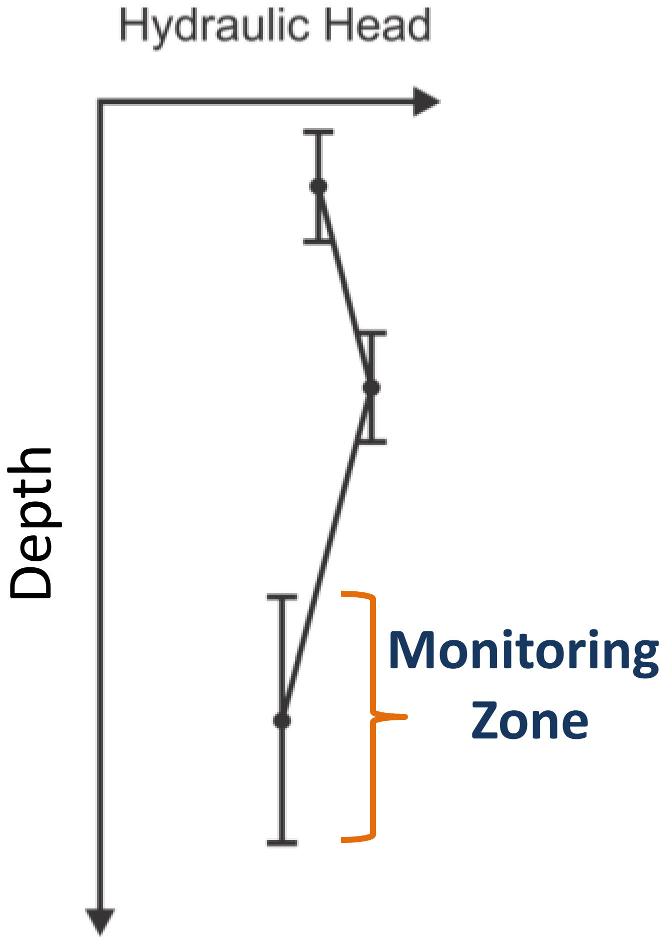
Parker, Gillham & Cherry, 1994



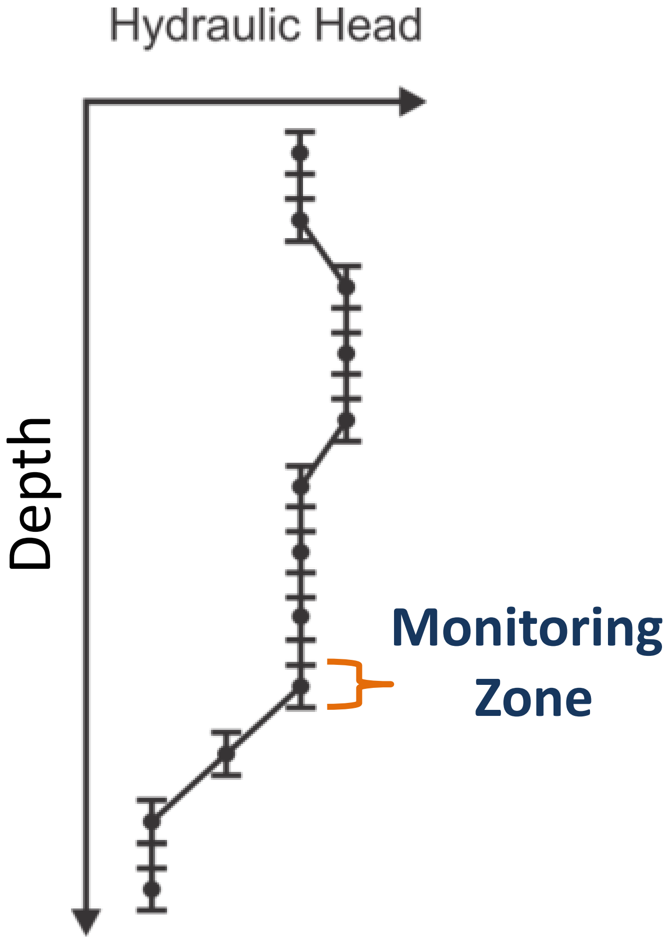
Parker et al., 2012

Characterization Informs Monitoring: Delineation of Aquitards and HGUs

Low Resolution (Sparse)



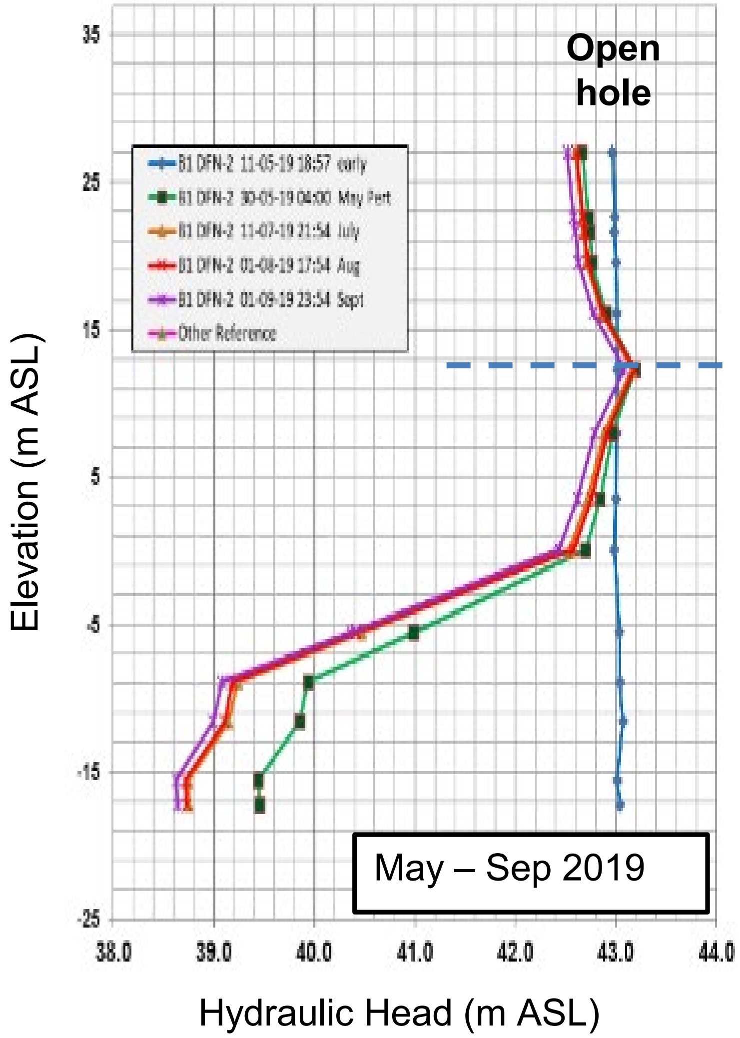
High Resolution (Detailed)



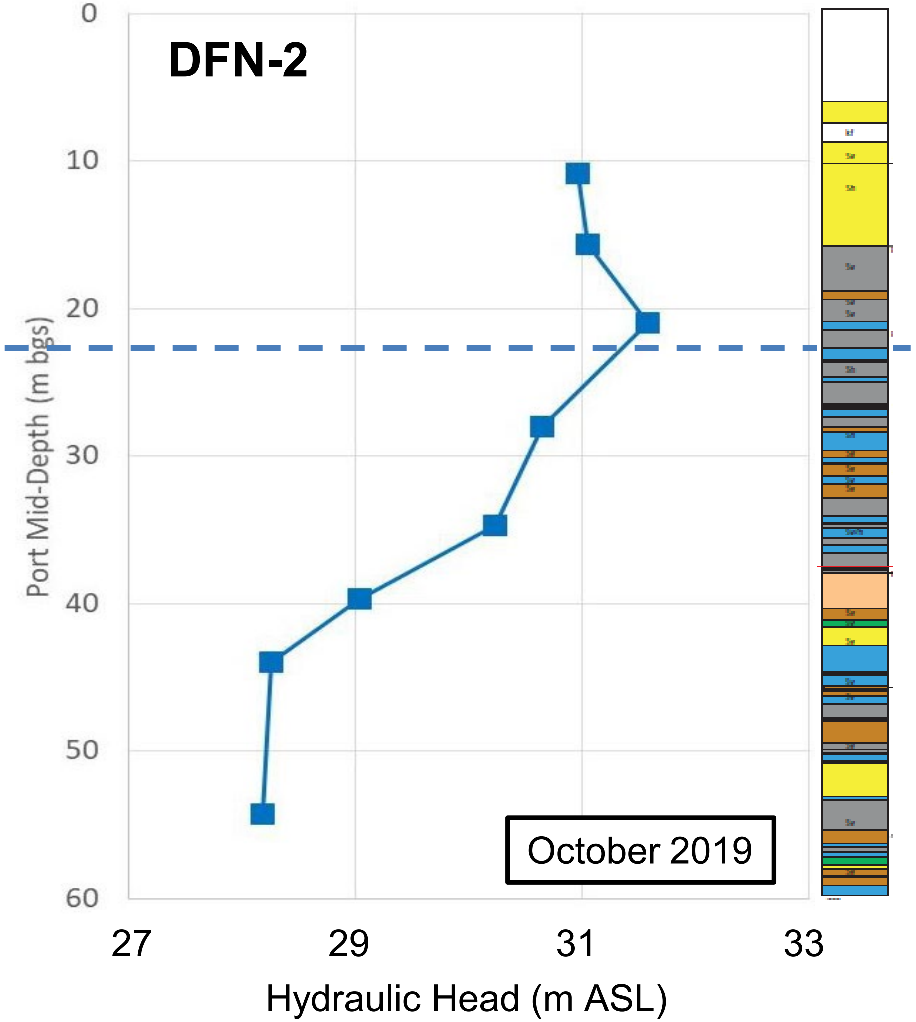
Sparse Profiles Do Not Resolve Position and Thickness of Aquitards or HGUs

Hydraulic Controls on Maximum Contaminant Depth

Temporary Transducer Deployments



Hybrid CMT MLS



Head Profiles Indicative of 'Aquitard' Units >25 m bgs

Appears to have limited deeper contaminant migration

Motivation for Development of G360 MultiPort System

- Versatility in borehole diameter
- Removable sensors in open tubes
  - pressure, temperature and EC readings
- Multiple groundwater sampling options
- Operational longevity w/o sensor obsolescence or failure
- Removable option – string of light-weight rubber packers
  - less expensive
  - easy abandonment