# Leveraging Advanced Geophysics and Machine Learning to Support Soil and Groundwater Remediation at the Hanford Site

Tim Johnson, Jose Hernandez-Mejia, Glenn Hammond, Piyoosh Jaysaval, Jon Thomle, Anton Sinkov, Matt Taubman, Hilary Emerson, Rob Mackley
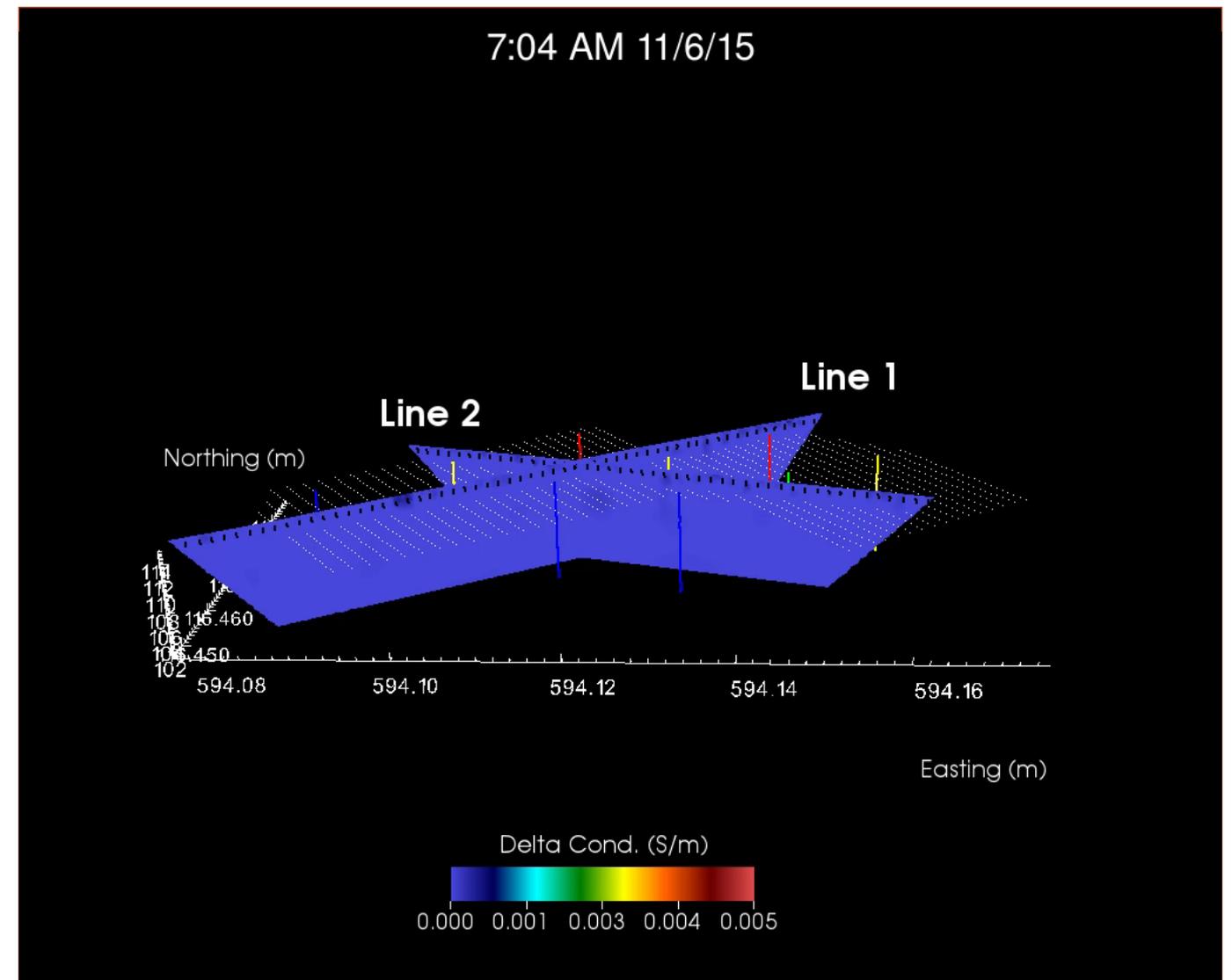
Motivation: Hanford 300 Area - In Situ Treatment of A Subsurface Uranium Source Zone

Plan view of 300 Area Treatment Site
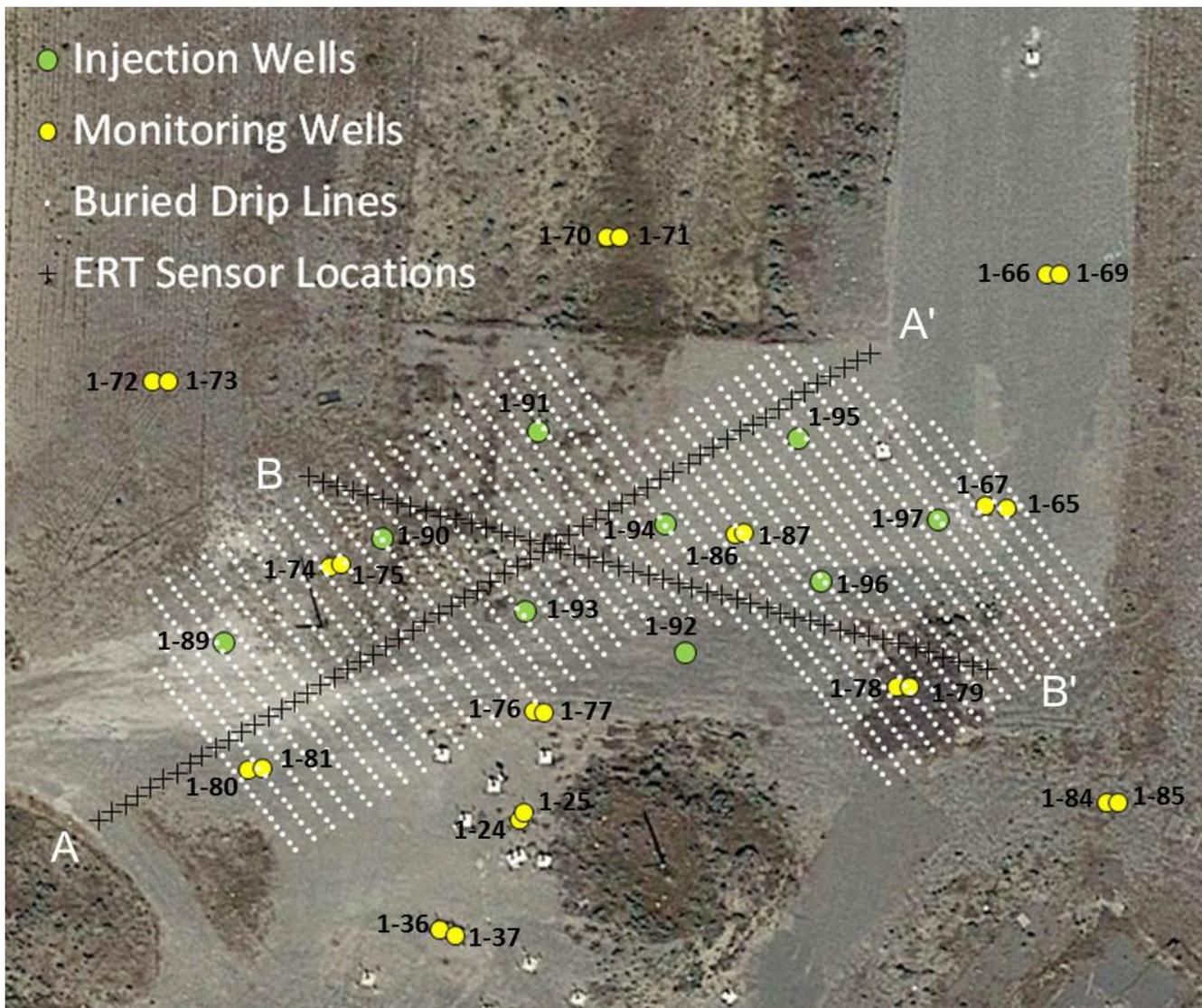
Time-Lapse ERT Imaging of Amendment Delivery

Challenges
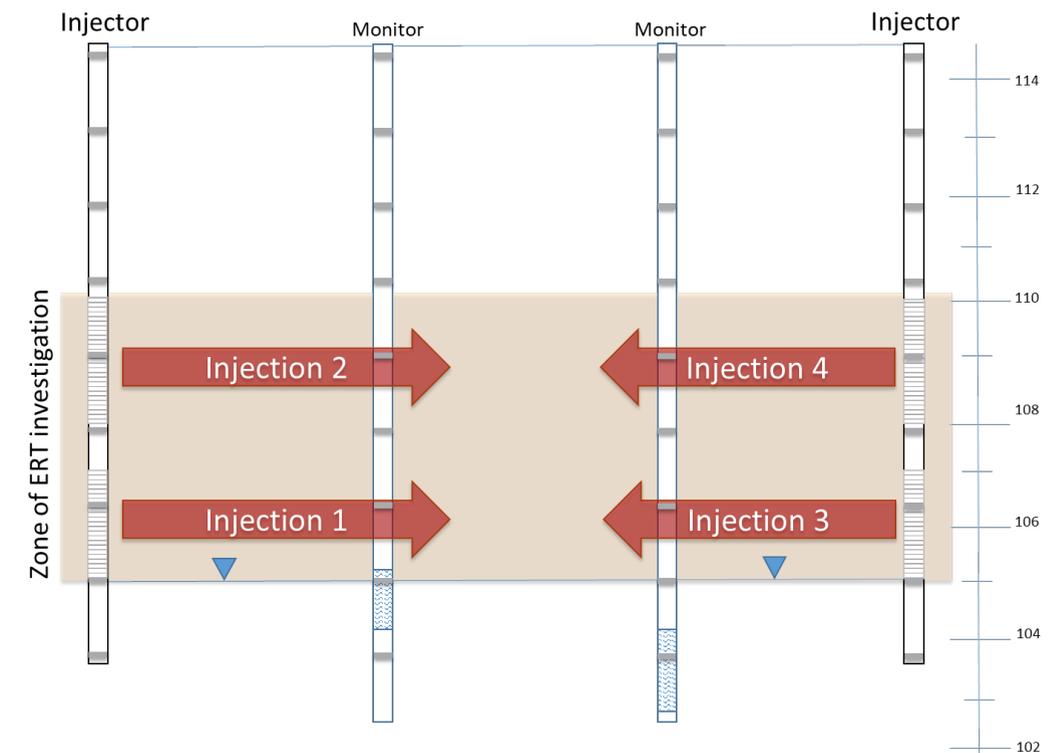
300 Area
Phase B
Polyphosphate
Injections

1. ERT Images are qualitative and limited resolution

2. We cannot 'see' geochemical reactions / changes in mineral surface properties

3. Uncertainty Quantification

Solutions:

1) Can we generate a Digital Twin (or many) that honor the monitoring data (joint inversion)?

2) Field SIP Imaging?

E4D Time-lapse Images of Phosphate Injections

animation

Opportunities: Challenge 1

Emerging generative AI methods are addressing long-standing challenges in joint inversion.

- Assimilation of all available data = more accurate estimation of subsurface heterogeneity

- Generation of equally probably subsurface models, or 'digital twins' for uncertainty estimates.

Conditional Diffusion Model

output

input
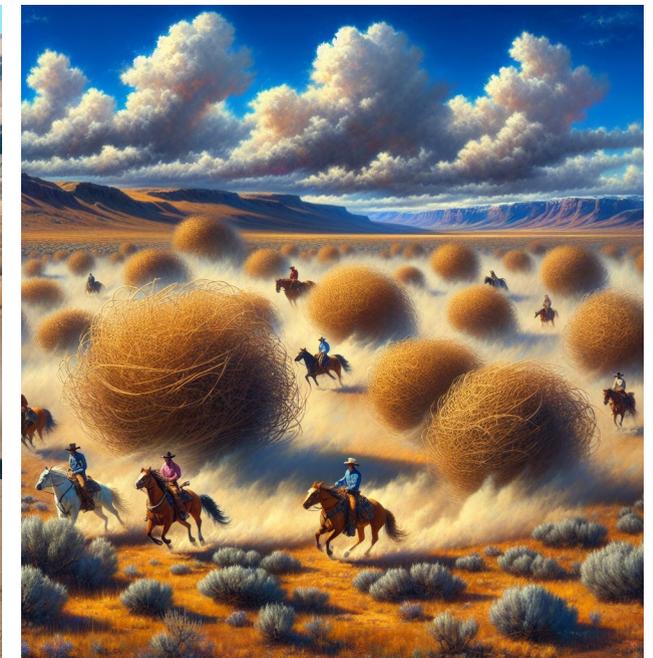
"Generate a realistic image of a bovine tumbleweed stampede with cowboys on horses in Richland Washington"

How do conditional diffusion models work?

CDM Training

Training Image
+ description
(e.g. fluffy dog)

Random Noise

Forward Process: Iterative Noise Addition

https://theaisummer.com/static/d007d60f773b61f4585cbec3869490d5/a878e/score-sde.png

Inverse Process: Iterative Denoising

Random Noise
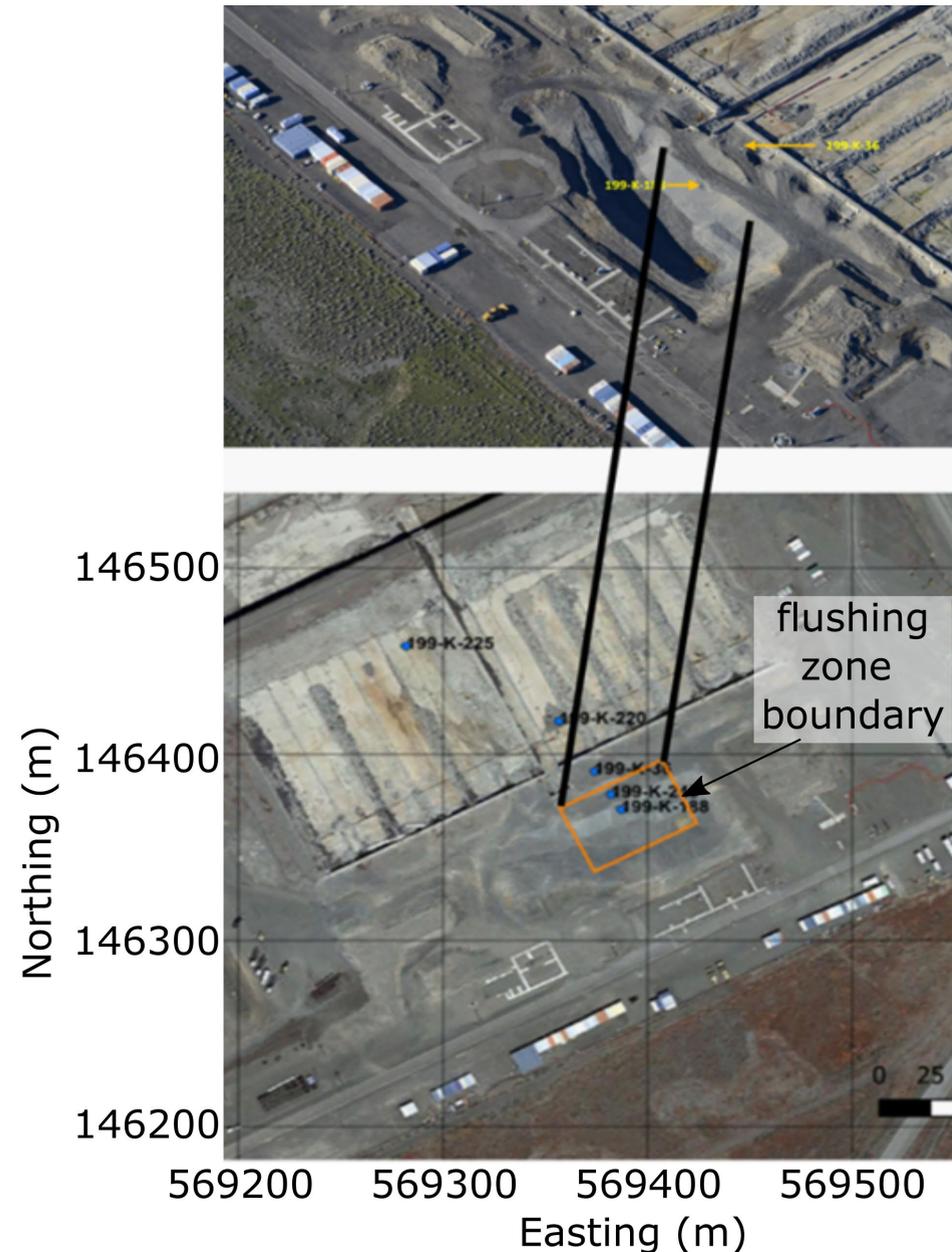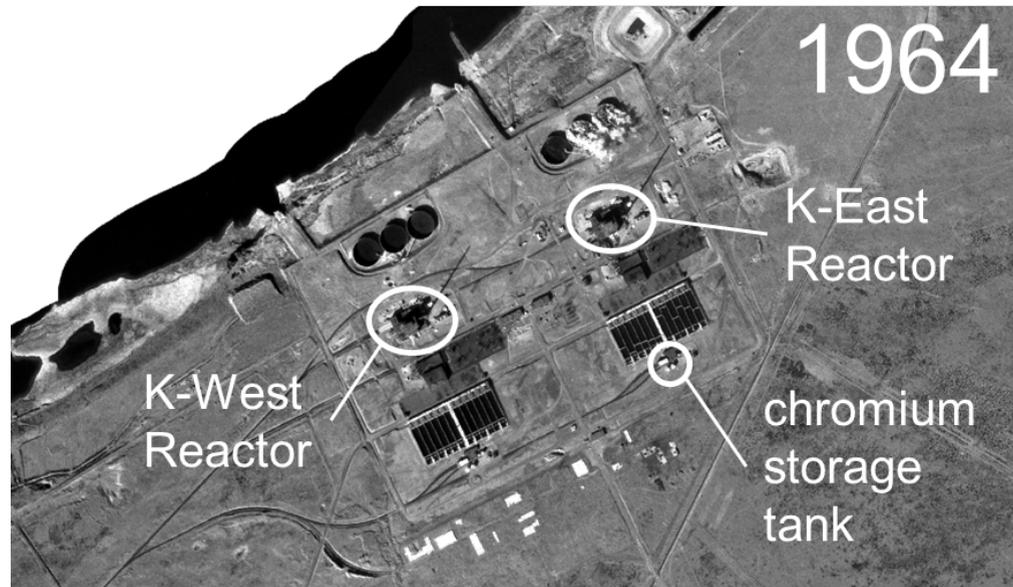+ conditioning data
(e.g. fluffy dog)

CDM Objective

Given an image of random noise, generate an image that honors an input condition (i.e. fluffy dog).

Image = PFLOTRAN digital twin
Input condition = Monitoring data

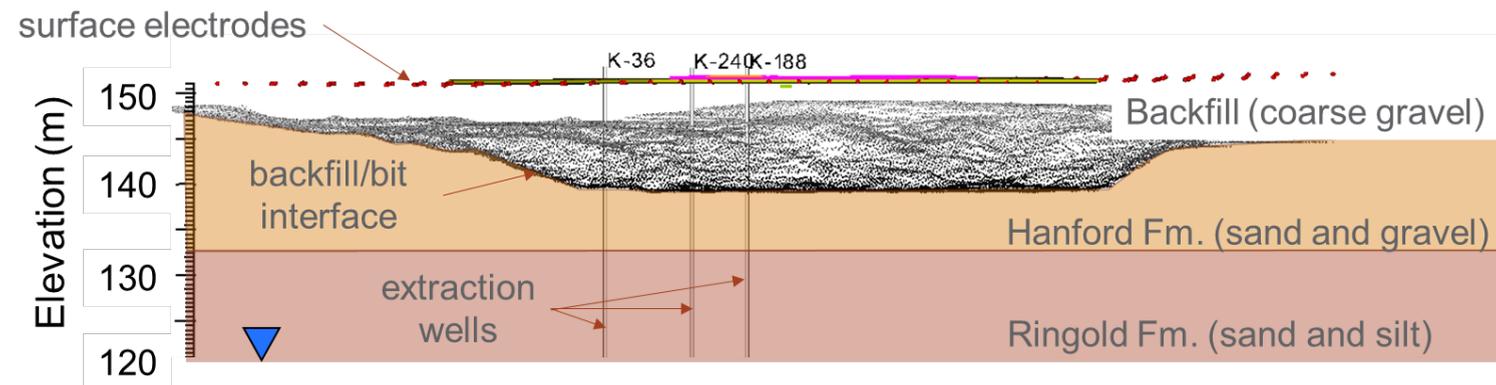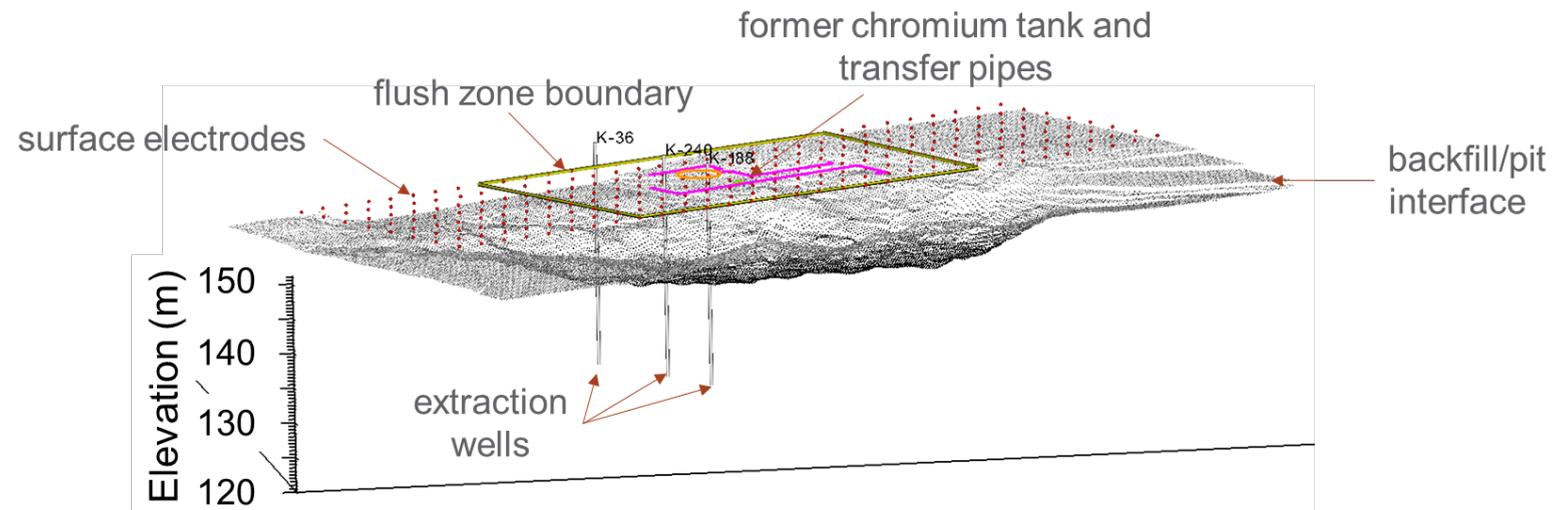# Test Case: Hanford 100-K Area Soil Flushing Test

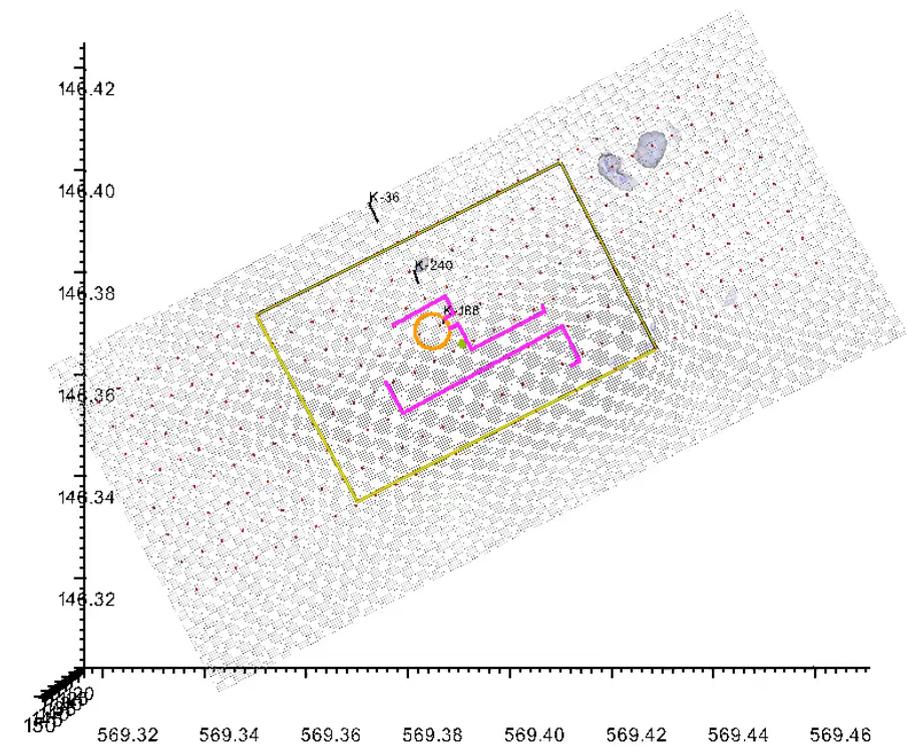## Hanford 100-KE Reactor Area

Flush Water Application

100-K Area Geology and ERT Monitoring Images

Soil Flushing Setup

Time-lapse ERT Images
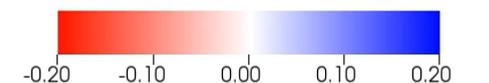
Subsurface Properties

- Hydrogeologic, unsaturated flow, and petrophysical properties in each of the three units.

- Native pore water and flush water fluid conductivity

- Bounded by literature values

- 29 parameters total

| Parameter	min value	max value
Hanford porosity	0.05	0.35
Hanford horizontal permeability [m^2]	2.00E-13	1.00E-07
Hanford vertical/horizontal permeability ratio	0.2	1
Hanford Archie's law cementation exponent	1.1	2.1
Hanford Archie's law saturation exponent	1.6	2.6
Hanford Archie's law tortuosity constant	0.8	1.2
Ringold unit porosity	0.2	0.5
Ringold horizontal permeability [m^2]	1.00E-12	1.00E-08
Ringold vertical/horizontal permeability ratio	0.2	1
Ringold Archie's law cementation exponent	1.1	2.1
Ringold Archie's law saturation exponent	1.6	2.6
Ringold Archie's law tortuosity constant	0.8	1.2
Pit porosity	0.05	0.35
Pit horizontal permeability [m^2]	2.00E-13	1.00E-07
Pit vertical/horizontal permeability ratio	0.2	1
Pit Archie's law cementation exponent	1.1	2.1
Pit Archie's law saturation exponent	1.6	2.6
Pit Archie's law tortuosity constant	0.8	1.2
Hanford and Pit VG-Alpha [1/m]	2.00E-05	0.009
Hanford and Pit VG-M	0.2	0.65
Hanford and Pit residual saturation	0.0055	0.24
Ringold VG-Alpha [1/m]	1.00E-05	0.008
Ringold VG-M	0.16	0.8
Ringold residual saturation	0.02	0.2
Hanford surface electrical conductivity [S/m]	1.00E-05	0.01
Ringold surface electrical conductivity [S/m]	1.00E-05	0.01
Pit surface electrical conductivity [S/m]	1.00E-05	0.01
Native pore water conductivity [S/m]	0.005	0.1
Flush water conductivity [S/m]	0.005	0.1

Training Data Generation

The CDM model self-trains by choosing which PFLOTRAN model to generate for examples.

Simulations are executed on high-performance computing systems.

Computationally demanding, but tractable

flush water

Change in Saturation (m)
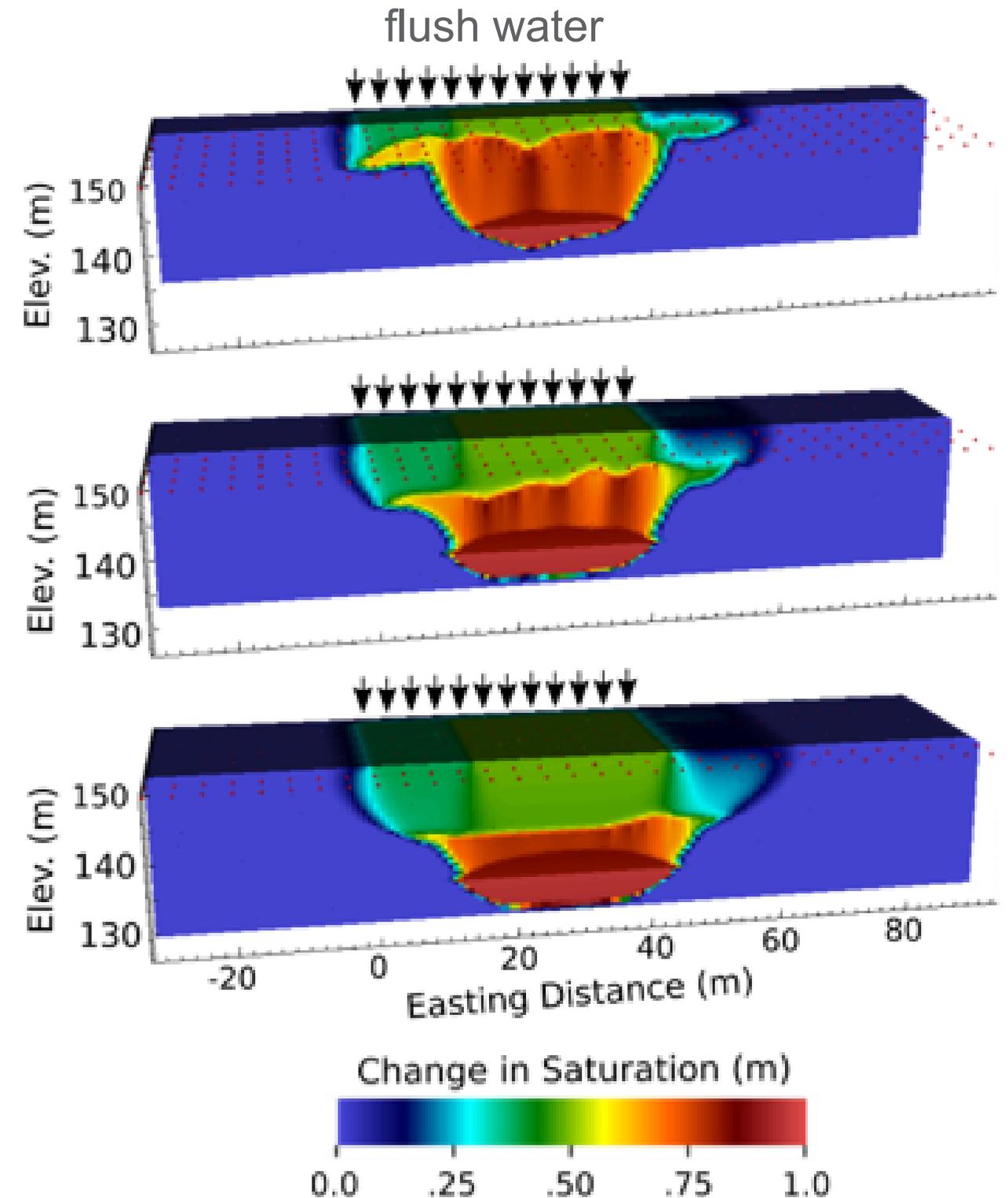
CDM digital twin generation performance: Raw ERT data matching
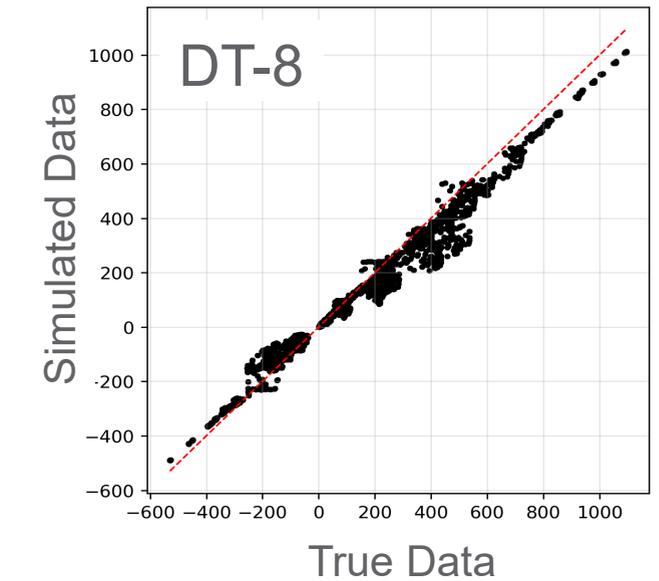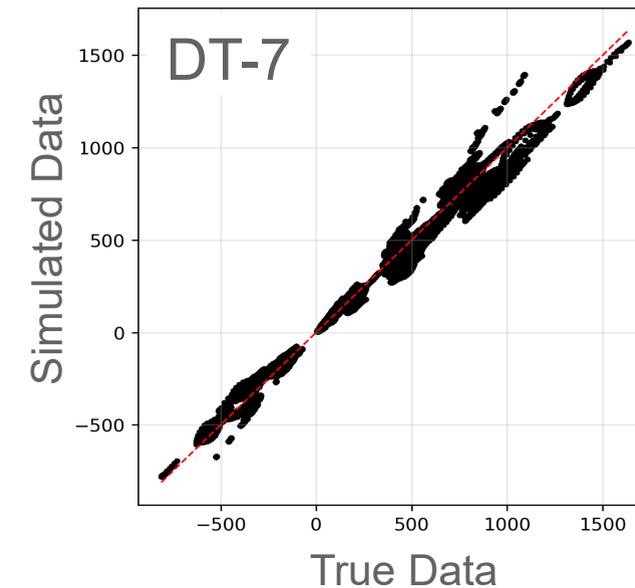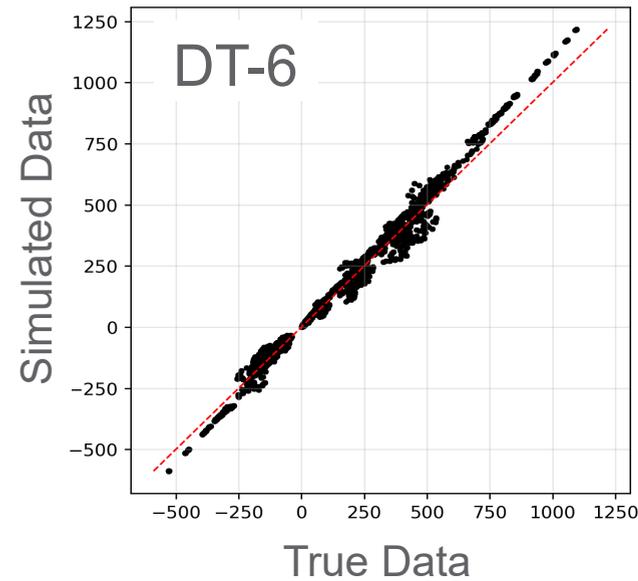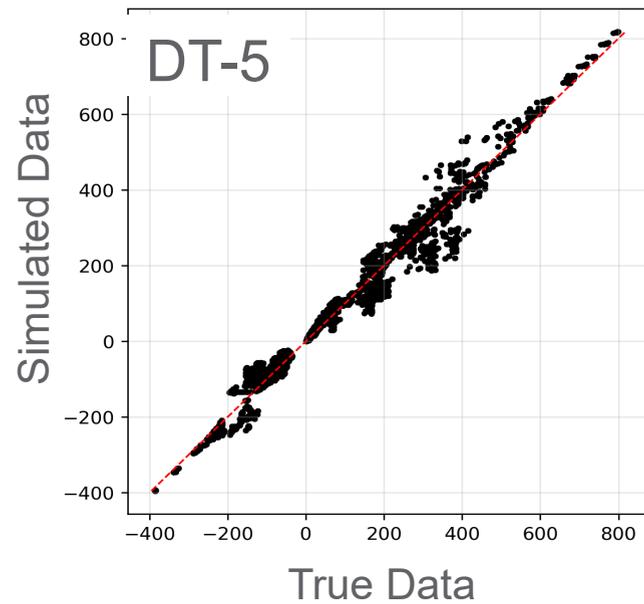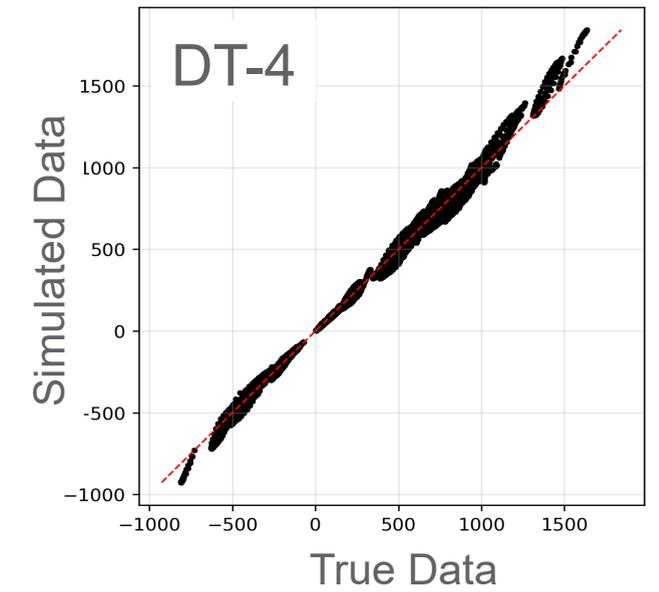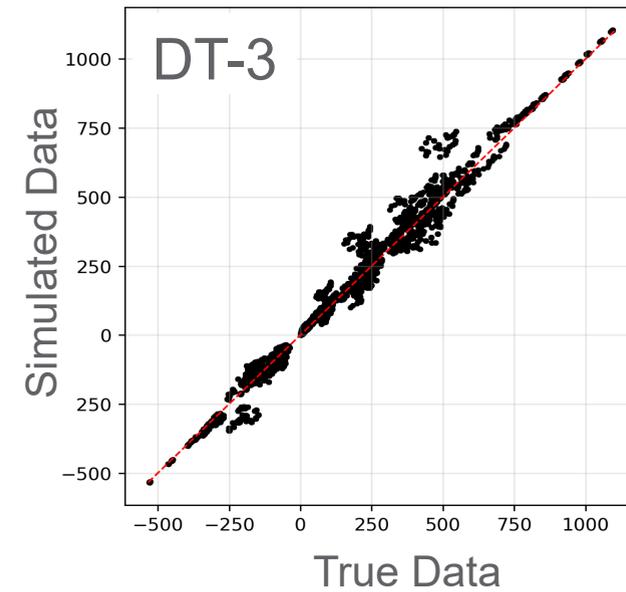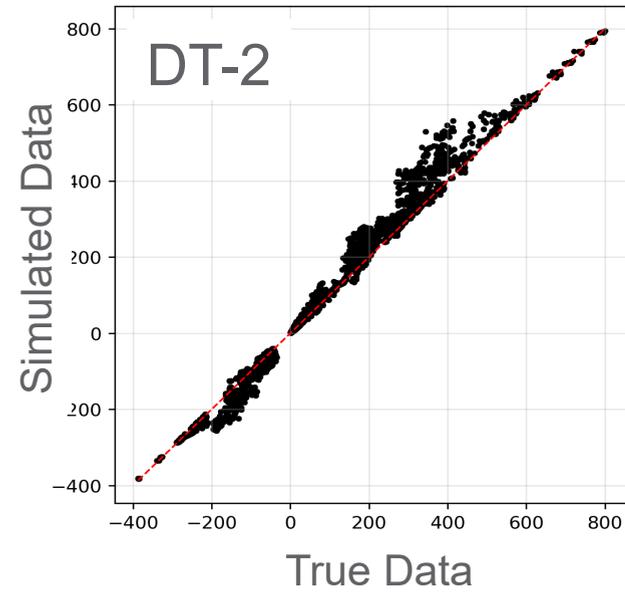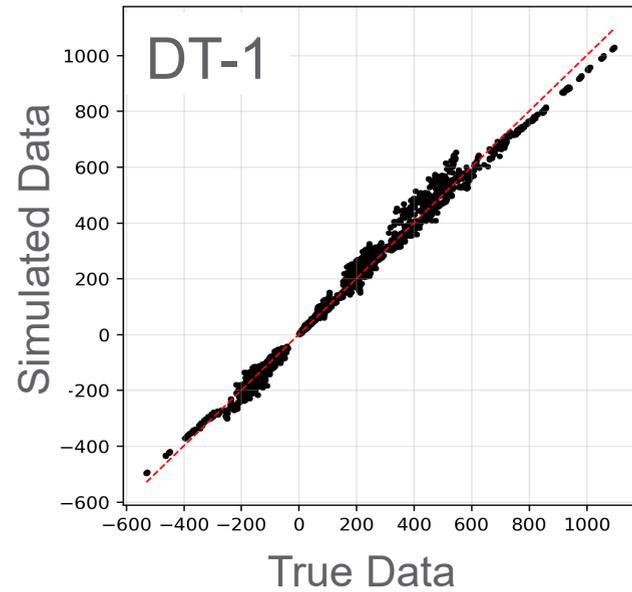
DT = Digital Twin
data values in ohm
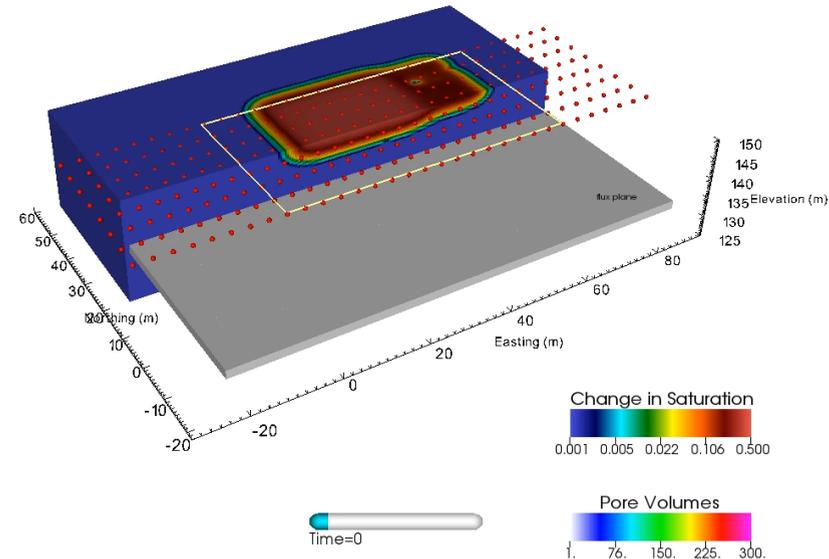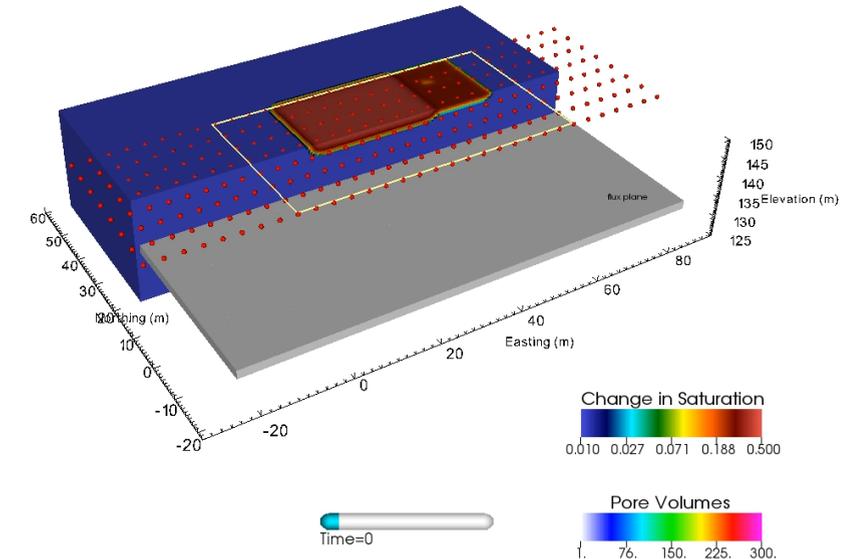
How well do the digital twins predict soil flushing behavior?

- Twin 1 and Twin 2 honor the ERT data
- Disqualified twin does not
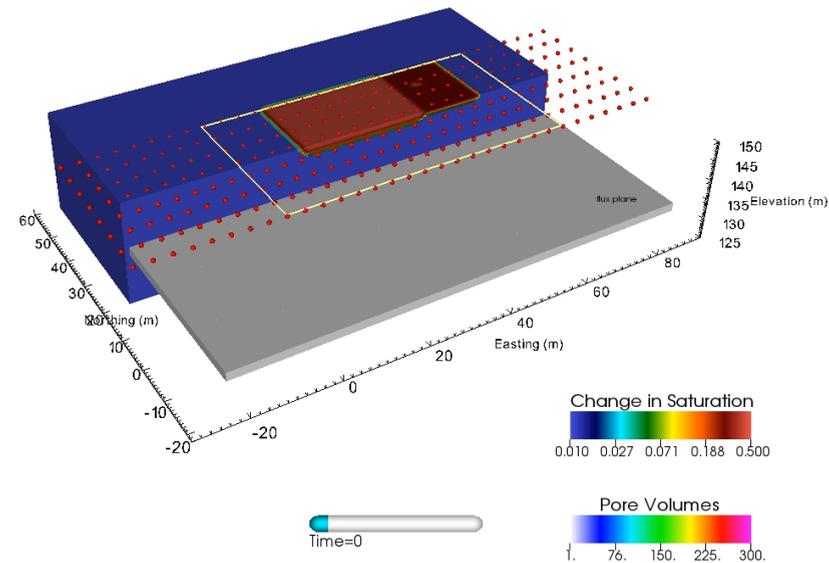- Prediction performance based on # flush water pore volumes
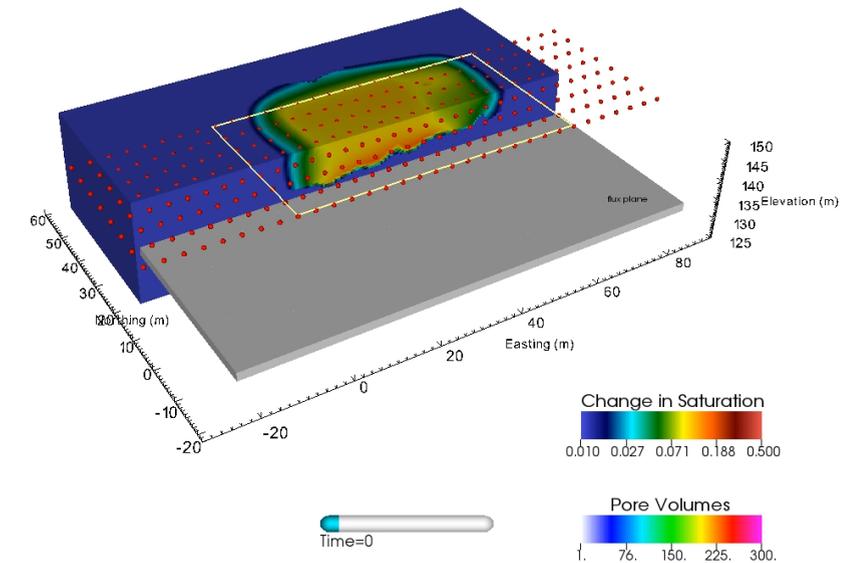
True Model

Digital Twin 1
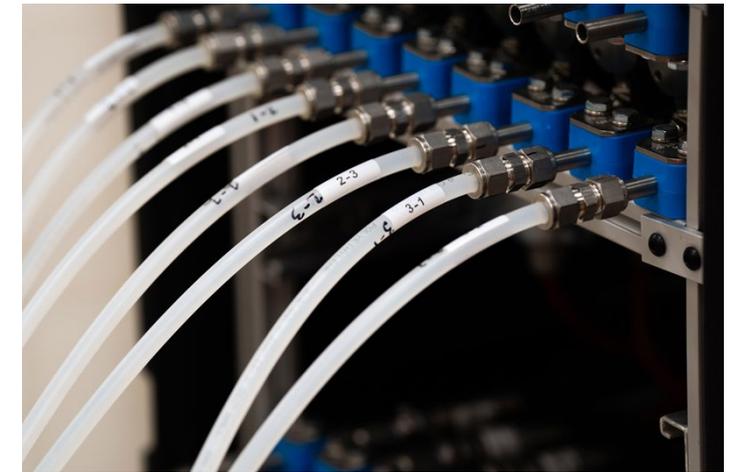

Digital Twin 2

Disqualified Twin

animation

Geophysical Imaging of Flow and Transport (GIFT) System

I-1   electrodes   screened fluid port   MI-1   MI-3   MI-4
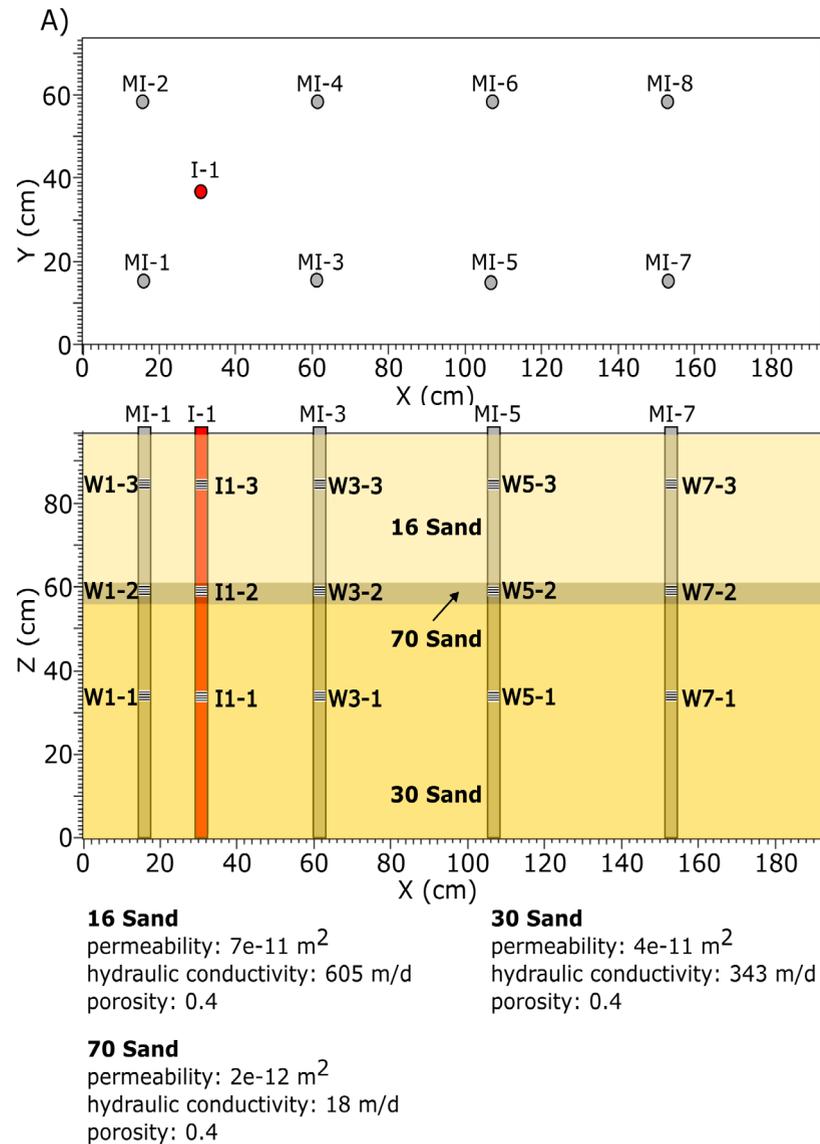
Objective:

- Calibration PFLOTRAN (Digital Twin) with CDM

- Use Digital Twin to design treatment delivery

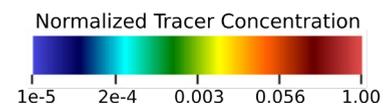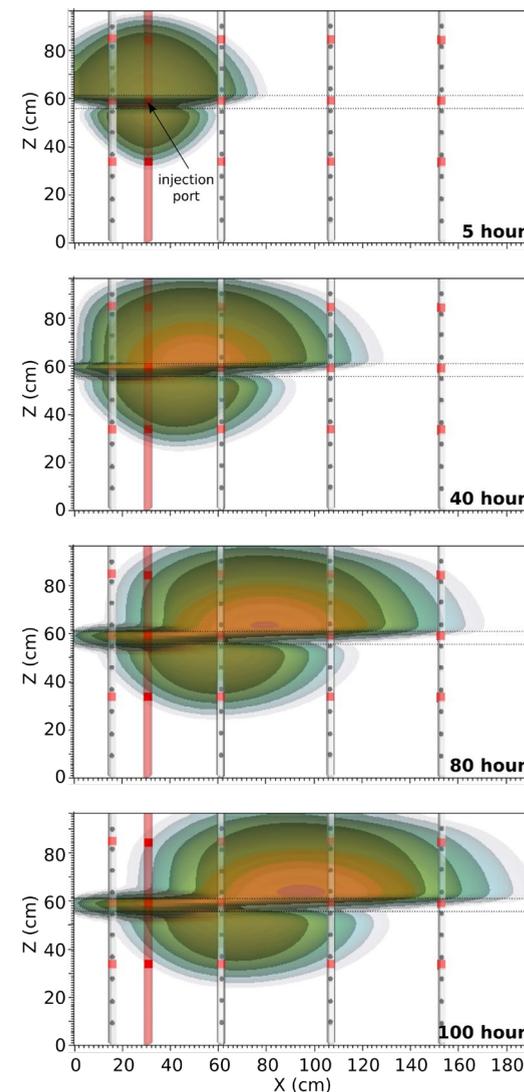- Assess delivery with ERT, monitor with SIP
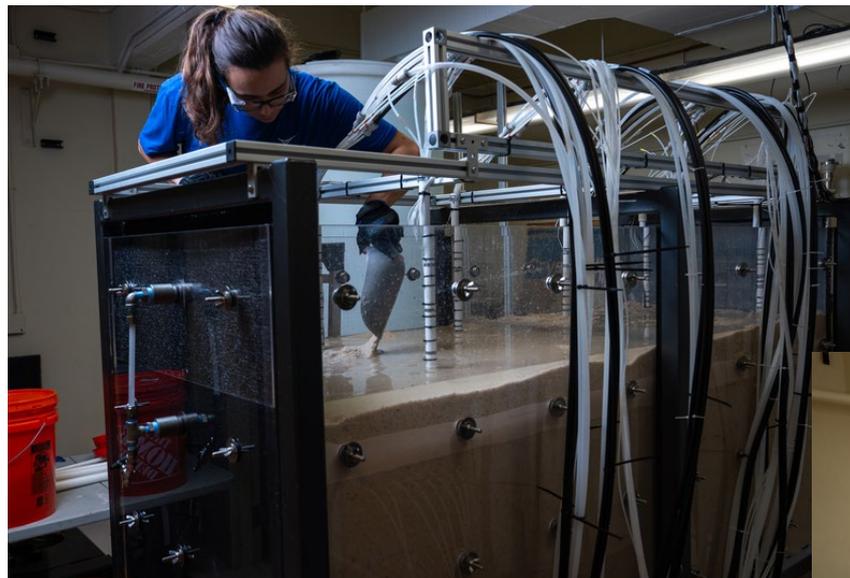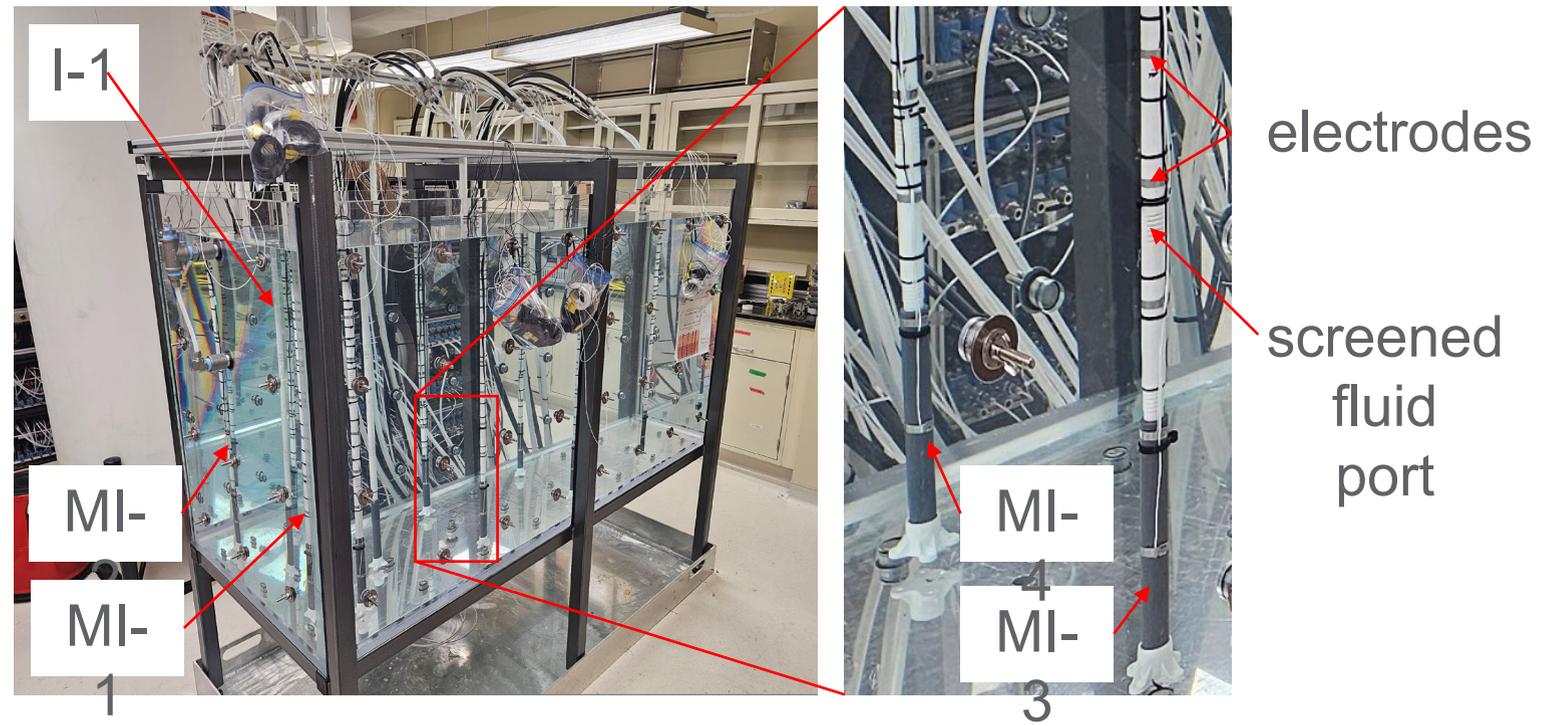
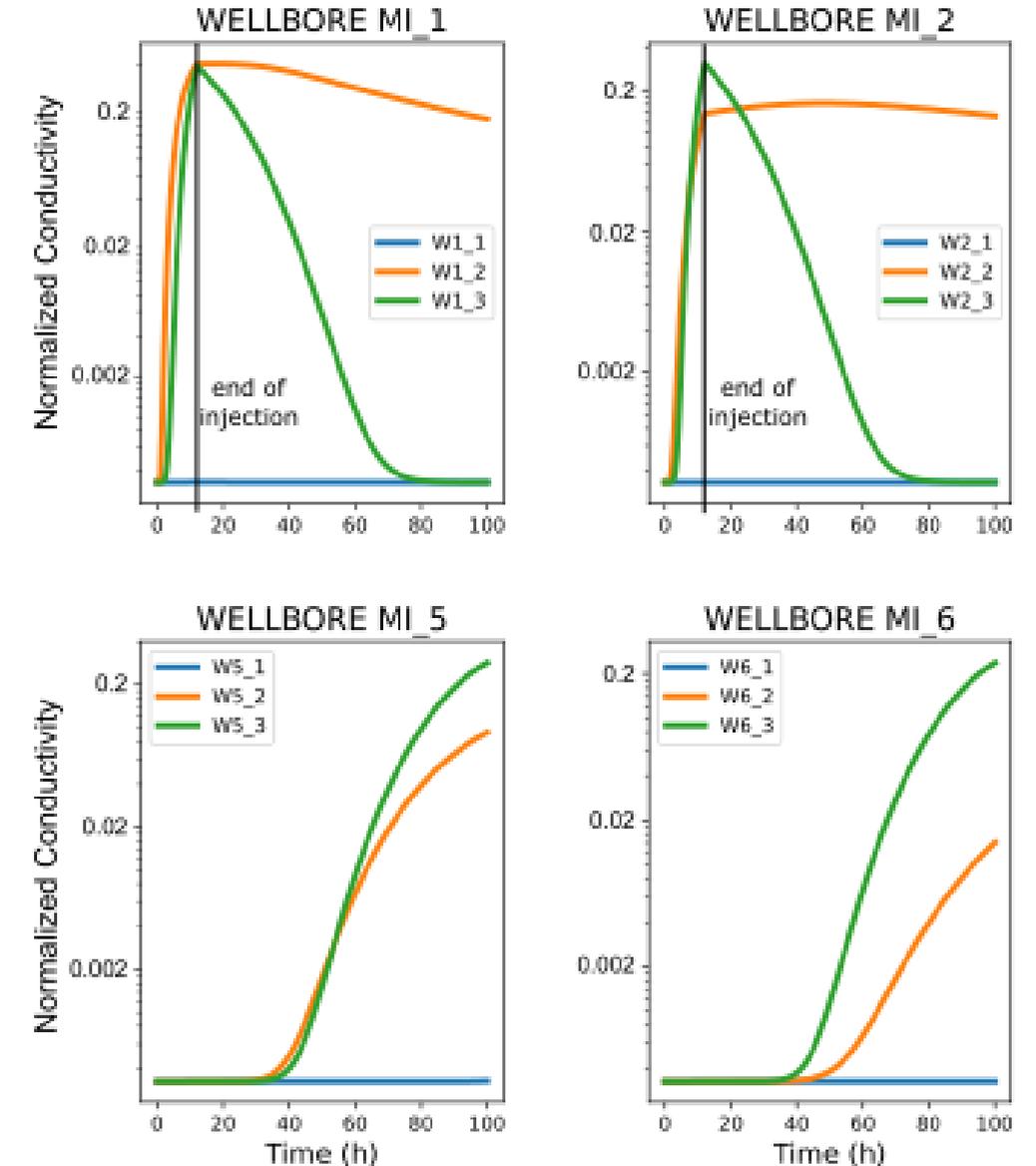# GIFT Tracer Experiment Simulations / Training Data Generation

Material Properties

A)

16 Sand
permeability: 7e-11 m^2
hydraulic conductivity: 605 m/d
porosity: 0.4

30 Sand
permeability: 4e-11 m^2
hydraulic conductivity: 343 m/d
porosity: 0.4

70 Sand
permeability: 2e-12 m^2
hydraulic conductivity: 18 m/d
porosity: 0.4

Tracer Simulations

Normalized Tracer Concentration
1e-5   2e-4   0.003   0.056   1.00

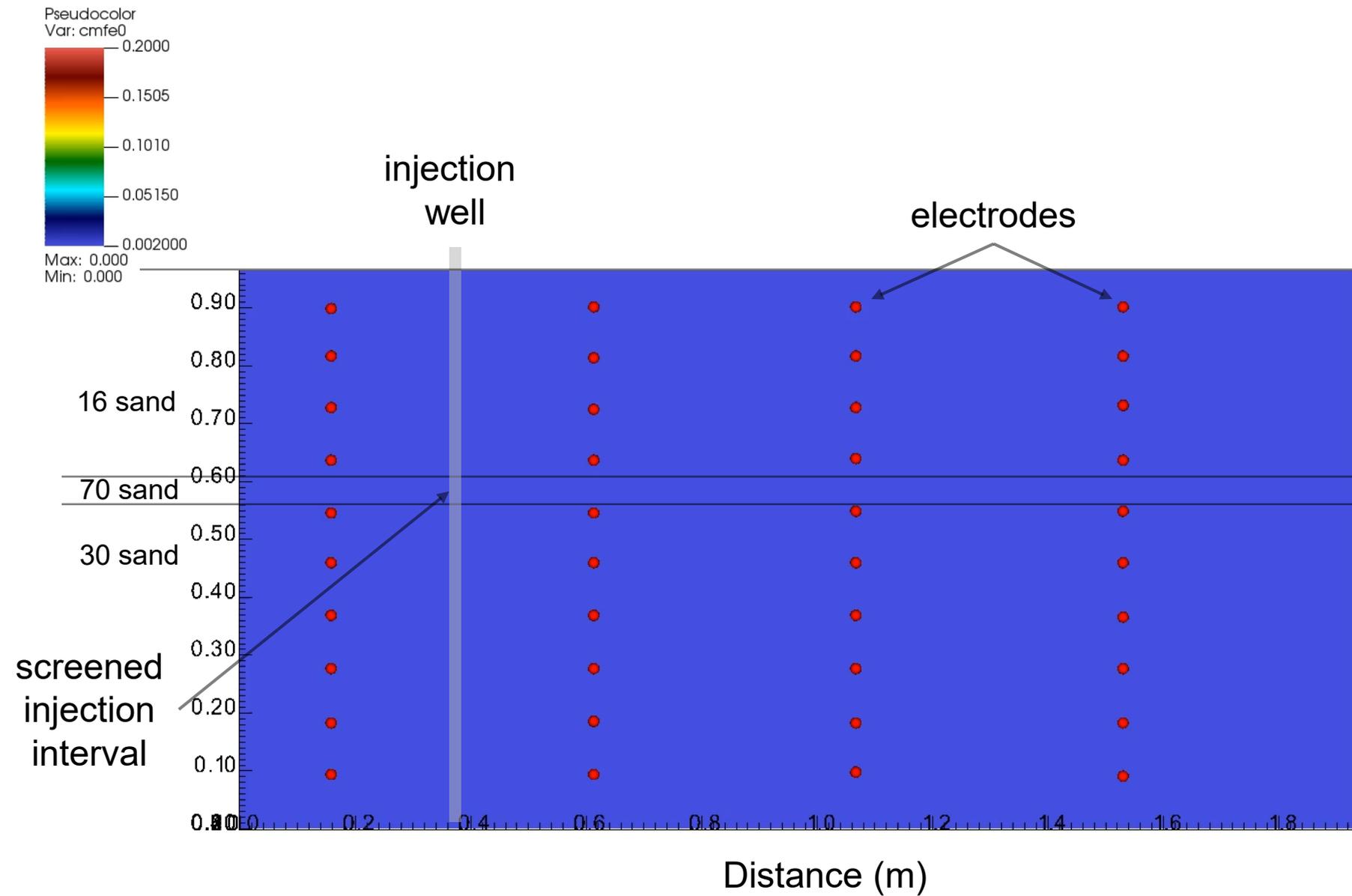## Example Breakthrough Curves

ERT Imaging

- Injected @ 20 ml/min for 12 hours

- 1 hour between images

- Fast flow through coarse (16) sand

- Delayed flow through fine (70) sand

- Density driven flow

- Tracer transport along injection well annulus during injection

Tracer Test #1 Time-Lapse ERT Imaging

Pseudocolor
Var: cmfe0
— 0.2000
— 0.1505
— 0.1010
— 0.05150
— 0.002000
Max: 0.000
Min: 0.000

injection well

electrodes

16 sand

70 sand

30 sand

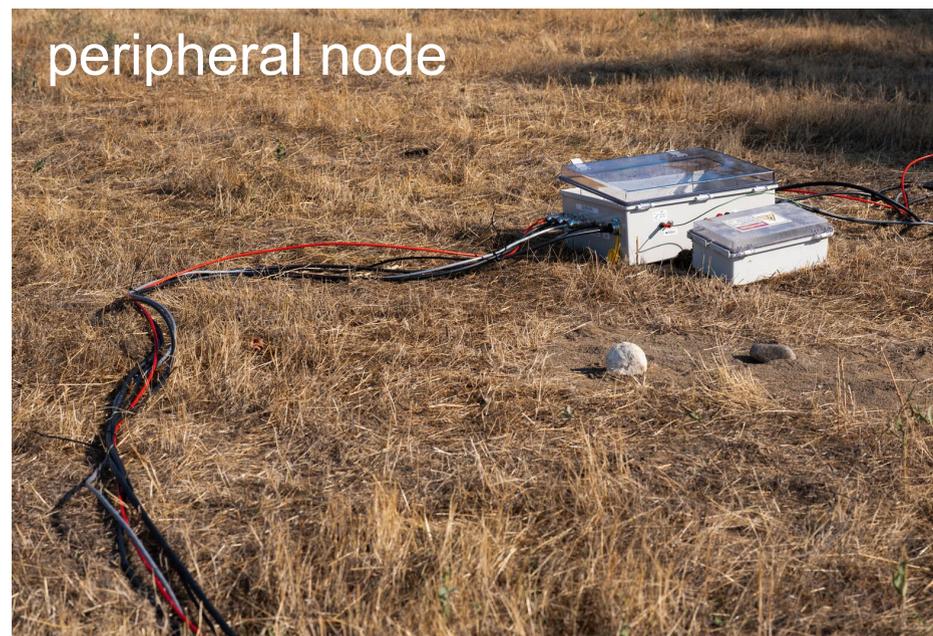screened injection interval

Distance (m)

Animation

Field Scale SIP (FS-SIP) System
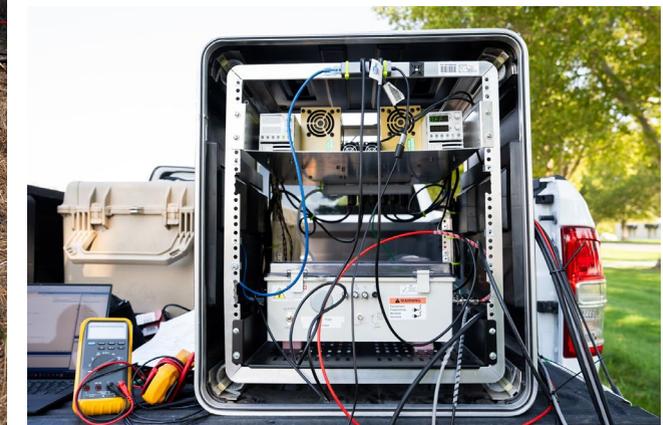
SIP Field Monitoring Challenges

- Electromagnetic Coupling
  - Cable coupling noise masks polarization responses
- Time Requirements
  - Up to days per image when low-frequencies are collected.

electrode installation (16 @ 20 m spacing)
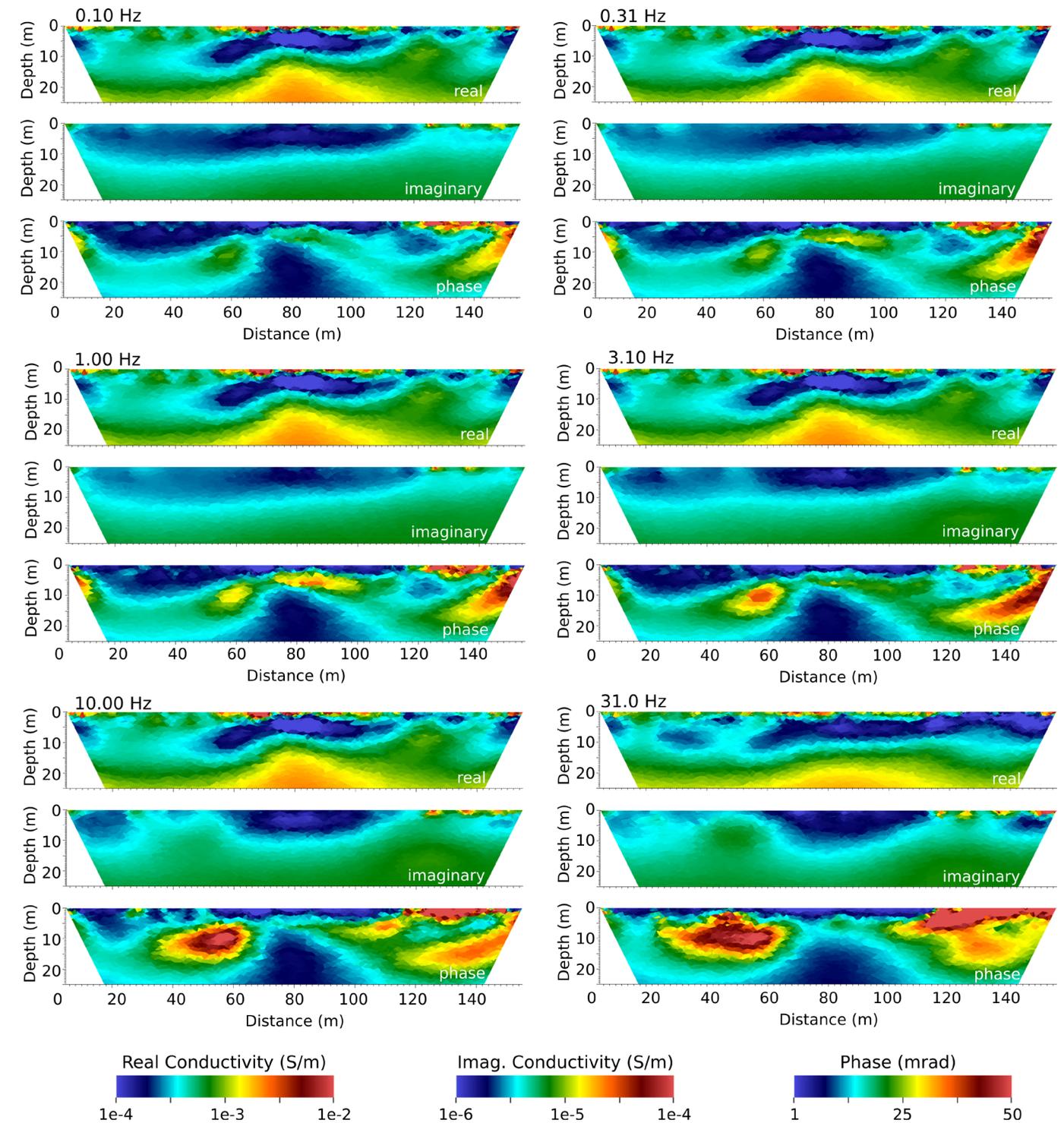

peripheral node

EM Isolation Cables

Control Unit

FS-SIP System Field Testing Image (Sept. 2025)

- 6 frequencies (1 mHz to 100 Hz) collected in 90 minutes.

- Excellent data quality

- Enables monitoring of amendment emplacement and post-emplaced geochemical reactions.
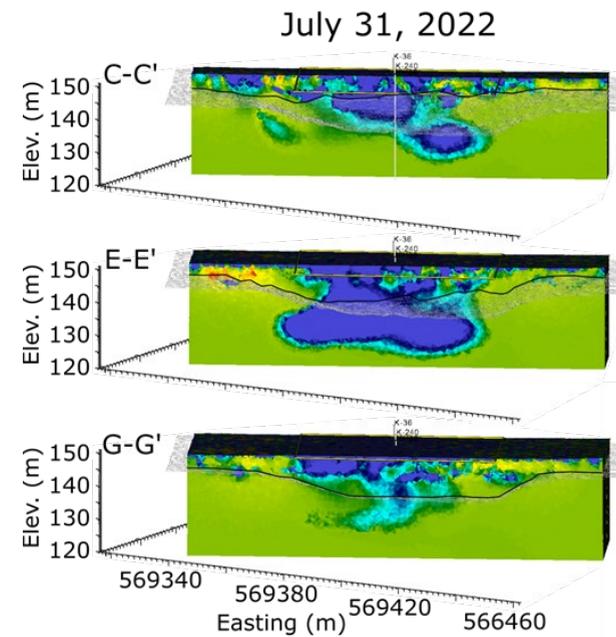
Static SIP Image Cross-Sections

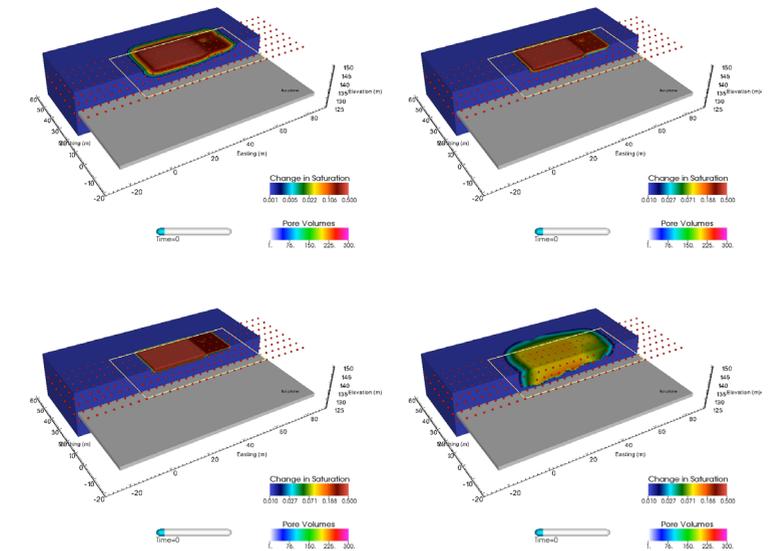Current: ERT Images

Future: Digital Twins

Take Home Messages

- Subsurface digital twin generation advancements enabled by AI.
  - More informative and actionable use of ERT monitoring data.

- Advancements in field-scale SIP monitoring.
  - New instrumentation to enable ERT-like SIP monitoring.

Next-Gen Field-Scale SIP Monitoring System

Thank you