Pacific Northwest
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DEEP VADOSE ZONE PROGRAM
@PNNL

Innovative and Advanced Technologies for Characterization of Complex Contaminant Mixtures

May 14, 2025

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Presented by Fred Day-Lewis and Judy Robinson

U.S. DEPARTMENT OF ENERGY
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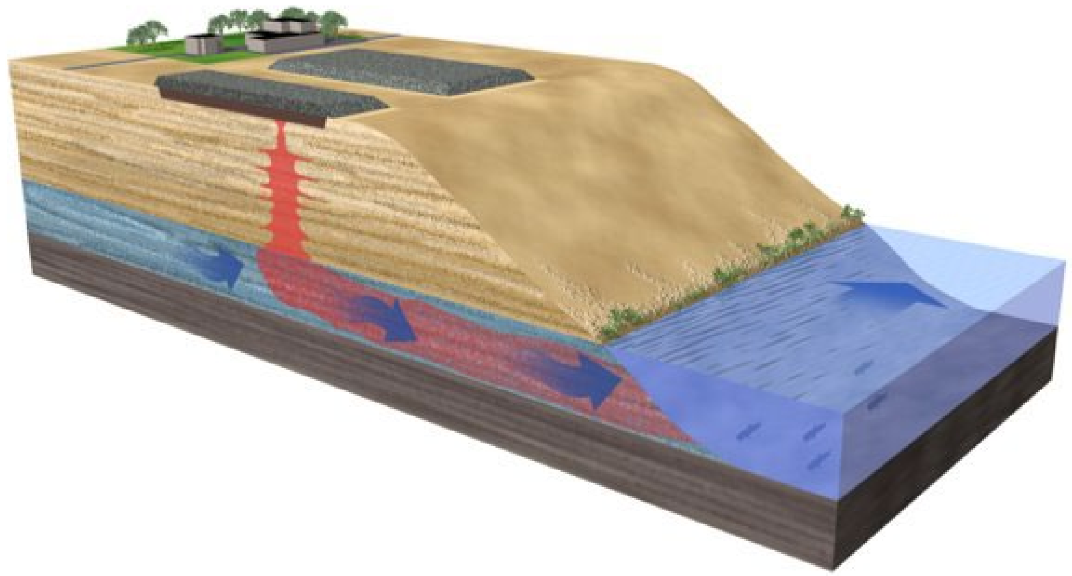
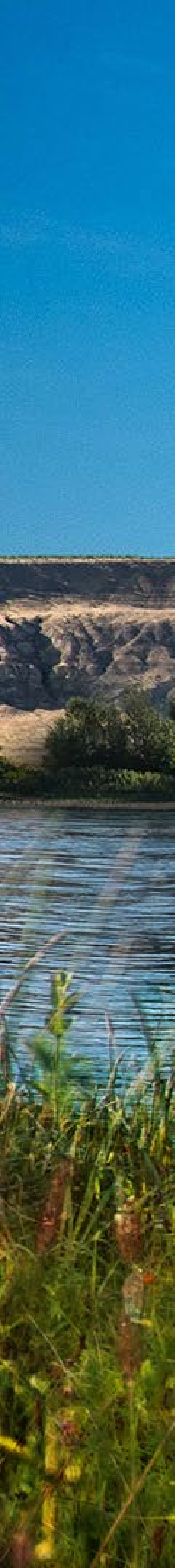
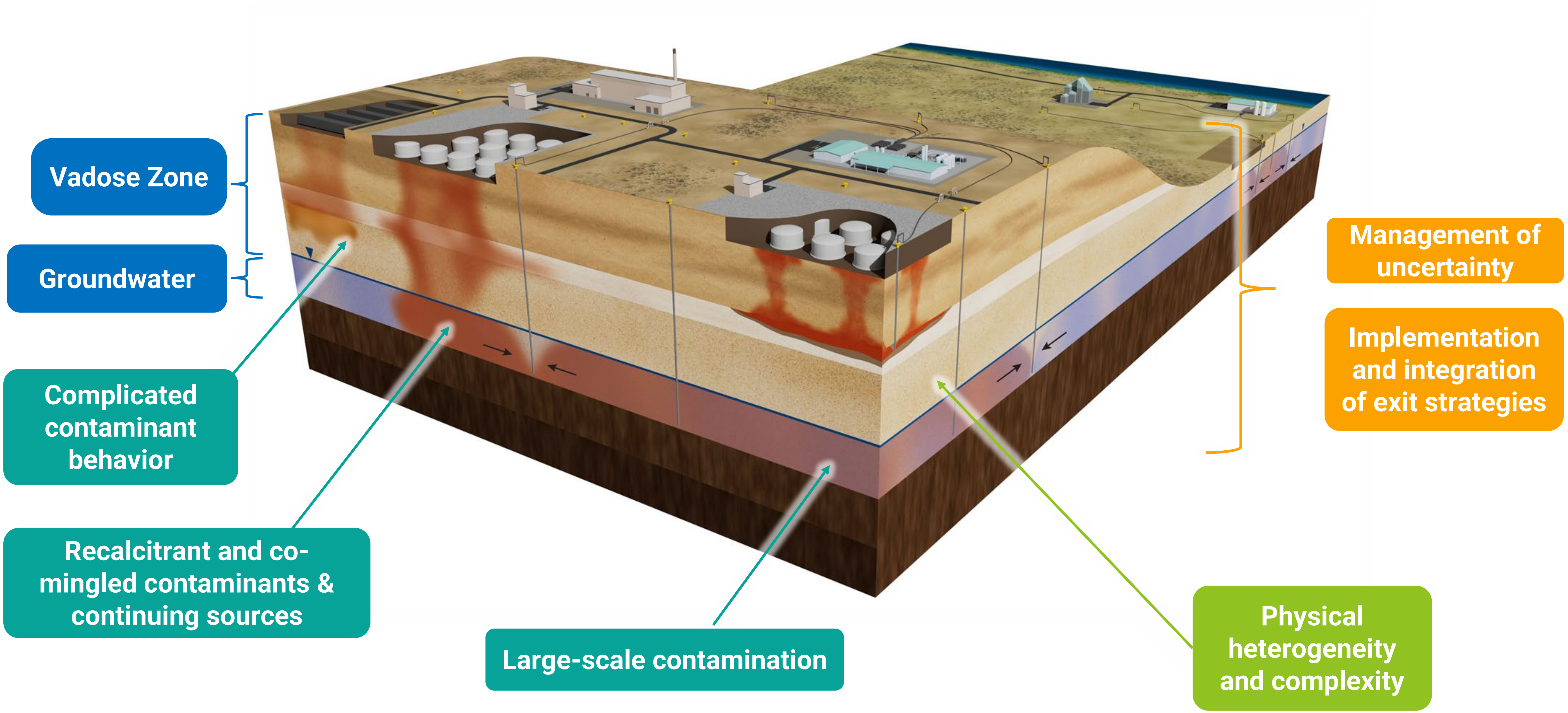
Outline

- Intro to Hanford Site & PNNL support for DOE Hanford Mission
- PNNL technology maturation, support for emerging technologies, and field testing
- Vertical characterization
  1. Vadose zone
  2. Groundwater
- Geophysical Characterization
  1. Stratigraphy / framework
  2. Monitoring transport through the vadose zone
- Knowledge/technology transfer and method selection
  - Method selection tools





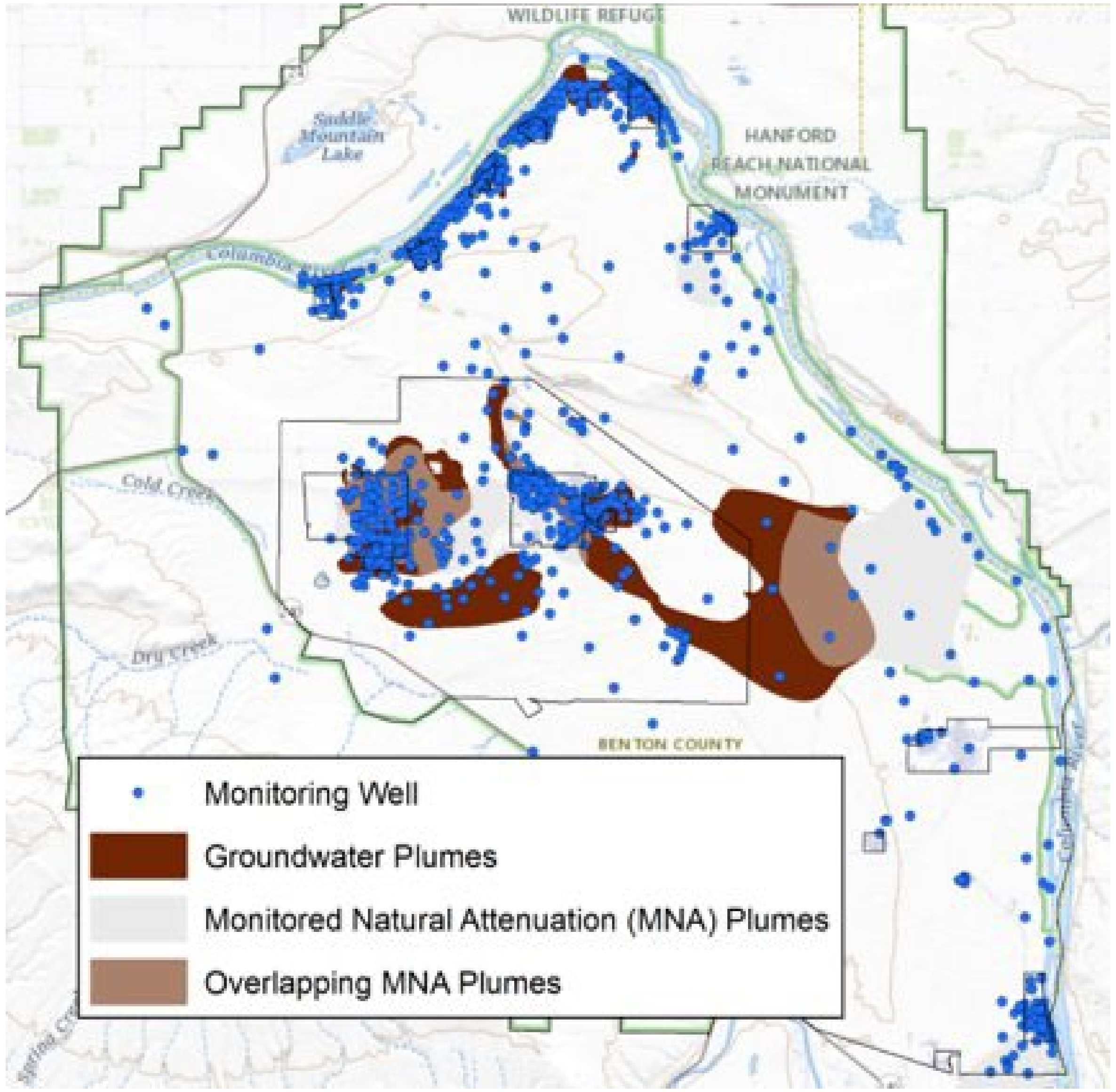
Environmental Remediation Challenges at Hanford



The impact of tank leaks to subsurface contamination is inadvertently exaggerated in the illustration.

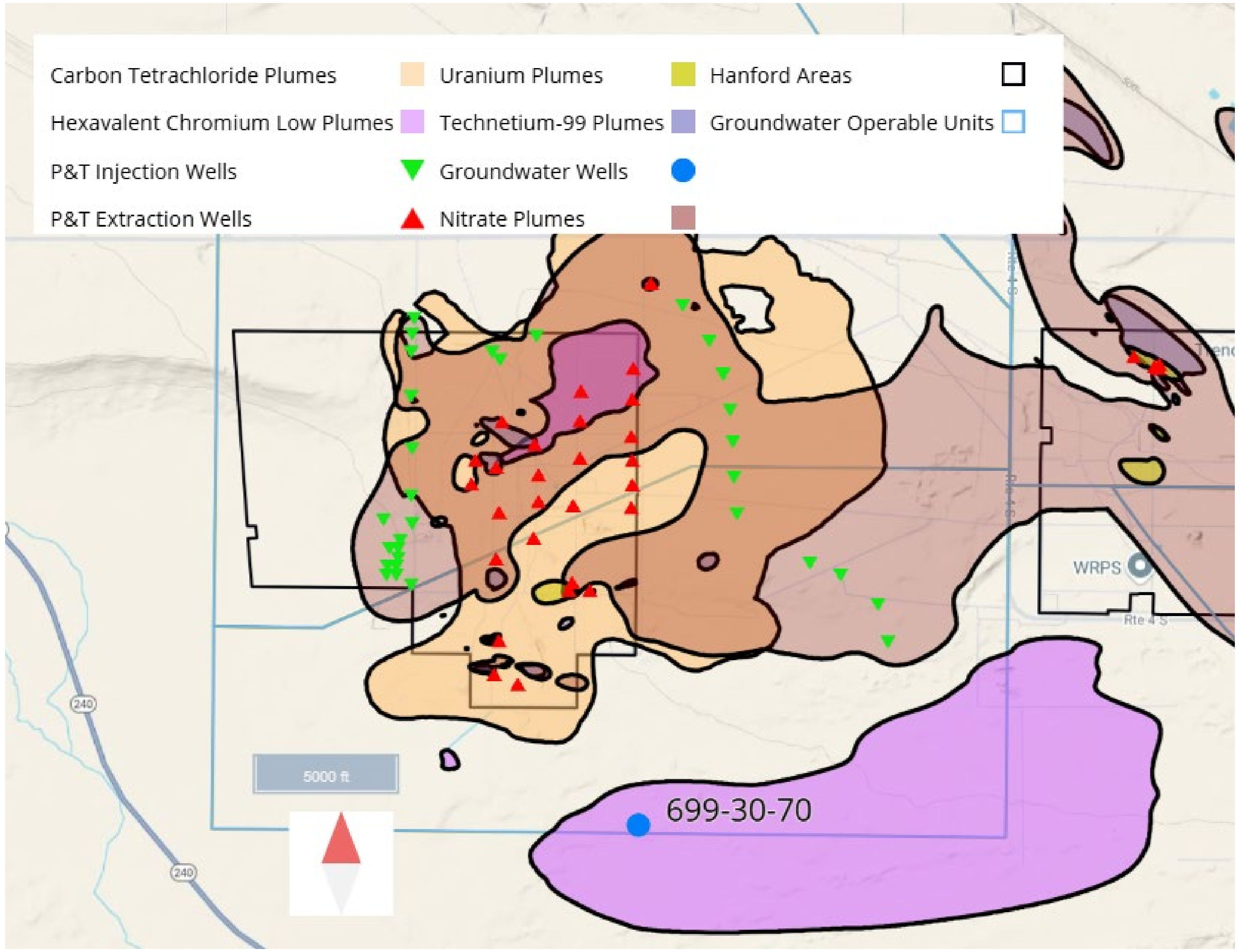
Historical context

- During World War II and the Cold War era, the government built and operated nine nuclear reactors along the Columbia River to produce plutonium and other nuclear materials
- Large chemical processing facilities separated plutonium from spent fuel rods
- Remediation efforts since the 1990s have been addressing areas of groundwater contamination
- Over 3000 wells and more wells installed yearly to expand sampling and monitoring capabilities, determine the extent of contamination, and support pump-and-treat operations

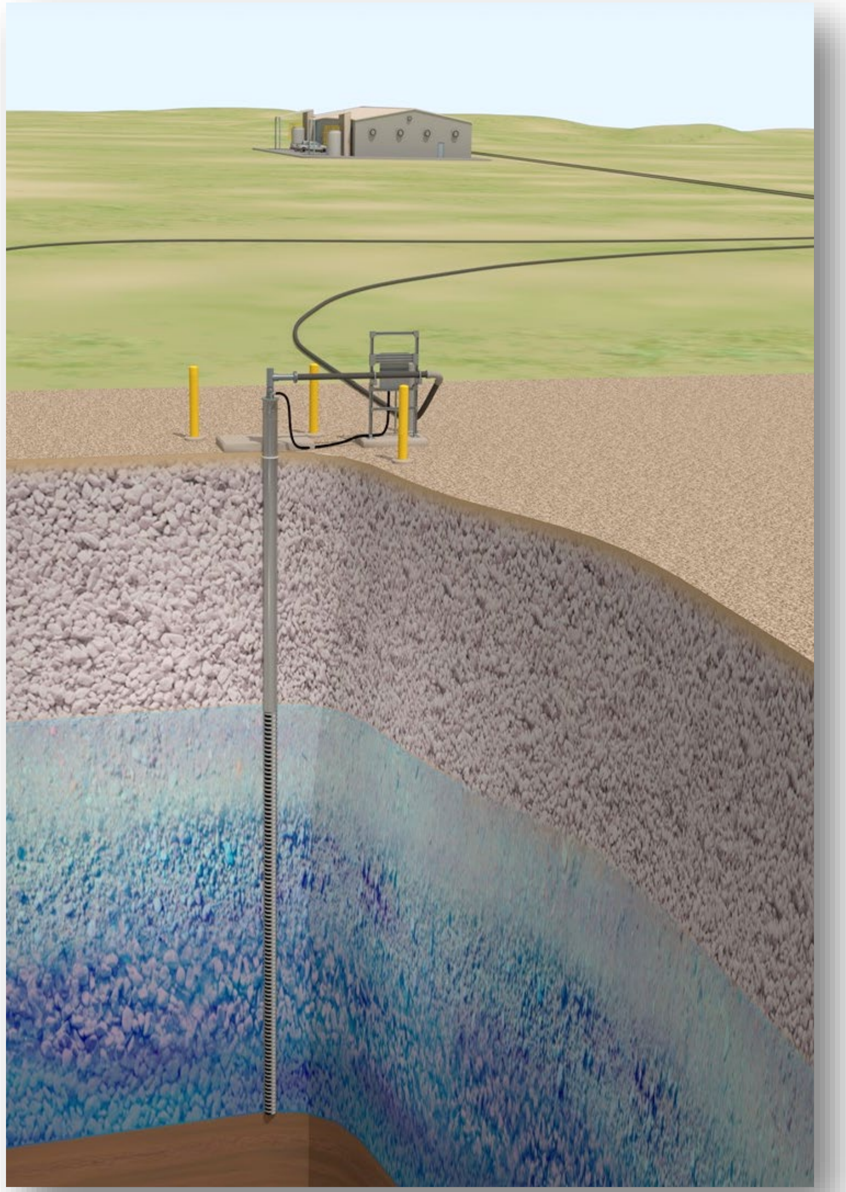


Environmental Remediation Challenges at Hanford

- Areal extent of site and contaminant plumes
- Multiple plumes
- Deep vadose zone
- Proximity to the Columbia River & dynamics of the hydrologic system
- Radiological contaminants
- Cost of wells
- 3D nature of contaminant plumes
- 3D heterogeneity



Vertical characterization in the Vadose Zone and Saturated Zone



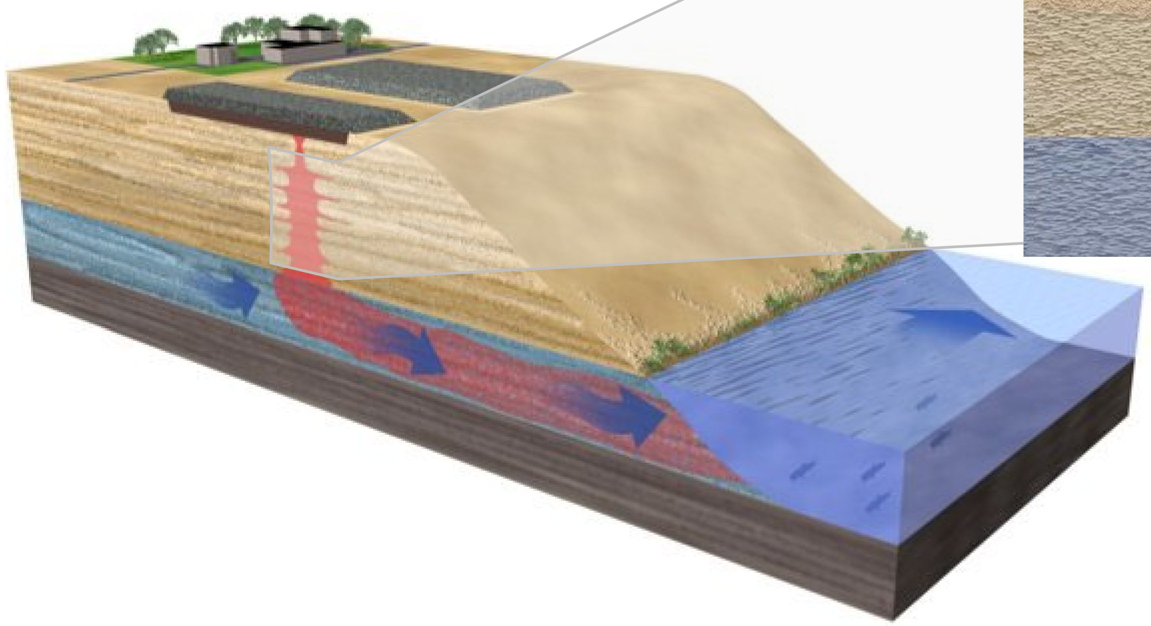
Groundwater P&T remediation at the Hanford Site.

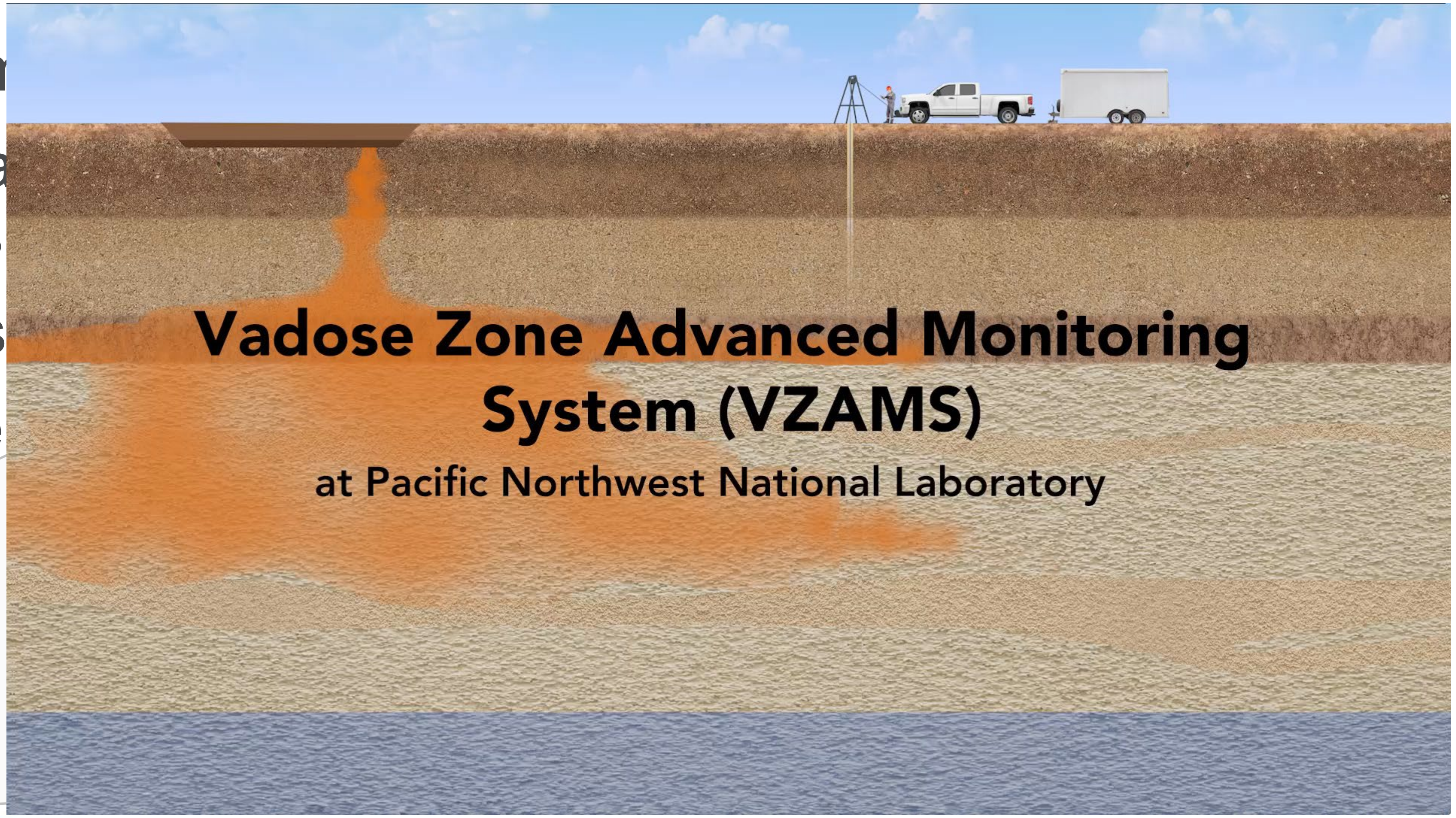
- Vertical characterization is necessary for the successful design and implementation of remediation
  - Increase the mass removal with P&T systems
  - Hanford 200 West Area P&T example
- Vadose zone: VZAMS
  - Characterizing heterogeneity
  - Characterizing contaminant distribution
- Saturated zone: Need to perform a combination of contaminant and hydraulic profiling methods
  - Understand the site-specific ‘personality’ of our long-screened wells
  - Identify and focus our extraction on the high-concentration zones
  - This involves utilizing the large network of existing long-screened P&T extraction wells

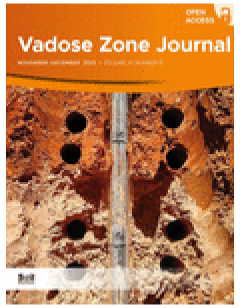
Vadose Zone: Advanced Vadose Zone Monitoring System (VZAMS)

- Subsurface heterogeneities m
- Assessing contaminant migra measurements at the same s
- Vertical migration in the VZ is
- Sampling under low moisture saturated GW

- Subsurface heterogeneities matter
- Assessing contaminant migration is difficult without repeat measurements at the same spatial locations
- Vertical migration in the VZ is very slow (cm – mm per year)
- Sampling under low moisture conditions is quite different than saturated GW

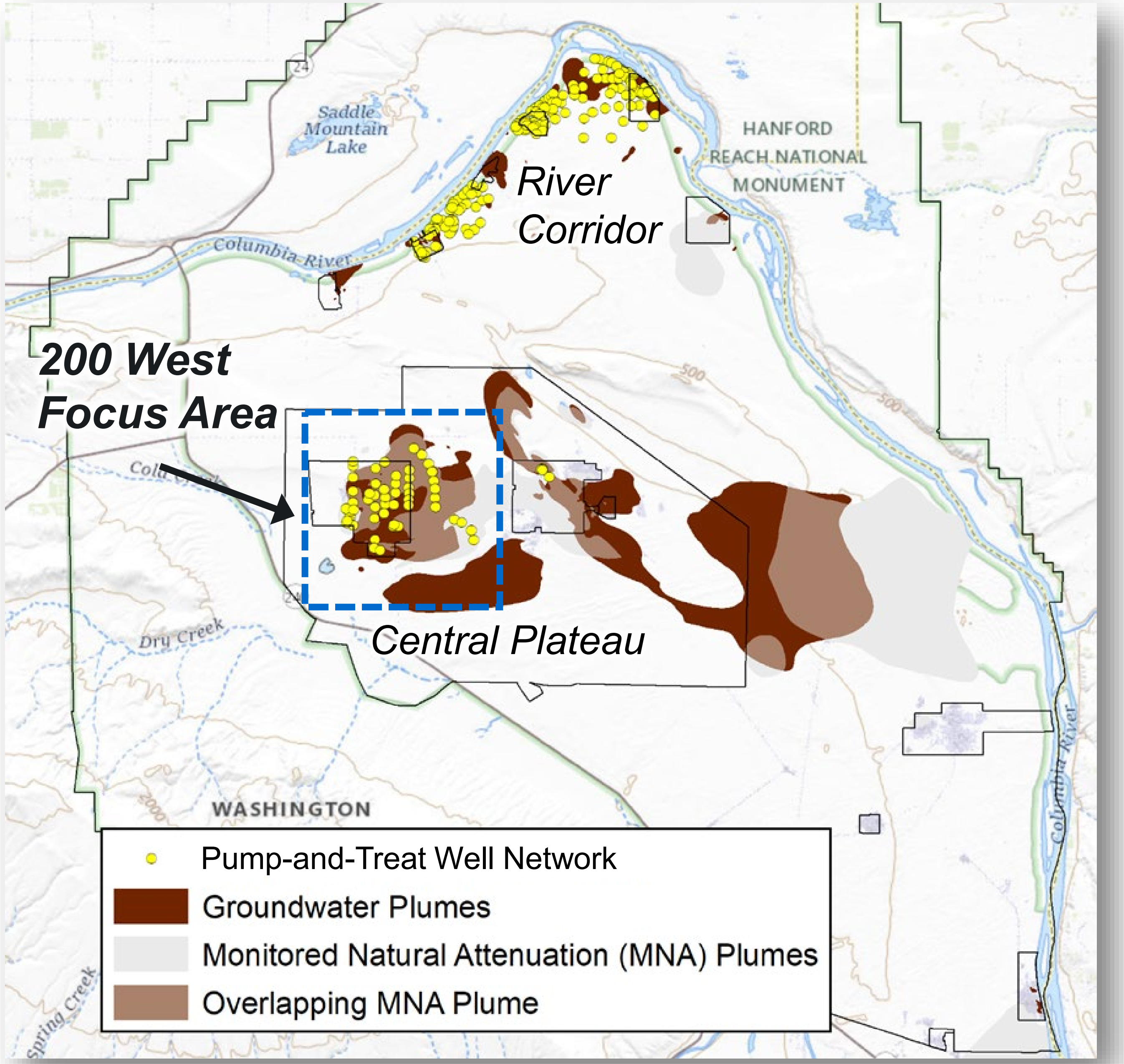






Linneman, D. C., Strickland, C. E., Appriou, D., Rockhold, M. L., Thomle, J. N., Szecsody, J. E., Martin, P. F., Vermeul, V. R., Mackley, R. D., & Freedman, V. L. (2022). Development of a vadose zone advanced monitoring system: Tools to assess groundwater vulnerability. Vadose Zone Journal, 21, e20223.

P&T Remedies at Hanford

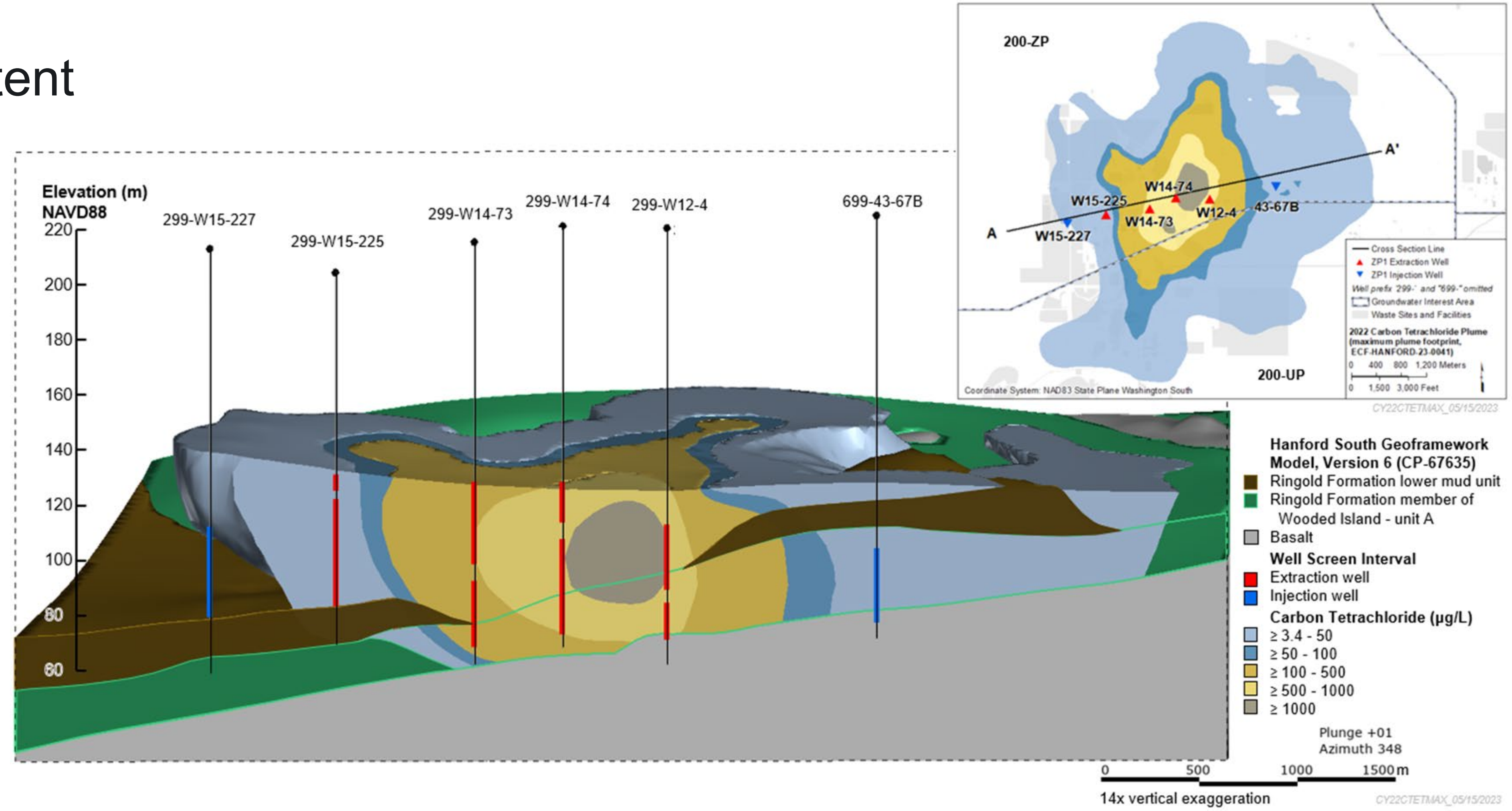


Hanford Site Groundwater P&T Wells (DOE, 2024)

- Five P&T's along the River Corridor
  - Largely a success story
  - Combined total flow of ~2,400 gpm
- P&T on the Central Plateau
  - 200 West P&T facility (3,500 gpm)
  - Extensive network of long-screened extraction and injection wells
  - Screened intervals >200 feet in length
  - Case study for this discussion

Long-Screened P&T Extraction Wells

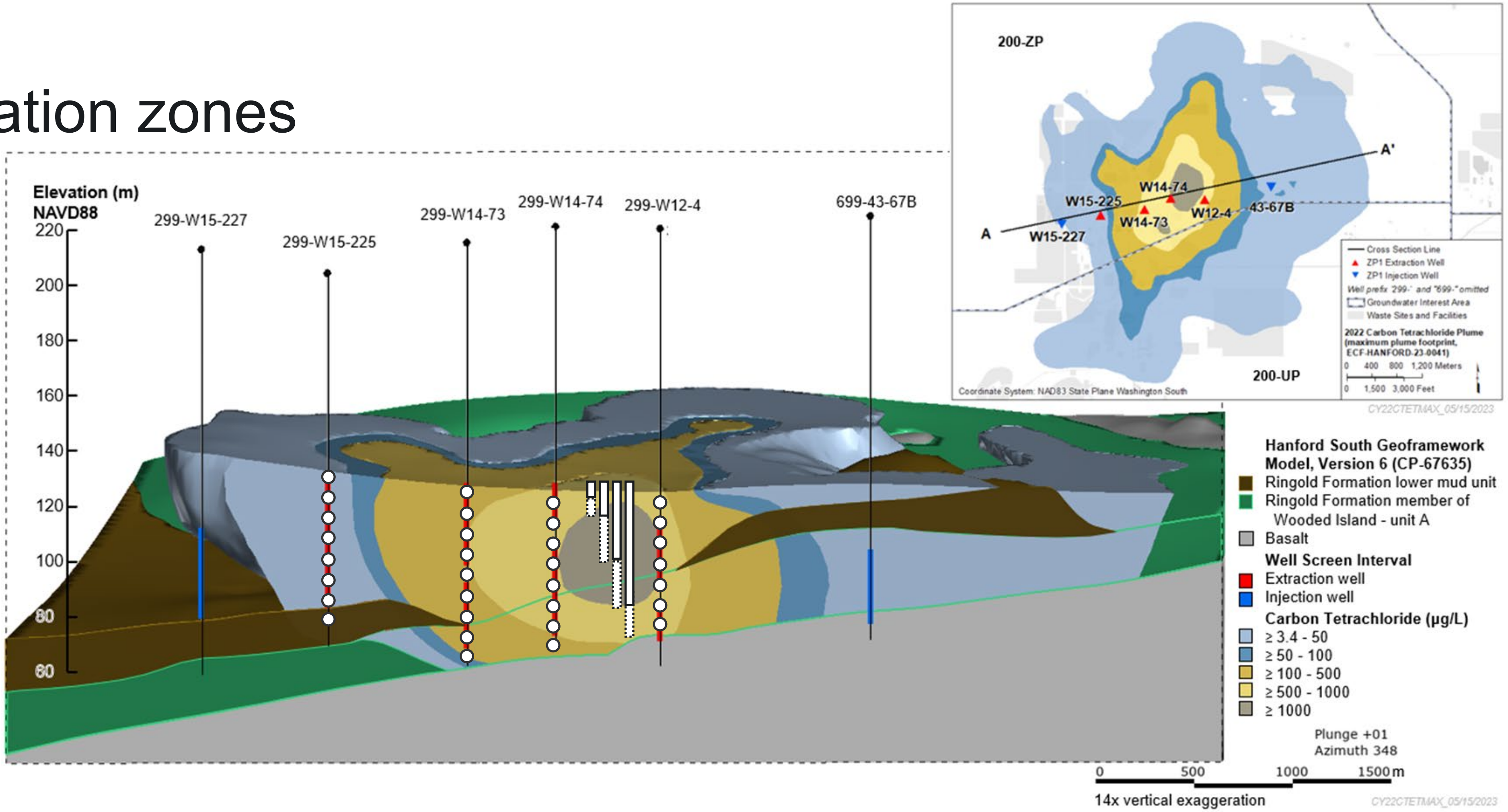
- Initial remedy optimization objectives
  - Volumetric removal
  - Hydraulic capture
  - Decrease plume areal extent
- 200-ft thick aquifer with multiple contaminants of concern
  - Fully-screened wells used commonly
- Contaminants are vertically distributed
- Progression to 3-D CSM and P&T remedy design



Three-dimensional carbon tetrachloride plume in the 200 West Area, 2022. (CPCCo, 2023)

Long-Screened P&T Extraction Wells

- Next phase of optimization – more focused extraction
  - Mass removal in high-concentration zones
  - Balancing facility capacity
- Identify the high-concentration zones
  - Existing long-screened wells
  - Multi-level completions
- Focused extraction
  - Retrofit existing LSWs
  - New discrete-zone wells



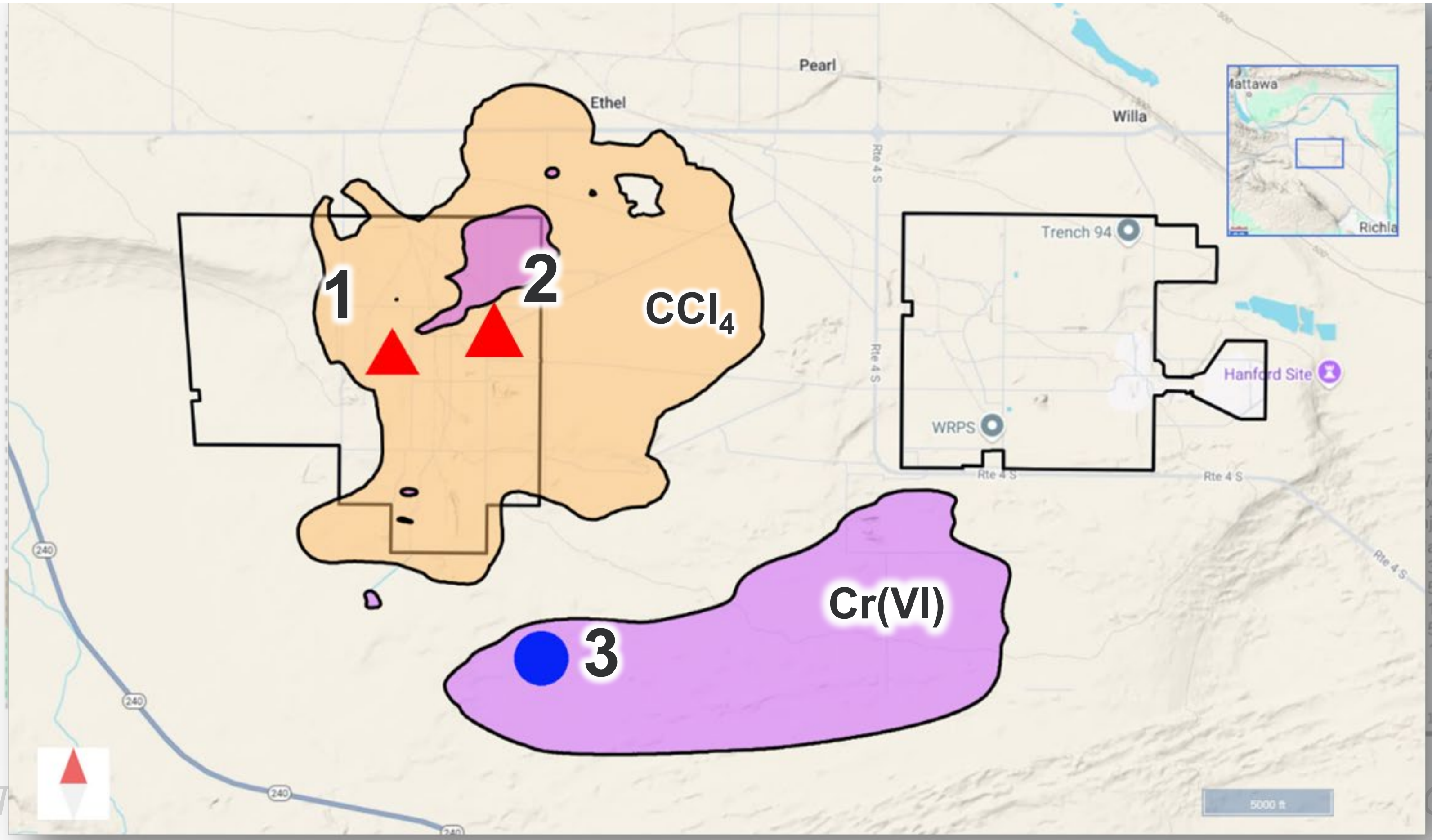
Three-dimensional carbon tetrachloride plume in the 200 West Area, 2022. (CPCCo, 2023)

Long-Screened P&T Extraction Wells (Phase II)

- Next phase of optimization – more focused extraction
  - Mass removal in high-concentration zones

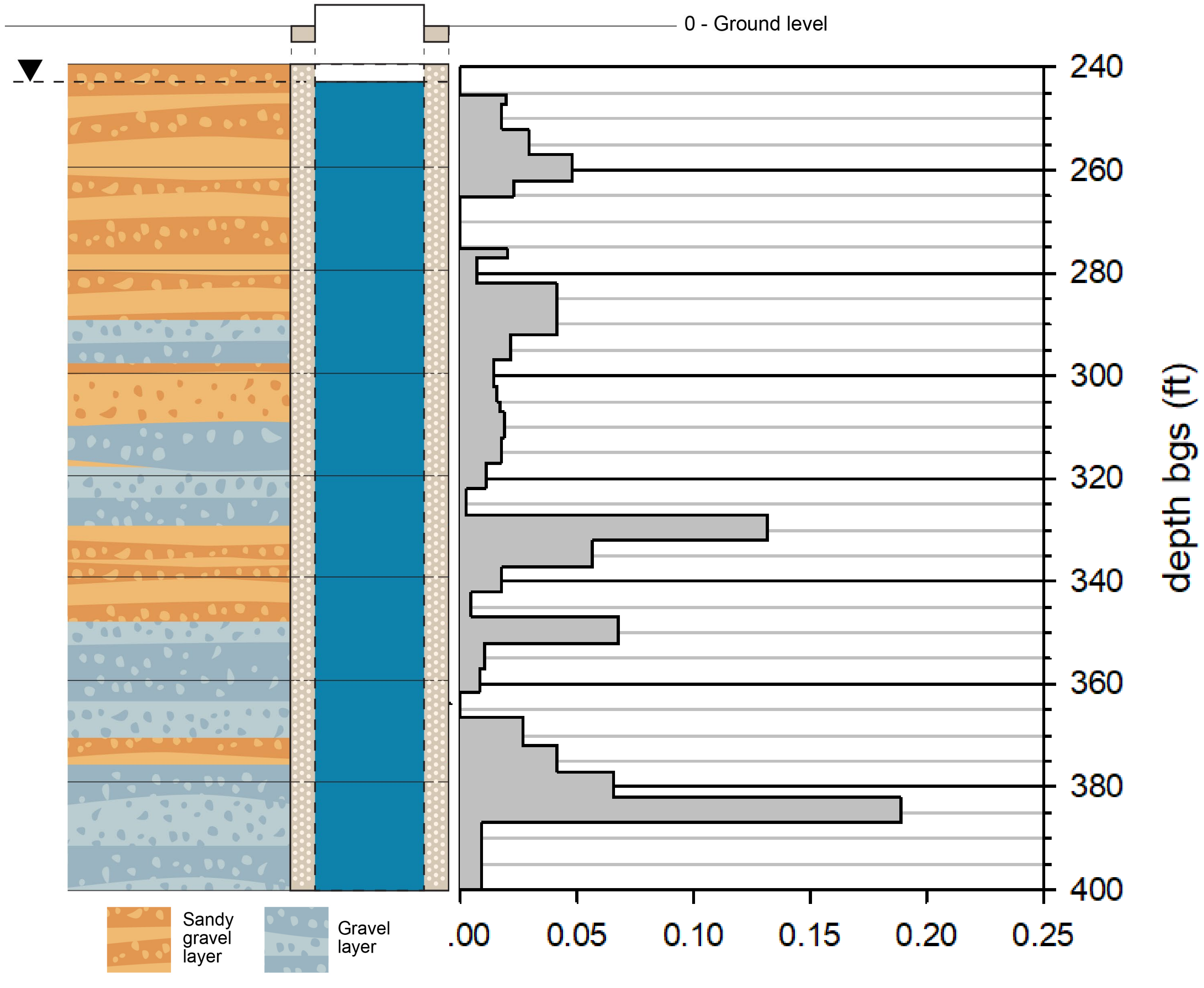
Focus of today's discussion – Hanford well examples

- **Identify the high-concentration zones**
  - **Existing long-screened wells**
  - Multi-level completions
- Focused extraction
  - Retrofit existing LSWs
  - New discrete-zone wells



CCo, 2023)

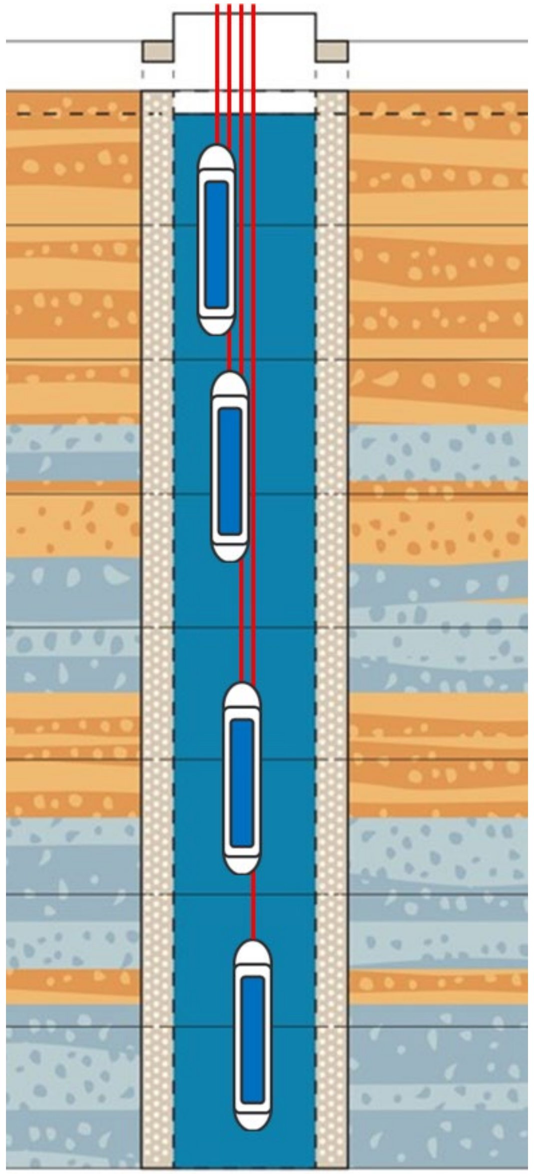
Mass Removal in a Long-Screened P&T Well



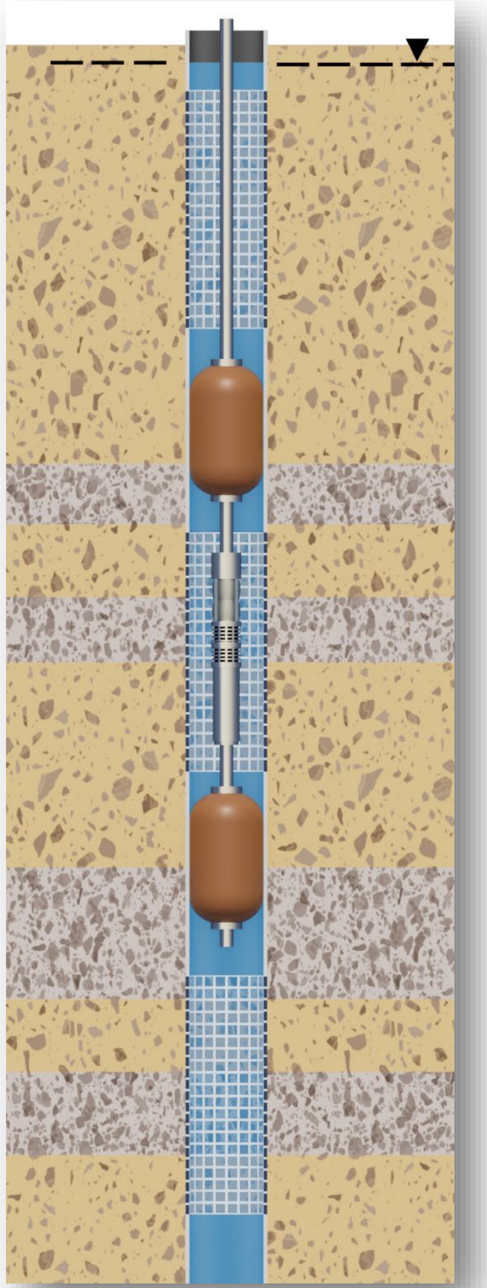
P&T extraction well 299-W15-225 (PNNL-18732)

- 200 West well example #1
  - P&T extraction well 299-W15-225
  - ~145 feet of screen
- Variation in hydraulic conductivity (K) with depth
  - Layered sands and gravels
- Flow in each zone is proportional to the relative K
- Concentrations of a pumped sample are [mostly] flow-weighted averages
  - Under equilibrium conditions

Vertical Characterization in Long-Screened Wells



Passive sampling in a long-screened well with Snap Samplers.

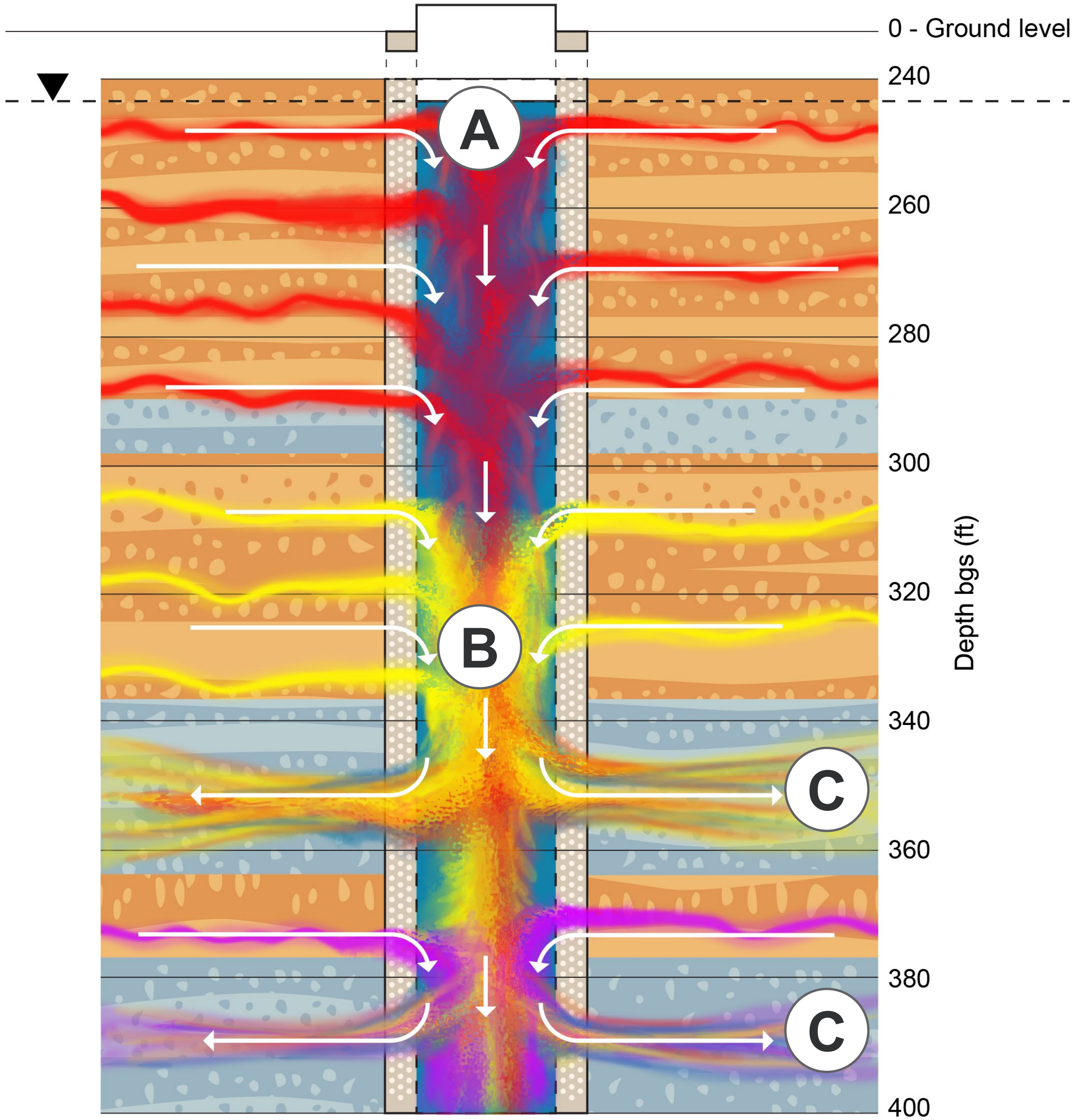


Straddle-packer pumping within a depth-discrete interval.

- Common contaminant profiling approaches for long-screened wells
  - Packer systems
  - Low/no-flow or passive sampling (bladder pump, Snap Sampler)
  - FLUTe liners
  - Stacked dynamic profiling (BESST Inc.)

Saturated Zone: Ambient Vertical Flow in the Long-Screened Well

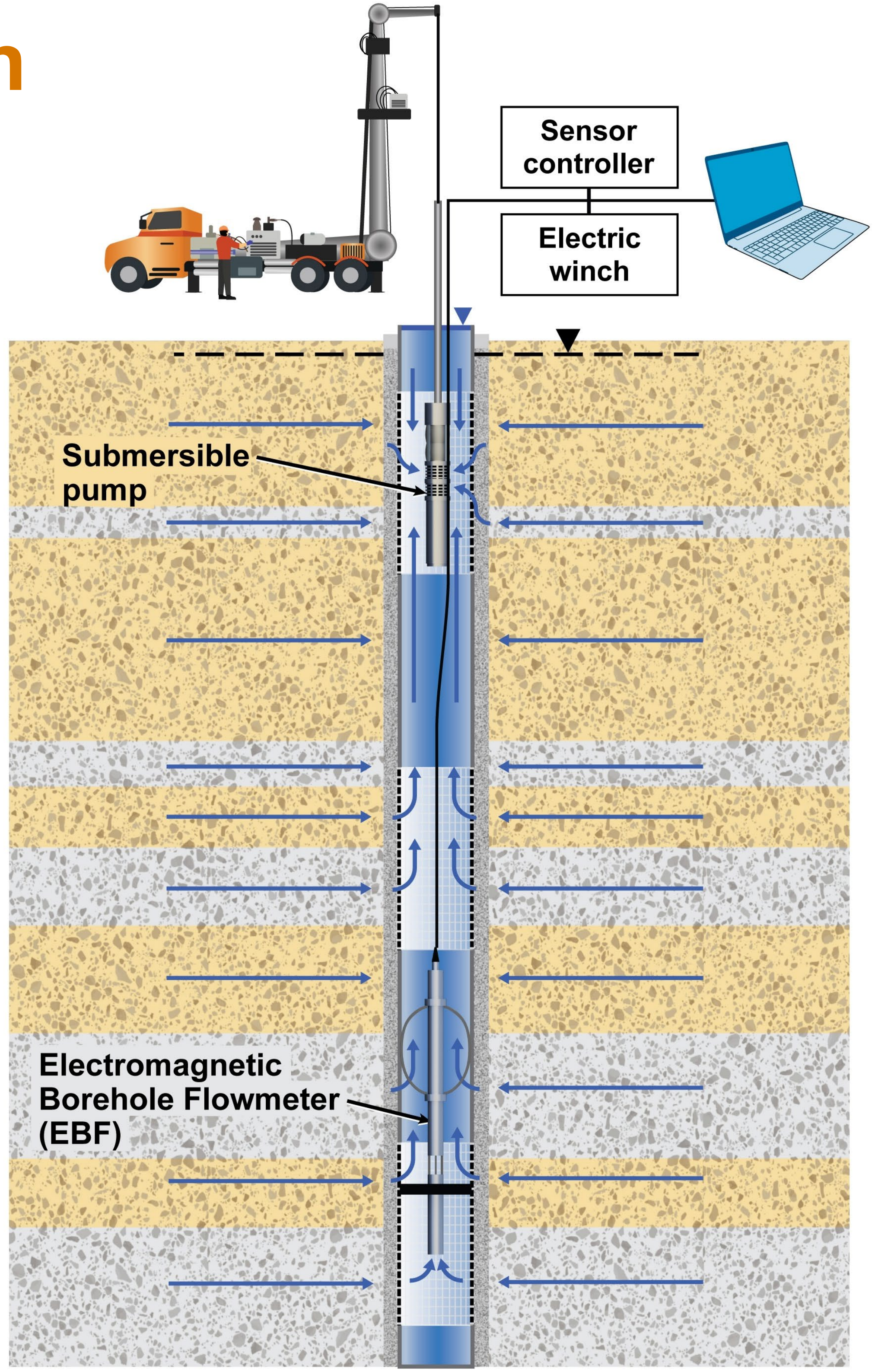
- Consider these locations passively sampled under ambient vertical flow
  A. Inflow zone – concentration in the adjacent aquifer layer at this depth
  B. Flow-weighted concentration in the aquifer layers at and above this depth
  C. Outflow zones – provides no concentration information for the aquifer at these depths
- Vertical flows need to be characterized
  - Multiple field-based methods



Schematic of possible flow patterns and contaminant mixing in a well.

Vertical Flow Characterization

- Electromagnetic borehole flowmeter (EBF)
  - Since the1990's
  - Highly-sensitive (20 mL/min)
  - Magnitude and direction of vertical flows
  - Inflow and outflow zones along the screen
- Ambient flow profiles
  - Needed for interpreting low/no-flow sample concentrations
- Dynamic flow profiles
  - Flow patterns while pumping
  - Proportional inflow related to hydraulic conductivity (K)
  - Needed for interpreting pumped sample concentrations

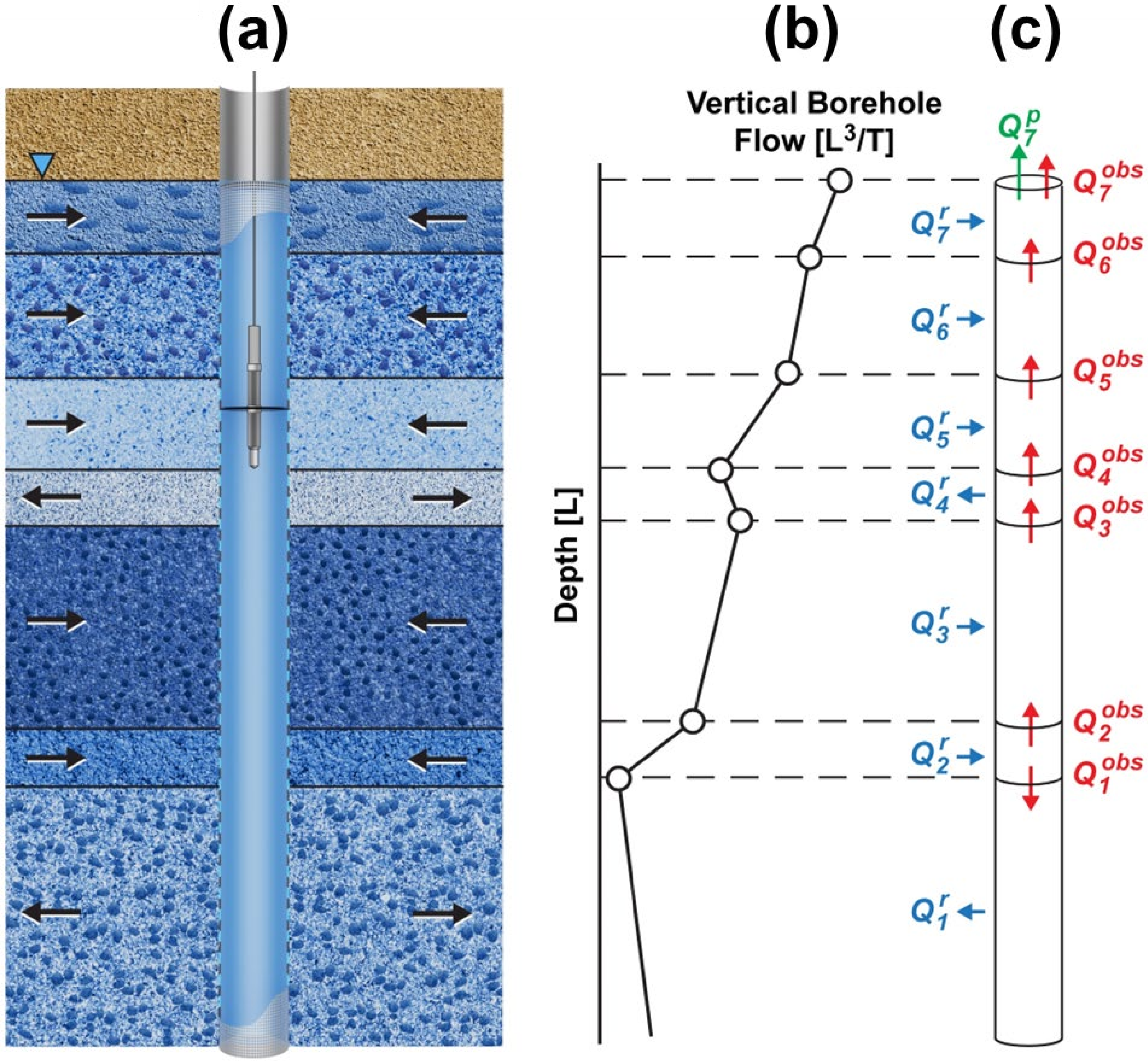


Schematic of dynamic EBF survey.

Quantitative combination of hydraulic and contaminant profiling

- Analytical model:
  - Water balance model for well
  - Steady-state radial flow in each layer (Thiem Eqn.)
  - Radial advective exchange with aquifer
- Data used:
  - Vertical flows from flowmeter data
  - Sampled concentration at multiple depths in the well (pumped, low flow, or passive)
- Inverse framework:
  - Can combine flow and sample data sets
  - Multiple pumping locations, rates, etc.
  - Pumping associated with sampling

[Day-Lewis, Mackley & Bence, 2023, Groundwater]



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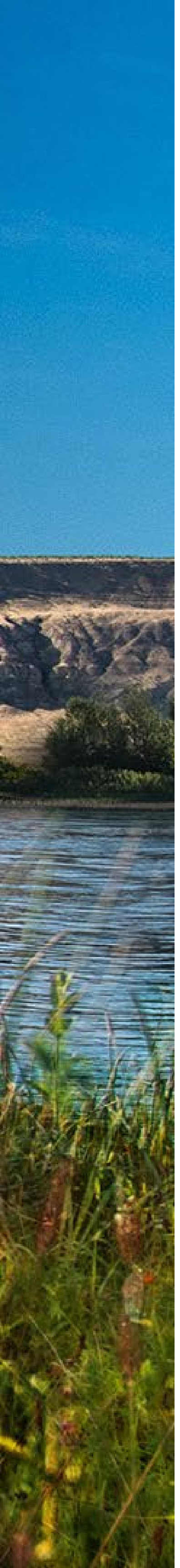
Analytical Model



2023 paper in Groundwater:

- Steady-state forward model
- Combining data collected under different flows
- Sensitivity & image appraisal (model resolution)

2024 paper in Groundwater:

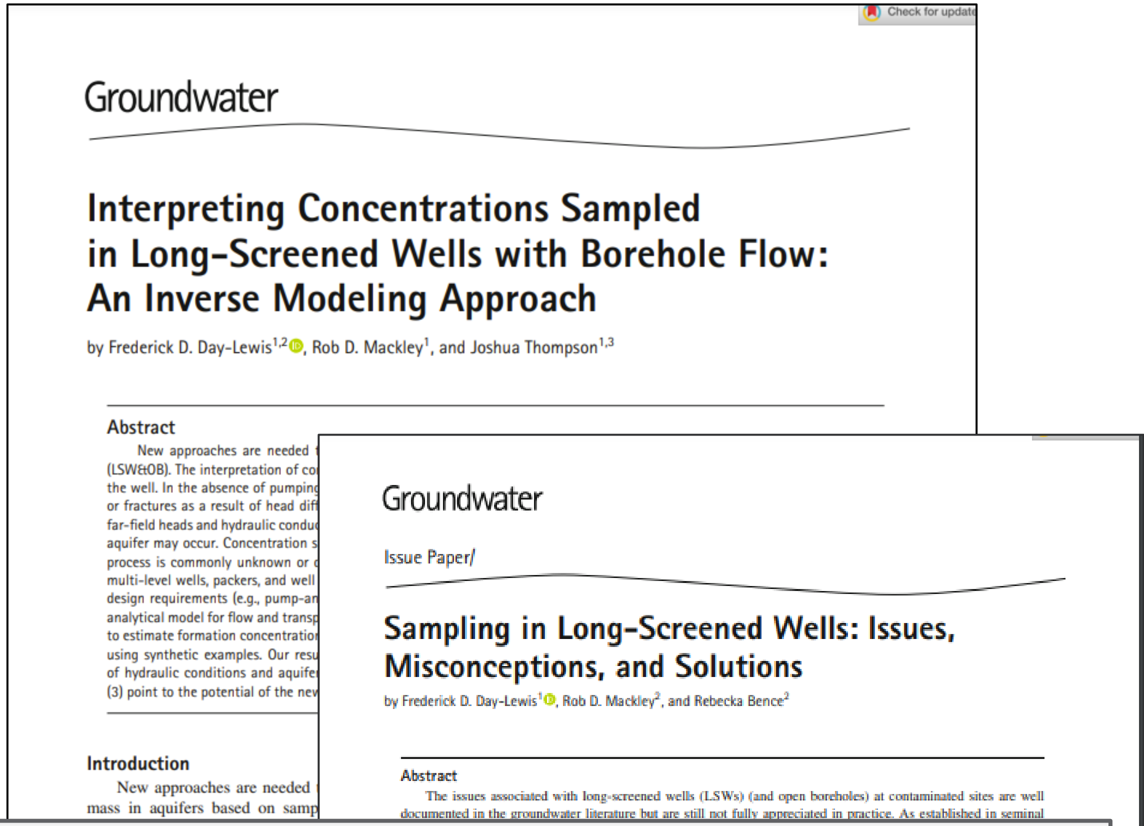
- Type scenarios for borehole flow and implications for sampling

Ongoing extensions in this work:

- Conversion to discrete-time
- Inverse framework for time-series concentration data

Advantages:

- Analytical
- Rigorous inverse framework
- Application to dilution, “hydrophysical logging,” etc.



Groundwater

Interpreting Concentrations Sampled in Long-Screened Wells with Borehole Flow: An Inverse Modeling Approach

by Frederick D. Day-Lewis[1,2], Rob D. Mackley[1], and Joshua Thompson[1,3]

Groundwater

Issue Paper/

Sampling in Long-Screened Wells: Issues, Misconceptions, and Solutions

by Frederick D. Day-Lewis[1], Rob D. Mackley[2], and Rebecka Bence[2]

Abstract
The issues associated with long-screened wells (LSWs) (and open boreholes) at contaminated sites are well documented in the groundwater literature but are still not fully appreciated in practice. As established in seminal

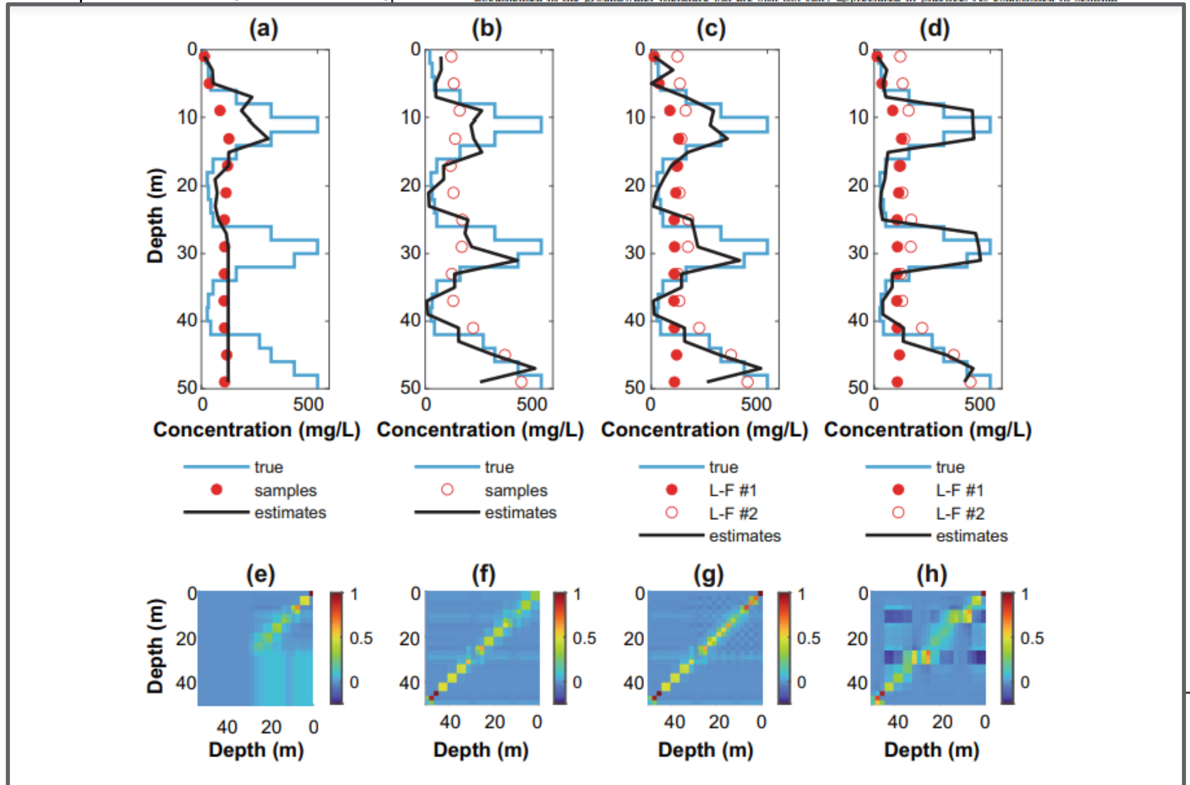


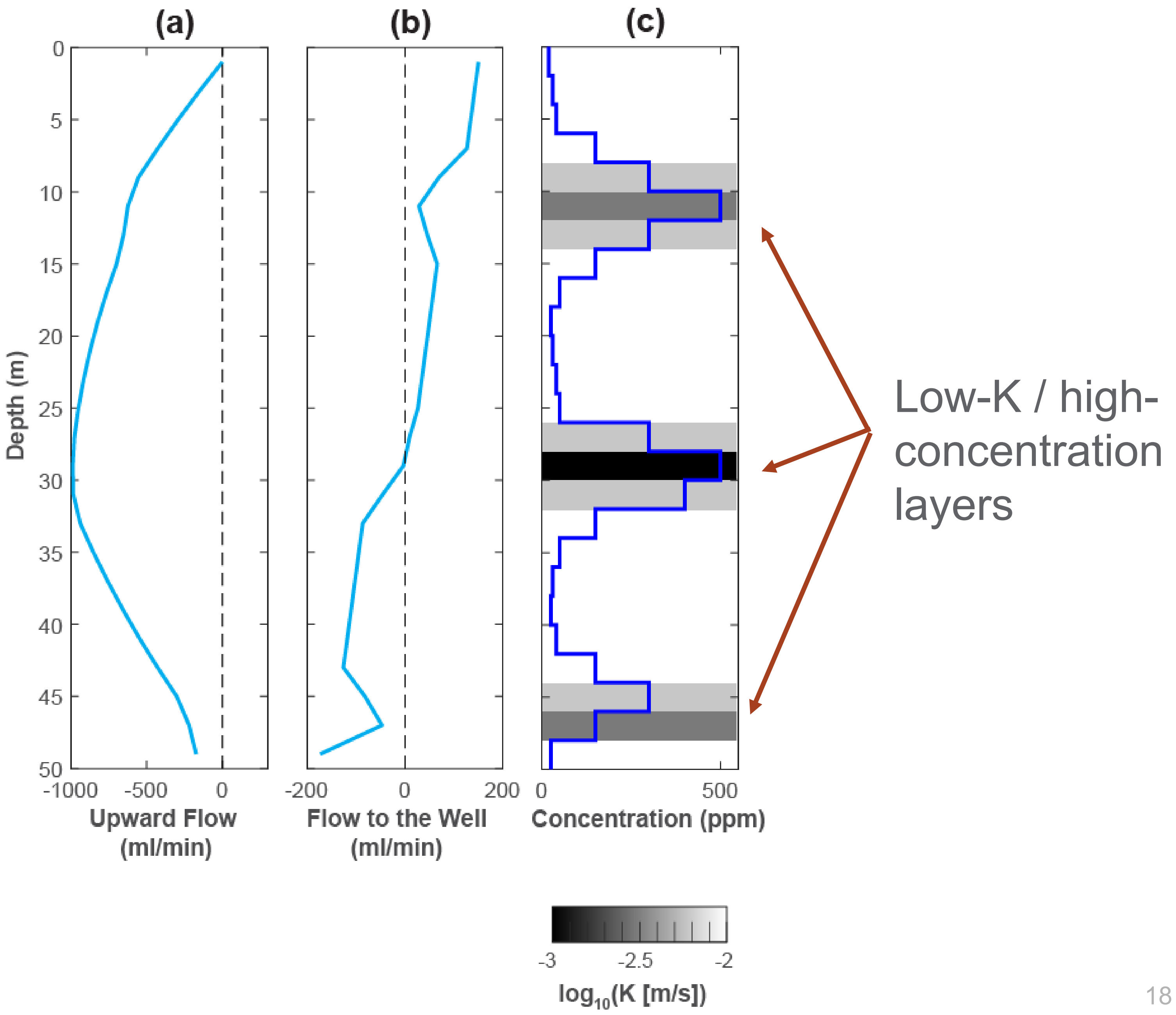
Figure 5. (a-d) Inversion results for (a) Example 1, inverting L-F data; (b) Example 2, inverting L-F data with secondary pumping from 1 m depth; (c) Example 3, jointly inverting data from Examples 1 and 2; and (d) Example 4, using the same data as 3 and a zonal mean. (e-h) Model resolution matrices for Examples 1–4, respectively.

Synthetic Example Setup

a. Hypothetical downward ambient flow profile, measured by EBF

b. Calculated radial exchange, based on EBF log

c. Hypothetical *K* and concentration profile



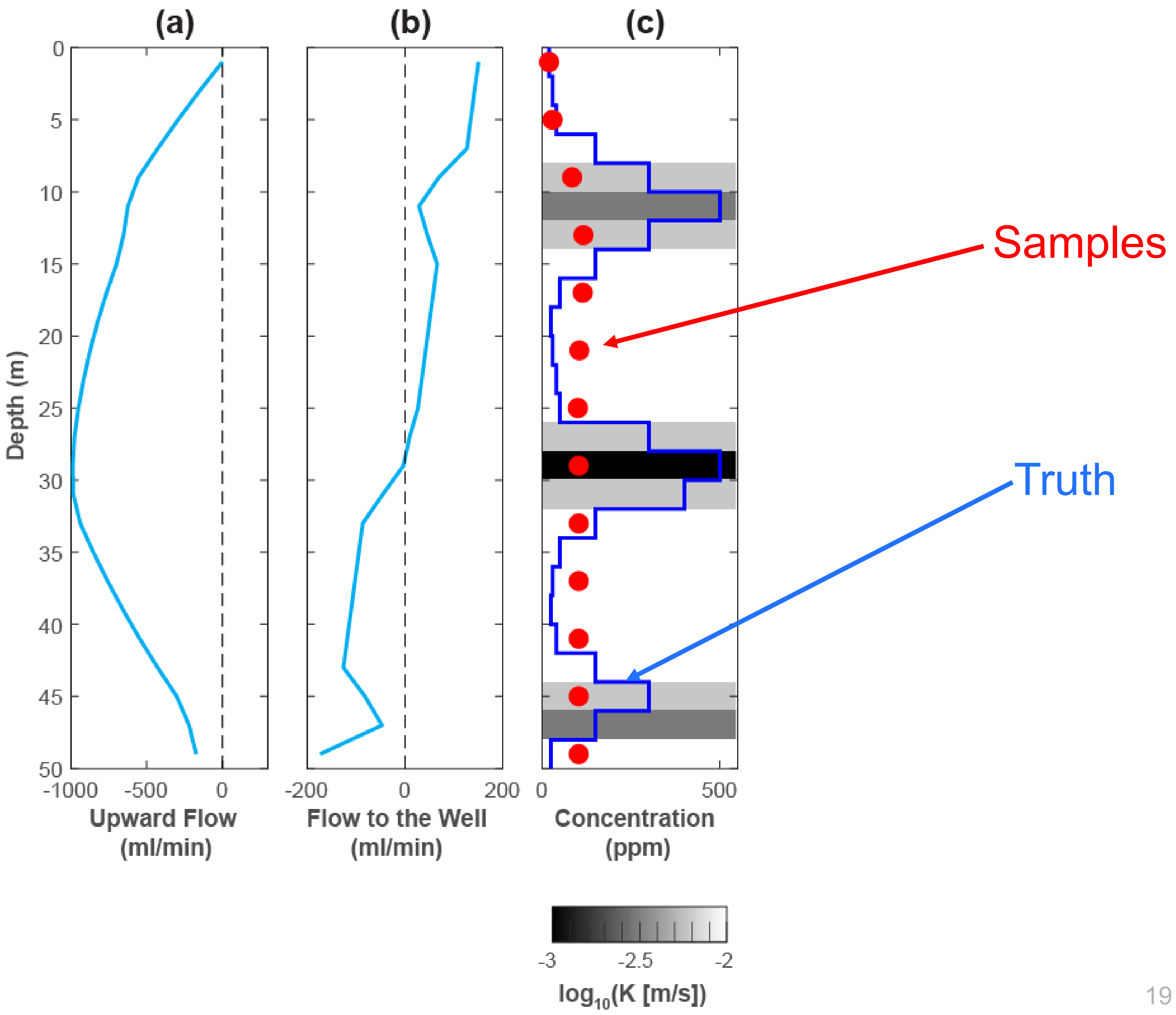
Data Requirements

a. Flow log under pumping
b. Calculated radial exchange
c. Low-flow concentration samples

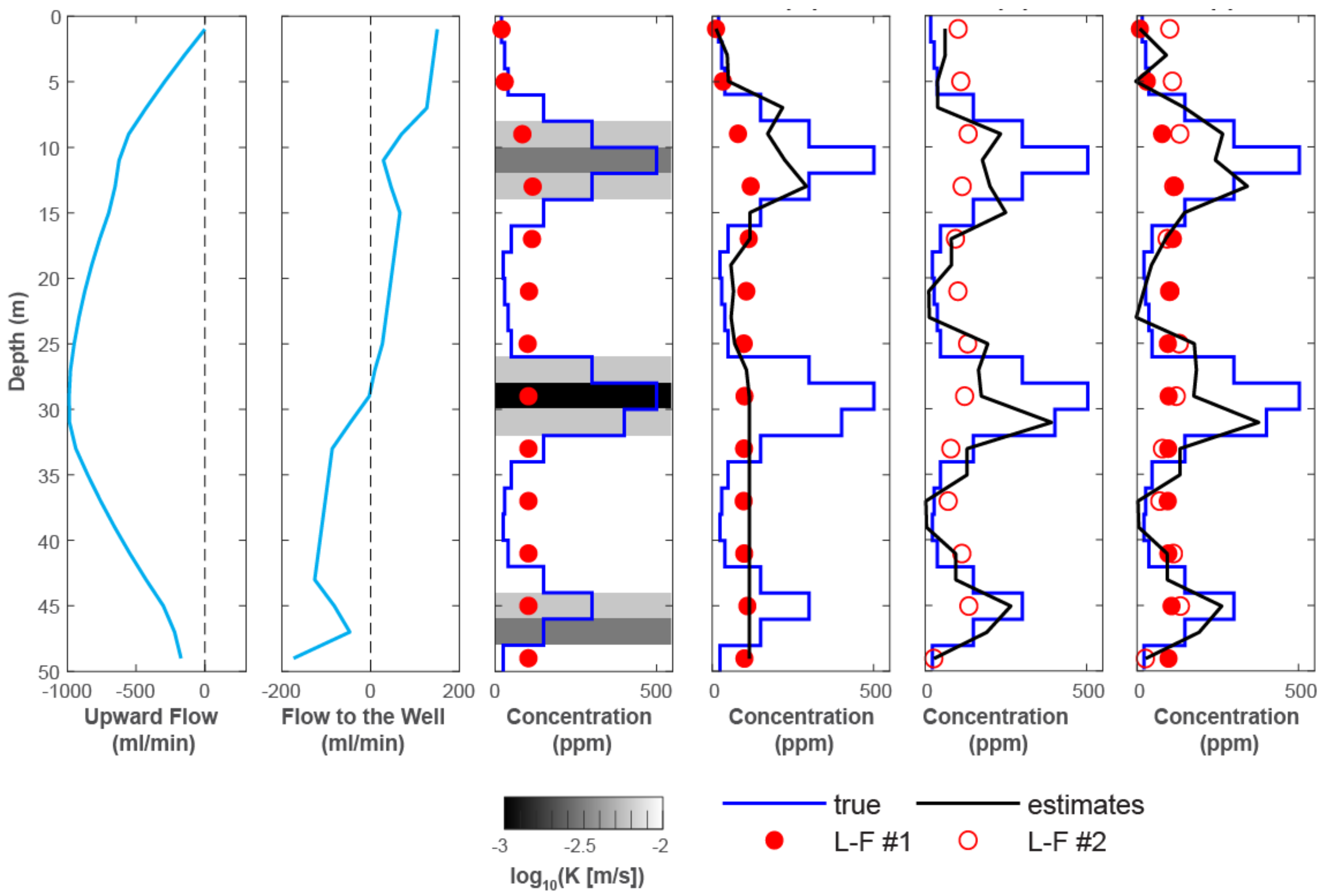
Concentration can be:

- Low-flow
- Passively sampled
- Integrated

In the presence of vertical borehole flow, samples are flow-weighted averages



Synthetic Examples

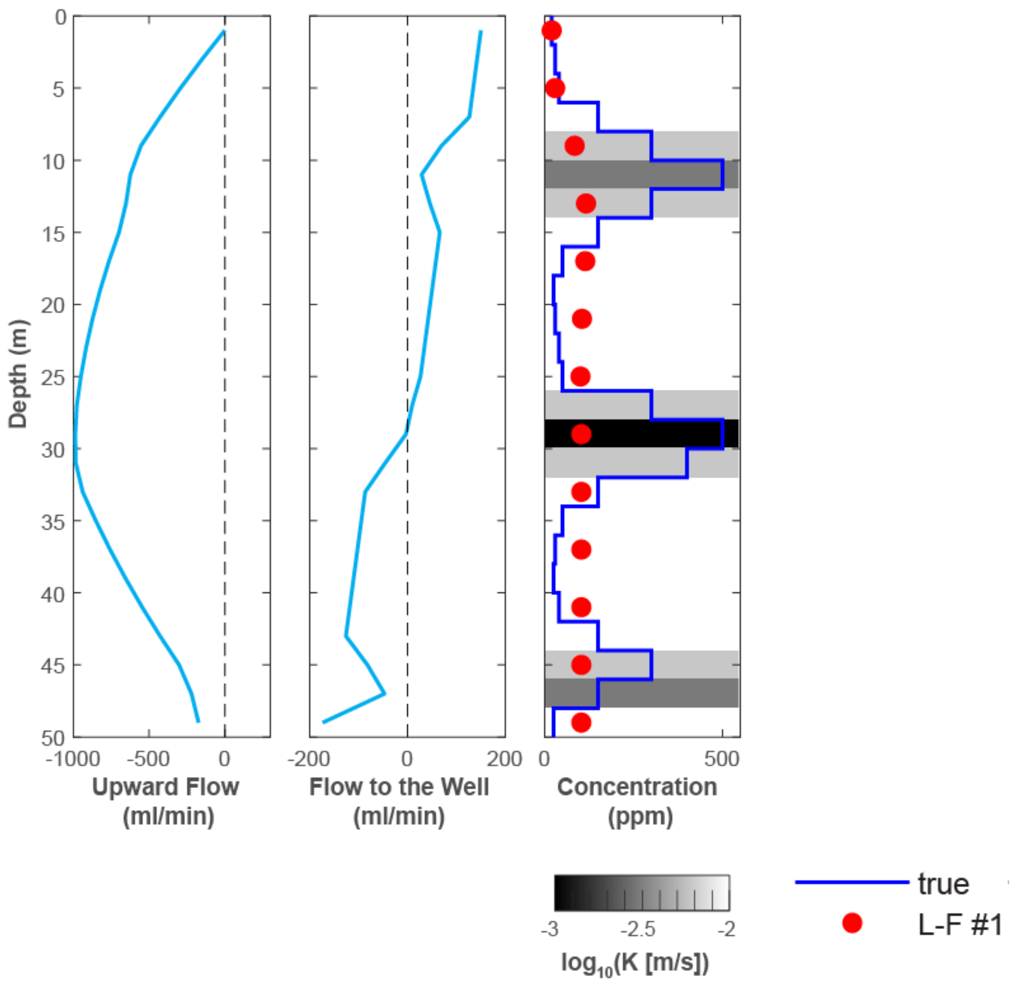


- Improvement compared to conventional interpretation of samples
- Better identifies locations and magnitude of contaminated zones
- Can integrate different datasets collected under different hydraulic conditions
- Still limited in zones of outflow

Synthetic Examples

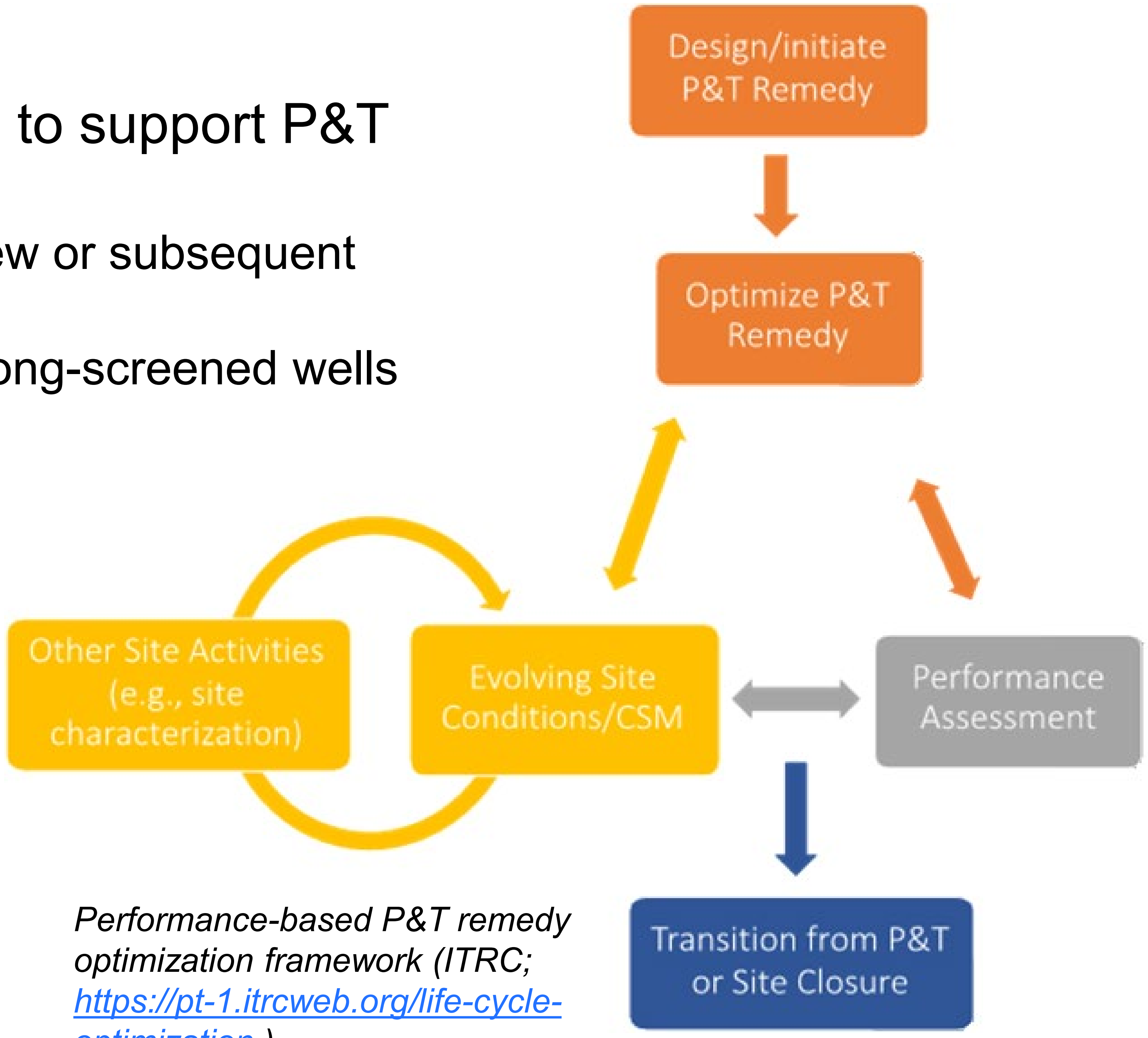
Assuming *K* profile and resulting flow-log data, we conduct

1. Low-flow (L-F) sampling → resolves shallow high-concentration layer
2. L-F sampling with pump at top of well to overcome ambient flow → resolves deeper high-concentration layers
3. Joint inversion of the two datasets from previous examples → further improvement

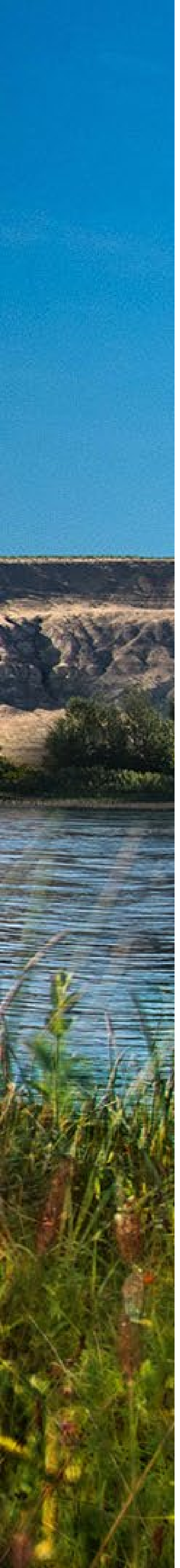


Take Aways

- Vertical characterization is needed to support P&T optimization (mass removal)
  - Increasingly necessary with each new or subsequent phase in the P&T lifecycle
  - Fully utilize the existing network of long-screened wells
- Characterization activities include
  - Sampling and testing during drilling
  - Collection of more contaminant concentration and flow profiles in existing wells
  - Identification of higher concentration zones for possible isolation
  - Mature and test next generation of profiling technologies and methods



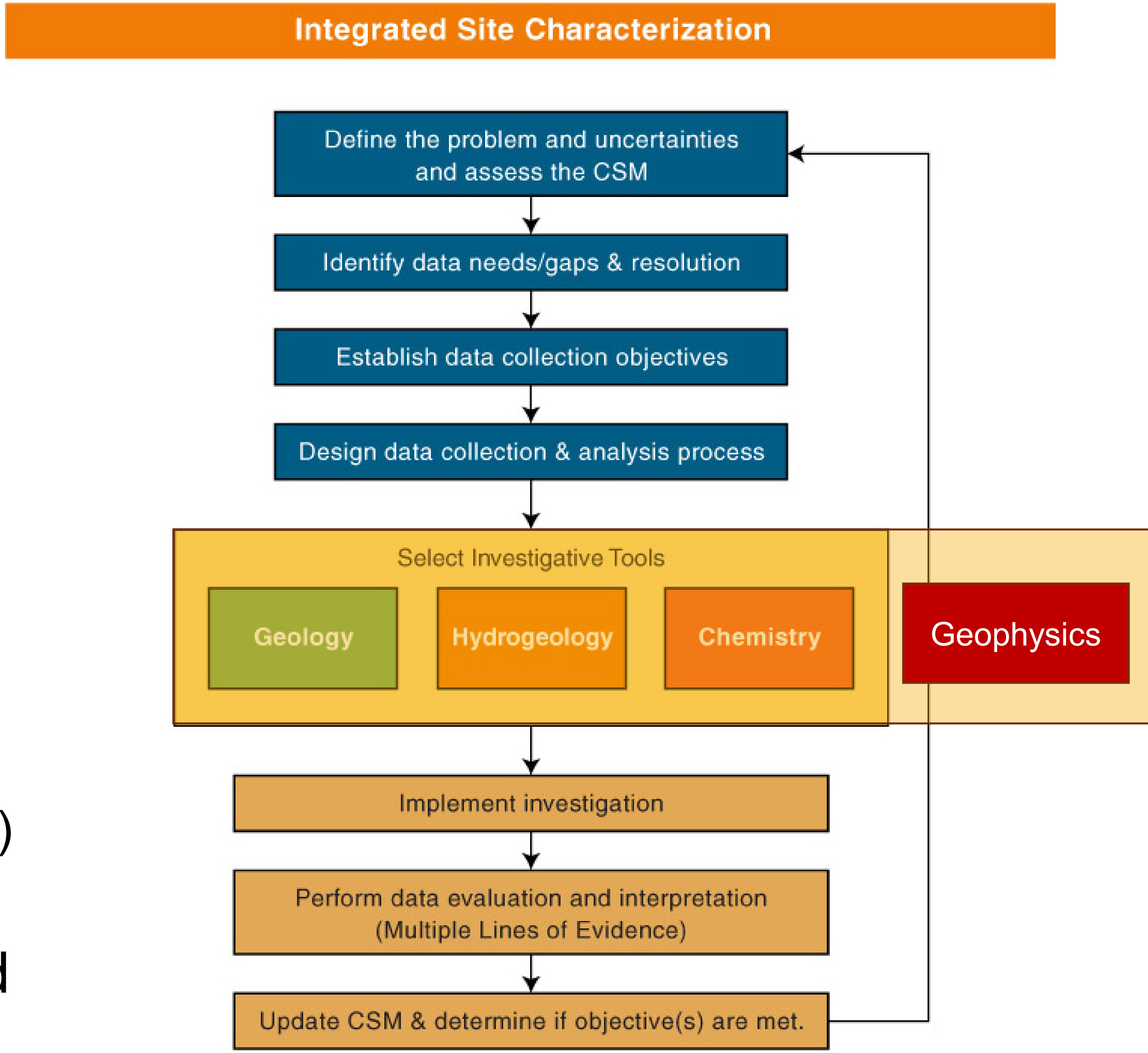
Performance-based P&T remedy optimization framework (ITRC; https://pt-1.itrcweb.org/life-cycle-optimization)



Geophysical characterization and monitoring

- Borehole data is the ‘gold’ standard however….
  - Expensive
  - Spatial interpolation required, may not capture heterogeneity, anistropy
  - Gaps between sampling events, trends may not be fully captured in quarterly or annual sampling
- Geophysical Data
  - Improved spatial coverage
  - Minimally invasive
  - Cost-effective (compared to well sampling)

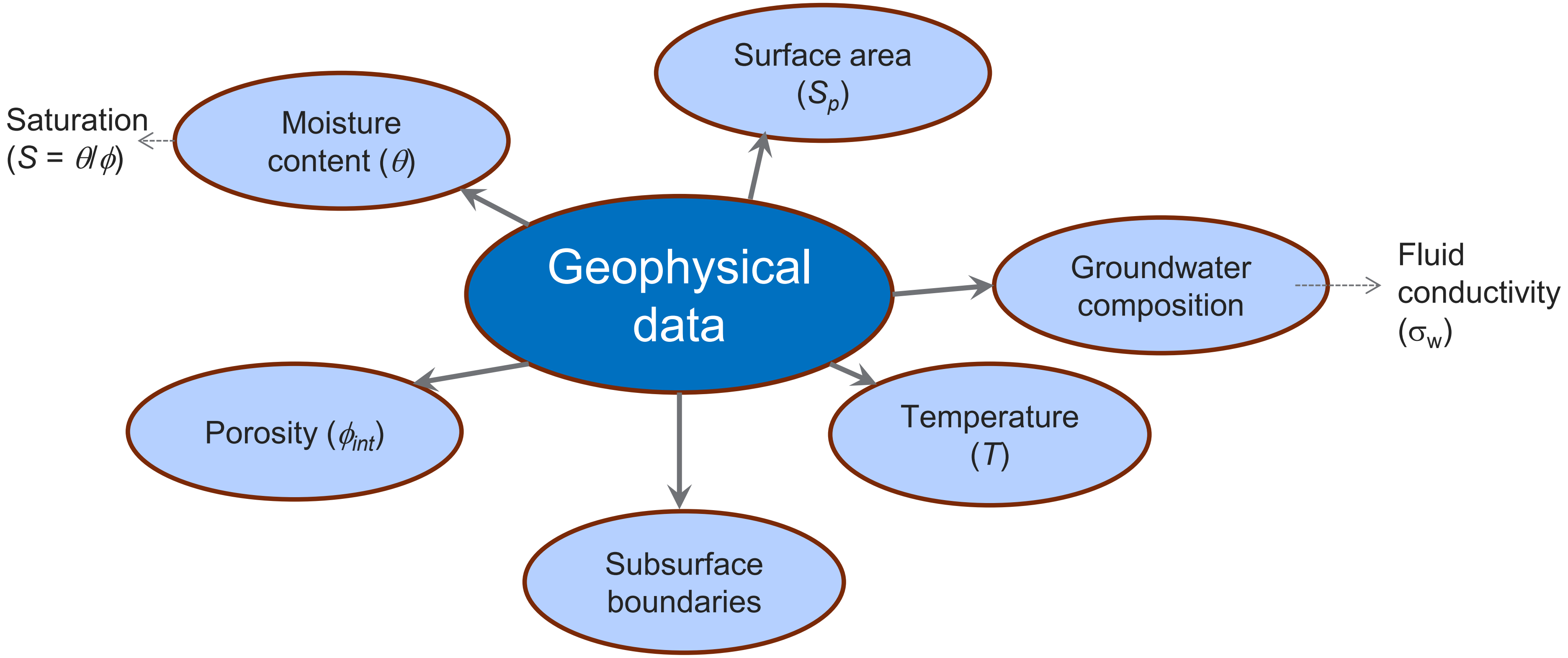
Geophysical data is best used when complementing borehole data and should not be considered a replacement



(ITRC 2015b) https://rmcs-1.itrcweb.org/4-adaptive-site-management/

Geophysical data: Why It's Useful

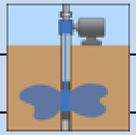
- Geophysical data collected is governed by several properties related to remedial processes

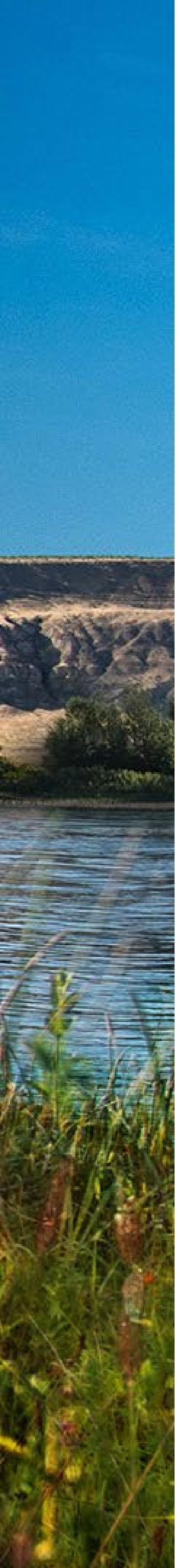


- Since geophysical data is sensitive to multiple physical properties, the interpretation can be non-unique
- The interpretation will be more robust when using several different methods, including all available site data

What can geophysical methods offer to characterize and monitor complex sites?

- Hanford Site Case Studies
  - ✓ Refining geological framework models
  - ✓ Remedial soil flushing
  - ✓ Monitoring of reactive amendment applications
- Applications and Knowledge transfer
  - ✓ Sampling analysis plan (SAP) – Method Selection Tool (MST)

Methods Toolbox (References)	Method Contributes to DQO	Site Conditions	Well Constuction	Overall Recommendation
Borehole Hydraulic Testing in Existing Wells				
21. Slug Tests 	●	●	○	✖
22. Pumping Tests (constant rate, step drawdown, etc.)				
Single-Well	●	●	○	✖
Multi-Well	○	–	–	✖
23. Borehole Flowmeter (e.g. EBF)	●	●	●	✔
24. Tracer Testing				
Single-Well	●	●	●	✔
Multi-Well	●	○	●	✖



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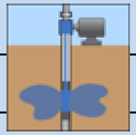
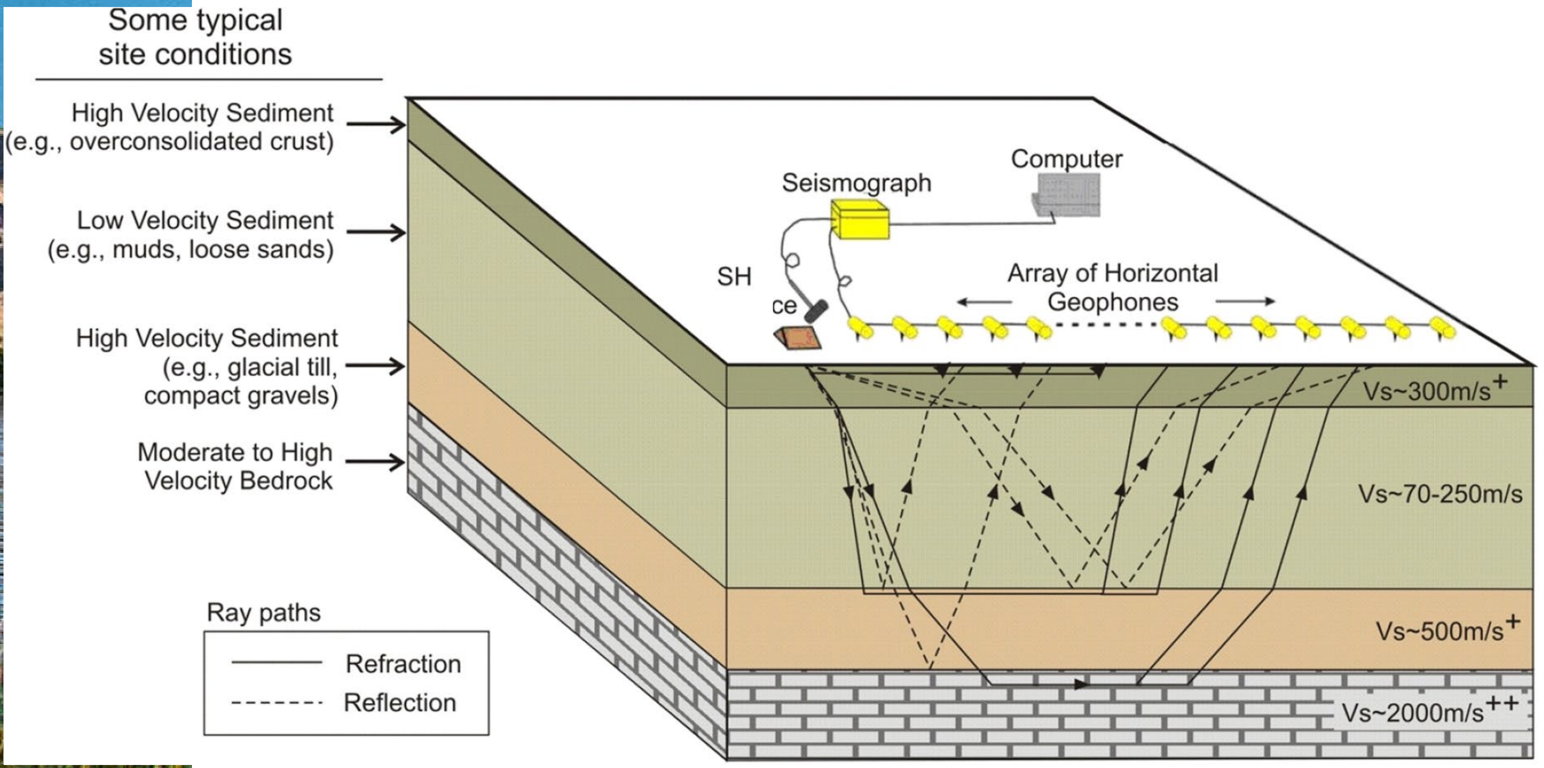
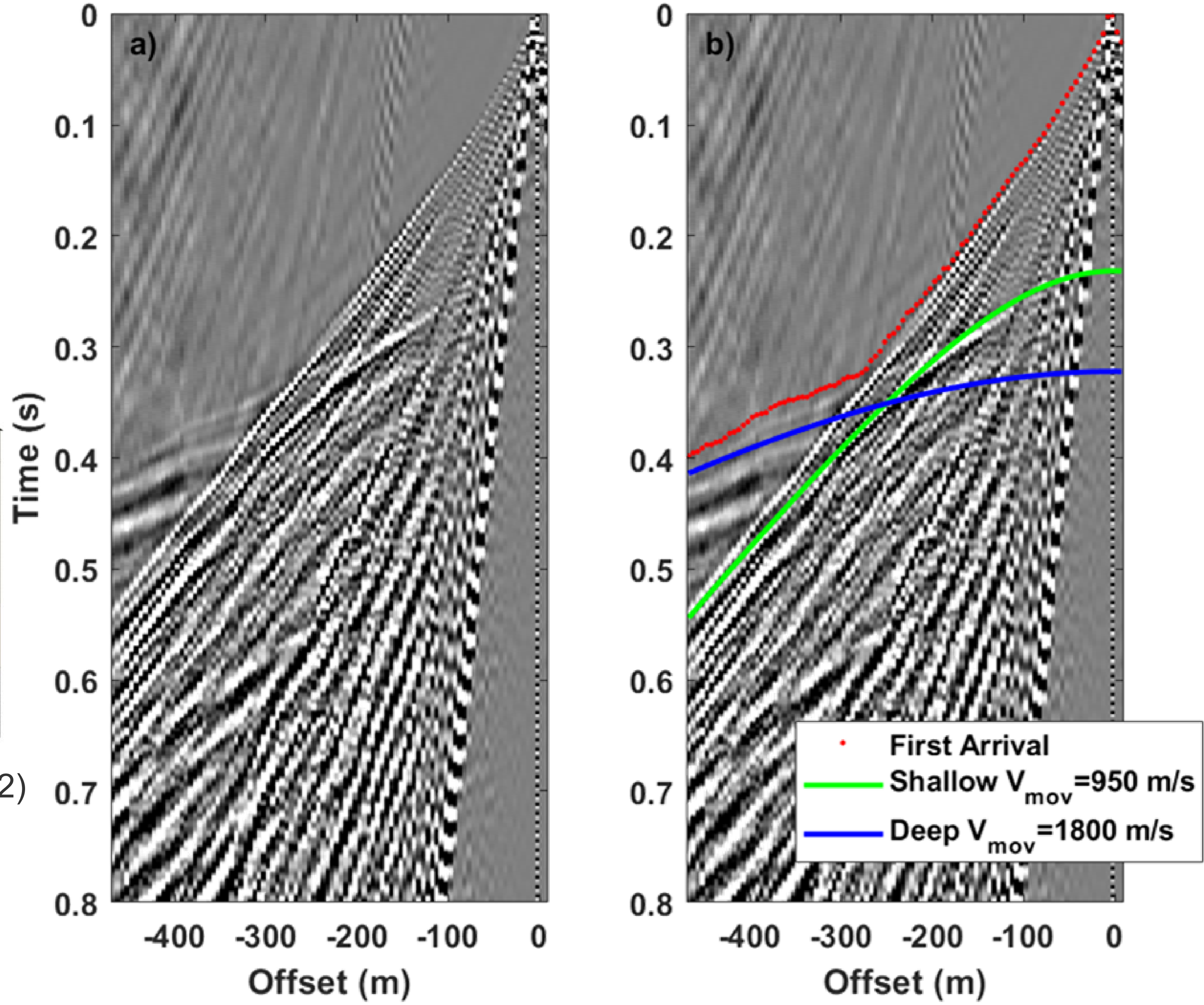
22. Pumping Tests (constant rate, step drawdown, etc.) 				
Single-Well	●	●	○	✖
Multi-Well	○	–	–	✖
23. Borehole Flowmeter (e.g. EBF)	●	●	●	✔
24. Tracer Testing				
Single-Well	●	●	●	✔
Multi-Well	●	○	●	✖

Seismic Surveying

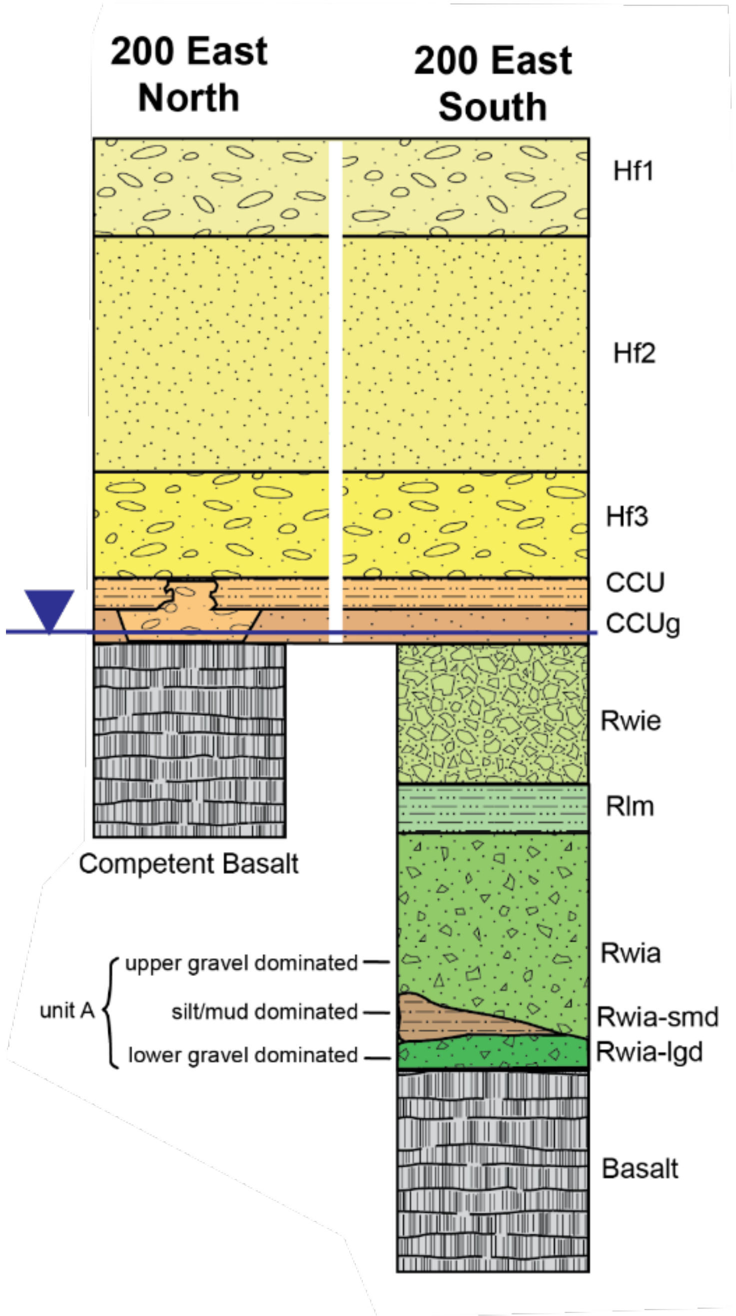
Seismic Reflection, Refraction



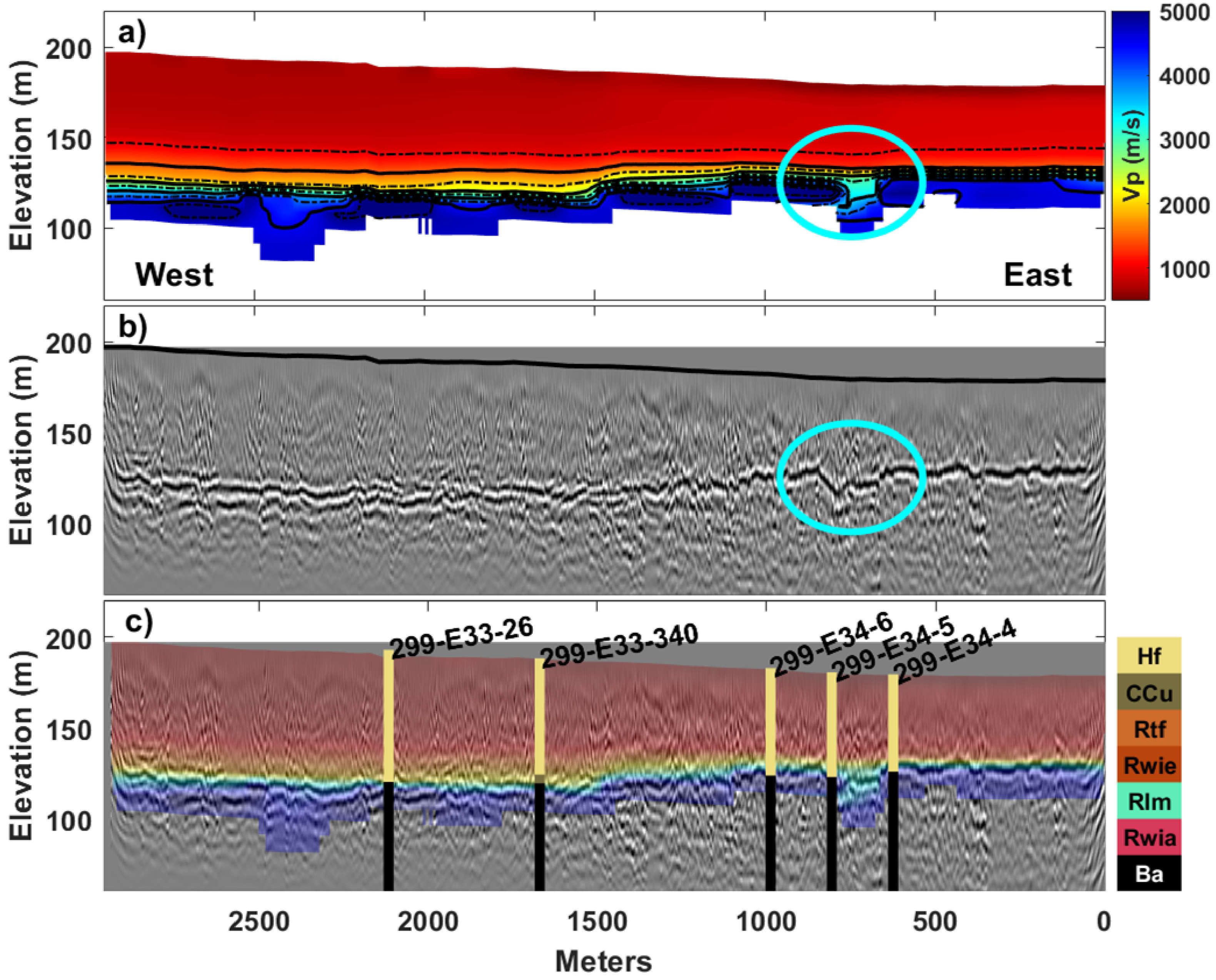
Hunter et al. (2015, 2022)



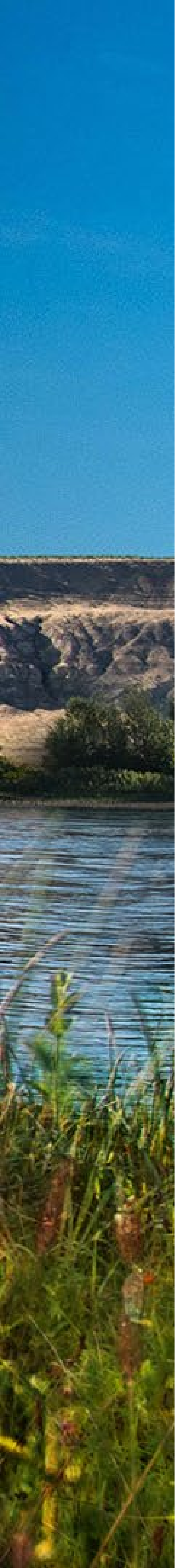
Hydrostratigraphy in Hanford 200 East Area



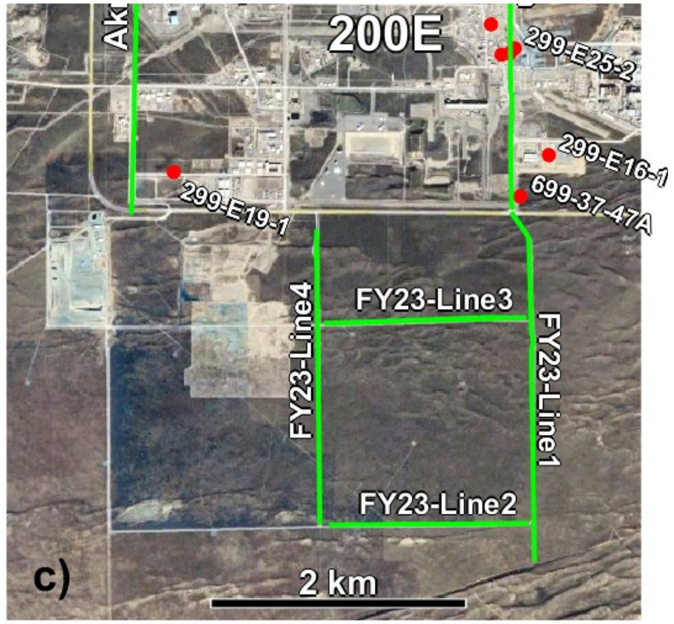
200 East Area 12th Ave

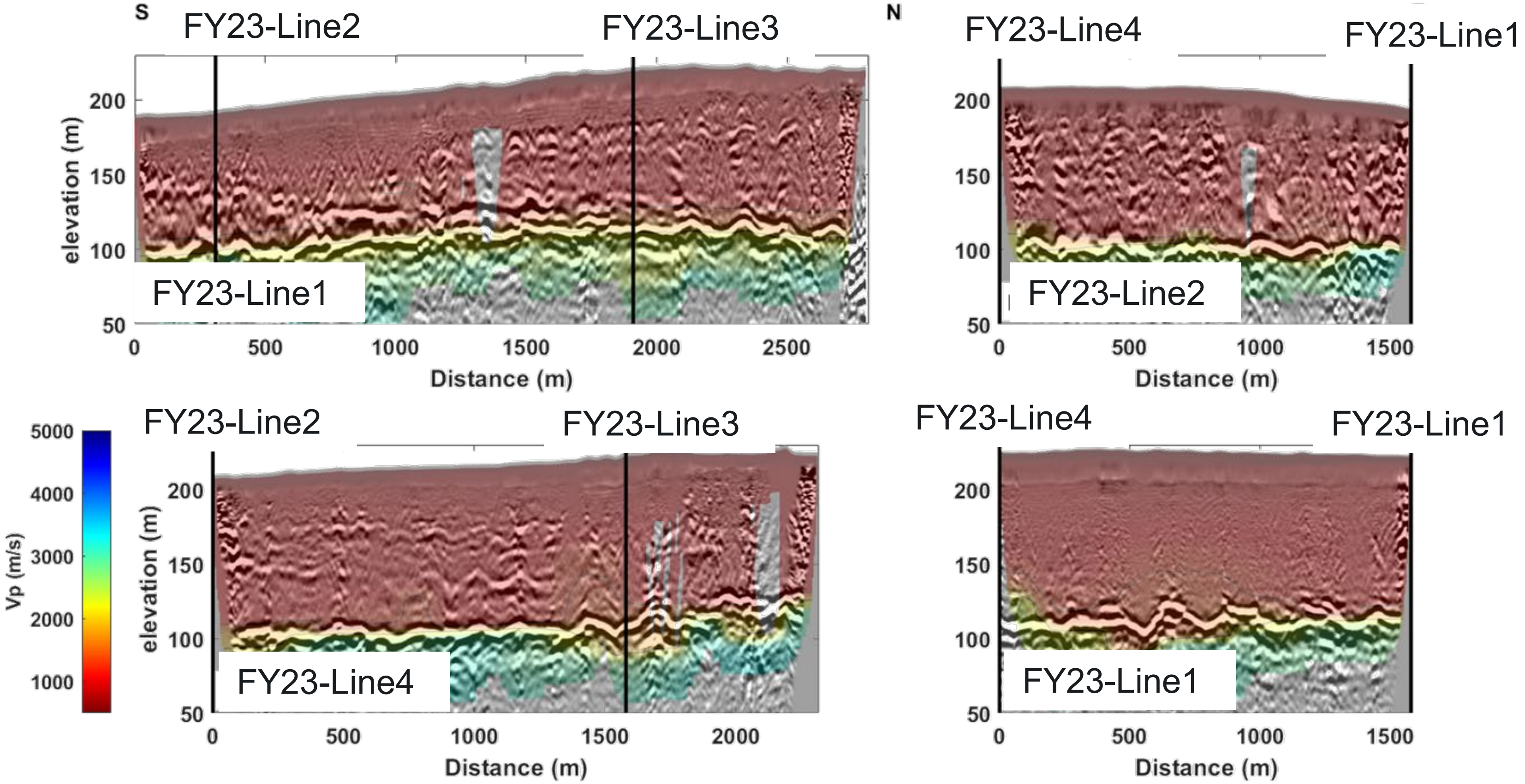


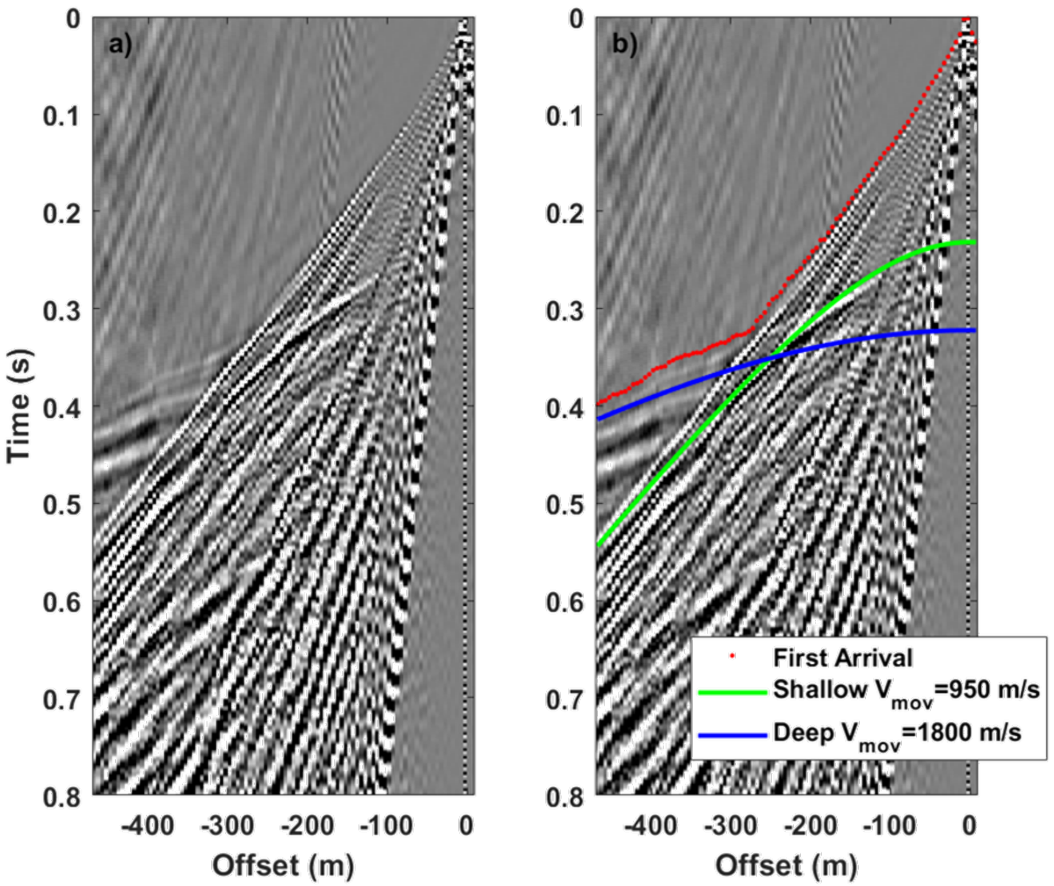
- Suprabasalt units other than Hanford formation are absent
- Reflector is the top of basalt, small Vp anomaly correlates with basalt topography imaged by pre-stack depth migration (cyan circle)
- Wells confirm absence of Ringold Formation



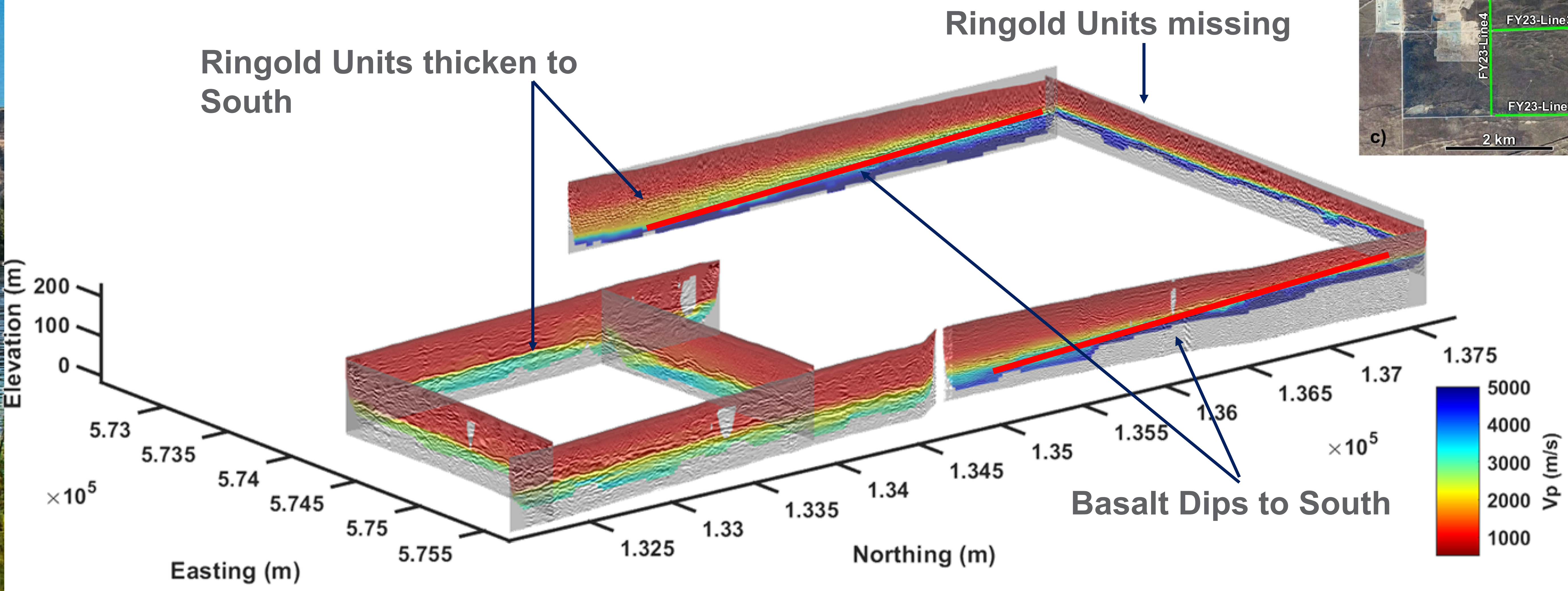
South of 200 East Area (NMO-shallow)

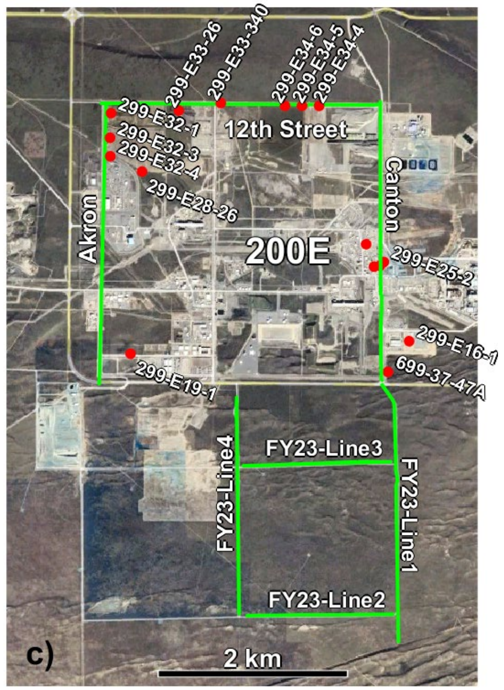


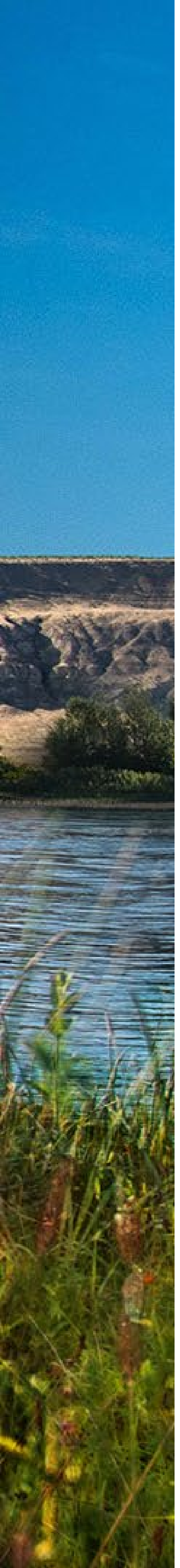




South and within 200 East Area Fence Diagram







What can geophysical methods offer to characterize and monitor complex sites?

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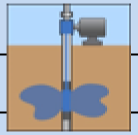
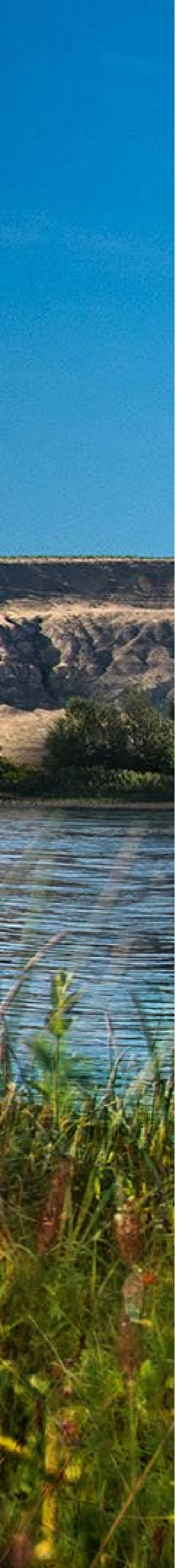


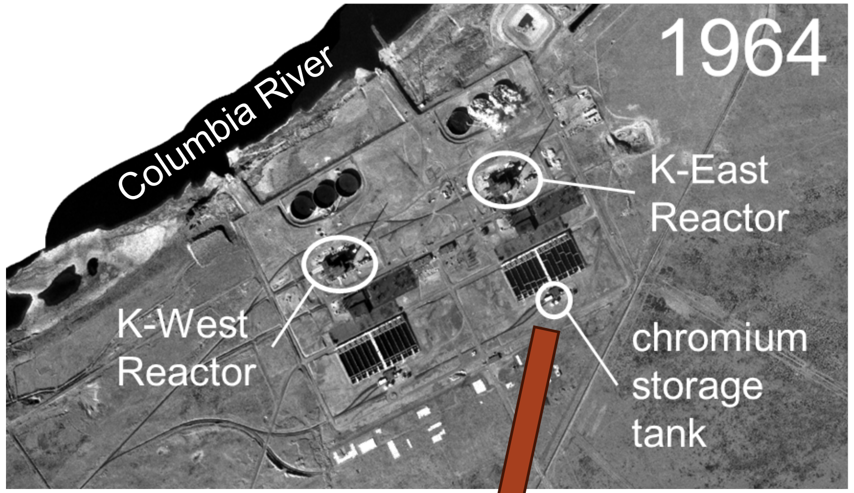
Methods Toolbox (References)	Method Contributes to DQO	Site Conditions	Well Constuction	Overall Recommendation
Borehole Hydraulic Testing in Existing Wells				
21. Slug Tests	●	●	○	✖
22. Pumping Tests (constant rate, step drawdown, etc.)				
Single-Well	●	●	○	✖
Multi-Well	○	–	–	✖
23. Borehole Flowmeter (e.g. EBF)	●	●	●	✔
24. Tracer Testing				
Single-Well	●	●	●	✔
Multi-Well	●	○	●	✖

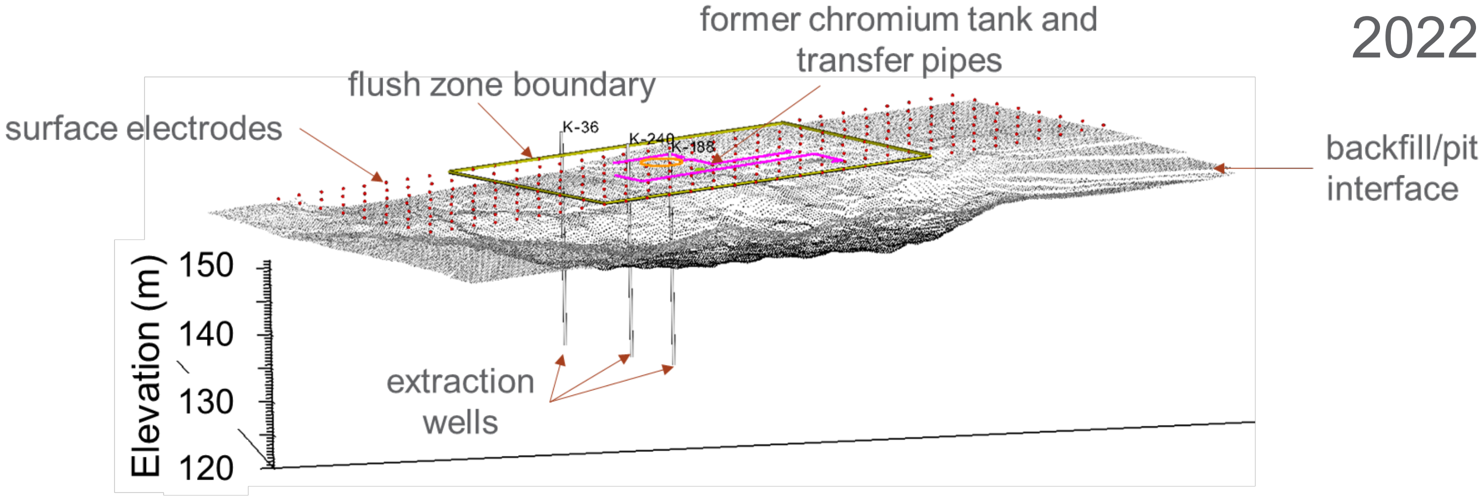


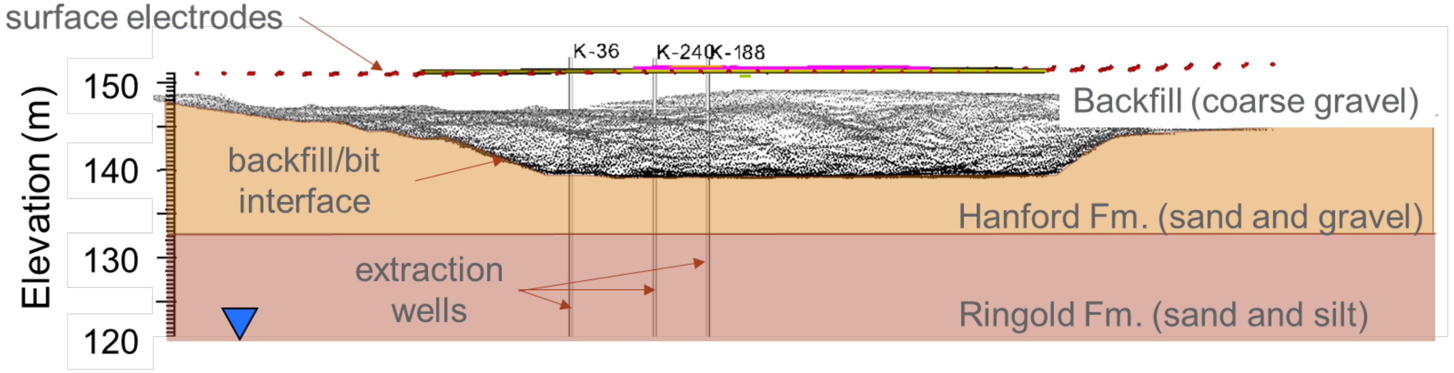
Real-time Autonomous 4D monitoring: Hanford 100K Area Soil Flushing Test

- Vadose zone hexavalent chromium contamination from historical operations
- Clean water applied at surface to flush water to aquifer
- Removed via pump and treat
- Monitored with sampling and 4D ERT imaging

Hanford 100K Reactor Area

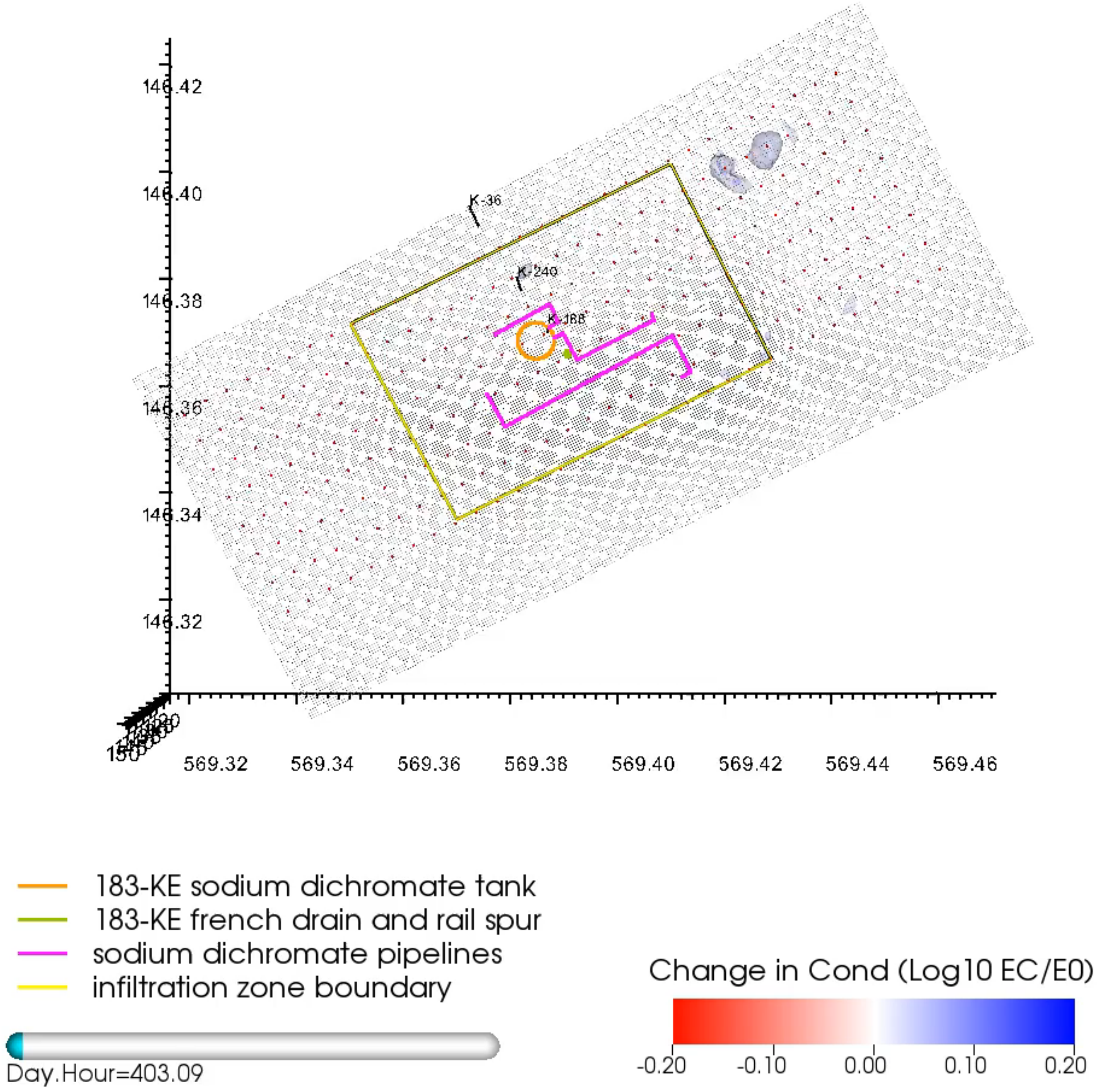






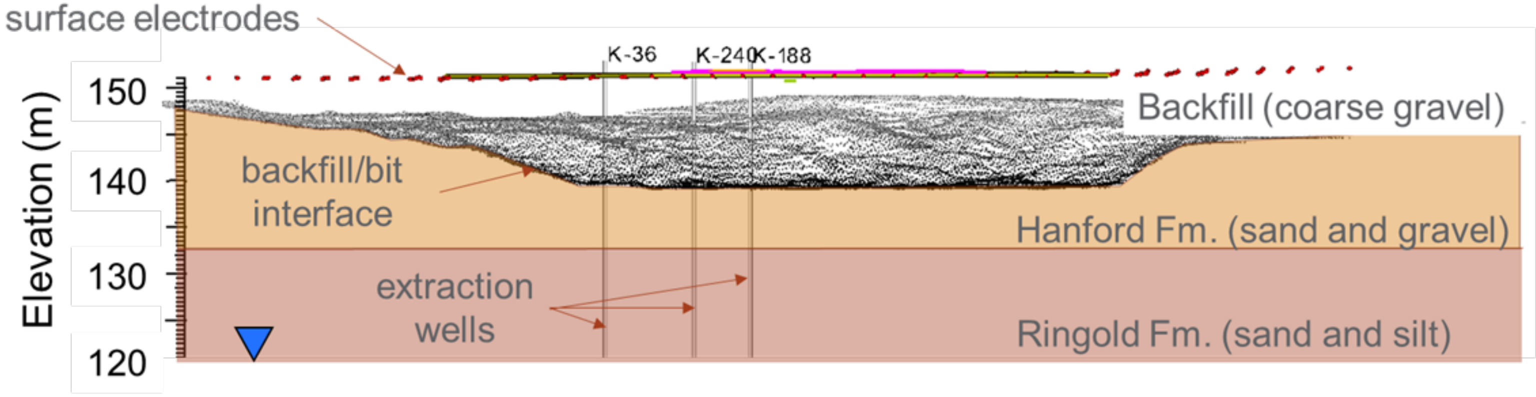
Real-time Autonomous 4D monitoring: Hanford 100K Area Soil Flushing Test

- Results provided an enhanced understanding of
  - Influence of the backfill material
  - Preferential flow paths and flow distribution



ERT, Multiphysics Simulation and Machine Learning

- Using all available data to calibrate a flow and reactive simulator (PFLOTRAN)
  - Flow, transport, ERT
  - Flush water application locations and rates from actual test
  - 28 days of flushing
  - ERT every 2 days
  - 29 unknown input parameters

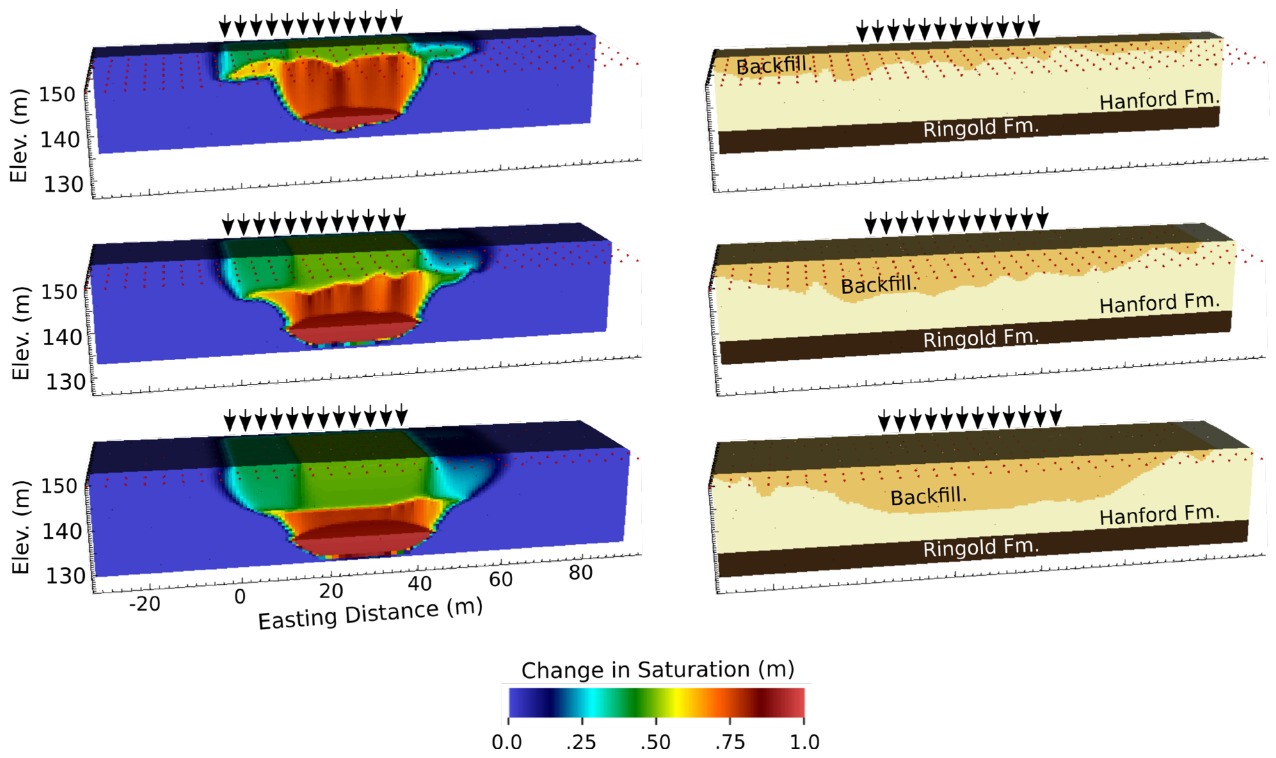


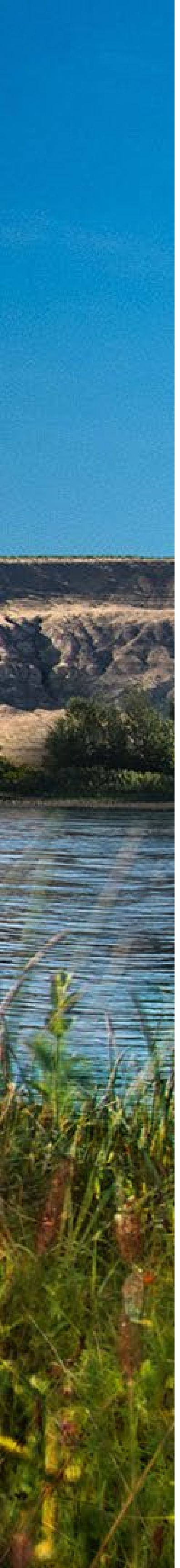
Parameters Estimated for Each Unit

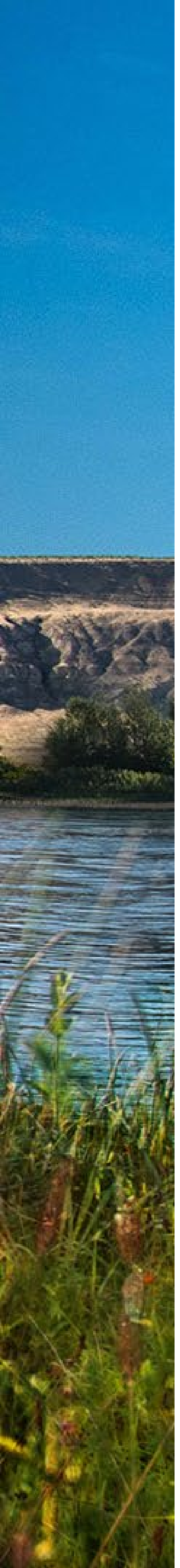
Porosity, horizontal permeability, vertical permeability, Archie's parameters (4), Van Genuchten parameters (3)

- Plus: native pore water fluid conductivity, flush water conductivity

Example Simulation: Change in Saturation at 14 Days







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ML for Calibrating Simulators with Uncertainty Modified Generative Collaborative Network

1. Generate Training Data

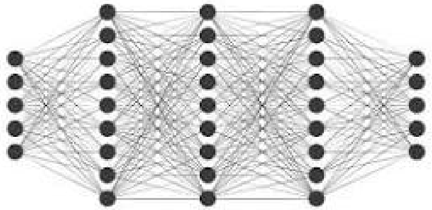
Random (bounded) parameter sets → PFLOTRAN

Training Data: Generate ERT or <u>other Data</u>

Compute 'Fit' with actual field data

2. Train Discriminator

Parameter Sets / PFLOTRAN models →



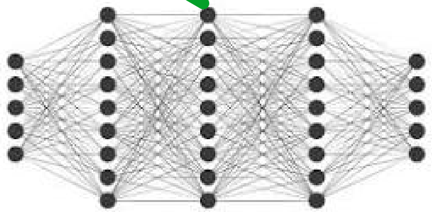
→ 'Fit' for a given model with actual field data

Discriminator is trained to predict 'fit'

3. Train Generator

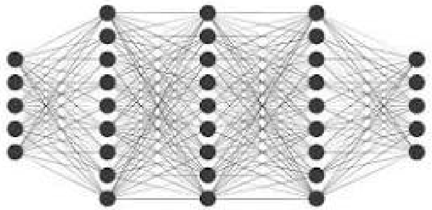
Random vector →

Update



Generator

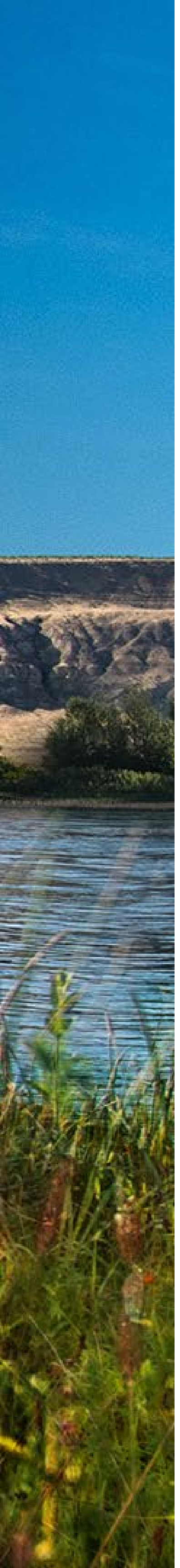
→ Predicted parameter sets →



Trained Discriminator

→ Is target 'fit' met? → Yes → Stop

No → Random vector



What can geophysical methods offer to characterize and monitor complex sites?

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  - ✓Monitoring of reactive amendment applications using induced polarization

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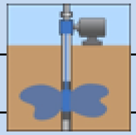
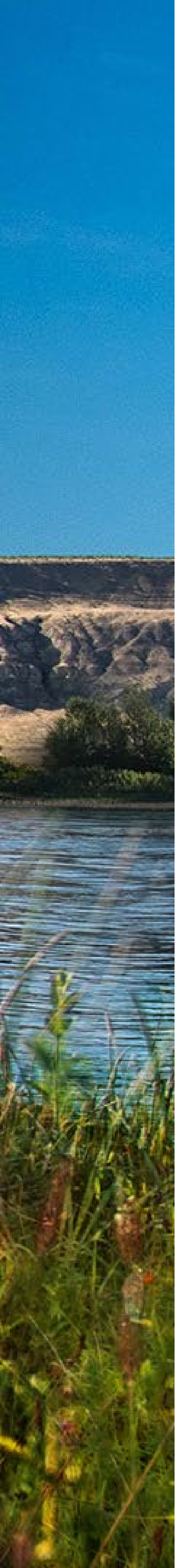
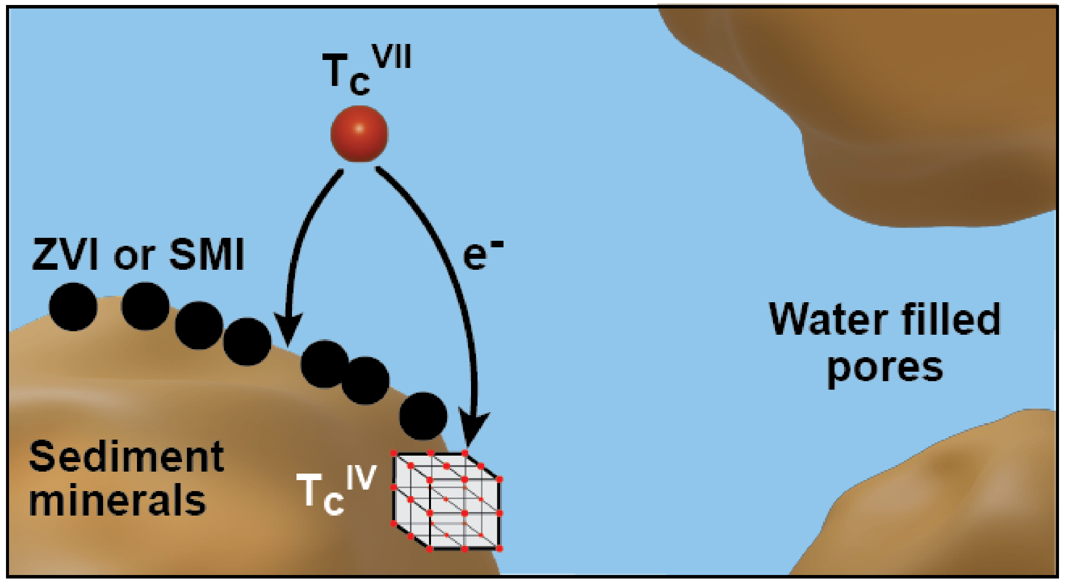
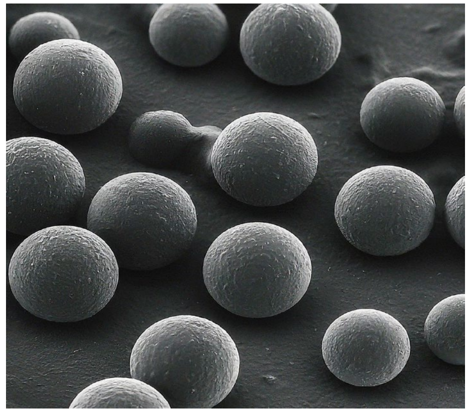
21. Slug Tests 	●	●	○	✖
22. Pumping Tests (constant rate, step drawdown, etc.)				
Single-Well	●	●	○	✖
Multi-Well	○	–	–	✖
23. Borehole Flowmeter (e.g. EBF)	●	●	●	✔
24. Tracer Testing				
Single-Well	●	●	●	✔
Multi-Well	●	○	●	✖

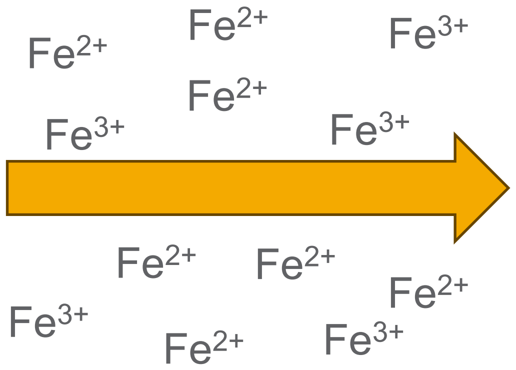


Monitoring sulfur modified iron (SMI) applications

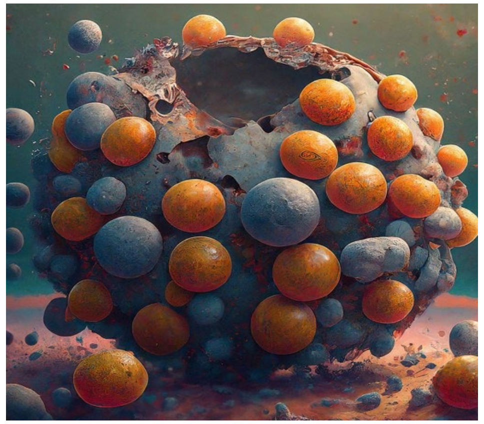




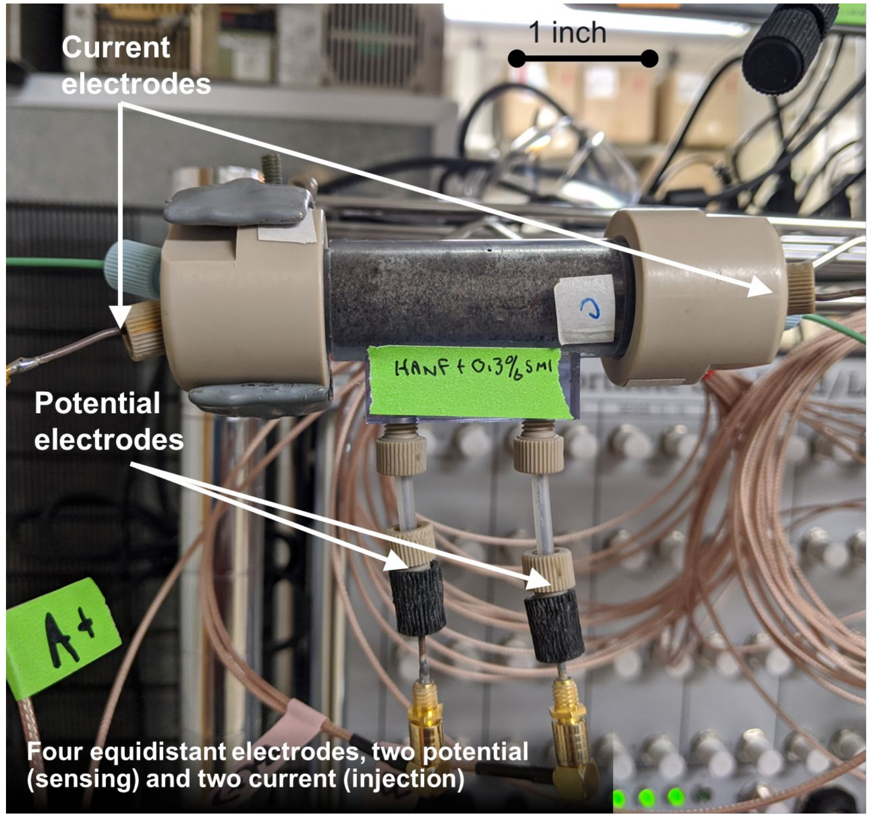
Step 1: Initial zero valent iron (with or without sulfur)



Step 2
Fe^{+2} oxidation and dissolution



Step 3: Fe^{+2} oxidation and precipitation

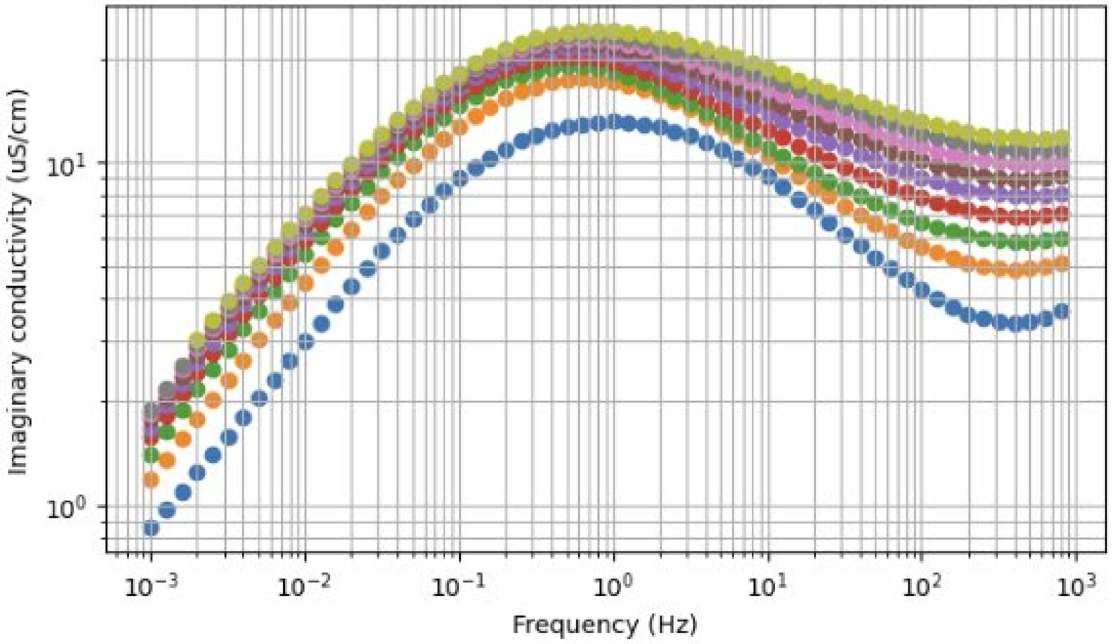


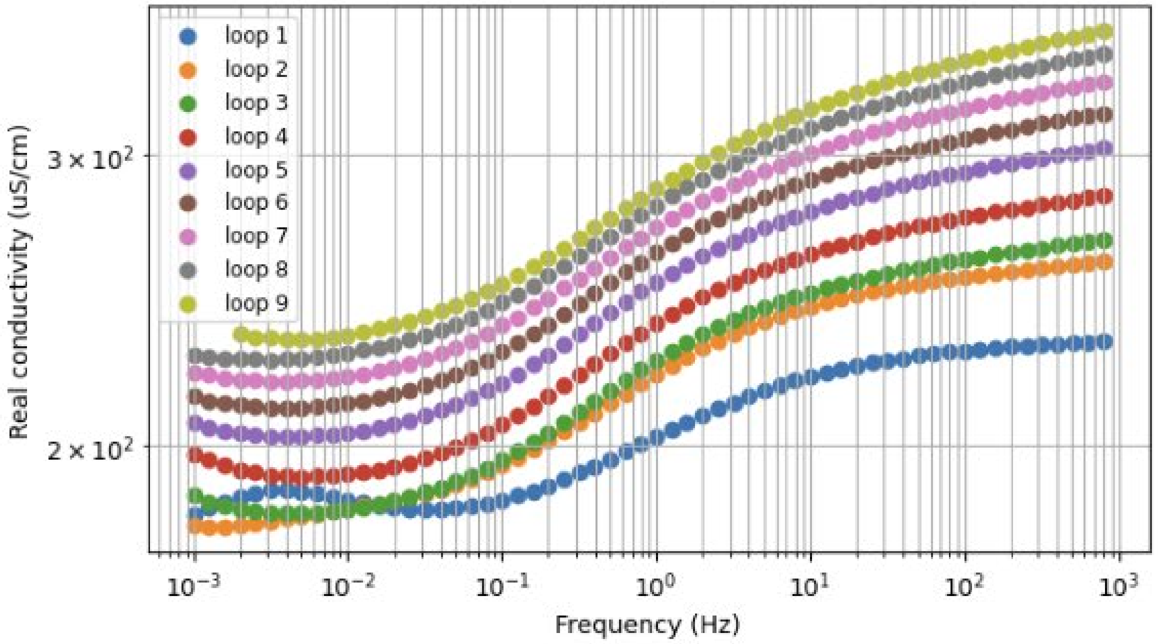
Laboratory column experiments collecting[3] temporal induced polarization (IP) data at multiple frequences

IP measures provides information on the volume concentration, size, porosity, and possibly mineralogy of electron-conducting minerals

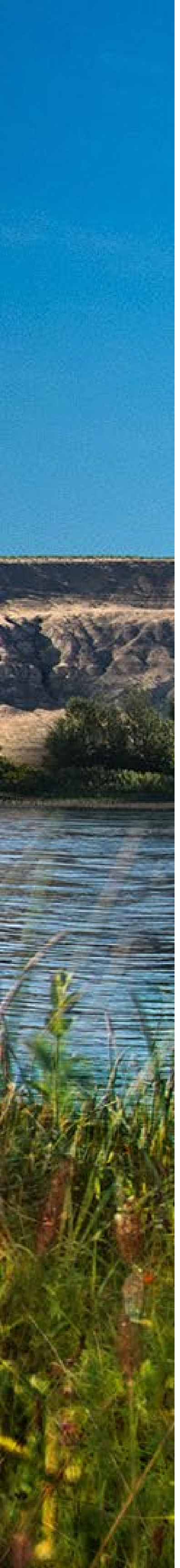
Complex resistivity, ERT + Induced Polarization

- Electrical resistivity tomography (ERT)
  - Ionic and surface conduction (pore space physical properties)
- Induced polarization (IP)
  - Reversible temporary charge storage (physical and geochemical properties)





Used together, ERT + IP provide detailed insights into subsurface environments.



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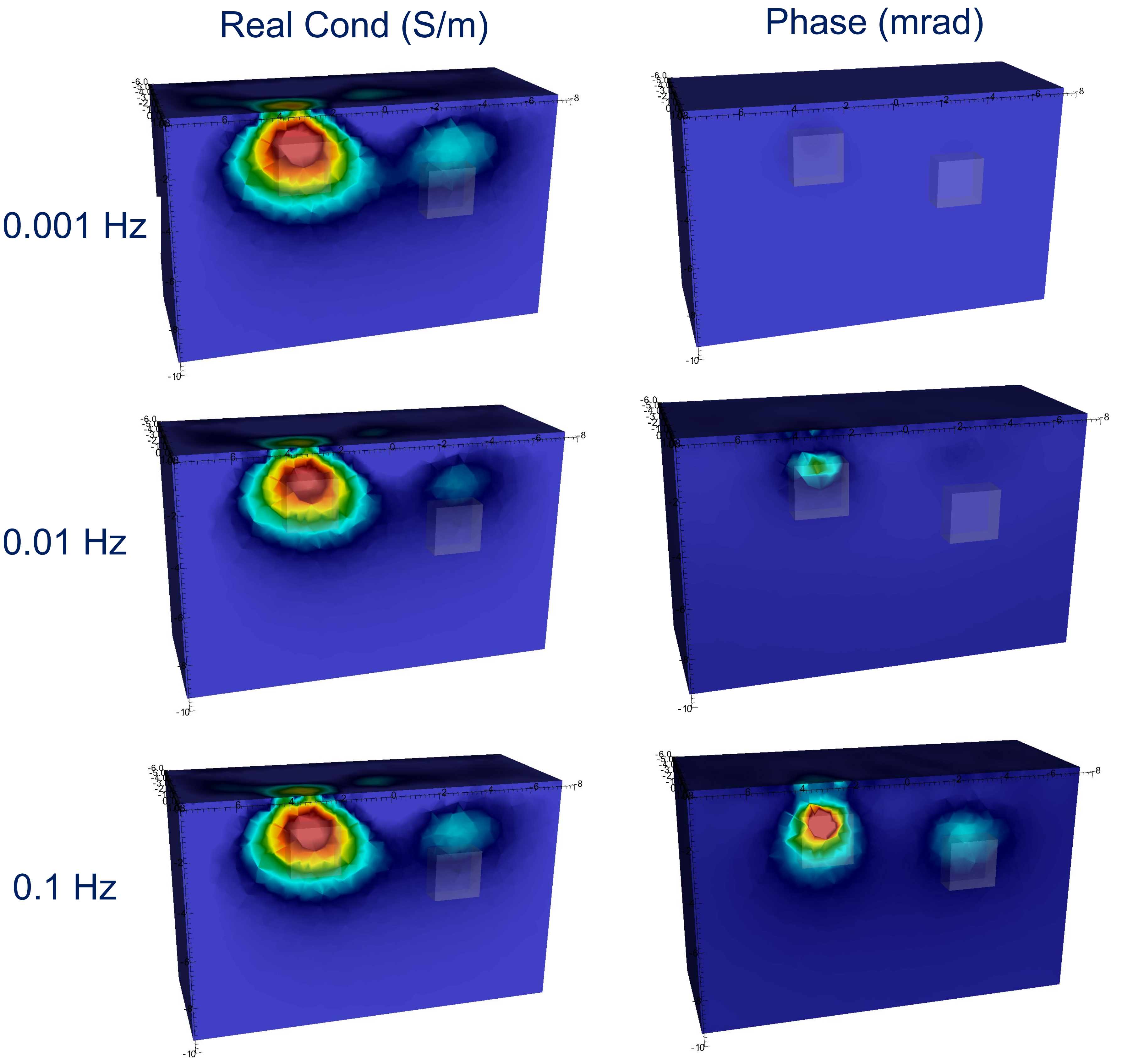
IP synthetic field imaging

- Using laboratory values at different frequencies, synthetic field data was generated



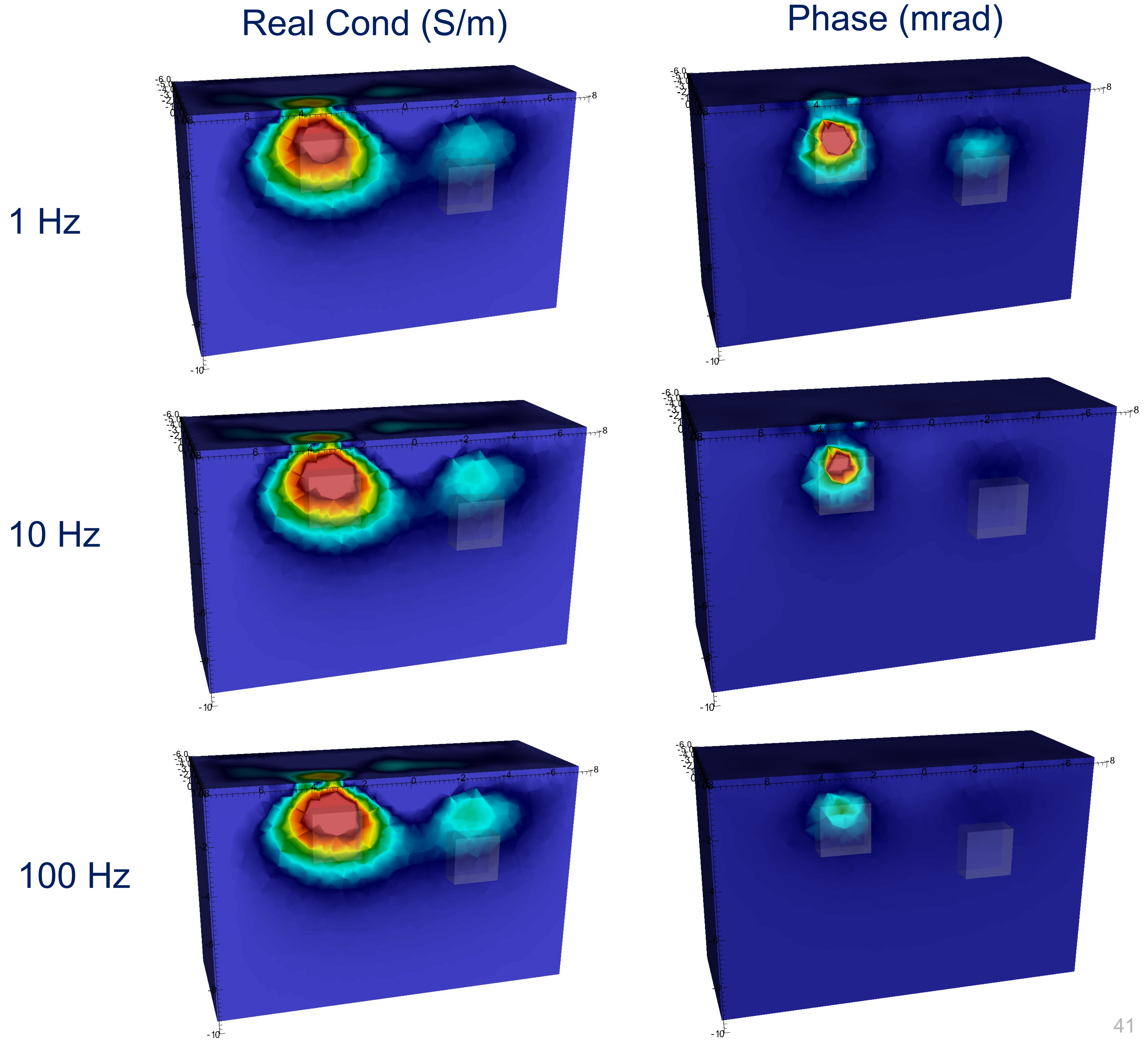
IP synthetic field imaging

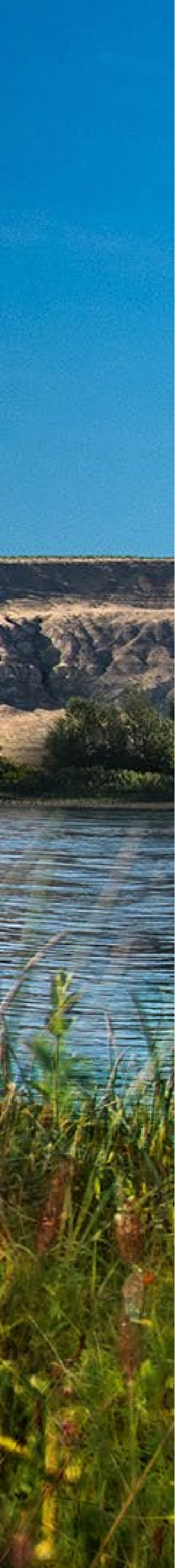
Real conductivity (ERT) answers:

- Where is the amendment located?

Phase (IP) answers:

- Where is the oxidation and reduction occurring?
- What is the best frequency to monitor chemical reactions?





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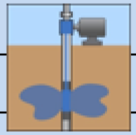
21. Slug Tests 	●	●	○	✖
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Single-Well	●	●	○	✖
Multi-Well	○	–	–	✖
23. Borehole Flowmeter (e.g. EBF)	●	●	●	✔
24. Tracer Testing				
Single-Well	●	●	●	✔
Multi-Well	●	○	●	✖

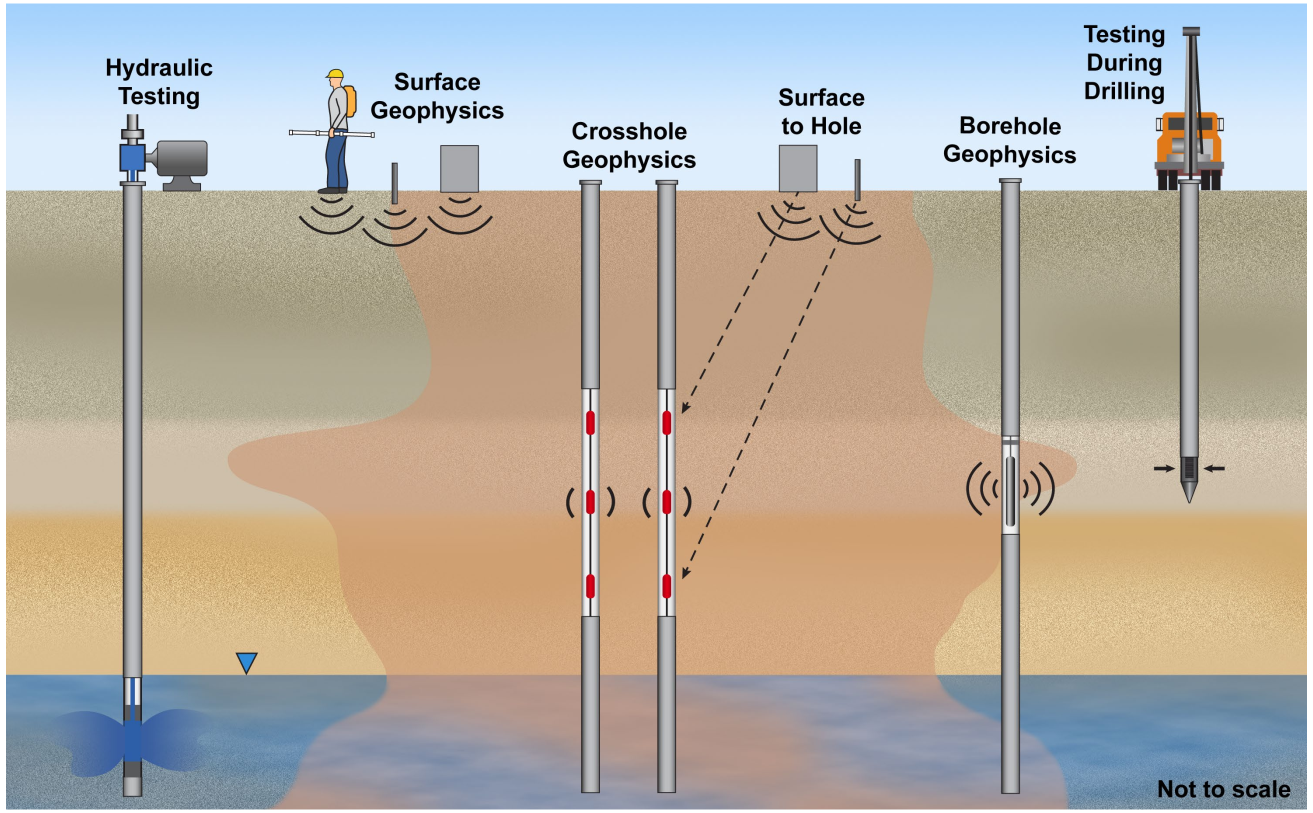
Knowledge Transfer

Motivation

- Facilitate an integrated and systematically planned strategy
- Provide an access point for engineers, hydrologists, geologists, project managers and regulators to site characterization methods

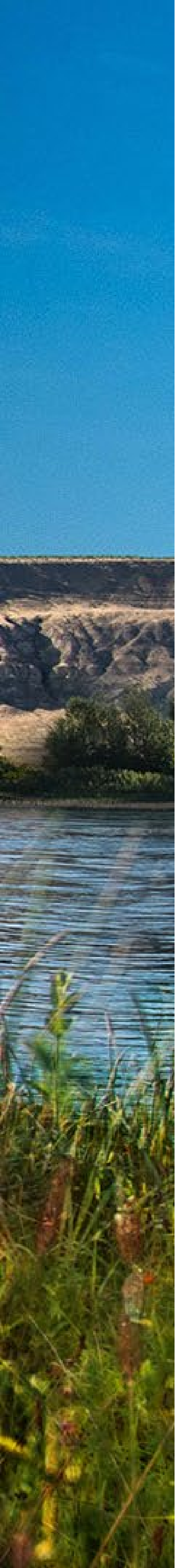
Goals

- Provide a common starting point for communicating how to meet site objectives through method selection tools
- Design a tool that is easy to use and navigate

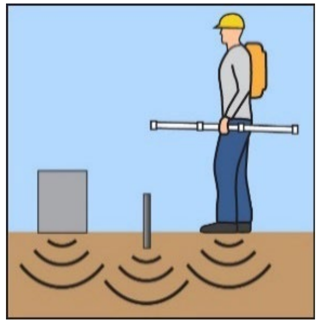
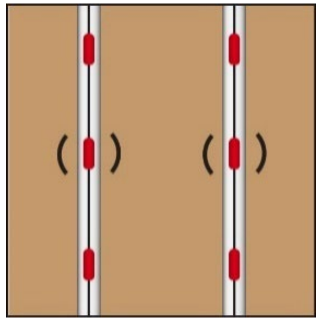
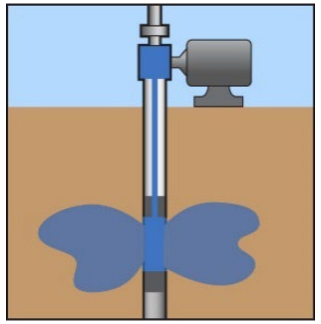
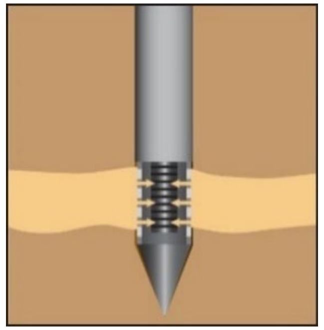


Sample Analysis Plan (SAP)-Method Selection Tool (Tool)

An excel based tool to facilitate a common starting point and communication amongst remediation professionals



SAP-MST – Geophysical and Hydraulic Methods

Surface

- Electrical resistivity tomography (ERT)
- Induced Polarization (IP)
- Electromagnetic (EM) (frequency and time-domain)
- Ground penetrating radar (GPR)
- Seismic Methods
- Magnetics

Surface-to-Hole and Crosshole

- ERT
- Seismic
- Vertical seismic profiling (VSP)

Borehole

- EM Logging
- DAS/DTS
- Neutron Porosity/Density Logging
- Neutron Moisture
- Gamma/Spectral Gamma Logging
- Resistivity
- Optical Televiewer (OTV)
- Fluid EC
- Acoustical Televiewer (ATV)
- Nuclear Magnetic Resonance (NMR) Logging
- Sonic Logs

Existing Wells

- Slug Tests
- Pumping (constant rate, step drawdown, etc)
  - Single-well
  - Multi-well
- Borehole Flowmeter (e.g EBF)
- Tracer Testing (single, multi-well)

Testing During Drilling

- Depth-discrete hydraulic testing
  - Slug
  - Pumping Tests (constant rate, step drawdown, etc)
    - Single-well
    - Multi-well
- Sampling (Soil and Groundwater)

Criteria for Method Selection
Identify Theme, Sat/Unsat, General objectives

- Draws from the Data Quality Objective (DQO) process to guide / plan for resource effective acquisition of data
- General themes are provided, and specific site objectives are grouped between saturated and unsaturated zones into Generalized DQOs

Theme	#	Generalized DQO	
Unsaturated Zone			
Contaminant Source and Behavior	A-1	Determine spatial distribution of contaminant source	Yes
	A-2	Determine downward flux of a contaminant source to groundwater (vadose to saturated zone)	No
Geology	B-1	Determine subsurface structure (stratigraphy, soil type, lithology)	No
Hydrogeologic Conditions	C-1	Estimate hydrogeologic properties (e.g., Kunsat)	No
Monitoring	D-1	Monitor vadose zone system dynamics (e.g., moisture content changes, contaminant migration, etc.)	No
	D-3	Monitor the spatial and temporal distribution of an amendment (e.g., delivery and transport of an injected chemical amendment, changes in moisture or porewater saturation during soil flushing) (vadose zone)	No
Subsurface Detection	E-1	Detect/delineate subsurface targets (e.g., archaeology, tanks, pipes, etc.) (vadose zone)	No

Saturated Zone			
Contaminant Distribution and Behavior	F-1	Characterize the spatial distribution of contamination	No
	F-2	Determine vertical contaminant concentration profile	No
Geology	G-1	Characterize the extent of specific geologic units	No
Hydrogeologic Properties (spatial, lateral, vertical, leakage?)	H-1	Characterize spatial distribution and heterogeneity of hydrogeologic properties (e.g. groundwater velocity, preferential flow pathways, high K zones)	Yes
	H-2	Estimate well and aquifer properties that relate to groundwater flow (e.g. specific capacity, hydraulic conductivity, specific yield and/or storage, aquifer thickness)	No
	H-3	Estimate hydrologic properties that relate to contaminant transport (e.g. porosity, dispersivity, sorption, mass transfer rates)	Yes
Monitoring	I-1	Monitor aquifer system dynamics (e.g., saturation change, water table fluctuation, contaminant migration, etc.)	No
	I-3	Monitor active remediation, such as extent of specific injectate (or amendment) as delivered (e.g., injected). This could be for a specific objective such as contaminant containment and/or source containment. Monitor contaminant migration in response to active remediation.	No
	I-4	Monitor post-active remediation conditions (e.g. monitored natural attenuation (MNA))	No

Criteria for Method Selection
Specify your site conditions

#	Site Conditions	
1	Is the investigation during drilling (i.e., not post drilling)?	No
2	Are there nearby wells that can be used for hydraulic observation?	No
3	Is the goal depth of investigation (DOI) > 30% of the length of a possible survey line?	No
4	Is there a large fluid conductivity contrast between native groundwater and target fluids (e.g., contamination, amendments)?	No
5	Is the target depth of investigation (DOI) within the top 5 m?	No
6	Is disturbance of the ground (e.g., installation of electrodes or geophones) prohibited?	No
7	Is there cultural EM interference (utilities, metal pipes, etc.)	No
8	Are there high conductive shallow materials in the near subsurface?	No
9	Is GPS signal problematic at the site?	No

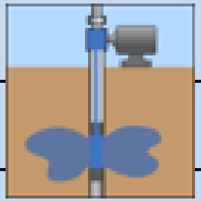
#	Well Construction	
10	What is the well casing material?	Steel
11	Are the screen(s) or open interval long relative to the length of the casing?	Yes
12	What material is in the annular space, around the casing?	native soil
13	If there's a pump in the well, is removal possible?	Yes

Site conditions and well construction questions represent controlling factors for/against the implementation of one or more geophysical or hydraulic methods

Methods recommended

✓ Recommended
X Not recommended
- Not applicable

● Criteria did not limit the selection of a method
○ Criteria did limit the selection of a method



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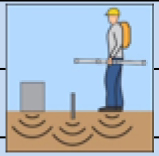
Multi-Well	○	-	-	✗
23. Borehole Flowmeter (e.g. EBF)	●	●	●	✓
24. Tracer Testing				
Single-Well	●	●	●	✓
Multi-Well	●	○	●	✗

Method details are provided

Methods Toolbox (References)		Method Contributes to DQO	Site Conditions	Well Constuction	Overall Recommendation
Surface Geophysical Methods					
1. ERT – Electrical Resistivity Tomography		●	●	●	✓
2. Induced Polarization		●	●	●	✓
3a. FDEM – Frequency Domain Electromagnetic	3b. Time Domain EM				
4. GPR – Ground Penetrating Radar					
5. Seismic Methods					
6. Magnetics					

Electrical Resistivity Tomography (ERT)

PNNL

Measures: Electrical resistivity to interpret (hydro)geologic features and contaminant transport within subsurface.

PROVIDES

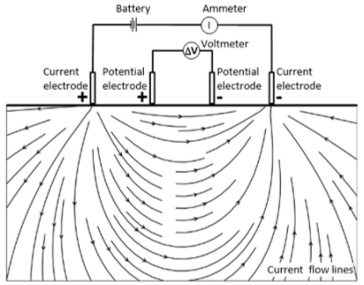
- Identification of subsurface features, including bedrock, saturation levels, porosity, and zones of electrical conductivity variation.
- Detection of fracture zones and conductive pathways, aiding in site characterization.
- Continuous monitoring of subsurface trends, such as changes in groundwater flow or contaminant transport.
- Valuable insights into the hydrogeology of a site, including aquifer properties and contaminant movement.

DETAILS

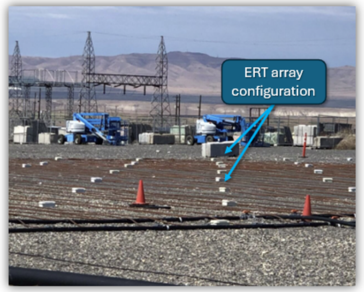
- Electrodes are shallowly inserted into the ground in a linear or 2D array, with investigation depth depending on electrode spacing (~0.2 – 0.3 times the survey length).
- Induced polarization (IP) data, capturing chargeability and pore-fluid properties, can be collected simultaneously using the ERT setup.
- Surveys require accessible field space and reliable power sources (e.g., solar panels or batteries) for extended monitoring.
- Conducted on land and water.

OPEN-SOURCE INVERSION SOFTWARE FOR 2D & 3D ERT DATA

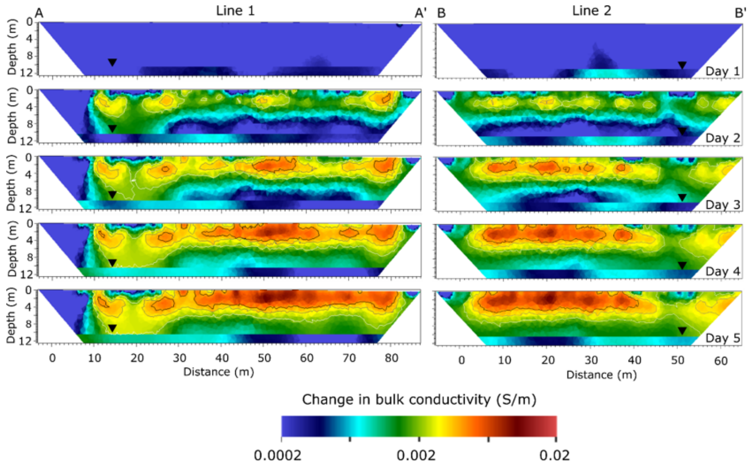
- E4D (https://www.pnnl.gov/get-e4d)



Schematic diagram of a *Schlumberger* array. Current and potential electrodes are used to inject current and measure resistance. A *geometric factor* (based on electrode array and spacing) is applied to obtain *apparent resistivity*.



Electrode configuration for resistivity imaging used to monitor in situ soil flushing at the Hanford 100-K East Area (Johnson et al., 2024).



Example of time-lapse electrical resistivity imaging produced over the first 5 days of phosphate infiltration for uranium sequestration. (Johnson et. al., 2022).

Logic Transparency / Sensitivity Analysis

- Selection Logic Matrix provides more detail on method selected
  - An ✓ indicates that the Generalized DQO was selected
  - If an X is shown in the Site Condition or Well Construction section, this rejected the usage of this method
  - If a method is not selected and there is no X, the method is not appropriate to meet the needs of the Generalized DQO selected

- Allows the user to determine impacts of individual selections

Methods Toolbox (References)	Recommended	Method contributes to Active DQO																Site Conditions									Well Construction			
		A-1	A-2	B-1	C-1	D-1	D-3	E-1	F-1	F-2	G-1	H-1	H-2	H-3	I-1	I-3	I-4	1	2	3	4	5	6	7	8	9	10	11	12	13
Borehole Hydraulic Testing																														
21. Slug Tests	✖											✔																		✖
22. Pumping Tests (constant rate, step drawdown, etc.)																														
Single-Well	✖											✔																		
Multi-Well	✖																													
23. Borehole Flowmeter (e.g. EBF)	✔											✔																		✖
24. Tracer Testing																														
Single-Well	✔											✔																		
Multi-Well	✖											✔													✖					

Determine downward flux of a contaminant source to groundwater (vadose to saturated zone)

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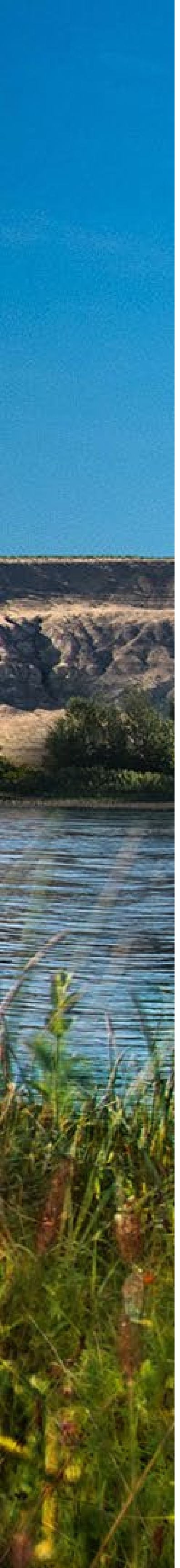
Take aways

- Geophysical methods are being implemented and explored for use on the Hanford Site to provide characterization and monitoring solutions for:
  - ✓ Refining geological framework models (Seismic reflection and refraction)
  - ✓ Remedy monitoring (Electrical resistivity tomography)
  - ✓ Monitoring of remedial reactions (Lab based induced polarization)
- Applications and Knowledge transfer are allowing for access to unfamiliar tools and a common starting point for site investigations
  - ✓ Sampling analysis plan (SAP) – Method Selection Tool (MST)



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Funding for this work was provided by the U.S. Department of Energy Hanford Field Office under the Deep Vadose Zone (DVZ).

Pacific Northwest National Laboratory is operated by Battelle Memorial Institute for the Department of Energy under Contract DE-AC05-76RL01830.

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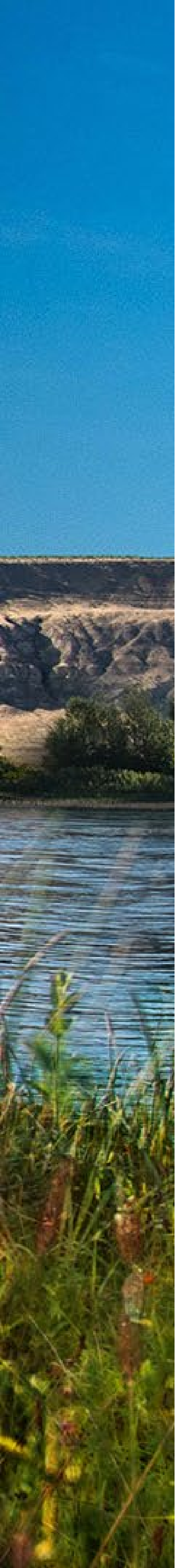

Thank you