Monitoring Leakage Pathways - Joint EM and Seismic

Project Number LBNL-ESD14095

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National Energy Technology Laboratory

Carbon Management and Oil and Gas Research Project Review Meeting – Carbon Storage

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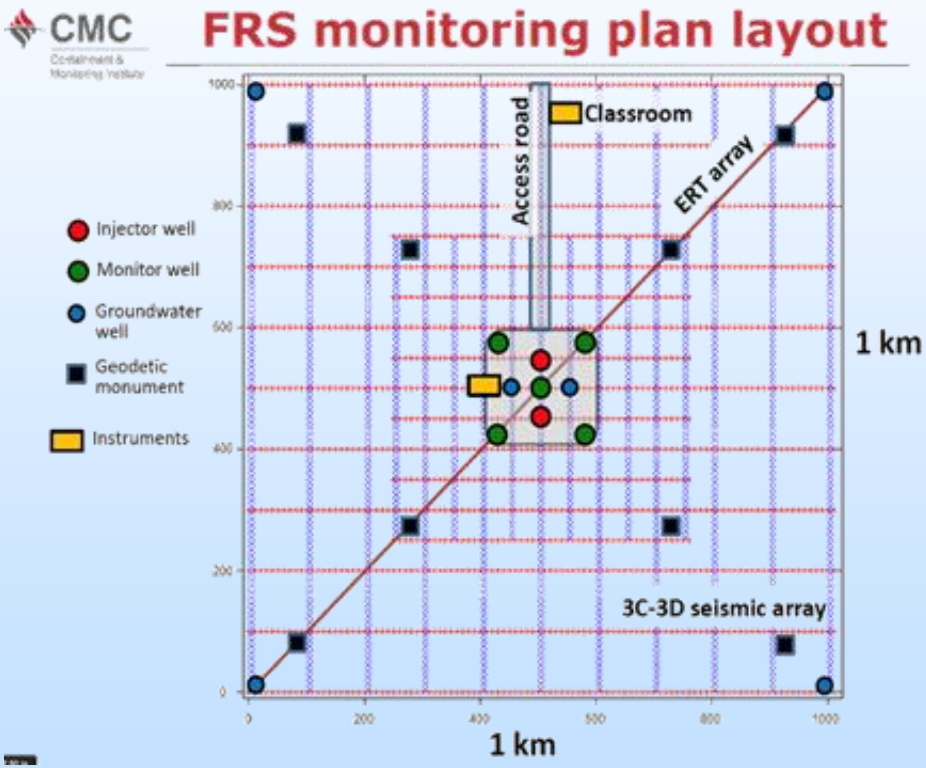
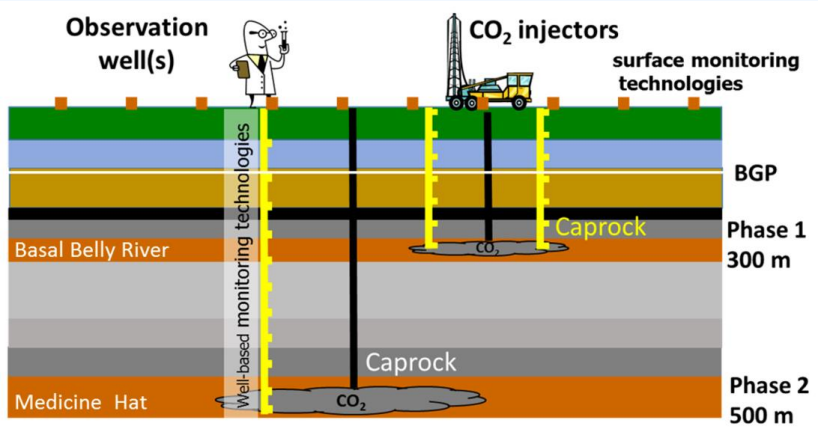
Presentation Outline

- Project background and description of the CaMI Site
- Processed/inverted baseline data
- New crosswell system hardware and test results
- Studies of electric field measurements
- Progress on joint inversion of crosswell seismic and EM data
- Conclusions

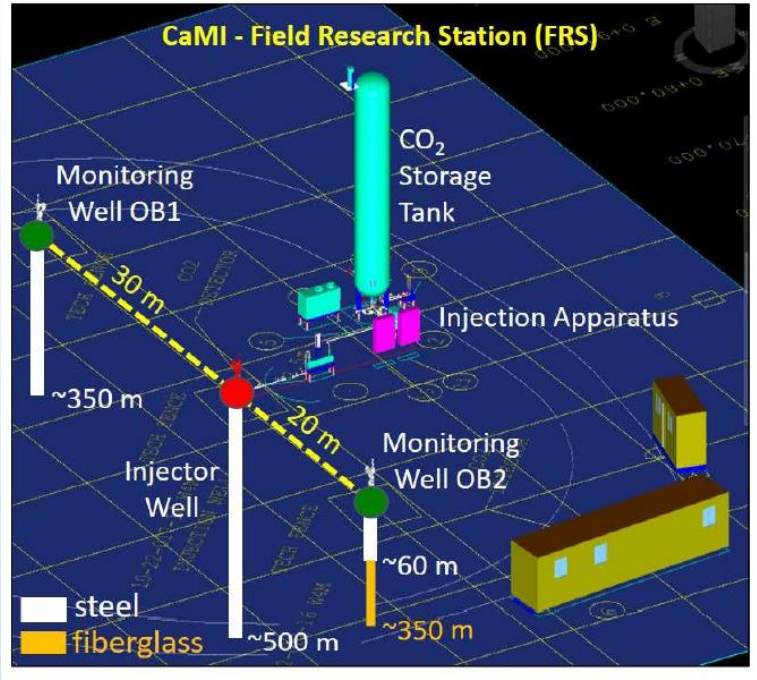
CaMI Field Research Station (FRS)



CaMI Field Research Station (FRS)

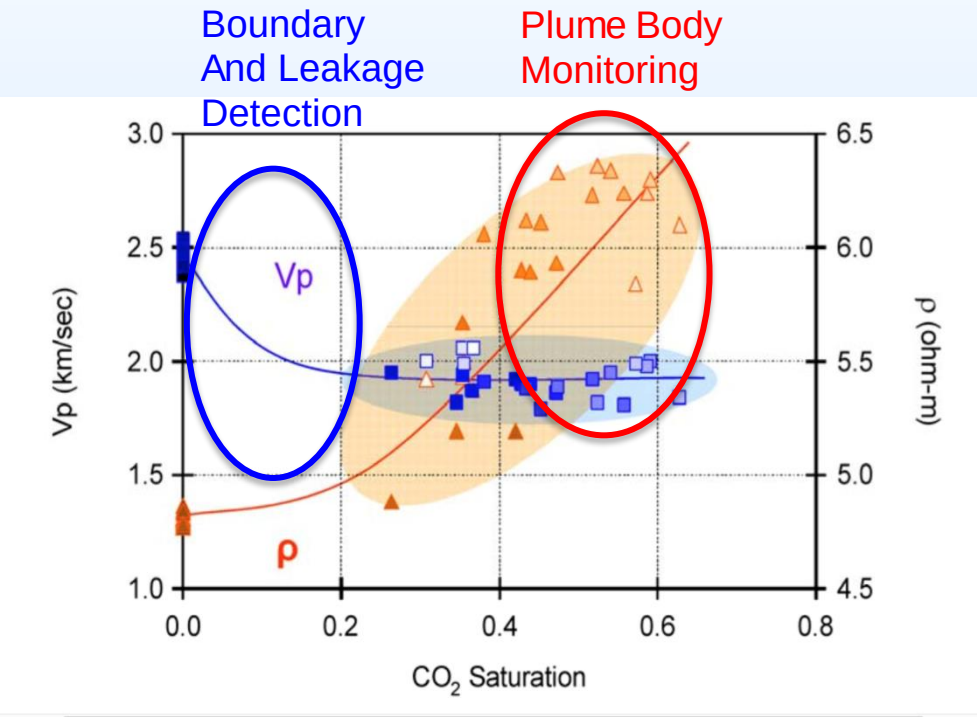


In general, CaMI-FRS site has layered geological structures.



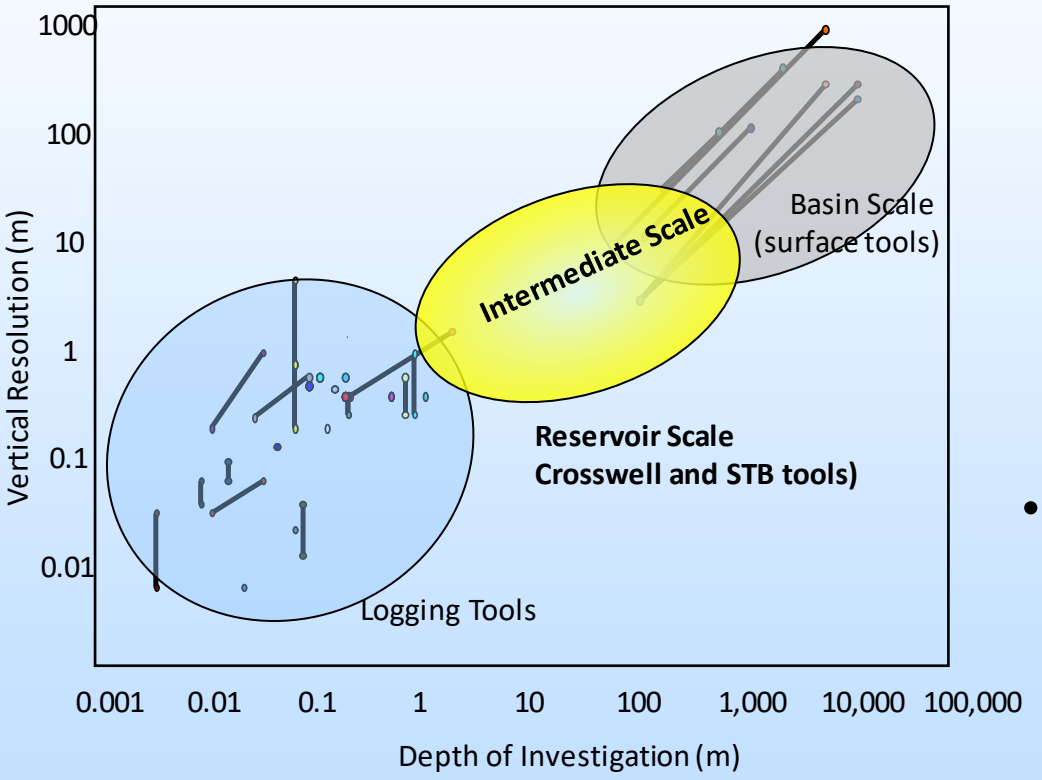
Transmitter well (Monitoring Well OB2) is highly deviated. OB1 is steel-cased, whereas OB2 is open-well (fiberglass).

Why Joint Seismic and EM?



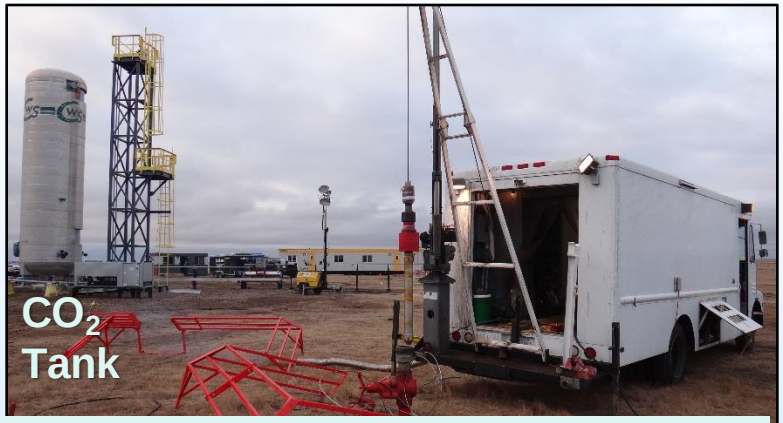
- Seismic has uncertainty at high CO_2 saturation and uncertainty in rock physics interpretation
- EM (conductivity) has strong sensitivity at all saturations and a single rock physics model (Archie's relation) and should complement seismic for estimating saturation within plume
- Ideally combine seismic, EM and flow models in joint inversion for CO_2

Why Crosswell Measurements?



- LBNL has a Unique Capability in in Borehole Seismic EM and Imaging
  - These tools fill a 'Resolution Gap' between Surface and Logging Methods, and thus can be Critical for Reservoir Scale Imaging
- LBNL and their partners also have numerical tools and experience in 2D and 3D Imaging
  - Joint EM/Seismic and Fluid Flow Imaging also Available

Crosswell Baseline Survey -2017



Piezoelectric source deployment in Well OB1

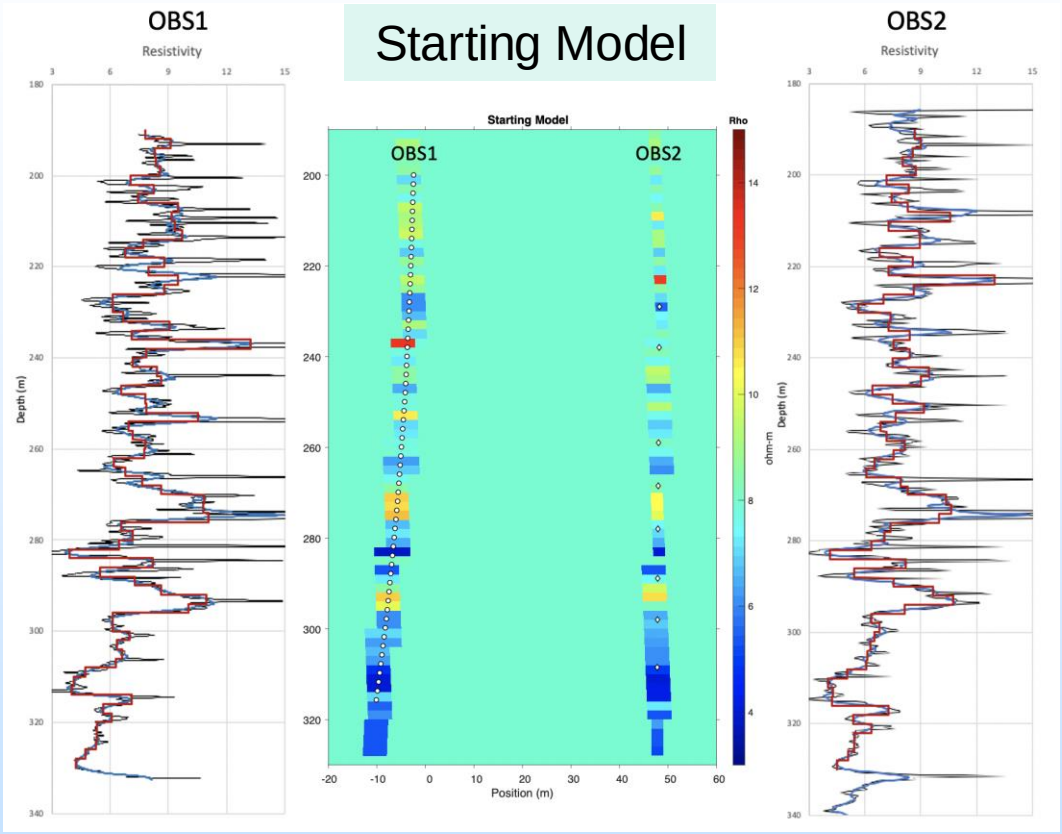
Magnetic source deployment in Well OB2

Dual Sensor EM string

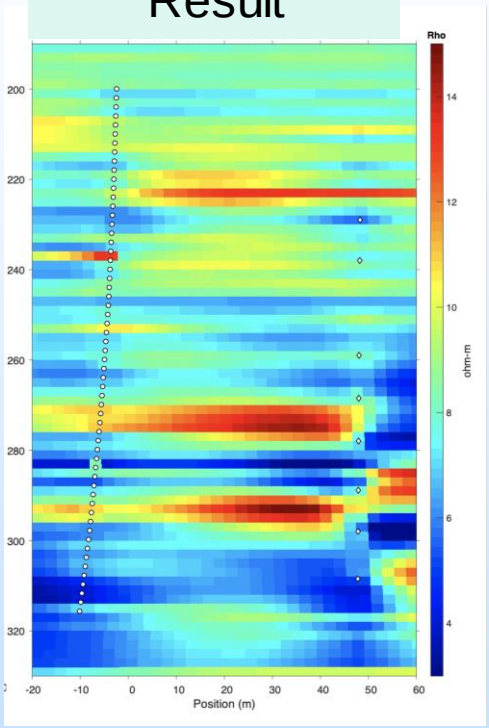
Hydrophone sensors deployment in Well OB2

Magnetic receiver deployment in Well OB1

Log-Constrained Inversion Workflow

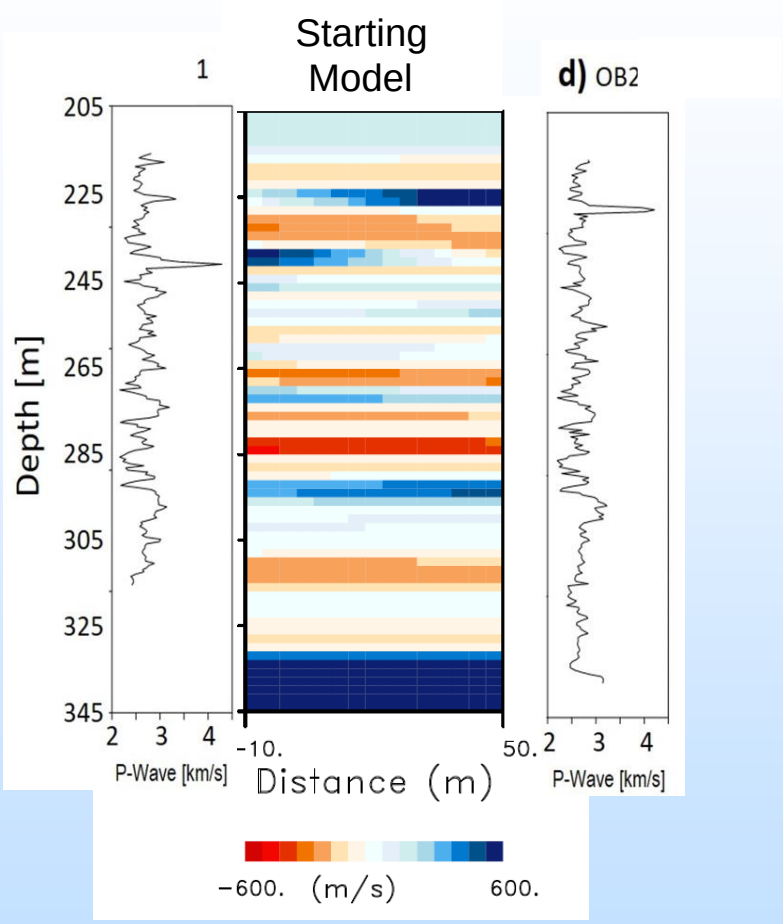


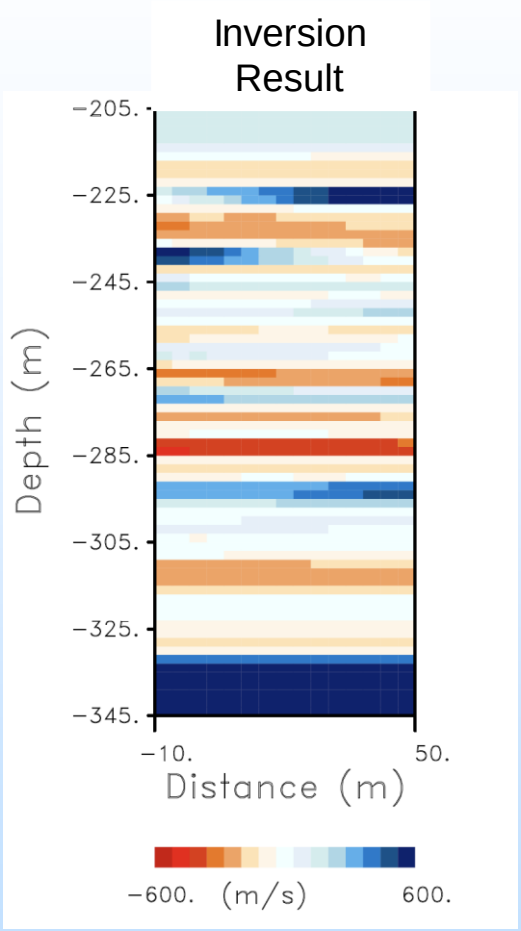
Inversion Result



- Inversion with resistivity log constraints at wells:
  - Upscaled/averaged resistivity logs are used as constraints.
  - Well deviation logs are used for correctly positioning sources and receivers

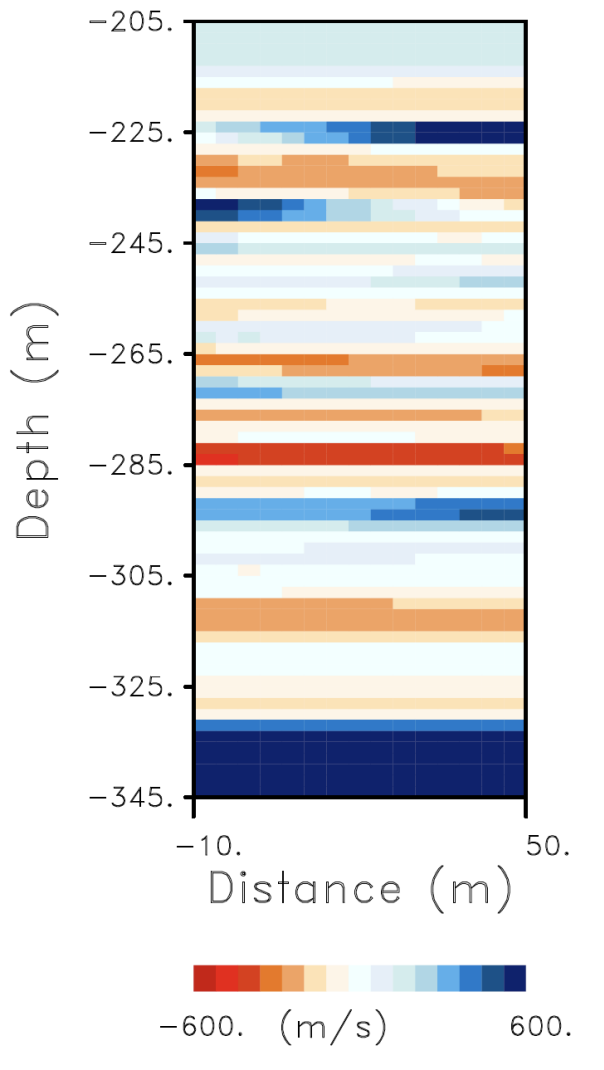
Log-Constrained Inversion Workflow

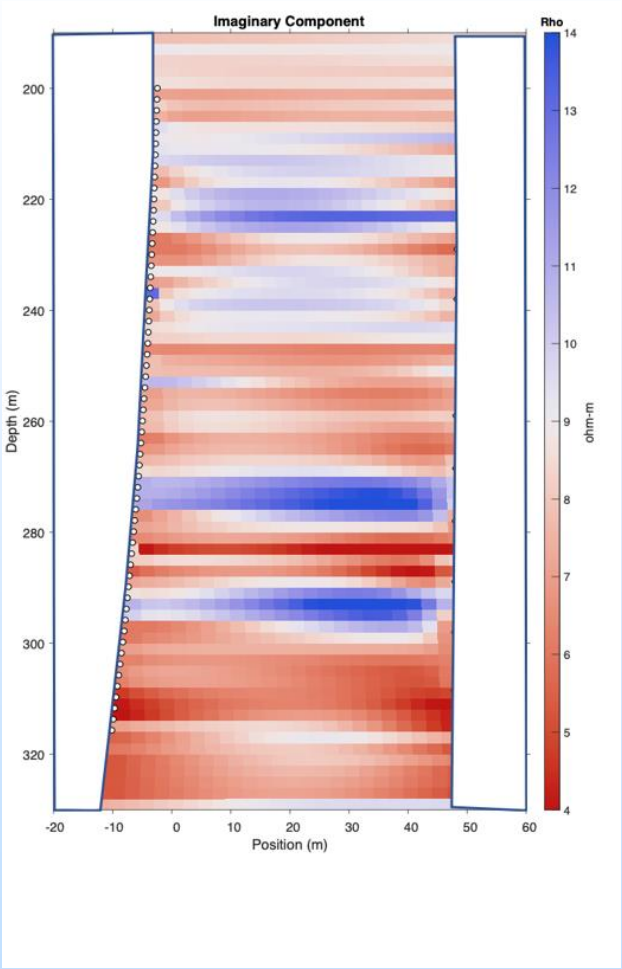




- Inversion with initial model created from sonic logs.
- Well deviation logs are used for correctly positioning sources and receivers.

Seismic and EM Image Comparison



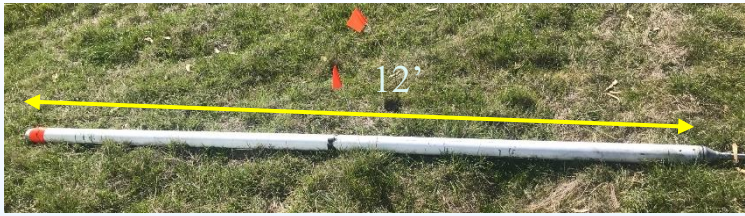


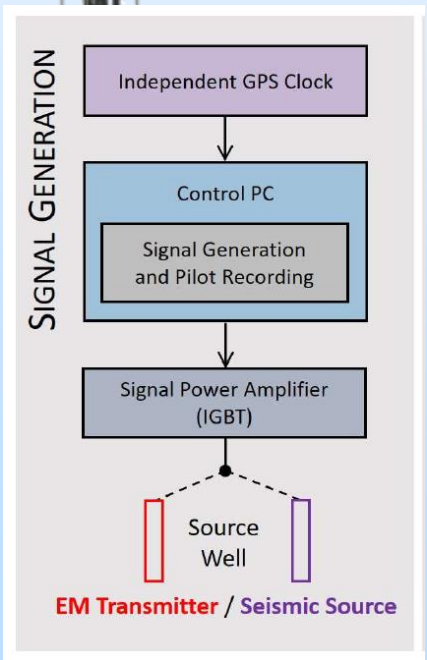
Testing of Crosswell System

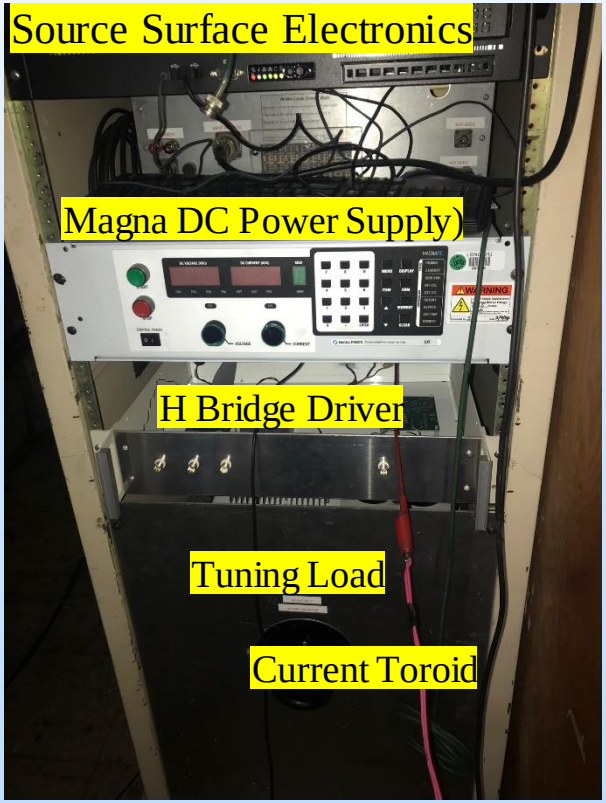
Breadvan Source Deployment at RFS Test Field Site

Seismic Source

EM Source

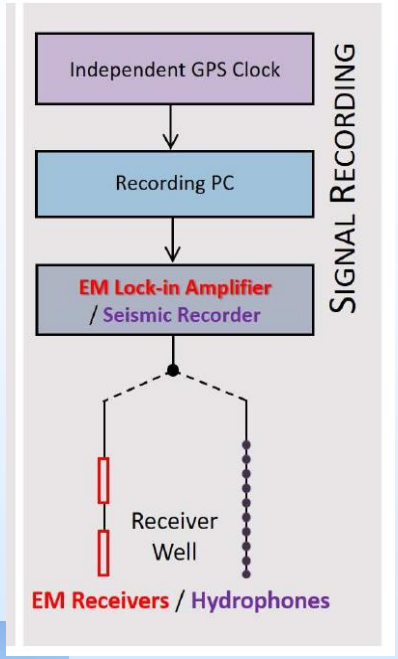




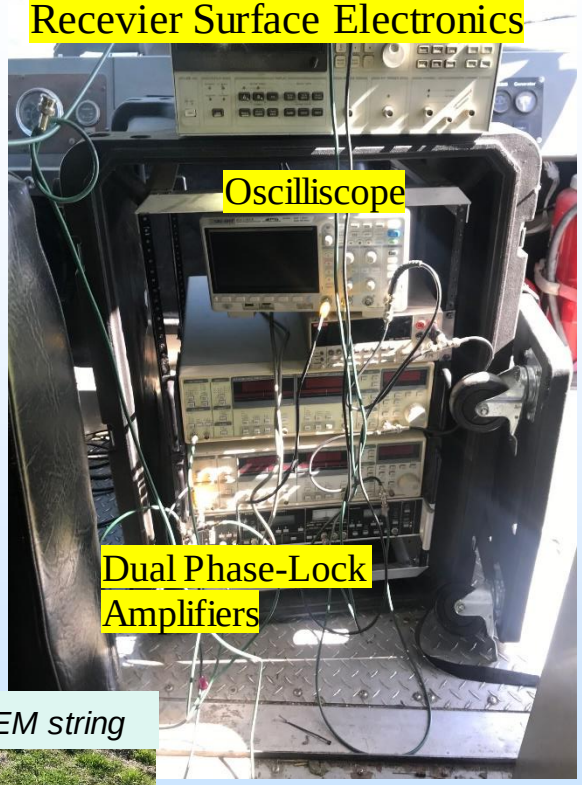


Testing of New Crosswell System

Receiver Trailer at RFS Test Field Site



Recevier Surface Electronics

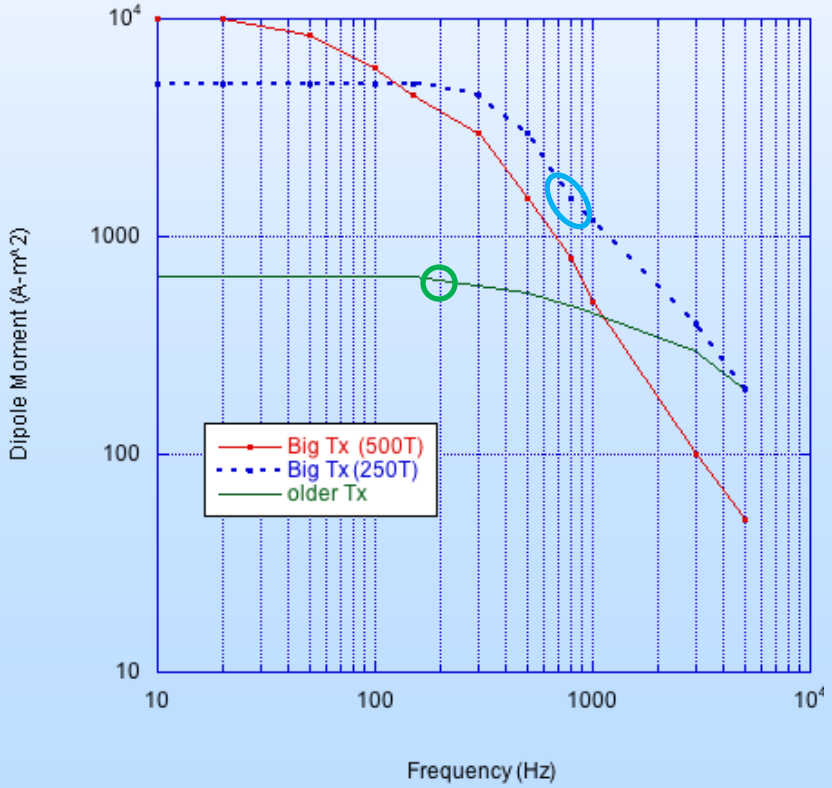


Dual Sensor EM string

Testing of Crosswell System

New Crosswell EM Tx

- Housing: fiberglass pipe
- Diameter: 3.5”
- Length: 12 ft
- Weight: ~150 lbs
- Tool head GH-7
  - Gerhardt-Owen 7 conductor
- Send amplified signal from the surface
  - Maximum 300 V
  - Maximum 2 amp/ wire



2017 Baseline Data Acquisition

2021 Time -Lapse Data Acquisition (estimated)

Testing of Crosswell System

Integrated EM System Testing

Testing of GPS Clocks

- Provides wireless connection between Tx and Rx electronics
- 0.1 degrees phase stability during daylong stability test

EM Data Acquisition

- Dual lock-in amplifiers
- PC acquisition using LabView

Continuous Active Source EM (CASEM)

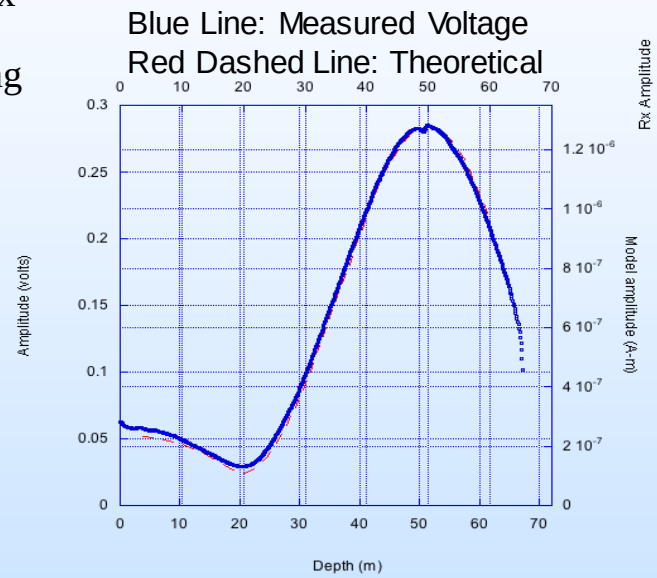
- Run for 60 hours continuously on house power at 650 Hz
- 0.1% amplitude repeatability
- 0.2^{o} phase repeatability

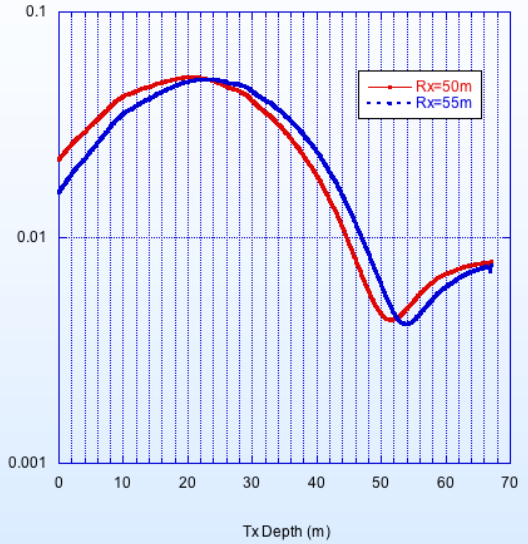
Correction for Receiver in Steel Casing

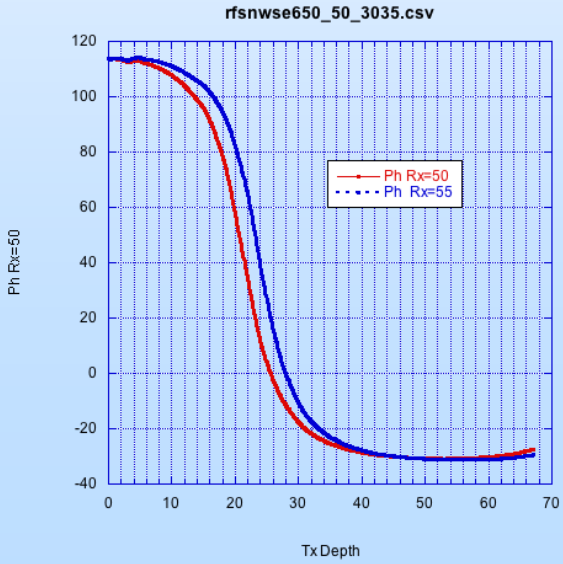
- Modification of MARE2DEM algorithm of Key (2016) for inversion of complex casing attenuation coefficient

Seismic Acquisition

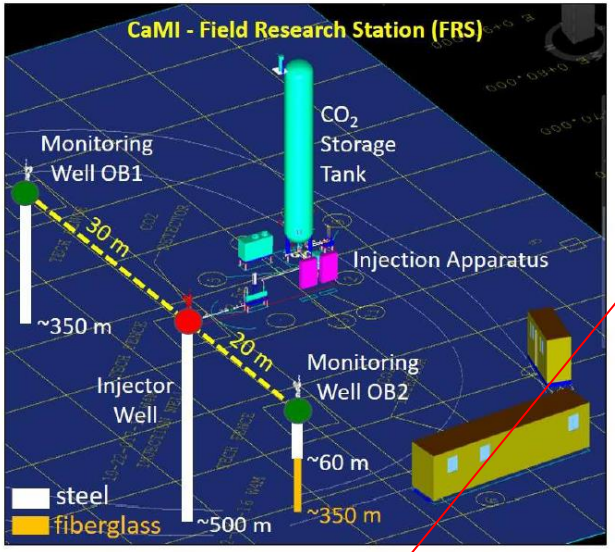
- Provided by Geometrics Geode
- Software currently being modified

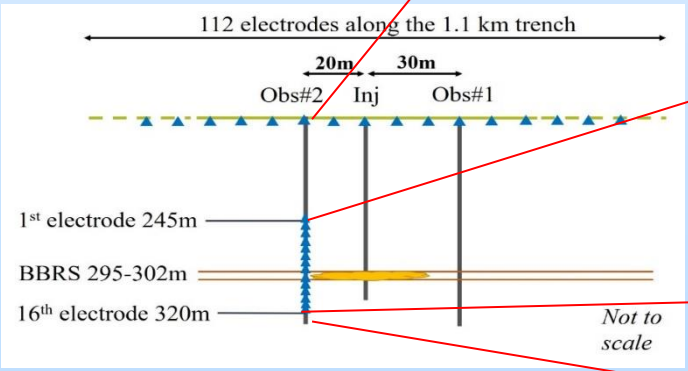




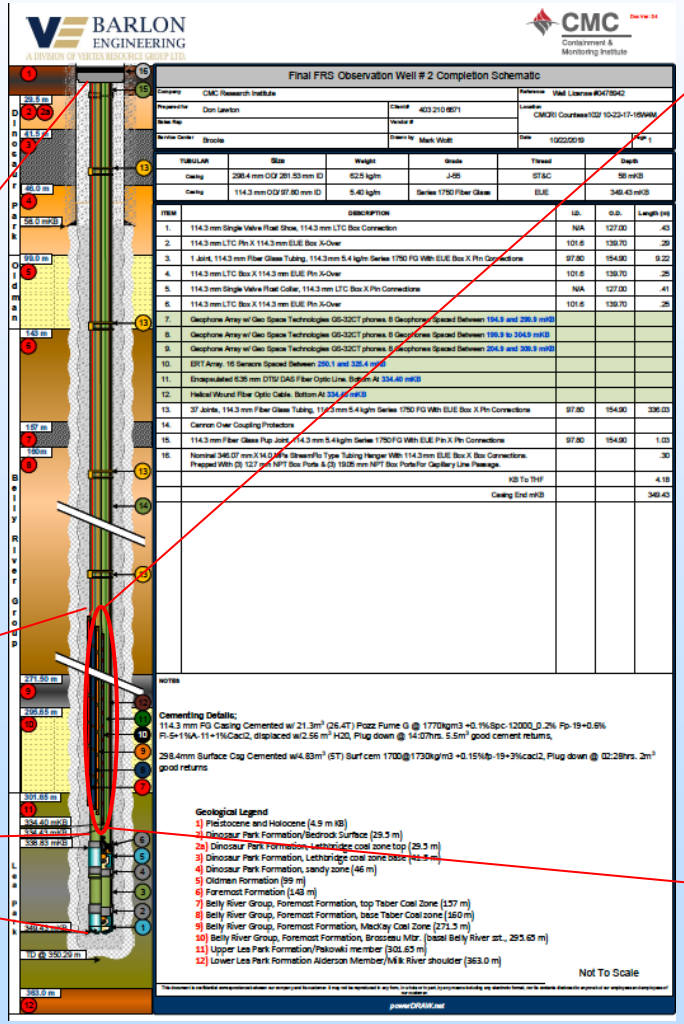


Electric Field Studies





Well OB2 Completion Diagram



Permanently Installed ERT Array

- Advantage over Crosswell EM
  - Provides 'galvanic' measurement which is more sensitive to resistive CO2 target
  - Crosswell 'inductive' magnetic field measurement more sensitive to conductors than resistors
- Disadvantage compared to Crosswell EM
  - Mostly sensitive along OB2 well: little interwell sensitivity
  - Crosswell EM more sensitive to interwell region
  - What if you don't have permanently installed electrodes?

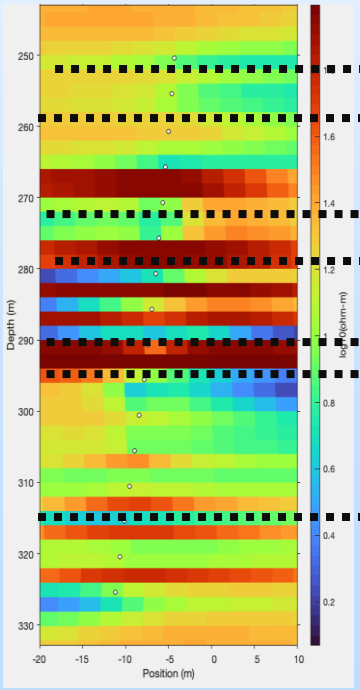
Electric Field Studies

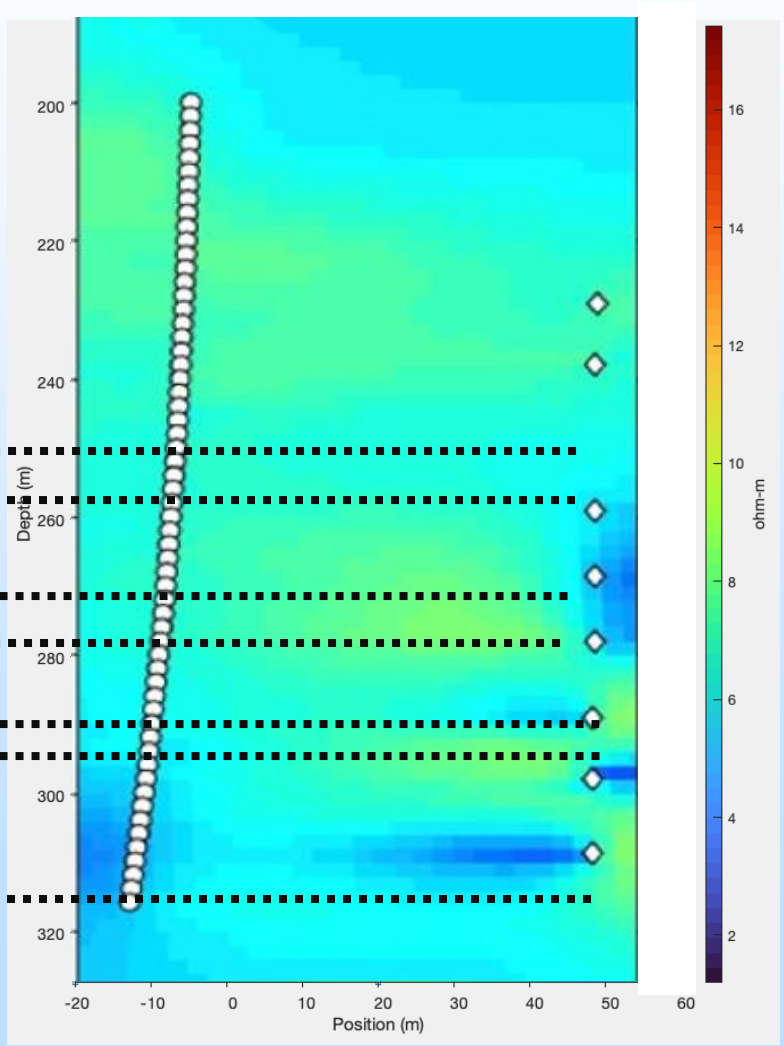
Baseline Unconstrained ERT Image Compared to Unconstrained Crosswell EM

Both Images from MARE2DEM algorithm of Key (2016)

ERT data provided by our partners at CaMI are described in Macquette et al. (2021 - to be presented at this year's SEG conference)

ERT





Electric Field Studies

Baseline Unconstrained ERT Image Compared to Log-constrained Crosswell EM

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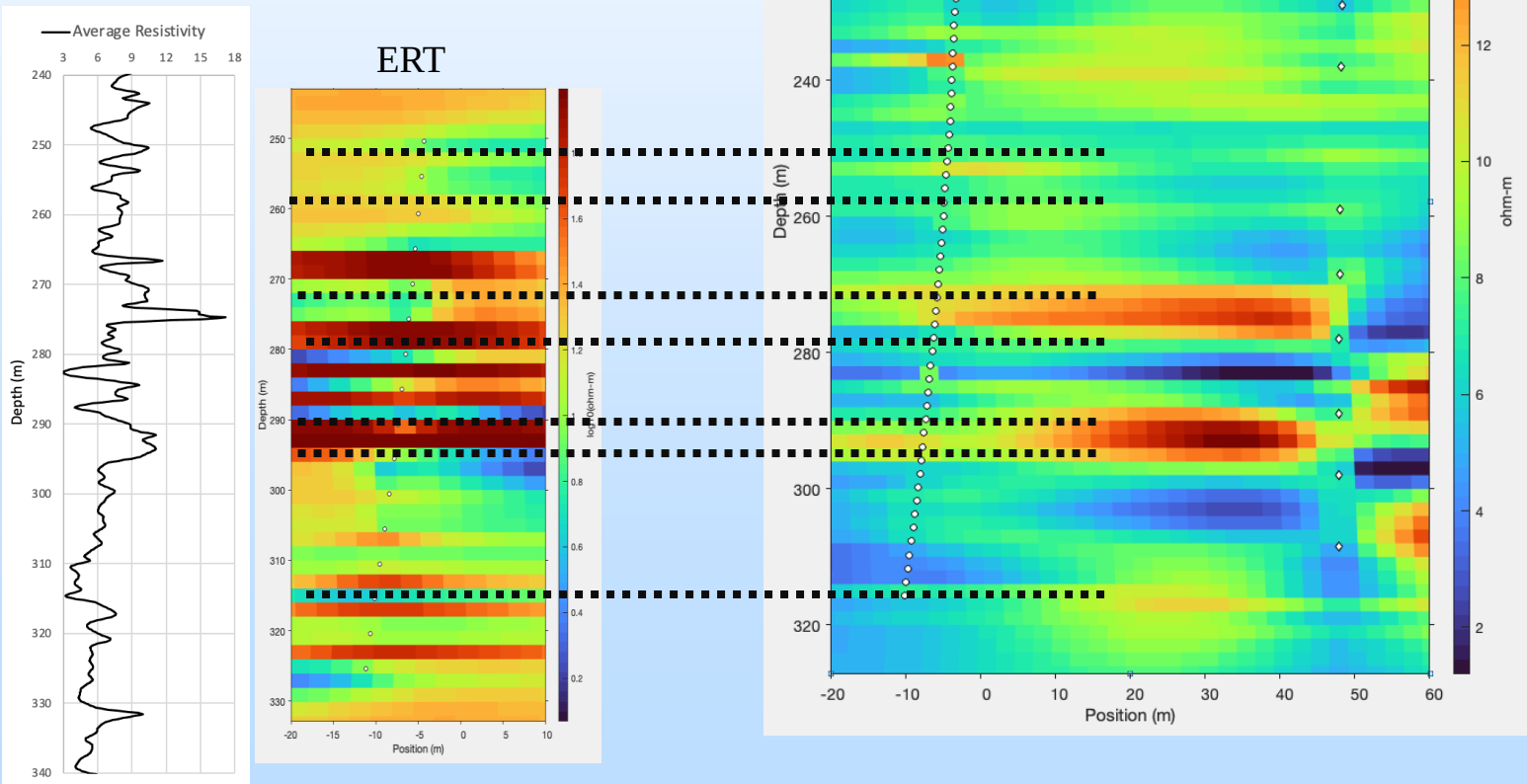


Electric Field Studies

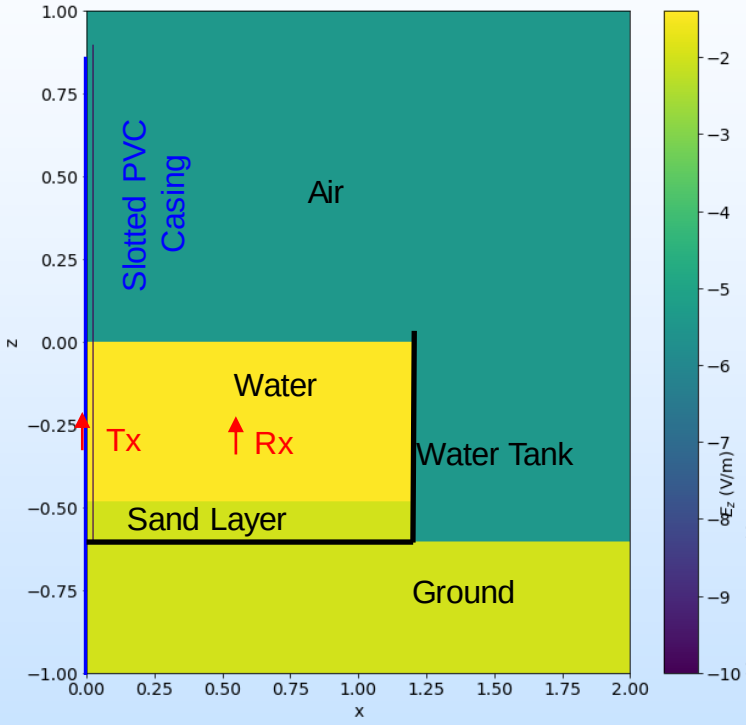
Scale Model Studies to Electric Field Measurements in Perforated Casings

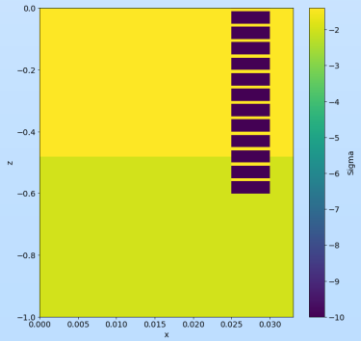
Source and Receiver

Slotted Casings

Electric Field Studies

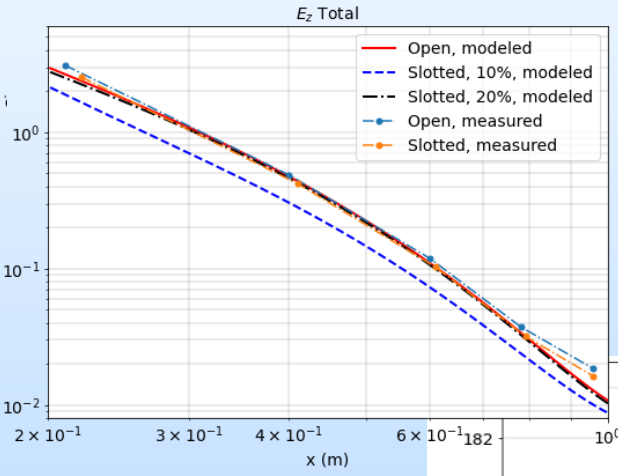
First Set of Studies: Comparison to Numerical Modeling Results

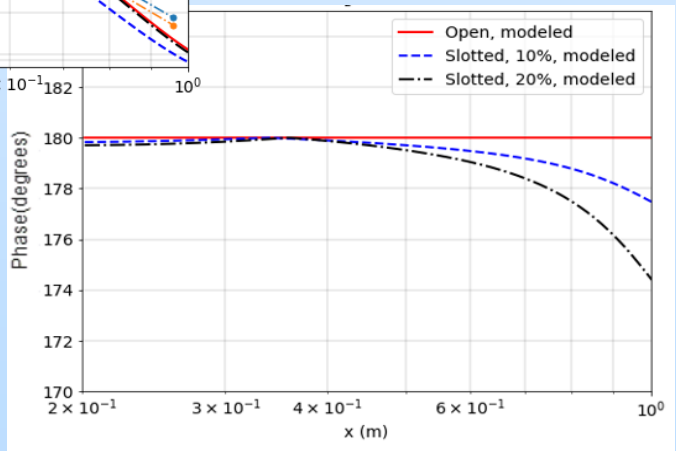




Zoom In on Casing

- Use 'SIMPEG2D' cylindrically symmetric finite volume code written by Lindsey Heagy of UBC.
- Compare to scale model results where horizontal distance between source and receiver is expanded



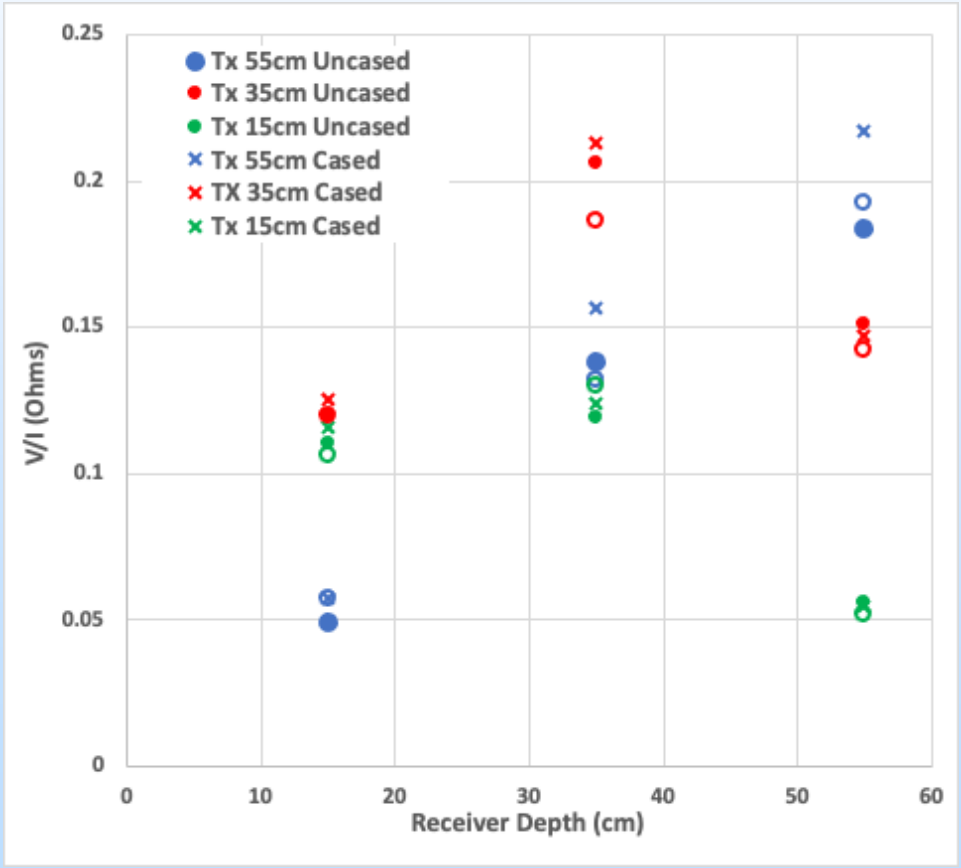


Electric Field Studies

Second Set of Studies: Traditional Crosswell Configuration

- Two ‘wells’ separated by approximately 60cm
  - 10cm dipole Tx at center: 15, 35, 55cm depth
  - 10cm dipole Rx at 60cm offset: 15, 35, 55cm depth
- Order of measurements
  - No casing around either
  - Slotted casing around Rx
  - Slotted Casing around Tx
  - Slotted casing around both Tx and Rx
  - Repeat no casing around either
- Plot repeat – no casing measurements with different casing measurements

Tx in Casing: Rx no Casing



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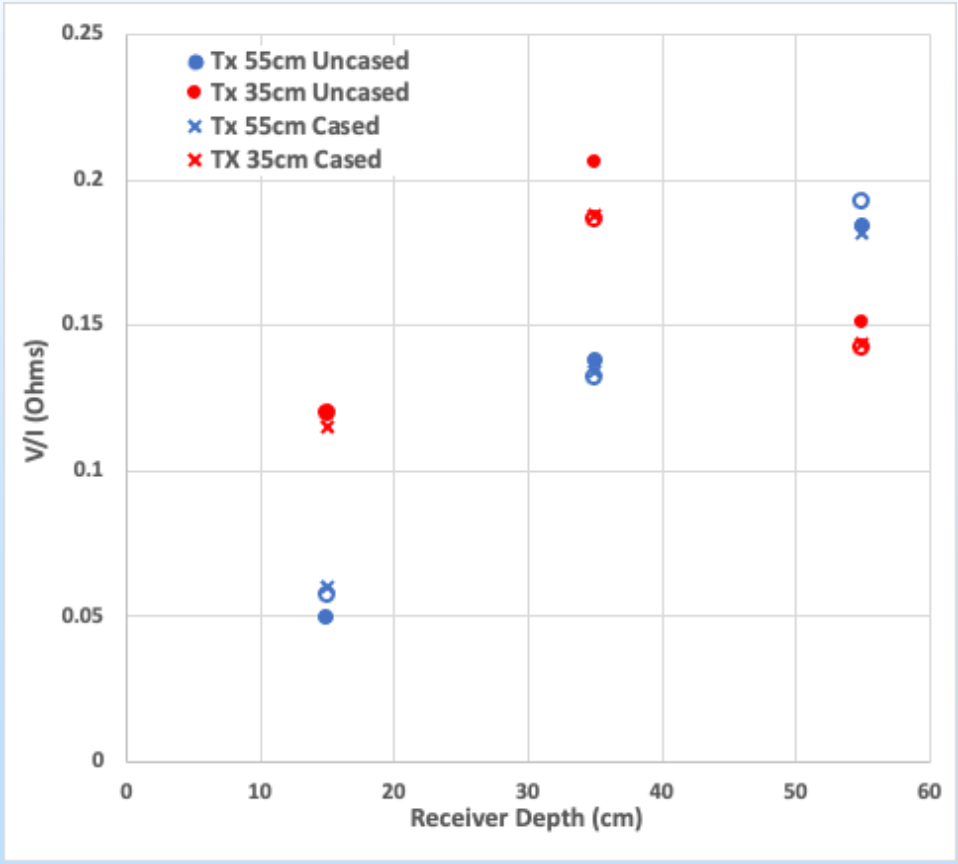
Tx and Rx in Casing



Joint Inversion of Seismic and EM data

Collaboration with the aCQurate Consortium, SINTEF, Norway

- LBL (David Alumbaugh) serves on the advisory panel
- Goals of the Consortium
  - Quantitative monitoring of reservoir parameters (stress, pressure, saturation, or strain in the overburden)
  - Create a method (software) to reliably integrate relevant CO_2 monitoring data:
    - Large-scale and high resolution
    - On-shore ((elastic?) FWI, ERT, gravity, uplift)
    - Off-shore (FWI, CSEM, gravity, uplift)
    - Quantitative
  - Hybrid structural-petrophysical inversion:
    - Combines robustness of structural joint inversion with quantitative petrophysics-based joint inversion
    - Petrophysical cross-parameter relations (e.g., from well logs) to constrain model parameters
    - 3D inversion uses static piecewise linear relationships, the correlation coefficients are treated as additional parameters and inverted for

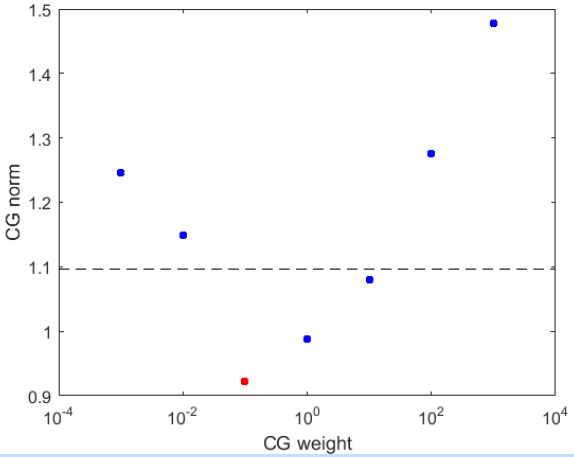
Joint Inversion of Seismic and EM data

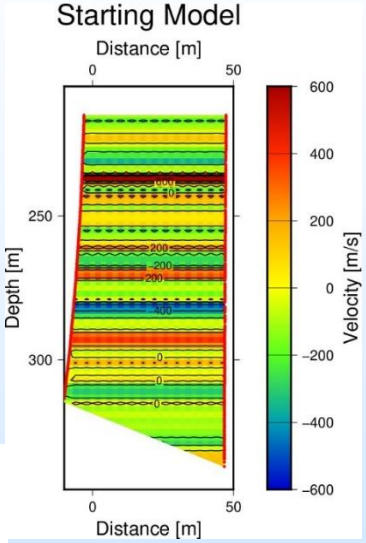
Structural ‘Cross-Gradient’ constrained joint inversion

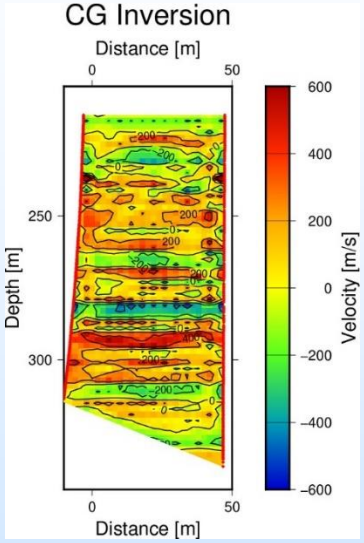
Seismic weight: 10^{-3}

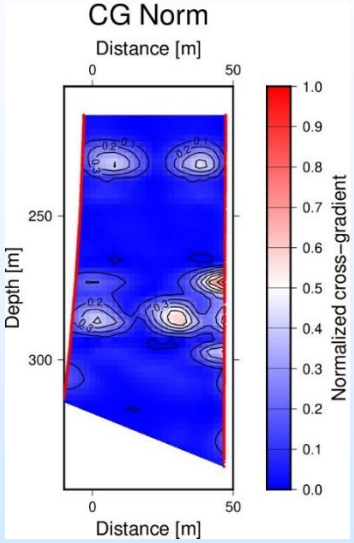
CSEM weight: 1

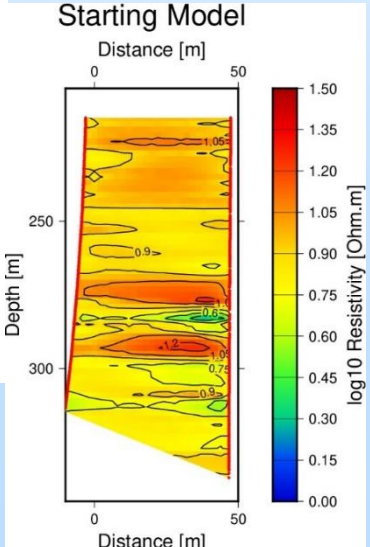
CG weight: 10^{-2}

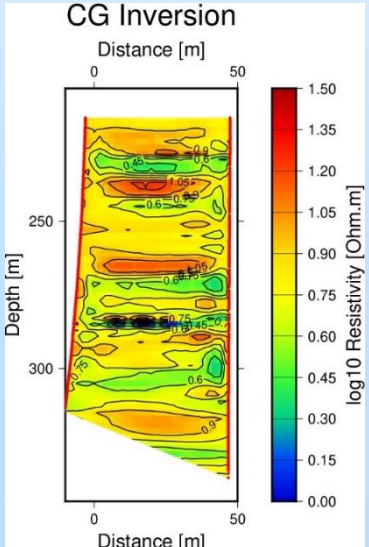


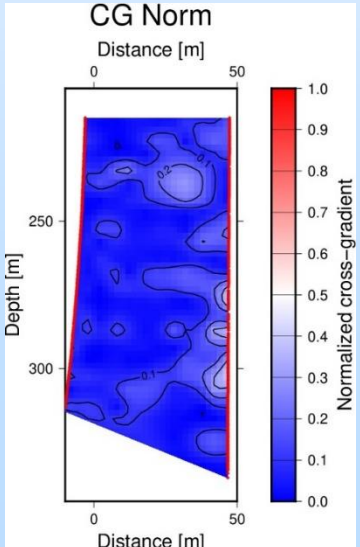












SINTEF

Joint Inversion of Seismic and EM data

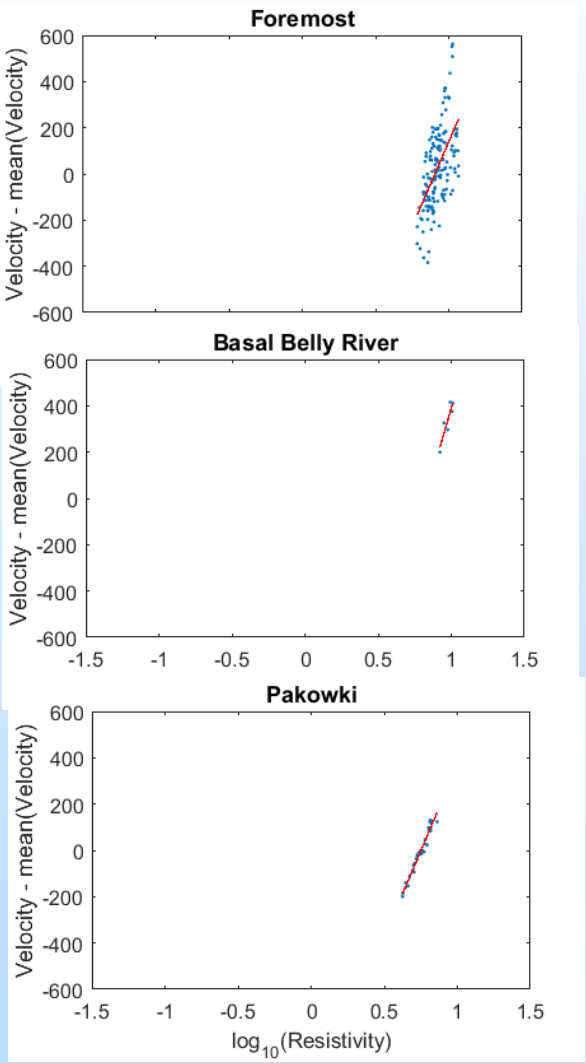
Petrophysical Joint Inversion: Constraint Development

Stratigraphical units of interest:

- Foremost (138.10-290.22 m)
- Basal Belly River (290.22-296.85 m)
- Pakowki (296.85-358.10 m)

Linear cross-correlation between model parameters:

$$\Delta v = B \log_{10} \rho + a$$

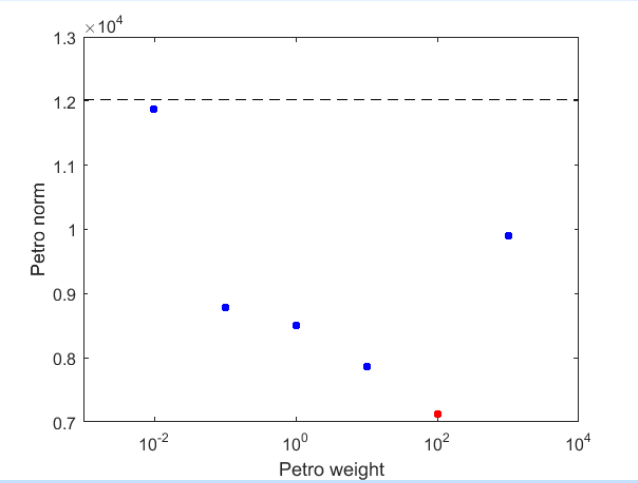


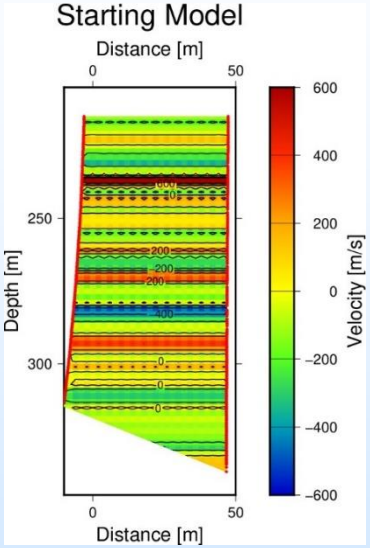
SINTEF

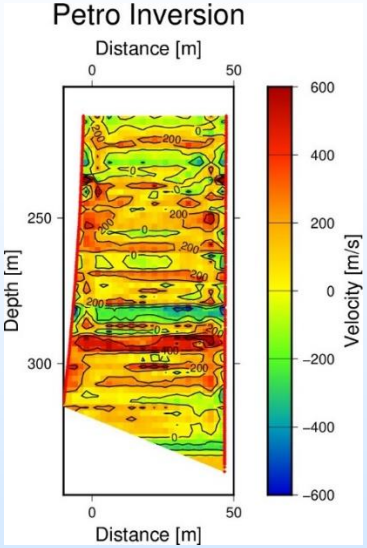
Joint Inversion of Seismic and EM data

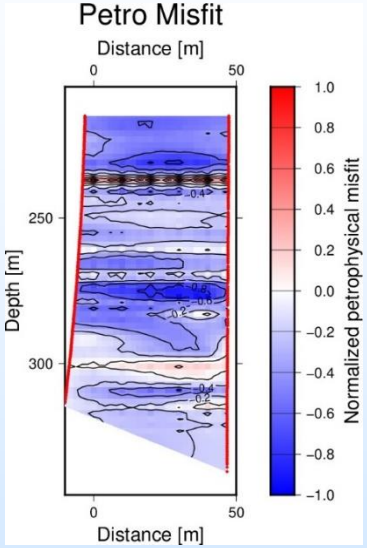
Petrophysical Joint Inversion: Results

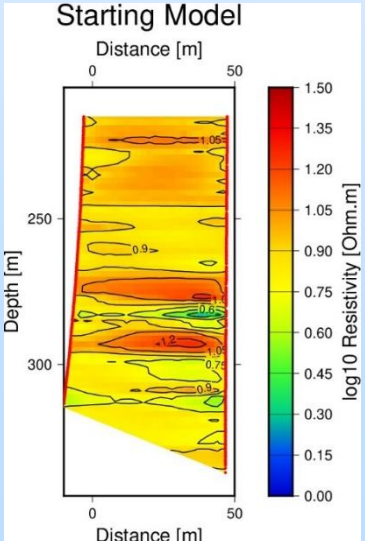
Seismic weight: 10^{-3}
CSEM weight: 1
Petro weight: 10^{2}

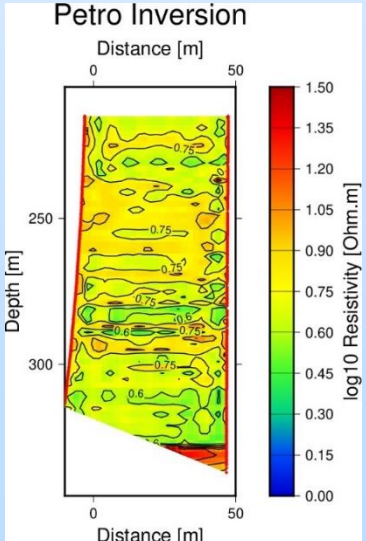


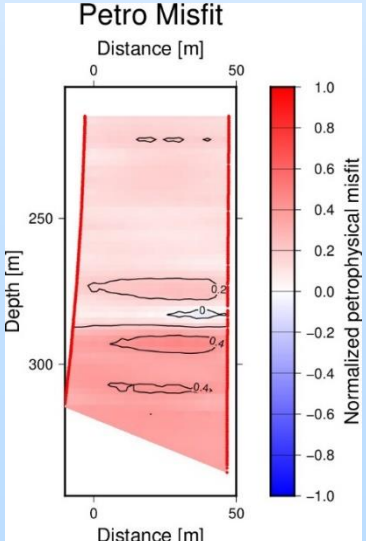










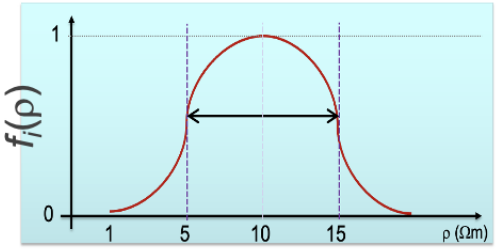


SINTEF

Joint Inversion of Seismic and EM data

New ‘Semblance’ Joint Inversion algorithm development going on at LBNL

Define an “*S*” model-objective functional:
The “match-count” ratio $S = {}^{N^a}/_{\tilde{N}^a}$ describes how close an image is to a given reference model.



$$S = \frac{N^a}{\tilde{N}^a} = \frac{\sum_i f_i(\rho)}{\sum_i f_i(\rho^{ref})}, \quad 0 \le S \le 1$$

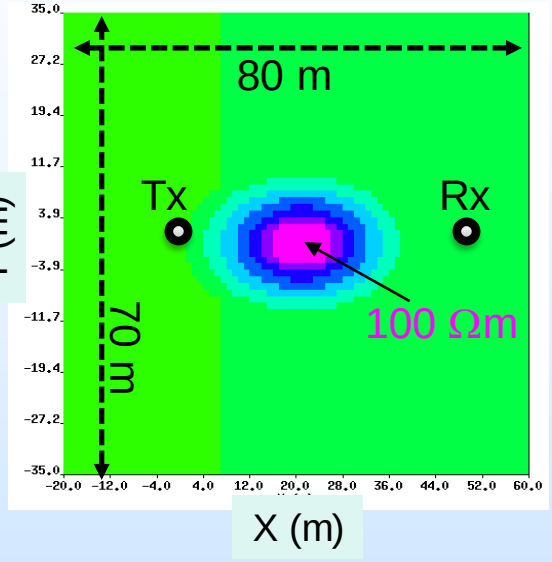
$$\phi^m = 1 - S, \;\; 0 \le \phi^m \le 1$$

$$\phi = \phi^d + \lambda \phi^m$$

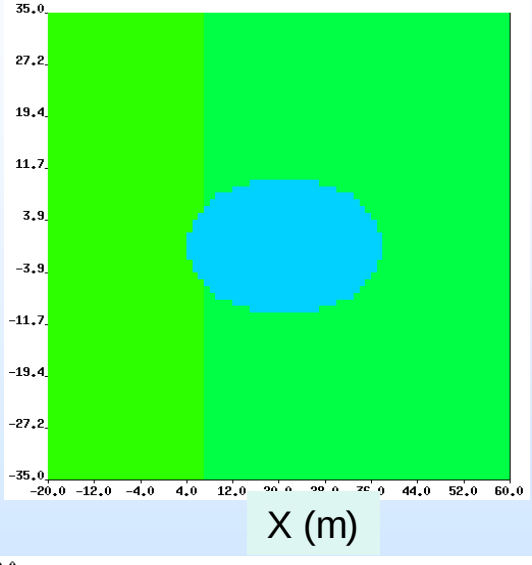
Joint Inversion of Seismic and EM data

New 'Semblance' Joint Inversion algorithm development going on at LBNL

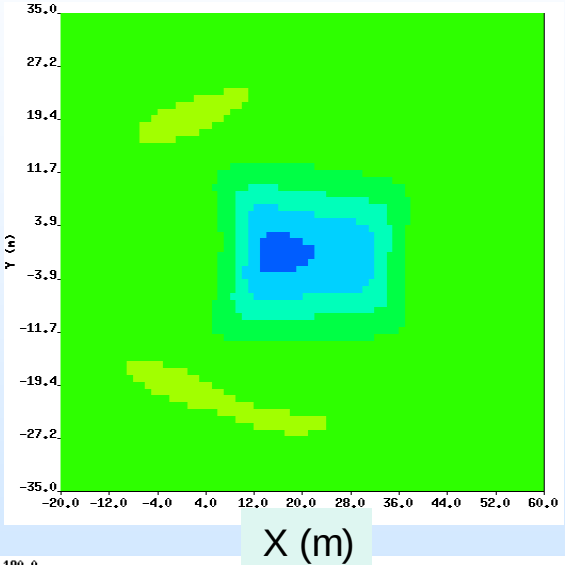
True model

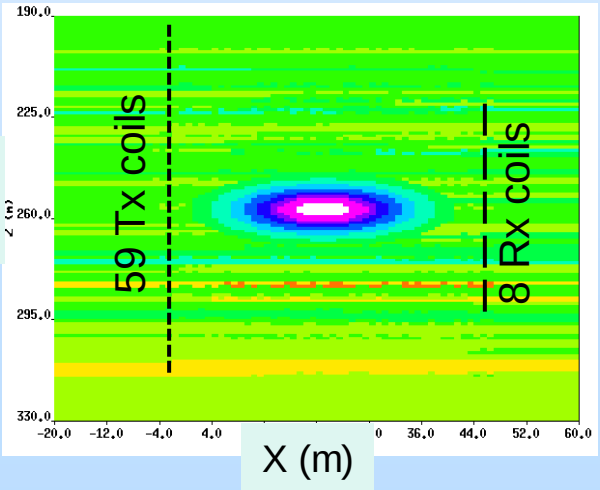


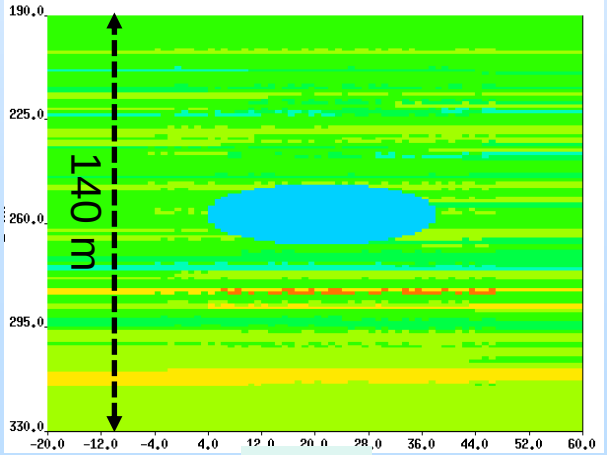
Reference model

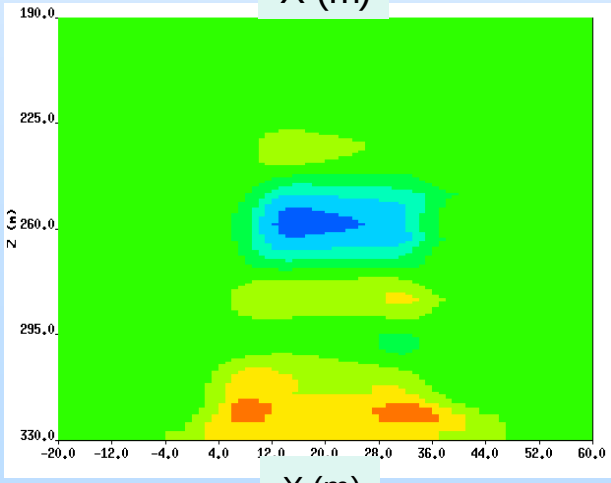


Inversion with S-Constraints









Accomplishments to Date

Background

- Baseline crosswell EM and seismic data acquired (2017)
- High resolution velocity and resistivity baseline images provided via log-constrained workflow
- CaMI currently injecting 600kg's CO_2 / week

LBL Crosswell System Improvements

- EM Transmitter: 10 to 20 times more power at low frequencies
- Use of GPS clocks for source-receiver synchronization eliminate ground loop problems
- 60 hour continuous operation indicates 0.1% amplitude and 0.2° phase stability which
- Inclusion of casing correction in MARE2DEM

Accomplishments to Date

Electric Field Studies

- Inversion of CaMI single-well baseline ERT data completed using the same MARE2DEM algorithm used for crosswell EM inversion, and are comparable to well logs and crosswell inversion results
- Model studies have proved that electric field measurements can be made in perforated/screened resistive casing as long as there is adequate hydraulic connection to the formation

Joint Inversion

- Initial joint inversion results have been completed on the baseline crosswell data collected at CaMI by our partners at SINTEF, with the structural cross-gradient approach proving to provide better results than petrophysically derived constraints

Lessons Learned

- CO_2 can be challenging to get into the ground (repeat CaMI data acquisition was delayed by this)
- The crosswell EM data need to be acquired at a higher frequency than was available for the baseline acquisition to improve resolution
- Repeat crosswell seismic data sets (2016 and 2017) showed poor repeatability.
- Crosswell seismic acquisition using DAS fiber proved to be of poor quality
- Current EM simulation technology can not provide accurate simulations at the range of scales required to simulate perforated resistive casing
- With current scale and numerical modeling capabilities we can not determine if a correction is required for electric field data collected in perforated resistive casing

Lessons Learned

- Deterministic joint inversion of crosswell seismic and EM data is difficult, with many 'knobs' and 'buttons' that need to be tweaked within the algorithms to produce optimal images
- The COVID pandemic has significantly delayed our ability to acquire time-lapse data at the CaMI site

Project Summary

- LBL has developed a crosswell system that can collect both seismic and EM data using many of the same components
- A well log constrained workflow has been developed to provide high resolution images of velocity and resistivity collected with the crosswell system
- The inclusion of electric fields in the EM data can improve resistivity resolution
- Joint inversion of crosswell seismic and EM data can provide higher resolution, structurally consistent images
- LBL hopes to return to CaMI this fall to make repeat measurements with the goal of imaging the CO_2 plume

Appendix

– These slides will not be discussed during the presentation, but are mandatory.

Benefit to the Program

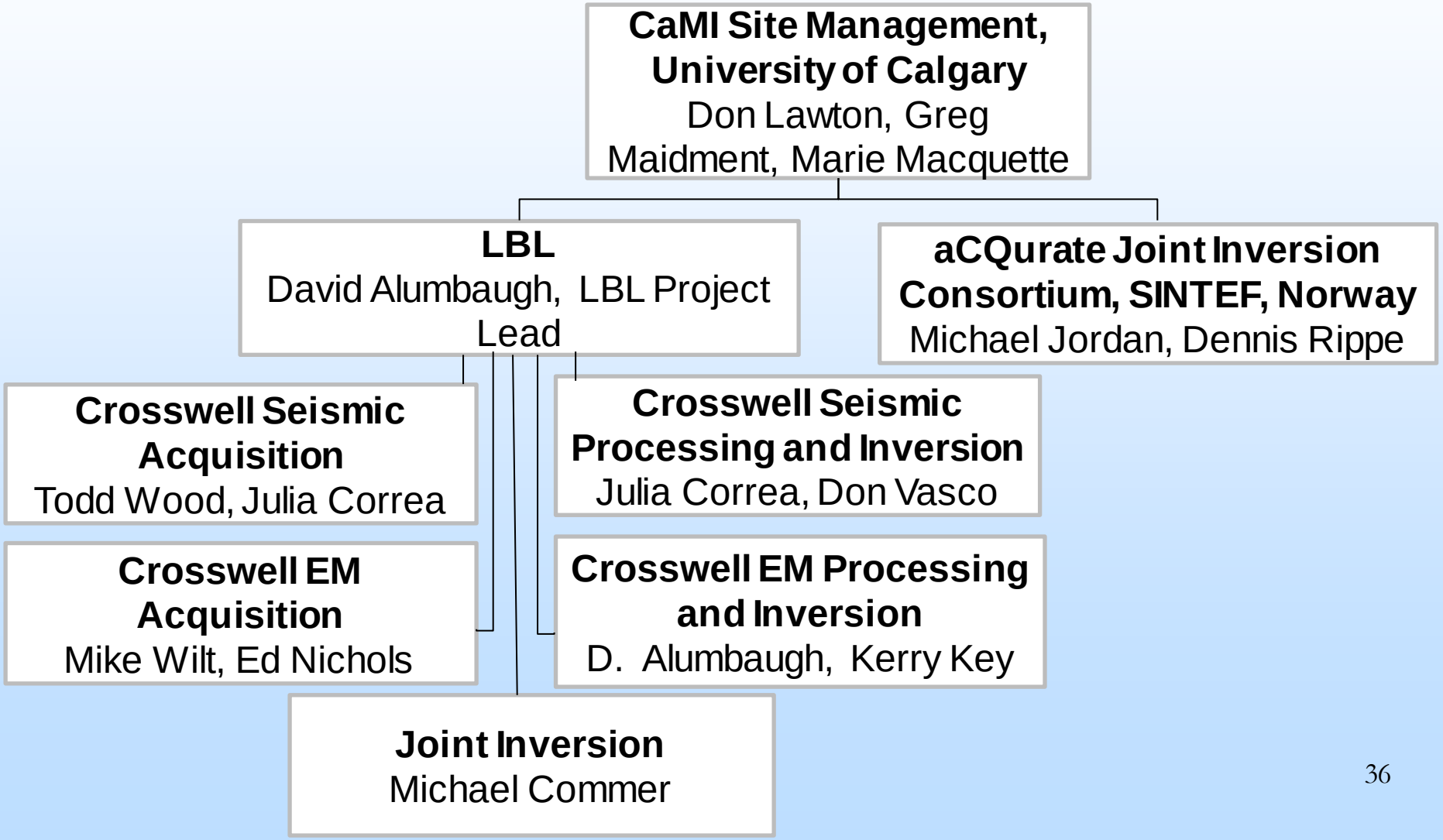
- In this task, LBNL is developing technologies to **improve monitoring and quantification** of an important aspect of carbon storage: geologic leakage pathways.
- This field experiment is crucial to understand **monitoring of gas-phase CO_2 at intermediate depth** for a leak into a secondary accumulation ("thief zone").
- The joint use of **seismic** and **EM** methods together will ultimately allow for the **imaging of subsurface CO2 over a wide range of saturations**.

Project Overview

Goals and Objectives

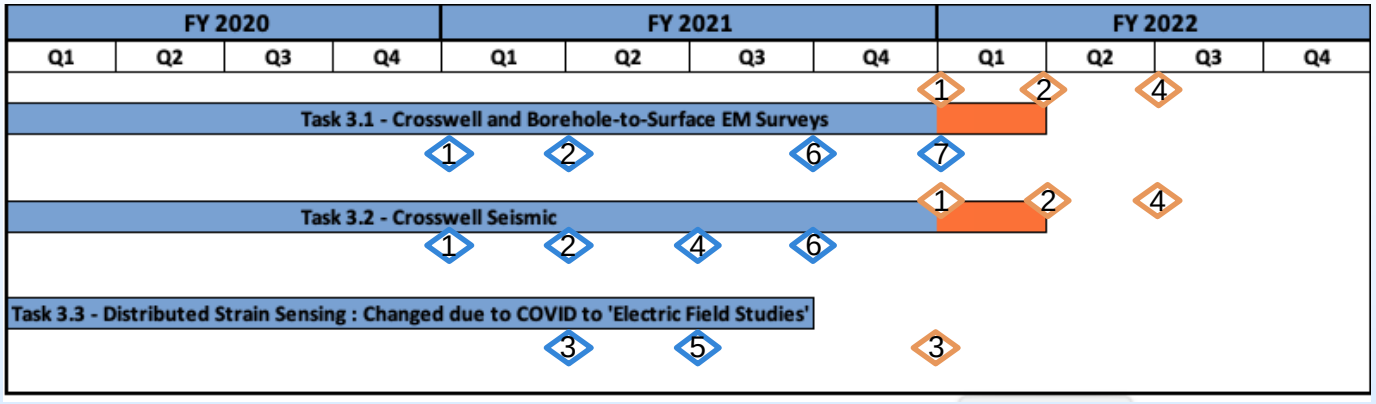
- **Funding:**
  - Started FY2021 with $624k in DOE Funding
  - Currently have $245k for remaining FY2021 Work
  - $0 Cost share other that what our partners (CaMI, SINTEF) are providing in in-kind contributions
- **Overall Project Performance Dates:** To date Task 3 of the CCSMR program has been funded by DOE on a year-to-year basis
- **Project Participants :** LBL, CaMI (University of Calgary, Canada), SINTEF (Norway)
- **Overall Project Objectives:**
  - 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

Organization Chart



Gantt Chart

From FY2020 PMP-SOPO



Color Scale

Original Planned Dates

Delays Due to COVID

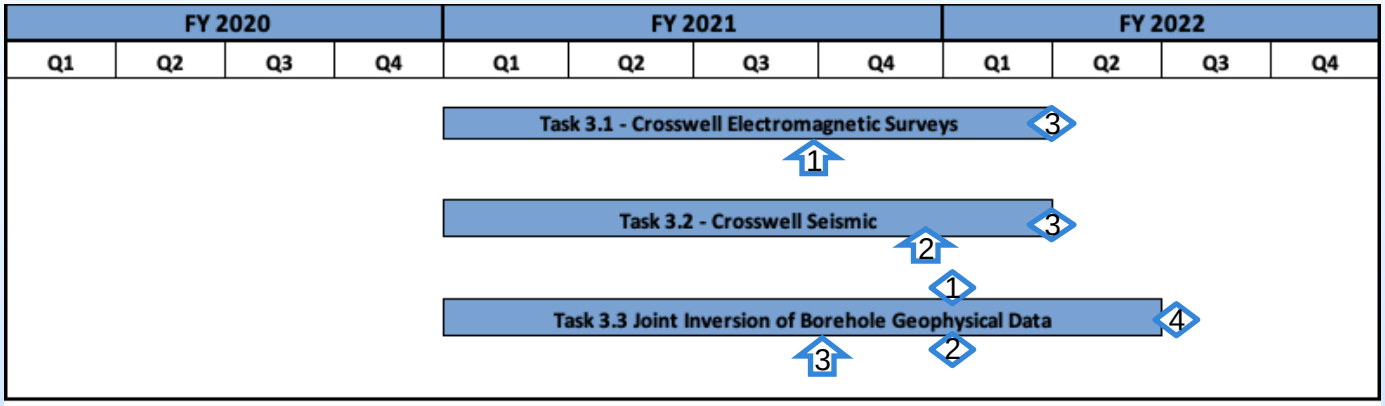
Major Milestones

1. Development of Sequential and Joint Inversion Capabilities
2. Crosswell EM, Seismic an Surface-to-Borehole First Repeat Surveys
3. DSS Dataset Acquisition During Injection : **Changed Due to COVID**
4. Sequential and Joint Inversion of Repeat EM, ERT, and Seismic Datasets
5. Analysis of DSS datasets for strain signature of CO_2 injection : **Cancelled Due to COVID**
6. Crosswell EM, Seismic an Surface-to-Borehole First Repeat Surveys : **Cancelled Due to COVID**
7. Sequential and Joint Inversion of Repeat EM, ERT, and Seismic Datasets : **Cancelled Due to COVID**

3. Develop Workflows for Electric Field Measurements in Perforated Resistive Casing

Gantt Chart

For FY2021 PMP-SOPO



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 Acquistion
4. Sequential and Joint Inversio of Repeat EM, ERT, and Seismic Datasets

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

Bibliography

- List peer reviewed publications generated from the project per the format of the examples below.