CCSMR Task 3: Joint crosswell seismic and EM monitoring of a shallow subsurface CO2 injection

Project Number LBNL-ESD14095

David Alumbaugh*, Stanislav Glubokovskikh, Edward Nichols, Michael Wilt and Tom Daley, LBNL
Kerry Key, Columbia University, NY
David Myer, Myer Consulting, San Diego, CA

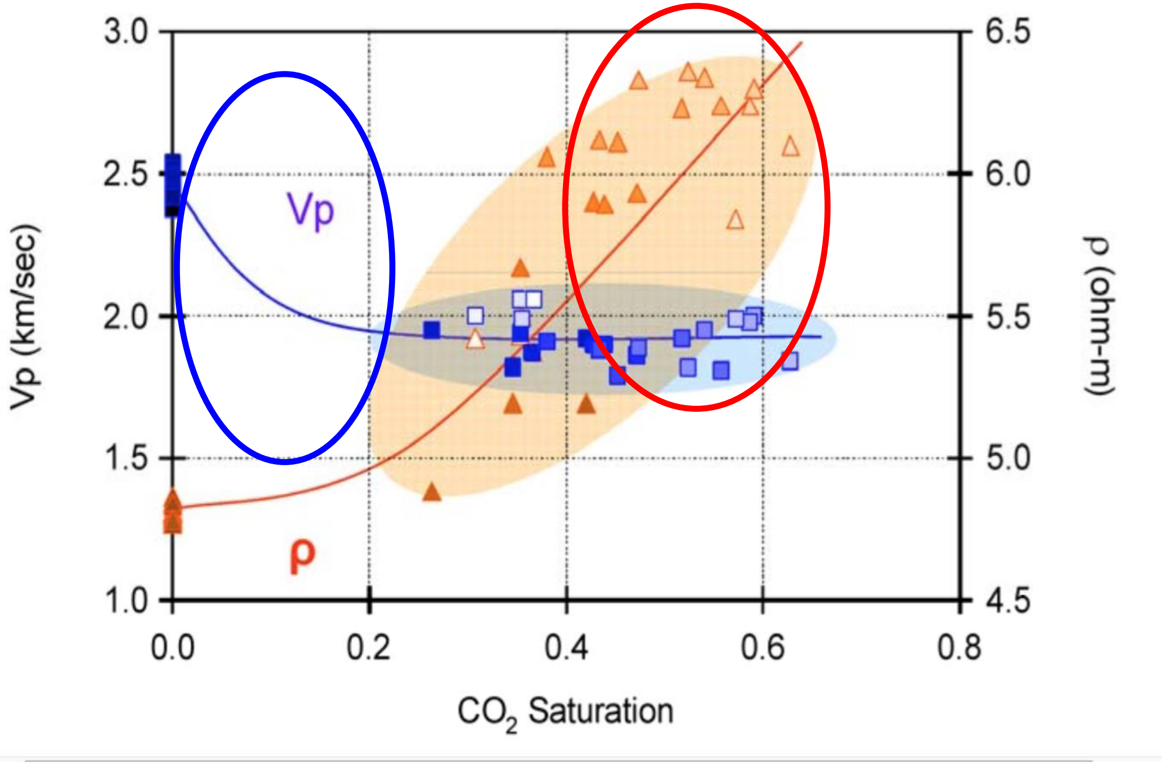
In Collaboration With
Don Lawson, Greg Maidment, Marie Macquet - University of Calgary, Carbon Management Canada CaMI
Michael Jordan – SINTEF, Norway

Background of Crosswell Methodologies

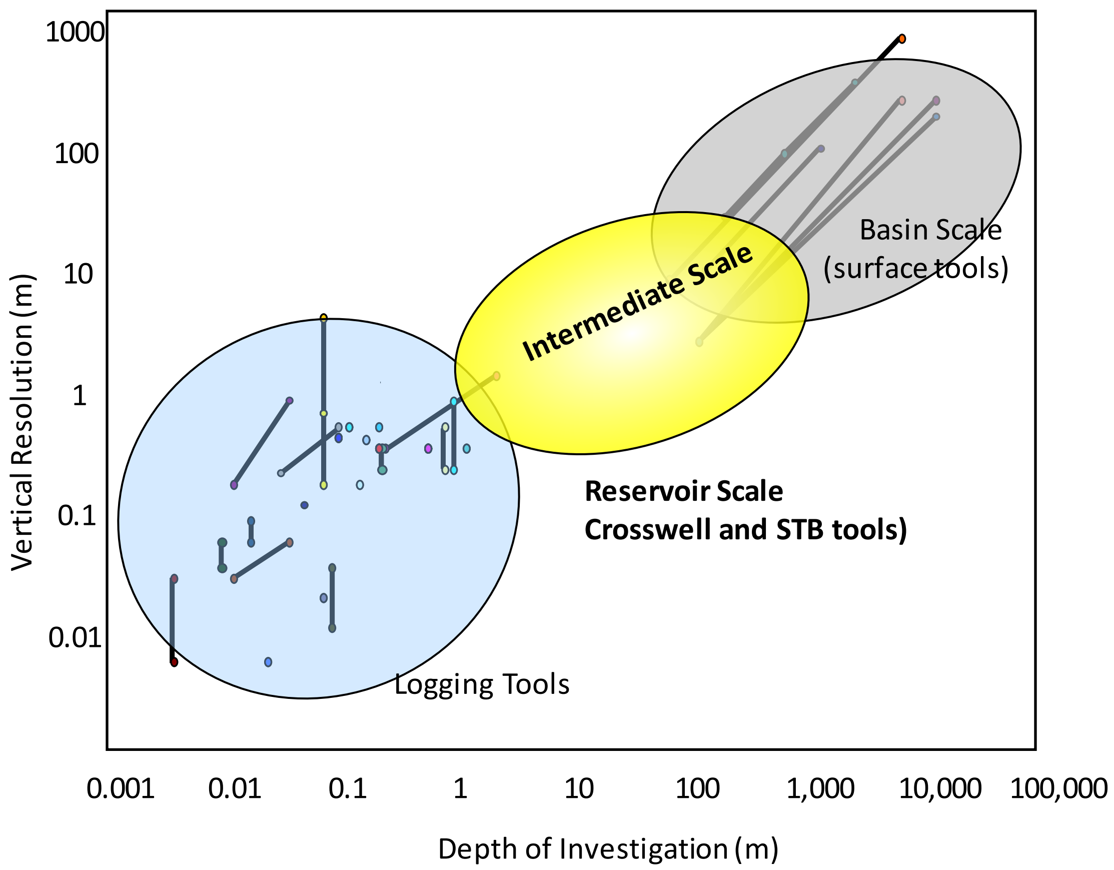
Why joint seismic and EM?

Boundary
And Leakage
Detection

Plume Body
Monitoring

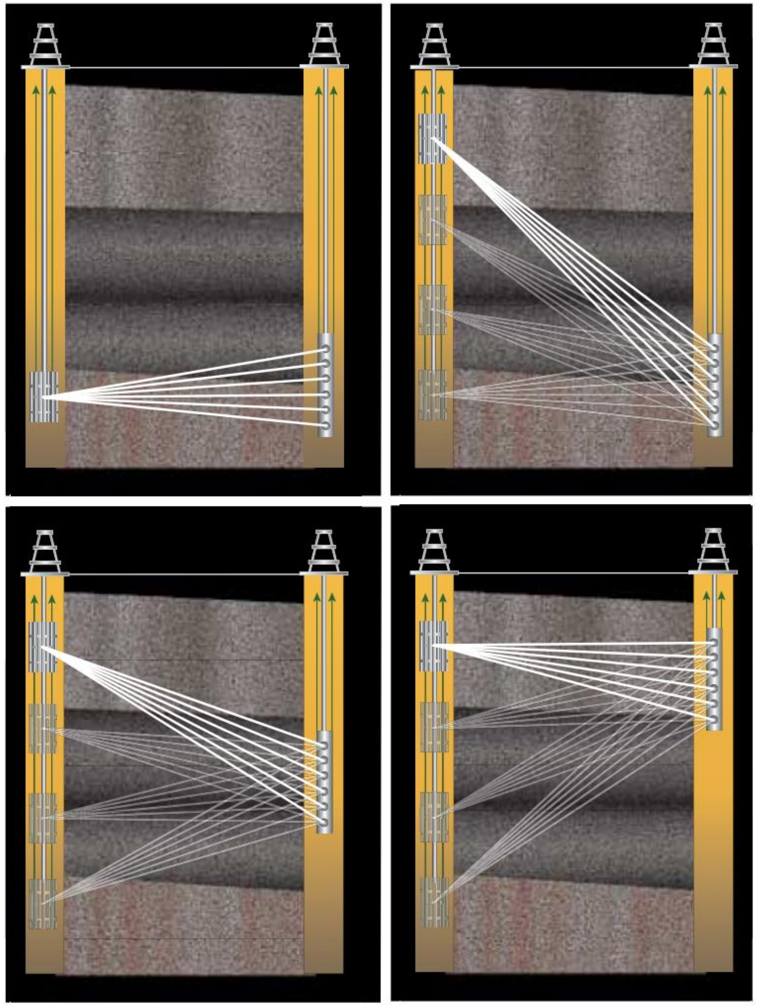


Why Crosswell?

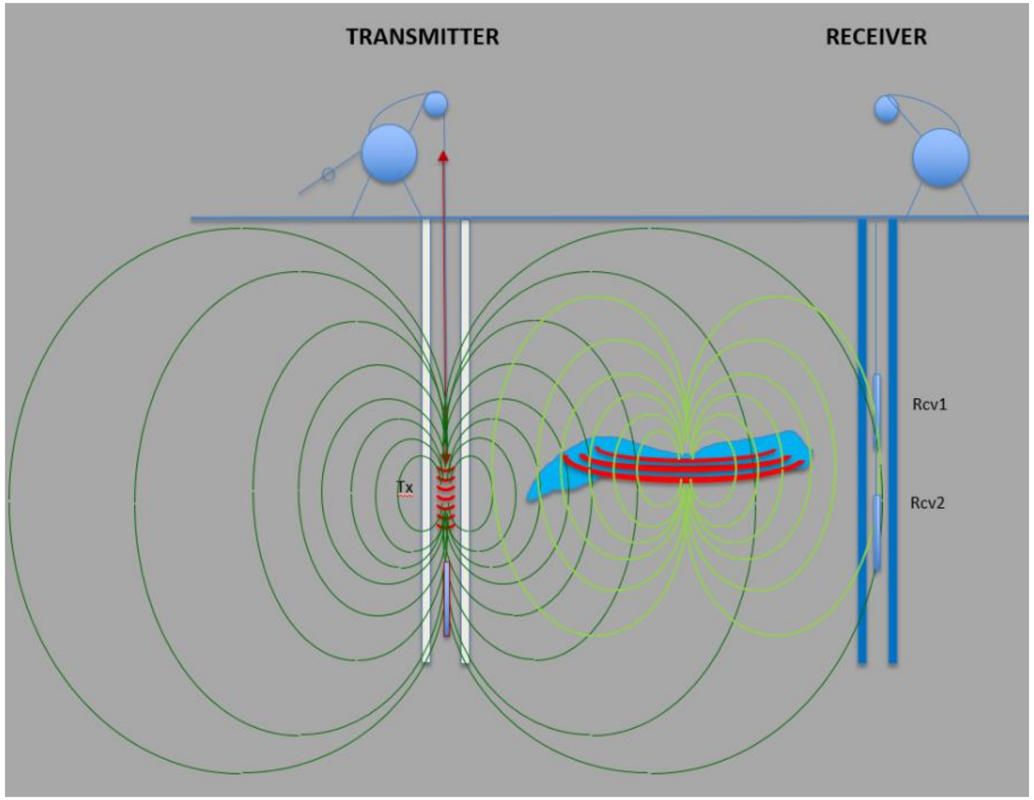


Background of Crosswell Methodologies

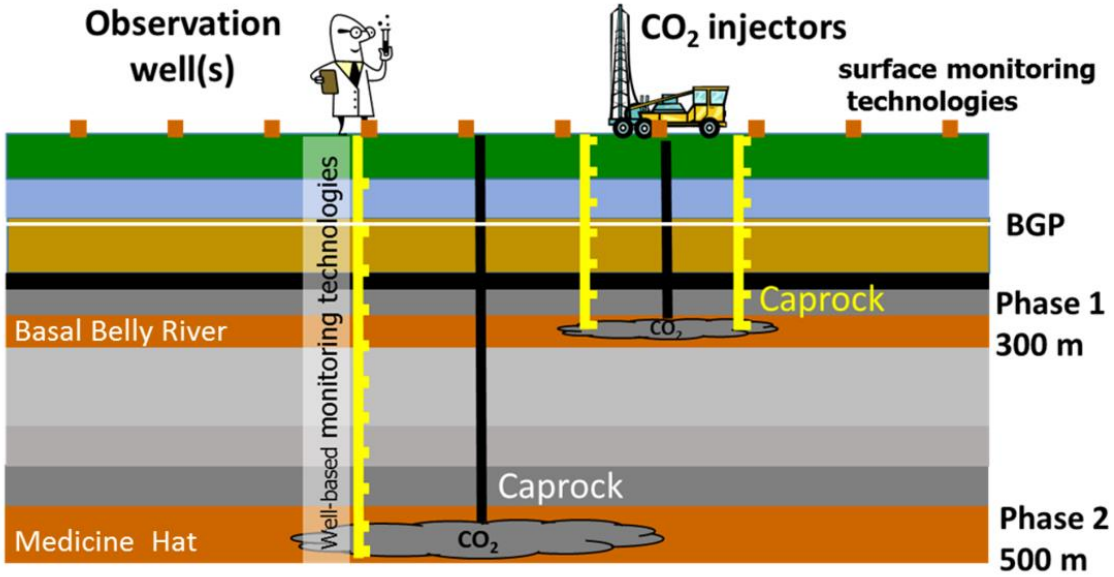
Crosswell Seismic Acquisition



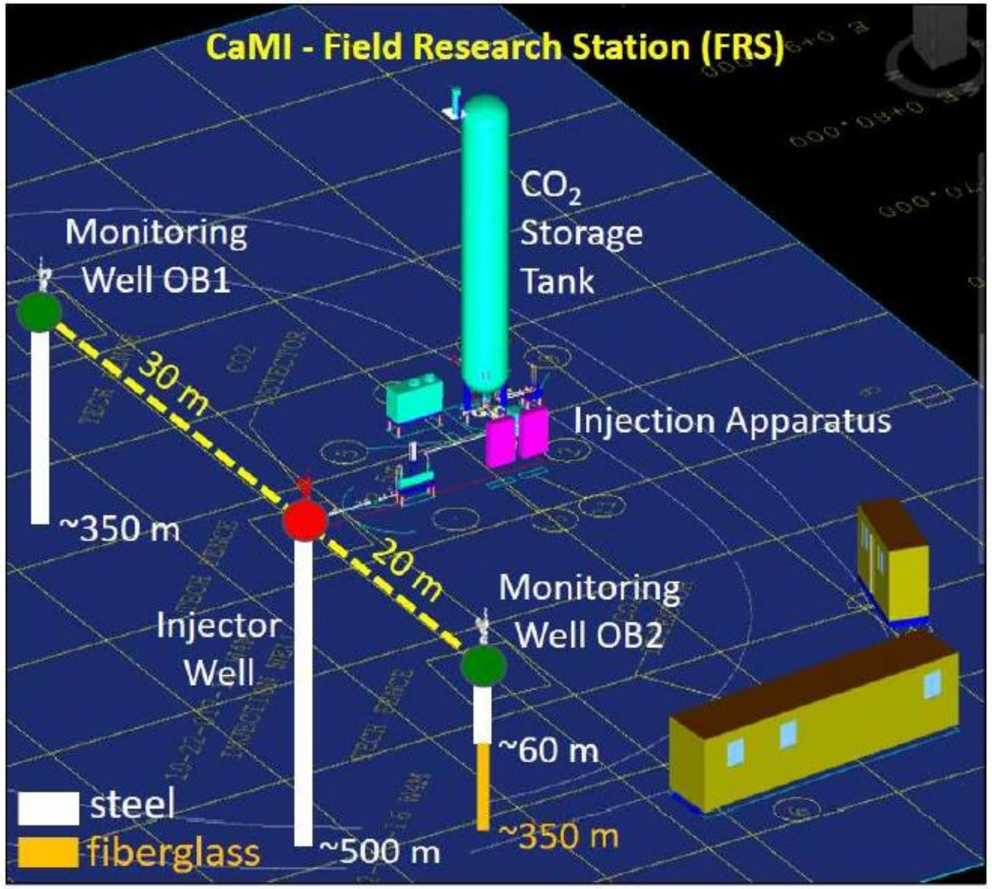
Crosswell EM Acquisition



Containment and Monitoring Institute Field Site



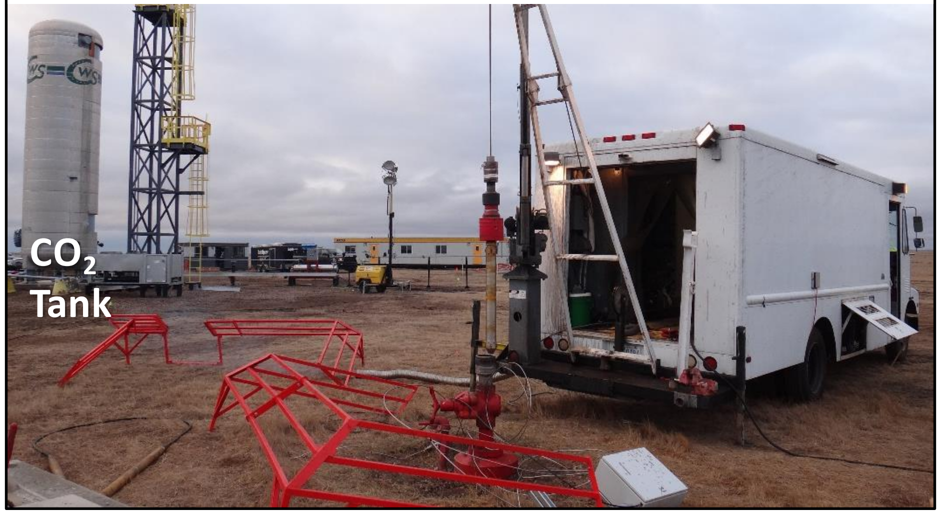
In general, the CaMI-FRS site has layered geological structures.



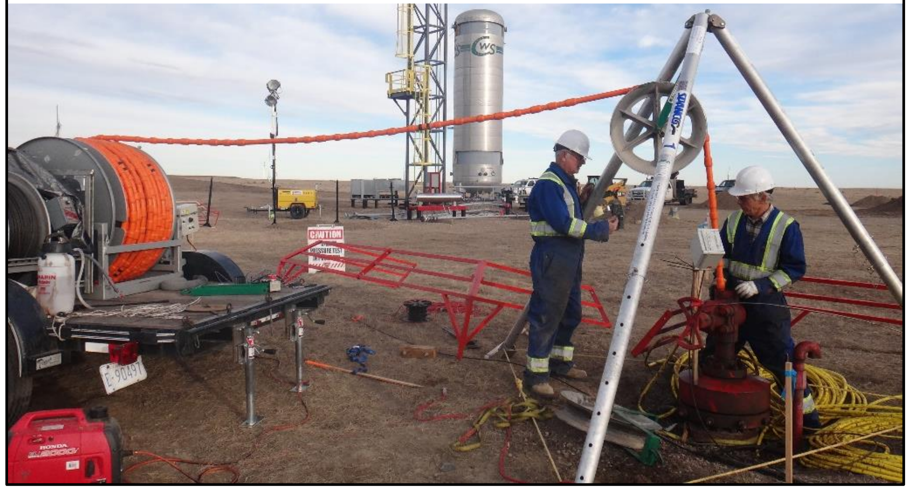
Transmitter well (Monitoring Well OB2) is highly deviated.
OB1 is steel-cased, whereas OB2 is open-well (fiberglass).

2017 Crosswell baseline Survey

Piezoelectric source deployment in Well OB1



Hydrophone sensors deployment in Well OB2



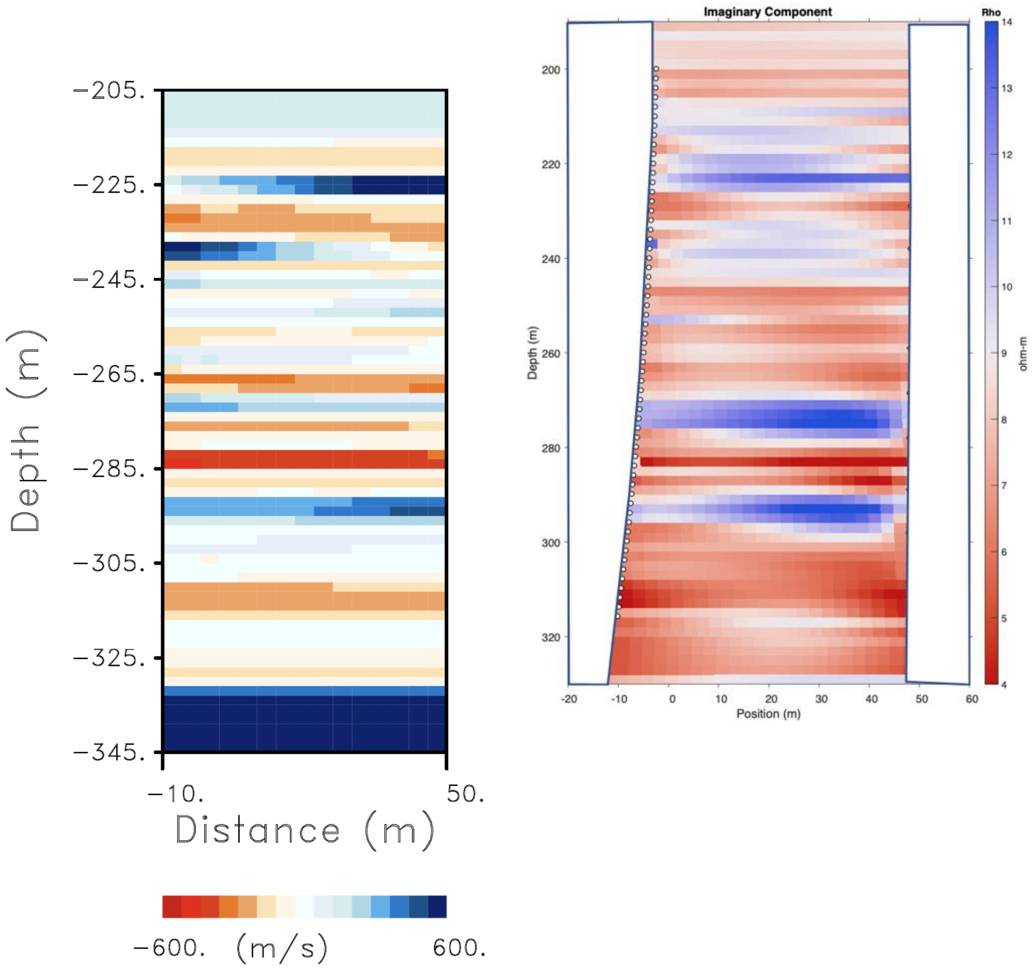
Magnetic source deployment in Well OB2

Dual Sensor EM string

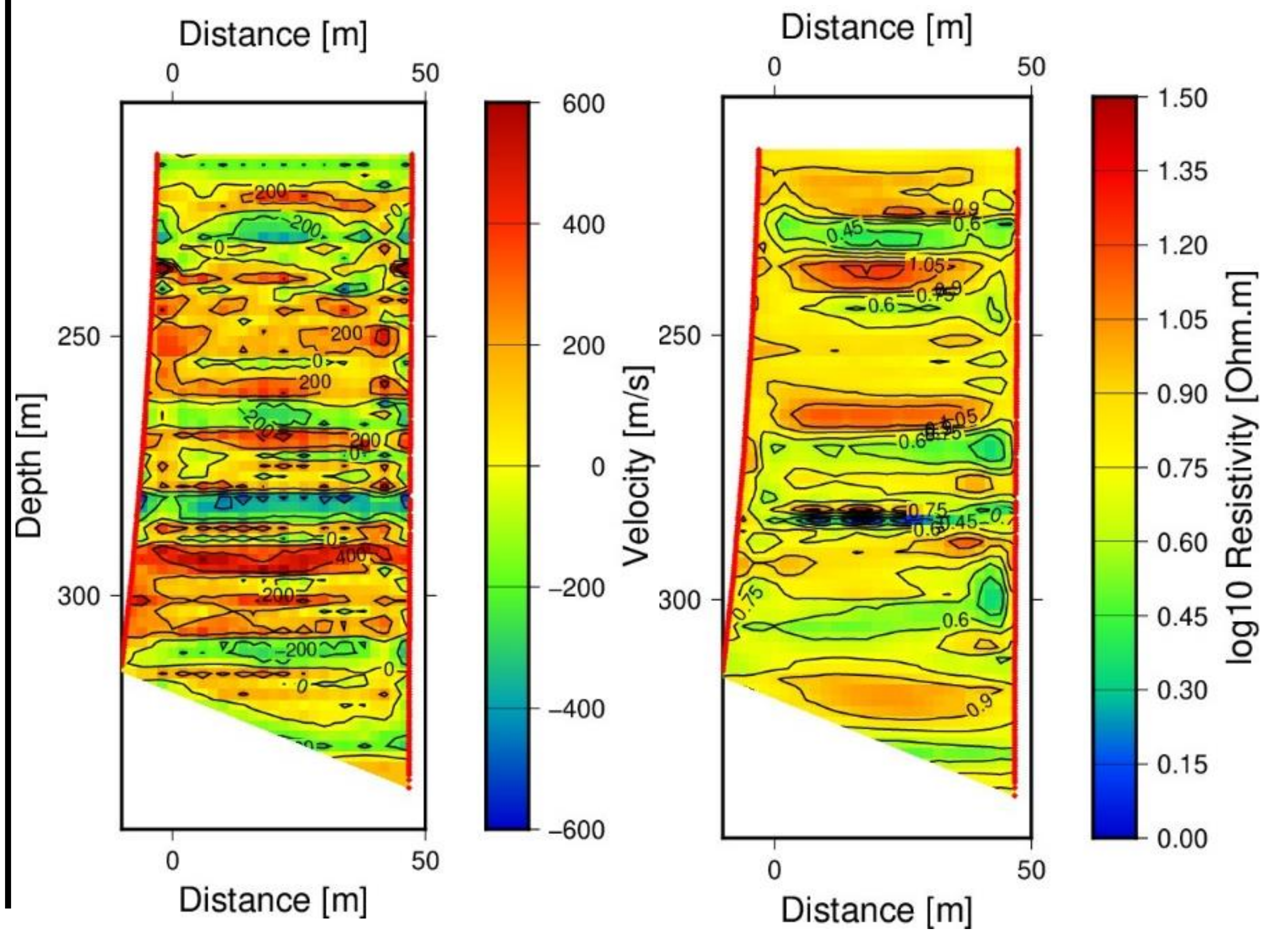
Magnetic receiver deployment in Well OB1

Inversion Results of Baseline Crosswell Data

Separate Well-Log Constrained Inversions



Joint Cross-Gradient Constrained Inversions

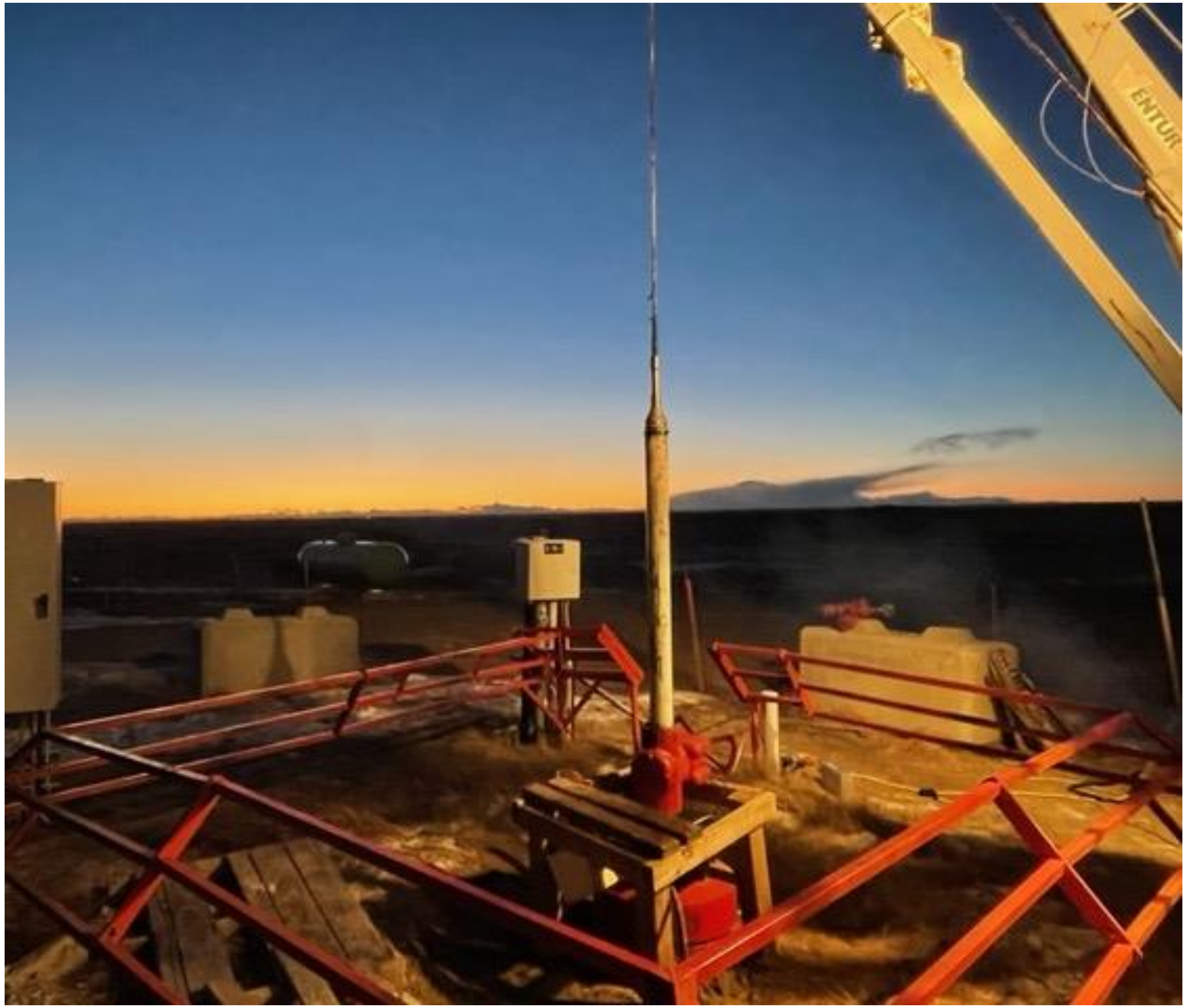


Provided by Michael Jordan of SINTEF, Norway

2021 Crosswell EM and Seismic Data Acquisition and Processing

(Delayed 1.5 years by COVID19 Border Closure)

2021 Crosswell Data Acquisition

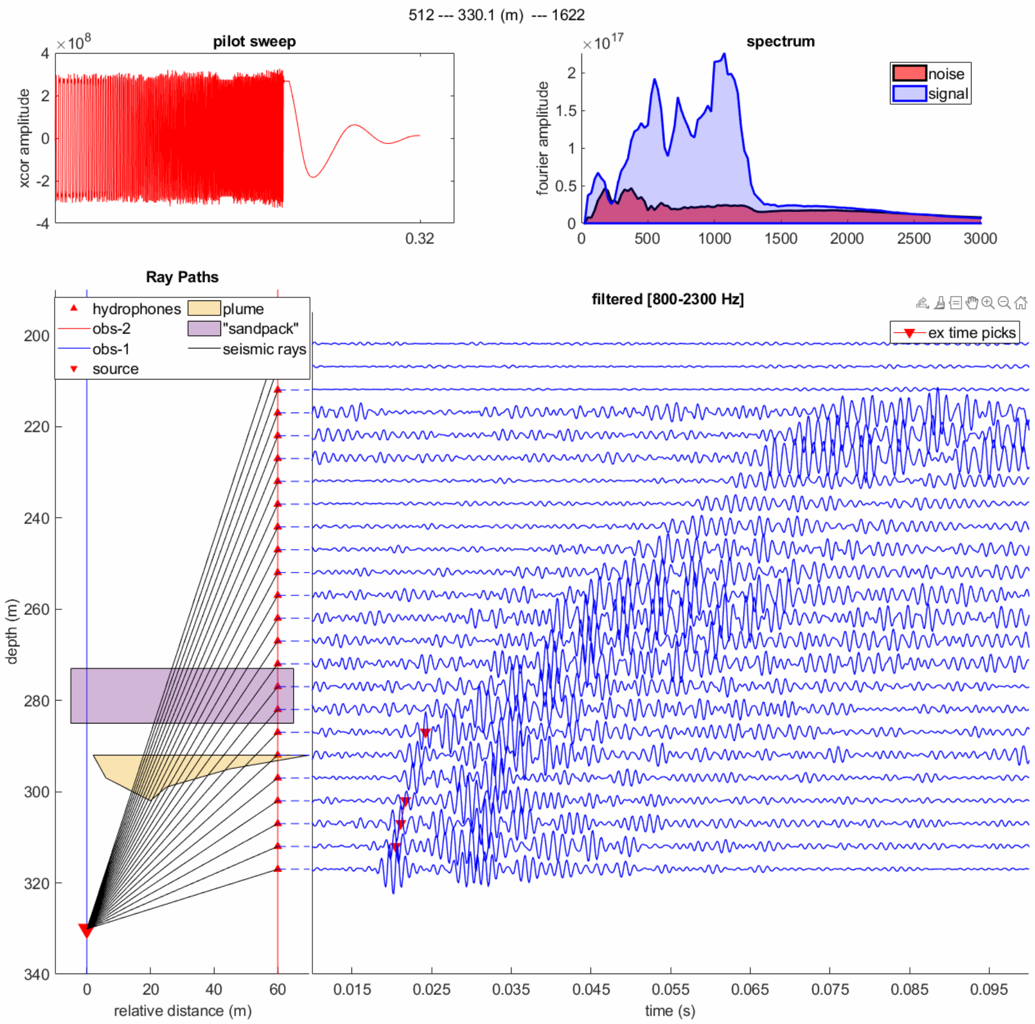


Crosshole Seismic Data Acquisition Schedule

- December 06, 2021:
  - Arrived at the site in the morning, deployed the piezoelectric source in OBS1 in the afternoon and run several QC shots
  - Hydrophone string cannot be deployed in OBS2, **borehole fluid froze**
- December 07, 2021:
  - Deployed the hydrophone string after a steam truck completed OBS2 in the morning
  - Acquired first test shots at 250 m by noon, **low signal-to-noise ratio, changed the planned acquisition parameters** after the inspection of the instrumentation and more test shots;
  - Completed ½ of the first profile (out of 5)
- December 08, 2021: standard acquisition of the first profile, completed ½ of the second profile (out of 5)
- December 09, 2021:
  - Completed the second profile
  - Problems with the stability of the source signature, diagnosed, **replaced the H-bridge switch**, completed ½ of the third profile
- December 10, 2021: standard acquisition
  - **Added permanent 3C geophones** to the acquisition system
- December 11, 2021: standard acquisition
  - Acquired two **long stacks (10,000 of shots)** overnight
- December 12, 2021:
  - Completed the last profile with refined source step

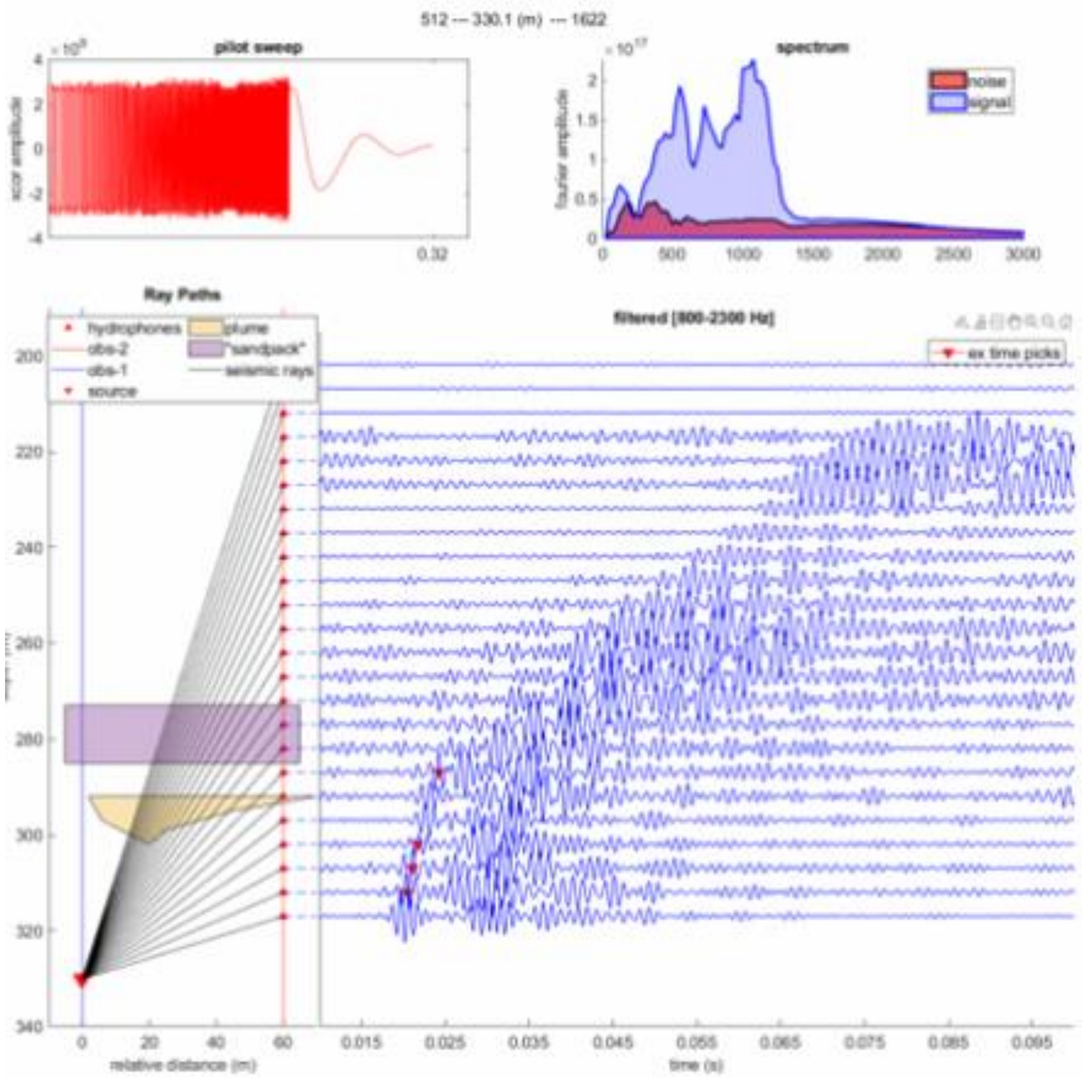
Raw data for the 3rd seismic profile

- ✓ Arrivals through the plume are visible outside of the plume
- ✓ Source affected by the plume 304-290 m not traceable?
- ✓ A 'sandpack' 270-282 m on the receiver side?
- ✓ Lower SNR compared with the baseline



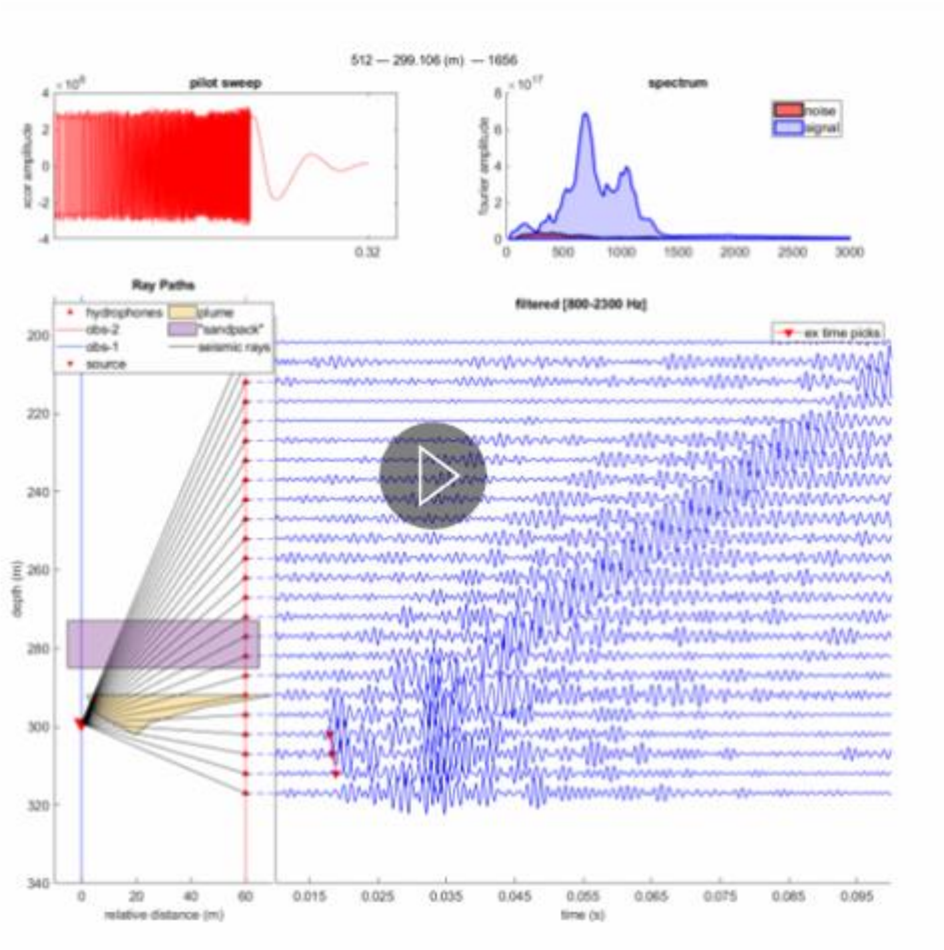
Raw data for the 3rd seismic profile

- ✓ Arrivals through the plume are visible outside of the plume
- ✓ Source affected by the plume
  304-290 m not traceable?
- ✓ A ‘sandpack’ 270-282 m on the receiver side?
- ✓ Lower SNR compared with the baseline



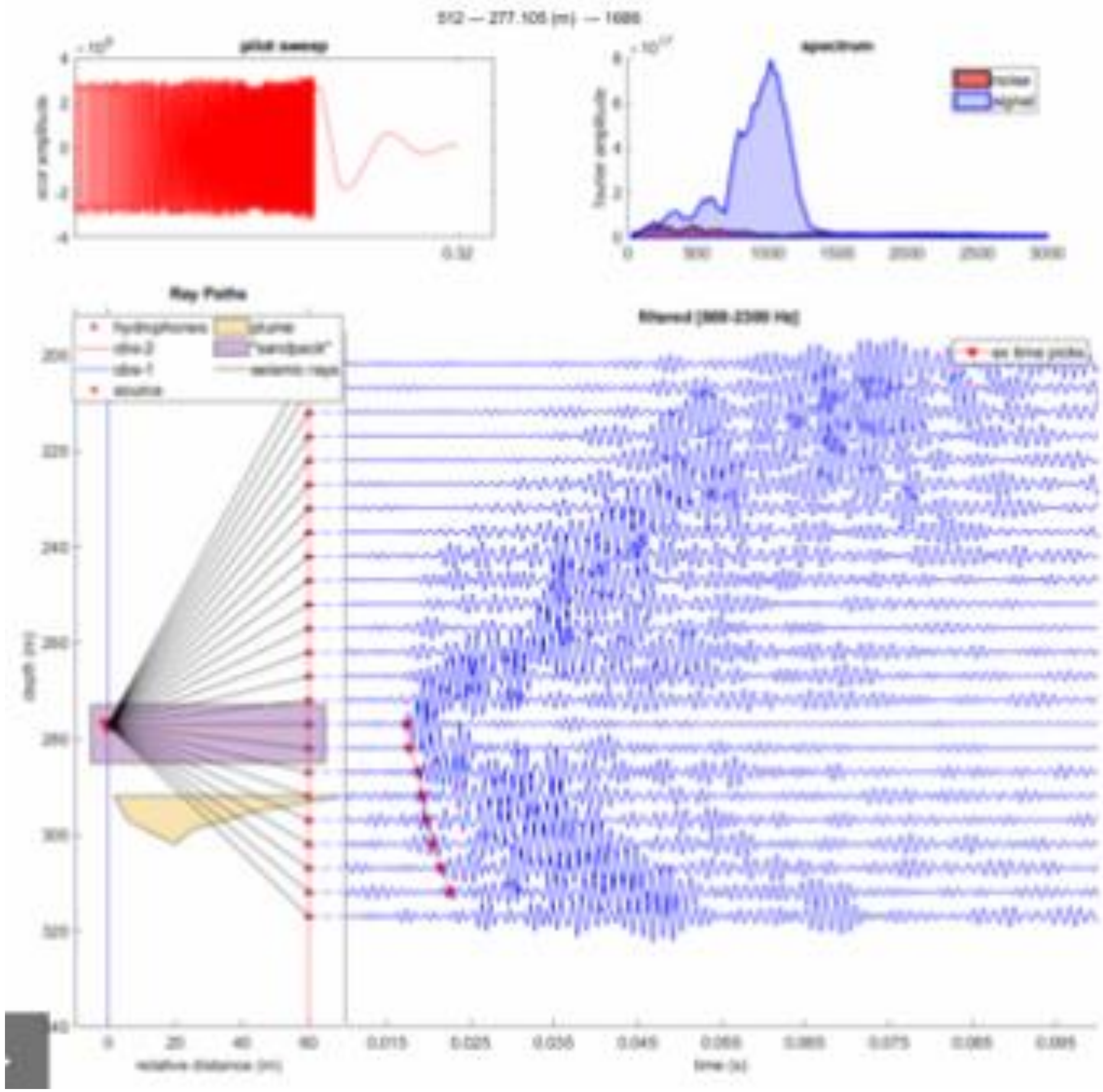
Raw data for the 3rd seismic profile

- ✓ Arrivals through the plume are visible outside of the plume
- ✓ Source affected by the plume
  304-290 m not traceable?
- ✓ A ‘sandpack’ 270-282 m on the receiver side?
- ✓ Lower SNR compared with the baseline



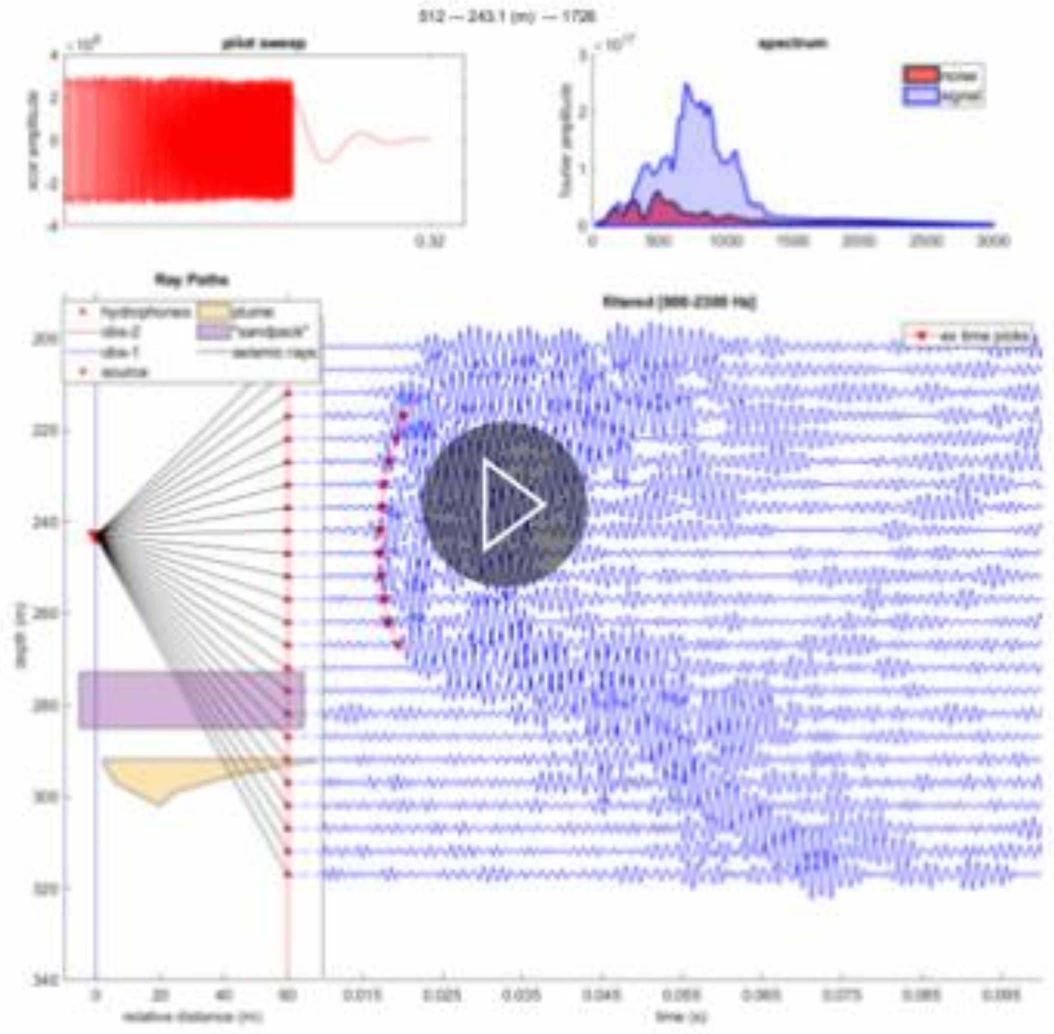
Raw data for the 3rd seismic profile

- ✓ Arrivals through the plume are visible outside of the plume
- ✓ Source affected by the plume
  304-290 m not traceable?
- ✓ A ‘sandpack’ 270-282 m on the receiver side?
- ✓ Lower SNR compared with the baseline



Raw data for the 3rd seismic profile

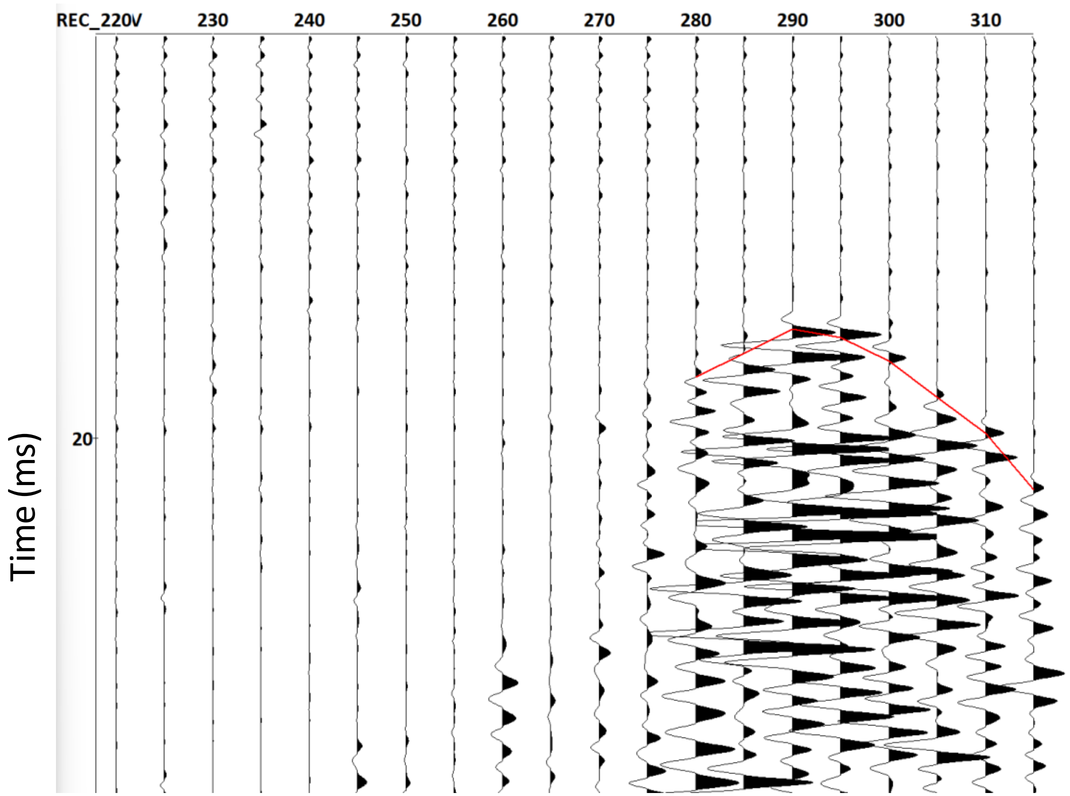
- ✓ Arrivals through the plume are visible outside of the plume
- ✓ Source affected by the plume
  304-290 m not traceable?
- ✓ A ‘sandpack’ 270-282 m on the receiver side?
- ✓ Lower SNR compared with the baseline



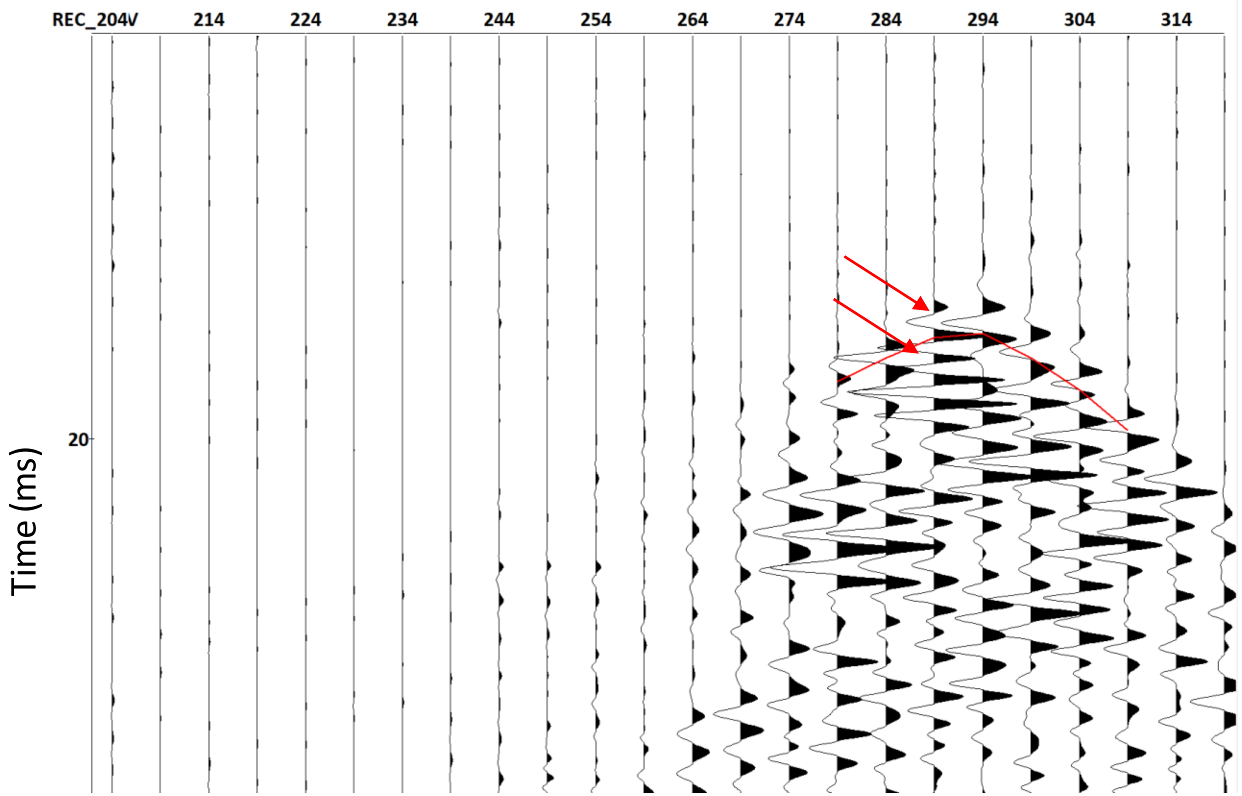
Waveforms Baseline/Monitor

source depth 285.5 m, above the plume

Baseline



Monitor

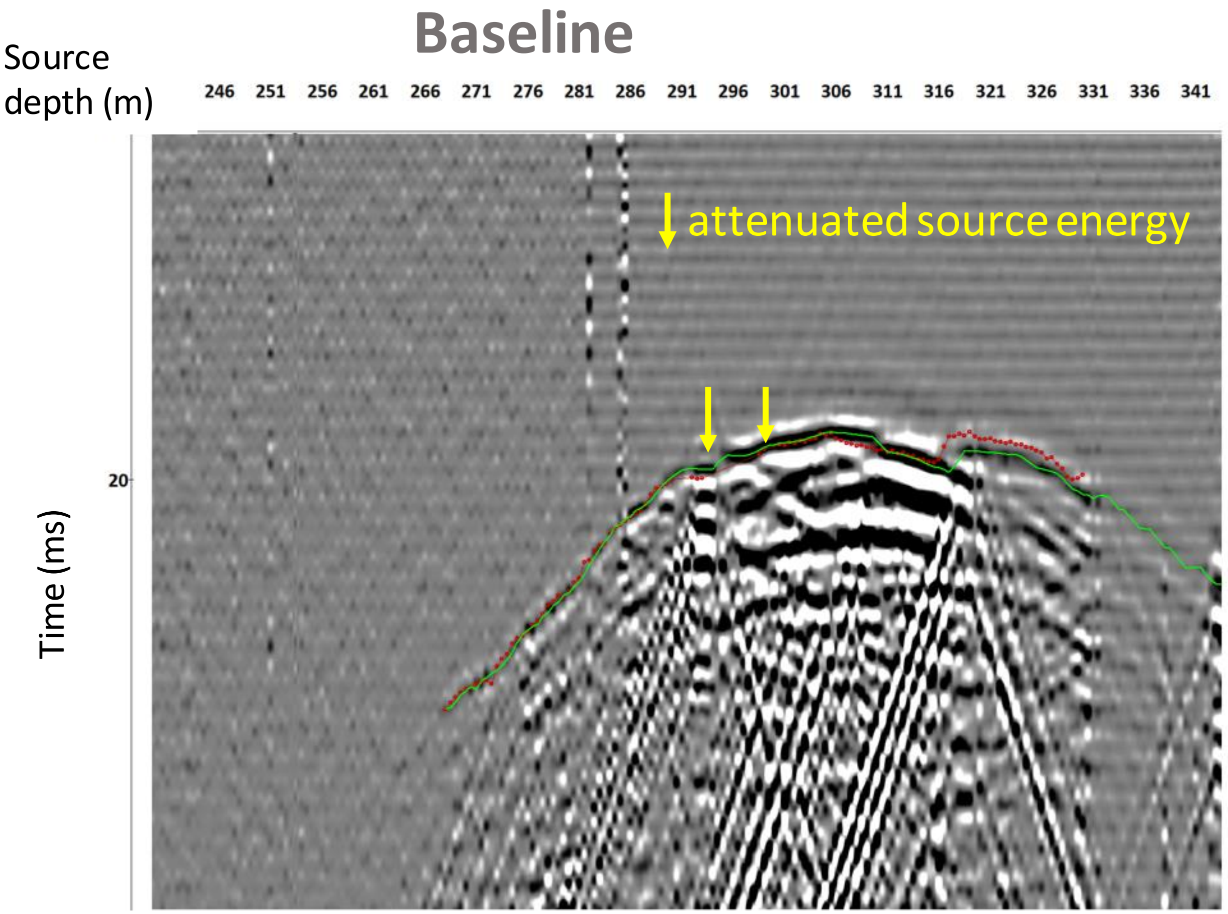


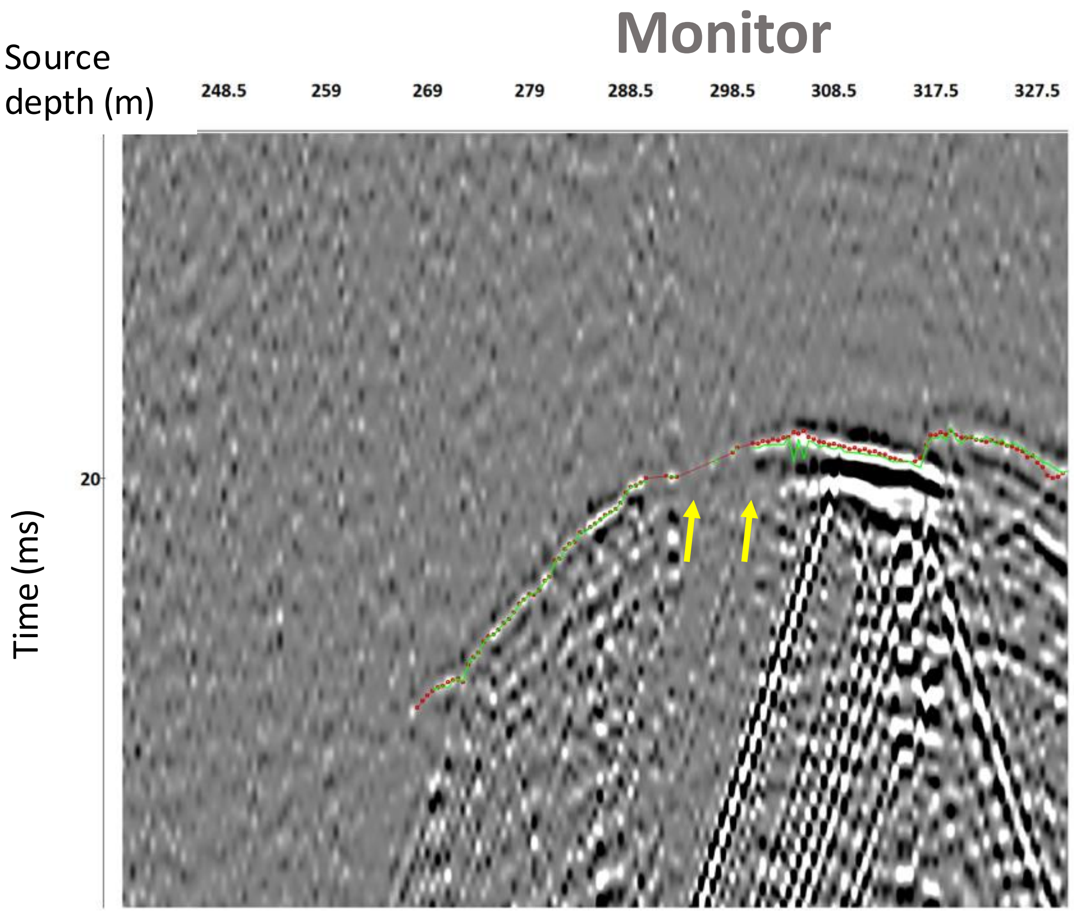
✓ Waveform differs for the two surveys + An offset-independent time delay

Key achievements

- Crosshole seismic data acquired, QC'd, and systematized
- Developed a robust workflow for P-wave arrivals picking:
  - Bandpass filtering to [800 -2200] Hz
  - Analysis of the power traces (keeping the sign)
  - Identifying the arrivals in the common-offset gathers (especially, zero-offset)
  - Picking the arrivals in the common-receiver gathers
  - Finalize the picks in the common-shot domain
- Consistent travel-time picks in the monitoring vintages:
  - Re-picked the Baseline
  - Picked the Monitor
- Seismic attributes extracted along the travel-time curves for the further plume mapping

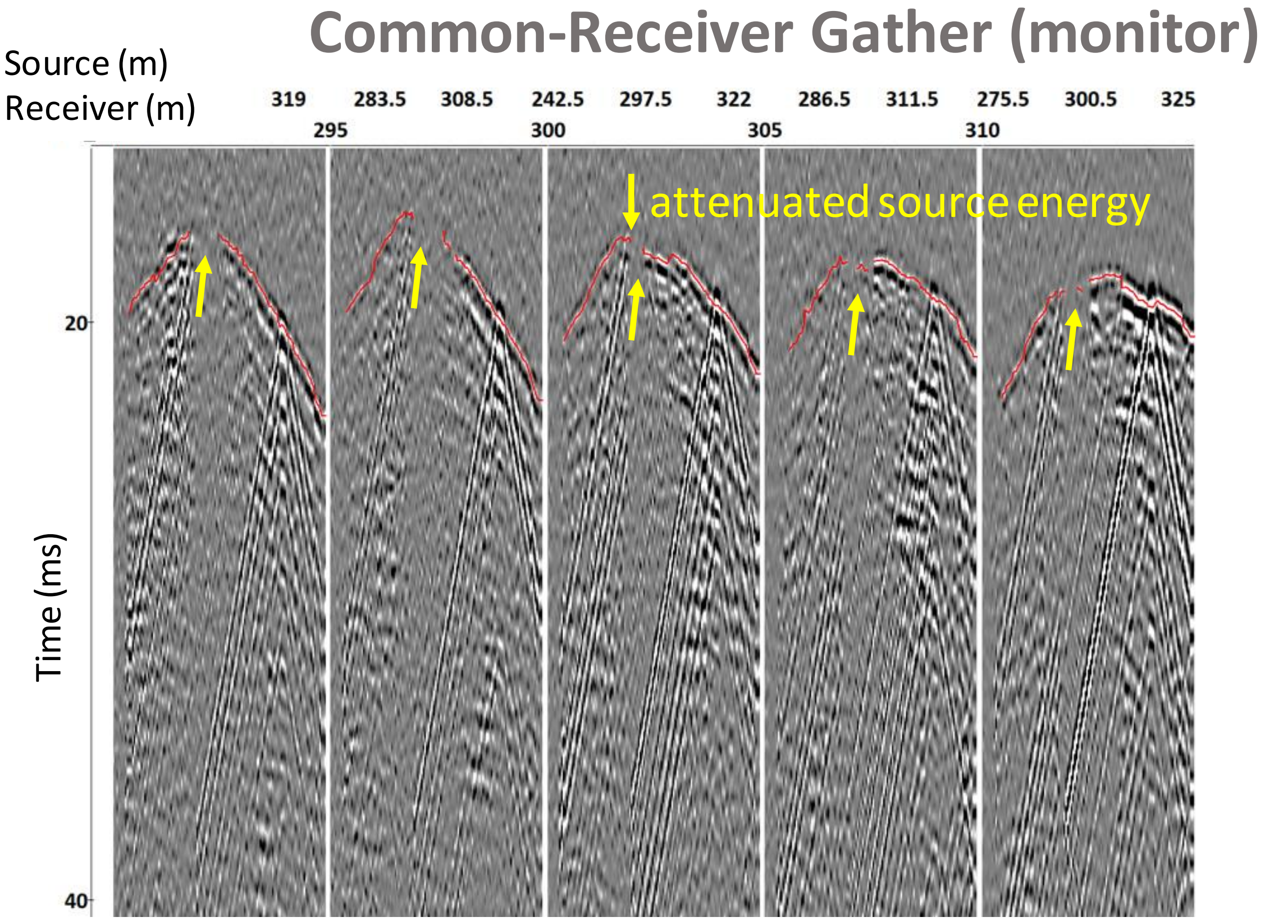
Arrival Picks at the receiver depth 314 m (below the plume)

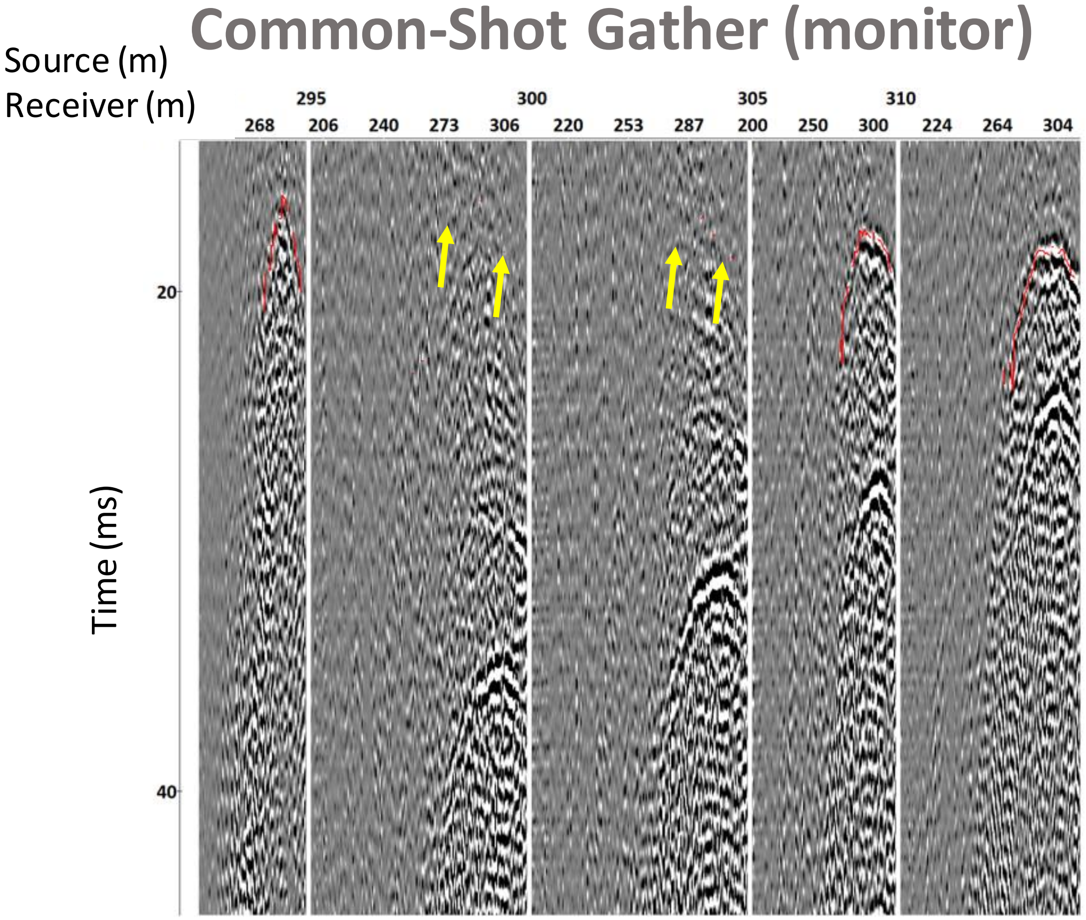




✓ The picks are well reconciled between the Monitor and Baseline vintages

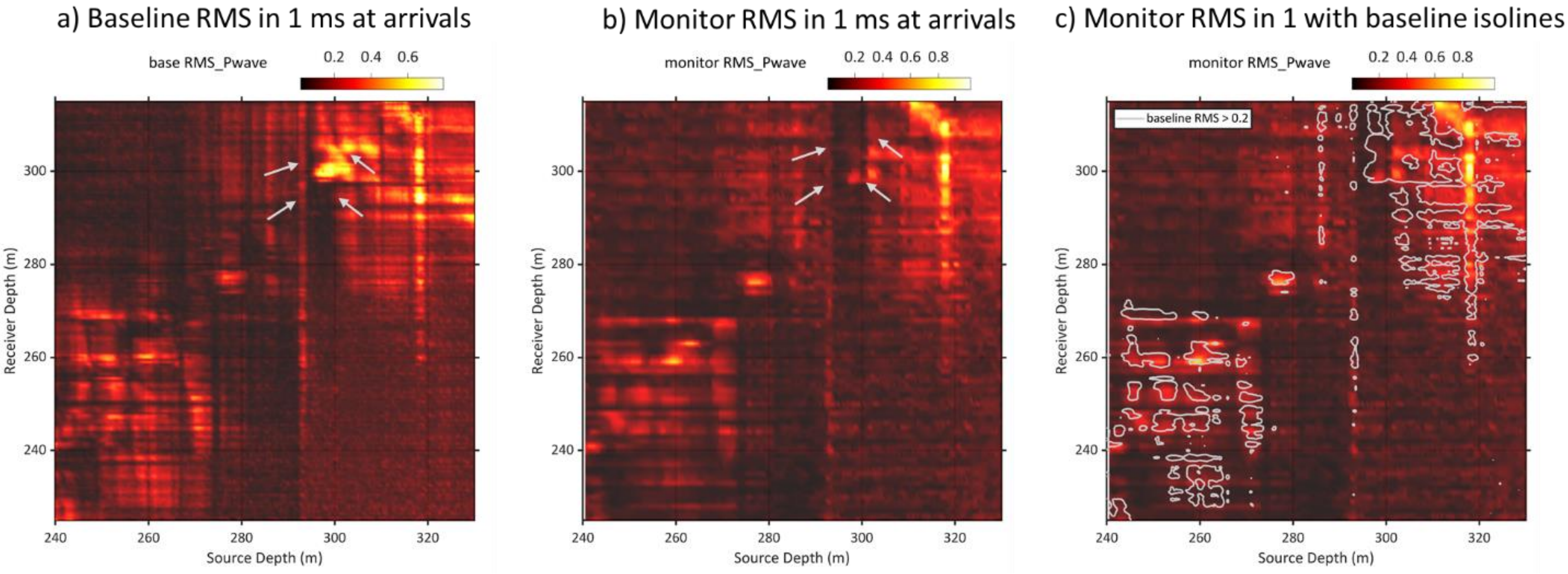
The effect of the plume on the source side



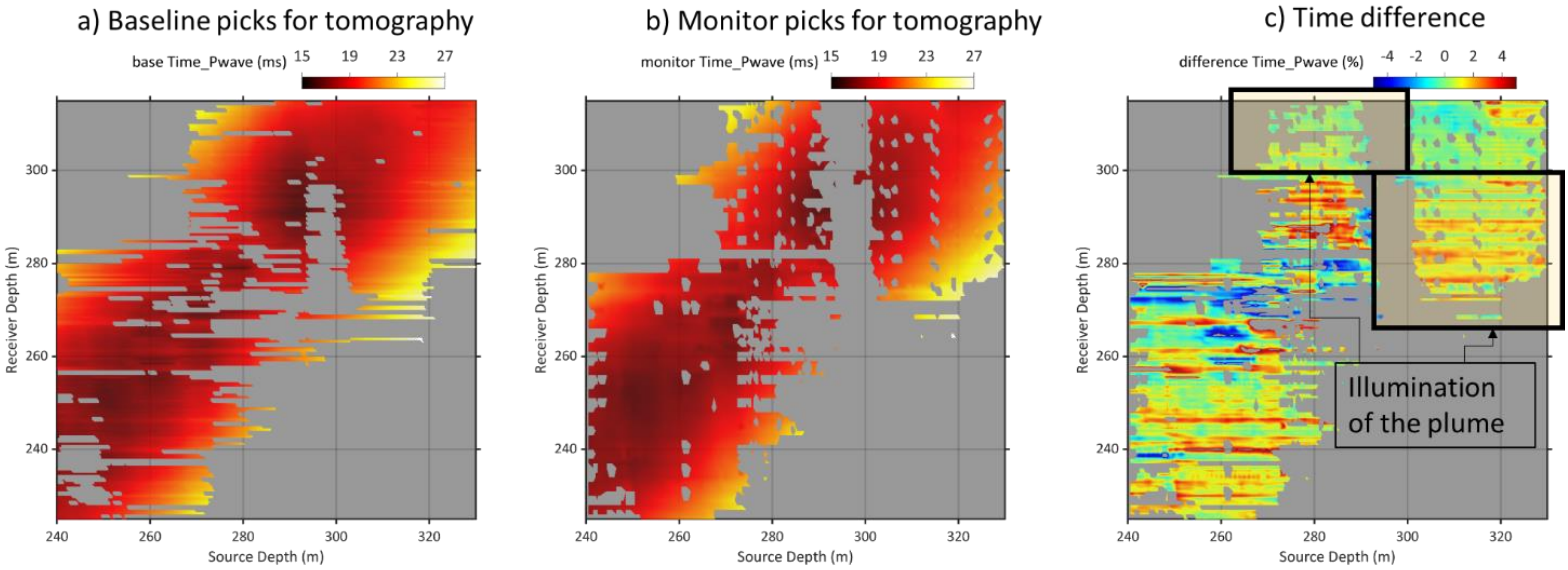


✓ Most Likely, Plume Reached OBS1 and Attenuated the Source Energy

Distribution of RMS Amplitudes

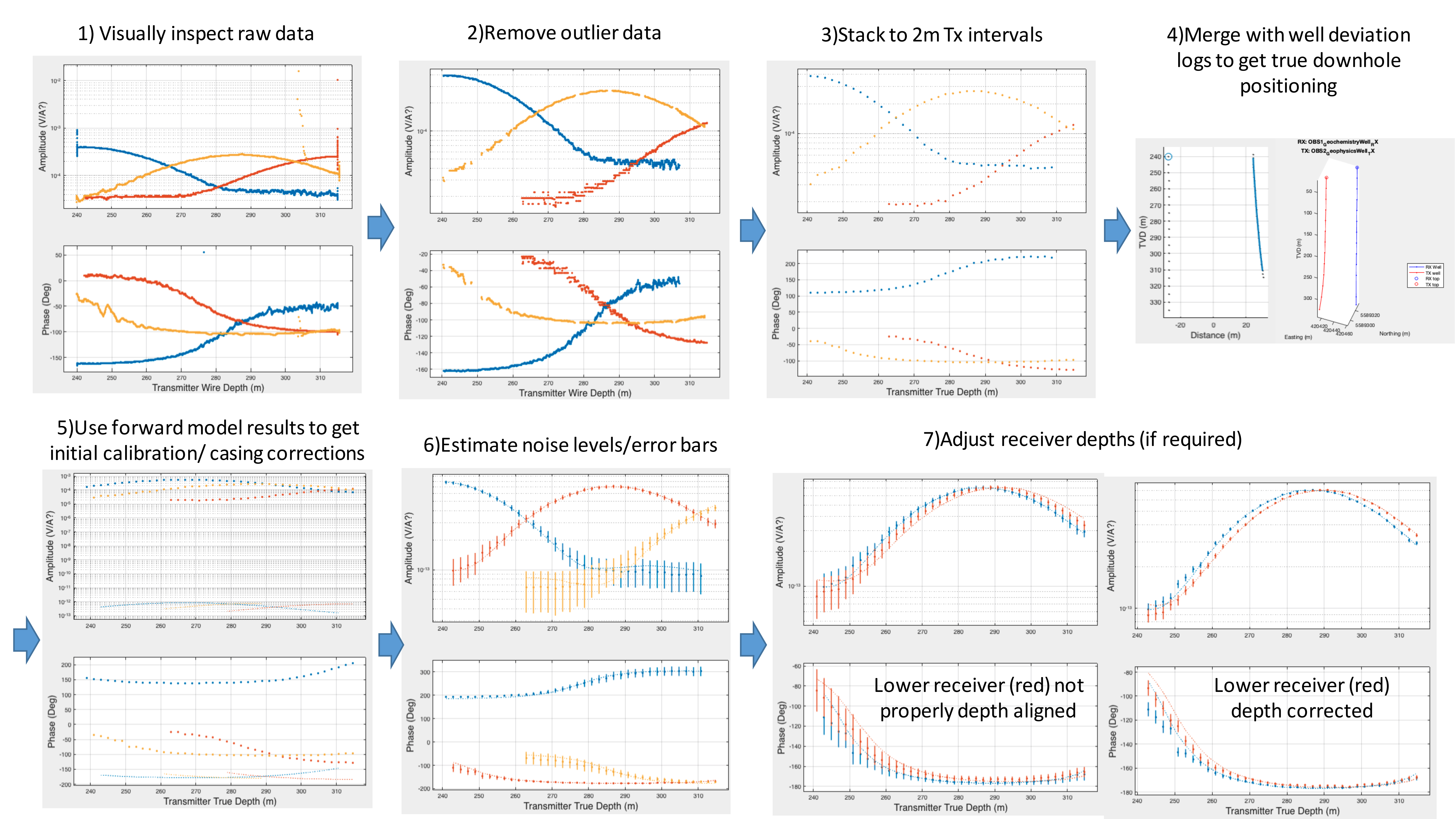


P-Wave travel Time Picks



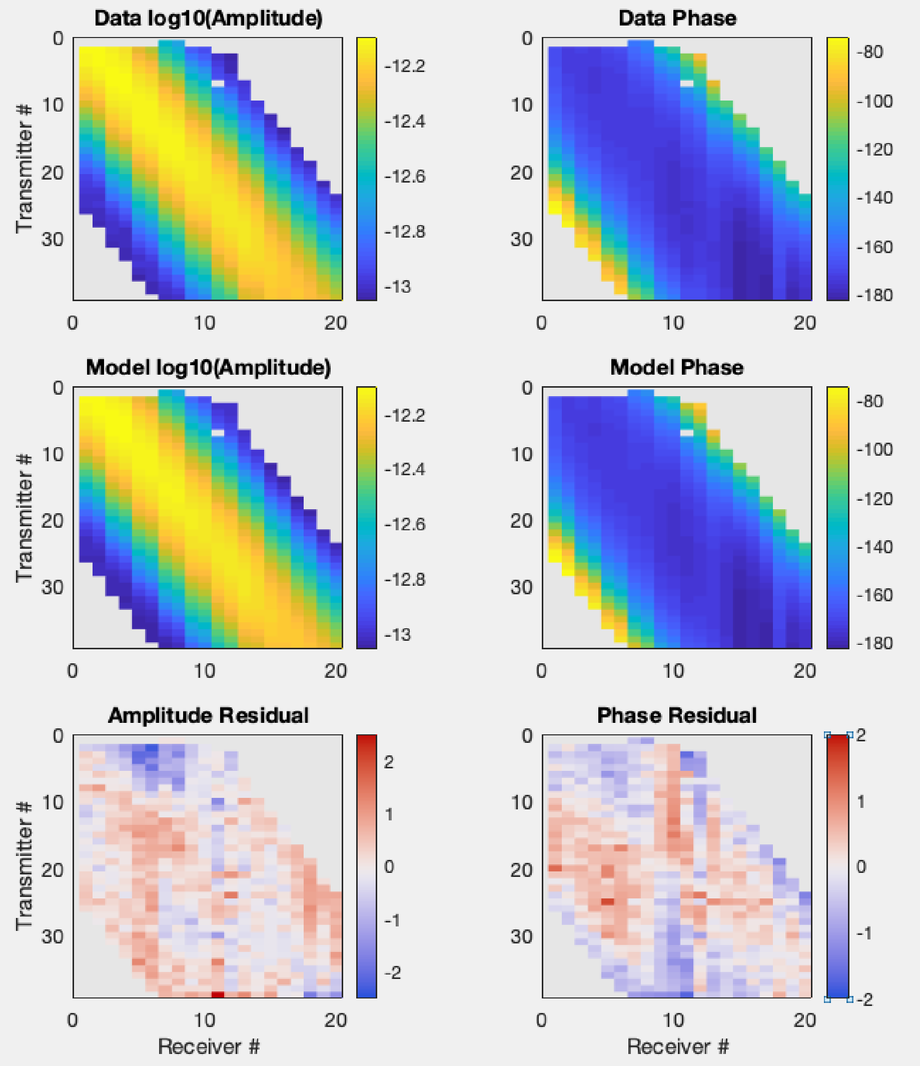
Crosswell EM Data Acquisition Schedule

- December 12, 2021 – Afternoon
  - Run new transmitter in OBS2 at 600 HZ - Fails after ~1 hour
  - Open up and find water in top of housing and short across to main power supply wires
- December 13, 2021
  - Fix new transmitter and fill top with mineral oil
  - Drop back down OBS 2 and start testing – again fails after 1 hour.
  - Position 2 – receiver string in OBS1 at 330m depth
  - Put old transmitter in OBS2
- December 14, 2021
  - Test old source at 319 Hz
  - Acquire over ½ data
- December 15, 2021
  - Finish 319 Hz data acquisition
  - Test old source at 200 HZ – Source shorts after minimal operation time
  - Fix short in old transmitter
- December 16, 2021
  - Test old source at 600 Hz
  - Acquire 600 Hz data set
- December 17 - Break down system and prepare for shipping back to US

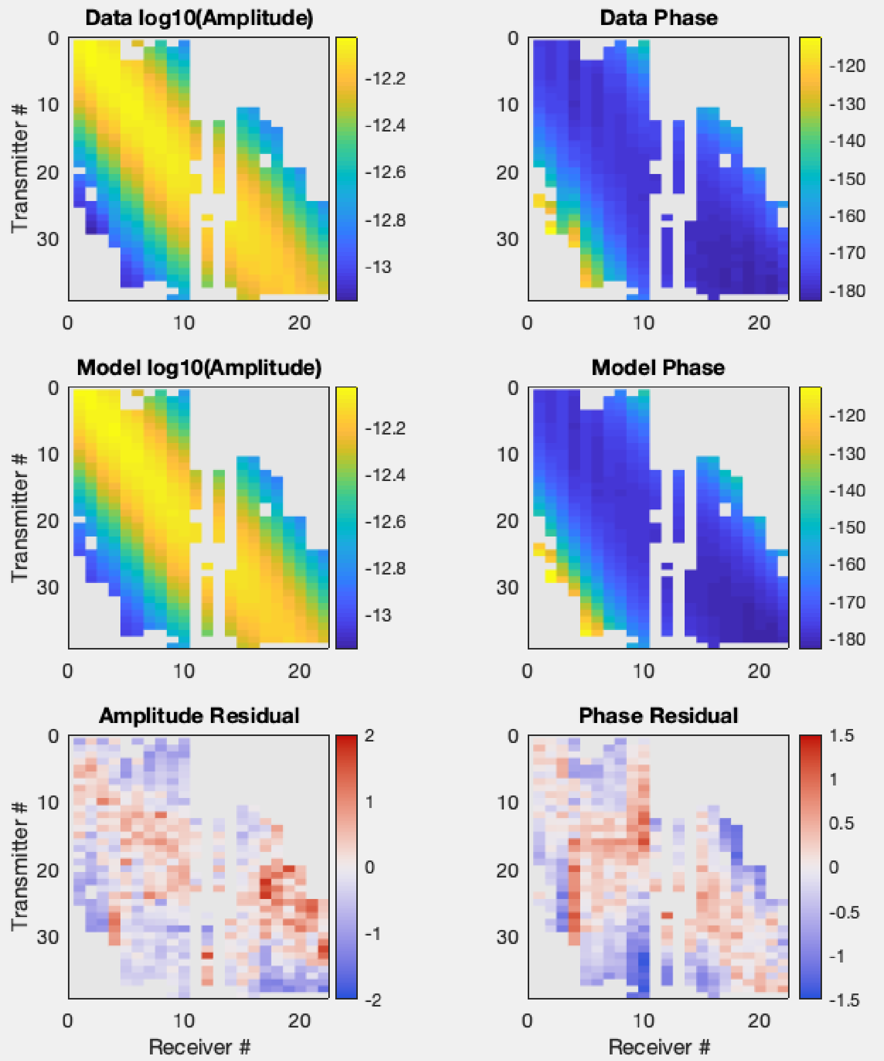


1) Visually inspect raw data
2)Remove outlier data
3)Stack to 2m Tx intervals
4)Merge with well deviation logs to get true downhole positioning
5)Use forward model results to get initial calibration/ casing corrections
6)Estimate noise levels/error bars
7)Adjust receiver depths (if required)
Lower receiver (red) not properly depth aligned
Lower receiver (red) depth corrected
Amplitude (V/A?)
Phase (Deg)
Transmitter Wire Depth (m)
Transmitter True Depth (m)
TVD (m)
Distance (m)
Easting (m)
Northing (m)

319 Hz Whole Space Data Fits

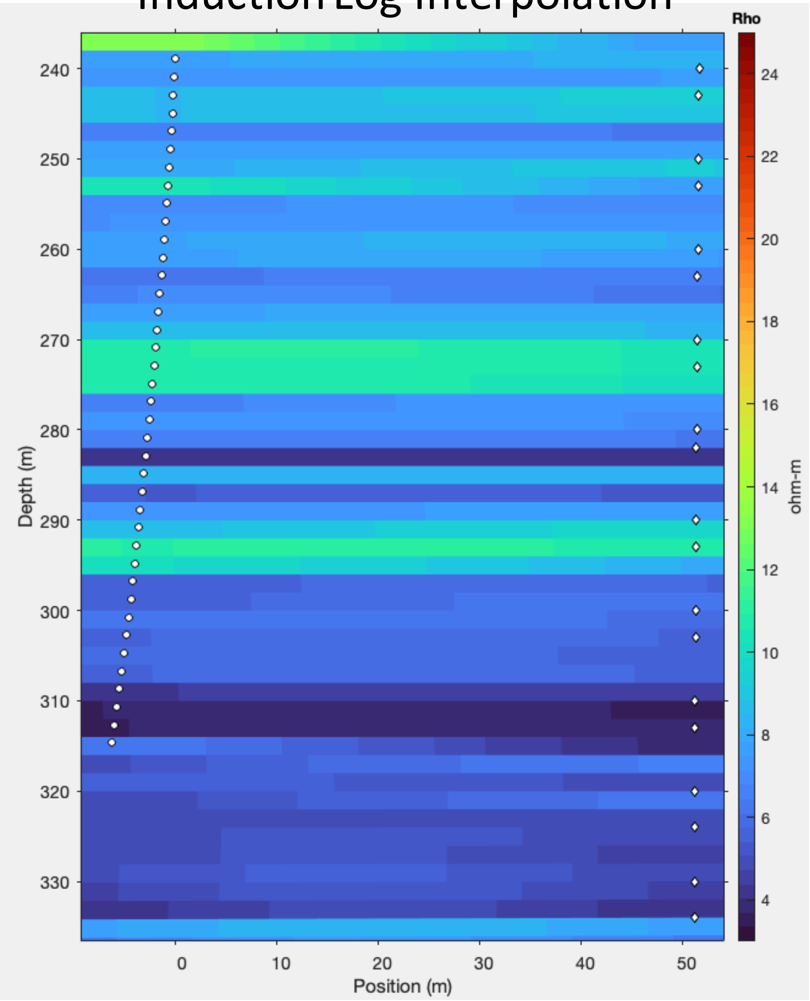


600 Hz Whole Space Data Fits

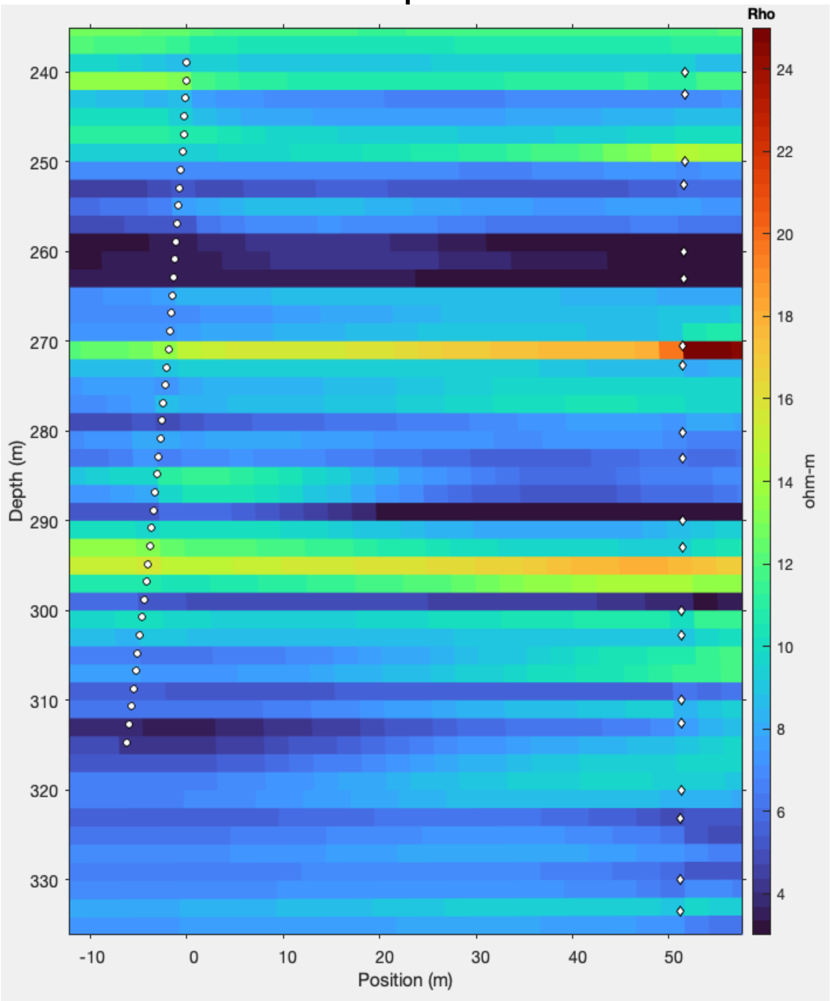


Crosswell EM data Processing

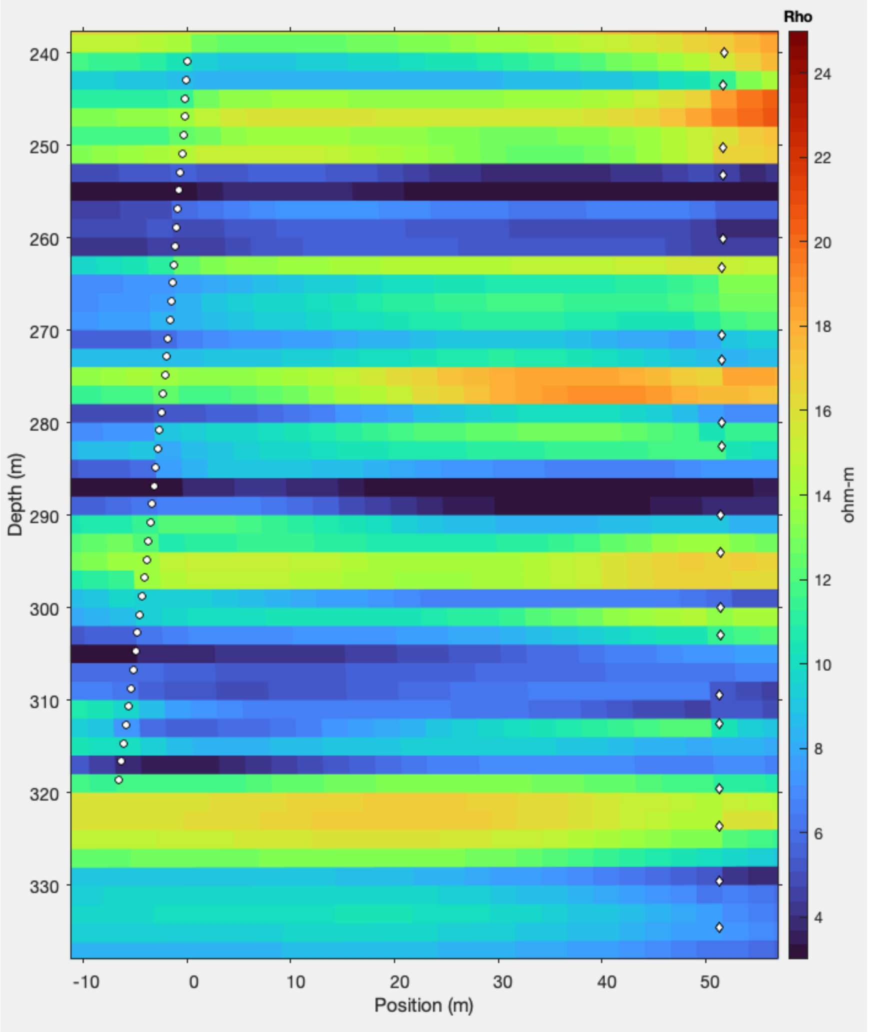
Induction Log Interpolation



319 Hz Whole Space Inversion

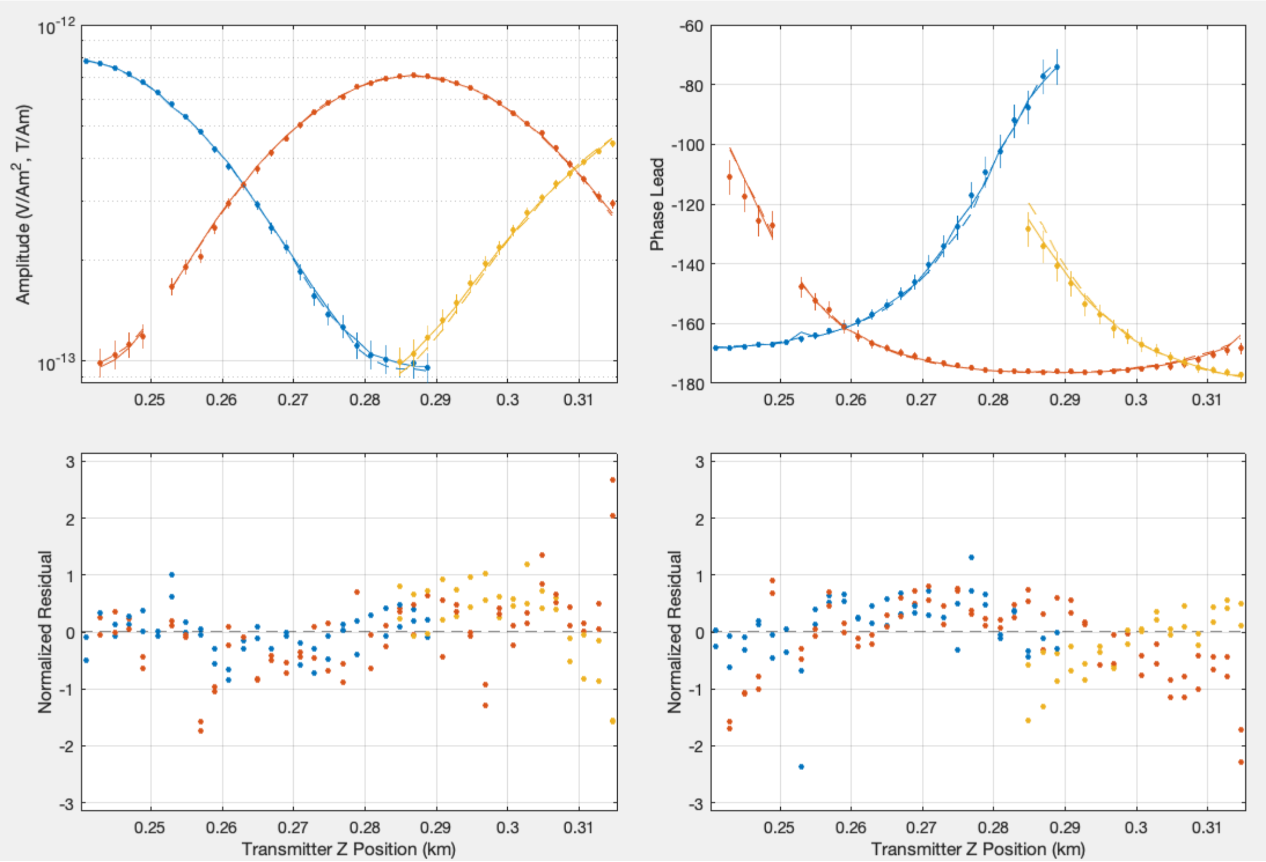


600 Hz Whole Space Inversion

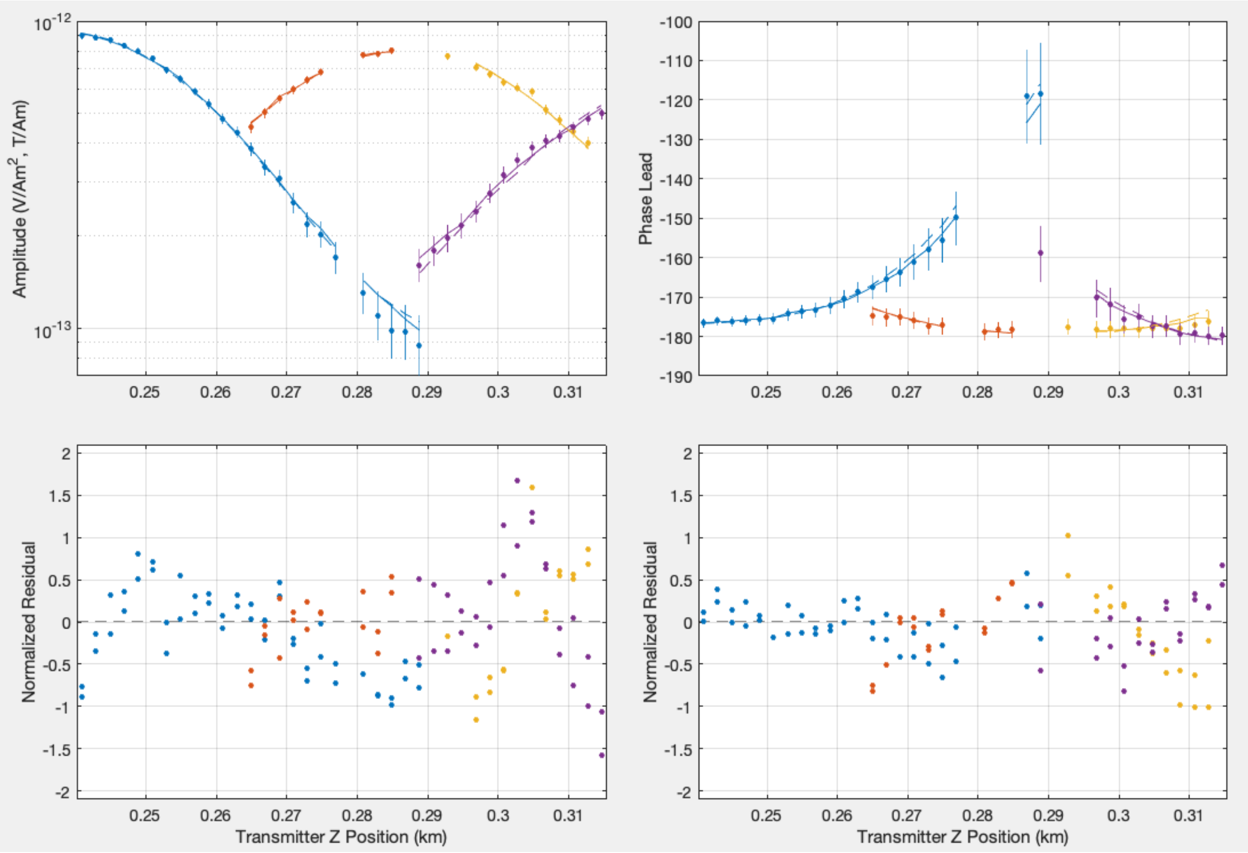


Crosswell EM data Processing

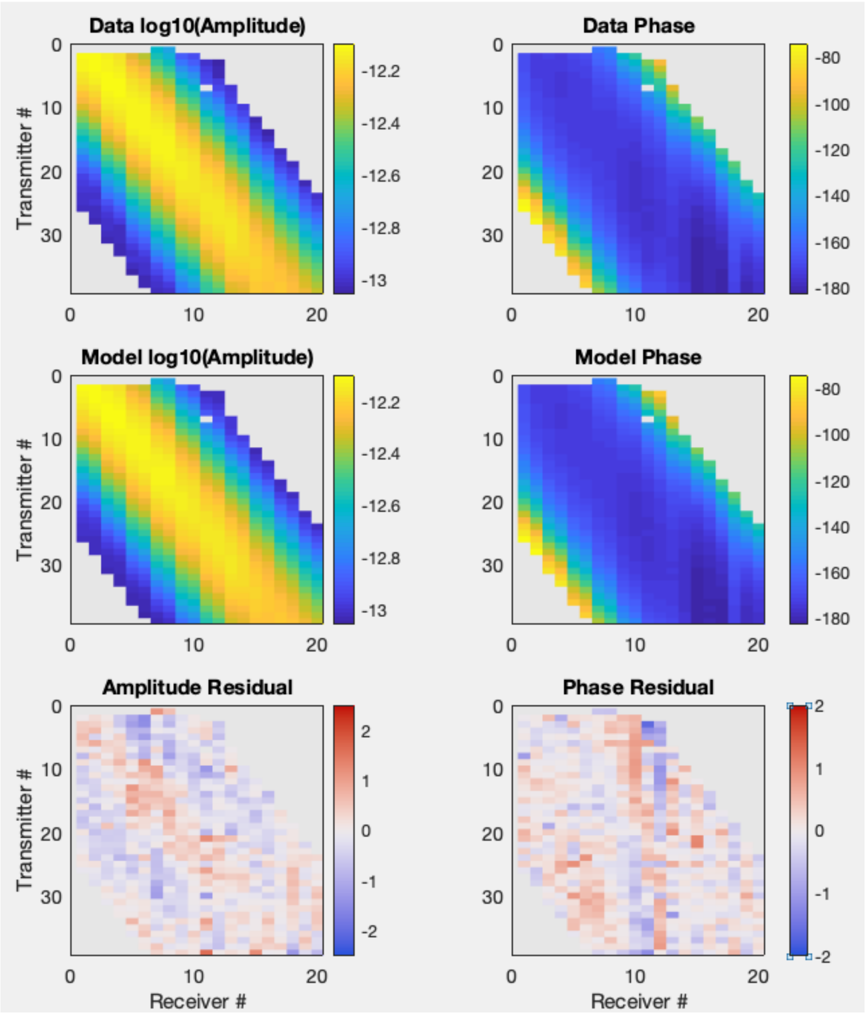
319 Hz Data Fit



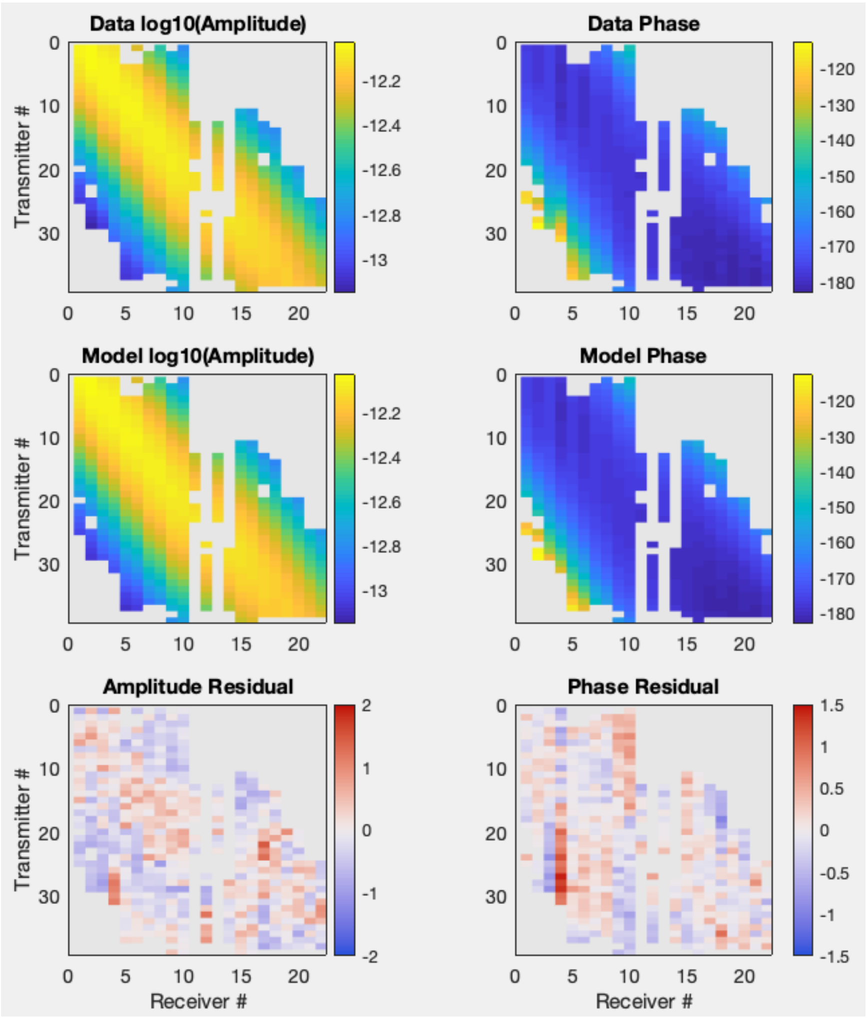
600 Hz Data Fit



319 Hz Whole Space inversion Data Fits

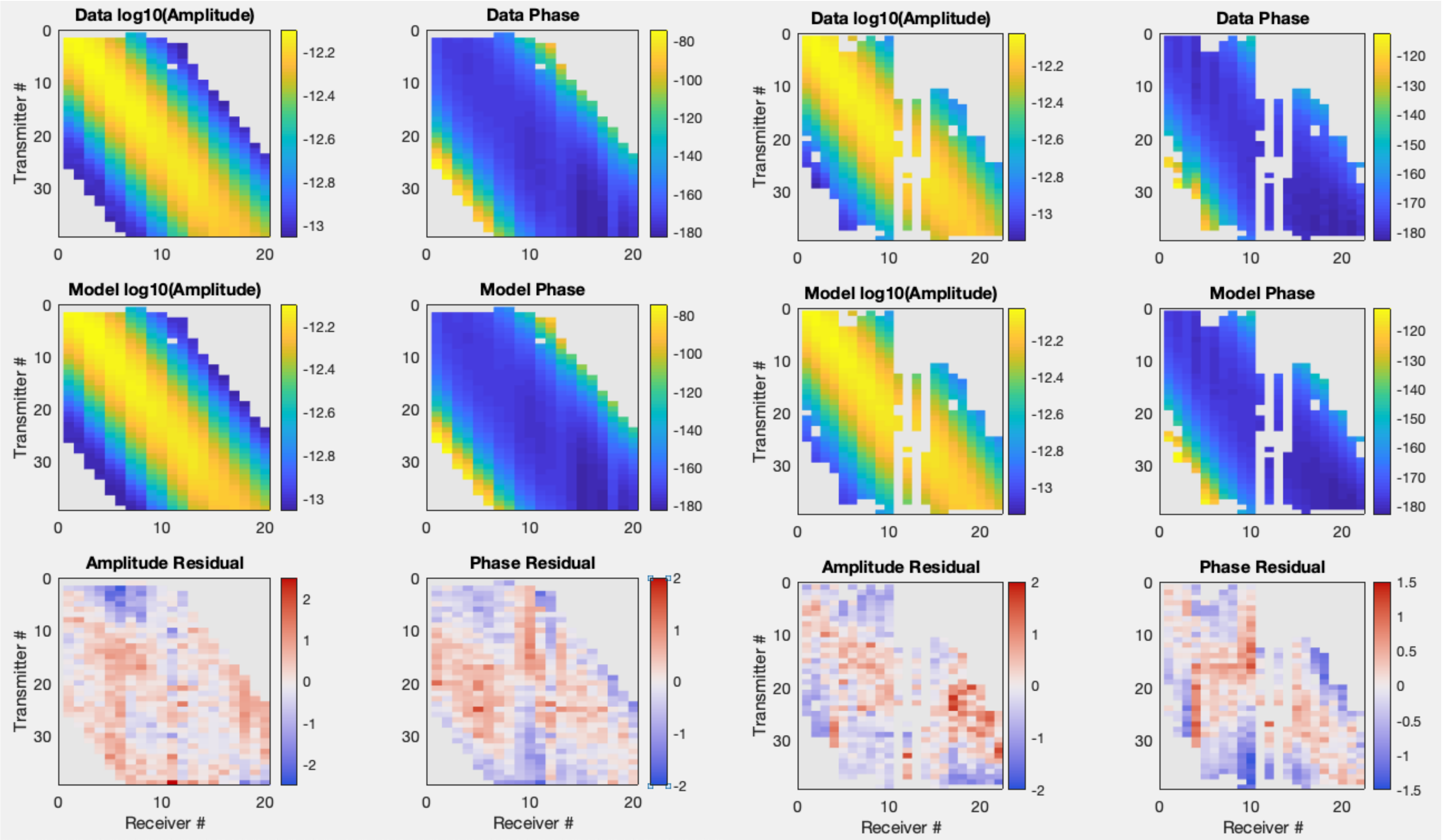


600 Hz Whole Space inversion Data Fits



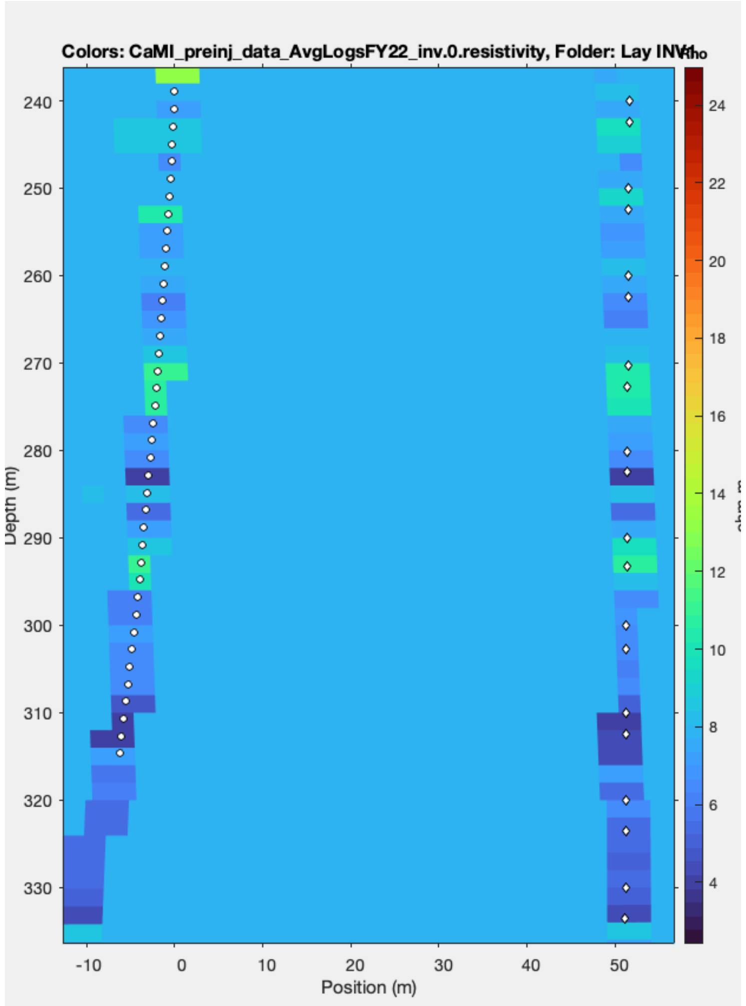
319 Hz Whole Space Data Fits

600 Hz Whole Space Data Fits

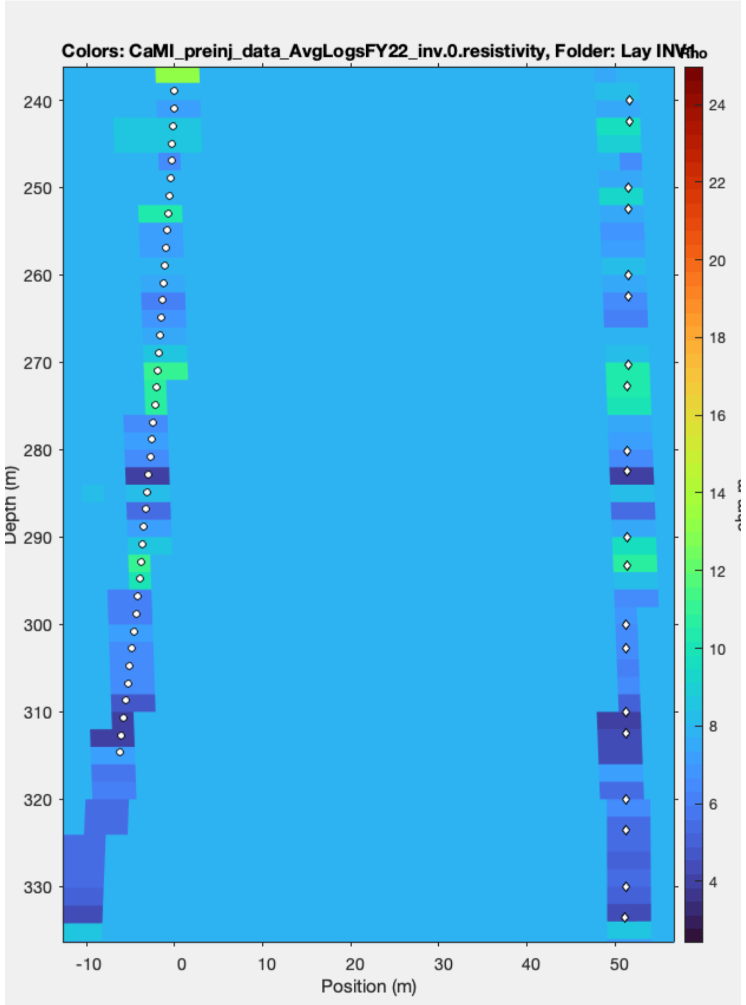


Crosswell EM data Processing Additional Editing

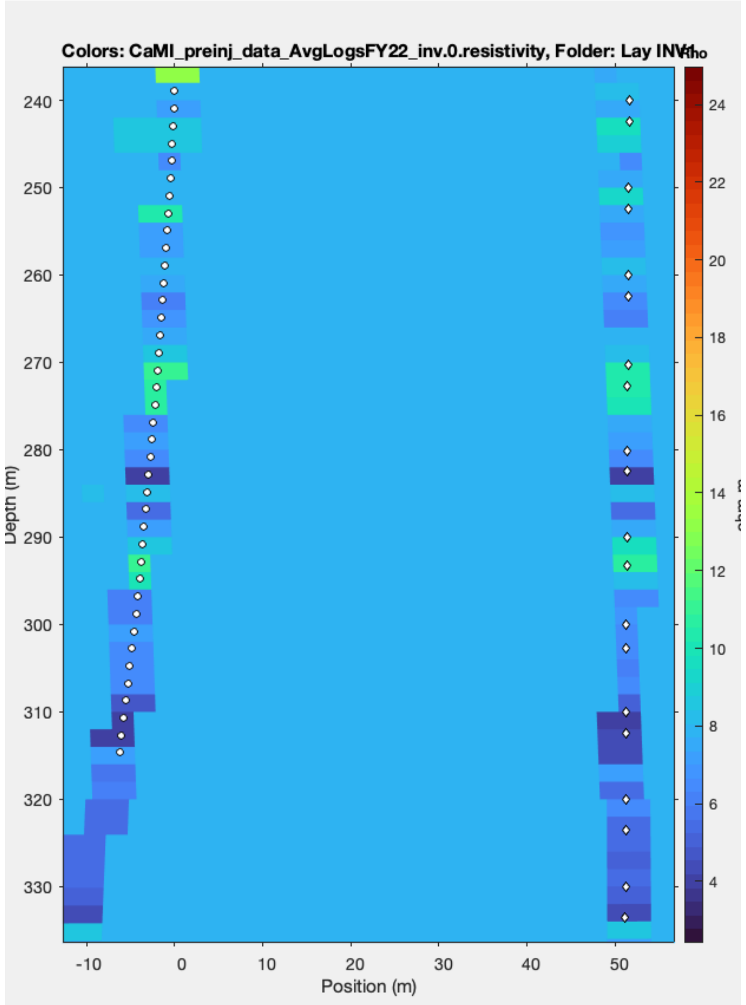
2017 200Hz Induction Log Constrained Inversion



319 Hz Initial Inversion Induction Log Constrained Inversion

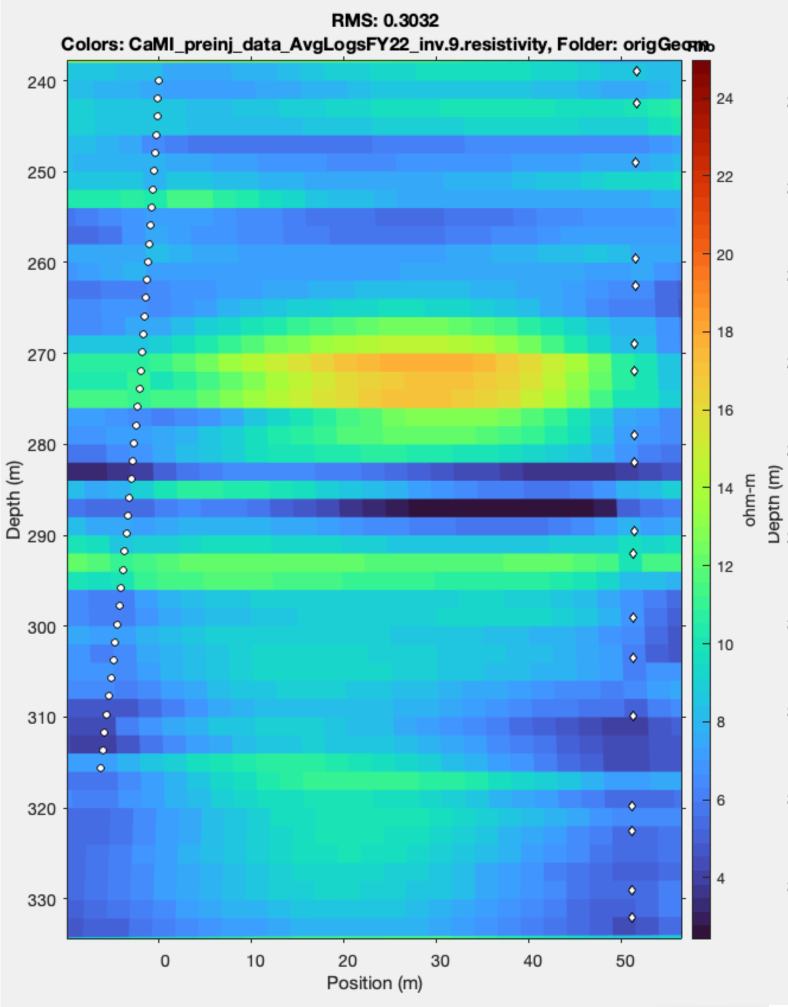


600 Hz Initial Inversion Induction Log Constrained Inversion

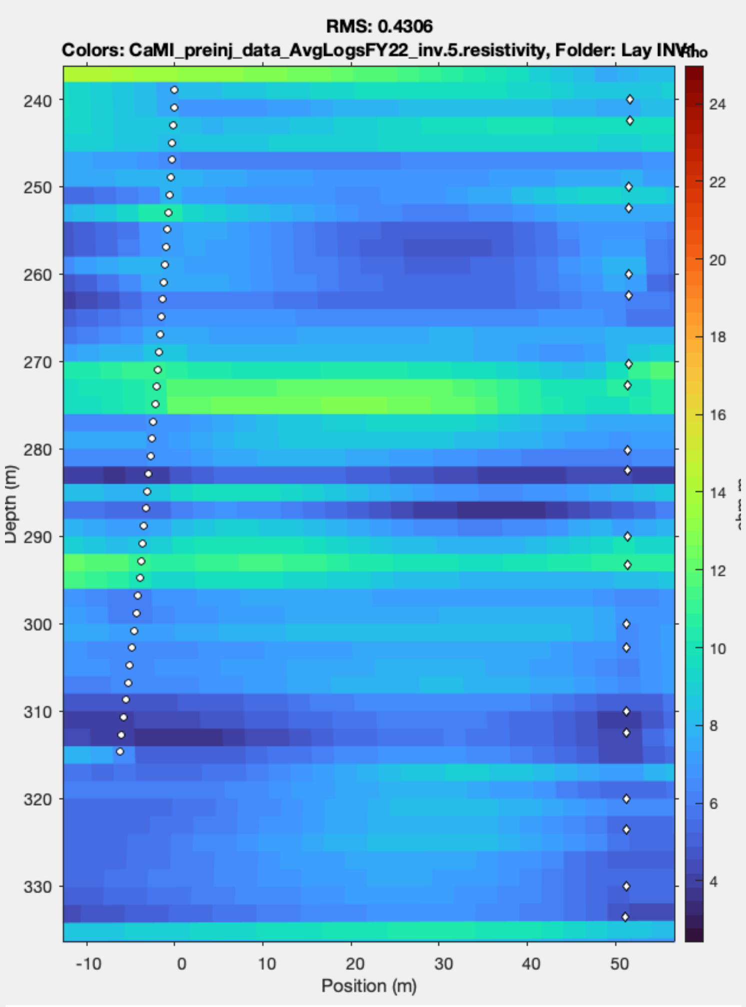


Crosswell EM data Processing Additional Editing

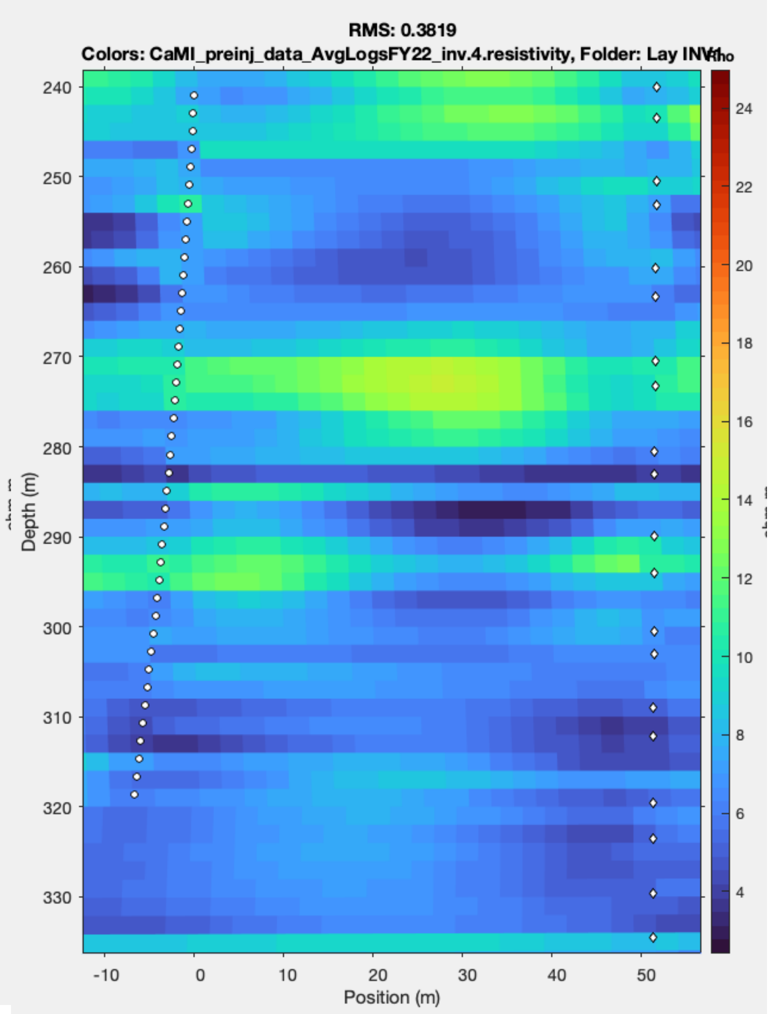
2017 200Hz Induction Log
Constrained Inversion



319 Hz Induction Log
Constrained Inversion

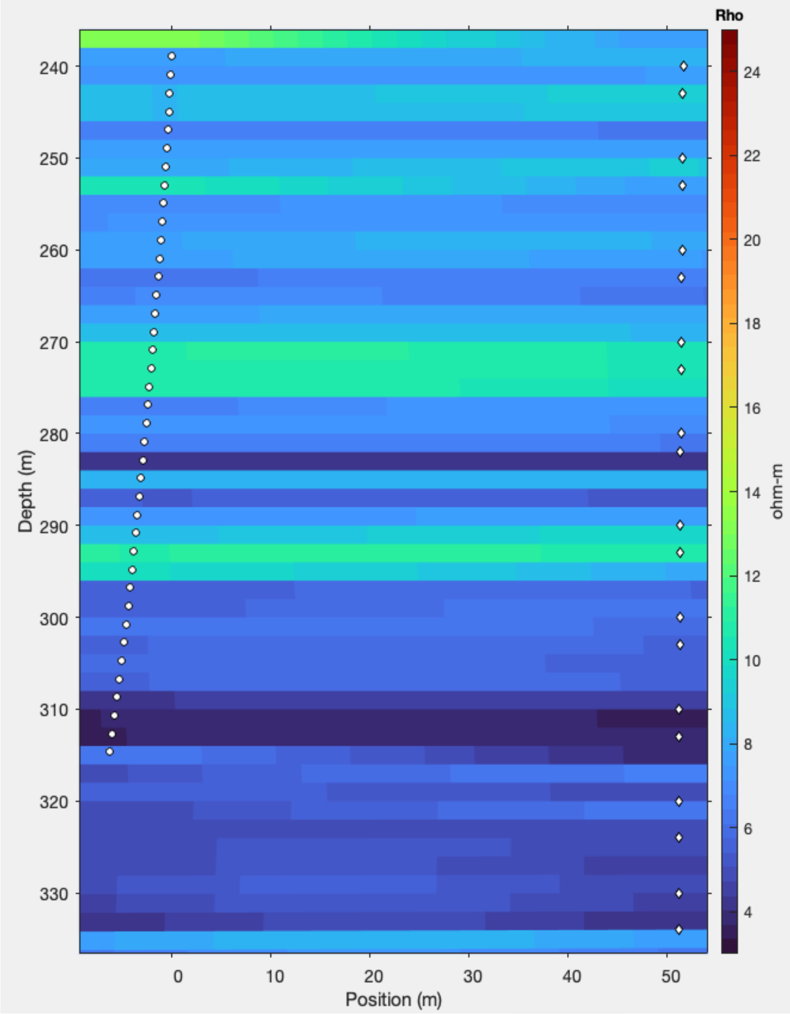


600 Hz Induction Log
Constrained Inversion

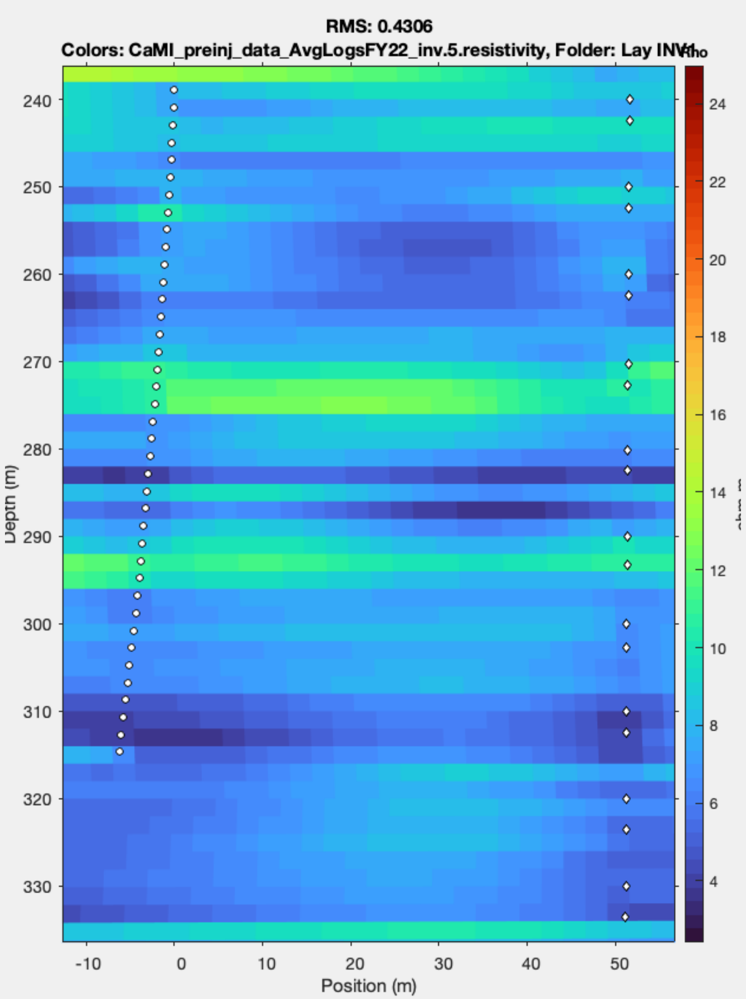


Crosswell EM data Processing Additional Editing

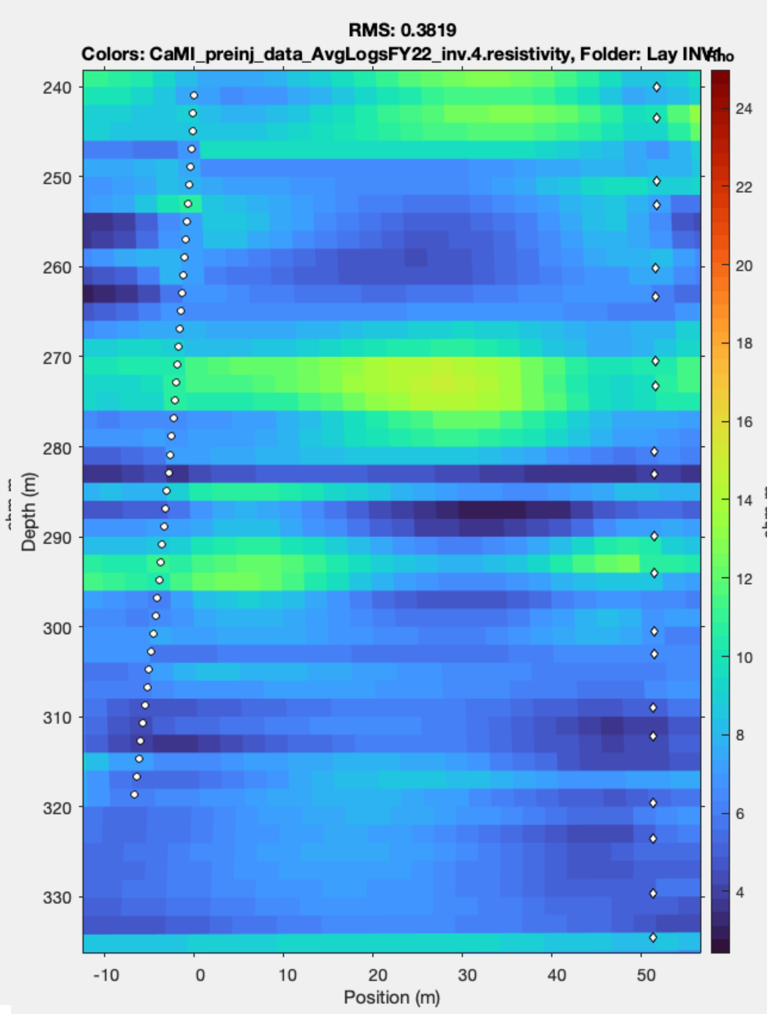
2017 200Hz Induction Log Constrained Inversion



319 Hz Induction Log Constrained Inversion

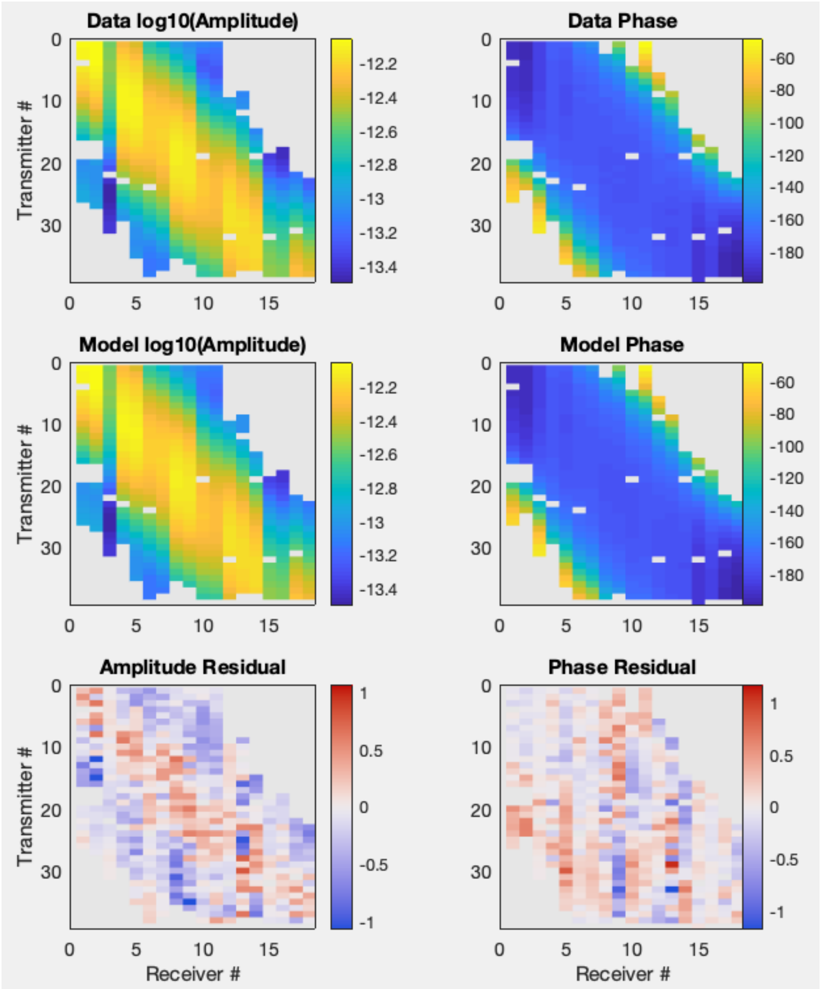


600 Hz Induction Log Constrained Inversion

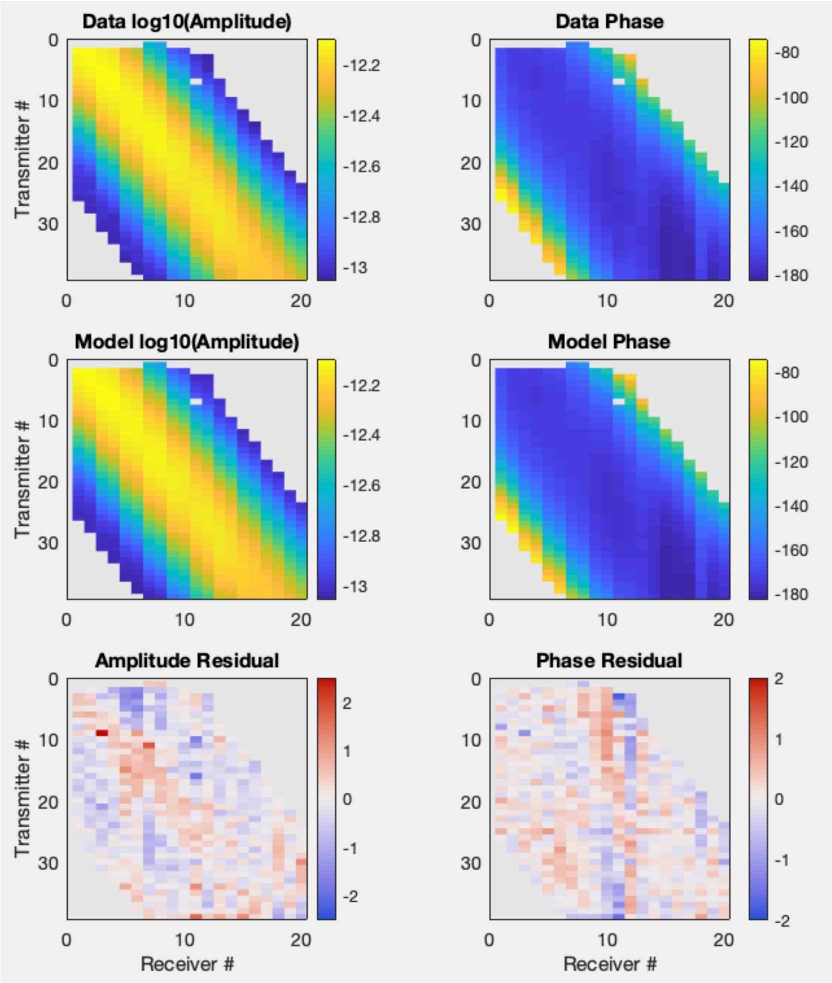


Crosswell EM data Processing

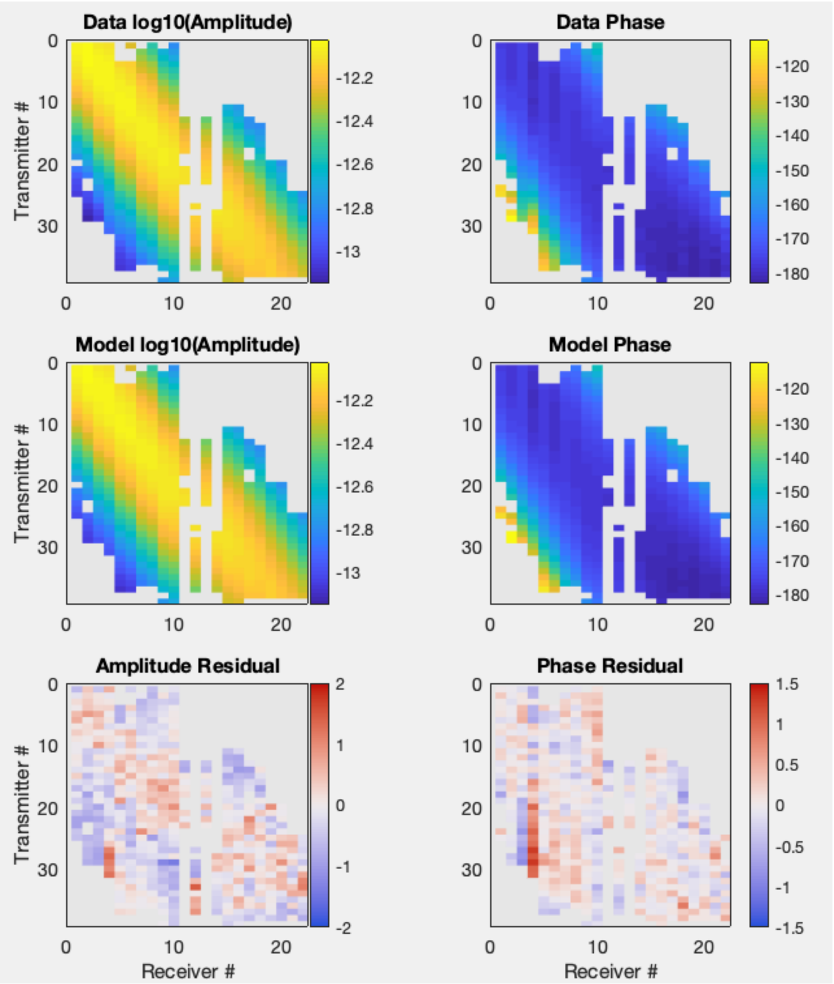
2017 200Hz Induction Log Constrained Inversion



319 Hz Induction Log Constrained Inversion

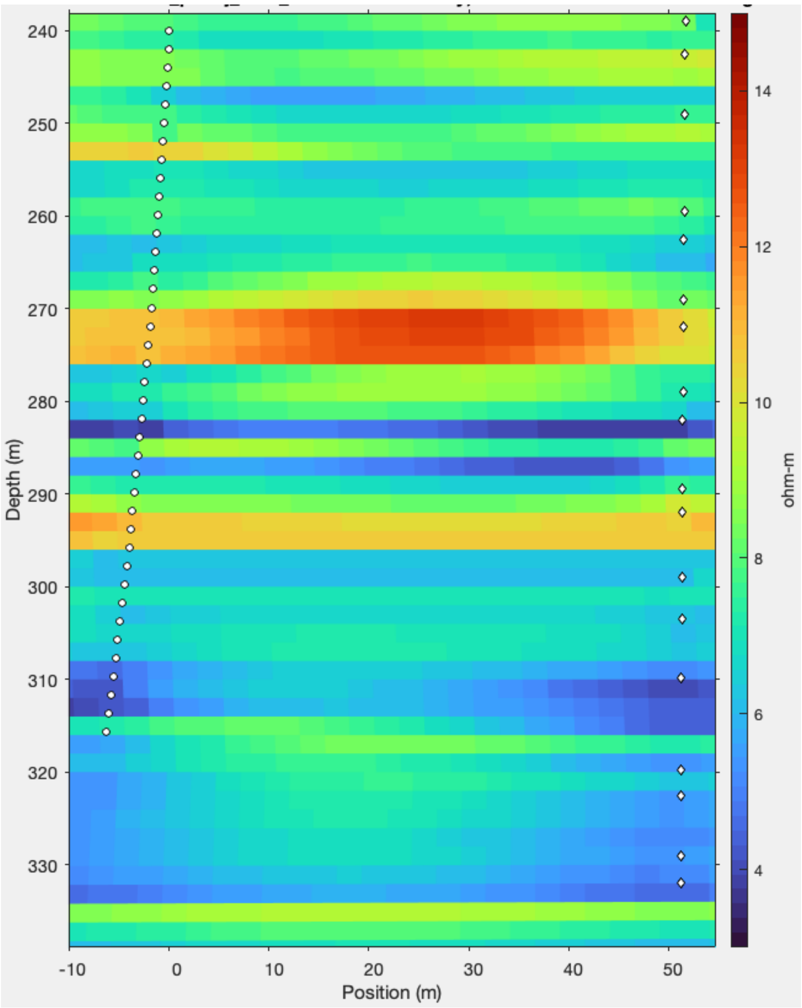


600 Hz Induction Log Constrained Inversion

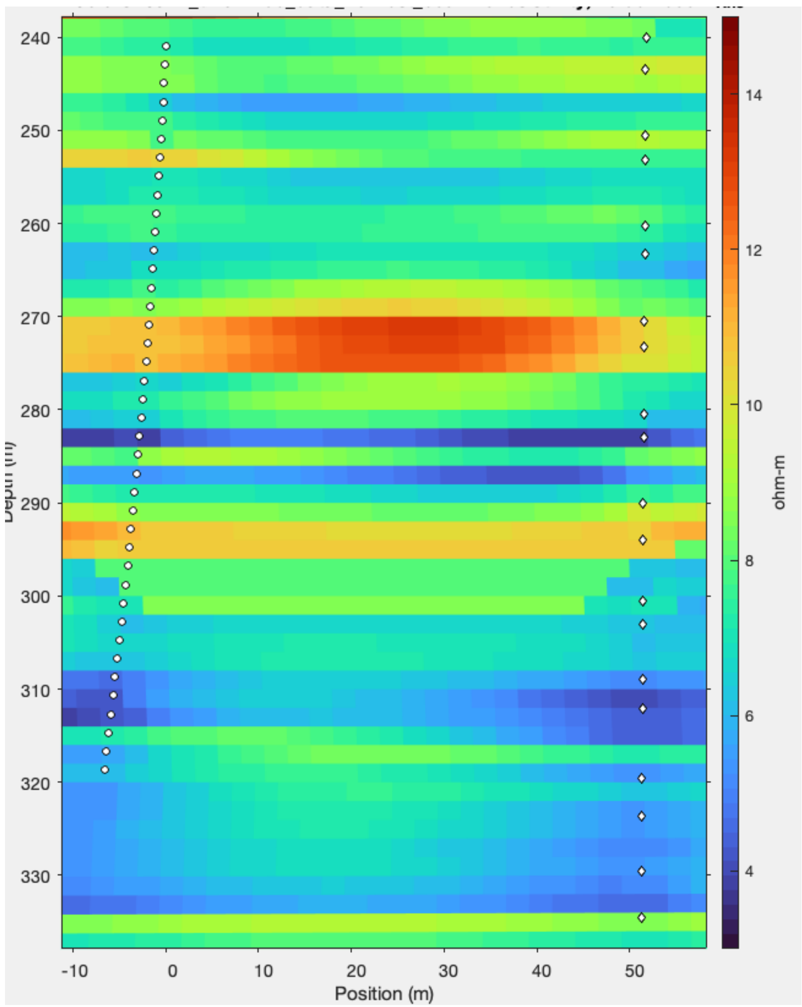


Model Sensitivity Study

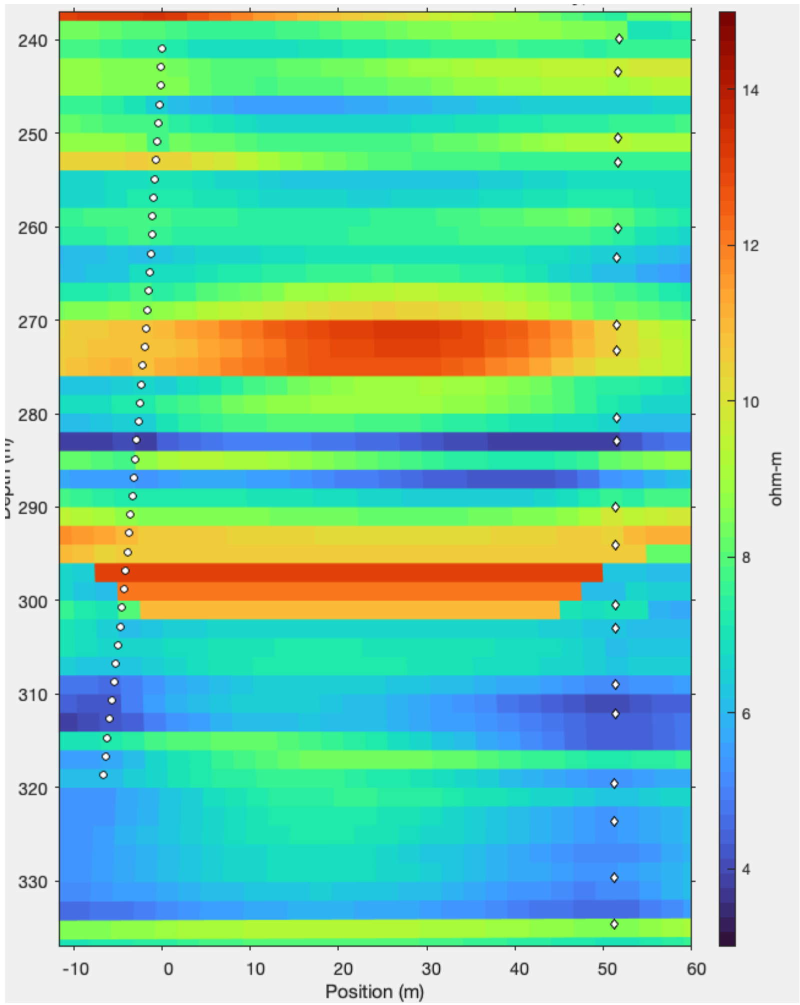
Pre-Injection model



20% Increase in Resistivity Plume

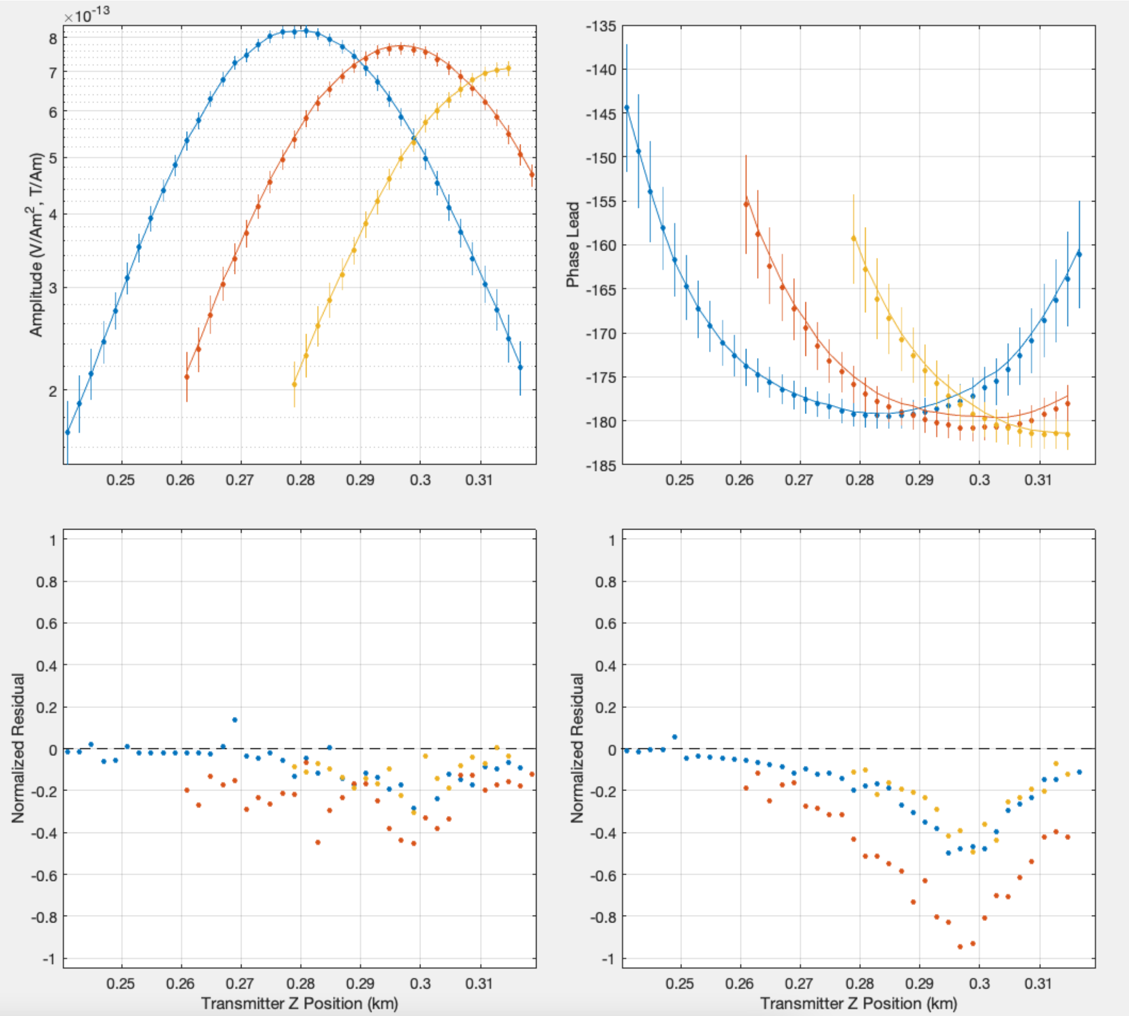


100% Increase in Resistivity Plume

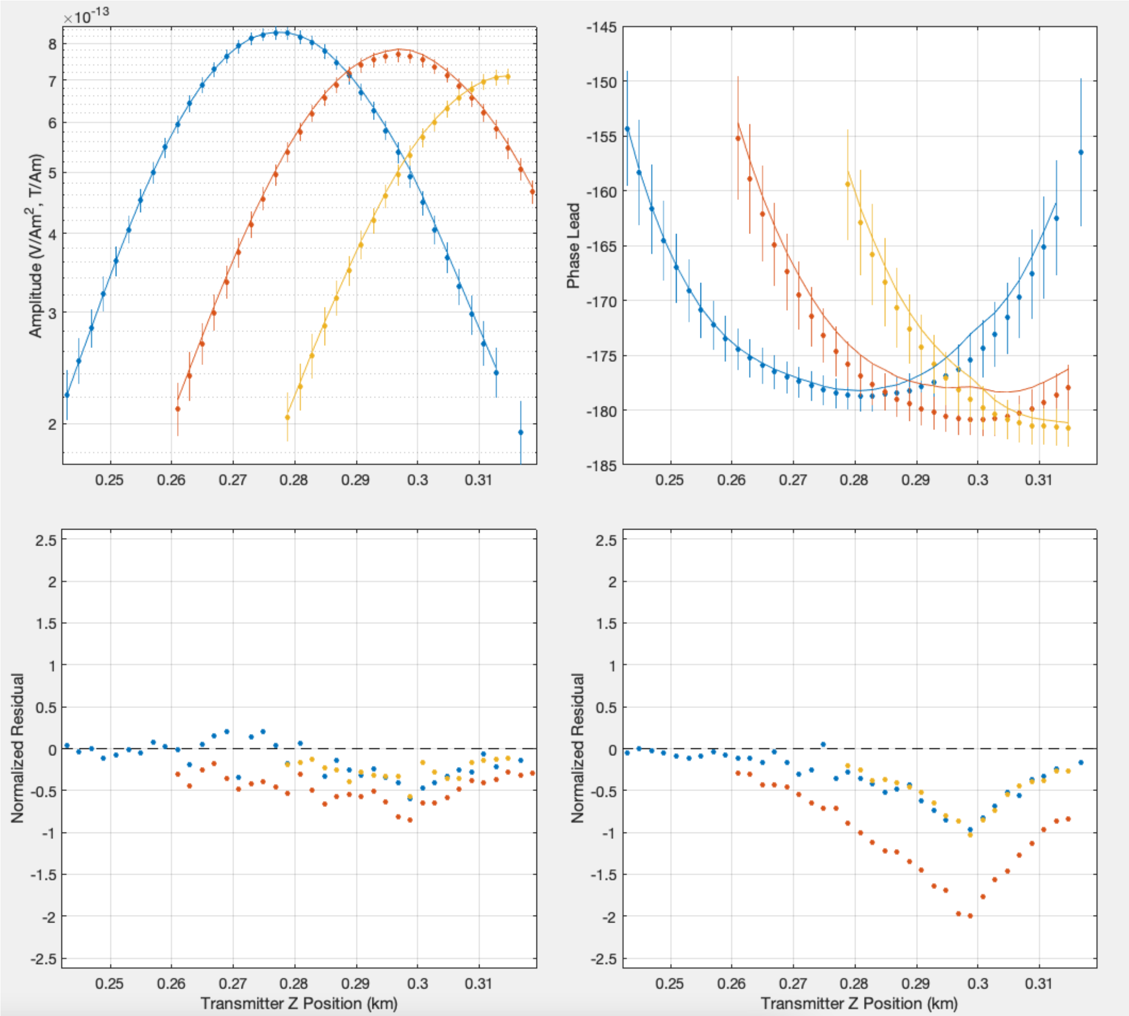


Model Sensitivity Study

20% Increase in Resistivity Plume

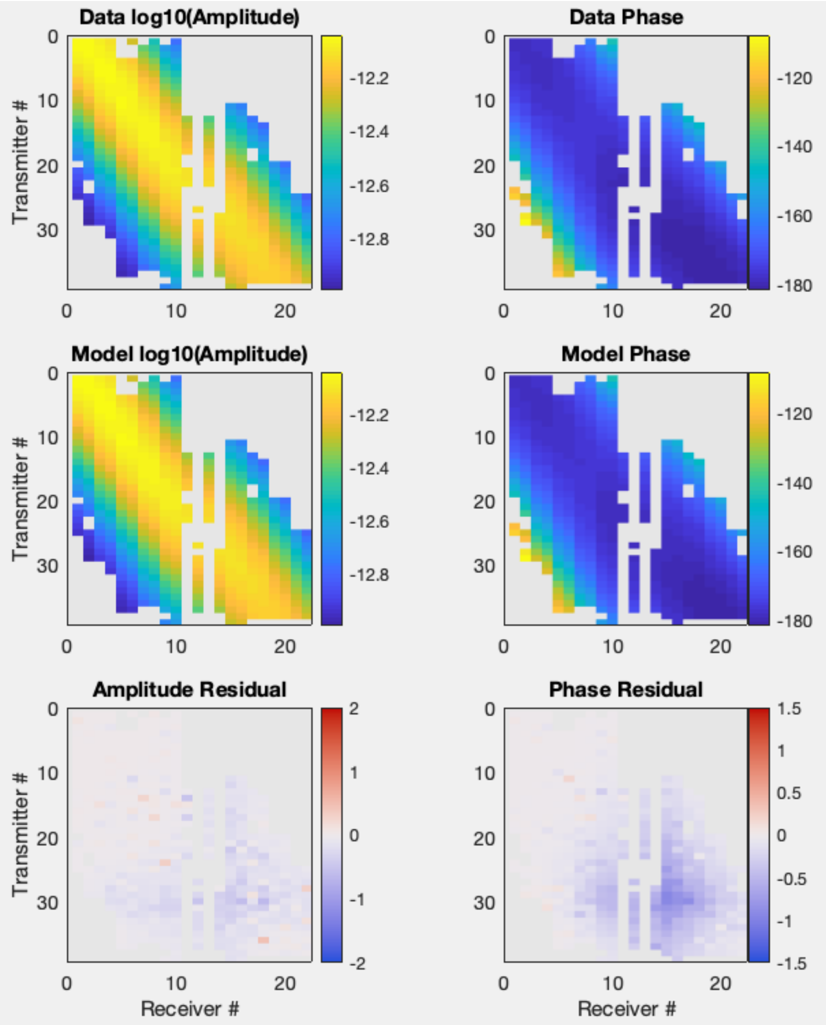


100% Increase in Resistivity Plume

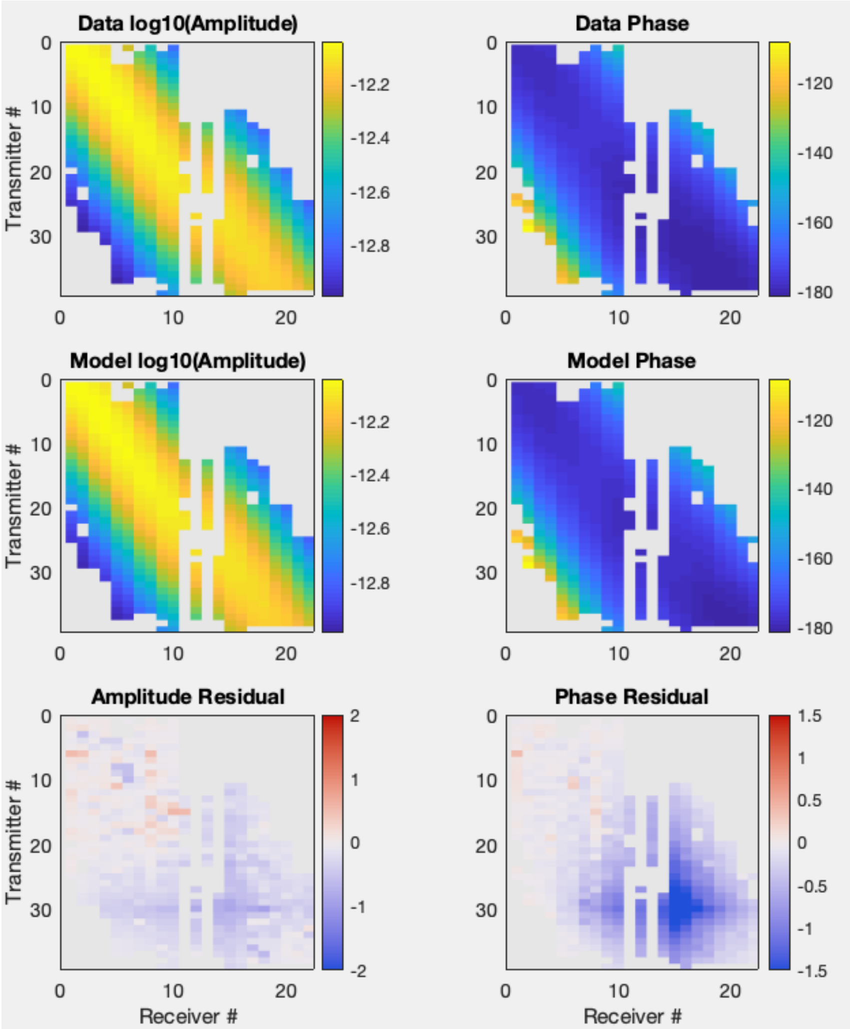


Model Sensitivity Study

20% Increase in Resistivity Plume

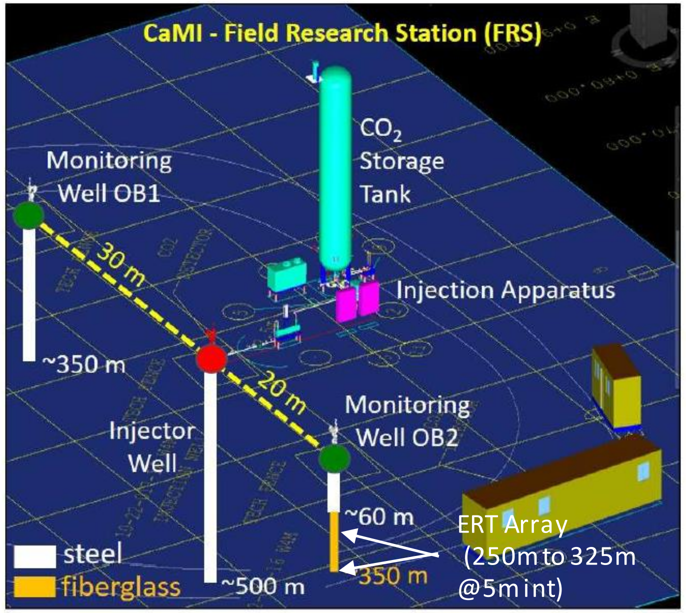


100% Increase in Resistivity Plume

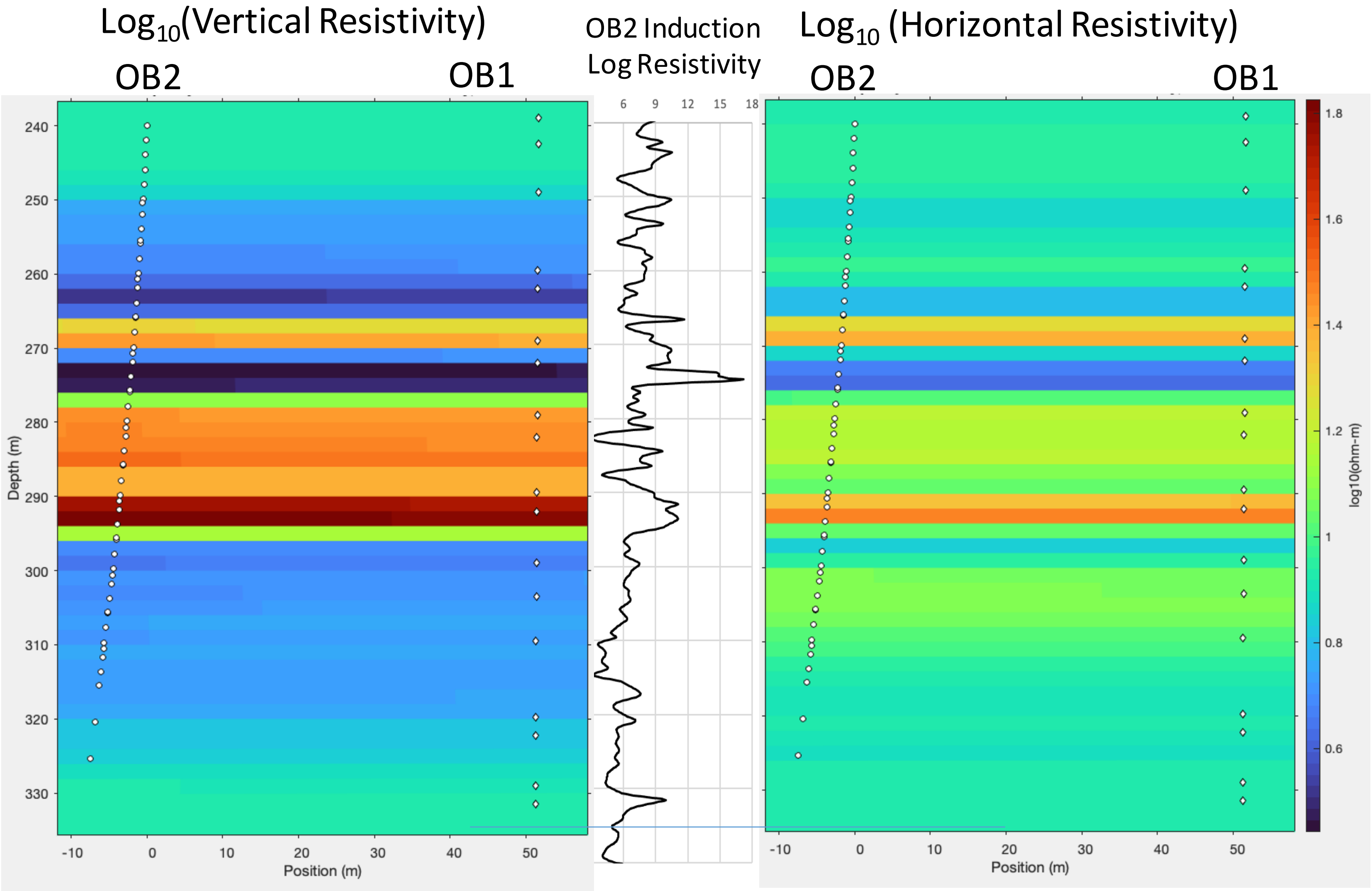


Recent Joint Inversion of CaMI Baseline Data

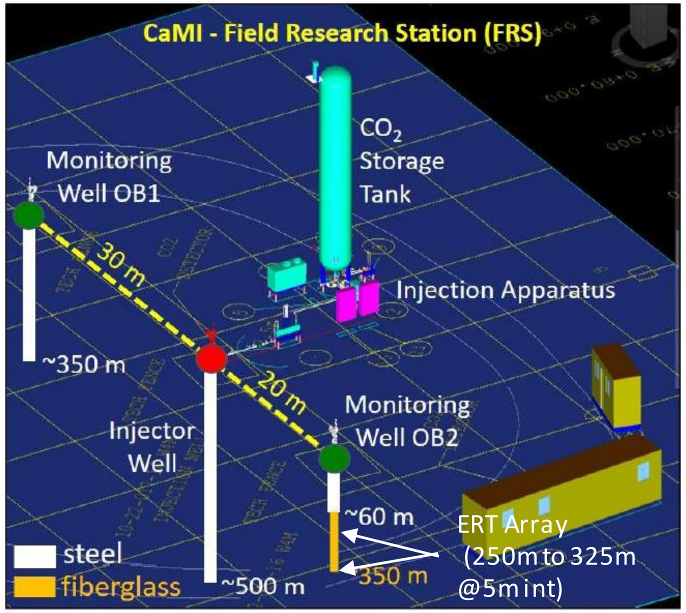
Joint EM & ERT Inversion



1. Joint inversion must employ anisotropic model
2. Results show initial attempts on 2017 background data with high lateral smoothing
3. Physics OK for resistive zones but not conductive zones…

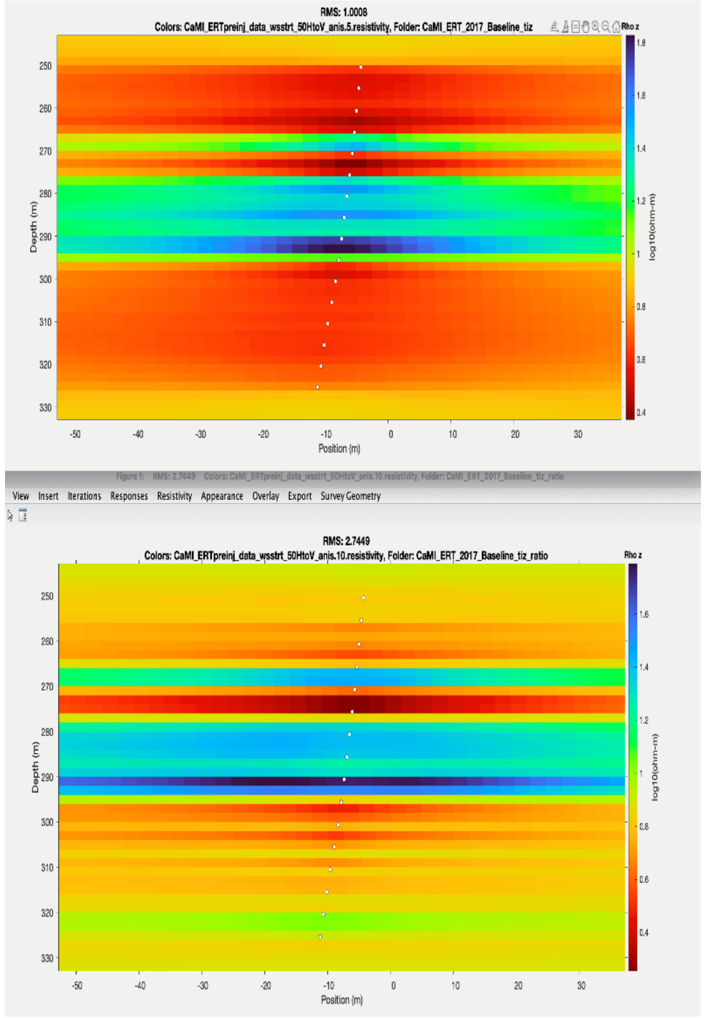


ERT Anisotropic Inversion Studies

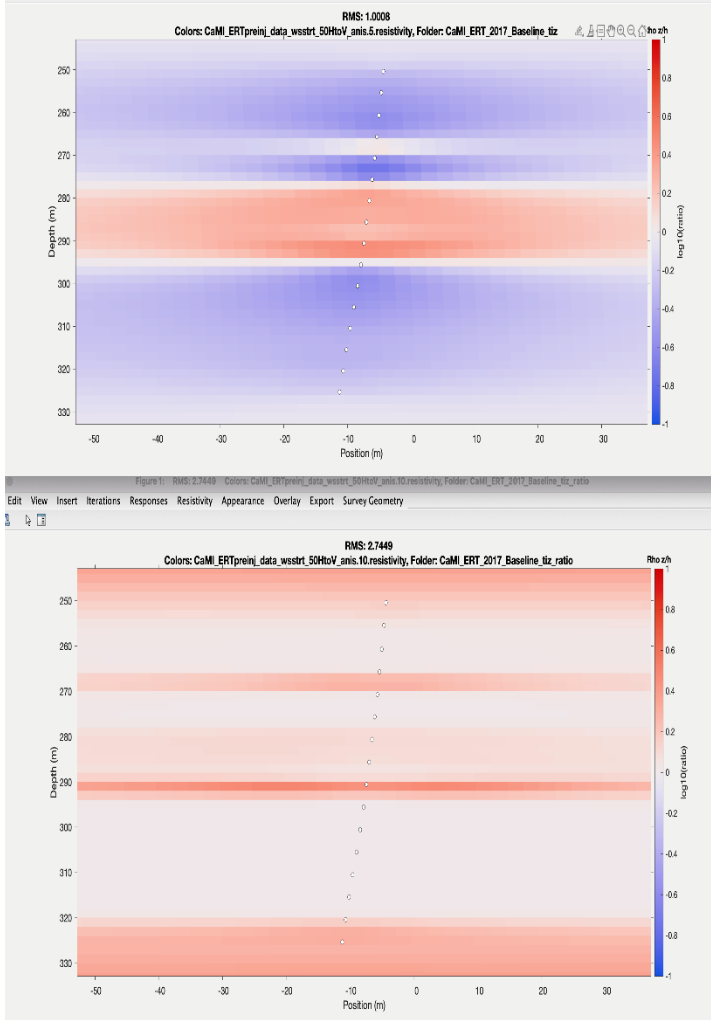


1. To see if we could improve the results, tried a different version of MARE2DEM that inverts for vertical resistivity and resistivity ratio.
2. Ran unconstrained and 'positivity constrained' anisotropic inversion
3. Positivity constrained inversion produced worse data fits

Log_{10}(Vertical Resistivity)



Log_{10}(Vertical /Horizontal)



Accomplishments

- We have built a unique crosswell geophysical data acquisition system that can collect seismic and EM data with sources and sensors that can easily be swapped in and out
- Baseline crosswell EM and seismic data acquired (2017)
  - Data inverted using stand-alone well-log constrained
  - Data also inverted using joint-structural and petrophysical constrained inversion approaches
  - Crosswell EM data jointly inverted with single well ERT data for anisotropic resistivity model
- Time-lapse crosswell EM and Seismic data set collected in December 2021 after ~41,000 tons of injection
  - Crosswell EM data collected and 391 and 600 Hz
    - Power on older EM transmitter increased relative to baseline survey
    - Efficiently processed using new MatLab based processing console
    - Inversions at both frequencies produce resistivities that match known values
  - Crosswell seismic data collected with peak frequency of ~1Khz
    - Spatial sampling interval reduced to 1m due to time constraints
    - Seismic attenuation very sensitive to presence of CO_2

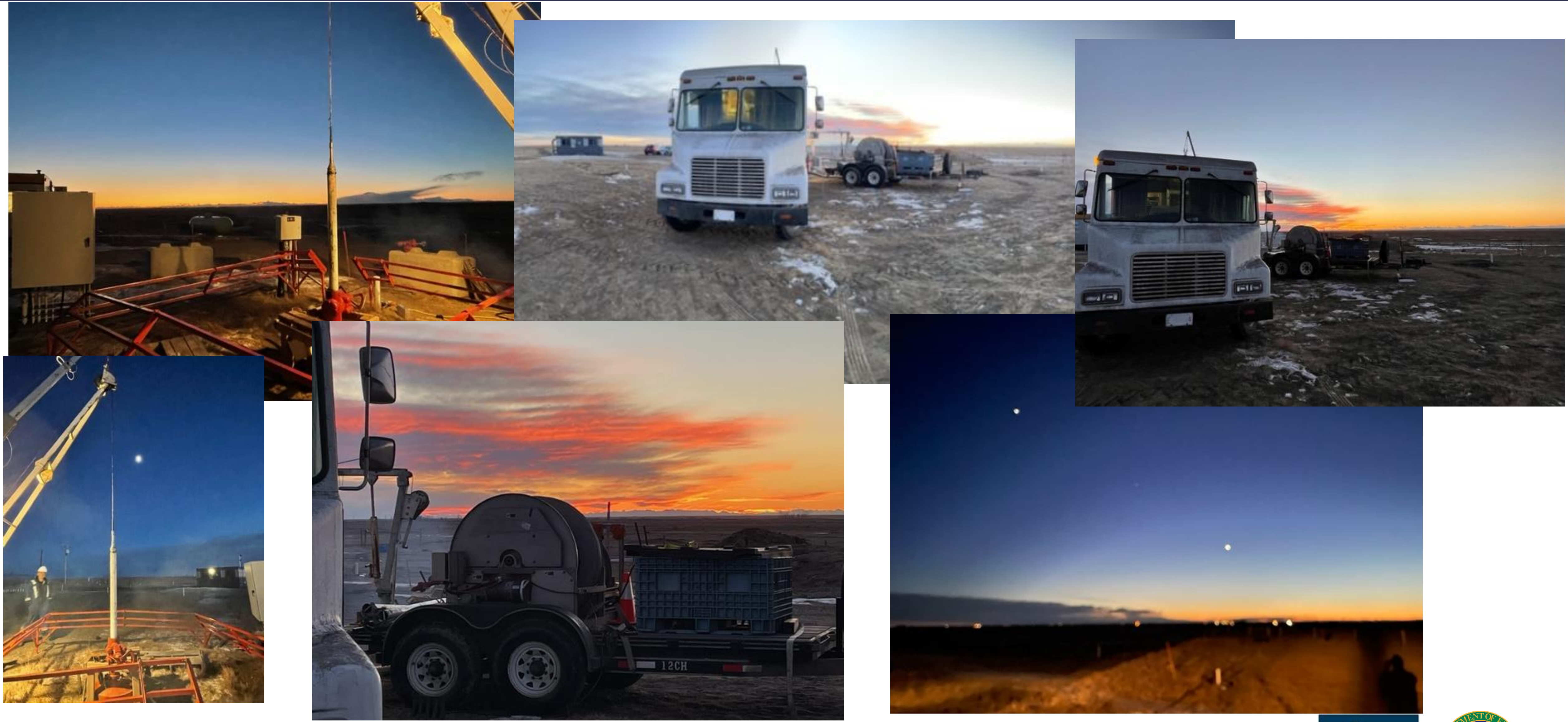
Lessons Learned

- Post injection seismic data very sensitive to low concentrations of CO_2
  - Attenuation caused by low concentration of CO_2 gas limits transmission through plume
  - Standard travel-time tomography cannot be employed due to high attenuation with source at plume CO_2 depth
- Changes in electrical resistivity too low in this case for CO_2 plume to be imaged using inductive Crosswell EM technique
  - Estimated resistivity change only 20% due to 8% change in CO_2 saturation
  - Steel casing on one well limits upper frequency, and hence image resolution, that can be obtained
- Joint anisotropic resistivity inversion of baseline crosswell EM and single well ERT produces reasonable results, but provide unrealistic horizontal versus vertical resistivity in electrically conductive zones

Acknowledgements

- We thank Don Lawton, the CaMI Consortium, and all their partners for site access and the help received during field activities.
- We thank LBNL's Geosciences Measurement Facility (GMF) for its support of custom instrumentation solutions.
- This research was supported by U. S. Department of Energy, National Energy Technology Laboratory, CCSMR program, under the U.S. DOE Contract No. DE-AC02-05CH11231.

Questions????



Appendix

Benefit to Program

- In this task, LBNL has developed technologies to **improve monitoring and quantification** of an important aspect of carbon storage: geologic leakage pathways
- The field experiment has been crucial to understand **monitoring of gas-phase CO_2 at intermediate depth** for a leak into a secondary accumulation ("thief zone"), and has demonstrated how gaseous CO2 in low concentrations affects subsurface geophysical properties
- The joint use of **seismic** and **EM** methods together will ultimately allow for the **imaging of subsurface CO2 over a wide range of saturations.** In this case we investigated the changes caused by low saturations of CO_2

Project Overview

- **Funding**
  - Started FY2022 with $245k in DOE funding
  - Re-purposed an additional $124k (LBL PID 105405 UAE/LLNL Project) to complete work
  - Currently have $32k left for presentations at this DOE program review and SEG annual meeting, as well as to publish the results
- **Overall Project Performance Dates:** To date Task 3 of the CCSMR program has been funded by DOE on a year-to-year basis
- **Project Participants :** LBL, CaMI (University of Calgary, Canada), SINTEF (Norway)
- **Overall Project Objectives for FY2021 Funding:**
  - Demonstrate, and acquire data with, LBL's borehole geophysical data acquisition systems
  - Validate use of joint EM and seismic data acquisition and imaging for imaging CO_2 in shallow conditions
  - Validate joint-inversion technologies for higher resolution imaging

Organizational Chart

CaMI Site Management, University of Calgary
Don Lawton, Greg Maidment, Marie Macquette

LBL
David Alumbaugh, LBL Project Lead

aCQurate Joint Inversion Consortium, SINTEF, Norway
Michael Jordan

Crosswell Seismic Acquisition
Stanislav Glubokovkikh, Ed Nichols

Crosswell Seismic Processing
Stanislav Glubokovkikh

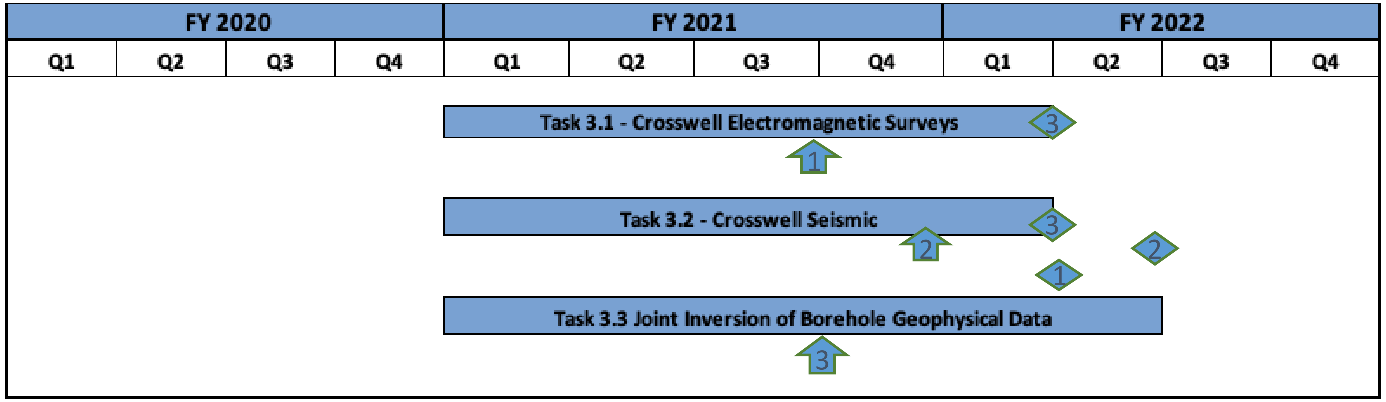
Crosswell EM Acquisition
Mike Wilt, Ed Nichols, David Alumbaugh

Crosswell EM Processing and Inversion
David Alumbaugh, Kerry Key, David Myer

Joint Inversion
Michael Commer

Gantt Chart

For FY2021 PMP-SOPO
Plume Monitoring – Joint EM and Seismic



Major Milestones

1. Complete Development of Sequential and Joint Inversion Capabilities
2. Joint Inversion of Crosswell EM and ERT Data Using the MARE2DEM Code
3. Crosswell EM and Seismic Repeat Surveys Acquisition
4. Sequential and Joint Inversion of Repeat EM, ERT, and Seismic Datasets – Not able to complete due to insufficient seismic data quality

Other Advances

1. Finish Testing of Crosswell EM System at RFS
2. Finish Testing of Crosswell Seismic System at RFS
3. Complete first inversion of CaMI Baseline ERT Data using MARE2DEM code