Assessment of Leakage Pathways Using Joint EM-Seismic, Borehole and Surface Technologies

Project Number: ESD14-095 (Task#3)

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U.S. Department of Energy

National Energy Technology Laboratory

Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting

August 26-30, 2019

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Presentation Outline

- Background on CaMI - Field Research Station (FRS)
- Why Joint EM and Seismic Geophysical Monitoring ?
- LBNL Progresses on Data Analysis:
  - Crosswell EM Data
  - Crosswell Seismic Data
- Next Steps:
  - Wireline System Upgrade
  - Repeat Survey Campaigns

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'

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

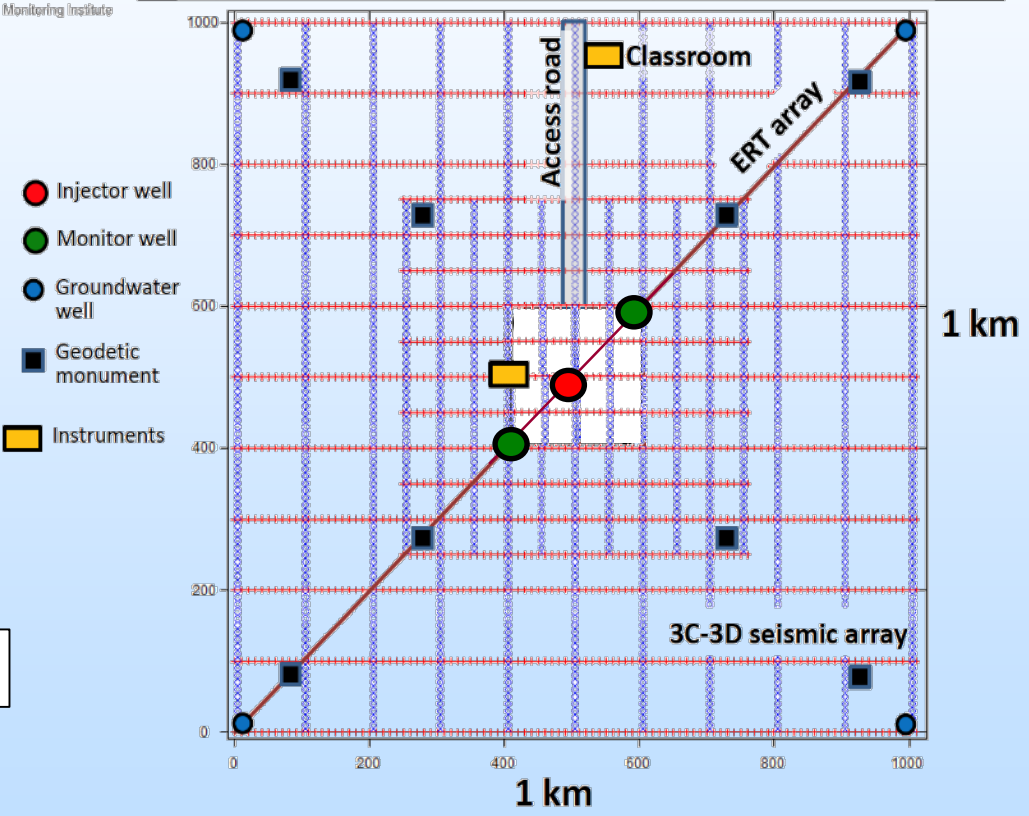
Primary LBNL Focuses

From Lawton, 2016

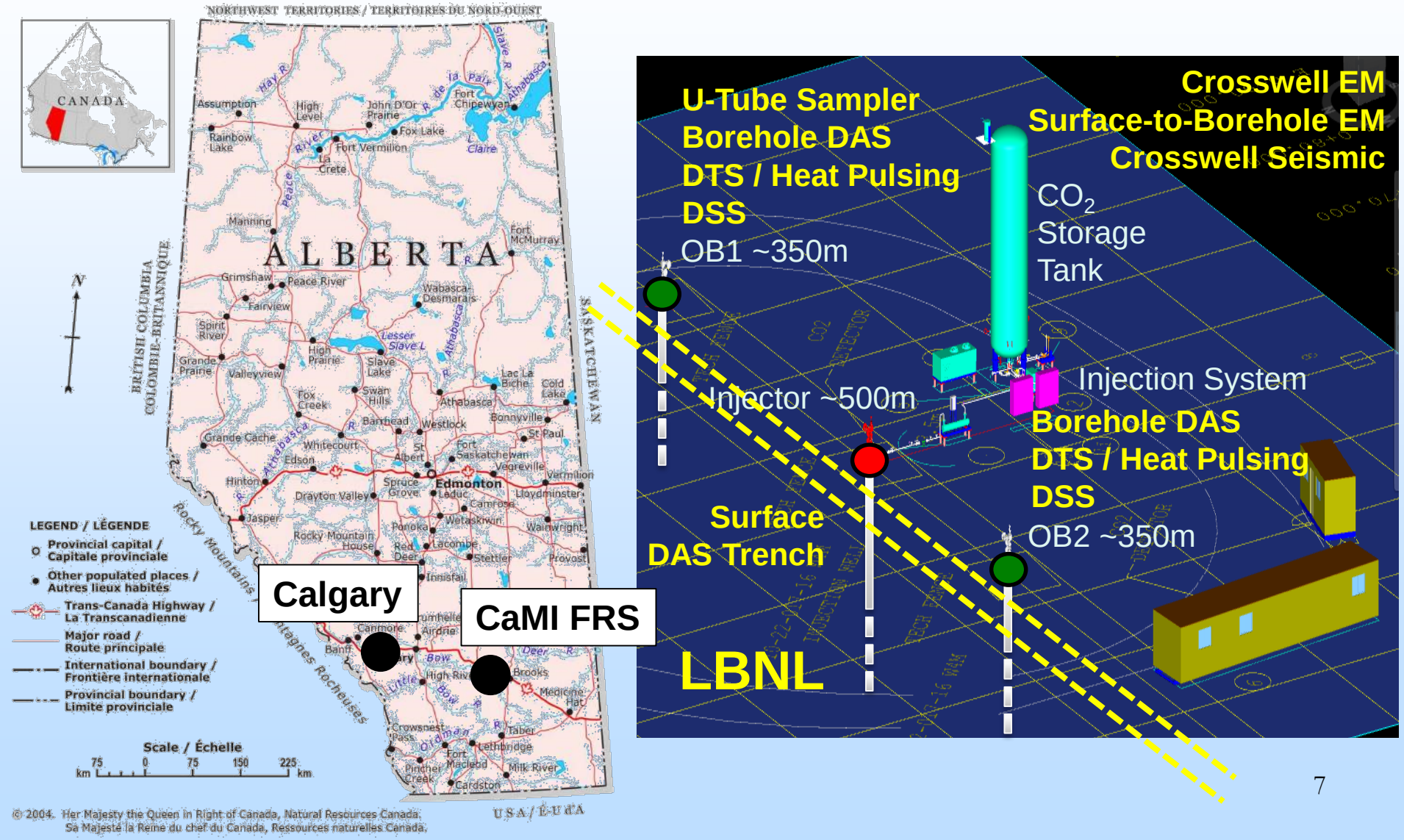
Field Research Station (FRS)

CMC
Containment & Monitoring Institute

FRS monitoring plan layout

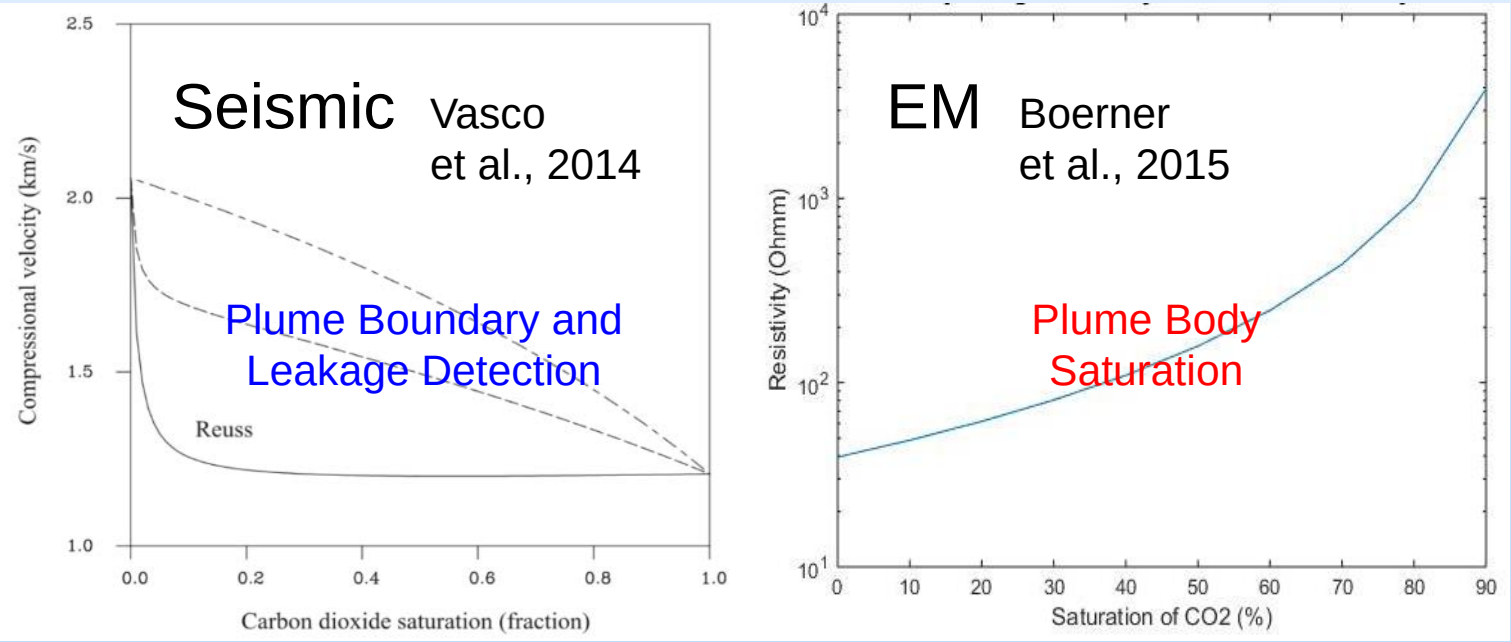


Field Research Station (FRS)

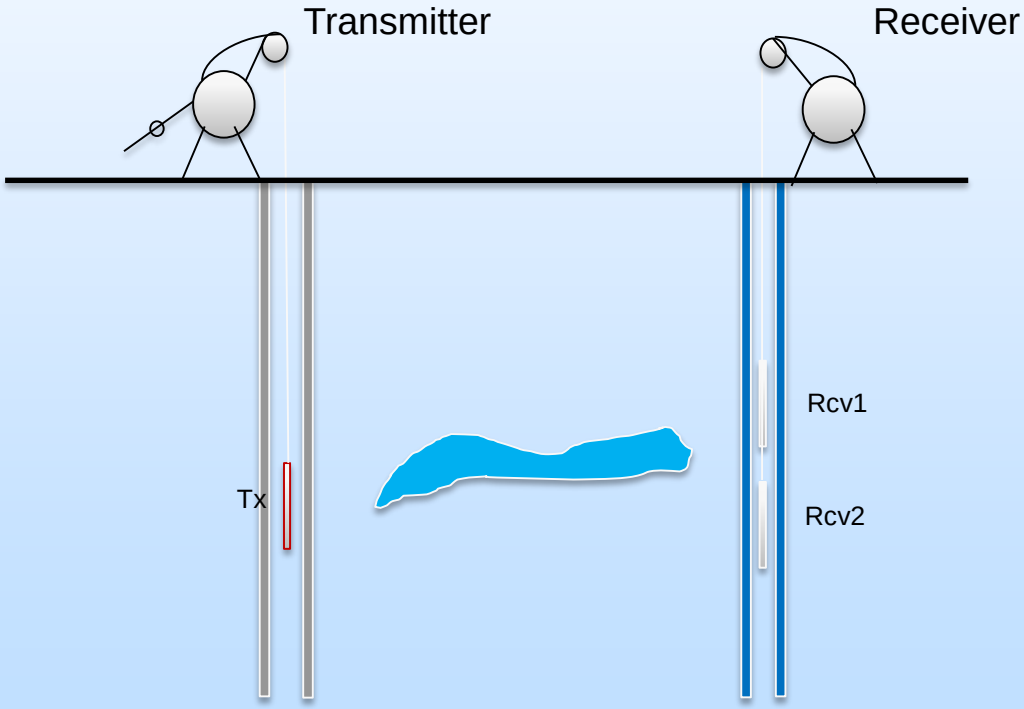


Why Joint EM + Seismic?

- Seismic is high-resolution but has uncertainty at high CO_2 saturation and uncertainty in rock physics interpretation
- EM (conductivity) has strong sensitivity at all saturations and a single rock physics model (Archie's relation) and complements seismic for estimating saturation within the injected plume
- Ideally combine EM, seismic, and flow models in joint inversion for CO_2
- Note: Geochemical alterations to rock frame are not currently integrated in either EM or seismic models (but working on that..)

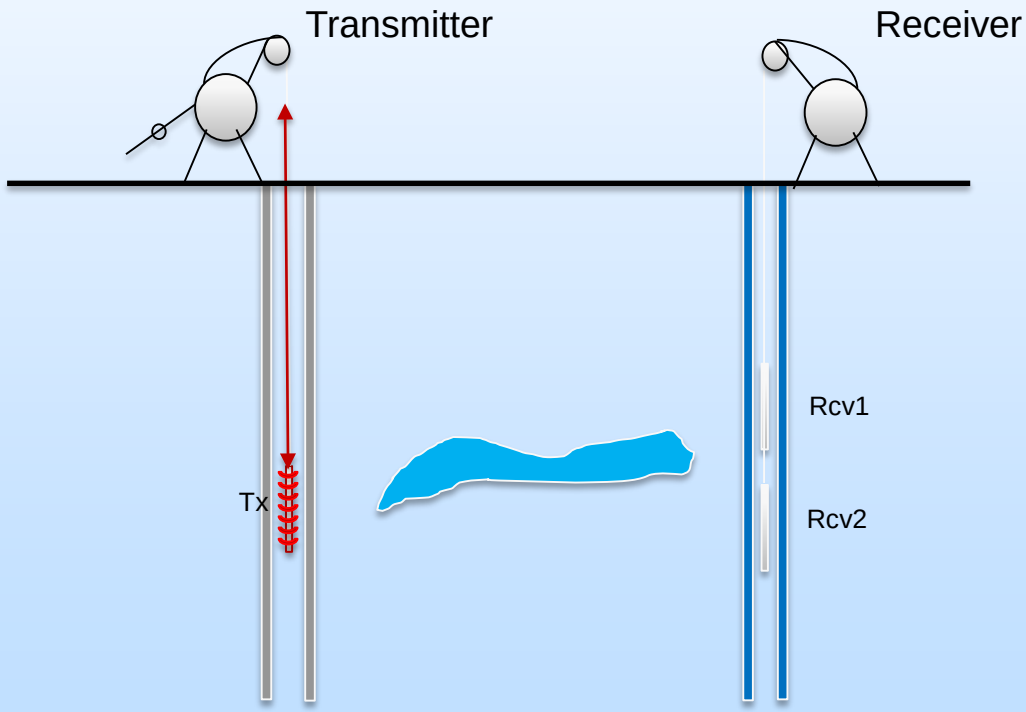


Inductive Method: Crosswell EM



Inductive Method: Crosswell EM

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



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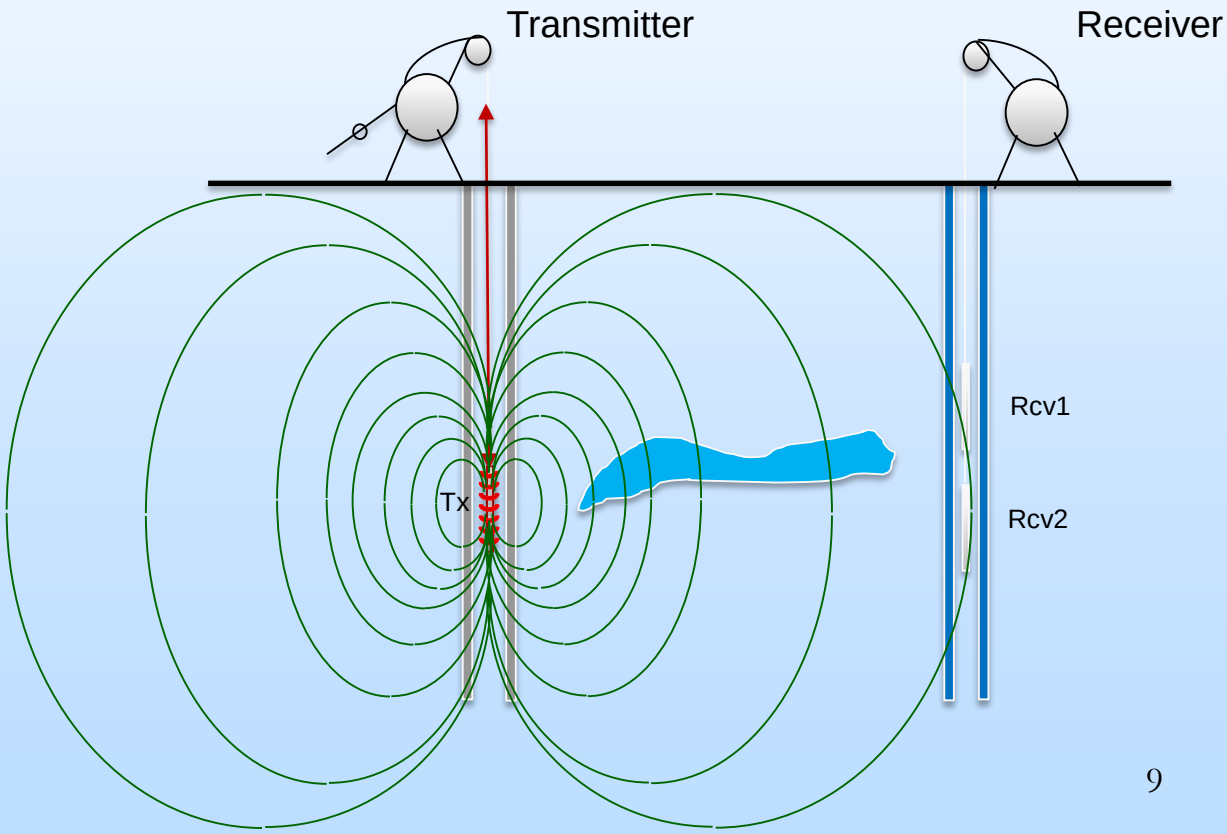
1) Time varying (sinusoidal) electric current input into solenoid transmitter
2) Time varying current produces time varying magnetic field



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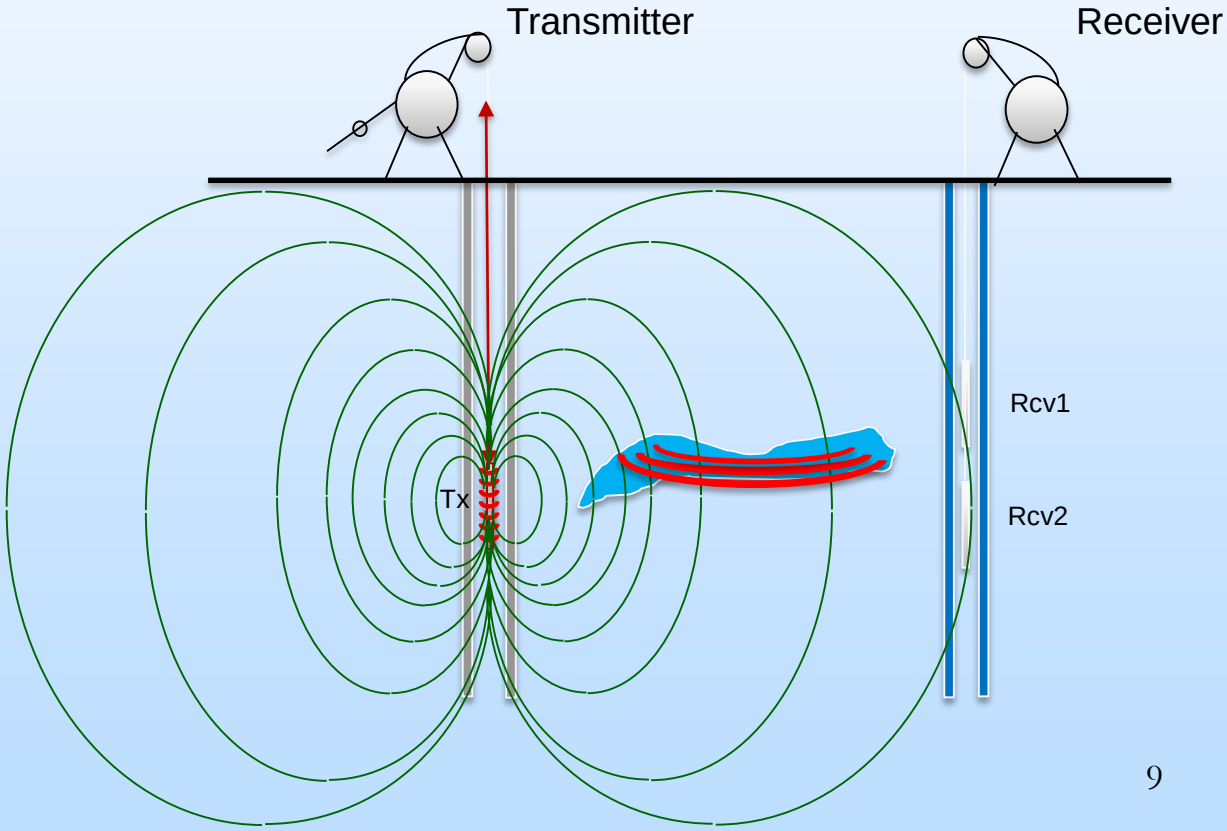
3) Time varying magnetic fields 'induce' secondary currents in conductive media



Inductive Method: Crosswell EM

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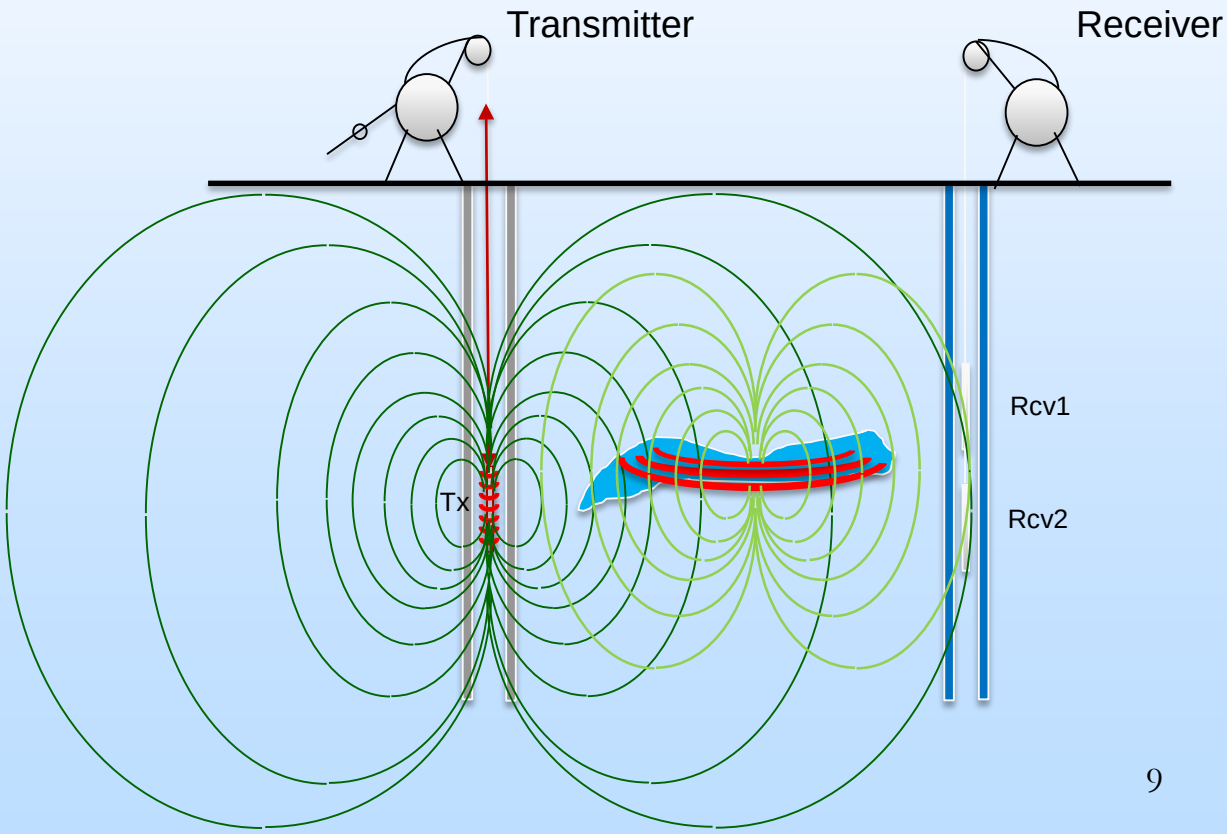
4) Secondary currents generate magnetic fields which are detected along with primary magnetic fields at receivers

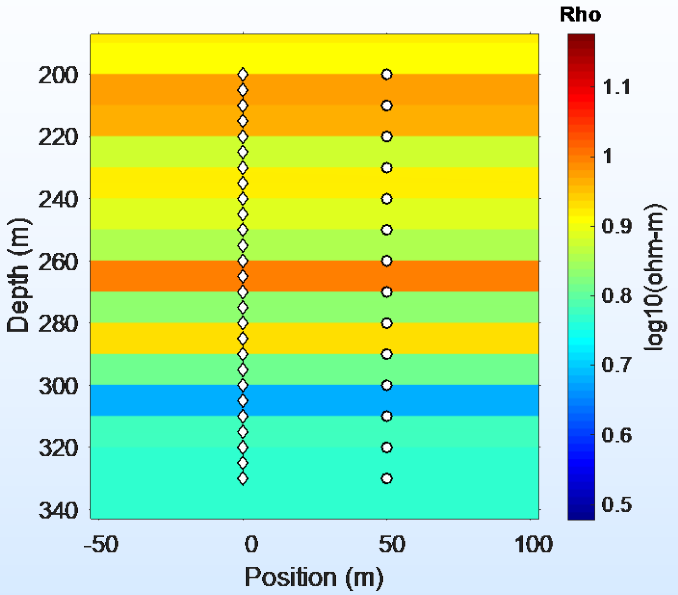


Primarily sensitive to conductors

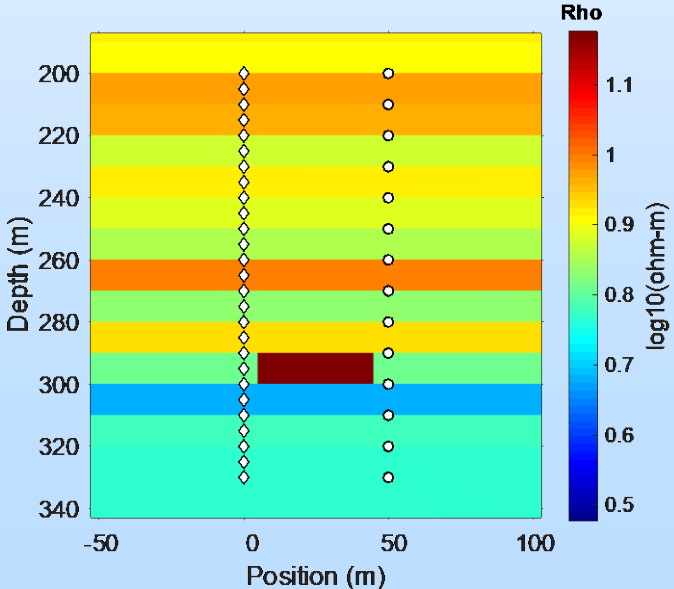
450 Hz Crosswell EM Simulation

- Models:
  - Background from logging data
  - 40m-by-40m-10m CO_2 structure at the center of the two wells, 30 Ohm-m
- Logging interval
  - CO_2 at 290-300m
  - Logging interval 330-200m
  - Source frequency: 200Hz and 450Hz
- Assume noise level of 1% of signal amplitude

Pre-Injection

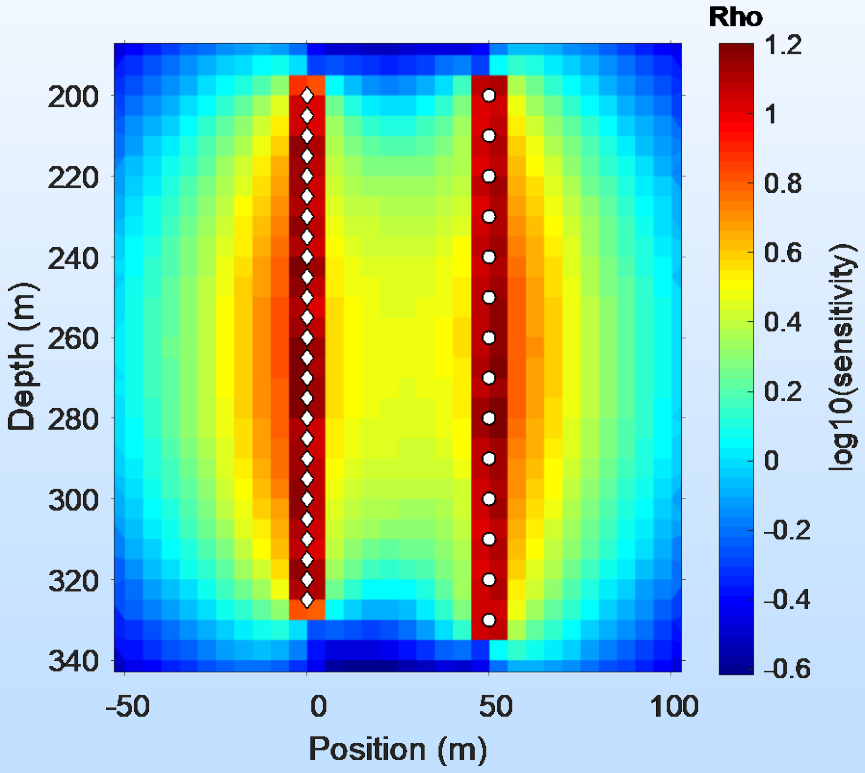


Post-Injection

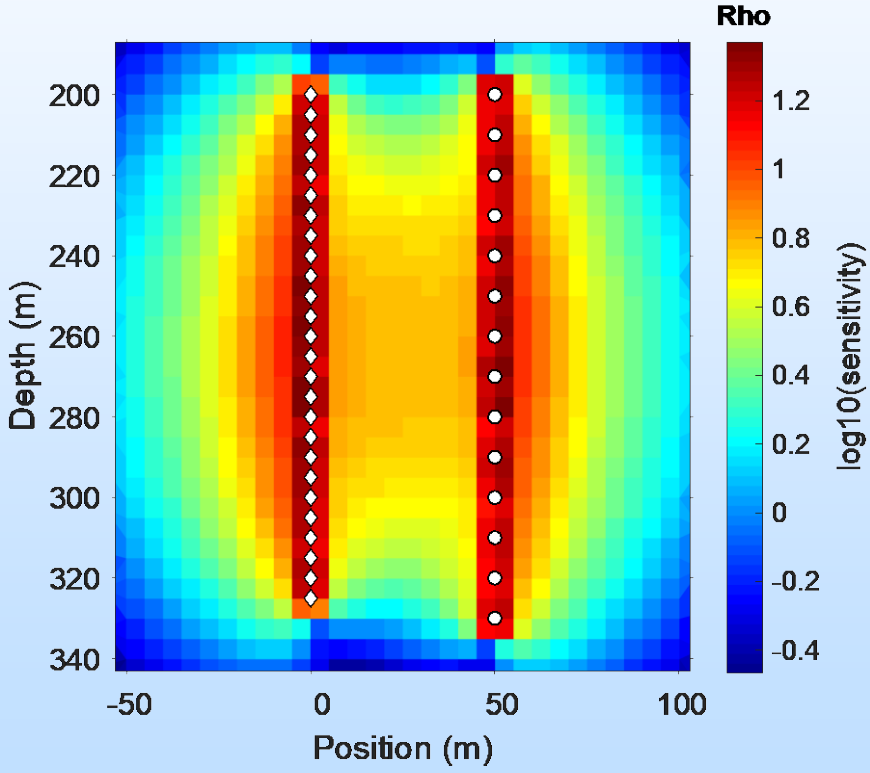


Crosswell EM Sensitivity

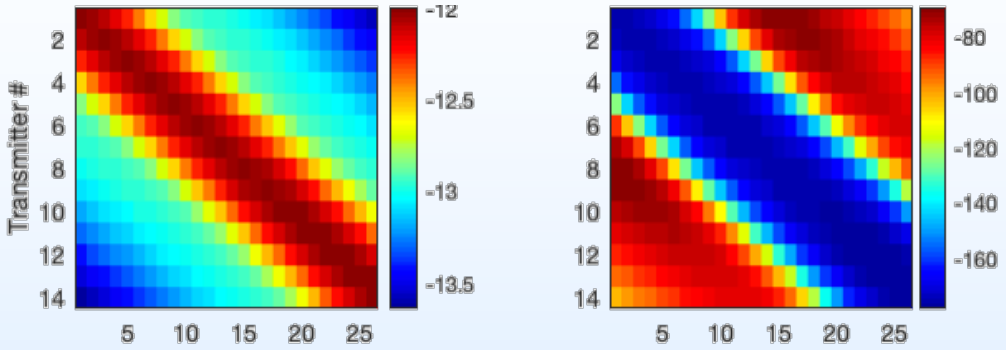
200 Hz



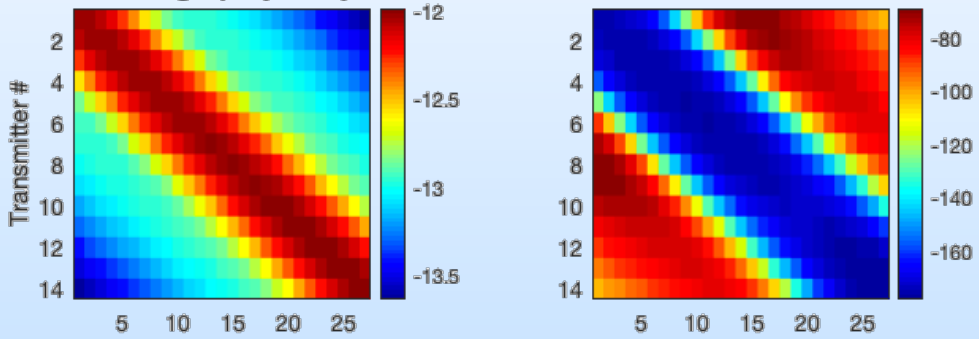
450 Hz



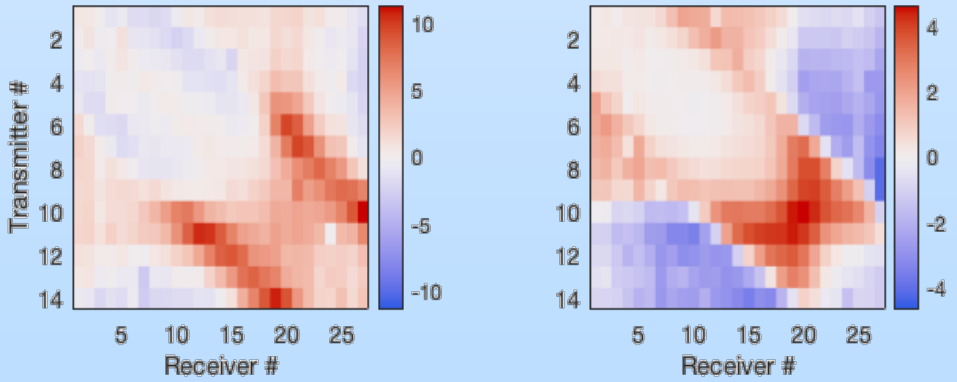
450 Hz Crosswell EM Simulation



Before Injection



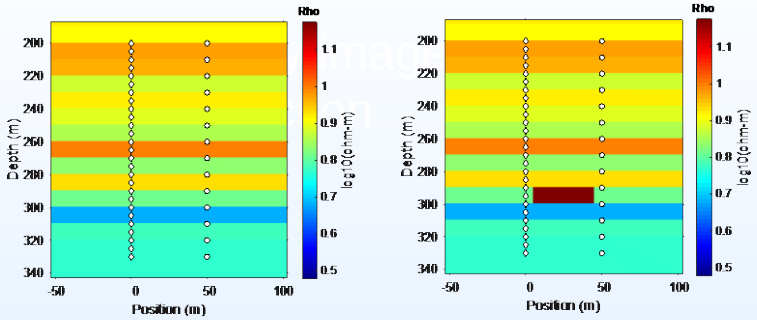
After Injection



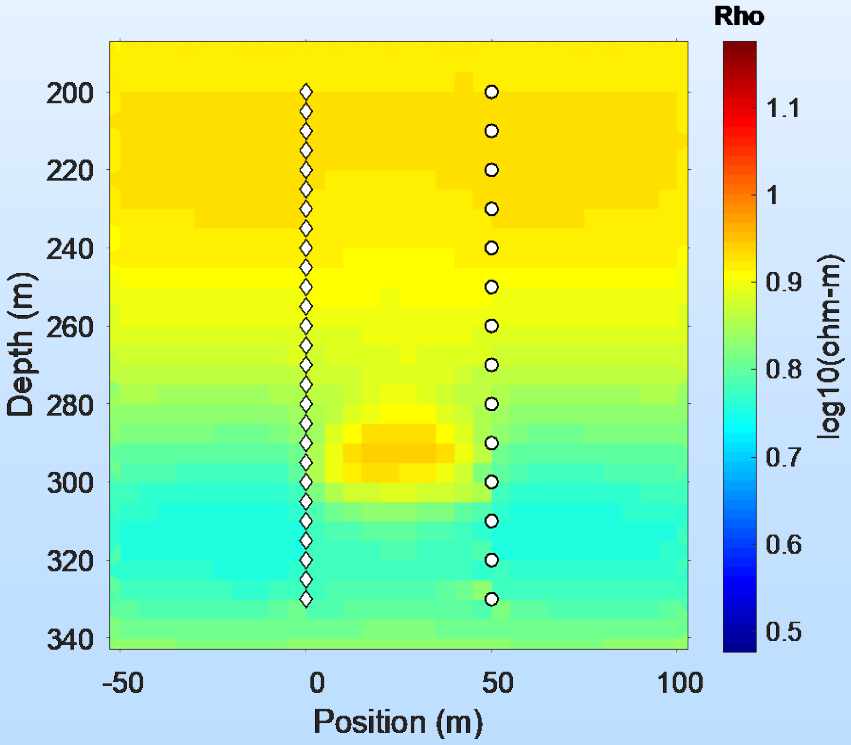
Difference

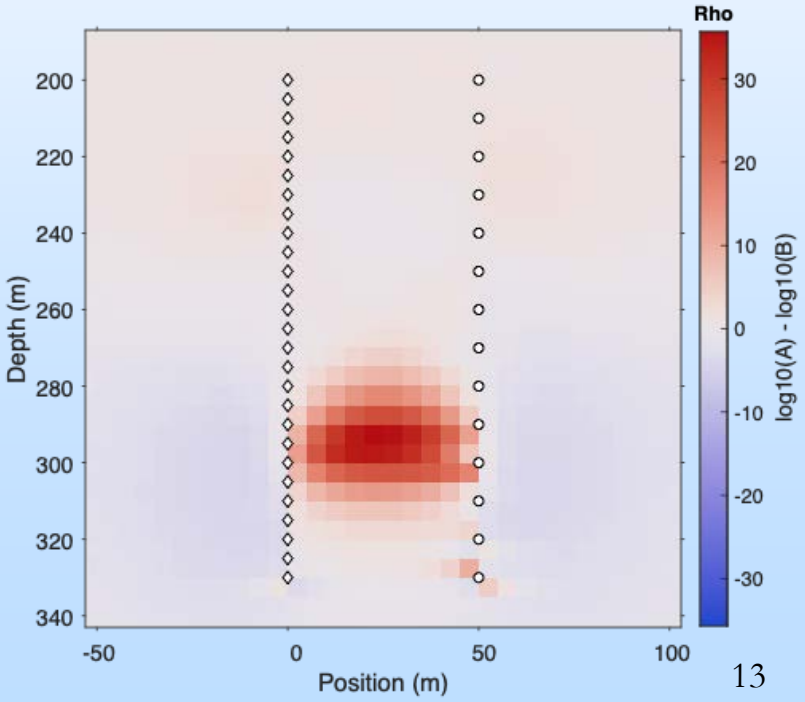
450 Hz Crosswell EM Simulation

- Uniform 8 Ohm-m Starting Model
- Preferential Lateral Smoothing and positivity



1 percent data fit





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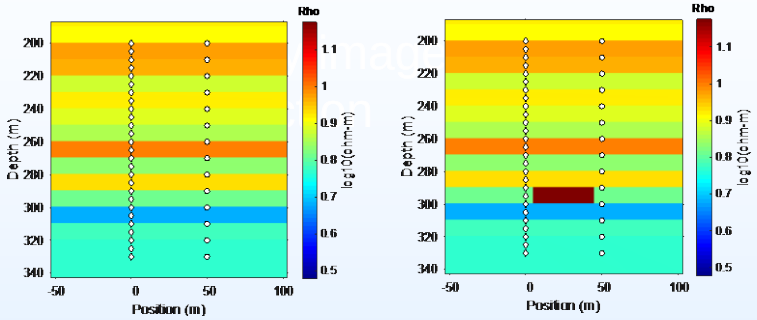

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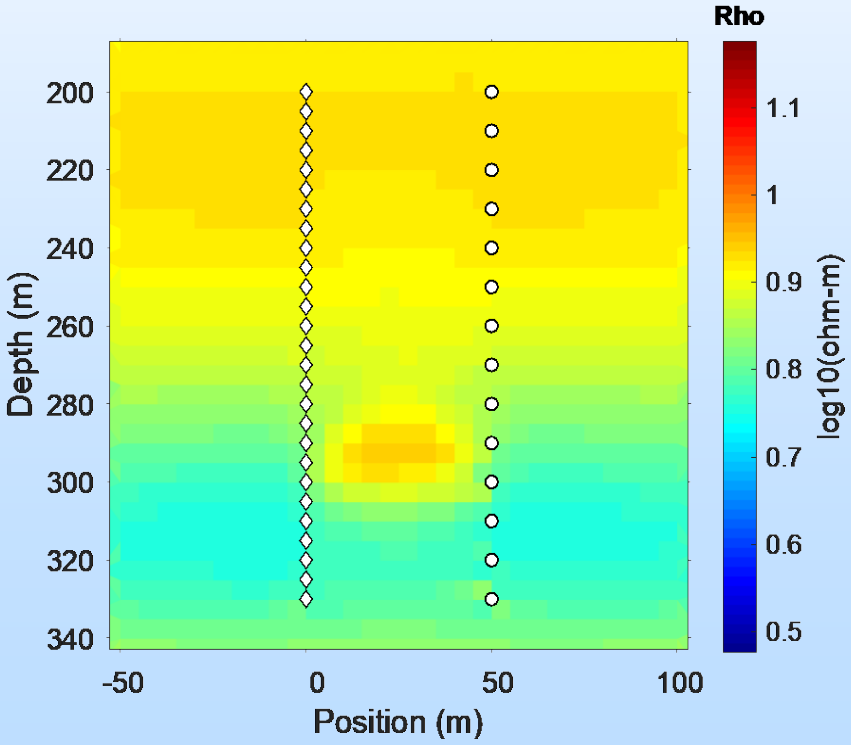
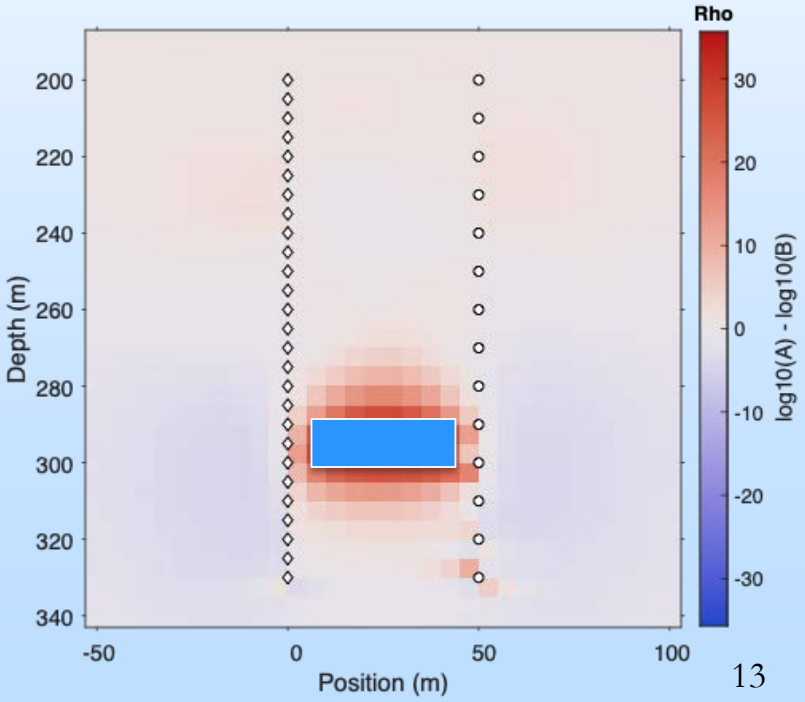


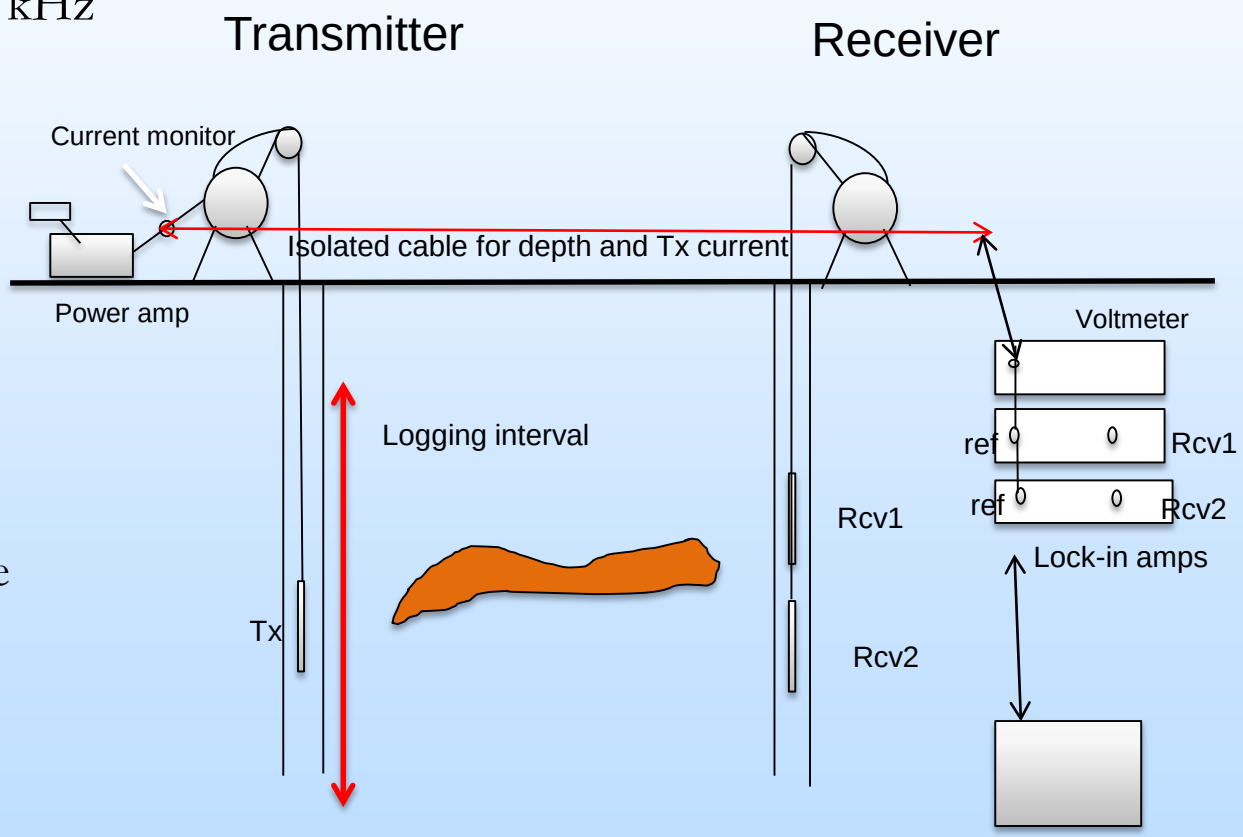


LBNL Crosswell EM System

Analog system (based on earlier LLNL hardware with new transmitter)

- Axial Tx and receivers (2 level)
- Frequency range 3 Hz-20 kHz

- Steel casing
  - High conductivity and magnetic permeability significantly attenuates signal
  - Currently the system can only handle one steel cased well occupied by the receivers
  - The transmitter must be deployed in a non-steel cased well



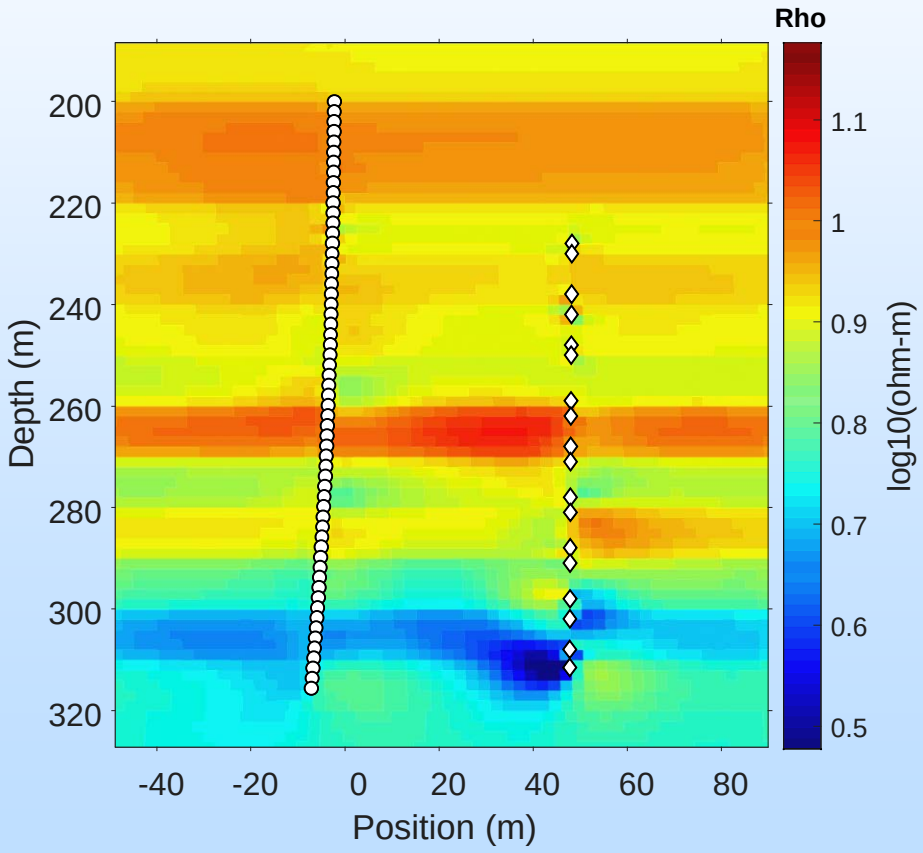
Baseline Crosswell EM Data Collection at CaMI

- A single fiberglass-steel well pair, spacing is 50m*
- Baseline (complete)
  - 200 Hz
  - 450 Hz (too noisy to use)

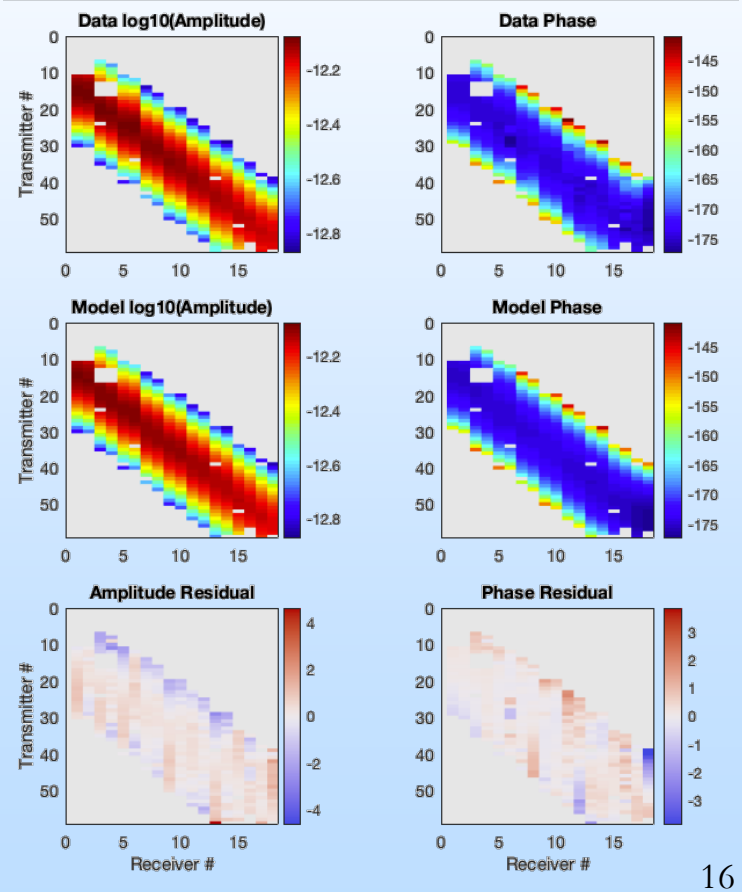
* Fiberglass well has electrodes mounted on outside of casing for ERT Survey, thus additional care must be taken in terms of transmitter data coverage

Recent Inversions with Deviation Corrections

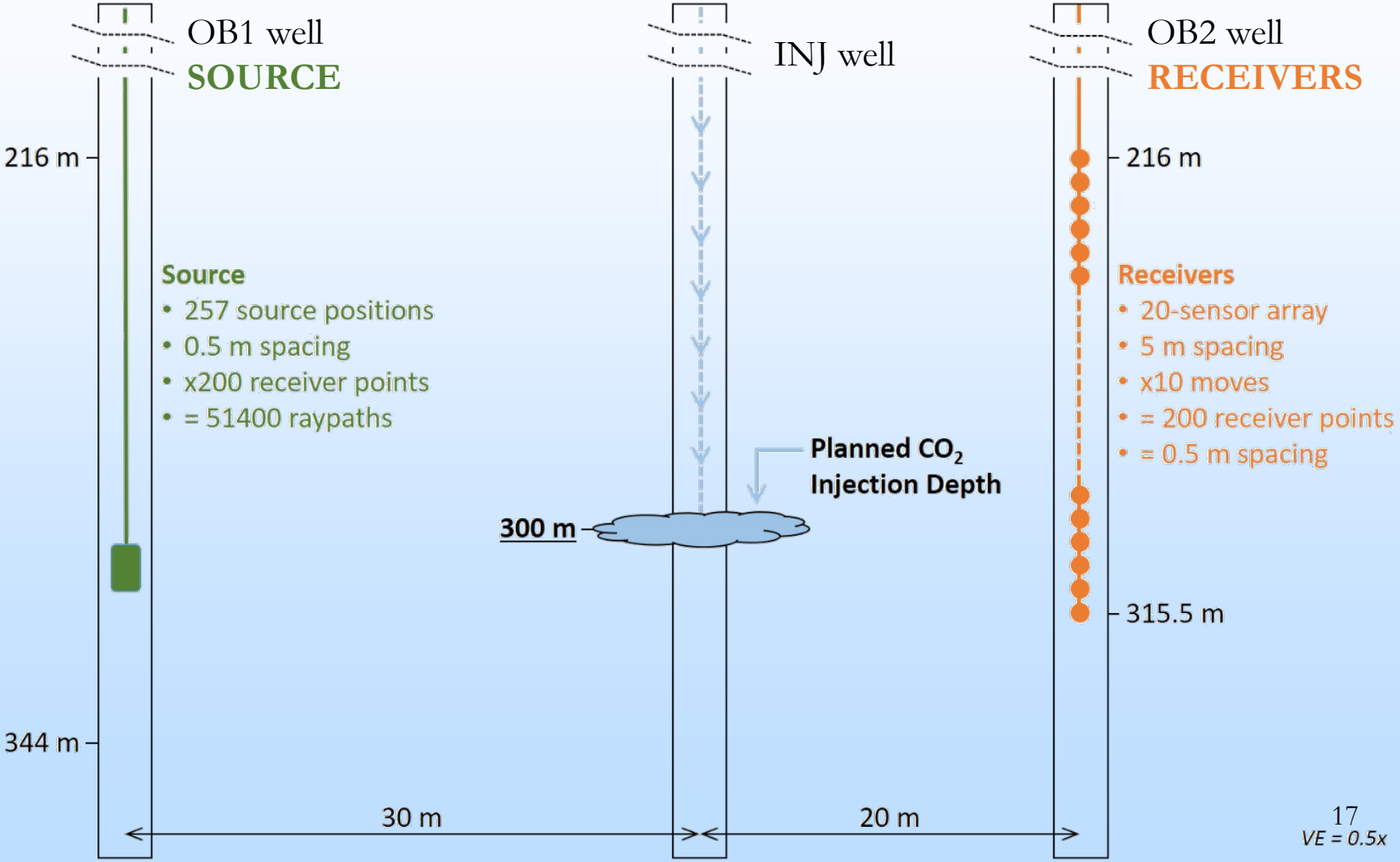
1D Model Start



Data and Misfit Errors

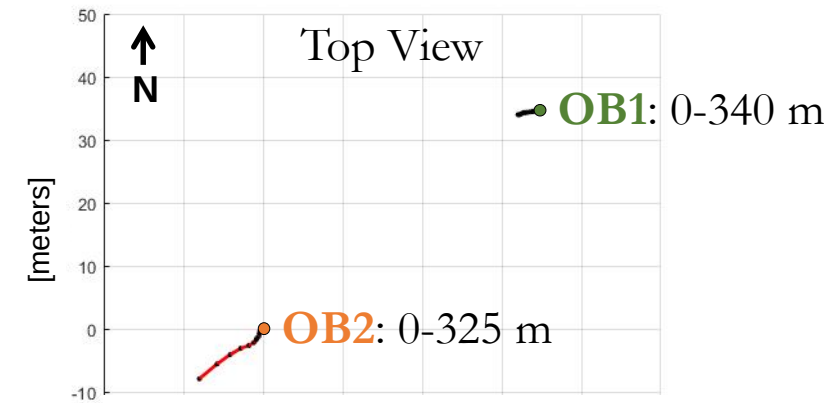


Crosswell Seismic Updates

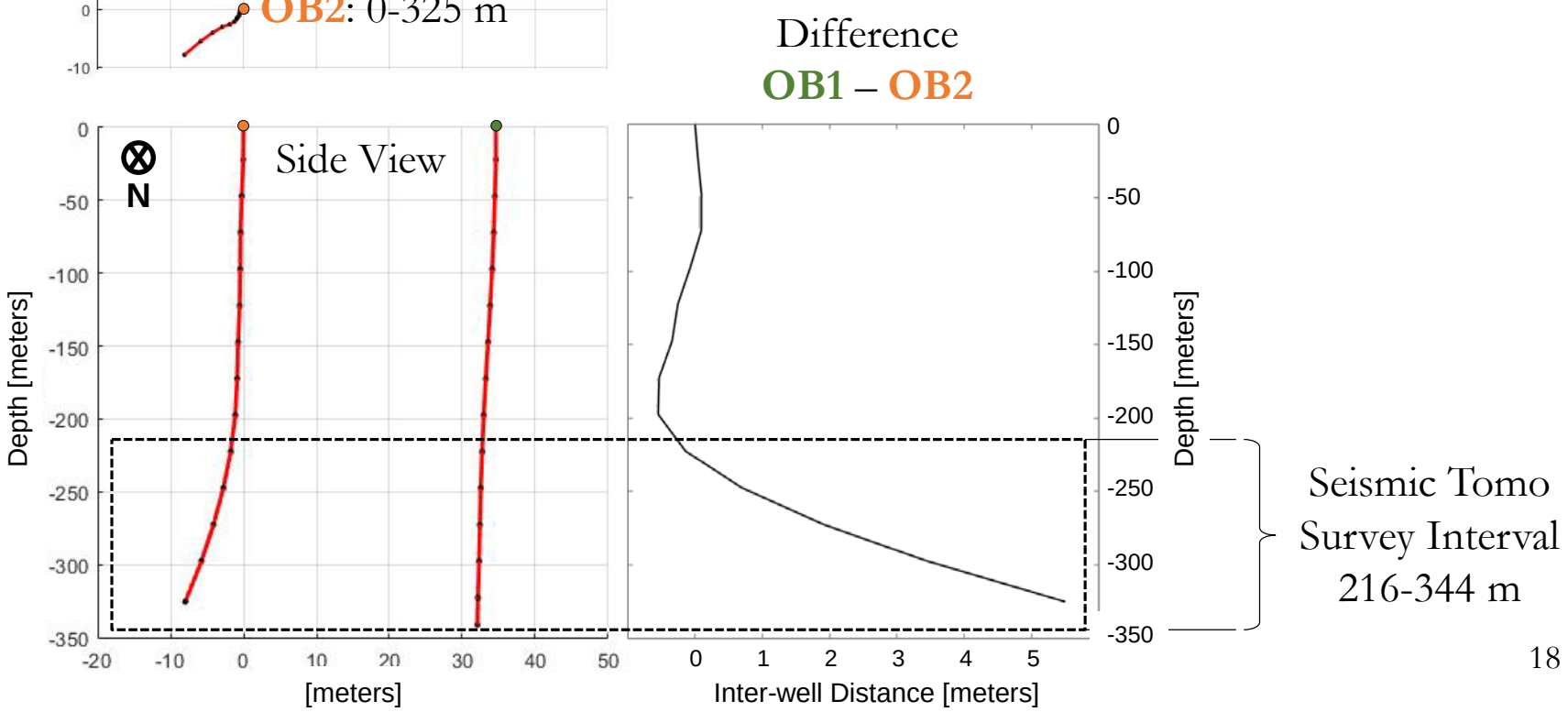


VE = 0.5x

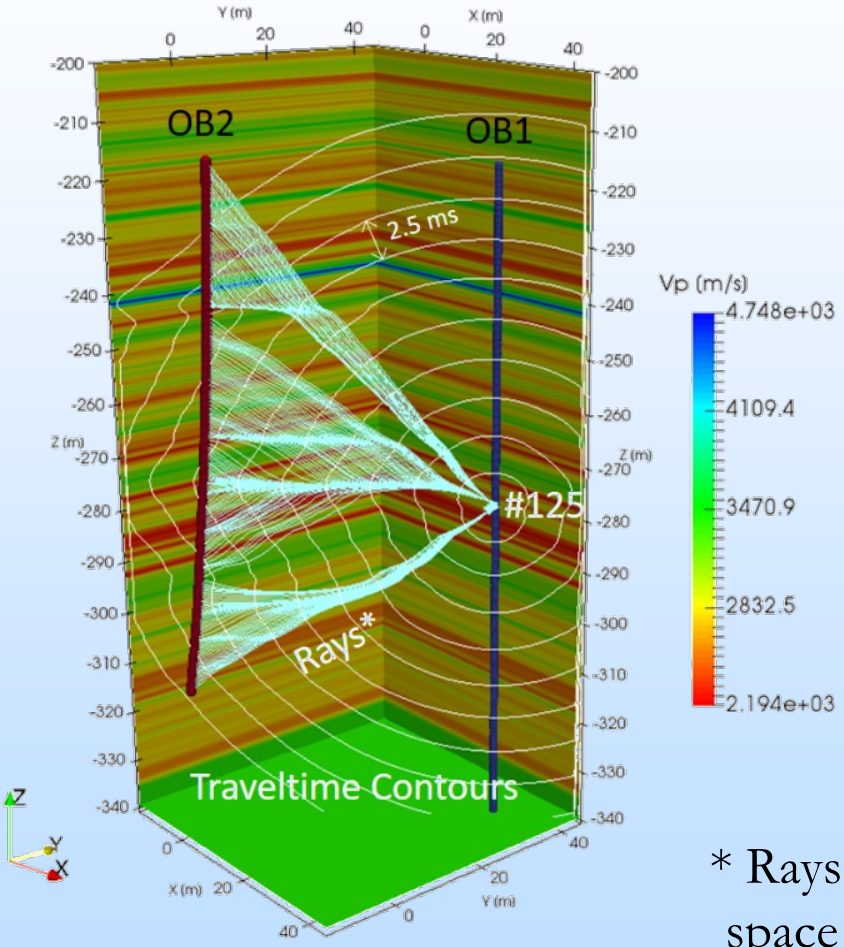
Crosswell Seismic Updates



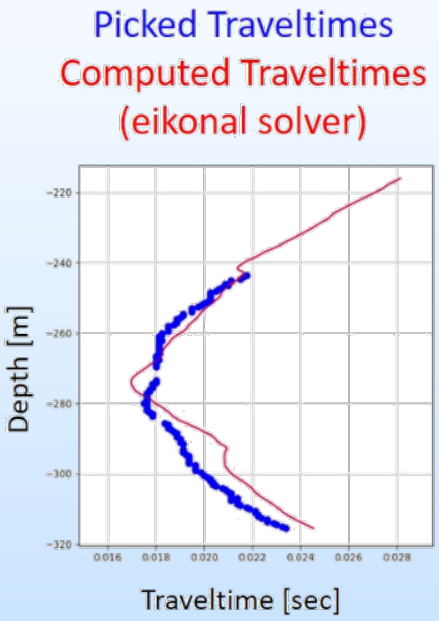
June 2019
Newly acquired Deviation Logs in OB1 and OB2

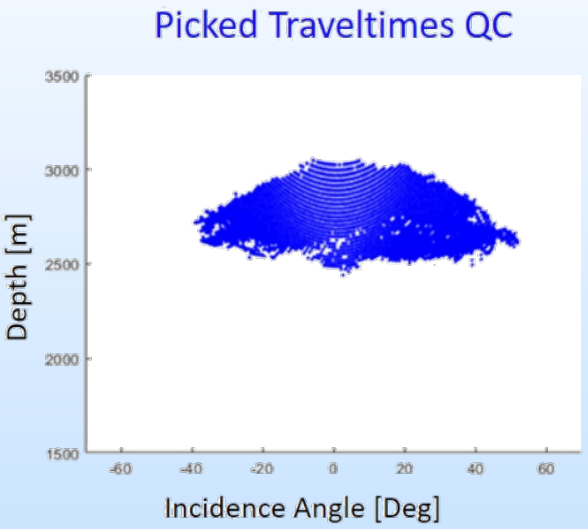


QC for Forward Modeling and Inversion



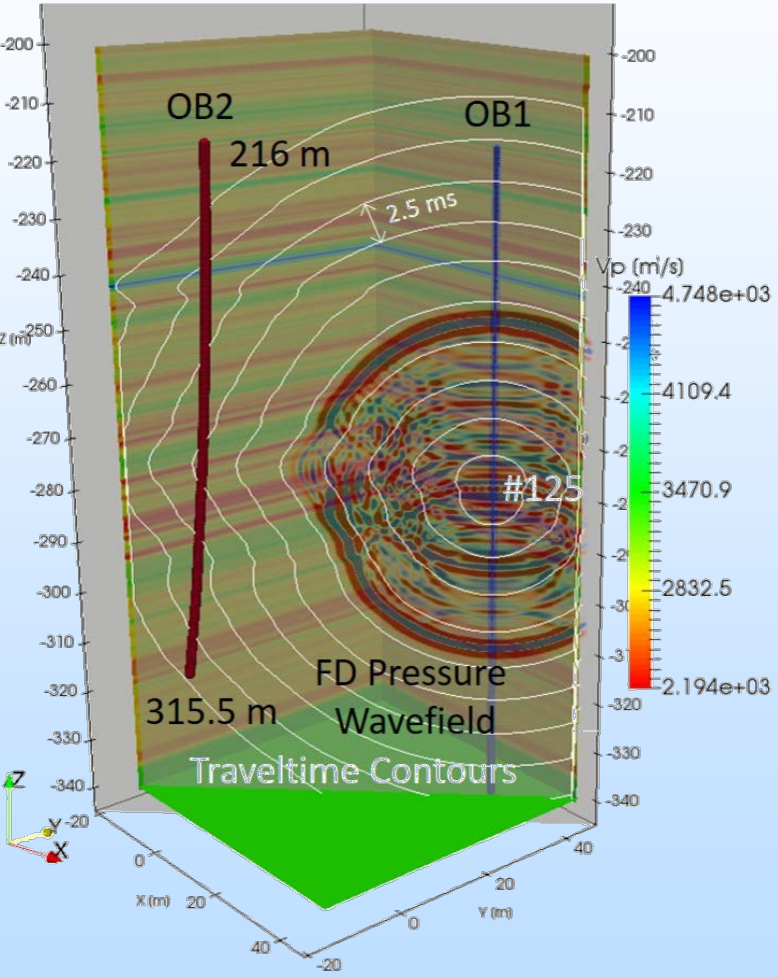
Seismic Traveltime Picks QC



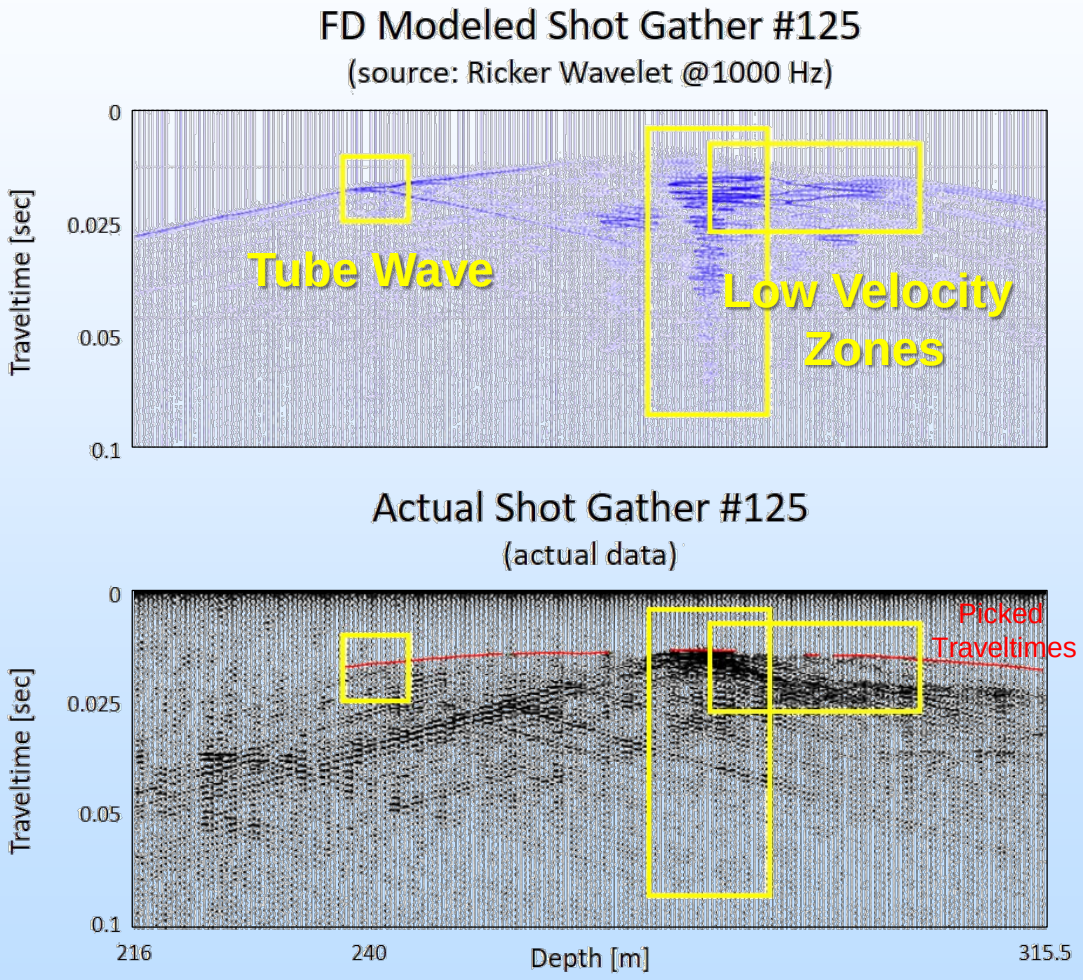


* Rays and traveltime contours: generated with O(3) space accurate fast sweeping FD (finite difference) eikonal code on staggered grid

QC for Forward Modeling and Inversion



Seismic Pressure Field



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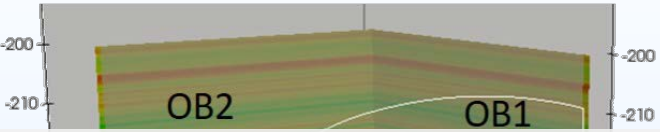
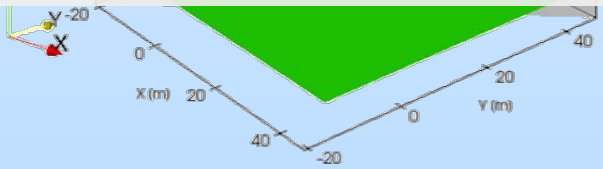
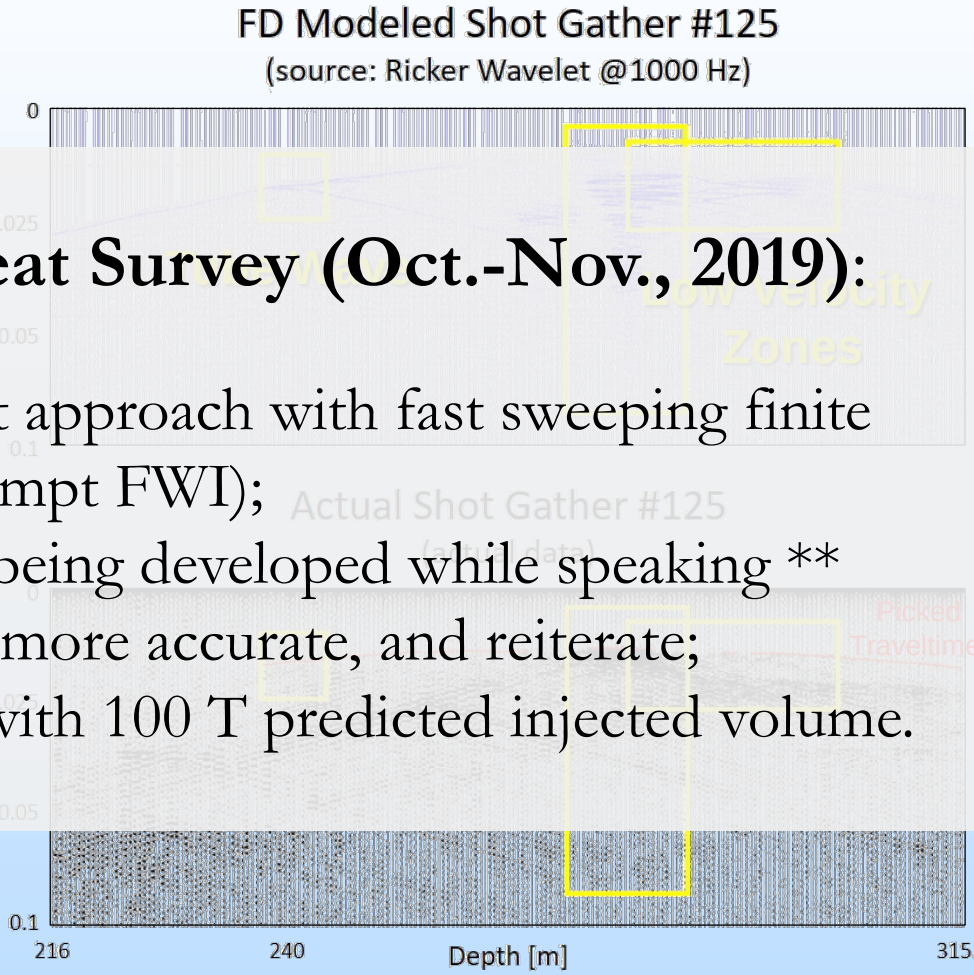




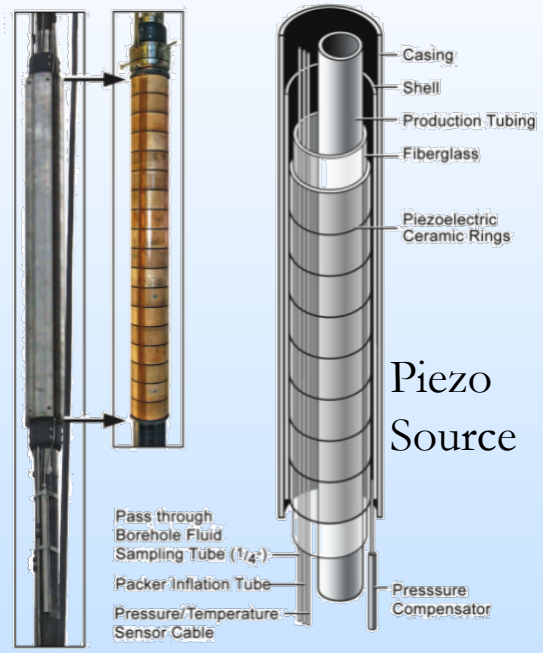


<u>BEFORE</u> Seismic Repeat Survey (Oct.-Nov., 2019):

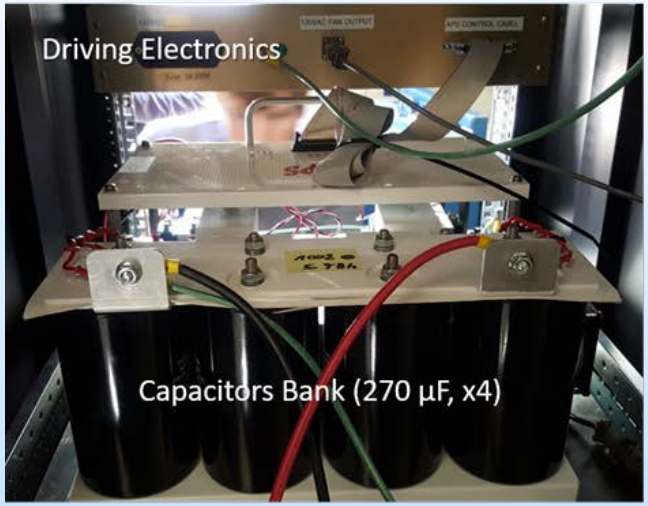
1) <u>Traveltime tomography</u>: adjoint approach with fast sweeping finite difference eikonal solver (+attempt FWI);
   ** Final Version of model being developed while speaking **
2) <u>Refine Earth Model</u> to make it more accurate, and reiterate;
3) Time-lapse CO_2 <u>simulation(s)</u> with 100 T predicted injected volume.

Crosswell EM and Seismic Technology Updates

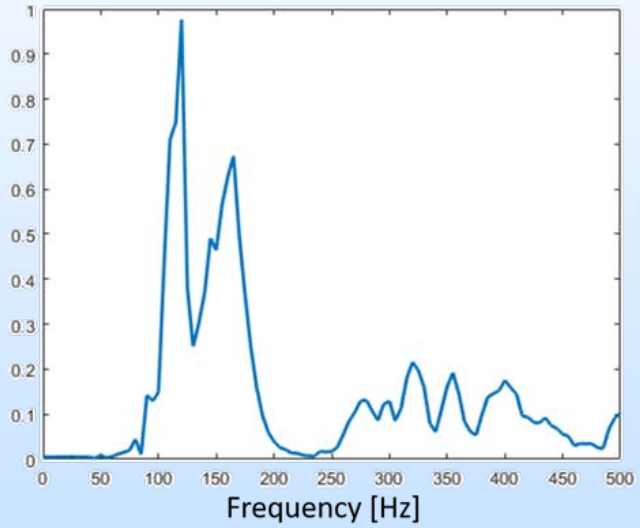
IGBT v2.0 Source Amplifier: 1) more power; 2) lower frequencies



High-Voltage IGBT Amplifier



Frequency Spectrum

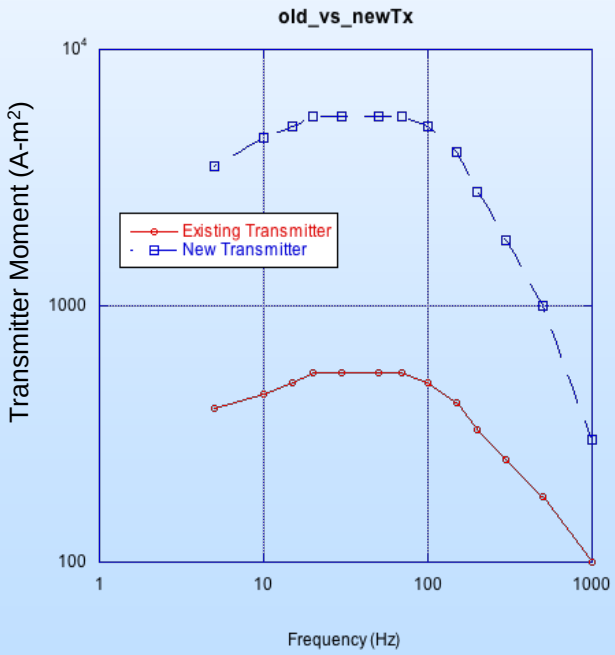


- Old Technology: 100s Hz
- IGBT v2.0: < 200 Hz

IGTB v2.0 – Insulated-Gate Bipolar Transistor – operates piezo source at higher power and lower frequencies, necessary for integrating with DAS and working at longer distances

New Amplifier used also as EM Source

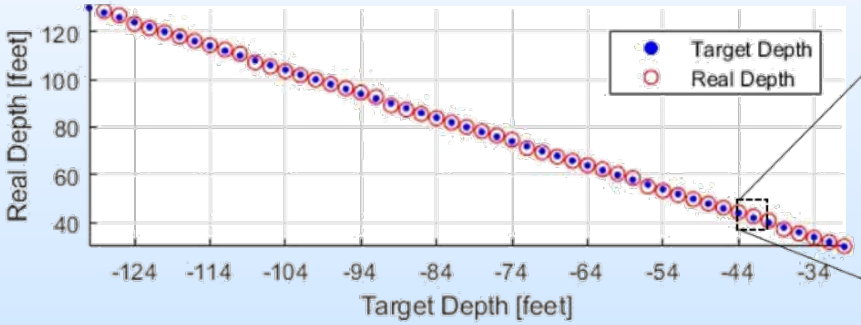
- When coupled with new antenna it produces much stronger moment
- Seismic and EM systems operate from same logging vehicle using same cable



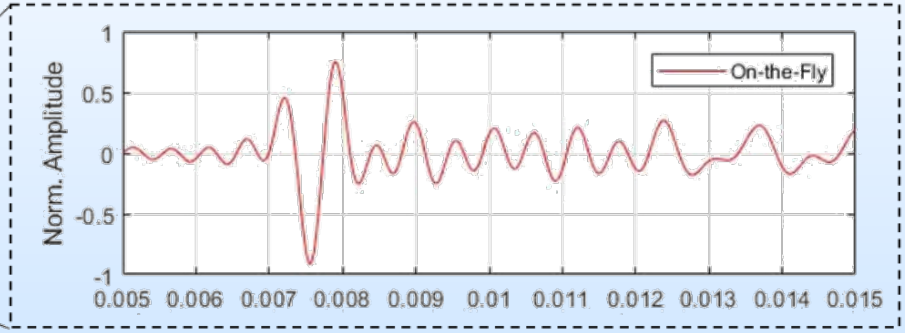
Optimized Seismic Acquisition

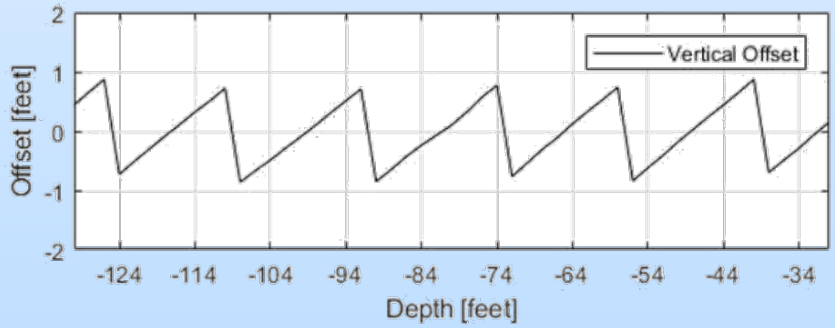
On-the-Fly seismic Acquisition : 1) 37% less time; 2) less stress on the wireline system

Depth coverage:
● target vs ◯ actual depth

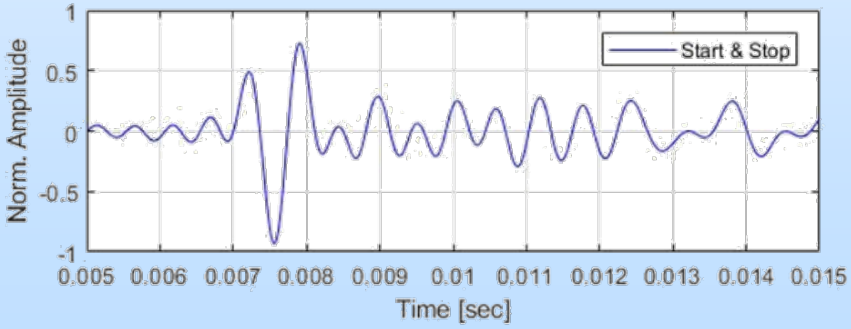


Trace acquired with On-the-Fly strategy:
Repeatability error = 0.002 milliseconds





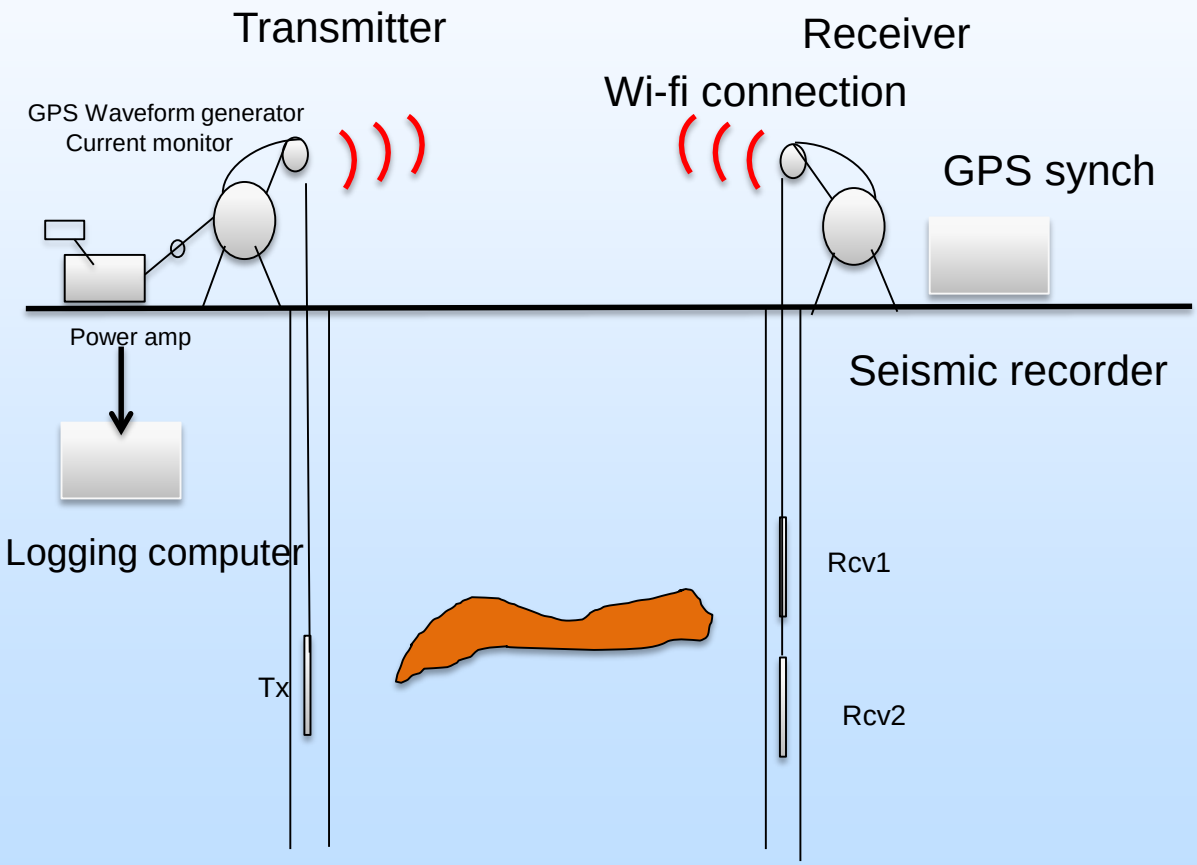
Offset between target and actual depth:
always within calculated boundaries



Trace acquired with
Start&Stop strategy

Crosswell EM System now Uses fully independent Tx and Receiver Sections

- GPS synch and wifi/link provides full TX, Rx isolation
- Battery powered seismic recorder can also provide for continuous precision monitoring
  - Continuous active source EM (CASEM)



CaMI-FRS Updates: Aug.2019

- 18 Tonnes of CO_2 injected to date (Aug. 2019)
- Injection will stop for 4-5 days (beginning of September) to change pump
- With newly installed (high-power) pump, injection will be continuous @0.5 Tonnes/day rate (no need for any extra step-up/down testing: all tests passed)
- ERT system is currently recording (daily measurement since July 2019)
- Added new industrial sponsor, Petronas to the current four (Total, Equinor, Chevron, Shell)

Next Steps

- First repeat surveys at CaMI-FRS, Oct.20 - Nov.1, 2019: Seismic and EM crosswell campaigns (EM collected at 10 Hz and 450+ Hz)
- Seismic crosswell test with DAS
- Joint inversion:
  - EM with ERT and STB in single physics approach
  - Crosswell seismic with EM in a joint-fluid flow approach

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
    Highlight: new HV amplifier, capable of low frequencies <100 Hz → acquire crosswell DAS

Accomplishments to Date

- Collaboration with CMC/CaMI on field site development and monitoring program
- 2nd generation source amplifier towards fully-integrated EM-Seismic acquisition and recording system (raised TRL)
- EM: new transmitter; inversion of baseline dataset with updated deviation logs; forward modeling for repeat survey design
- Seismic: development of poro-elastic, anisotropic inversion + modeling code; preliminary QC on forward modeling for repeat survey design; optimized acquisition strategy

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

- Carbon Management Canada (CMC) Containment and Monitoring Institute (CaMI) Field Research Station (FRS)

- We thank CMC Research Institutes Inc. for access to the CaMI Field Research Station 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 Don Lawton (University of Calgary).

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

- **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)

Gantt Chart

Task	Milestone Description*	Fiscal Year 2019				FY20	Planned Start	Planned Completion Date (Reporting	Actual Start	Actual End	Comment (notes, explanation of deviation from plan)
		Q1	Q2	Q3	Q4		Date	Date)**	Date	Date	
Milestone 2-1 (A)	SOV/DAS automated data processing algorithms and workflows			x			10/1/2018	6/30/2019 (7/31/2019)			AOP Tracked
Milestone 2-2 (B)	Data report on SOV/DAS baseline surveys and initial testing of 2nd Gen SOV				x		10/1/2018	9/30/2019 (10/31/2019)			
Milestone 2-3 (C)	Data acquisition and analysis covering monitoring period					Q1	10/1/2018	12/31/2019 (1/31/2020)			
Milestone 2-4 (D)	CO_2 plume detection - difference of DAS/SOV surveys					Q2	10/1/2018	3/31/2020 (4/30/2020)			
Milestone 3-1 (A)	Forward modeling based on baseline EM and Seismic datasets using a sequential approach and current LBNL simulation code				x		3/1/2019	9/30/2019 (10/31/2019)			
Milestone 3-2 (B)	Cross-well EM and Seismic Repeat Surveys acquisition					Q2	11/1/2019	3/31/2020 (4/30/2020)			
Milestone 3-5 (C)	Surface-to-Borehole EM Repeat Survey acquisition					Q2	11/1/2019	3/31/2020 (4/30/2020)			
Milestone 3-4 (D)	EM and Seismic feasibility tests for continuous active monitoring during injection (CASSM, CESM)					Q3	11/1/2019	6/30/2020 (7/30/2020)			
Milestone 4-1 (A)	Sonde testing plan development and test-cell fabrication plans. Planned Completion (Reporting) date: Q3 6/30/19 (7/31/19)			x			3/1/2018	6/30/19 (7/31/19)			
Milestone 4-1 (B)	Results of testing of high sensitivity sensor. Planned Completion (Reporting) date: Q4 9/30/19 (10/31/19)				x		3/1/2018	9/30/19 (10/31/19)			
Milestone 4-1 (C)	Report on deployment of sonde in deep well. Planned Completion (Reporting) date: Q3 6/30/20 (7/31/20)					Q3	11/1/2019	6/30/20 (7/31/20)			
Milestone 4-2 (D)	Sensitivity analysis of the high-sensitivity sonde and comparison with baseline technology; outline of tech-to-market pathway for new technology. Planned Completion (Reporting) date: Q4 9/30/20 (10/31/20)					Q4	11/1/2019	9/30/20 (10/31/20)			
Milestone 5-1 (A)	In-situ assessment of the mechanical coupling between formation, cement, fiber and casing			x			4/22/2019	6/30/19 (7/31/2019)			

Gantt Chart (continued)

Task	Milestone Description*	Fiscal Year 2019				FY20	Planned Start Date	Planned Completion Date (Reporting Date)**	Actual Start Date	Actual End Date	Comment (notes, explanation of deviation from plan)
		Q1	Q2	Q3	Q4						
Milestone 5-2 (B)	Data collection (DSS, P, T) from 01/01/2019 to 01/05/2019			x			4/22/2019	6/30/19 (7/31/2019)			
Milestone 5-3 (C)	Calibration of the hydraulic properties of our numerical model				x		6/30/19	9/30/19 (10/31/2019)			
Milestone 5-4 (D)	Data collection from 01/05/2019 to 01/12/2019				x		9/1/19	9/30/19 (10/31/2019)			
Milestone 5-5 (E)	Comparison with measurements made by the RITE institute using different technology Planned					Q1	TBD	12/31/19 (1/31/2020)			
Milestone 5-6 (F)	Lessons learn on: existing cables design, deployment technology and technology to be used					Q2	TBD	3/31/20 (4/30/2020)			
Milestone 5-7 (G)	Geomechanical numerical simulation using Cami field data					Q2	TBD	3/31/20 (4/30/2020)			
Milestone 5-8 (H)	Development of a new optical cable (TRL4).					Q3	TBD	6/30/20 (7/31/2020)			
* No fewer than two (2) milestones shall be identified per calendar year per task (per previously separate project)											**Note: Milestone reporting accompanies quarterly report, one month after end of quarter.

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