CCSMR Task 3: Electromagnetic Measurements and Modeling for the Wyoming CarbonSAFE Site

Project Number LBNL-ESD14095

David Alumbaugh* and Evan Um, LBNL

In Collaboration With
J. Fred McLaughlin, Charles Nye, and Robert Gregory, University of Wyoming
Giacobe Moe and Field Crew- Zonge International

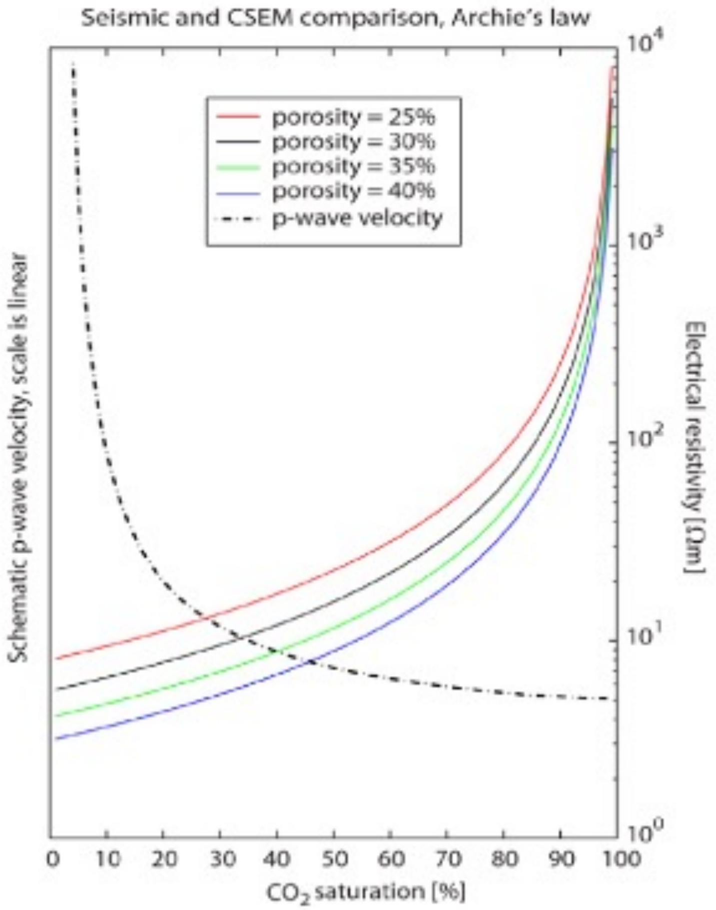
Why the Interest in EM Geophysics for Monitoring?

Geophysical Monitoring of CCUS

- Specific geophysical monitoring techniques are not required by the current EPA Class VI permitting process
- Normally time lapse (4D) seismic (either VSP or surface reflection) is assumed to be the best choice for monitoring
- Nine Class VI proposals for Region 5 currently under review involve injection into the Mount Simon Sandstone
  - All nine have seismic method as their principal 3D monitoring technique
  - Seven of the nine are only relying on some type of time lapse surface seismic (they are also acquiring passive seismic data)

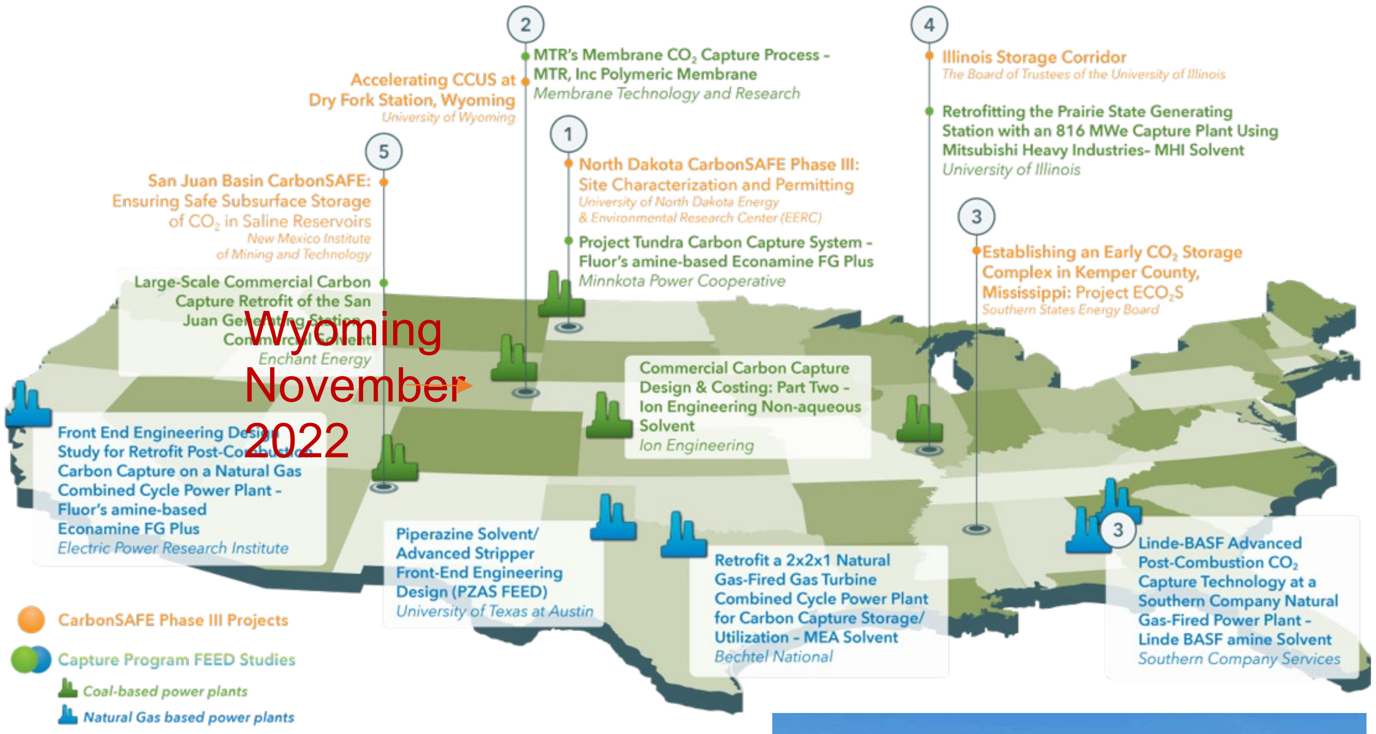
Possible Issues

- Mount Simon Sandstone Injections
  - Many of the subunits in Mount Simon are very old and 'stiff'
  - Preferential flow in high permeability units may result in thin CO_2 plumes
  - These factors can result in very little seismic response
- Seismic velocities sensitive to low but not higher saturation changes



As shown on the right, EM resistivity is more sensitive to high saturations, and since resistivity is primarily a function of pore fluid rather than rock matrix, EM methods may have higher sensitivity in some cases than seismic….

EM Measurements at The Wyoming Dry Fork Station CarbonSAFE Site



Map View of EM Sources and Receivers

Legend

Transmitters

TxNS	North-South transmit dipole shown by red line
TxEW	East-West transmit dipole shown by blue line – Connects to wellhead PRB1
TxPR	Dipole connecting to wellhead PRB1 to PRB2

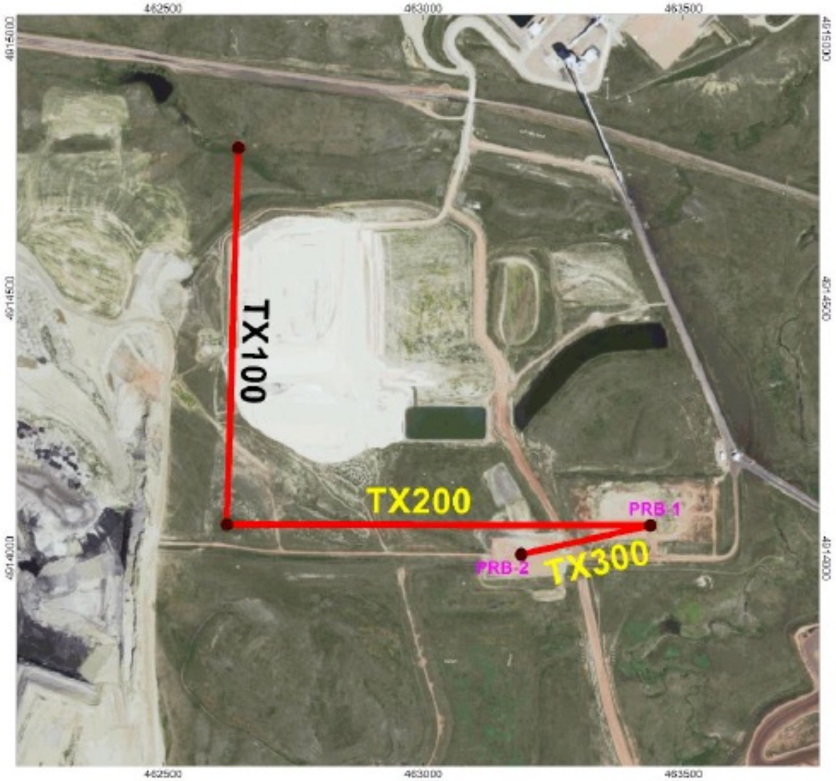
Receivers

SR*	Stationary Receivers – Do not move position day to day
MR#*	Mobile Receivers (2) # = Day of Deployment *=a or b receiver

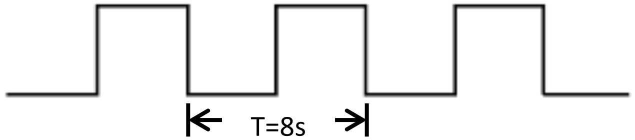
BERKELEY LAB

Description of EM Sources and Receivers

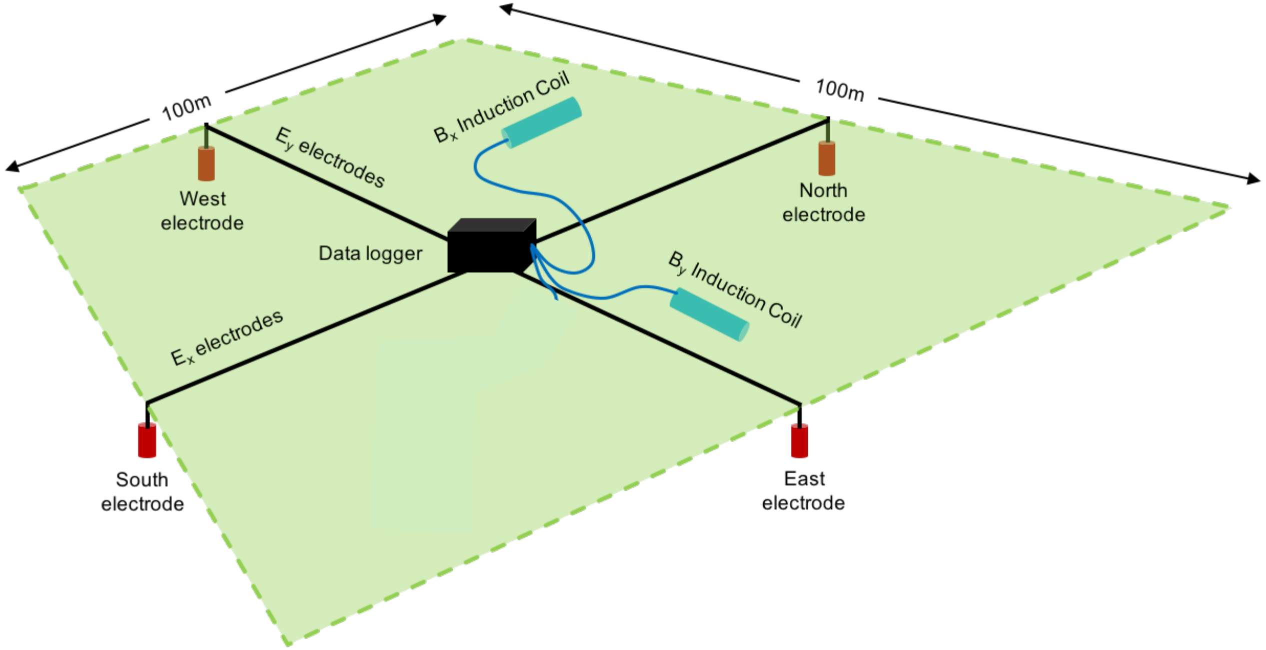
Blow up of Source Deployment



Zonge GGT-10 Transmitter used to transmit a 0.125Hz Square Wave



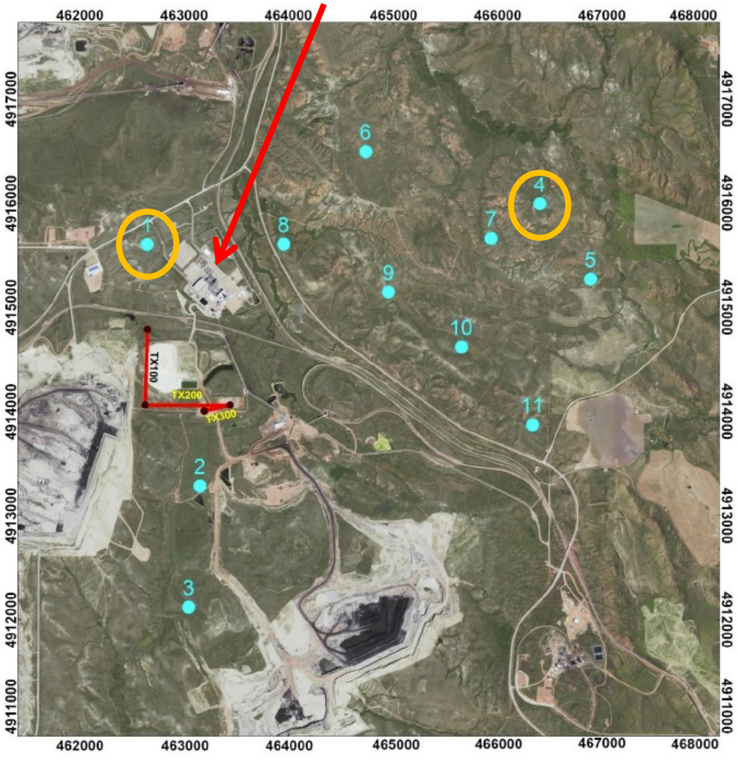
Receiver Deployment

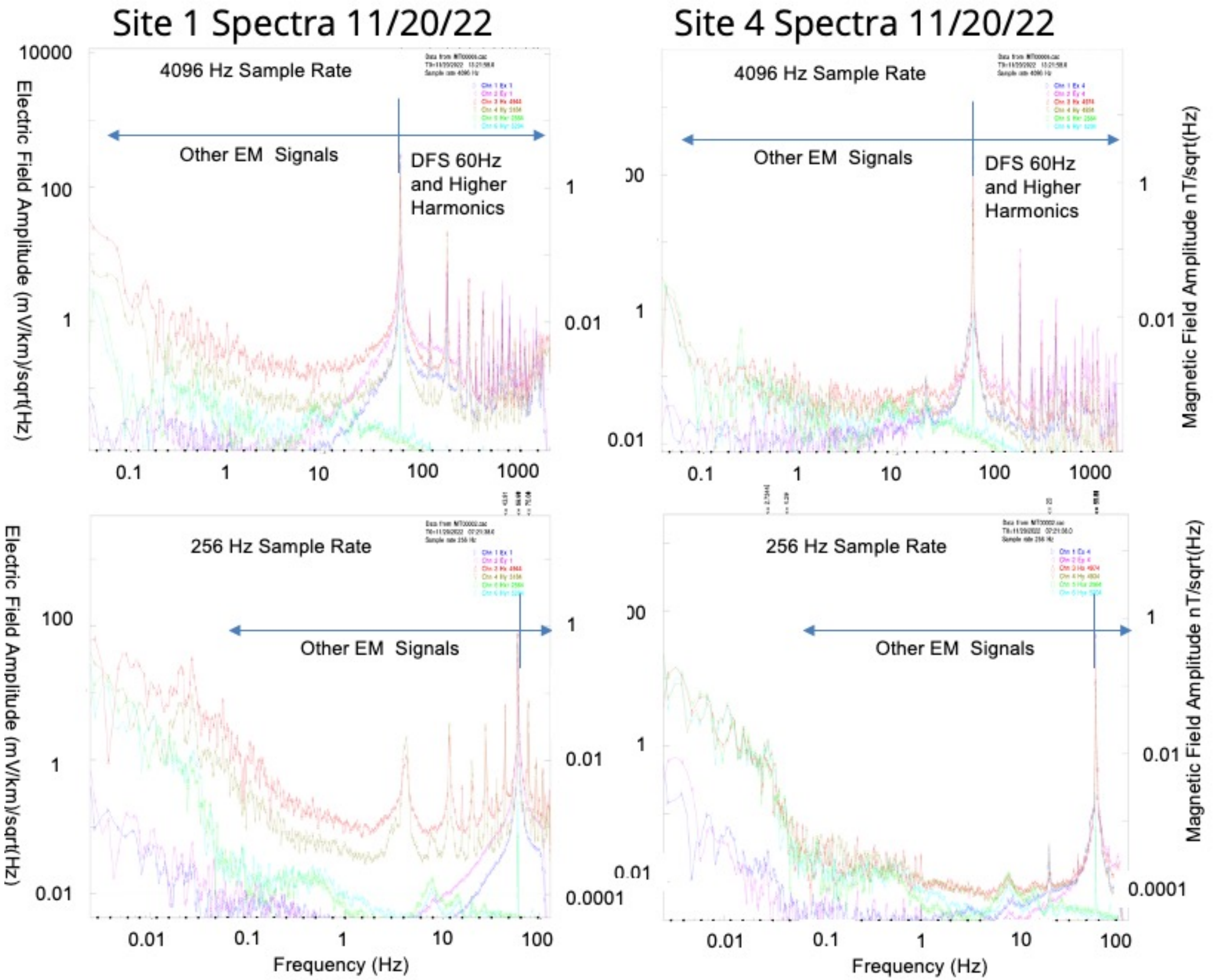


Zonge 32 bit ZEN acquisition unit used at each station
Zonge ANT/4 Coils used for magnetic field measurement

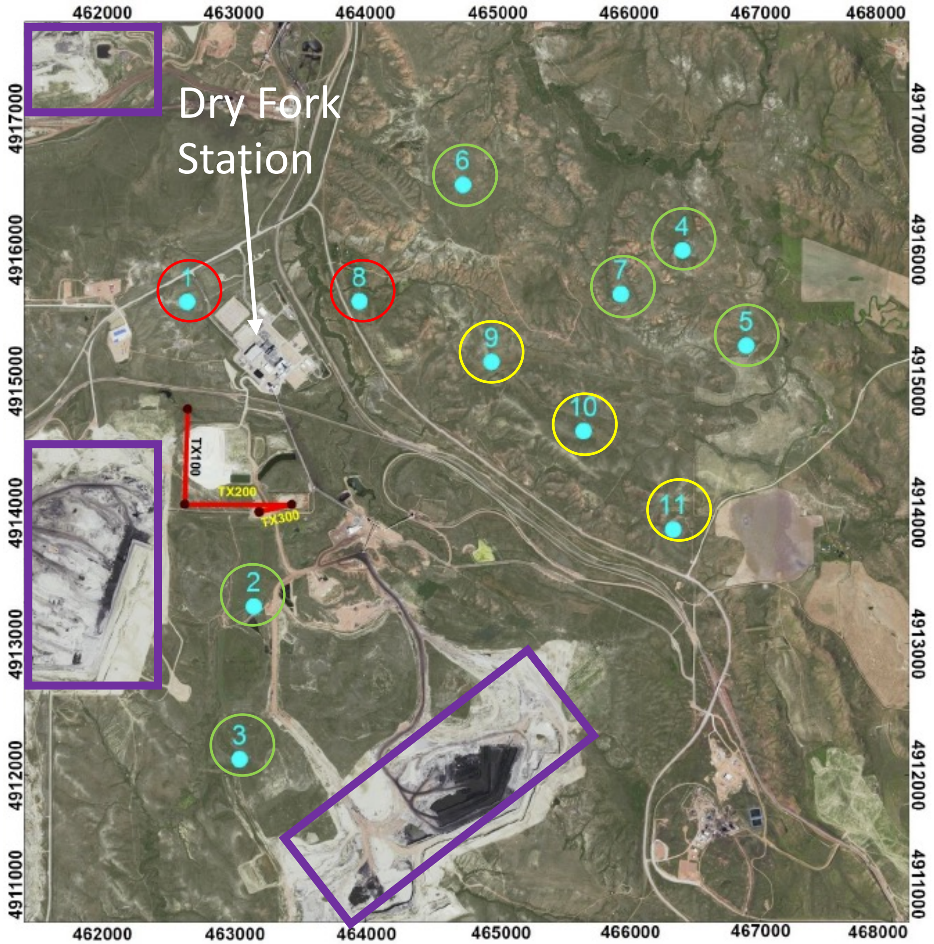
EM Spectral 'Noise' Measurements at The Wyoming Dry Fork Station

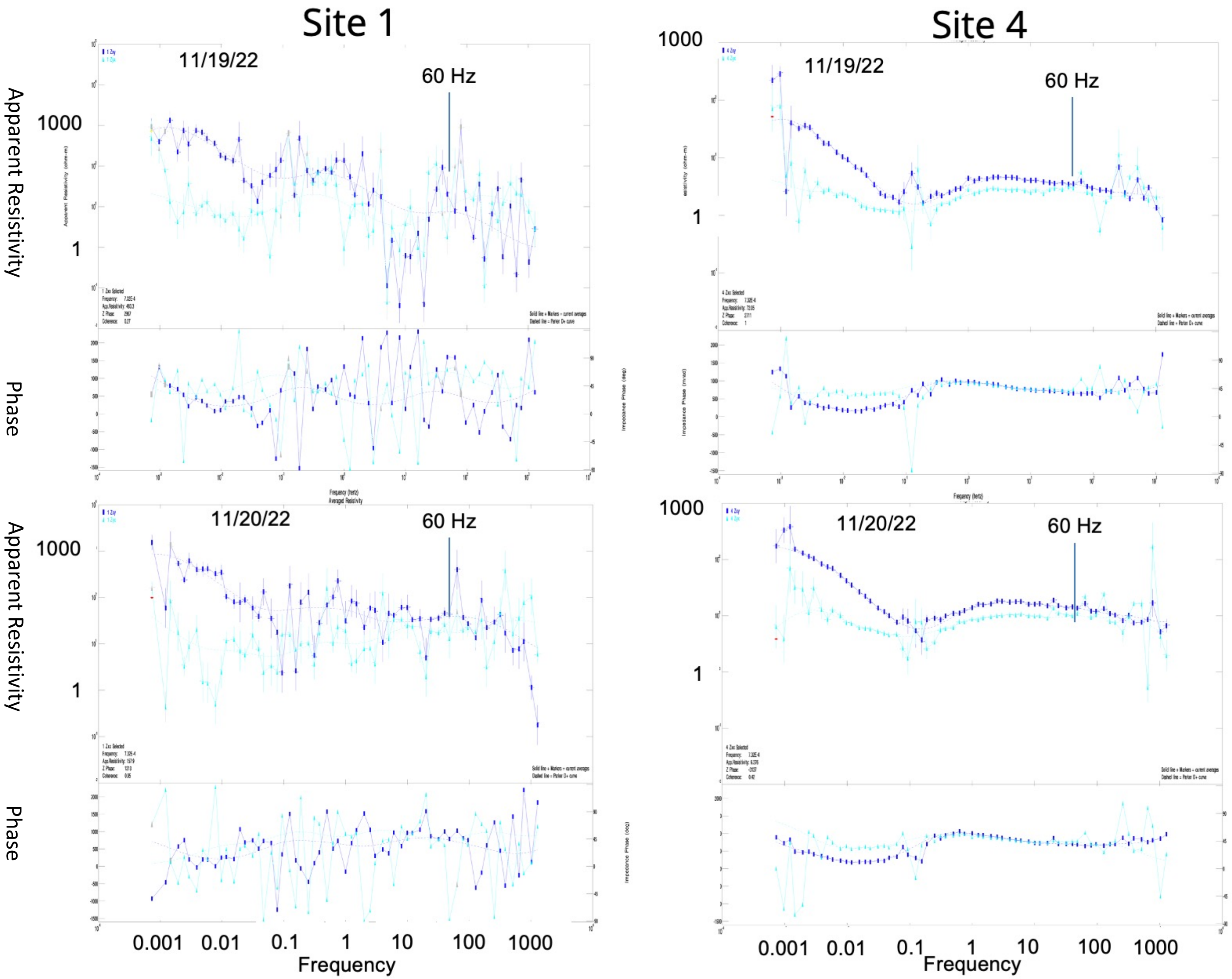
Dry Fork Station





Processed Magnetotelluric Data at The Wyoming Dry Fork Station





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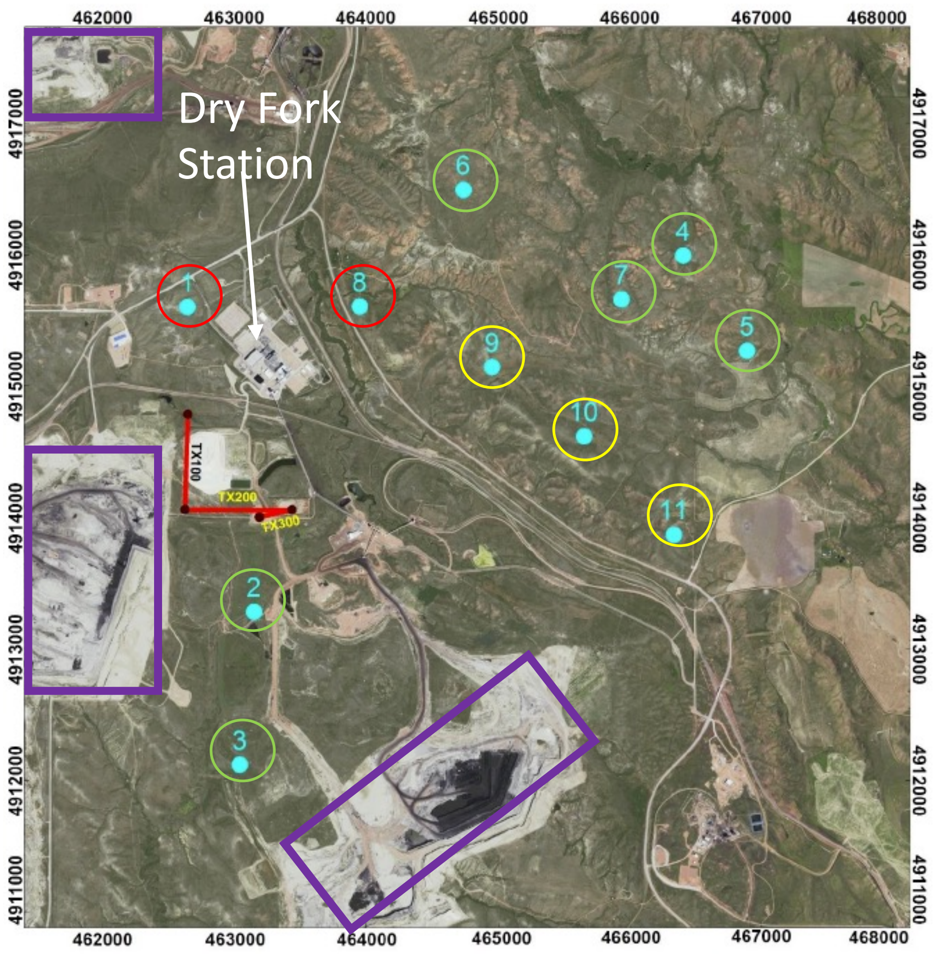
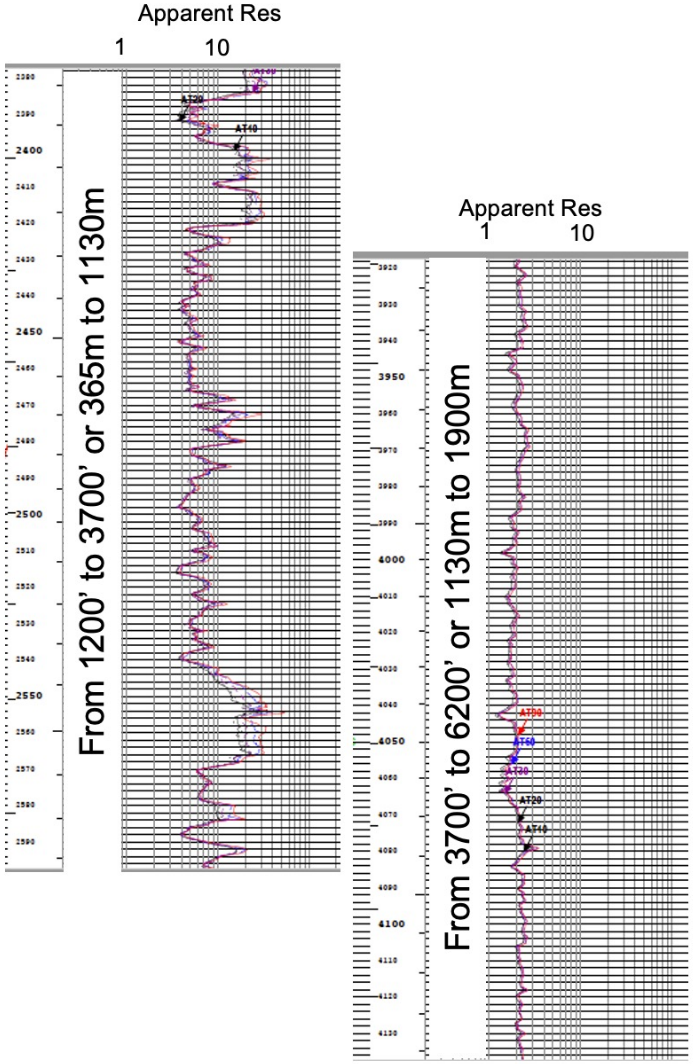
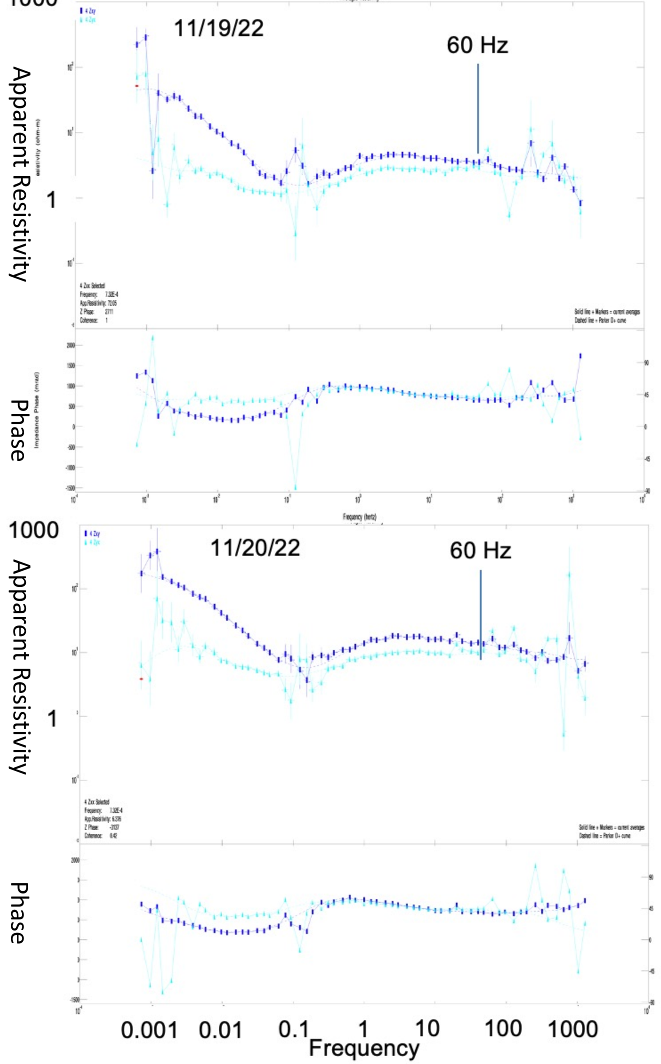


UW PRB1 Induction Log



Site 4



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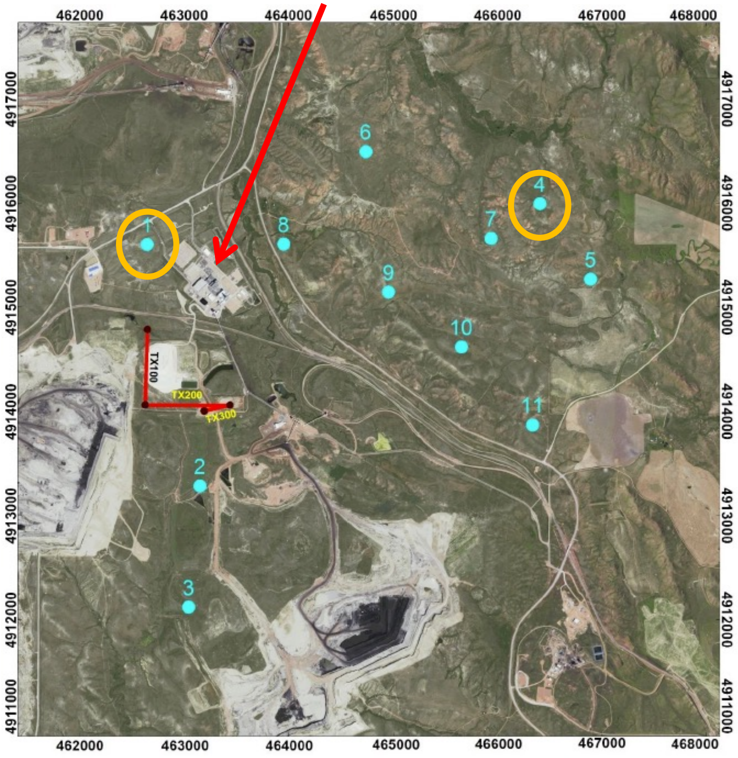
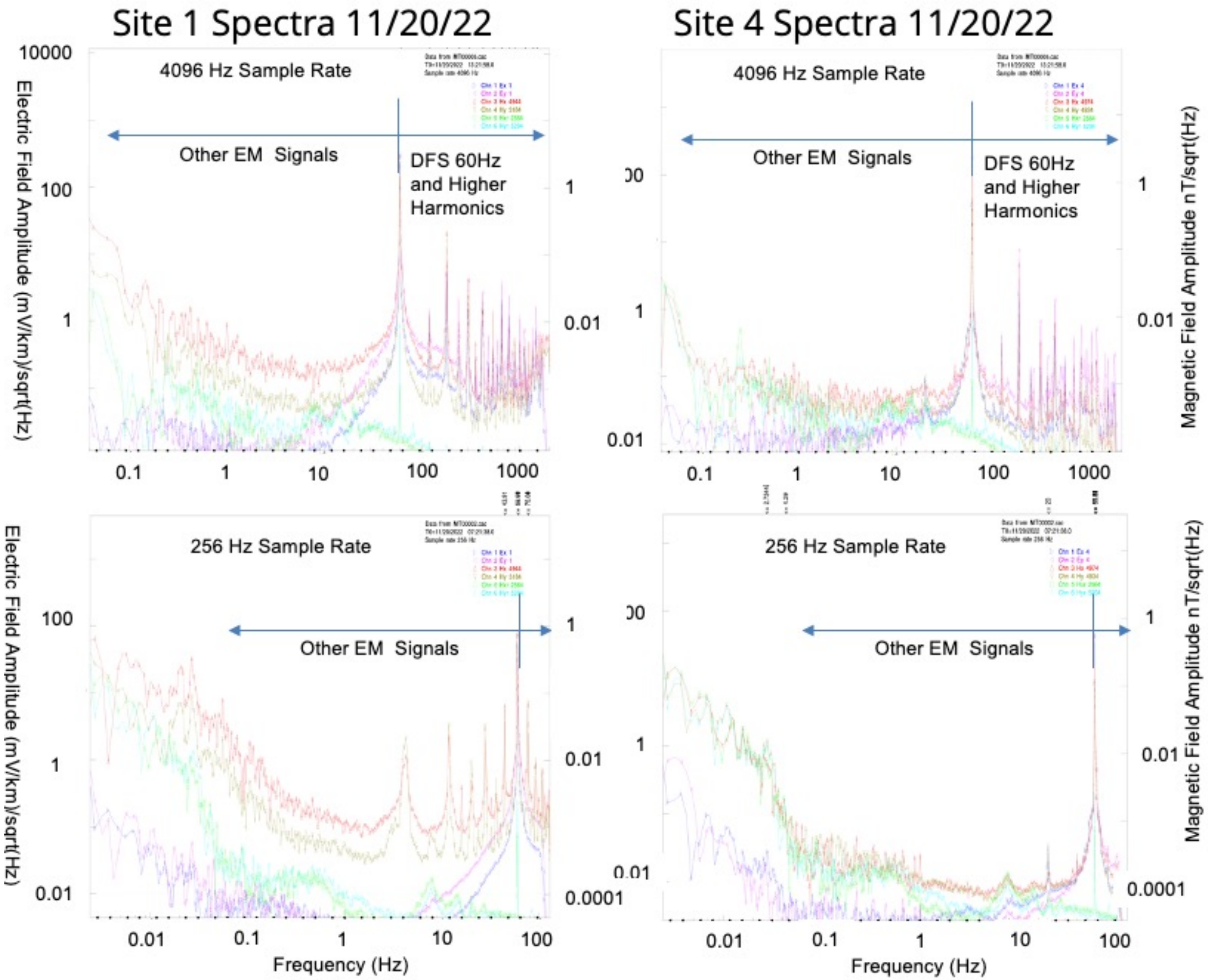
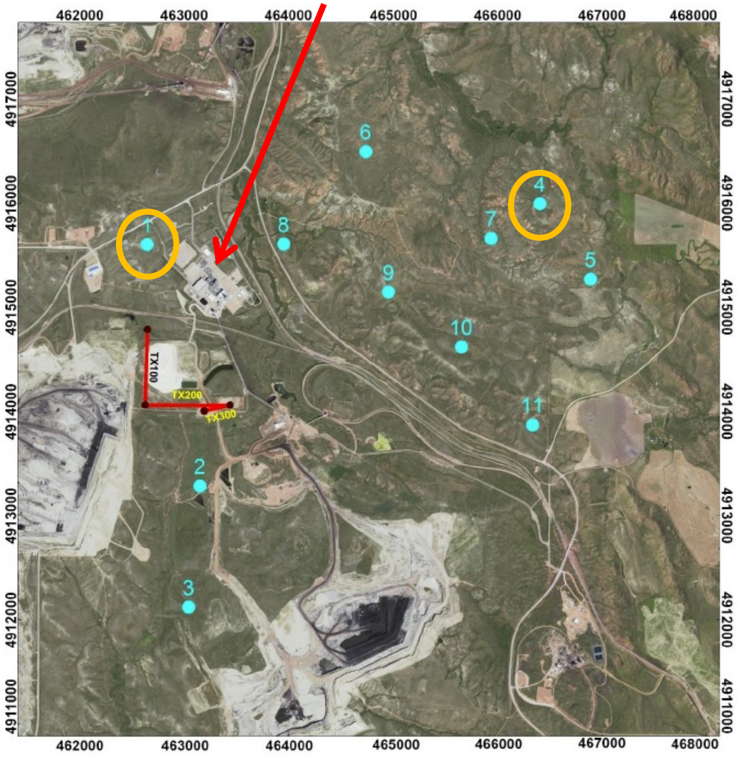


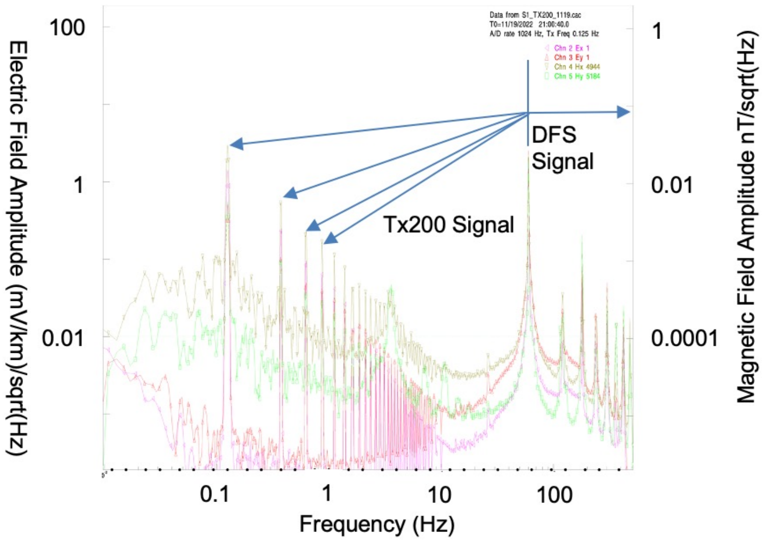


CSEM Measurements

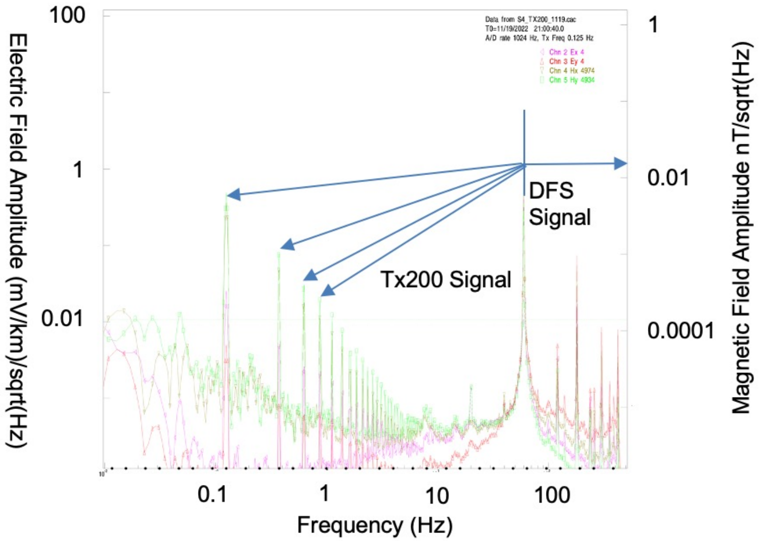
Dry Fork Station



Site 1

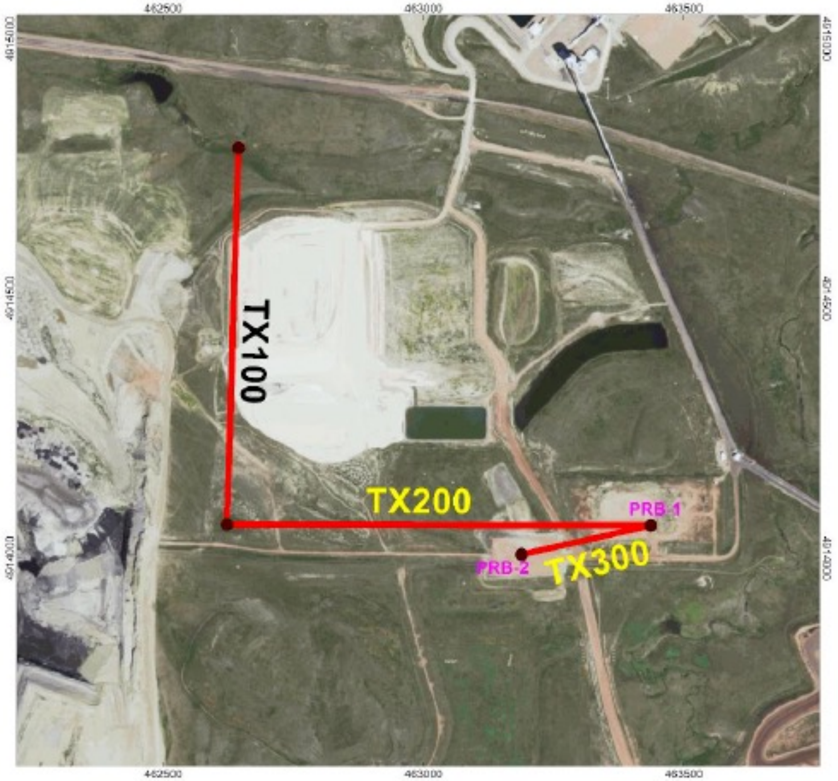


Site 4



Description of EM Sources and Receivers

Blow up of Source Deployment



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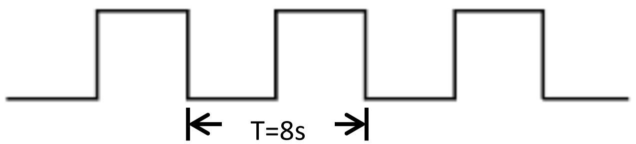
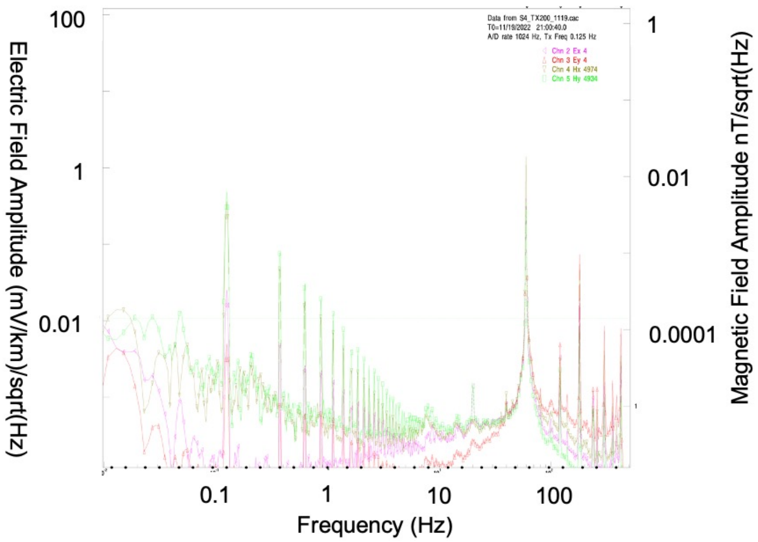
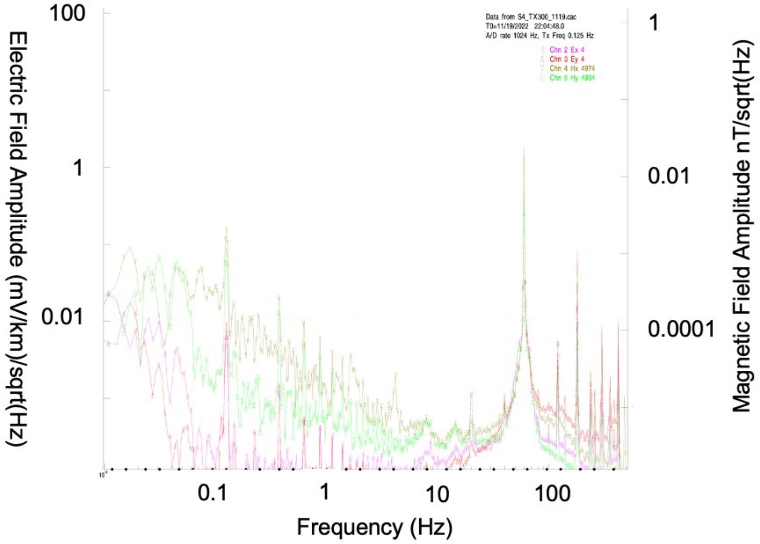


TX200



Tx300



3DEM Modeling – Creation of Model

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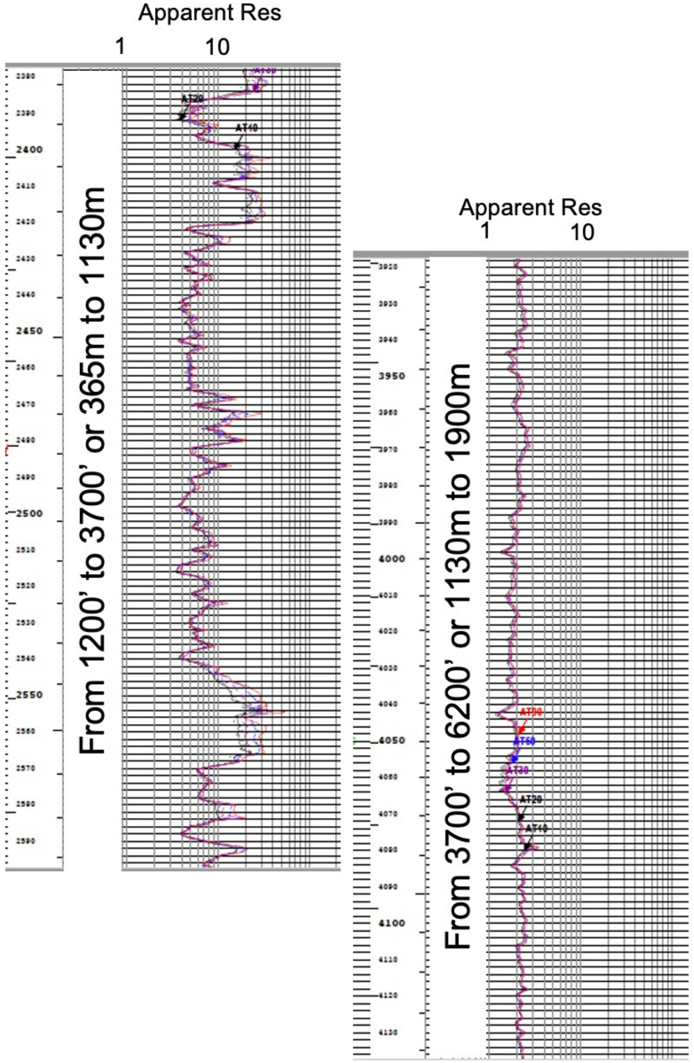
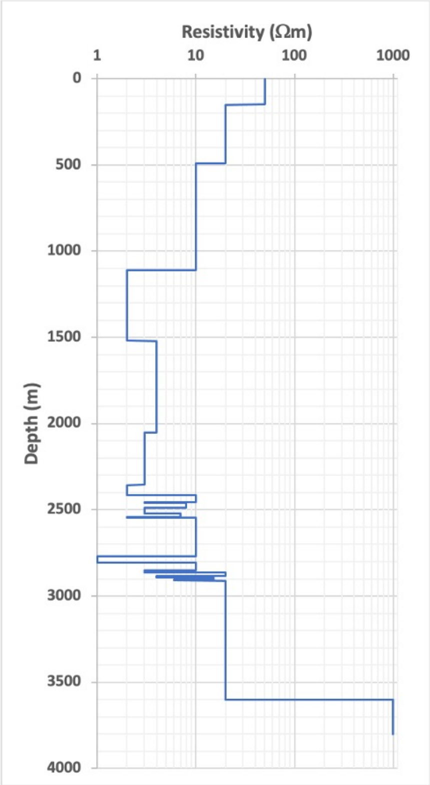


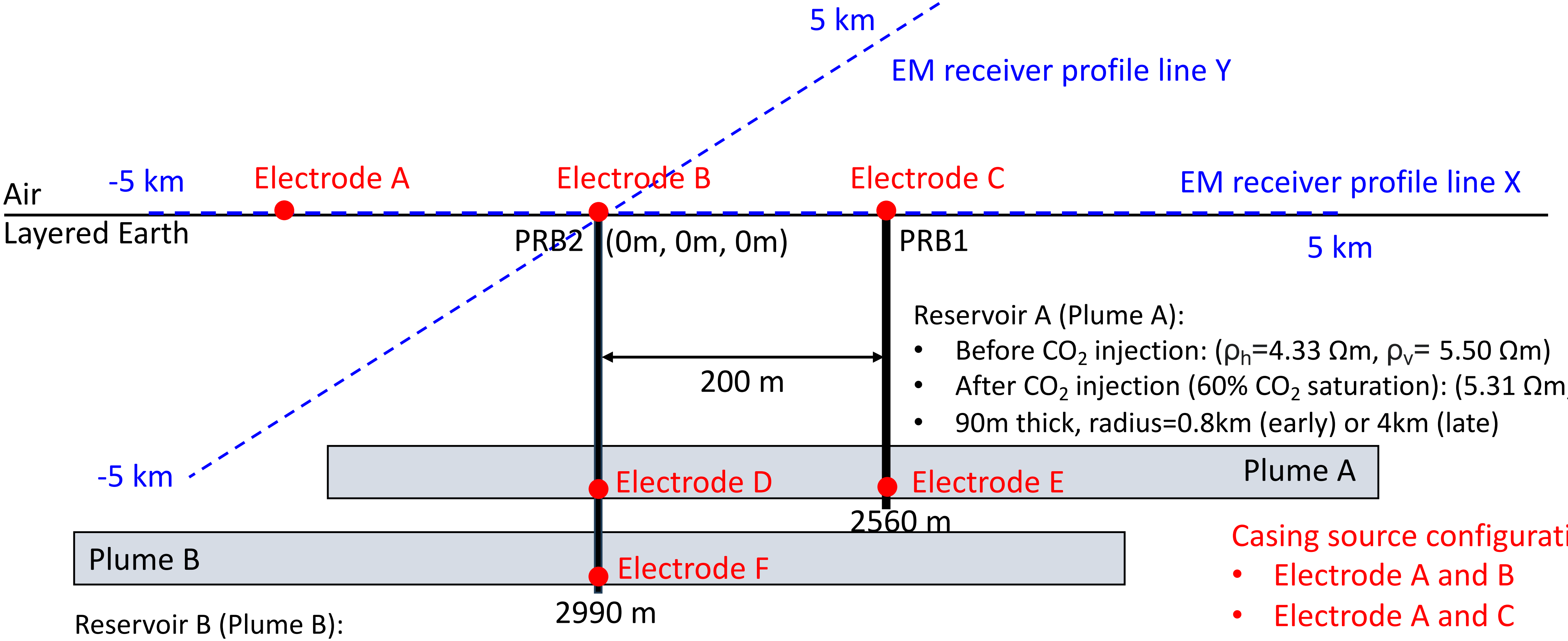
Layered Resistivity Model

Depth Range (m)	**Resistivity**
0-150	50 Ωm
150-490	20 Ωm
490-1110	10 Ωm
1110-1520	2 Ωm
1520-2050	4 Ωm
2050-2355	3 Ωm
2355-2415	2 Ωm
2415-2455	10 Ωm
2455-2460	3 Ωm **
2460-2490	8 Ωm
2490-2520	3 Ωm
2520-2540	7 Ωm
2540-2545	2 Ωm**
2545-2770	10 Ωm
2770-2805	1 Ωm
2805-2850	10 Ωm
2850-2865	3 Ωm**
2865-2885	20 Ωm
2885-2890	4 Ωm**
2890-2905	15 Ωm
2905-2910	6 Ωm**
2910-3600	20 Ωm
3600-inf	1000 Ωm



	Porosity	Reservoir Resistivity (Sw=1)	Fluid Resistivity	Reservoir Resistivity (Sw=0.4, Sco2=0.6)
Reservoir 1	0.35	3	0.61	30.93
Reservoir 2	0.3	2	0.42	29.46
Reservoir 3	0.2	3	0.35	54.13
Reservoir 4	0.15	4	0.30	83.33
Reservoir 5	0.1	6	0.24	153.09

3DEM Modeling – Creation of Model



Reservoir A (Plume A):

- Before CO_2 injection: (ρ_h=4.33 Ωm, ρ_v= 5.50 Ωm)
- After CO_2 injection (60% CO_2 saturation): (5.31 Ωm, 8.58 Ωm)
- 90m thick, radius=0.8km (early) or 4km (late)

Reservoir B (Plume B):

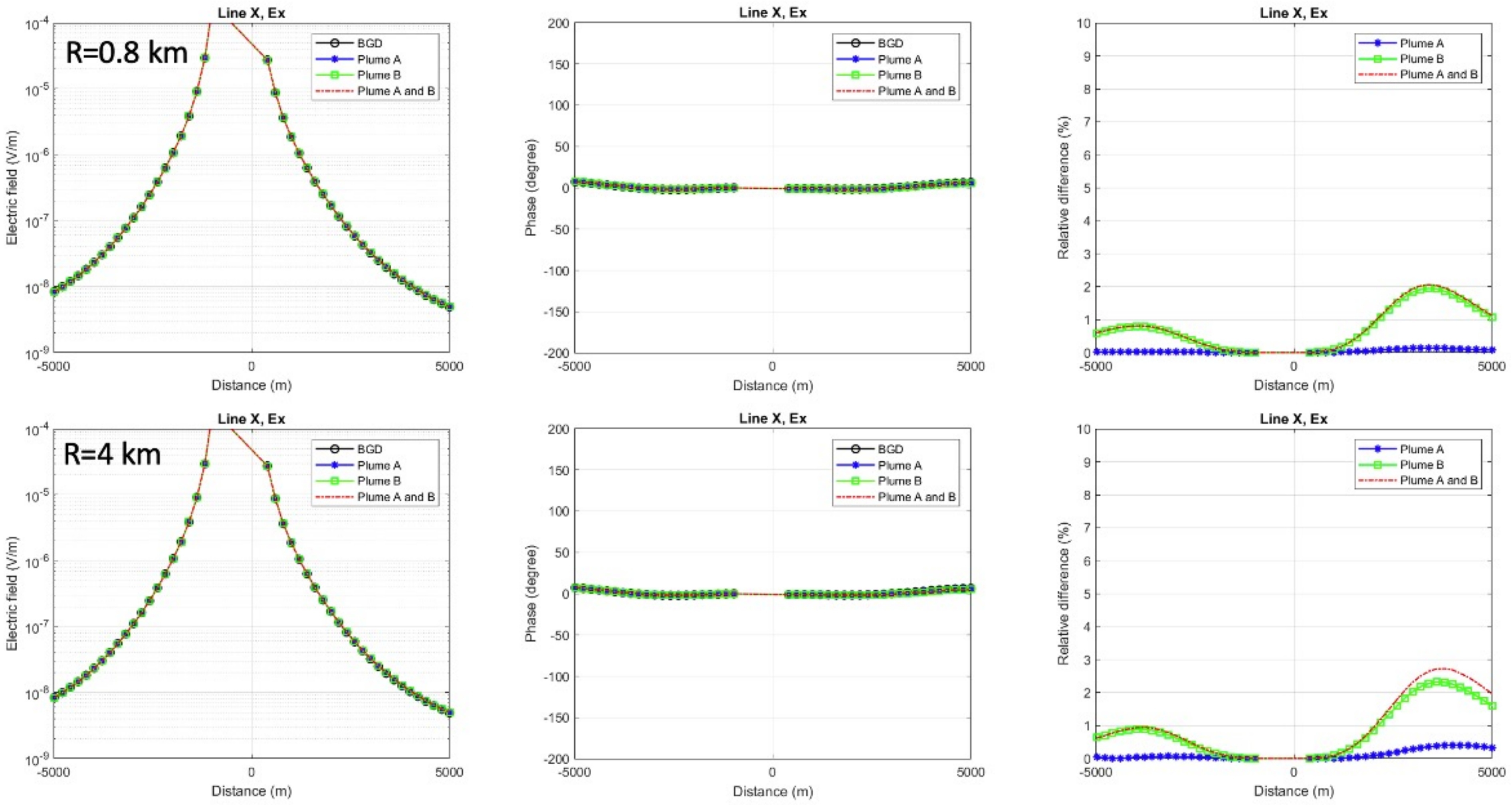
- Before CO_2 injection: (ρ_h=6.61Ωm, ρ_v= 12.0 Ωm)
- After CO_2 injection (60% CO_2 saturation): (25.3 Ωm, 43.7 Ωm)
- 60m thick, radius=0.8km (early) or 4km (late)

Casing source configurations:

- Electrode A and B
- Electrode A and C
- Electrode B and C
- **Electrode A and F**
- Electrode A and E
- **Electrode F and E**

3DEM Modeling – Tx with Electrodes A&F (Similar to TX200)

Ex along Line X



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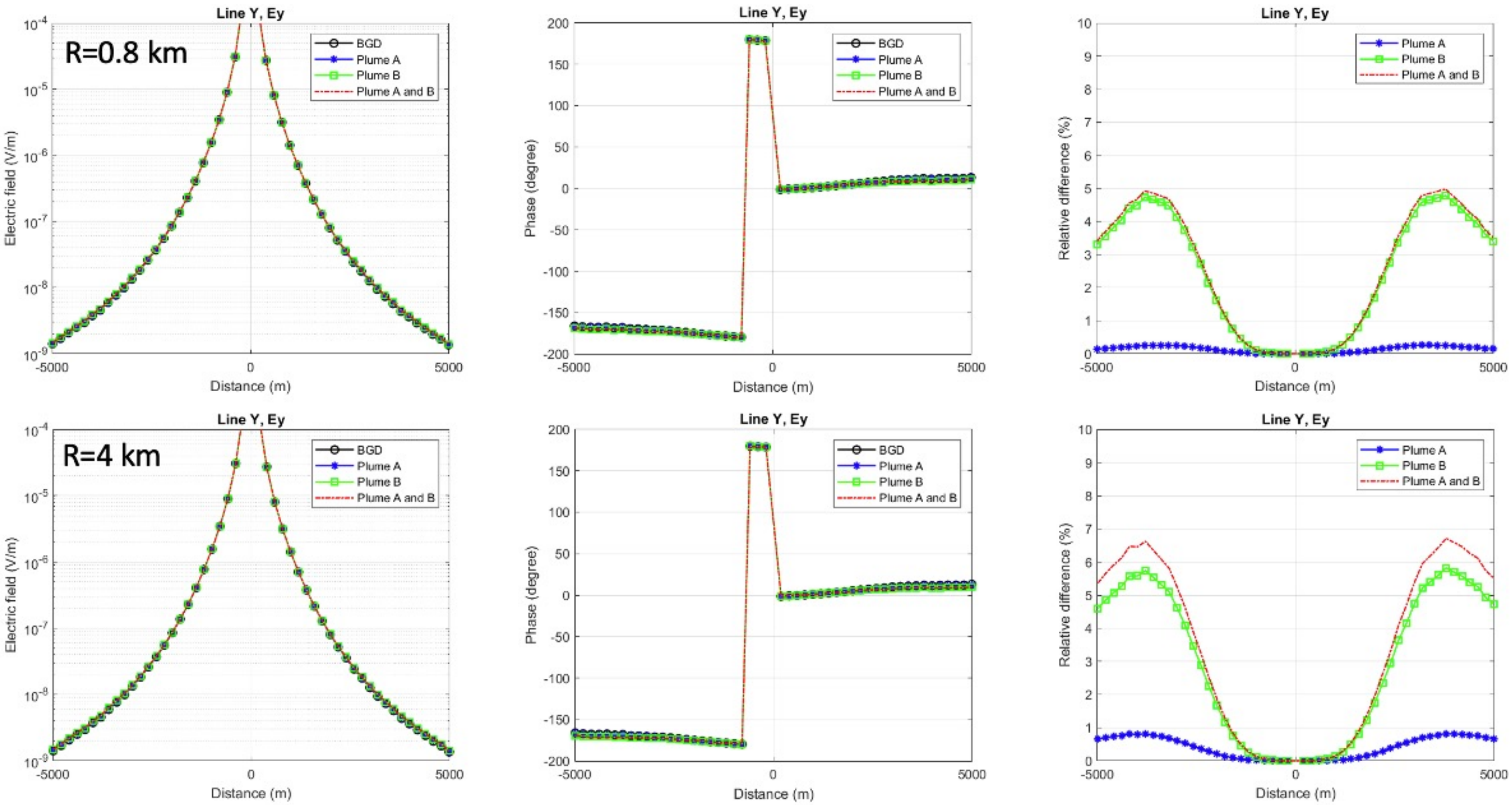
Ey along Line Y



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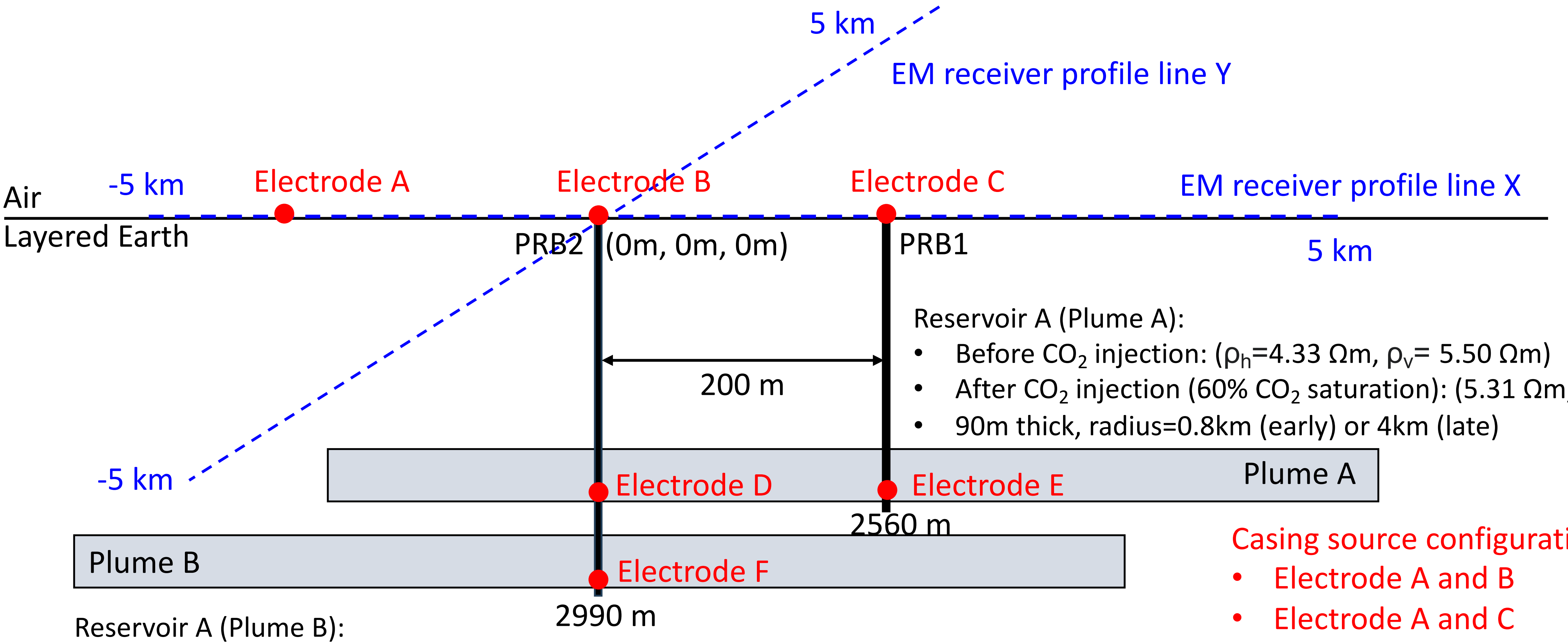

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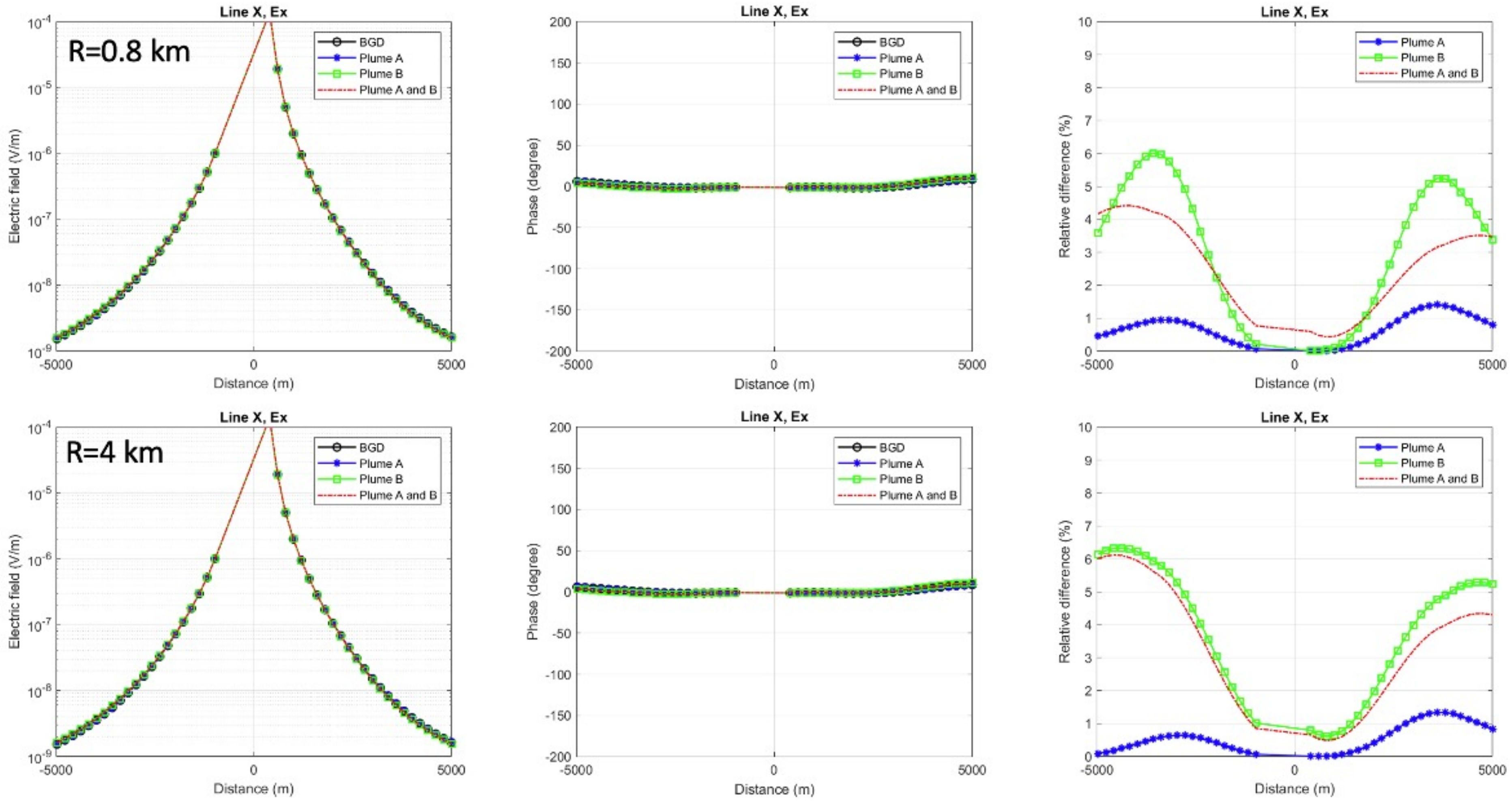

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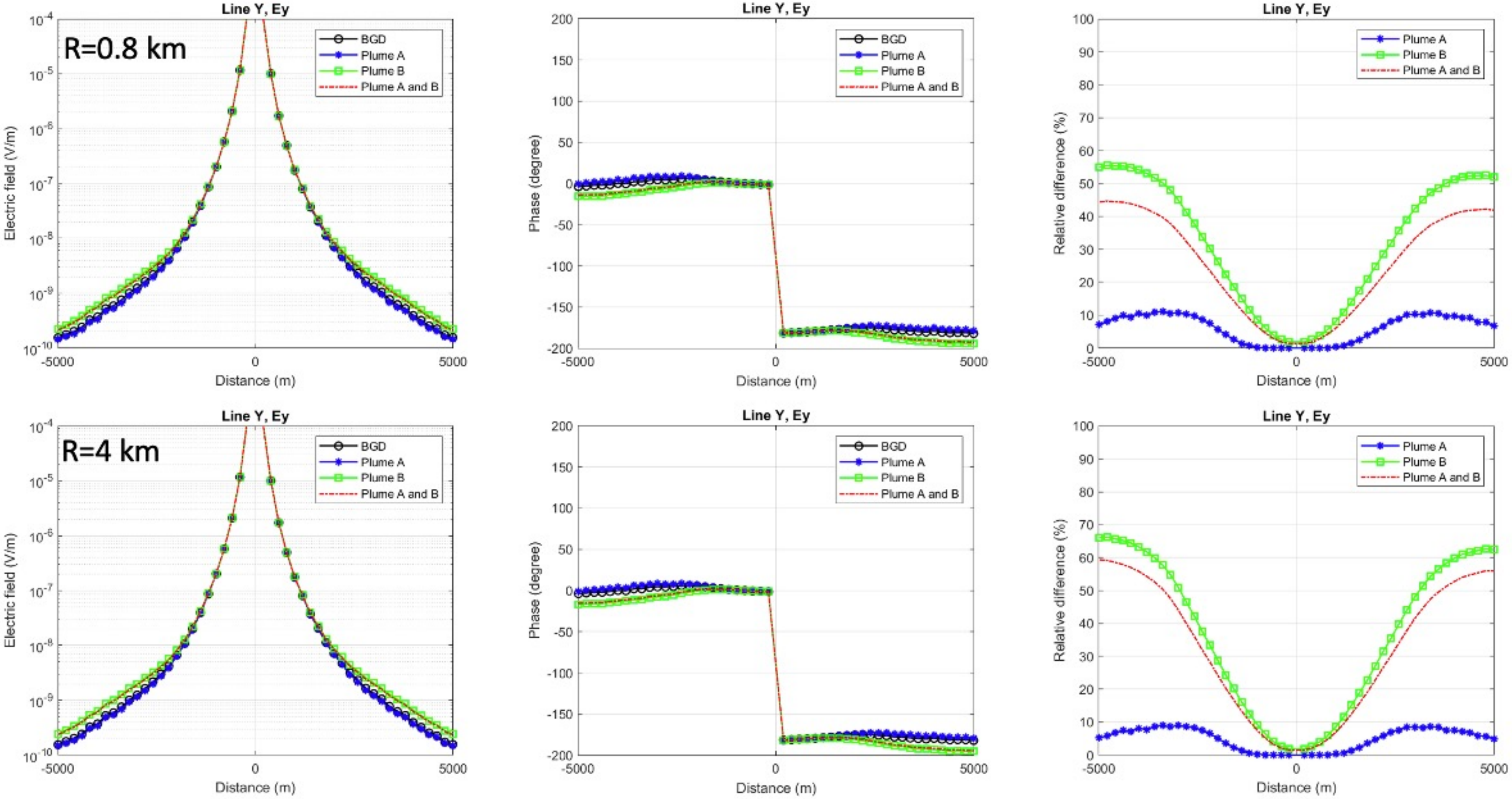


Lessons Learned

- EM measurements can be made adjacent to coal fired power plants, at least at frequencies below 60 Hz
- At the Wyoming CarbonSAFE site
  - MT data were able to be recovered for sites more than 2km away from the powerplant and as well away from roads
  - CSEM electric field data below 10 Hz could be recovered at the lowest frequencies within 500m of the power plant
  - Magnetic field data were more susceptible to powerplant noise due to the coils 'clipping' the signal
- 3D CSEM modeling of hypothetical plume injections at the Wyoming CabonSAFE site have shown
  - Electric fields have sensitivity to the plume providing at least one of the source electrodes is located at the bottom of a (injection) well that penetrates the injection zone
  - Magnetic fields are insensitive to the resistive plume

Acknowledgements

- We thank J. Fred McLaughlin, Charles Nye, and Robert Gregory of the University of Wyoming for their help in gaining access to the Dry Fork Station site and surrounding mine lands, and for providing information regarding CCUS plans for the site
- We thank Zonge International for collecting the data
- 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

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

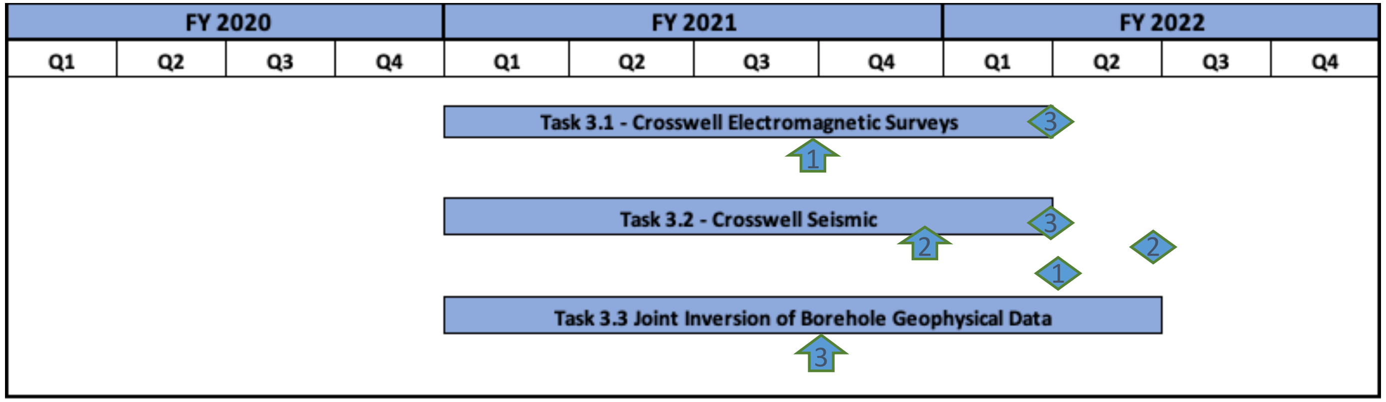
- **Funding**
  - Started FY2022 with $245k in DOE funding
  - Re-purposed an additional $124k (LBL PID 105405 UAE/LLNL Project) to complete work
  - Currently have $32k left for presentations at this DOE program review and SEG annual meeting, as well as to publish the results
- **Overall Project Performance 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
    - **Crosswell Seismic Acquisition**
      Stanislav Glubokovkikh, Ed Nichols
    - **Crosswell EM Acquisition**
      Mike Wilt, Ed Nichols, David Alumbaugh
    - **Crosswell Seismic Processing**
      Stanislav Glubokovkikh
    - **Crosswell EM Processing and Inversion**
      David Alumbaugh, Kerry Key, David Myer
    - **Joint Inversion**
      Michael Commer
  - **aCQurate Joint Inversion Consortium, SINTEF, Norway**
    Michael Jordan

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 Inversio 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