Integrated Plume Monitoring using Joint EM-Seismic and Strain Sensing

Project Number: ESD14-095 (Task#3)

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U.S. Department of Energy

National Energy Technology Laboratory

DOE NETL's FE R&D Virtual Review Meeting – Carbon Storage

September 8 - 11, 2020

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<u>Acknowledgement</u>

Don Lawton
Kirk Osadetz
Greg Maidment

UNIVERSITY OF CALGARY
Global Research Initiative in Energy Research

CMC RESEARCH INSTITUTES

Presentation Outline

- Why Joint EM-Seismic Geophysical Monitoring ?
- Background on CaMI - Field Research Station (FRS)
- LBNL Progresses on Data Analysis:
  - Integrated EM-Seismic System
  - Crosswell EM Data
  - Crosswell Seismic Data
  - Individual Data Inversion
  - ~~Repeat surveys acquisition~~ *Postponed due to Covid-19*
- Next Steps:
  - Framework for Join-Inversion
  - Repeat Survey Campaigns, dates TBD

Motivation

2011 - White Paper on Field Testing Needs for Geological Carbon Sequestration (Daley et al., 2011) listed 3 priority field tests:

- A deep (supercritical CO_2) injection into a high permeability, near-vertical fault or fracture zone
- **An intermediate injection simulating secondary accumulation from leakage of gas-phase CO_2**
- A shallow injection studying groundwater impacts from leakage

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Crucial experiment testing monitoring gas-phase CO_2 at intermediate depth as an analog for a leak into a 'thief zone'

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Motivation

Crucial experiment testing monitoring gas-phase CO_2 at intermediate depth as an analog for a leak into a 'thief zone'

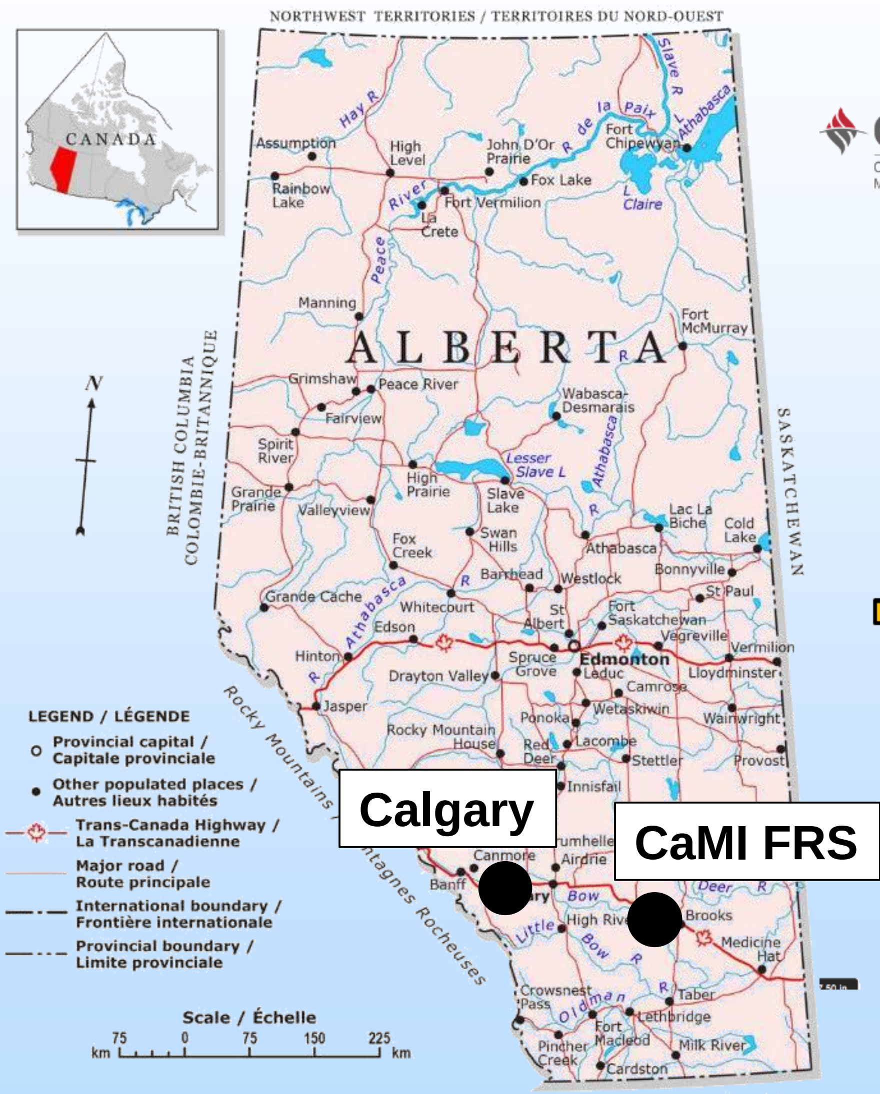
CaMI/UofC – Field Research Station (FRS)

- A world-leading site for development and demonstration of MMV technologies for fluid containment and conformance
- Undertake controlled CO_2 release at 300 m (Phase 1) & 500 m (Phase 2) depth; up to 1000 t/yr
- Determine CO_2 detection thresholds for different monitoring technologies
- Improve and develop monitoring technologies for tracking the CO_2 plume migration and for cap rock assessment
- Monitor gas migration at shallow to intermediate depths and impacts on intermediate depth groundwater (CO_2 and CH_4)
- Determine fate of CO_2 & CH_4 (trapping/dissolution)
- University & industry field training & research
- Integrating engineering and geoscience
- Public outreach & education

Primary LBNL Focuses

From Lawton, 2016

Field Research Station (FRS)



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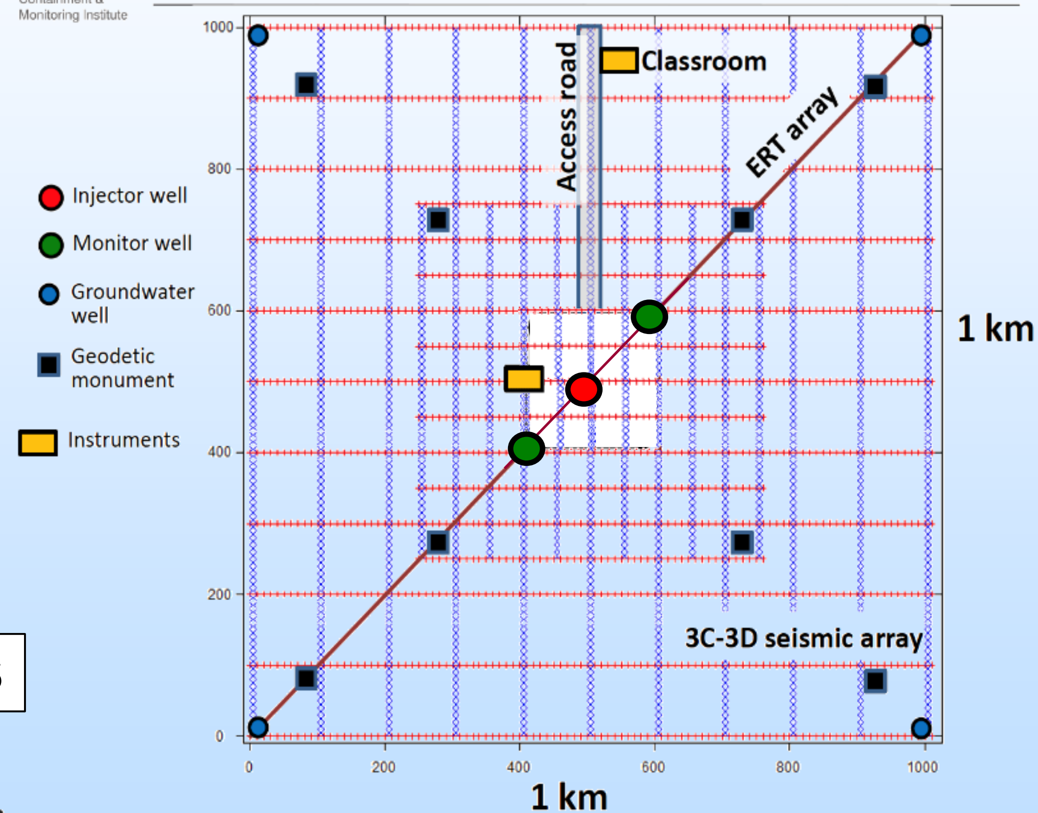
Sa Majesté la Reine du chef du Canada, Ressources naturelles Canada.

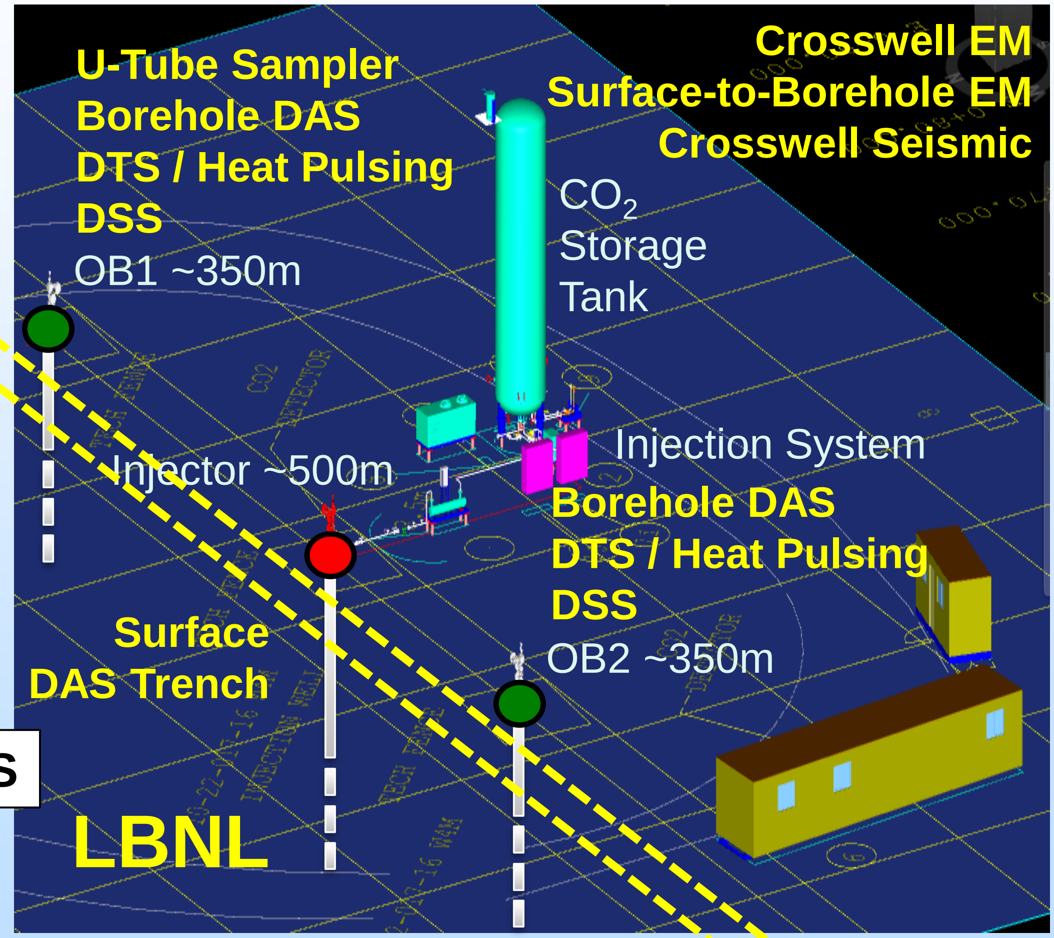
CMC Containment & Monitoring Institute

FRS monitoring plan layout



https://cmcghg.com/cami

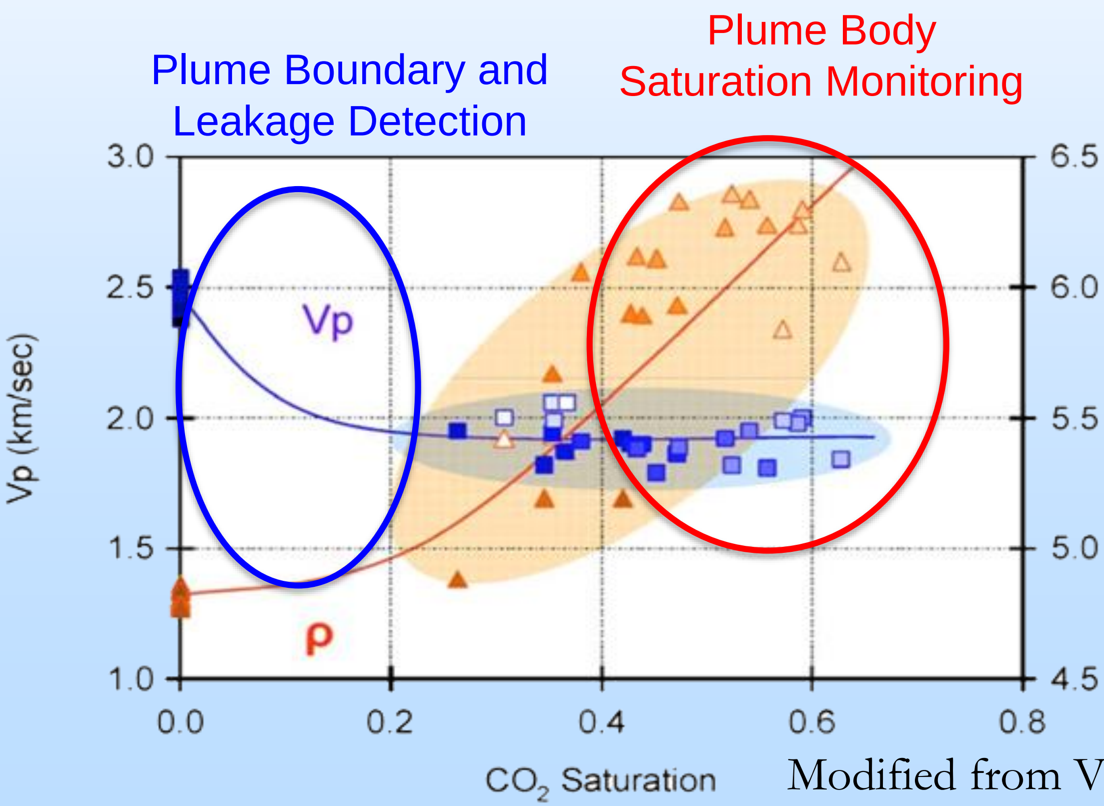
Field Research Station (FRS)



https://cmcghg.com/cami

Why Joint EM + Seismic?

- Seismic is high-resolution but has uncertainty at high CO_2 saturation and uncertainty in rock physics interpretation
- EM has strong sensitivity at high saturations and a single rock physics model (Archie's relation) to complement seismic

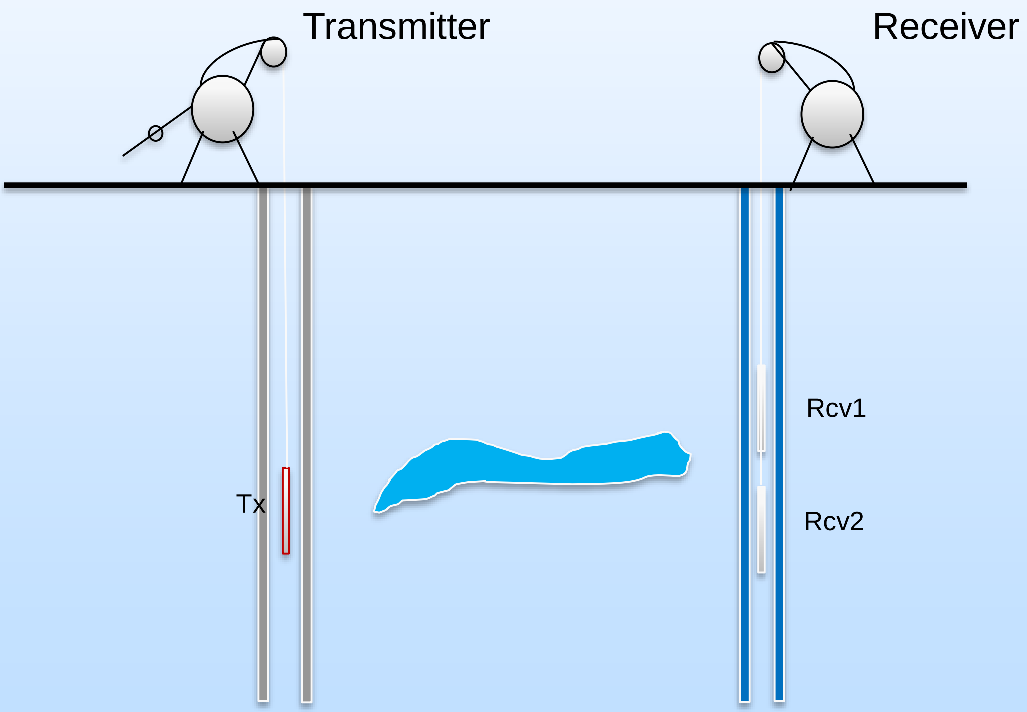


Modified from Vasco et al., 2014

GOAL

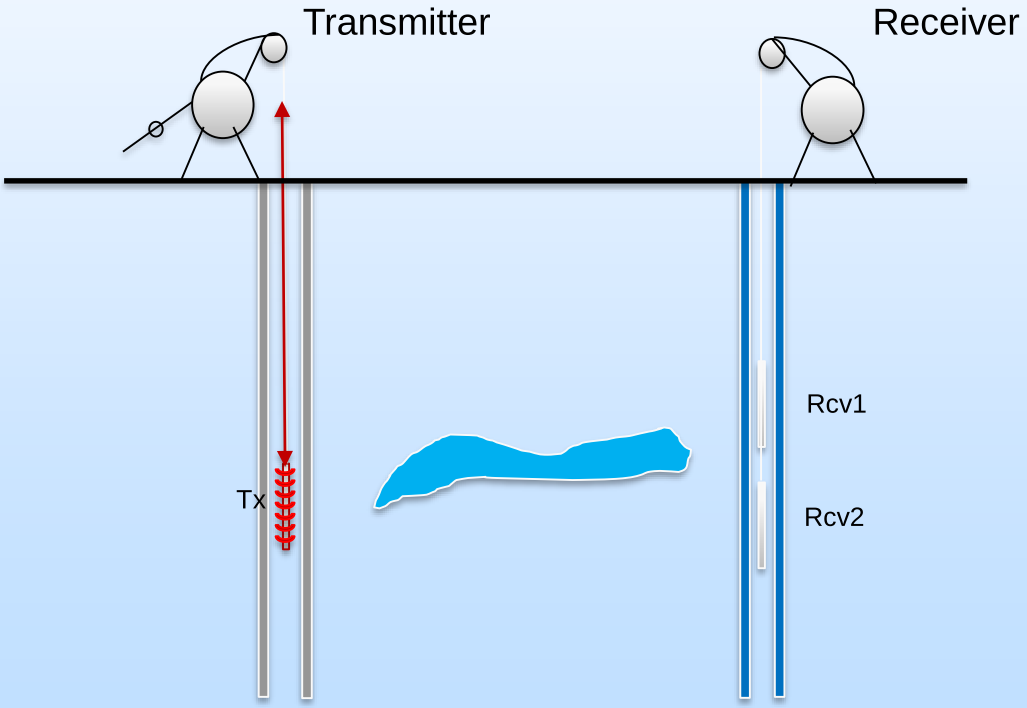
Ideally combine EM, seismic, and flow models in joint inversion for comprehensive CO_2 plume monitoring

Inductive Method: Crosswell EM



Inductive Method: Crosswell EM

1) Time varying (sinusoidal) electric current input into solenoid transmitter



Inductive Method: Crosswell EM

1) Time varying (sinusoidal) electric current input into solenoid transmitter
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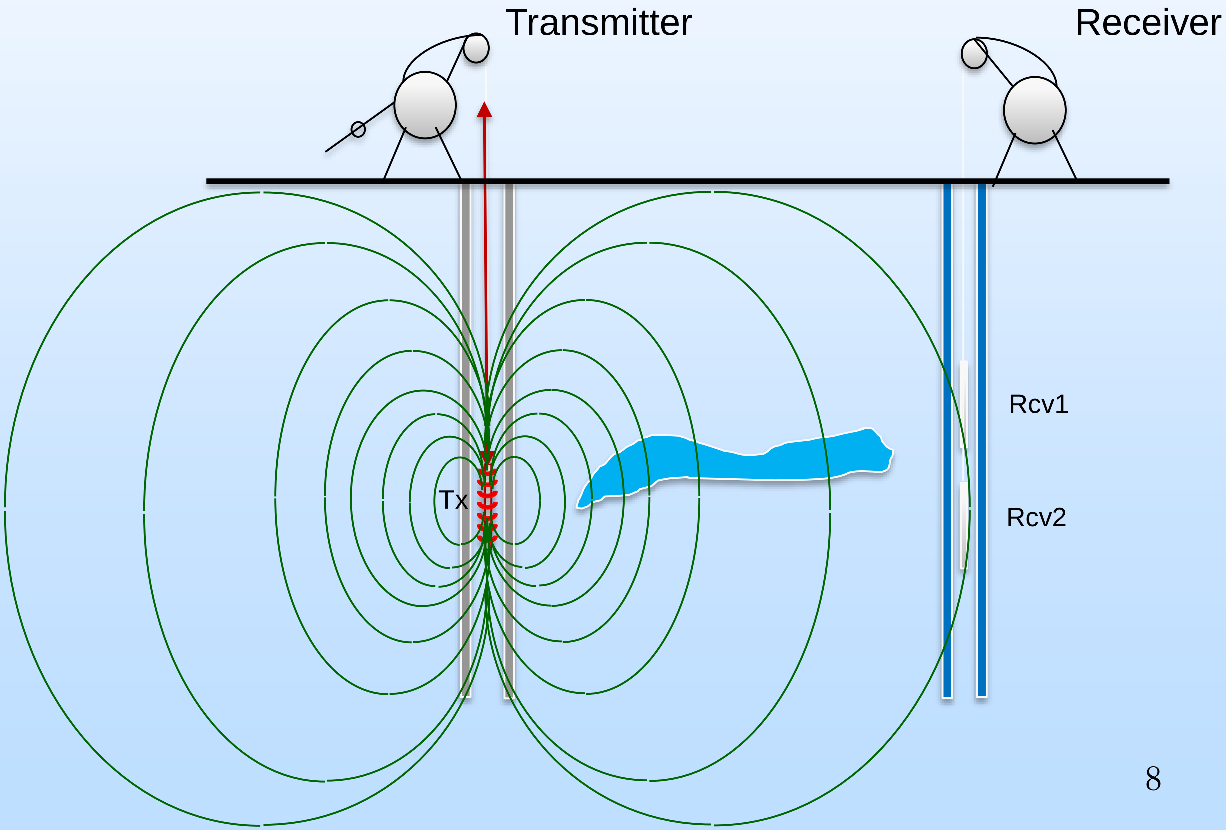

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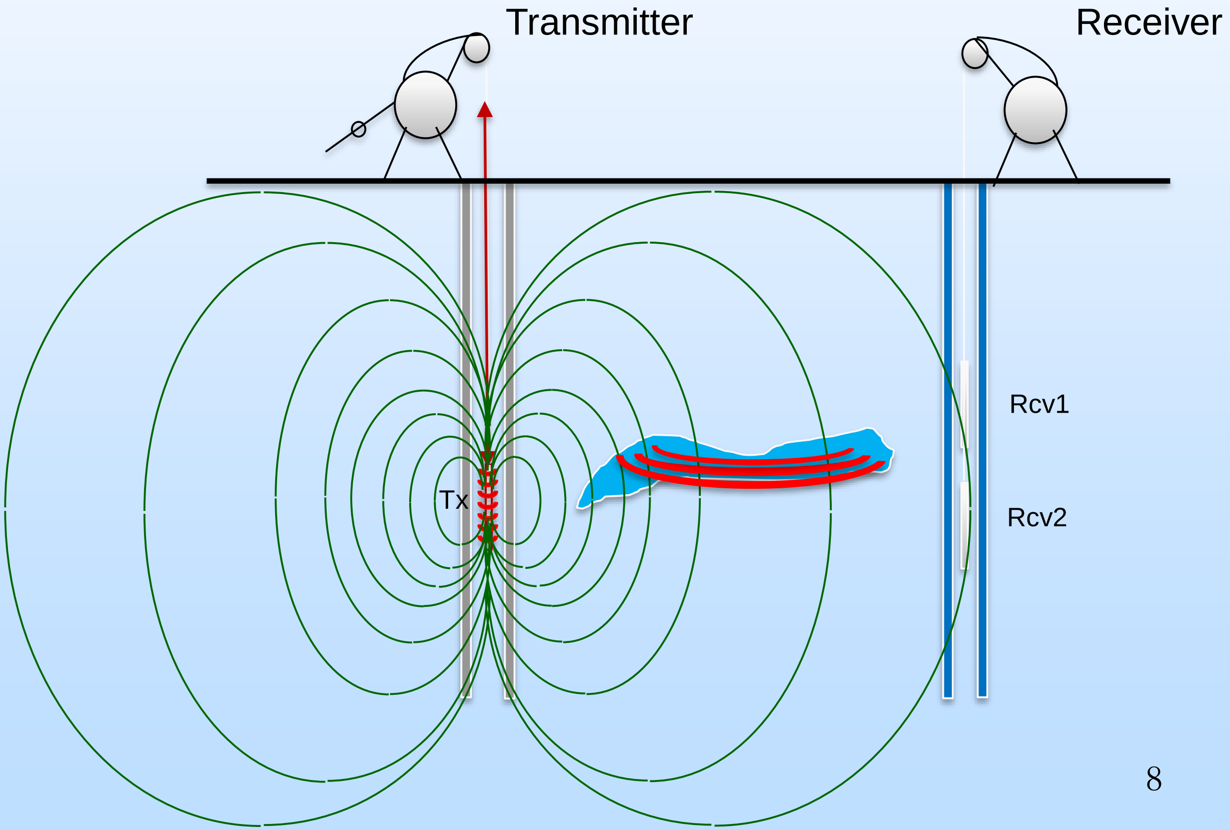

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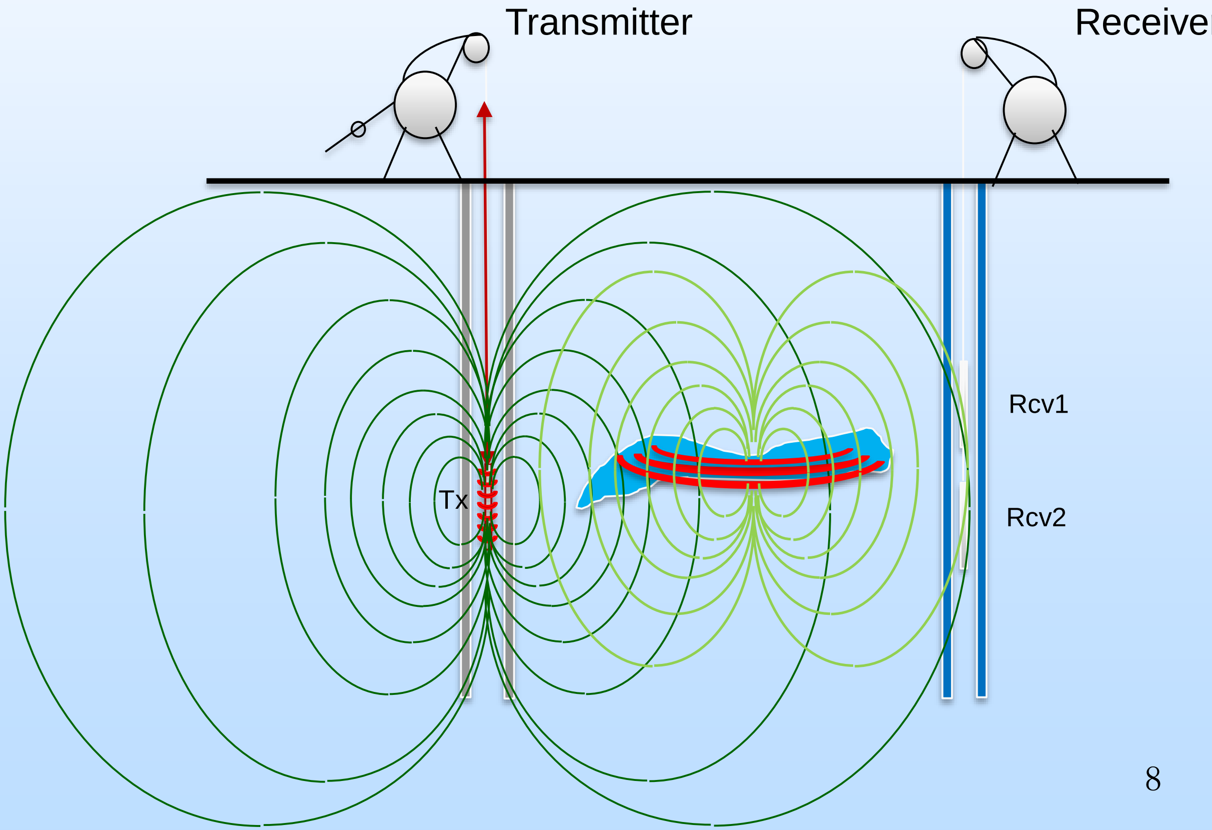
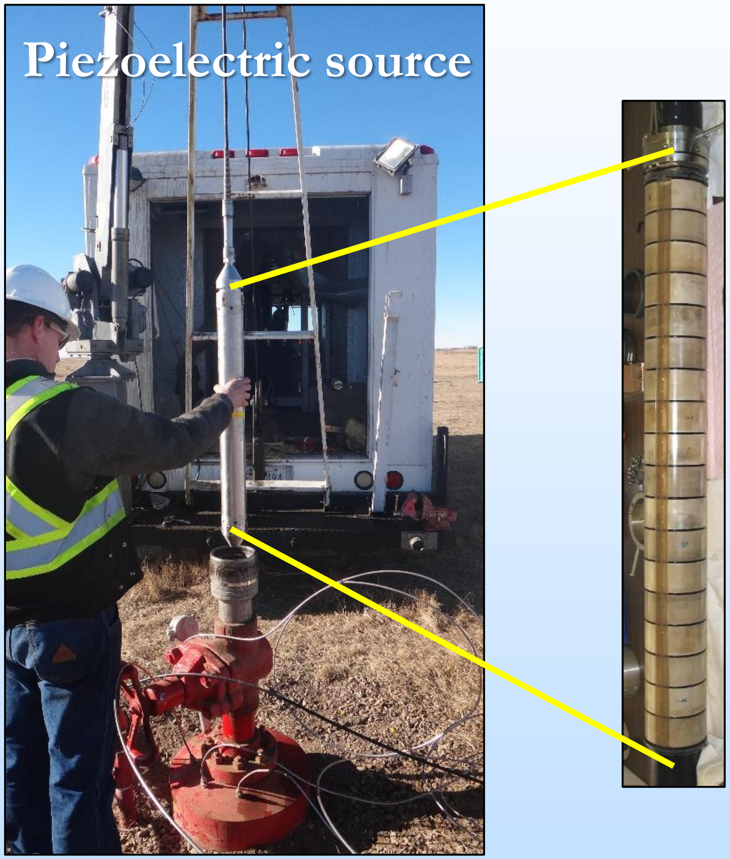
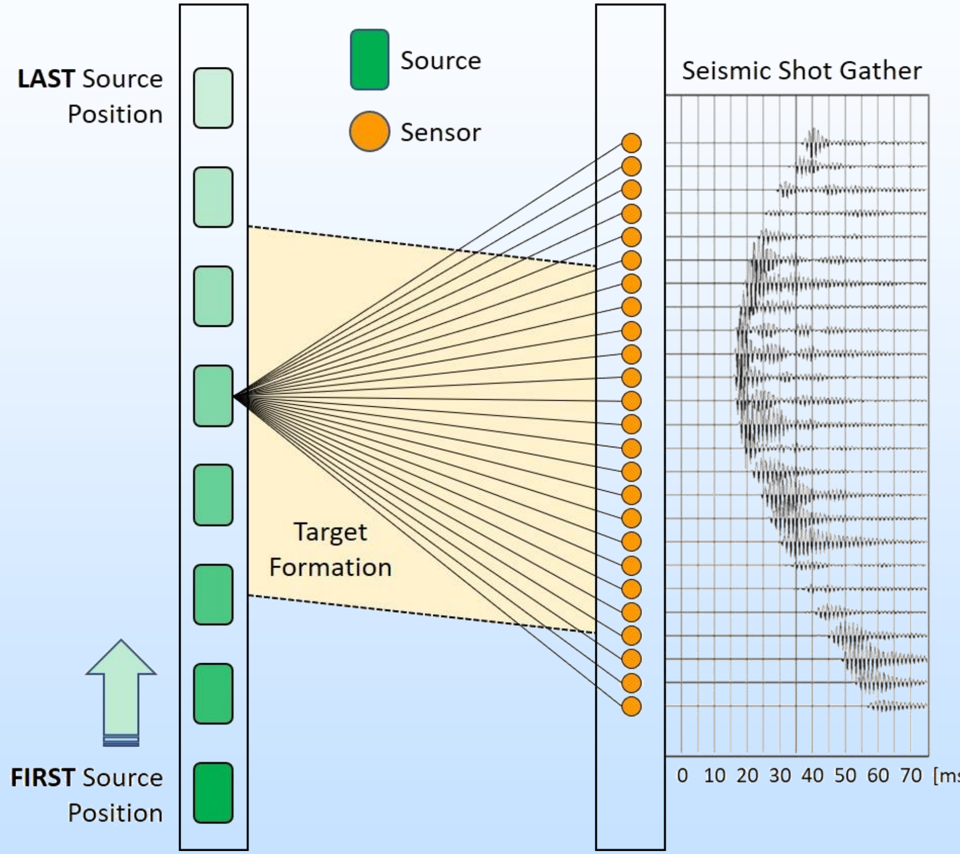
4) Secondary currents generate magnetic fields which are detected along with primary magnetic fields at receivers



Primarily sensitive to conductors

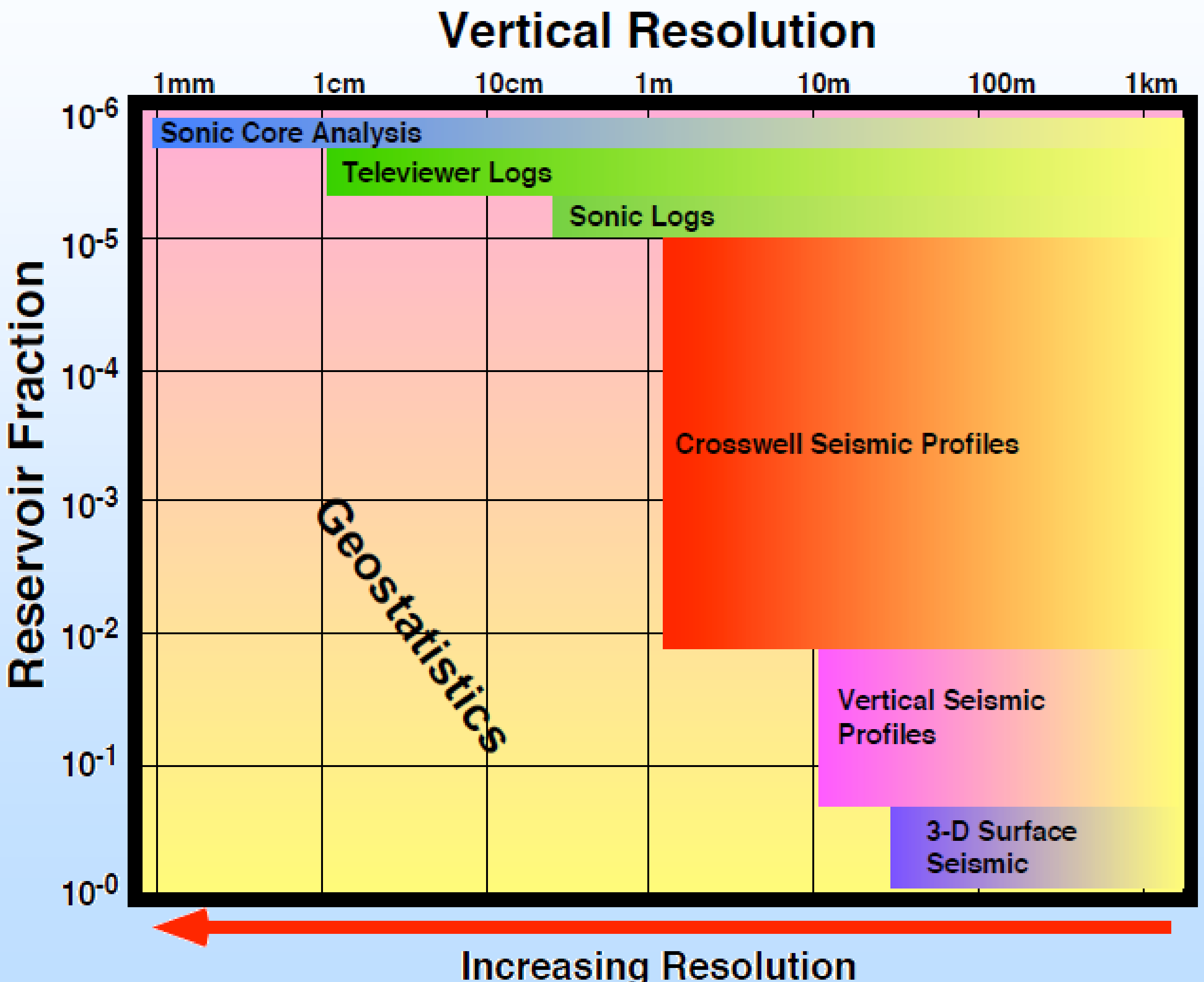
Crosswell Seismic





- Lead-Zirconate-Titanate ceramic rings stack
- Highly durable (lifetime of millions of cycles)
- Highly repeatable
- Broad frequency: Hz to kHz

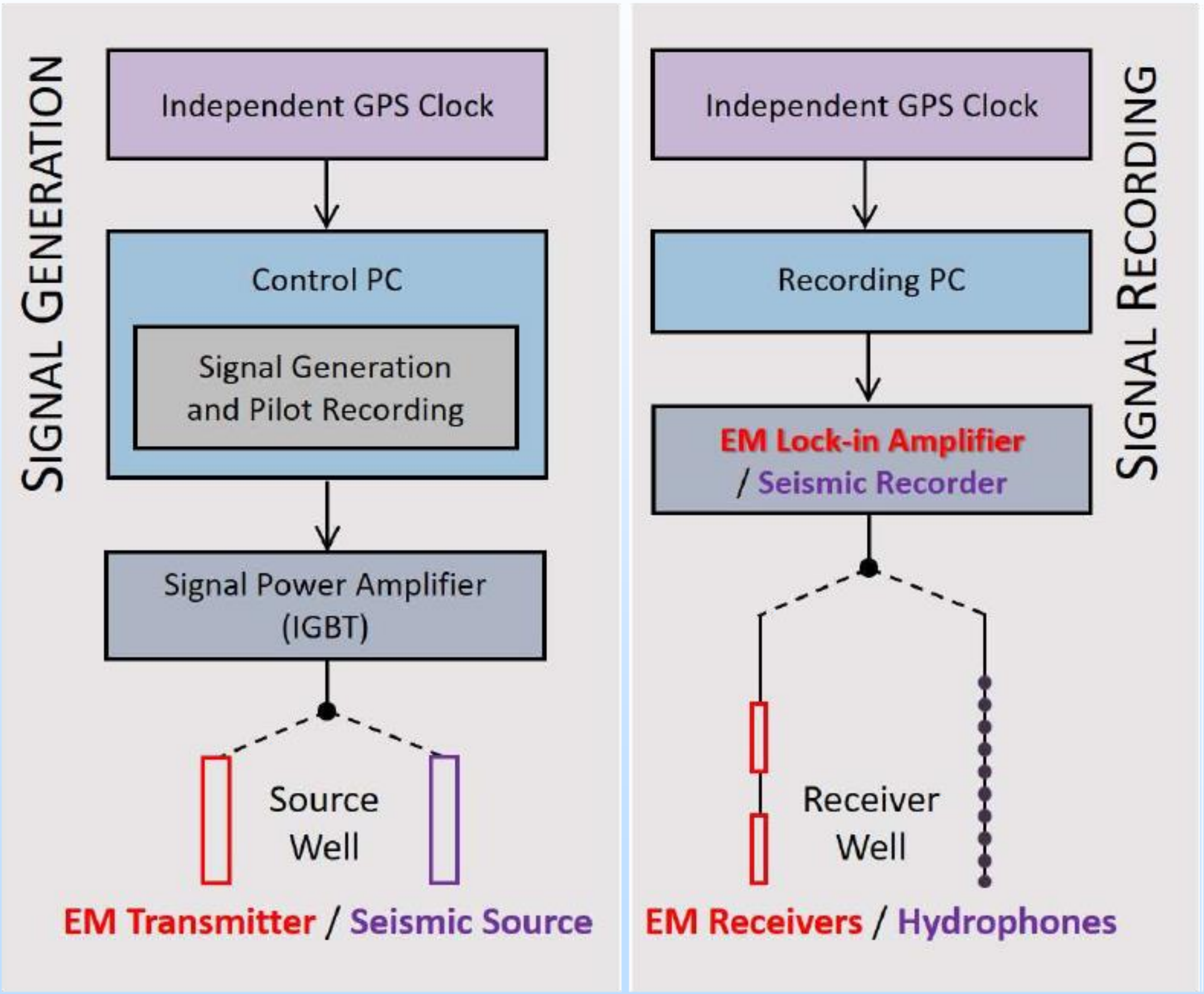
Why Crosswell Geophysics?



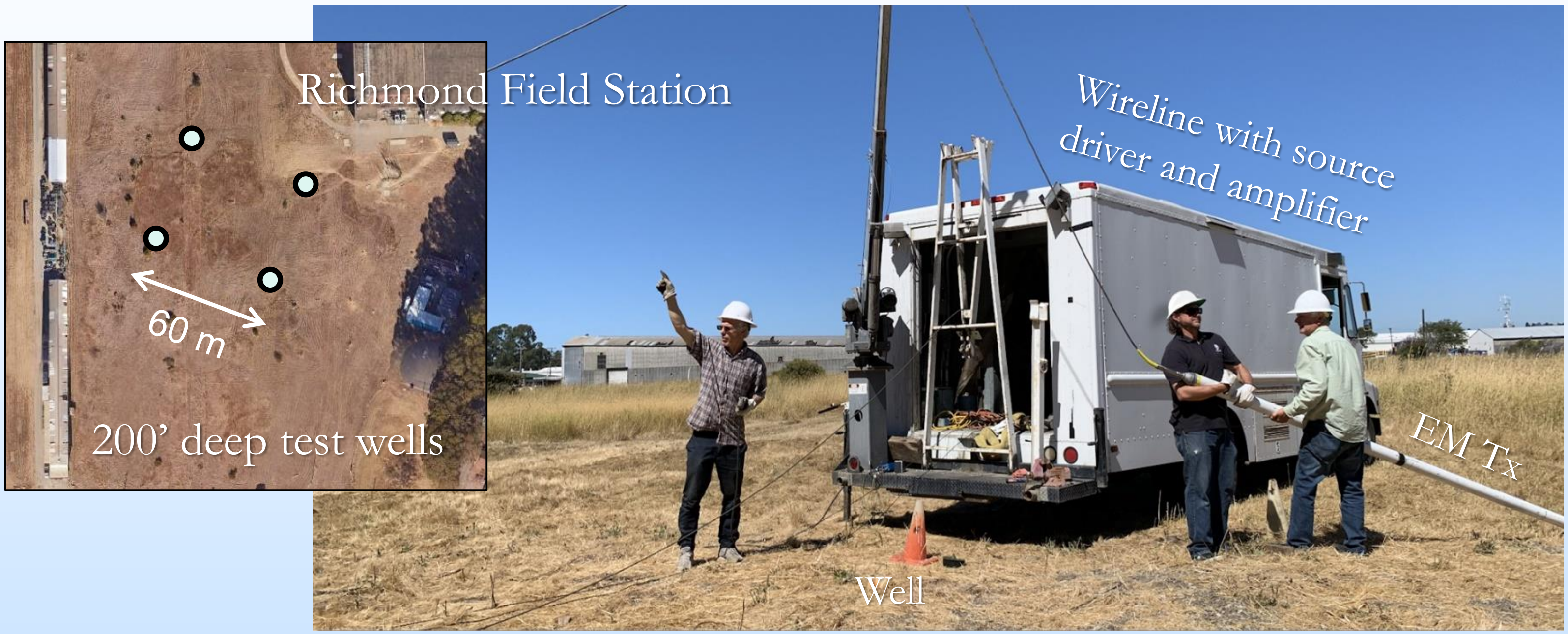
Required for <u>robustly tracking</u> the movement of CO_2 and <u>defining the boundaries</u> of the CO_2 plume.

From Harris and Langan, 1997

Welcome to the Fully Integrated System



Optimization at local Field Test Site



- GPS wireless synchronized acquisition between Tx and Rx
- High/Low-frequency system testing with new EM transmitter
- Wireline speed test for autonomous seismic acquisition

Crosswell EM Baseline Survey

- A single fiberglass-steel well pair, interwell spacing is = 50 m
- Baseline data acquisition:
  - 200 Hz (presented here)
  - 450 Hz (too noisy to use)
- Transmitter interval: 2 m
- Two receivers spaced at 5 m: data from the top receiver used in this work

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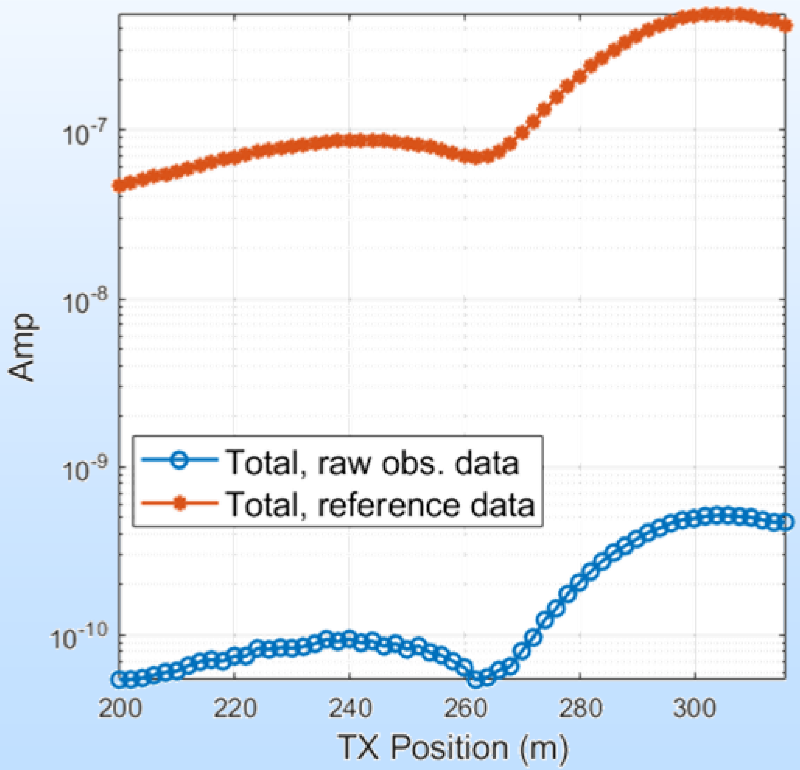
Crosswell Seismic Baseline Survey

- Source: Piezoelectric stack → sweep signal at 350-2500 Hz frequency range
- Vertical Coverage: 257 source positions with 0.5 m increment → 128 m

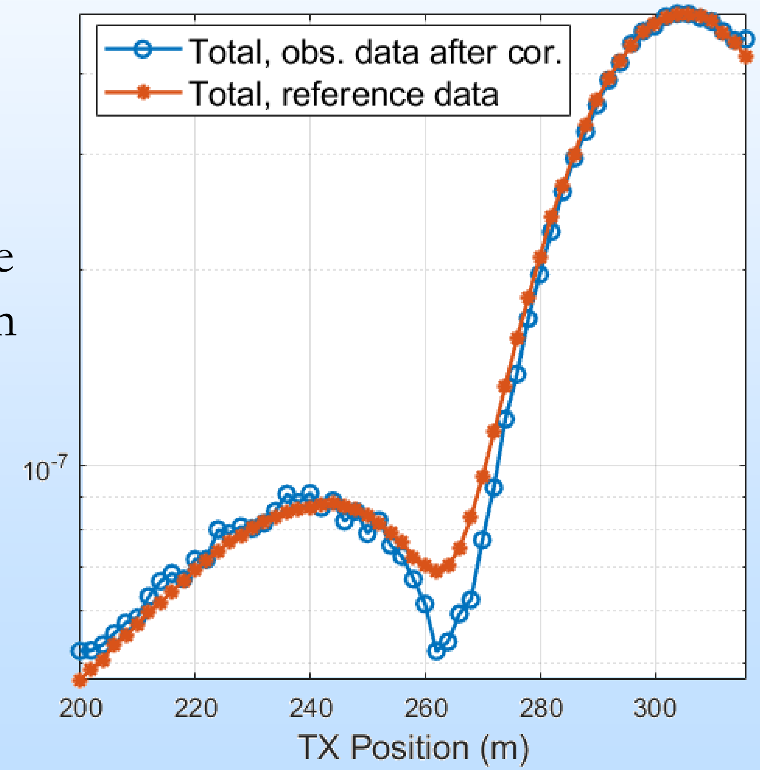
- Sensors: Hydrophone array → 20 sensor elements at 5 m spacing
- Vertical Coverage: 10 array moves with 0.5 m increment → 99.5 m

Correction for Steel-Casing Effects

- Manually find a complex number that removes the casing effects at a given receiver position when the raw data are multiplied by the number



Amplitude Correction



Common Receiver Gather

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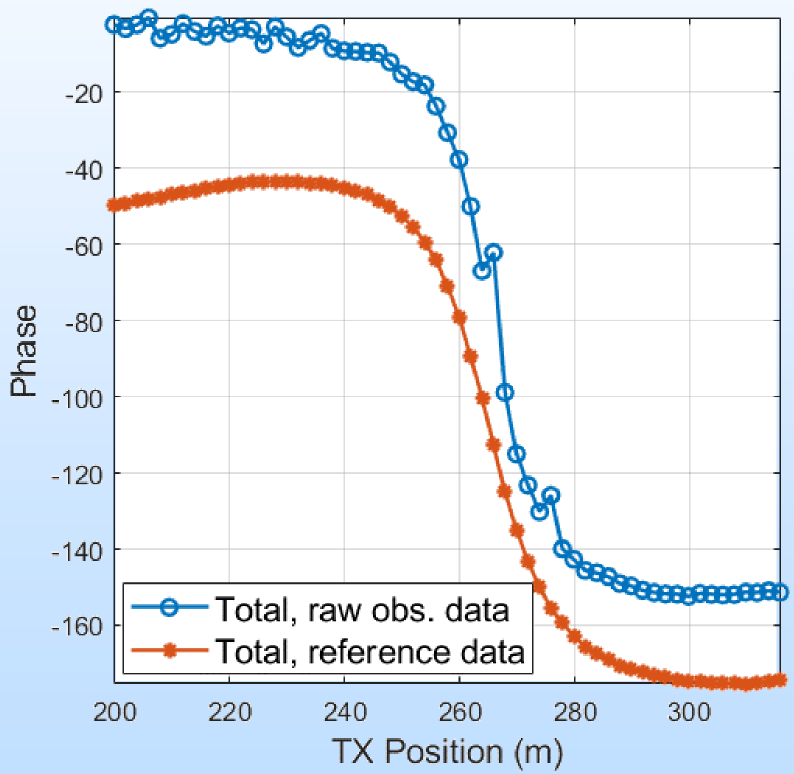
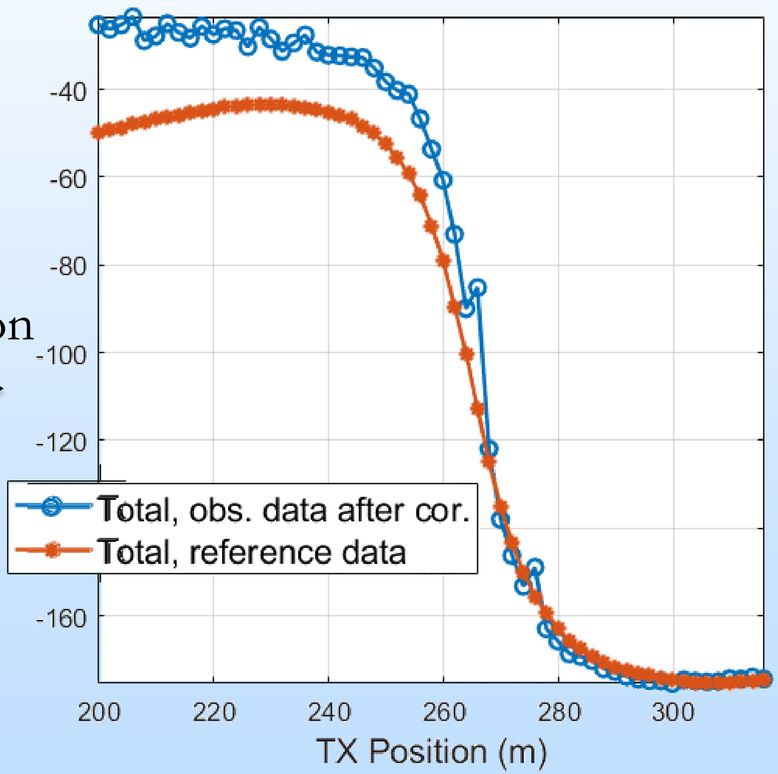
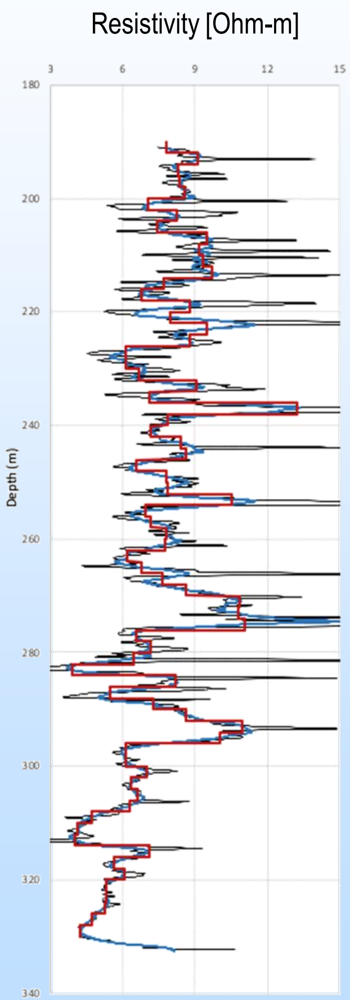


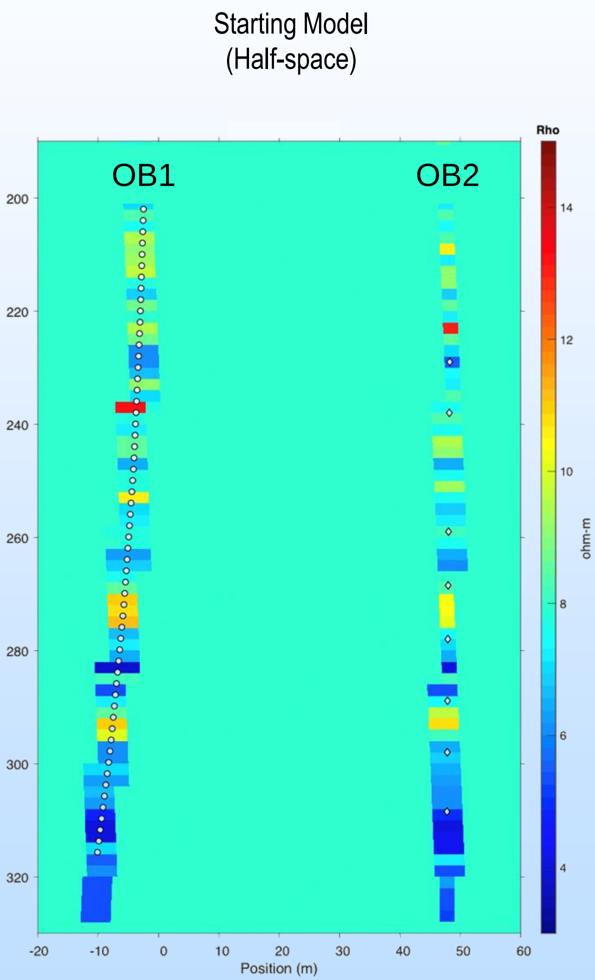
Phase Correction

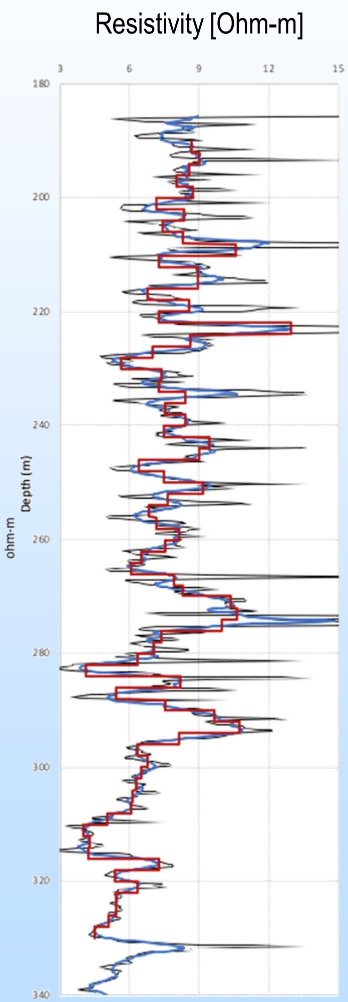


Common Receiver Gather

Crosswell EM Inversion (200 Hz)

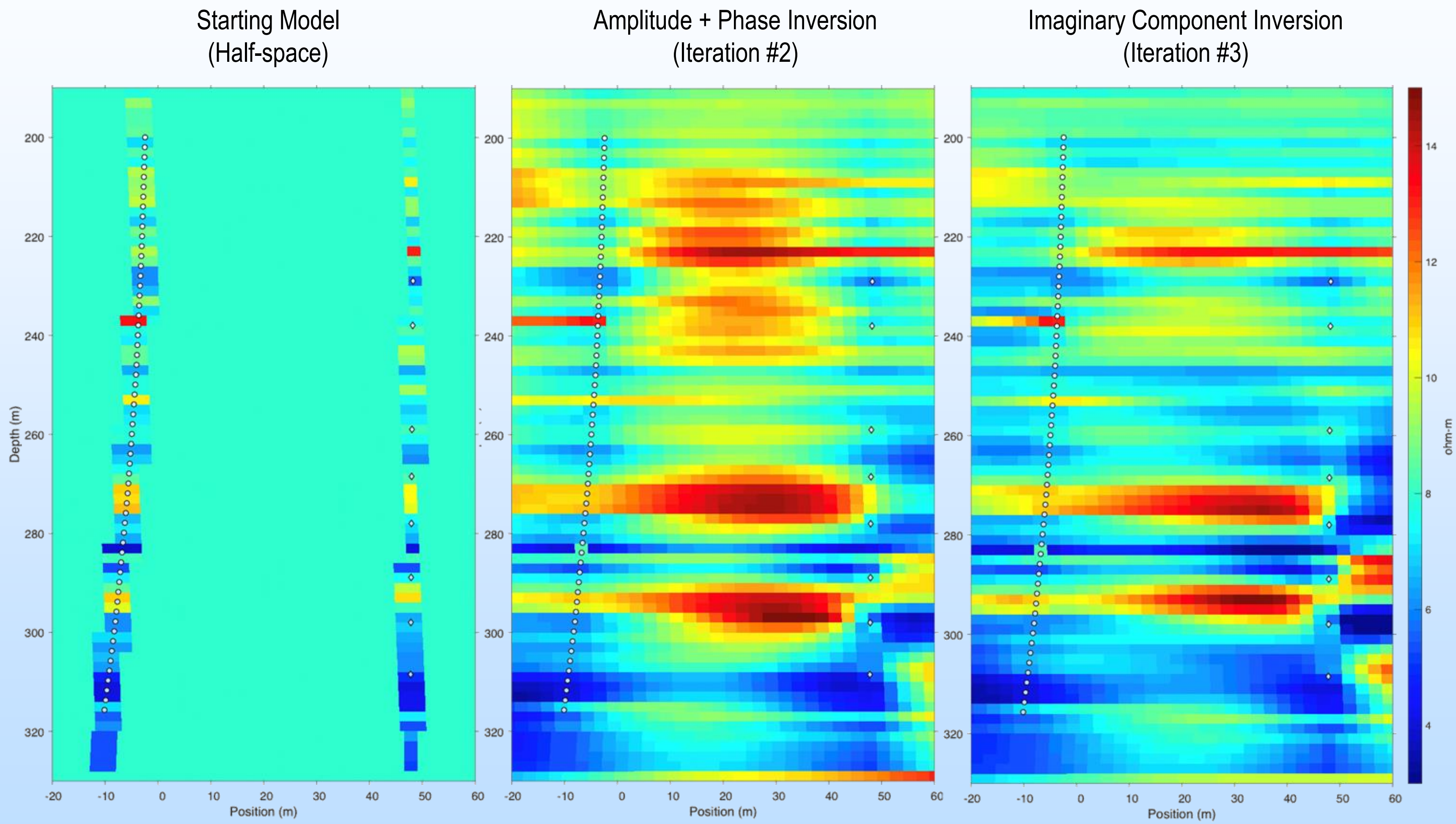






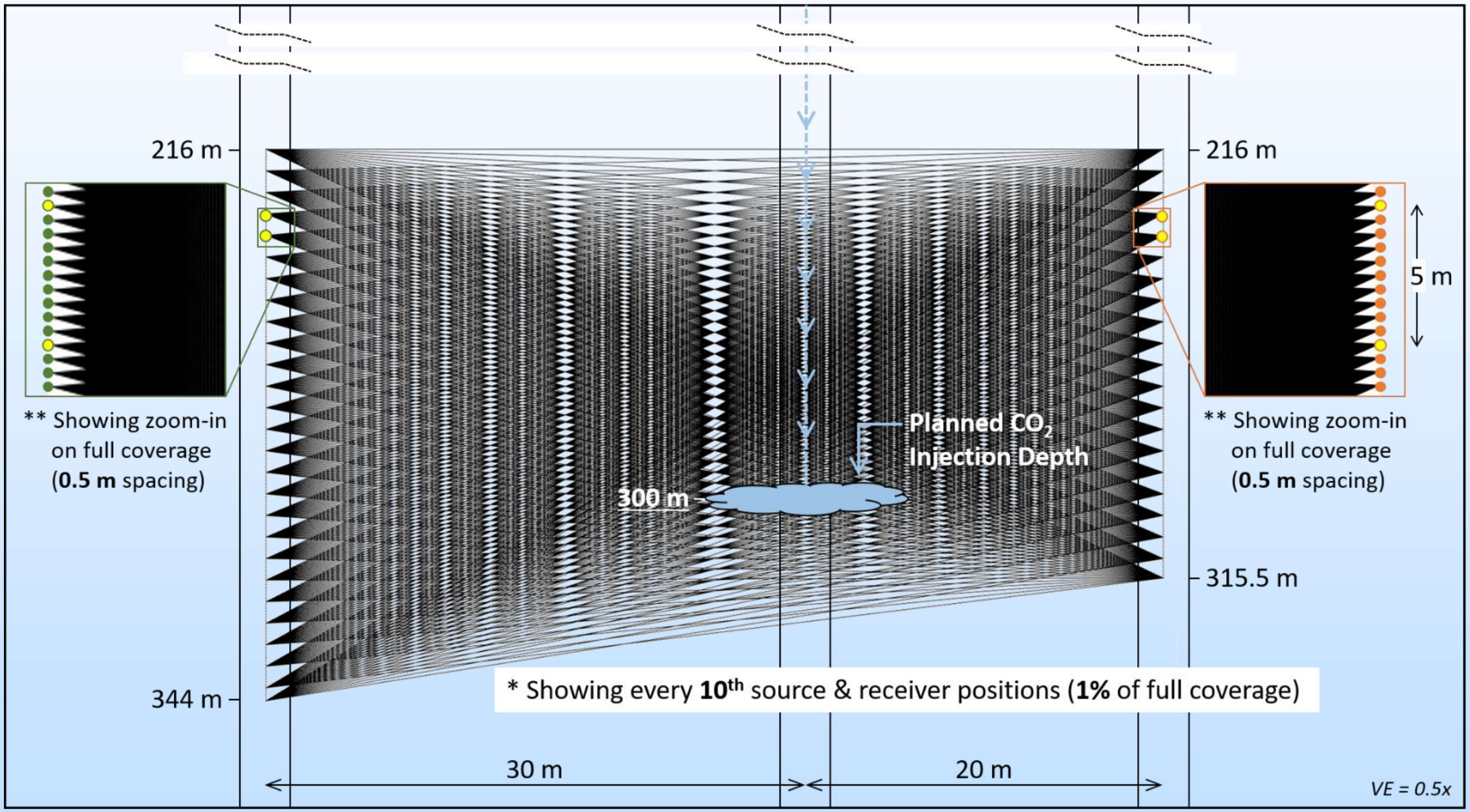
- Upscaled/averaged resistivity logs are used as constraints
- Well deviation logs are used for correctly positioning sources and receivers
- Sparse receiver locations
- MARE2DEM (K. Key, 2016)

Crosswell EM Inversion (200 Hz)



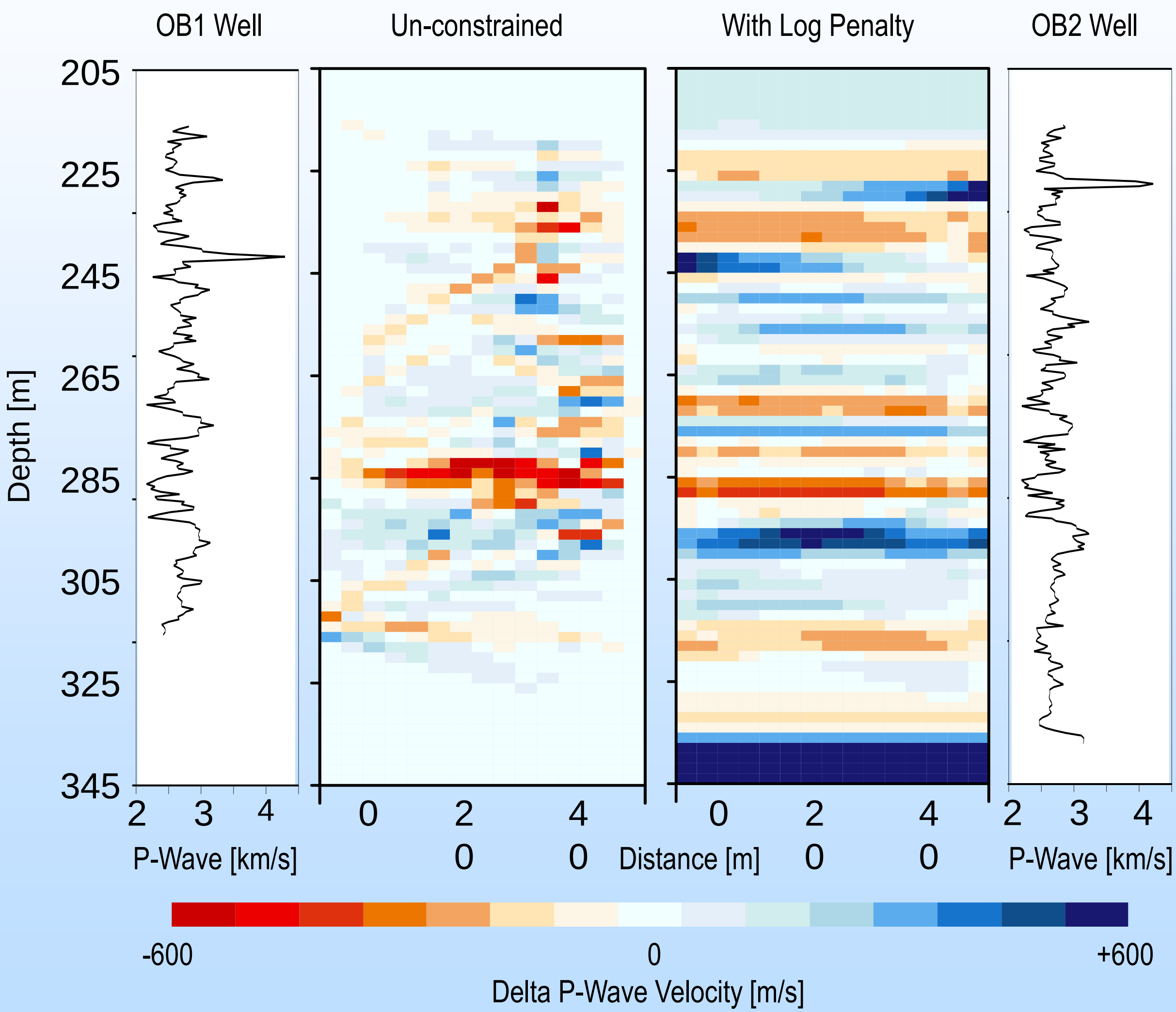
Crosswell Seismic Geometry

128 m Vertical Coverage



99.5 m Vertical Coverage

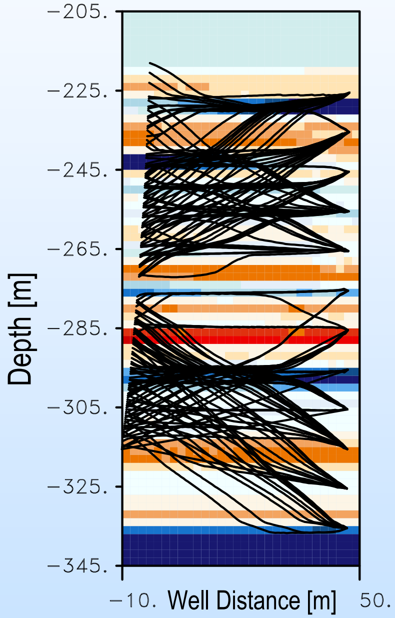
Crosswell Seismic Inversion



- Inversion based on half-space, homogeneous velocity model
- Initial velocity = 2.517 km/s
- Regularization to match well logs
- Trajectory-based approach that improves upon the eikonal equation approximation over multiple iterations

Crosswell Seismic Inversion

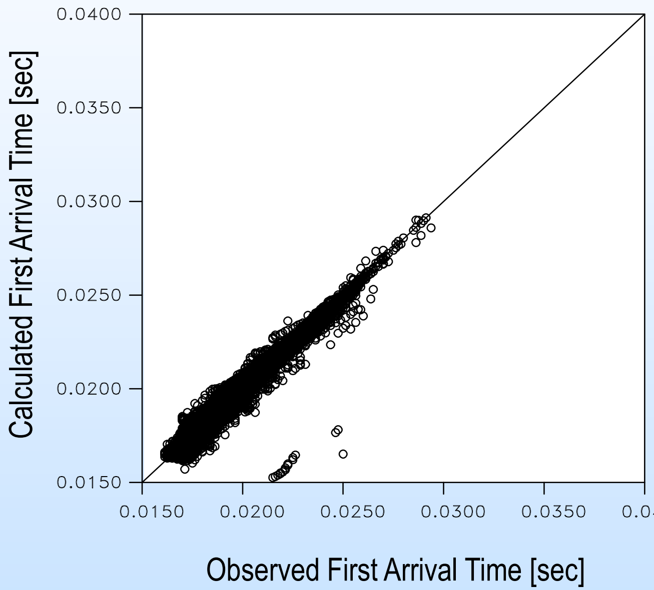
Ray-path Tracing



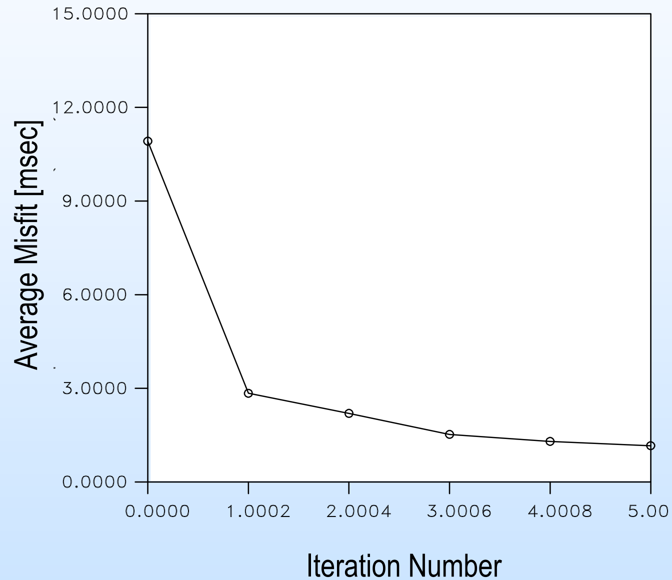
-600 0 +600

Delta P-Wave Velocity [m/s]

Log of First Arrival Times

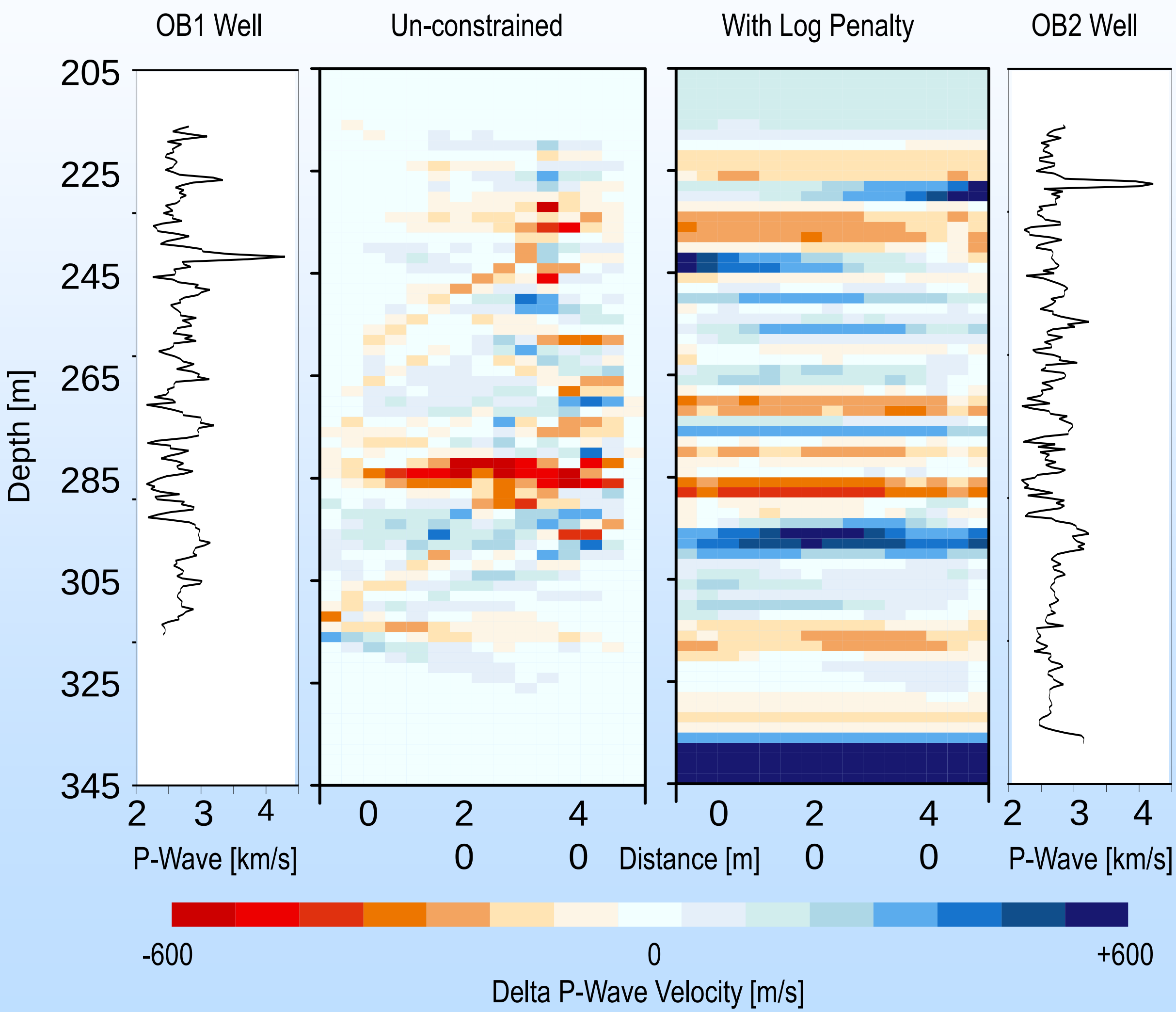


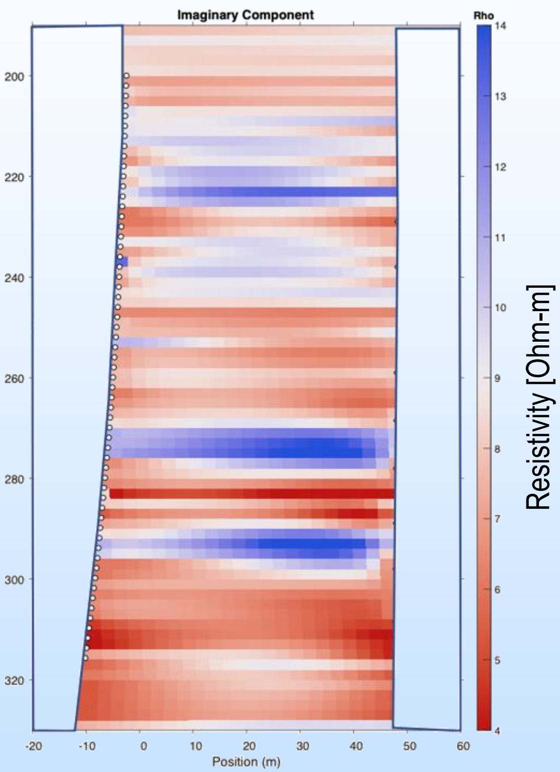
Data Misfit through Iterations



- Many ray-paths bend sharply into high velocity layers.
- Eikonal equation approximation appears to be breaking down

EM vs. Seismic Inversions





CaMI-FRS Updates: Aug.2020

- 26 Tonnes of CO_2 injected to date (Aug. 2020)
- Switch in injection mechanism: from high rates over short periods of time towards a more constant injection rates over longer times (longest continuous injection time to date = 72 hrs.)
- Increased the injectivity up to 400 kg/week
- Recent acquisition of surface microseismic and active seismic datasets using CaMI permanent geophones array (24 x 3C)
- ERT, DTS, seismic VSP datasets indicate the presence of the injected CO_2. CaMI estimate that the extent of the plume has progressed to the halfway point between OB2 and the injection well
- Canadian border still closed to non-essential travel (Sept. 4, 2020)

Accomplishments to Date

- Continuous collaboration with CMC/CaMI on field site development and monitoring program
- Processed and analyzed EM and seismic baseline surveys
- Development of individual inversion capabilities
- Development of capabilities for forward modeling for repeat survey design
- Optimization of acquisition strategies to minimize field occupancy
- Fully integrated EM-Seismic system (shared wireline, Tx source driver, Rx recording system: <u>raised TRL</u>)

Next Steps

- Repeat surveys during injection: dates TBD according to international travel restrictions.
  - Optimistic plan: late October 2020
  - Realistic plan: April-May 2021
- Acquisition Plan:
  - EM+Seismic crosswell
  - EM surface-to-borehole
  - Seismic (piezo) into DAS
  - DSS (topic merged from Task #5)
- Joint inversion:
  - EM with ERT and STB in single physics approach
  - EM+Seismic multi-physics approach (sequential and joint)

Credits: M. Shevalier, UCalgary

Synergy Opportunities

- EM
  - Crosswell EM tomographic survey within BEST (Brine Extraction and STorage) project in Pensacola, Florida. *Michael Wilt, David Alumbaugh, Evan Um, Ed Nichols*
- Seismic
  - Crosswell time-lapse tomography and real-time active monitoring of steam/water injection for EOR, Lost Hills, California. *Pierpaolo Marchesini and Chevron*
  - Real-time active monitoring of rapidly-changing fluid pathways at active oil field, Cymric, California. *Pierpaolo Marchesini and Chevron*
- EM+Seismic
  - aCQurate Project: multi-physics dataset inversion using code developed by SINTEF (Norway). Hybrid structural-petrophysical joint inversion: robust + quantitative approach. *David Alumbaugh, Evan Um, and Michael Jordan* https://www.sintef.no/en/projects/acqurate

Acknowledgments

- Funding for LBNL was provided through the Carbon Storage Program, U.S. DOE, Assistant Secretary for Fossil Energy, Office of Clean Coal and Carbon Management, through the National Energy Technology Laboratory (NETL), for the project "Core Carbon Storage and Monitoring Research" (CCSMR) under contract No. DE-AC02-05CH11231

- We would like to thanks the Geophysical Measurement Facility (GMF) @LBNL for technical and field support

- We thank CMC Research Institutes Inc. for access to the Containment and Monitoring Institute (CaMI) Field Research Station (FRS) and for logistical support during the field campaigns

Appendix

Benefit to the Program

- Program goals being addressed:
  - Develop and validate technologies to ensure 99 percent storage permanence;
  - Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness.
- Project benefits:
  - Deployment and testing of new monitoring technologies and methodologies;
  - Broader learnings from leveraged international research opportunities;
  - Rapid transfer of knowledge to domestic programs.

Project Overview

- The Core Carbon Storage and Monitoring Research Program (CCSMR) aims to advance emergent monitoring and field operations technologies that can be used in commercial carbon storage projects. This effort aligns with program goals:
  - Improve estimates of storage capacity and sweep efficiency
  - Develop new monitoring tools and technologies to achieve 99% storage confirmation
- Success criteria is if we are able to advance the technology readiness level (TRL) of targeted technologies from a level of TRL 2 – 3 up to 4 – 5 through leveraged field testing opportunities, with field sites being used as in-situ laboratories.

LBNL's Goal and Objectives

Contribute to a comprehensive monitoring program with:

- Integration and technology maturation of Crosswell EM and Seismic into a multi-physics monitoring approach to improve CO_2 saturation estimates and joint inversion;
- U-Tube fluid sampling;
- Distributed Temperature Sensing (DTS) + heat pulse monitoring;
- Surface and borehole straight + helical Distributed Acoustic Sensing (DAS);
- Distributed Strain Sensing (DSS).

Organizational Chart

Carbon Management Canada (CMC) organized the Containment and Monitoring Institute (CaMI), led by Prof. Don Lawton (University of Calgary) https://cmcghg.com/cami

Project field site is CaMI-Field Research Station (FRS), Newell County, Alberta, Canada

- **Collaborating Research Institutions**

  British Geological Survey (UK)

  CMR (Norway)

  GFZ (Germany)

  Imperial College (UK)

  INRS (Canada)

  LBNL (USA)

  Natural Resources Canada (Canada)

  NTNU (Norway)

  Princeton University (USA)

  SINTEF (Norway)

  University of Bristol (UK)

  University of Calgary (Canada)

  University of Edinburgh (UK)

  University of Freiberg (Germany)

  University of Guelph (Canada)

- **Commercial Partners**

  Chevron (USA)

  Equinor (Norway)

  Petronas (Malaysia)

  Shell (UK-Netherlands)

  Total (France)

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Gantt Chart

Task	Milestone Description*		Fiscal Year 2021				Planned Start Date	Planned Completion Date (Reporting Date)**	Actual Start Date	Actual End Date	Comment (notes, explanation of deviation from plan)
		FY20	Q1	Q2	Q3	Q4					
Milestone 3-1 (A)	Development of sequential and joint inversion capabilities based on baseline EM and Seismic datasets using internally-developed LBNL processing code and external partner contributions (SINTEF, Norway)	Q4FY20					7/1/2020	9/30/2020 (10/31/2020)			
Milestone 3-2 (B)	Crosswell EM, Crosswell Seismic, and Surface-to-Borehole EM First Repeat Surveys acquisition. Assessment of feasibility for EM and Seismic continuous monitoring during injection using (CESM and CASSM). Tentative reporting date pending the lift of current travel restrictions		X				10/1/2020 (Tentative)	12/31/2020 (1/31/2021)			
Milestone 3-3 (C)	DSS dataset acquisition during injection. Tentative reporting date pending the lift of current travel restrictions		X				10/1/2020 (Tentative)	12/31/2020 (1/31/2021)			
Milestone 3-4 (D)	Sequential and joint inversion of repeat EM and Seismic datasets			X			1/1/2020 (Tentative)	3/31/2021 (4/30/2021)			
Milestone 3-5 (E)	Analysis of DSS datasets for strain signature of CO_2 injection and hydro-mechanical coupling			X			1/1/2020 (Tentative)	3/31/2021 (4/30/2021)			
Milestone 3-6 (F)	Crosswell EM, Crosswell Seismic, and Surface-to-Borehole EM Second Repeat Surveys acquisition				X		4/1/2021 (Tentative)	6/30/2021 (7/31/2021)			
Milestone 3-7 (G)	Sequential and joint inversion of second repeat EM and Seismic datasets					X	1/6/2021 (Tentative)	9/30/2021 (10/31/2021)			

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