Charged Wellbore Casing Controlled Source Electromagnetics (CWC-CSEM) for Reservoir Imaging and Monitoring: FE0028320

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U.S. Department of Energy

National Energy Technology Laboratory

CO2 Capture Technology Project Review Meeting

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Full Project Team

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Collaborators

- Denbury Resources, Inc.
- Energy and Environmental Research Center (EERC)

Presentation Outline

- Project Overview
- Methodology
- Current Status
- Accomplishments
- Lessons learned
- Summary

Project Overview

Production-scale verification of CWC-CSEM as MVA technology

- Multi-phase system, fluid content change alters electrical conductivity
- Dynamic system with CO_2 injection, time-lapse monitoring
- Cost-efficient monitoring through use of existing wellbores

Integrated reservoir MVA

- Coupled simulation
- Constrained inversion
- History matched with time-lapse CWC-CSEM and production data
- Collaboration with site operator - Denbury Resources, Inc.

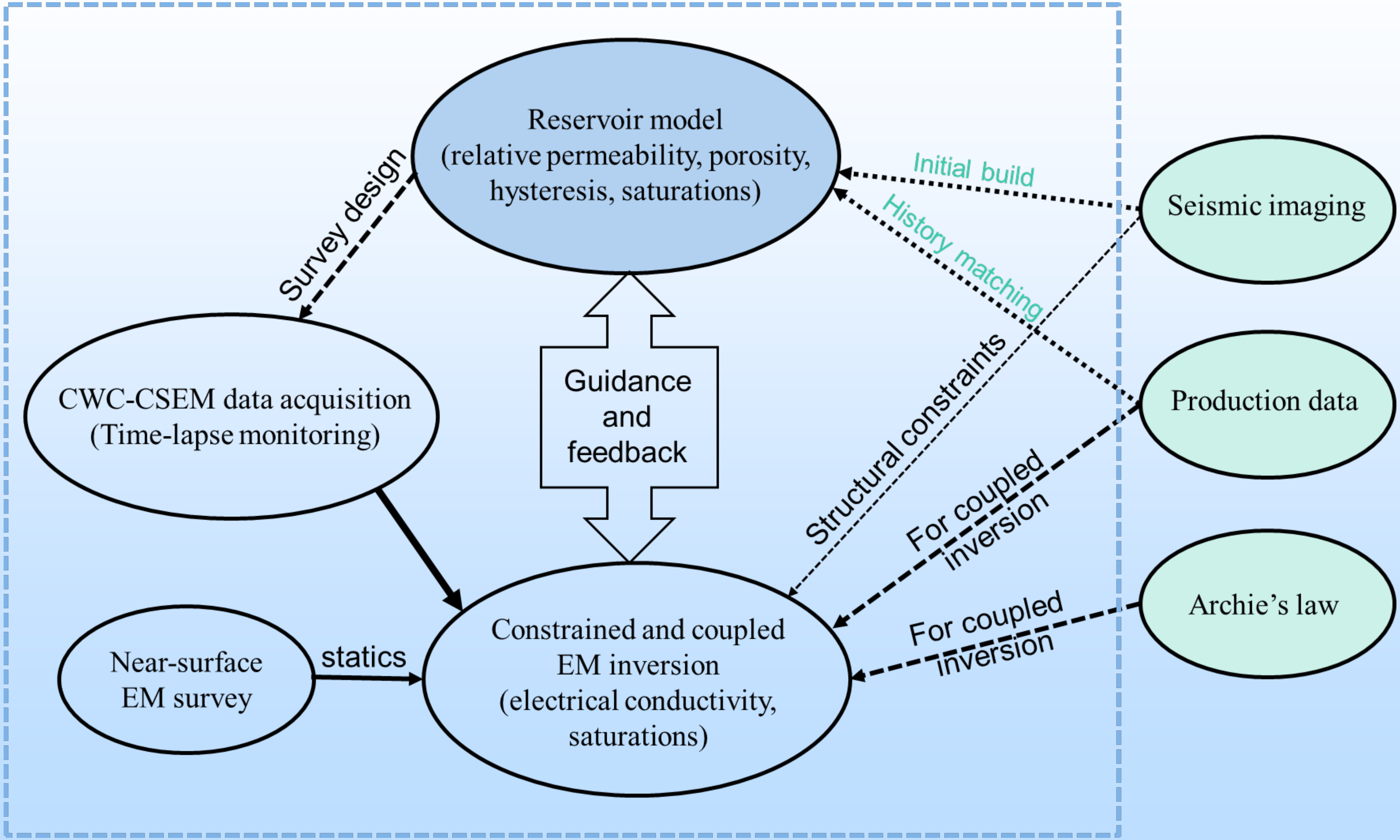
Field site: Bell Creek, Montana

Methodology: Underlying Method

Charged wellbore casing controlled source electromagnetics

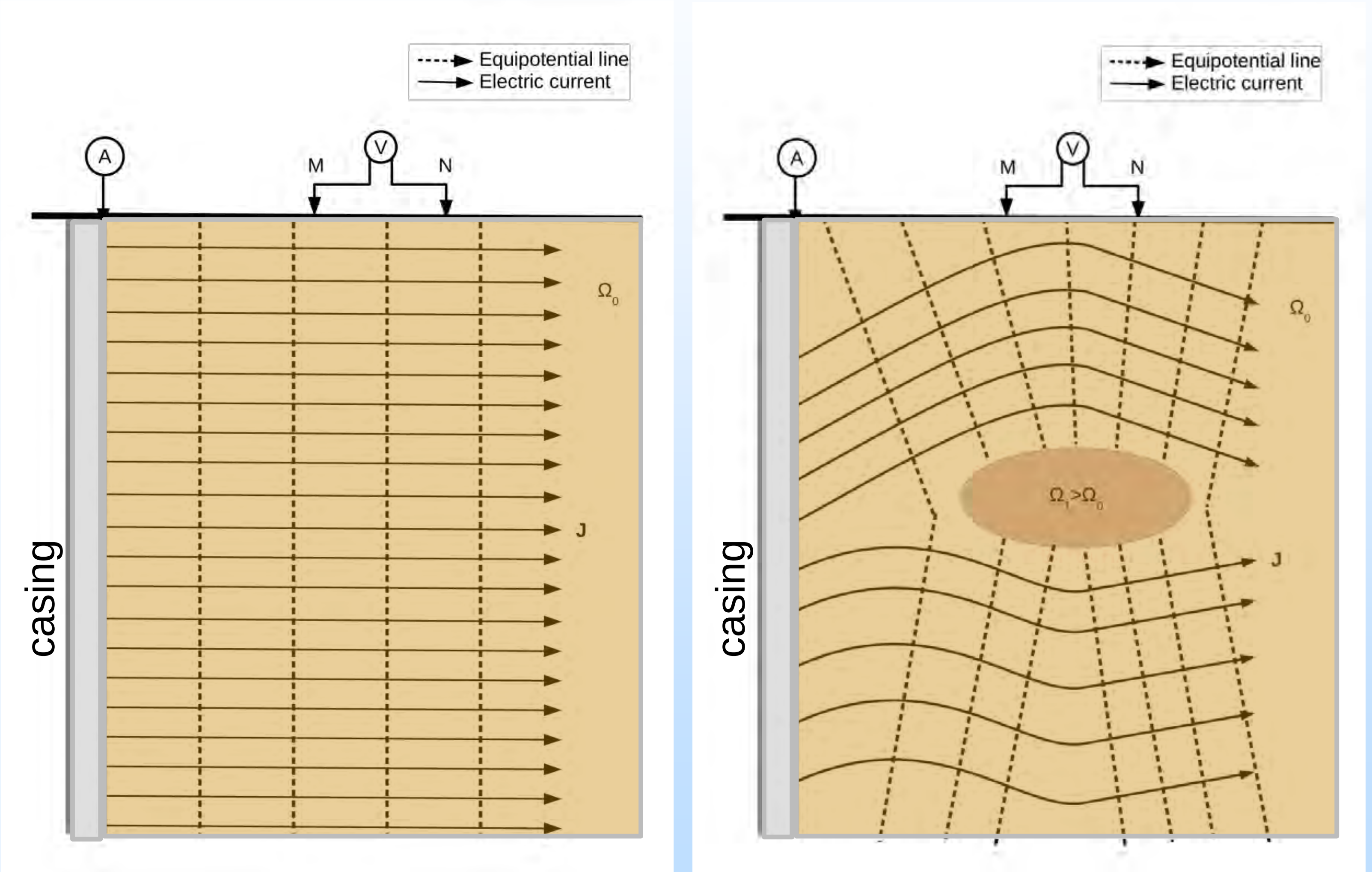
1. Electrical conductivity tied to reservoir fluid phase (oil / CO_2 / water)
2. Development and maturation at active CCS-EOR project
3. Constrained inversion using data from existing characterization
4. Static near-surface correction from transient EM data
5. Integration with reservoir simulation
6. History matching for validation

Methodology: Workflow



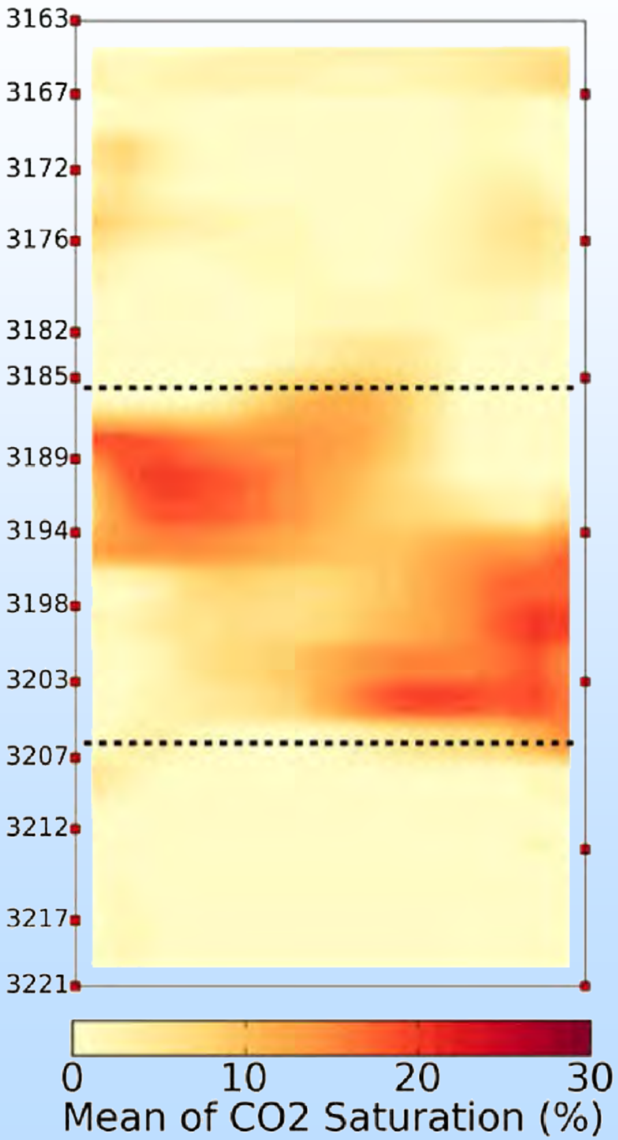
Methodology: CWC-CSEM Principle

- CSEM transmitters inject current through legacy borehole casings deep into subsurface
- Current flows around resistive bodies (CO_2)
- Surface measurements of E and B fields
- Time-lapse measurements to observe changes
- 4D inversion of electrical conductivity



No internal borehole access!

Methodology: CWC-CSEM Basis



Archie's Law $R_t = a\phi^{-m} S_w^{-n} R_w$

Waxman-Smits $\phi_t^m S_{wt}^n \left(\frac{1}{R_w} + \frac{BQ_V}{S_{wt}} \right)$

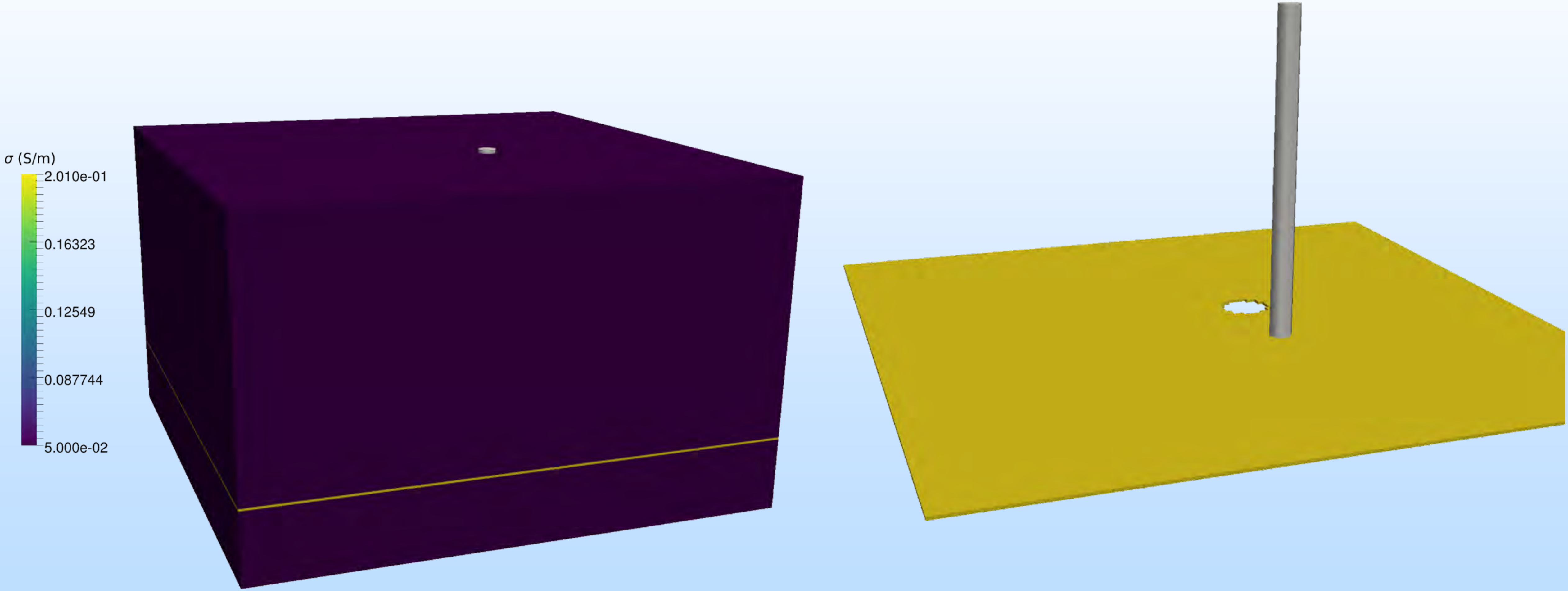
- R_t saturated rock resistivity
- *a* tortuosity factor
- φ porosity
- *m* cementation factor
- S_w saturation of water
- R_w brine resistivity

- Conductivity changes have been shown to be effective in mapping saturation in CCS settings (Yang et al., 2014)
- Archie's law and similar empirical relationships map resistivity to saturation
- Crosswell ERT requires dedicated wellbore jewelry and specialized construction

Image from: Xianjin Yang, Xiao Chen, Charles R. Carrigan, and Abelardo L. Ramirez (2014). "Uncertainty quantification of CO_2 saturation estimated from electrical resistance tomography data at the Cranfield site". In: International Journal of Greenhouse Gas Control 27.Supplement C, pp. 59 –68. issn: 1750-5836.

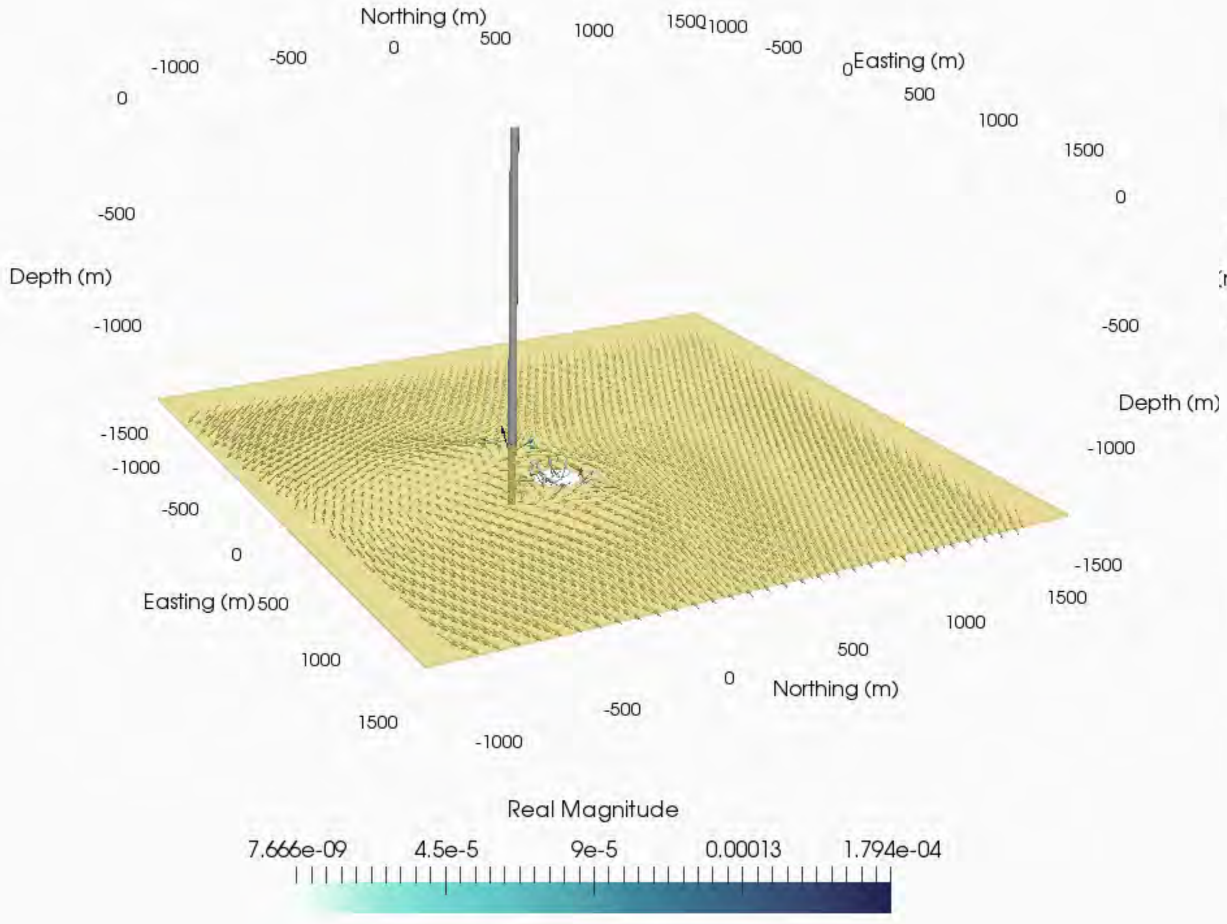
Methodology: CWC-CSEM Simulation

Resistive CO_2 plume near charged wellbore casing

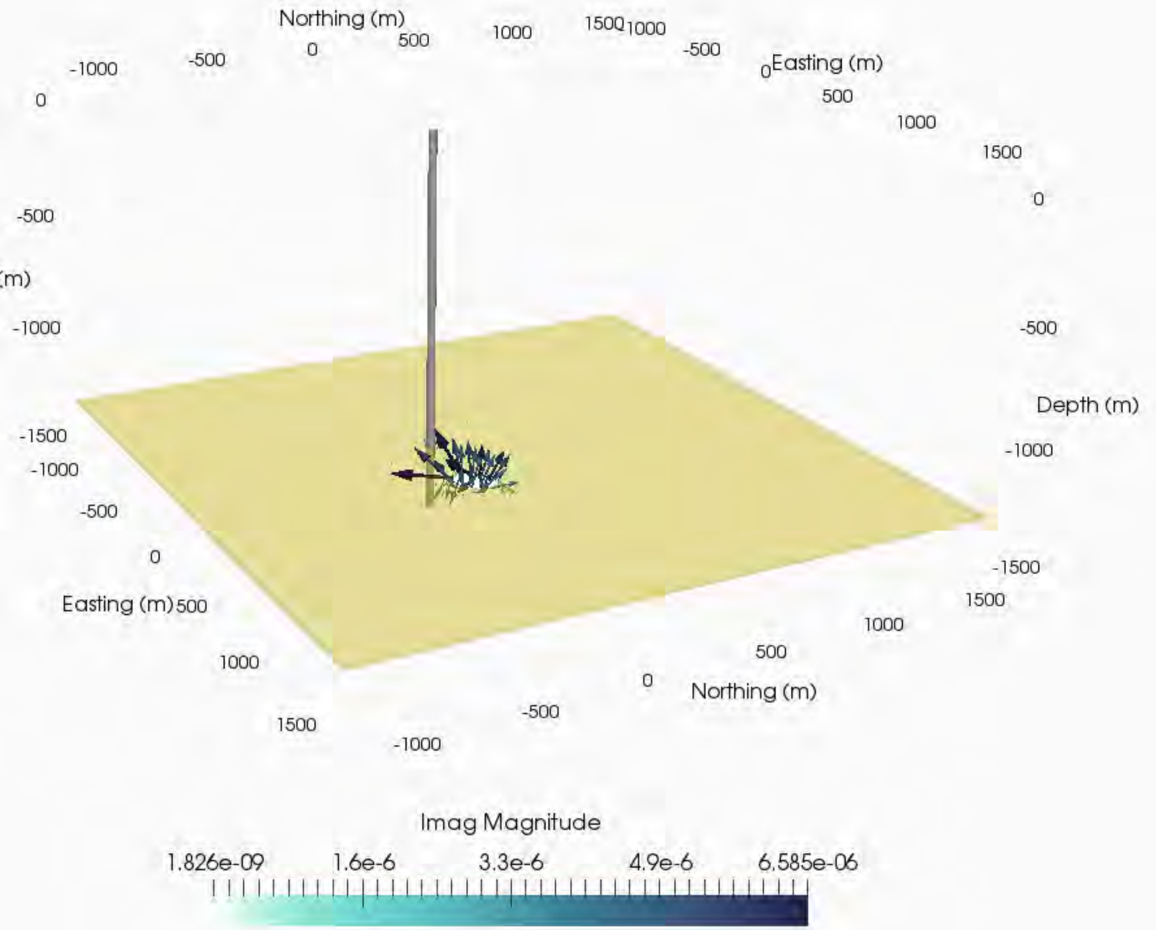


Methodology: CWC-CSEM Simulation

Real component

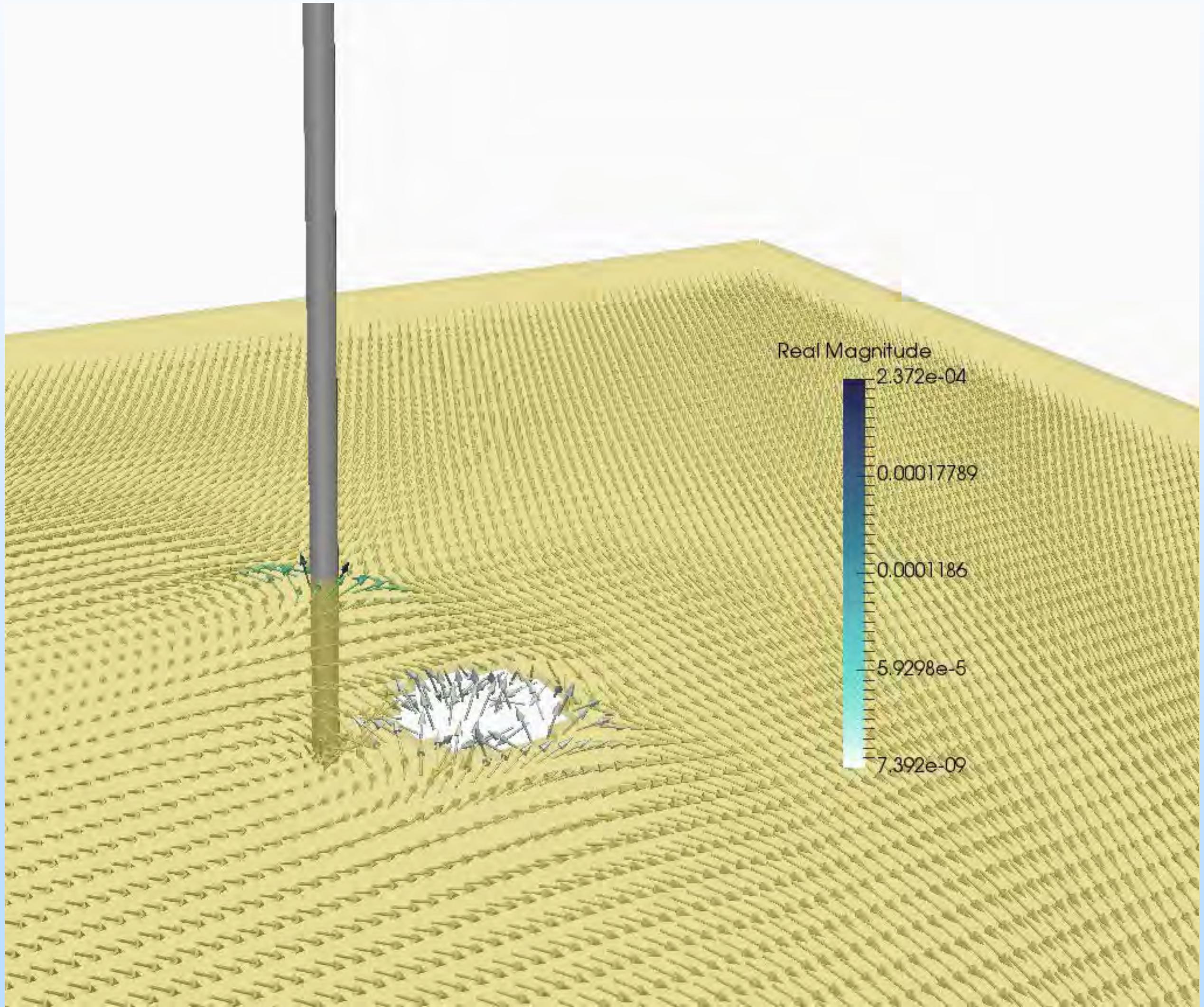


Imaginary component

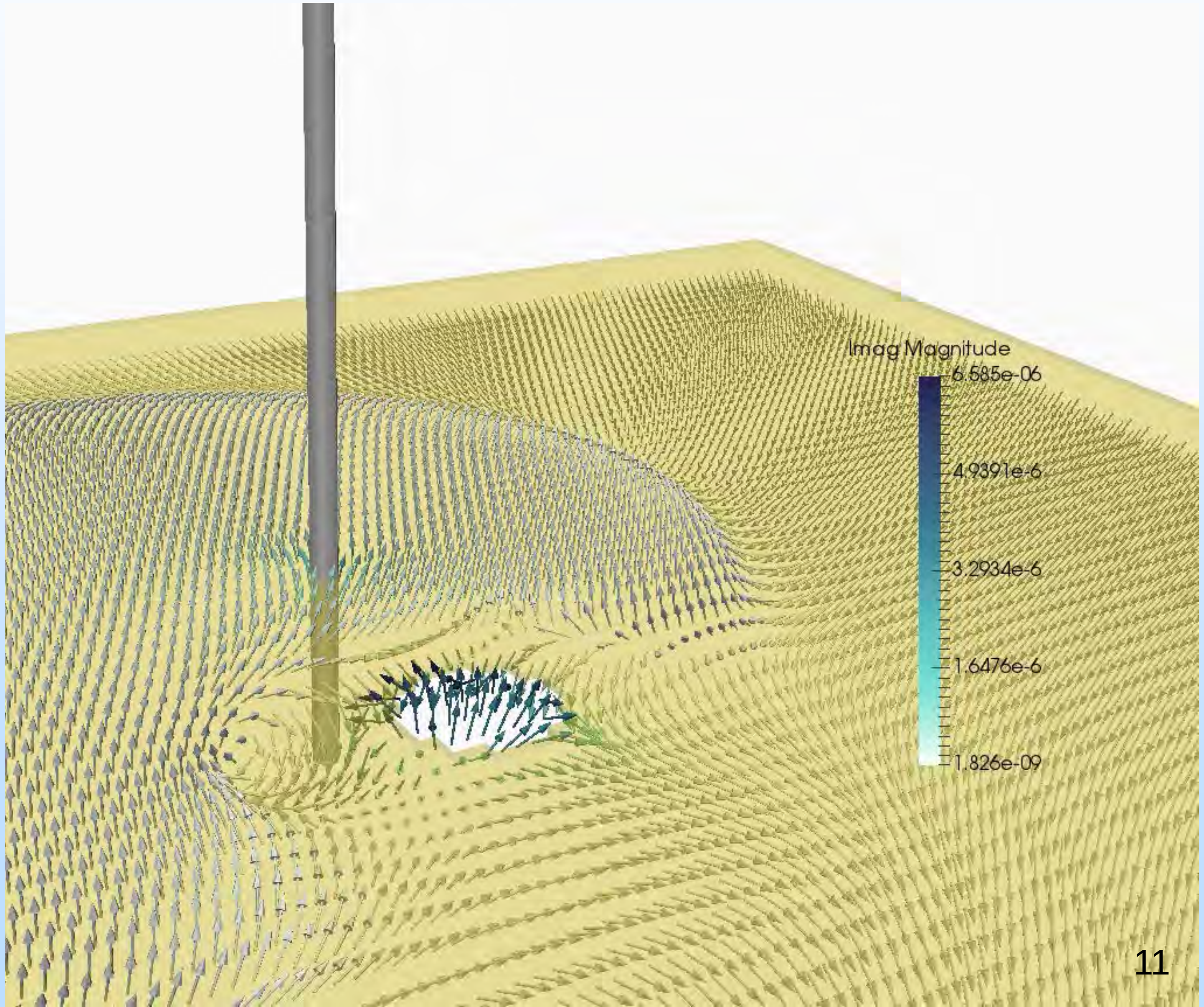


Methodology: CWC-CSEM Simulation

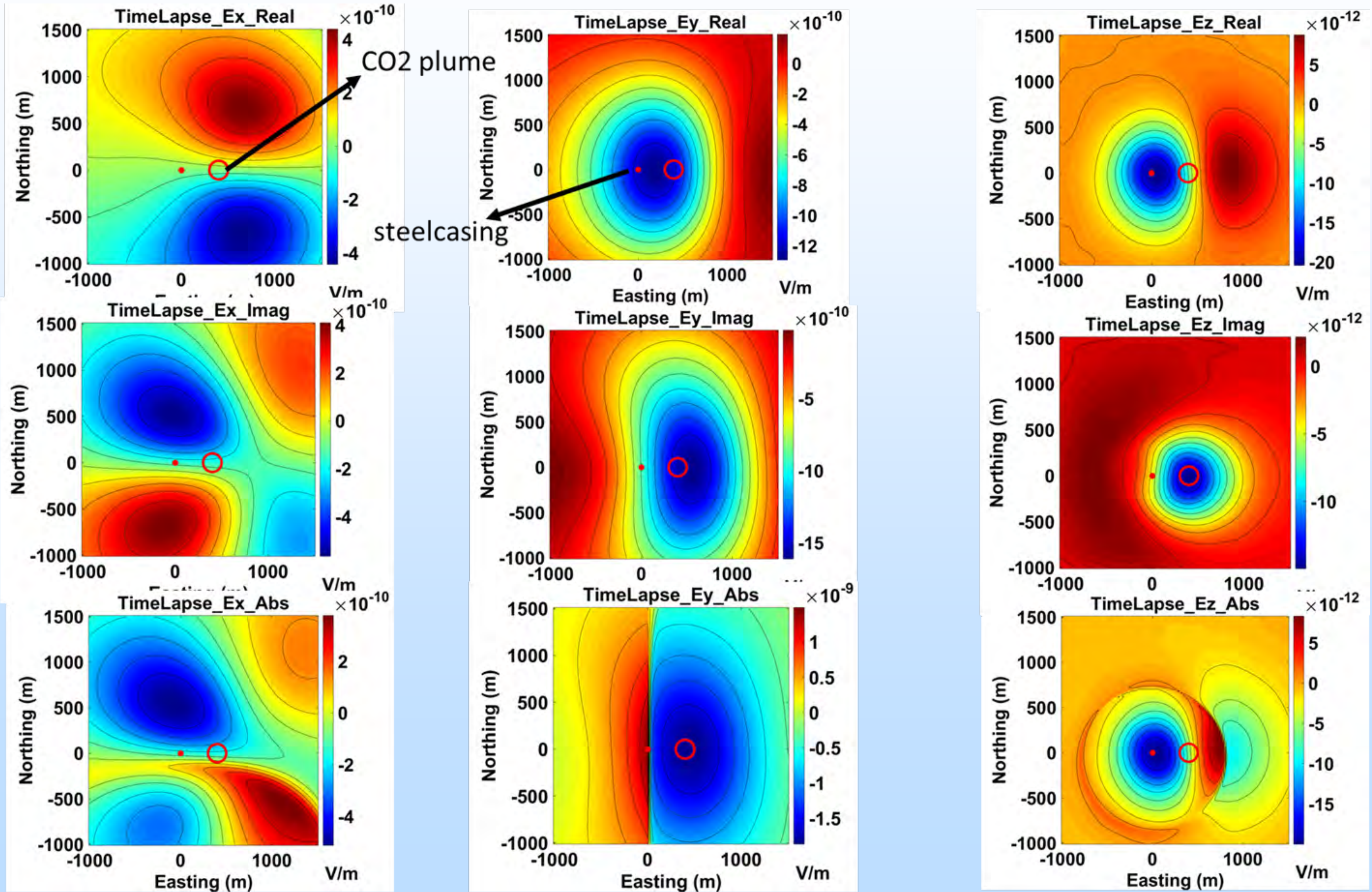
Real component



Imaginary component



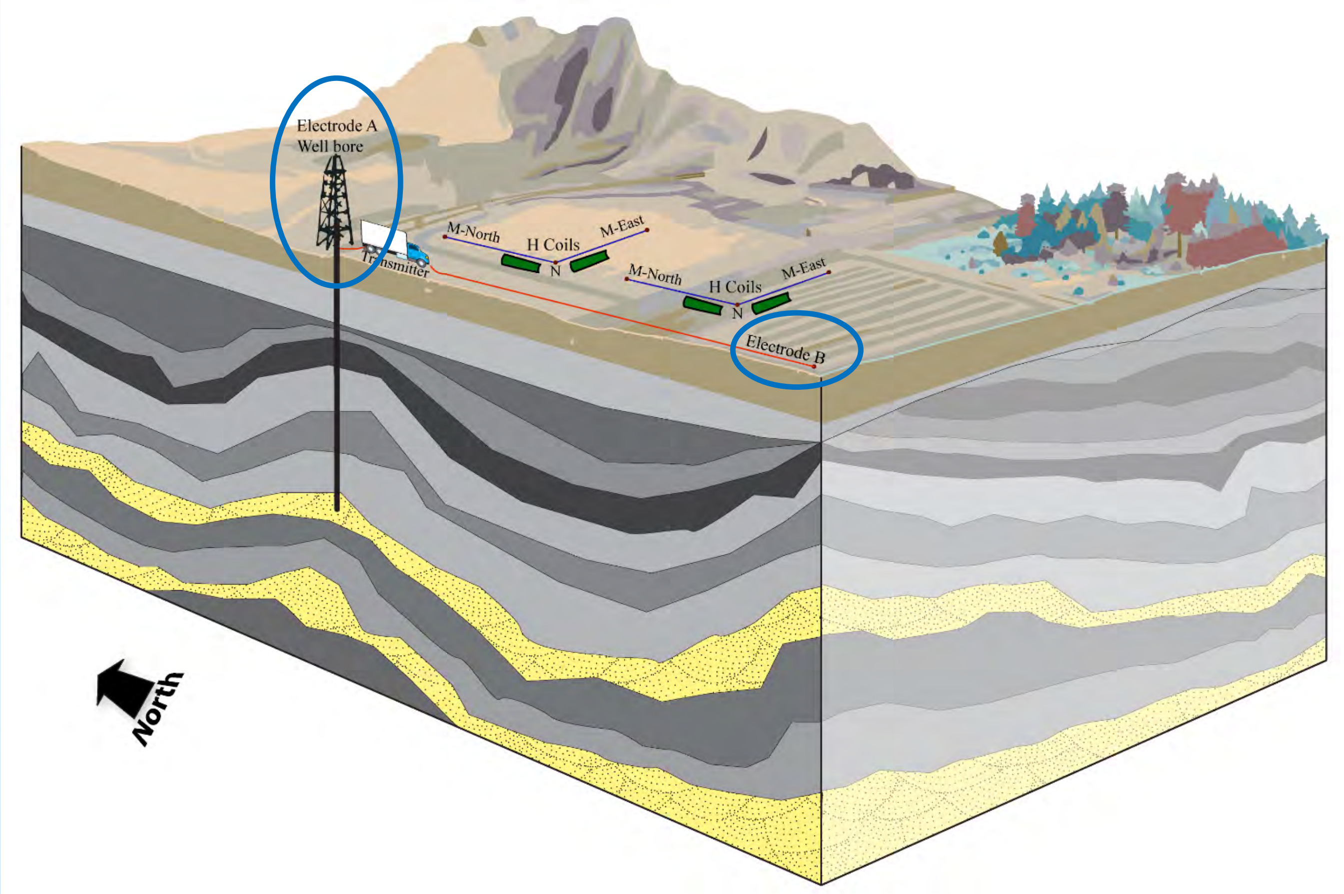
Methodology: CWC-CSEM Simulation



Methodology: CWC-CSEM Deployment

Transmitter Scenario 1: Borehole to Surface

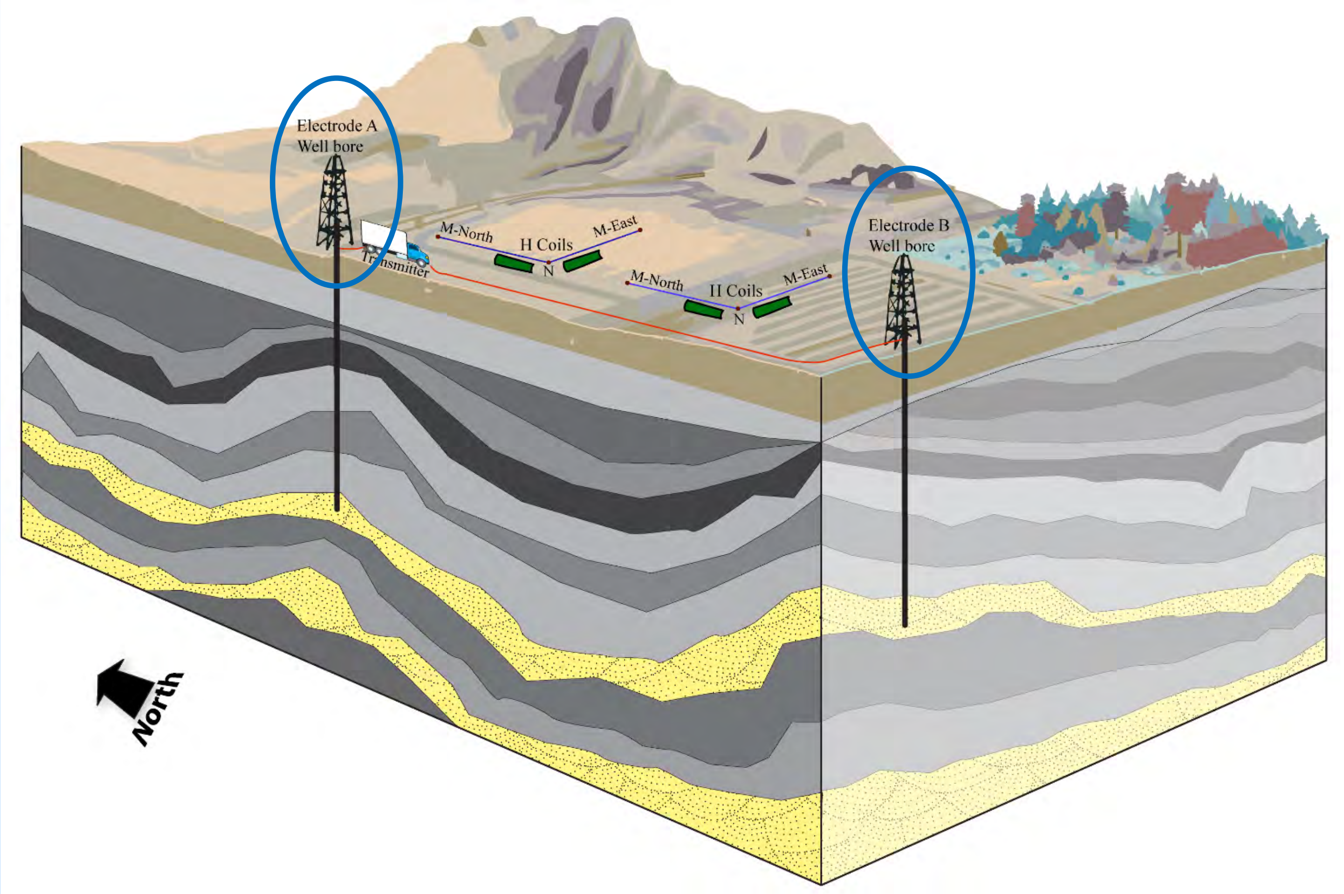
- Simplest configuration
- Only requires single borehole
- Rely on a conventional surface electrode



Methodology: CWC-CSEM Deployment

Transmitter Scenario 2: Borehole to Borehole

- Improved depth of investigation
- Current path between casings
- Less invasive, easier setup
- Requires additional access



Methodology: CWC-CSEM Deployment

Base Camp

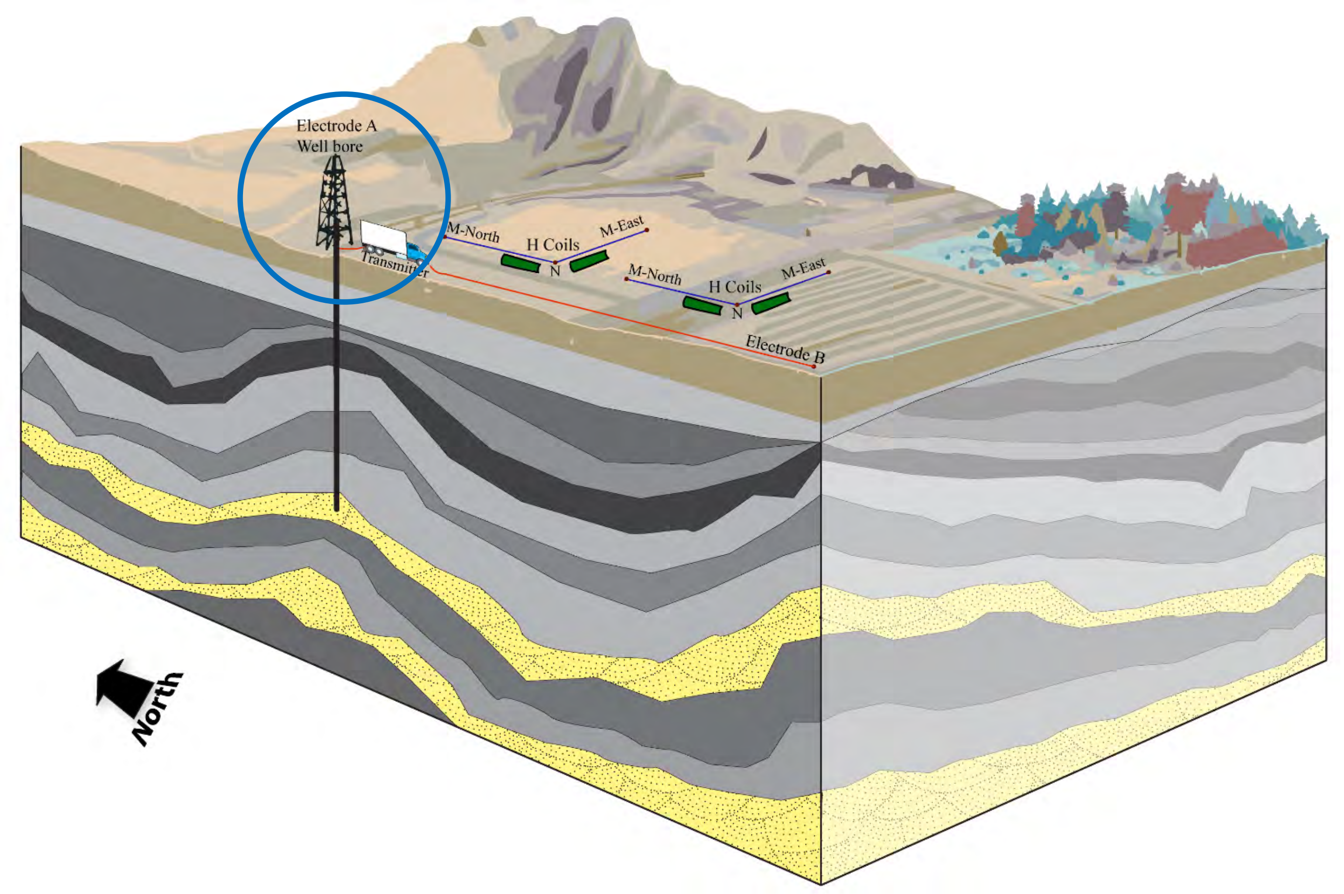
Generator

Base Tent

Transmitter

Electrode A

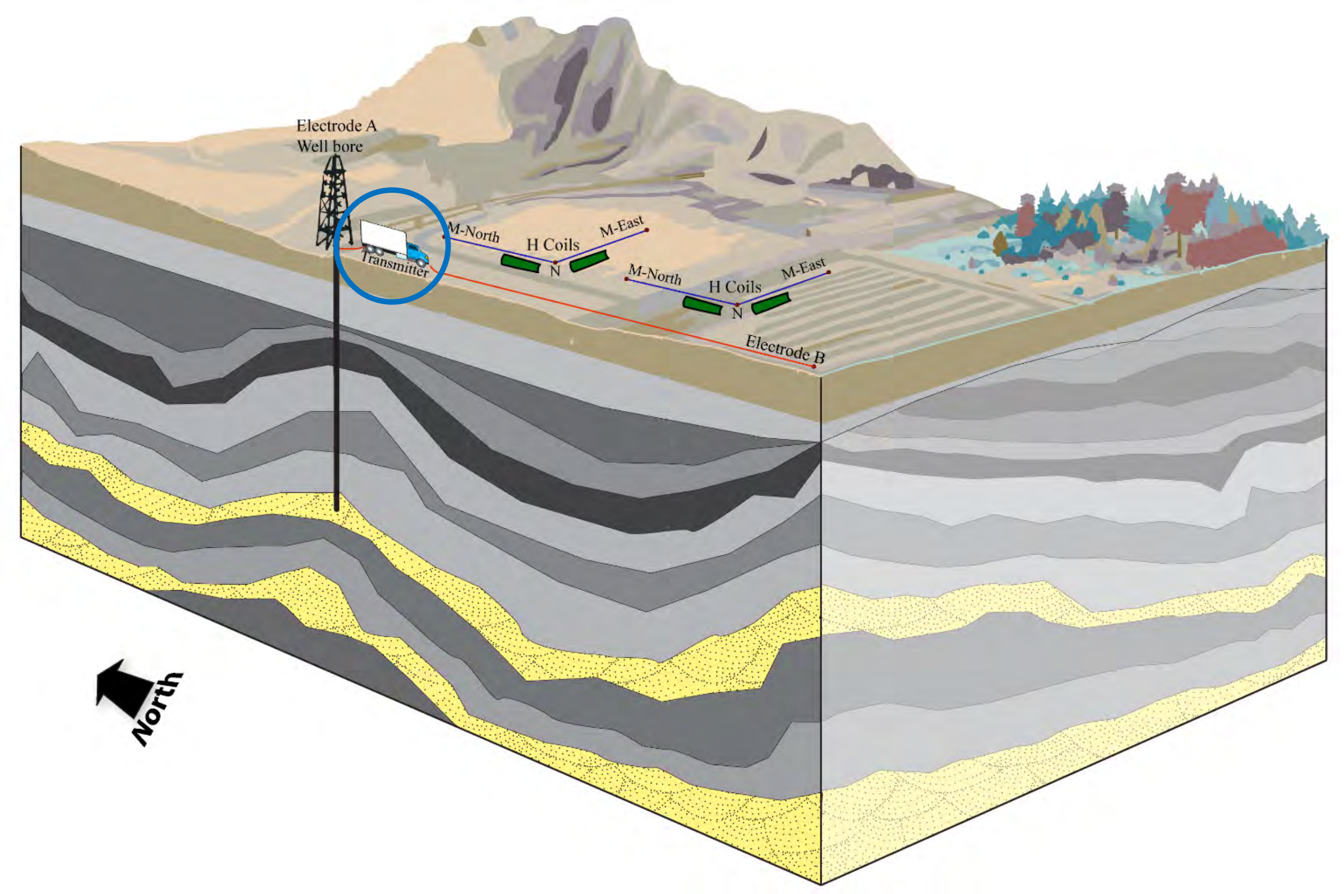
TX Wire



- Established next to Electrode-A borehole
- Provides shelter for personnel and electronics
- Close to Denbury office

Methodology: CWC-CSEM Deployment

Transmitter Station

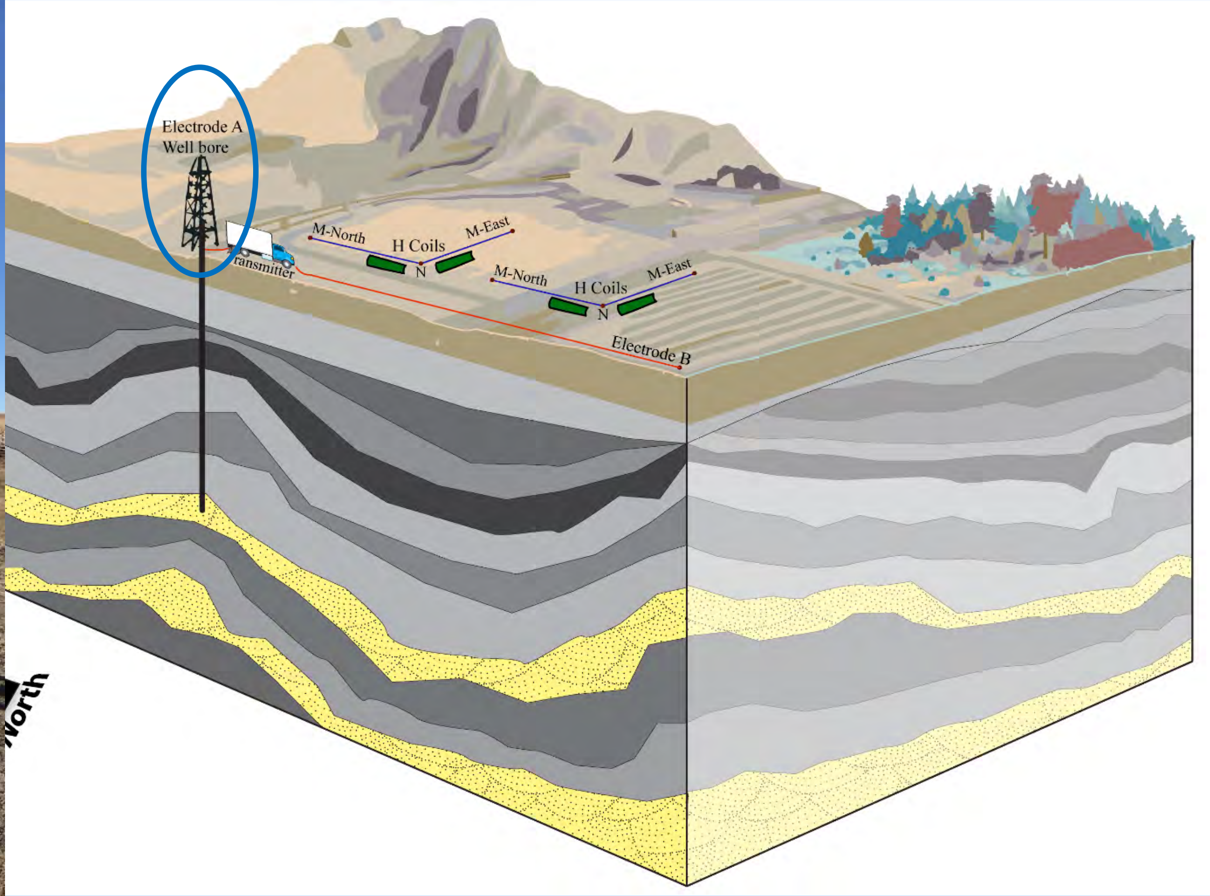


- Transmitter box, Iso-amp, Zen-receiver, Laptop
- Full transmission cycle: ~ 4-hours
- Transmission run continuously throughout each day while the receivers are moved every 4-hours to ensure that they capture a complete transmission cycle

Methodology: CWC-CSEM Deployment

Transmitter: Borehole Electrode

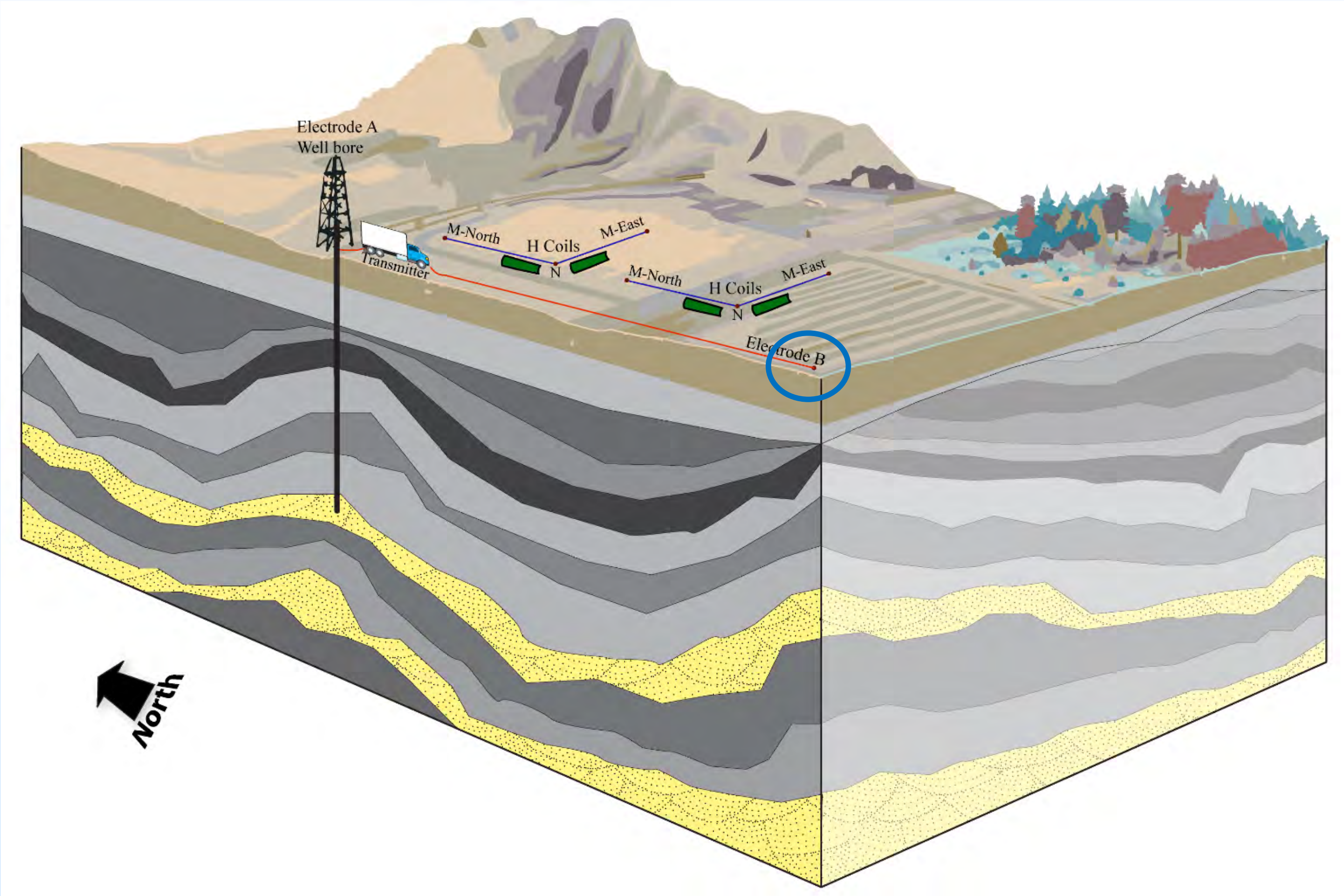
- Electrode A always
- Electrode B for borehole-borehole array
- Tx wire connected to production tubing of legacy wells
- 25 Amps; 200 Volts
- Full transmission cycle is approximately 4 hours
- Warning signs placed on the wells
- Provides direct contact with reservoir



Methodology: CWC-CSEM Deployment

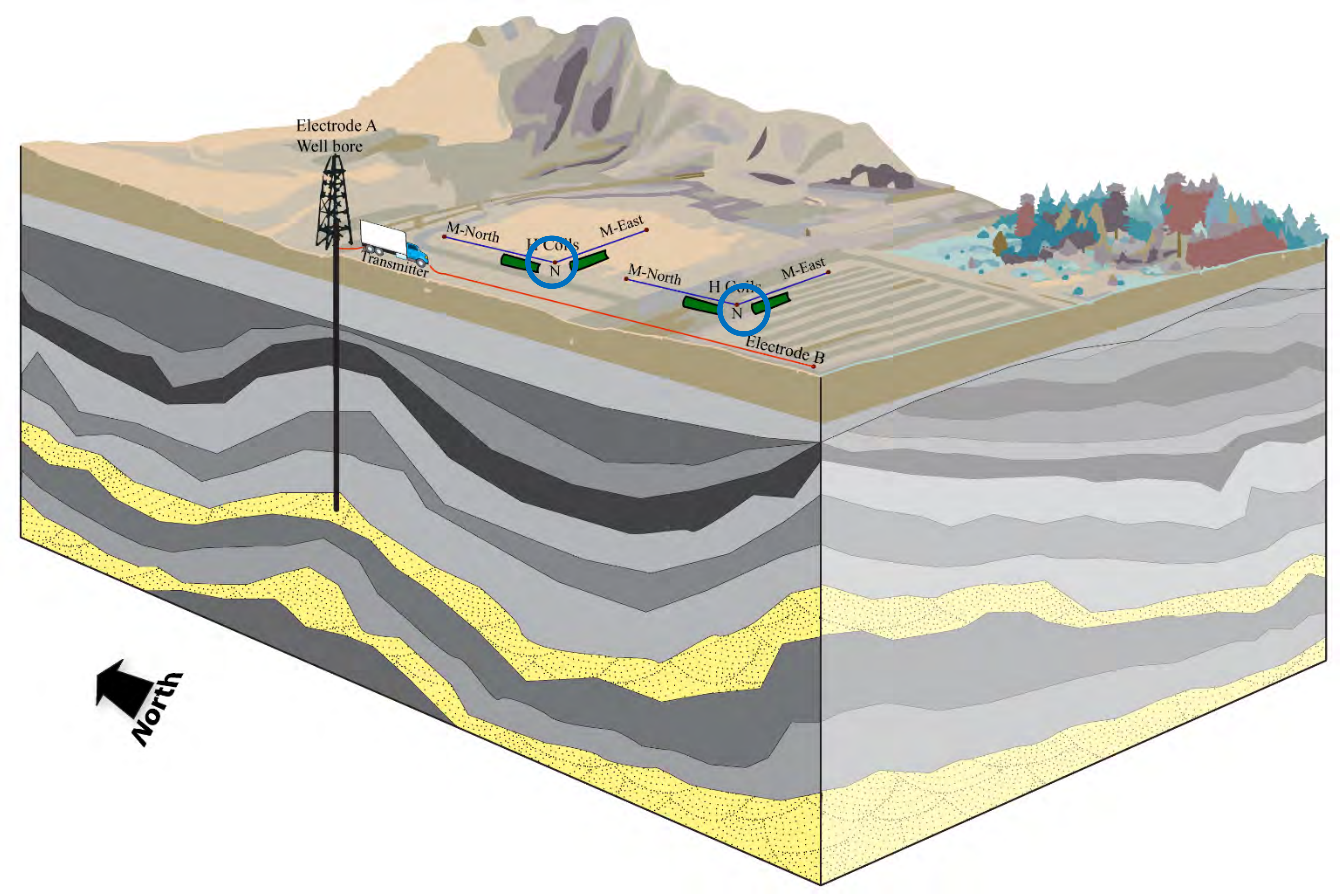
Transmitter: Surface Electrode

- Tx Electrode – B (scenario-1)
- “Layer-cake” construction
- Alternating layers of aluminum foil, soil, and a lot of salt water
- Buried at approximately1-ft depth



Methodology: CWC-CSEM Deployment

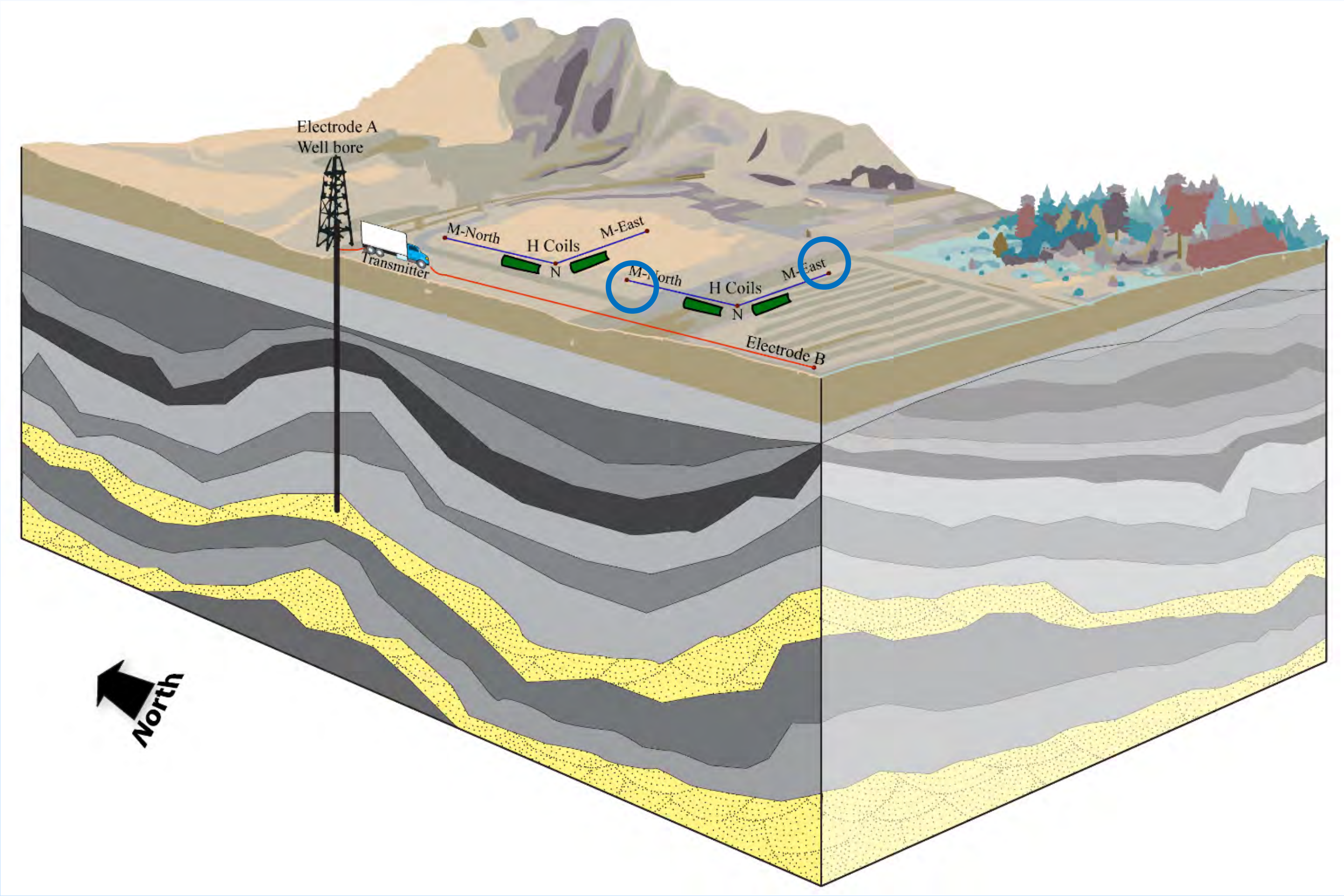
Receiver Box



- South-west corner of each Rx Station
- Sealed box with Zen receivers and batteries
- Connects to receiver electrodes and B-coils
- Data collected for a minimum of 4-hours for full transmission cycle
- Data downloaded with laptop before moving the Rx station to the next location

Methodology: CWC-CSEM Deployment

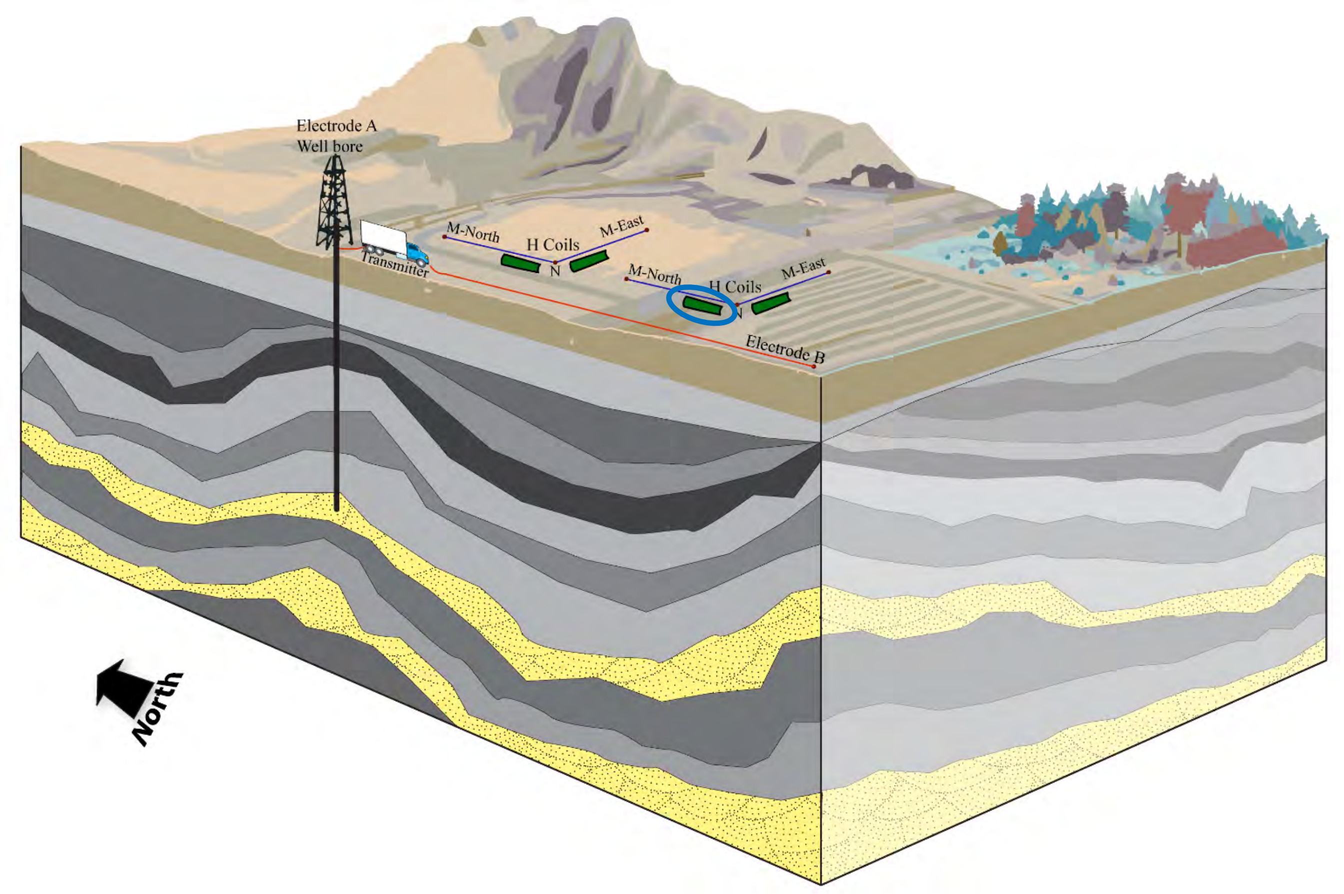
Receiver Sensors: E-Field



- Center electrode near the receiver box in the south-west corner
- Additional electrodes buried 100-m to the north and east of the center electrode in L-shape
- Vector E-field measurements

Methodology: CWC-CSEM Deployment

Receiver Sensors: B-Field



- Three sensors measuring horizontal and vertical components of the B-field
- Located near center receiver station
- Approximately 1-ft deep for horizontal components

Current Status

Project Year 2017: Recap

- Significant initial developments
  - Reservoir simulation modeling
  - EM modeling codes
  - Field survey planning
- Unexpected setback
  - Loss of initially planned field site due to internal re-organization of site operator
  - Initial field survey planning and reservoir simulations no longer valid
- Project adjustment
  - New field site agreement with enthusiastic operator: Denbury Resources, Inc.
  - Algorithms and procedures from initial field site in place and ready for new site

Current Status

Current Project Year

- Budget Year coincides with calendar year; Updated PMP
- Currently eight months into BY-2
- New reservoir simulation data fully available, modeling on track
- Three field surveys since last Annual Review Meeting
  - One test survey at a local ASR site in Arvada, CO: August 2017
  - Two field surveys at new CCS-EOR site: October 2017, May 2018
- Remaining for BY-2
  - Continue reservoir and EM modeling, data integration, interpretation
  - One more field campaign in BY-2: October 2018

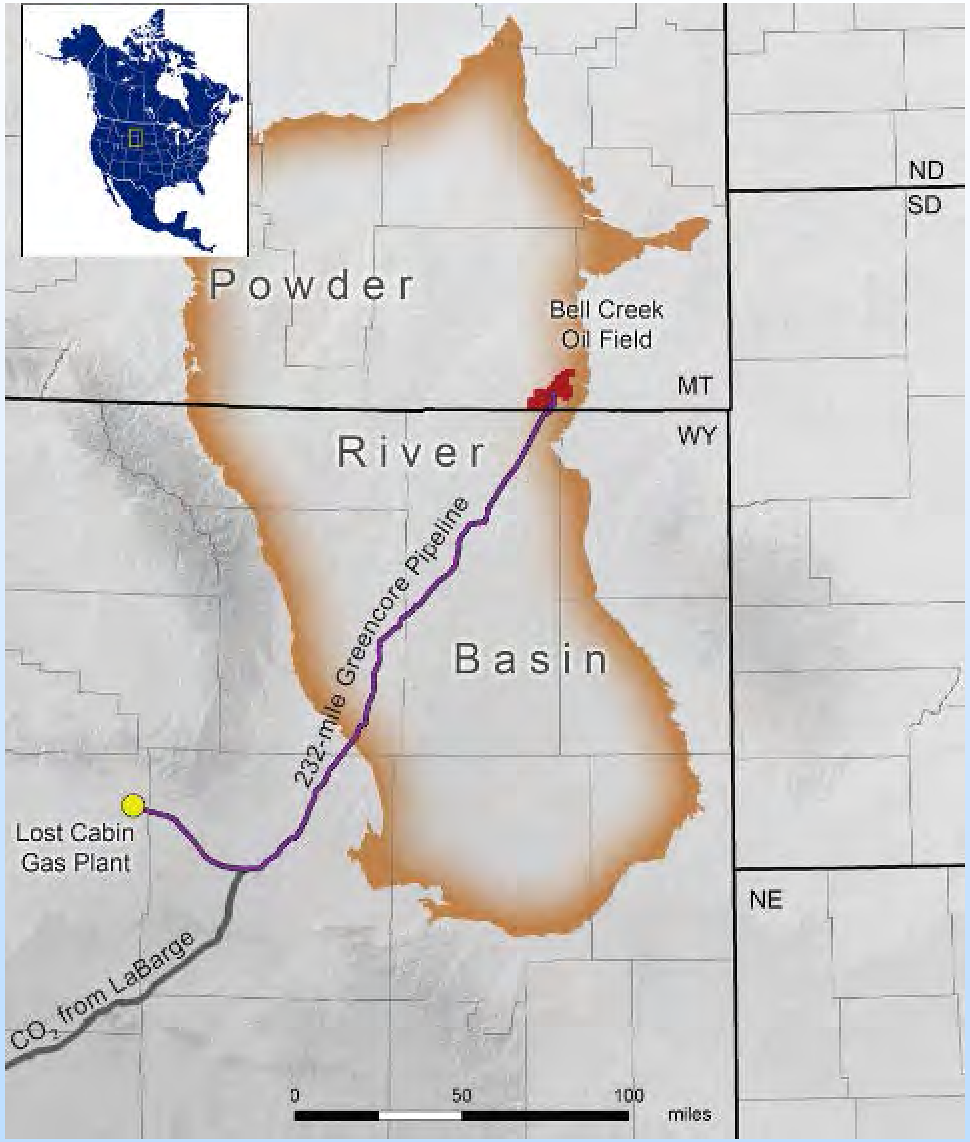
Accomplishments: Field Surveys

Field campaigns

- Two completed at CCS-EOR site

Site Background

- Bell Creek Integrated EOR & CO2 Storage Project
- Powder River Basin
- South-eastern Montana

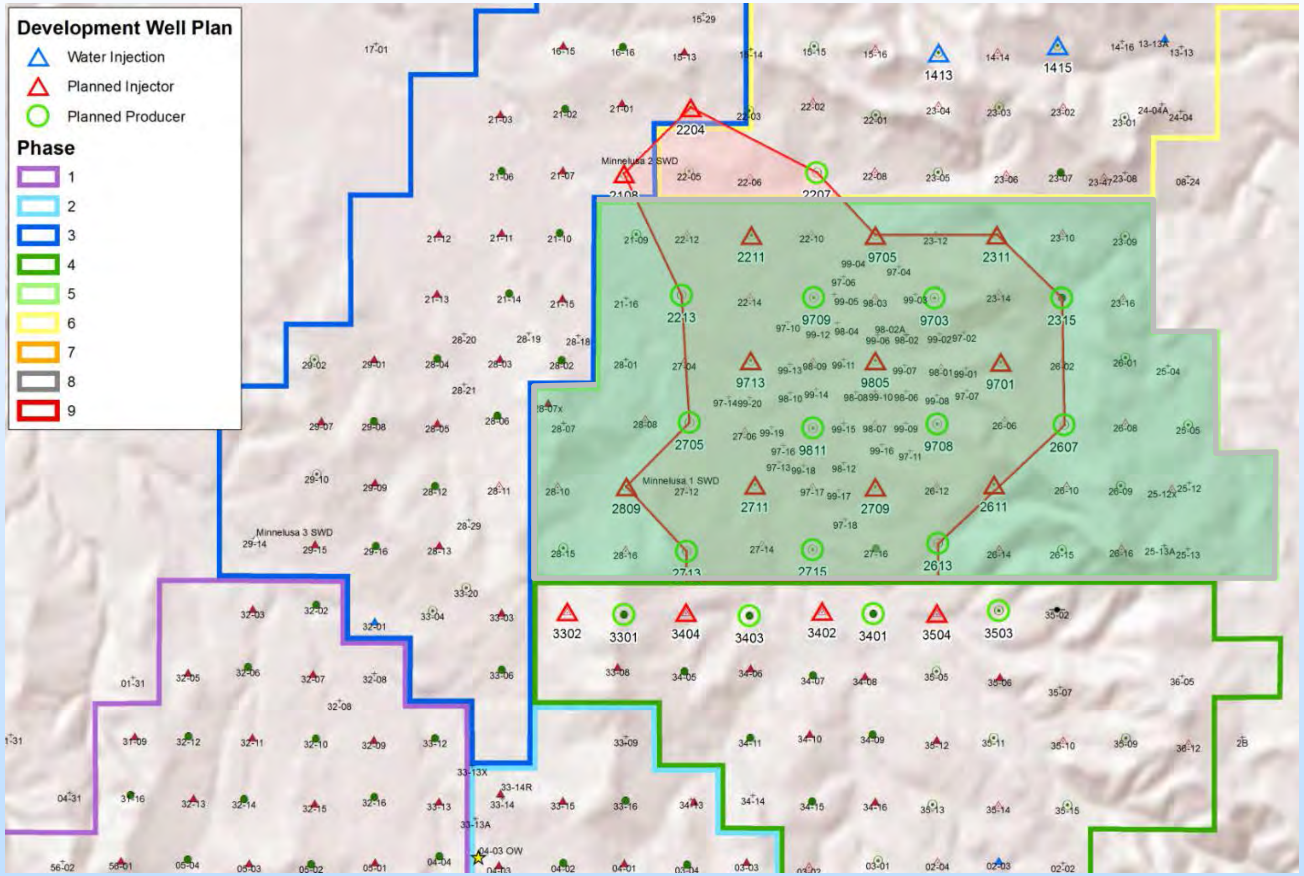


https://www.undeerc.org/pcor/co2sequestrationprojects/BellCreek.aspx

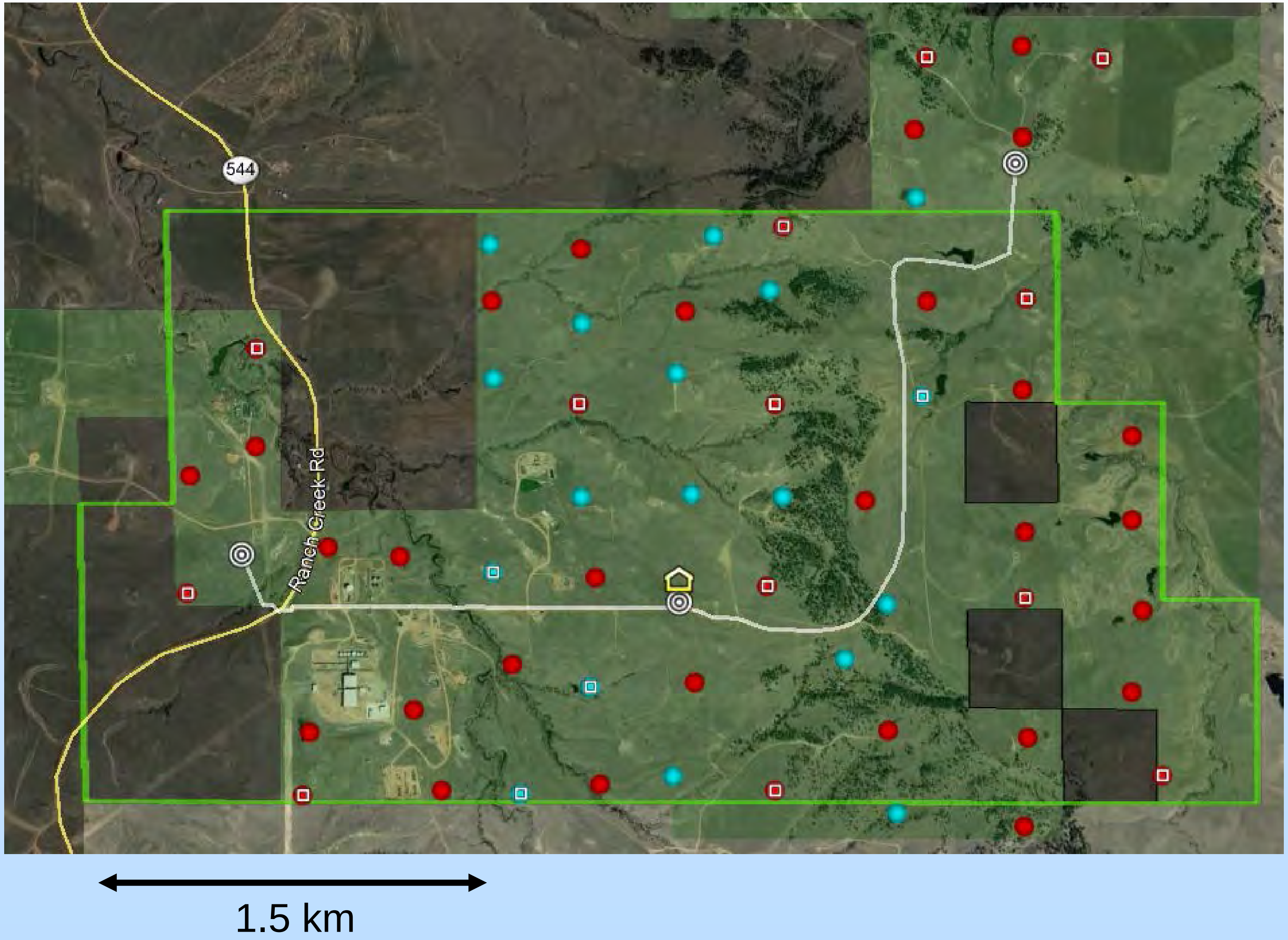
Accomplishments: Field Surveys

Bell Creek Production

- Denbury Resources, Inc.
- 9 phases of production
- Current project is within the phase-5 production area
  - Outlined in light-green
  - Approximate 2-km x 3-km area
  - Started in Summer 2017
  - Combination of private, Denbury, and BLM lands



Accomplishments: Field Surveys



Phase 5 Area

Accessible lands

Non-accessible lands

CWC-CSEM Tx Boreholes [3]

Tx Wire between boreholes [2]

CWC-CSEM Rx – 2017 [18]

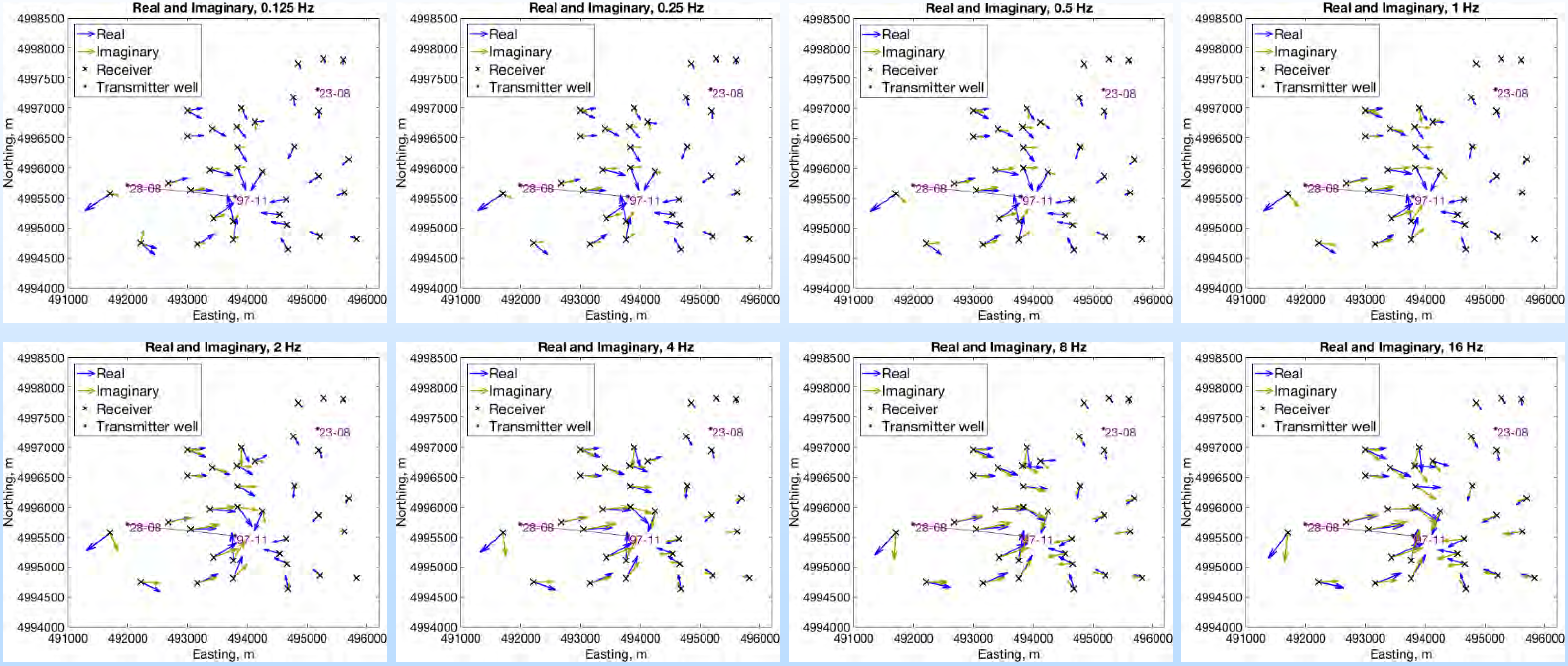
CWC-CSEM Rx – 2018 Extended [47]

TEM Stations [20]

Accomplishments: Field Surveys

CWC-CSEM Field Data

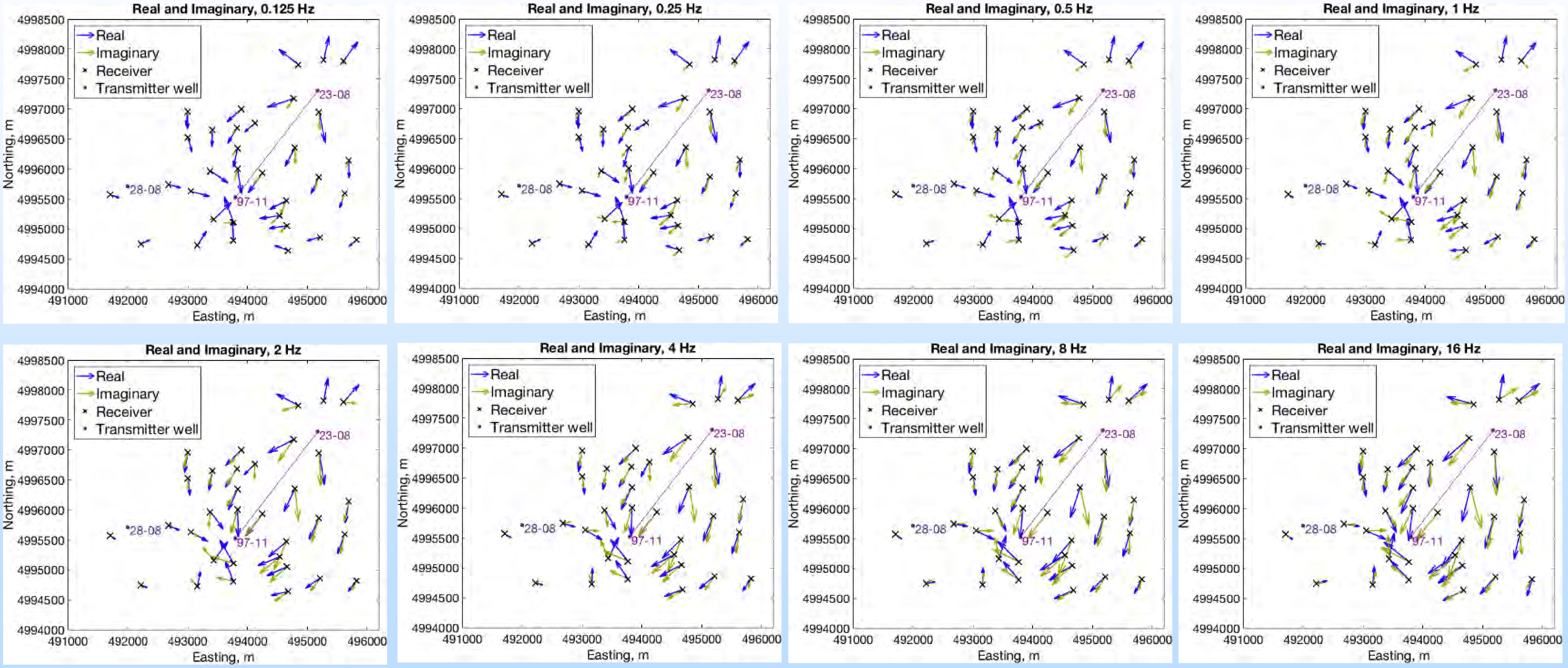
E-field Data, June 2018, Borehole-pair one (magenta line)



Accomplishments: Field Surveys

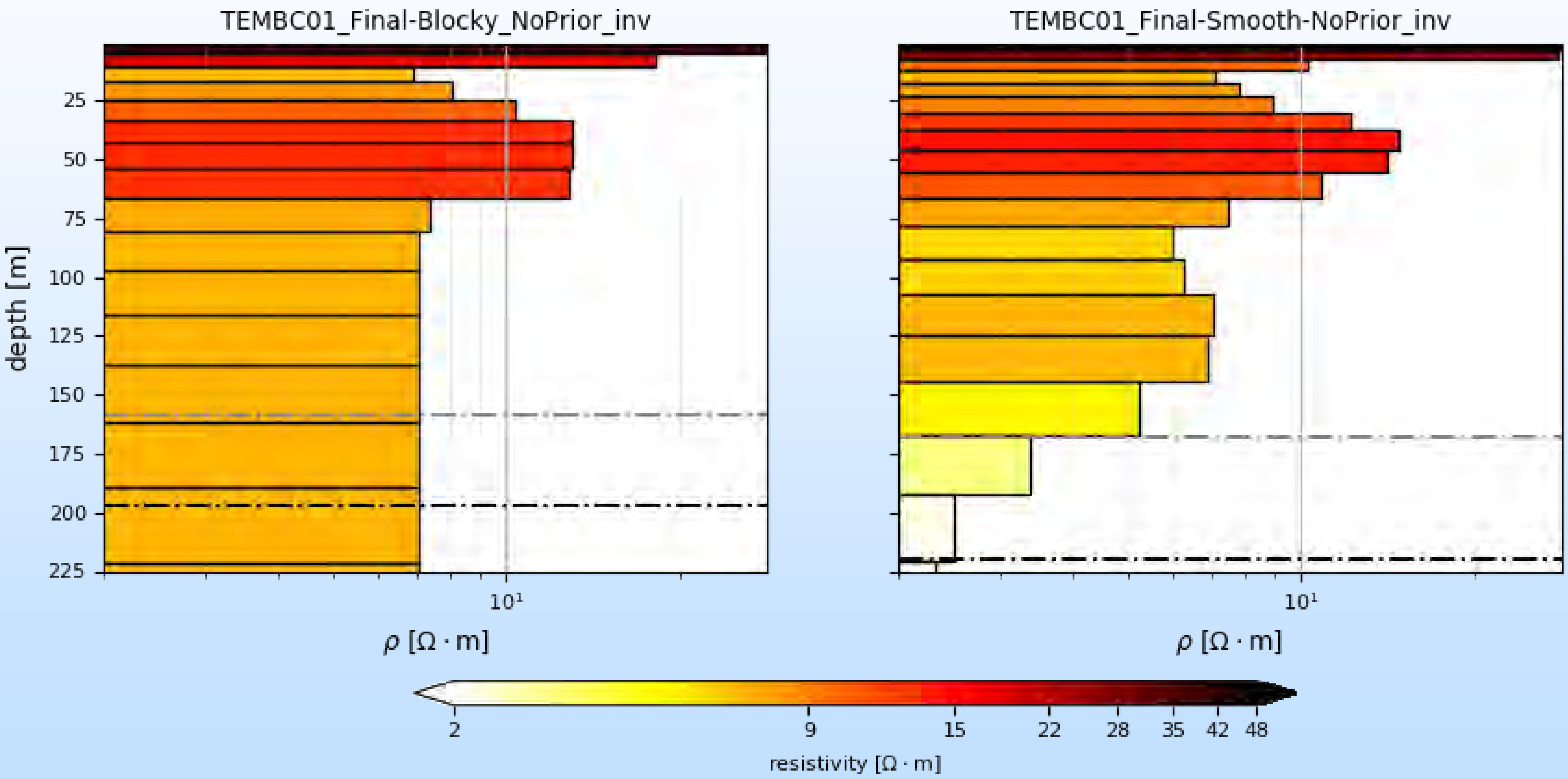
CWC-CSEM Field Data

E-field Data, June 2018, Borehole-pair two (magenta line)



Accomplishments: Field Surveys

TEM Data Acquisition and Inversion

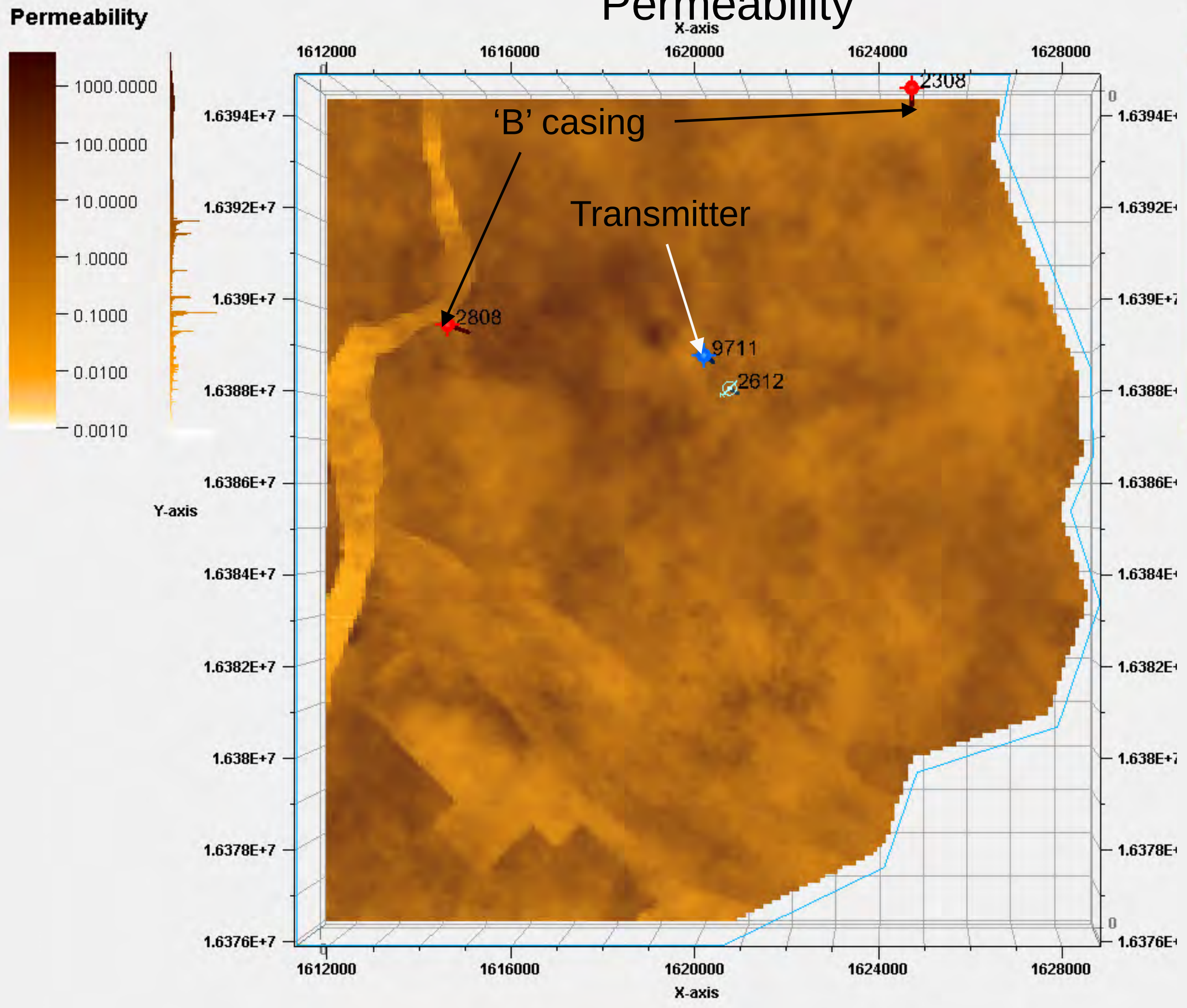


- Used in static correction
- Complements induction logs, which do not cover near surface
- Fast, mature, and reliable geophysical technique

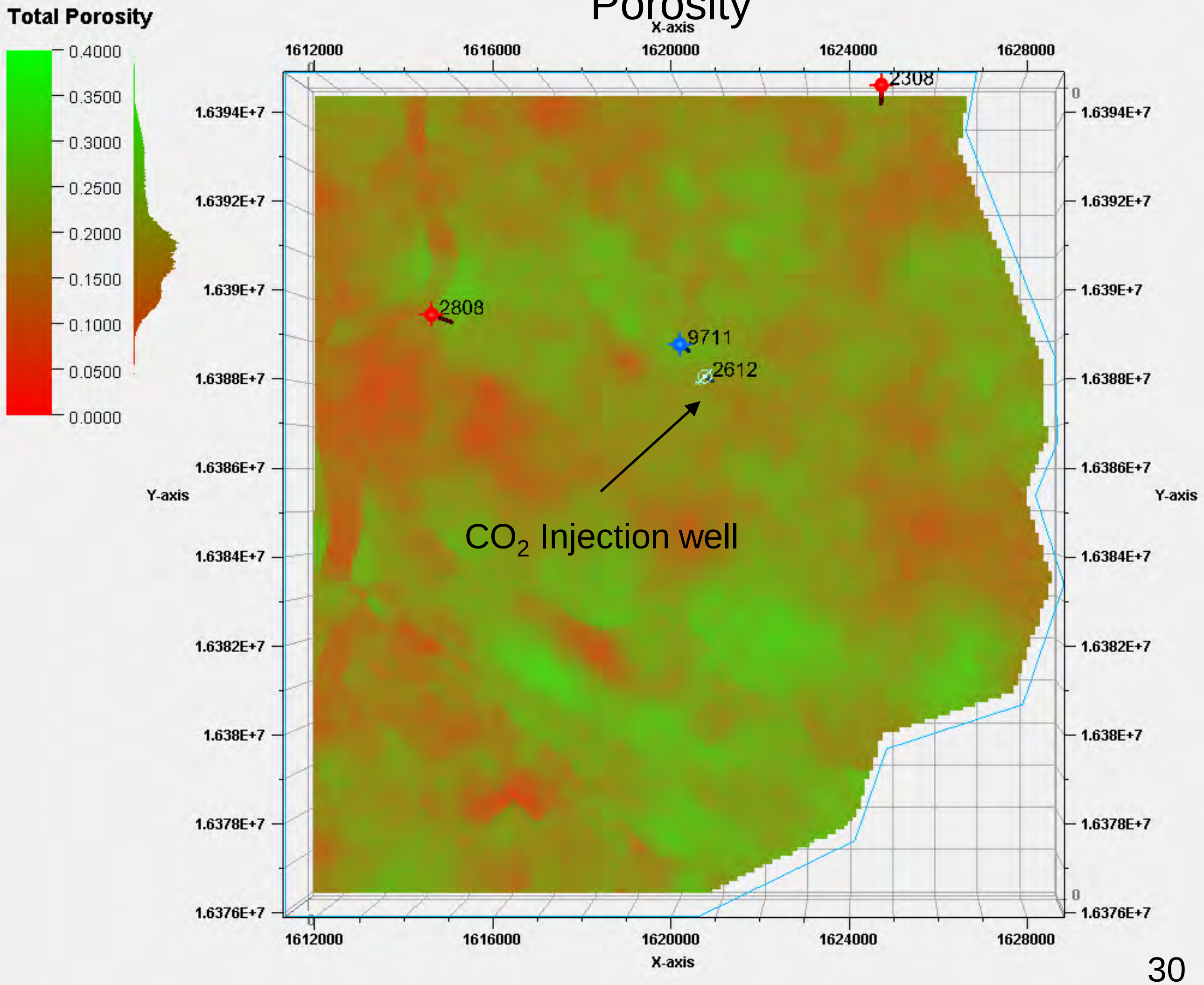
Accomplishments: Reservoir Model

Reservoir Model Properties

Permeability



Porosity



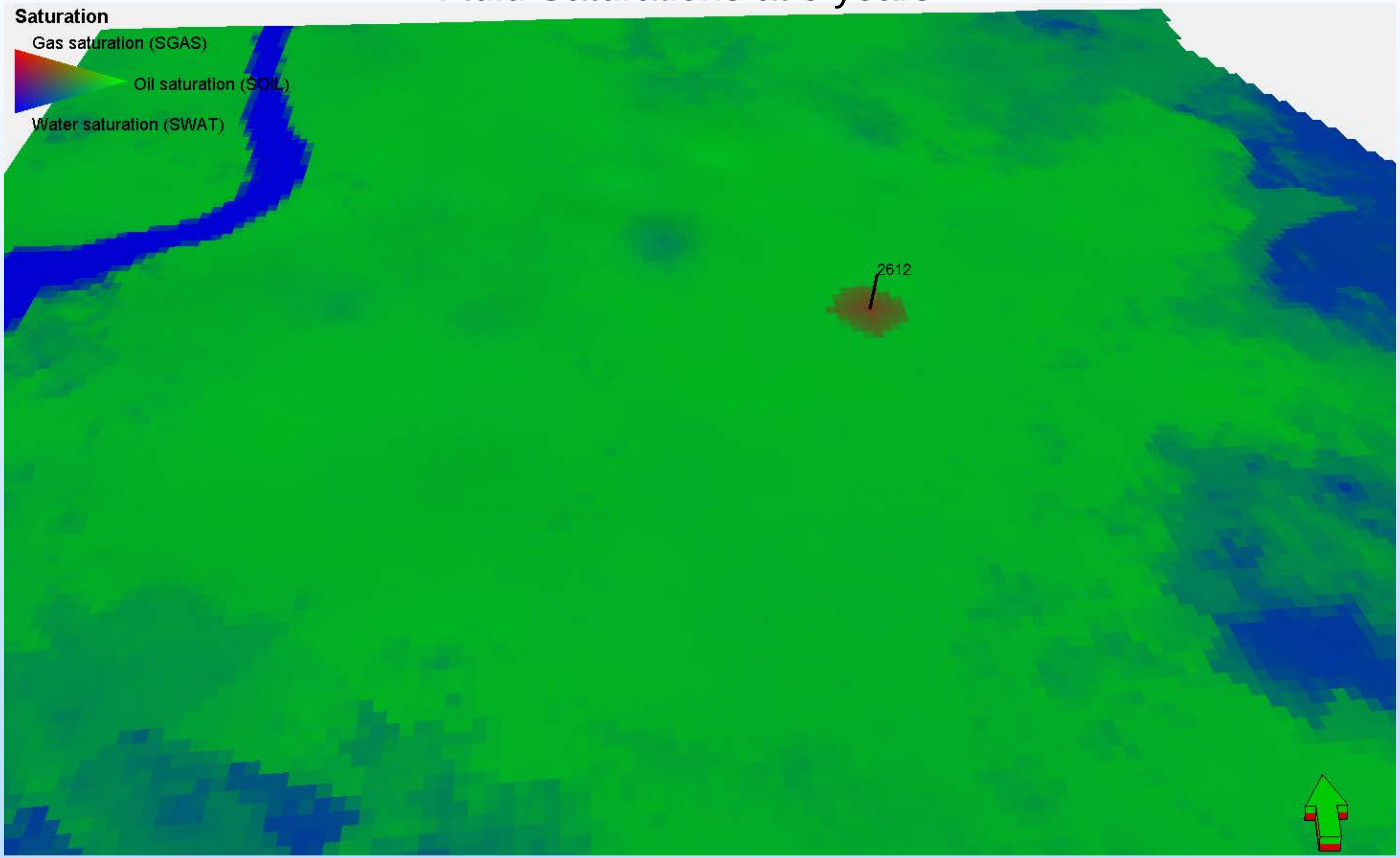
Accomplishments: Reservoir Model

Initial Simulation Results

<u>Injection</u>
Single well - 2612
Injection Rate: 2,000 MSCF/d
Injection Time: 5 years
Total CO_2 injected: 100,000 tons

<u>Grid</u>
174 x 188 x 14
411,152 active cells

Fluid Saturations at 5 years

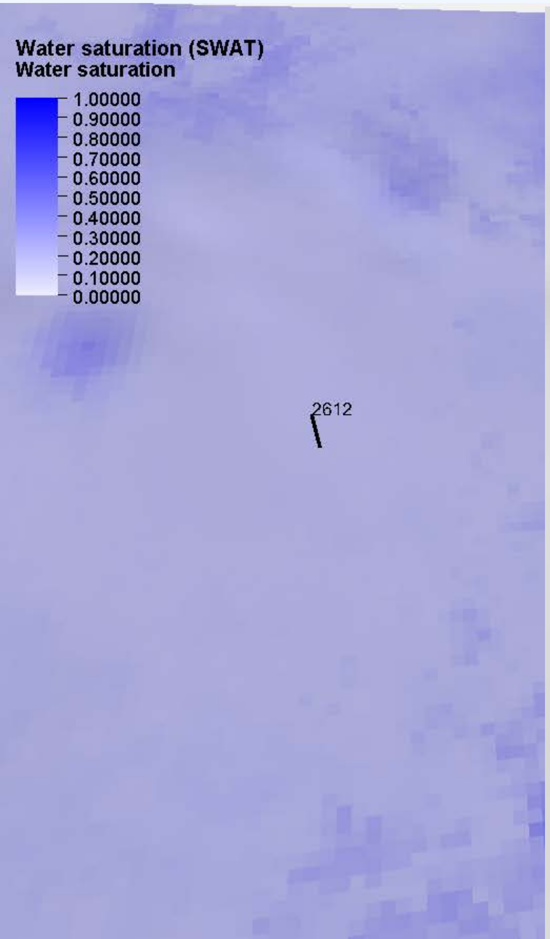


Accomplishments: Reservoir Model

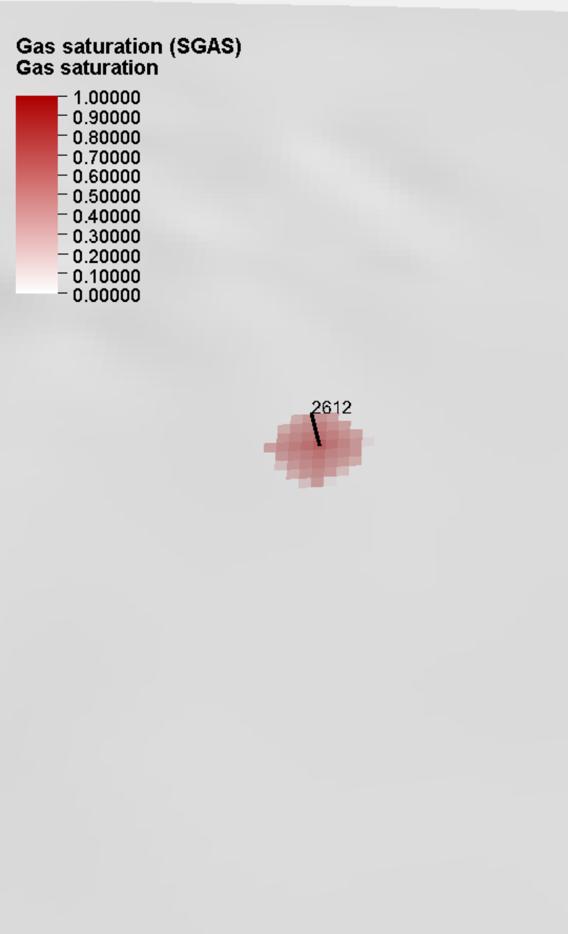
Initial Simulation Results

5 years CO_2 injection

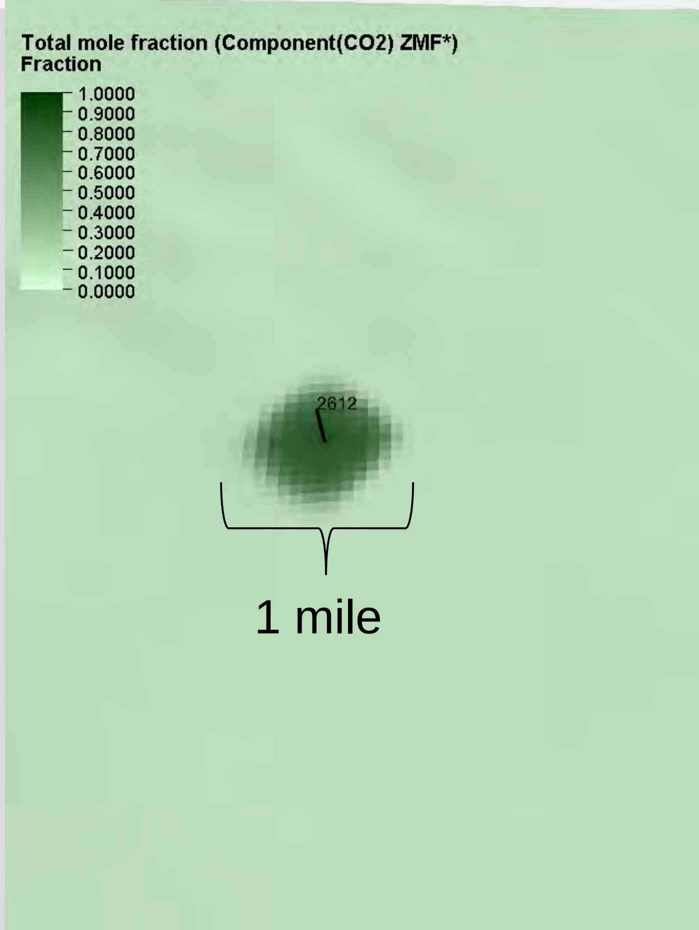
Water Saturation



CO_2 Gas Saturation



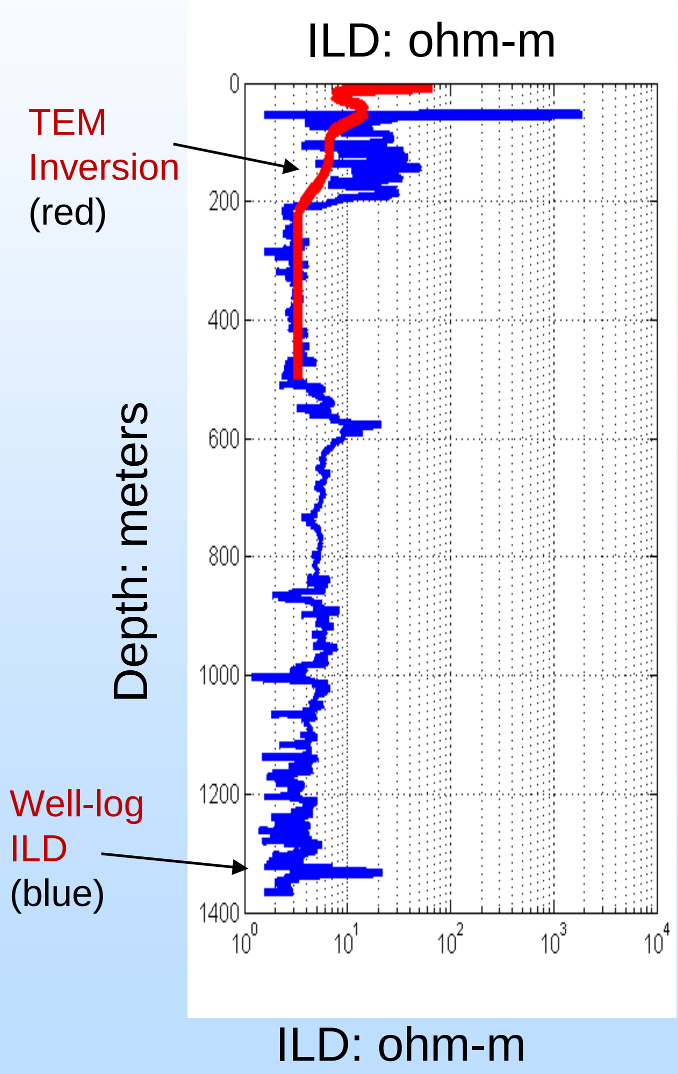
CO_2 in Oil Saturation

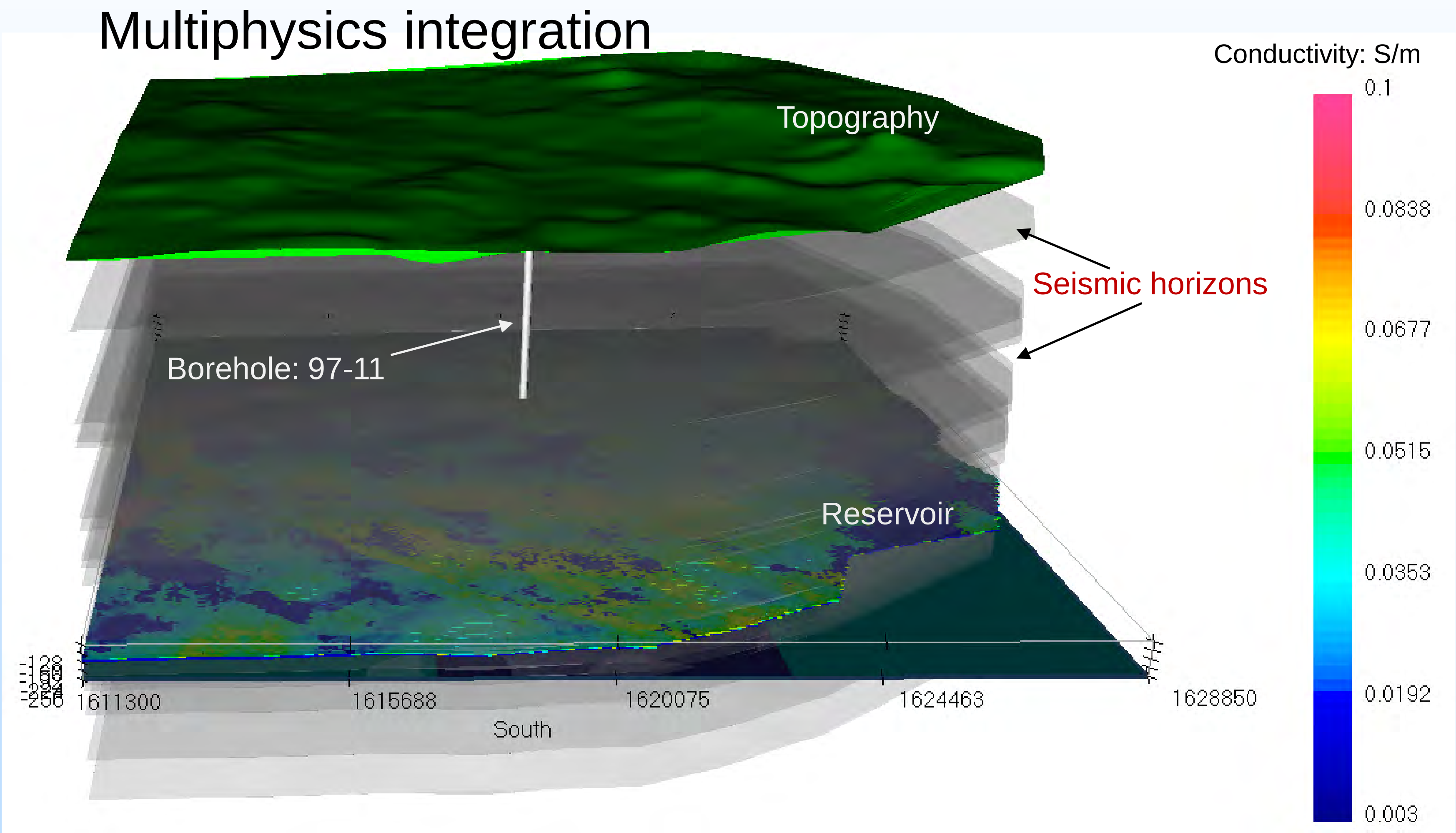


Oil Saturation

Accomplishments: Data Integration

Reservoir model: Expanding to conductivity for EM





Accomplishments: Data Integration

Reservoir model: Expanding to conductivity for EM

Archie's law applied to reservoir simulation data at each time instance

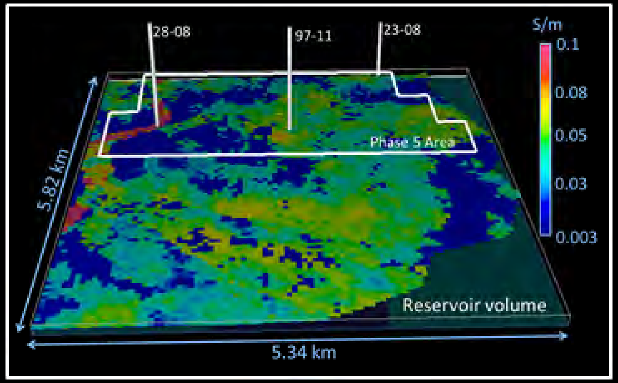
$$\sigma_B = \sigma_w \, \varphi^m \, S_w^n$$

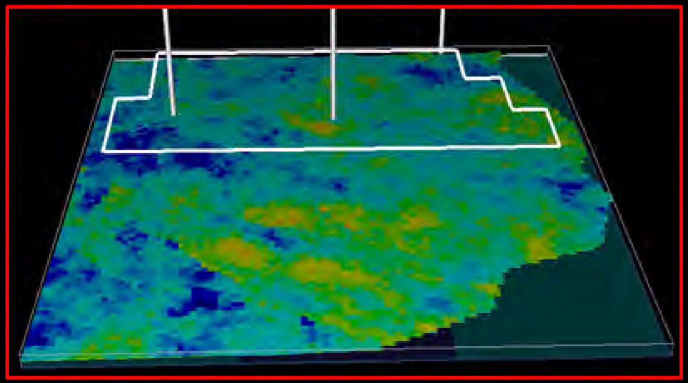
Temperature / TDS

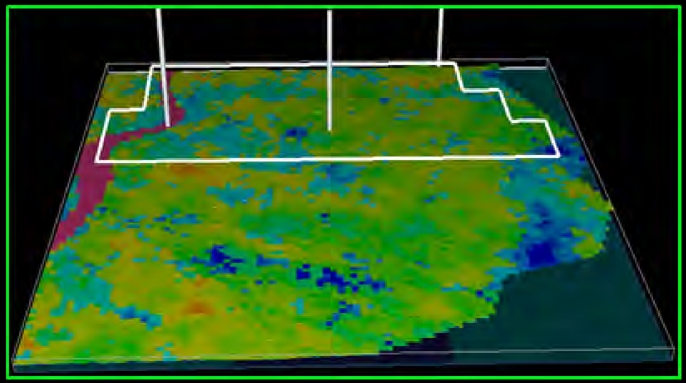
Conductivity

Porosity

Water saturation

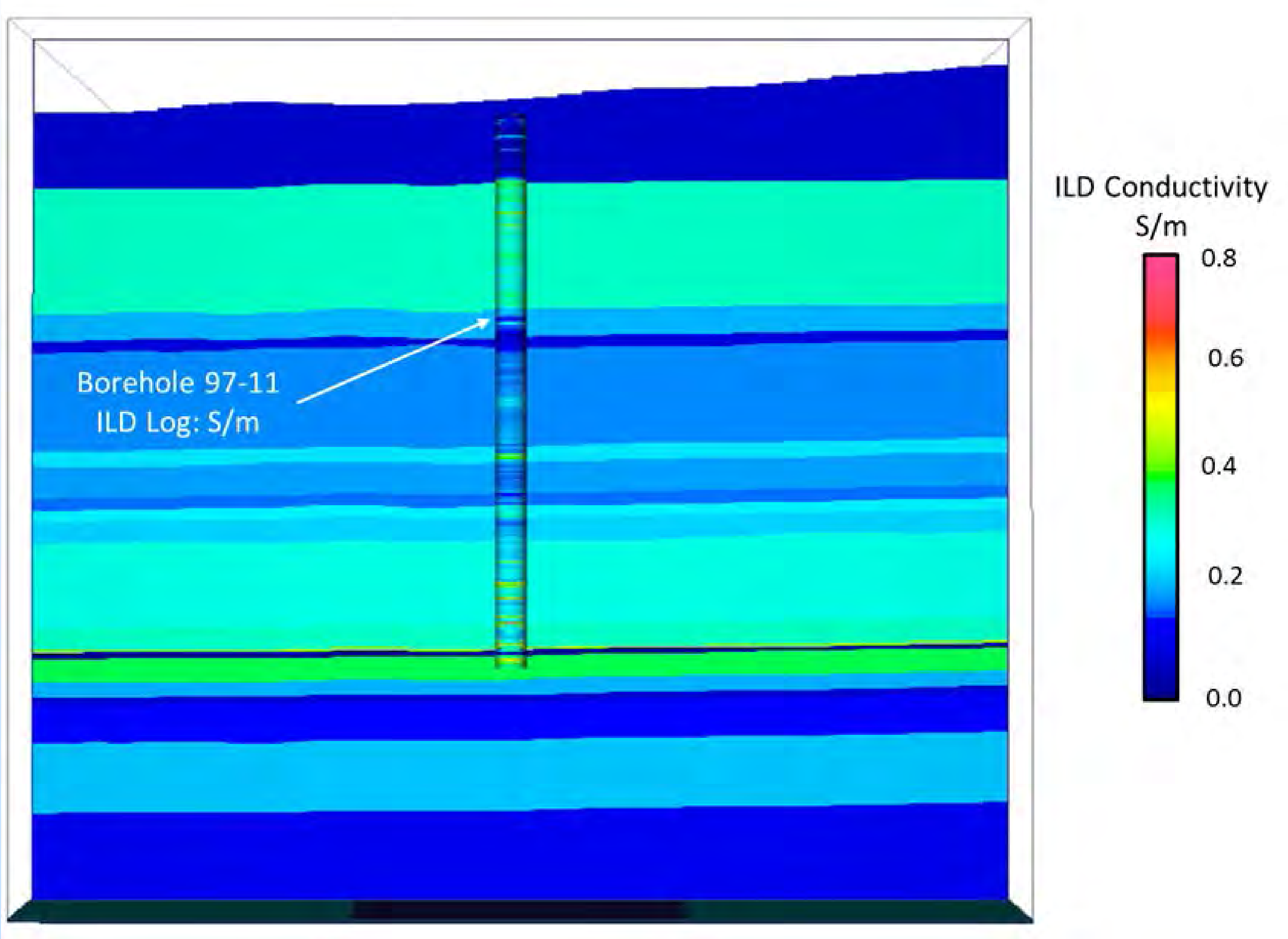






Accomplishments: Data Integration

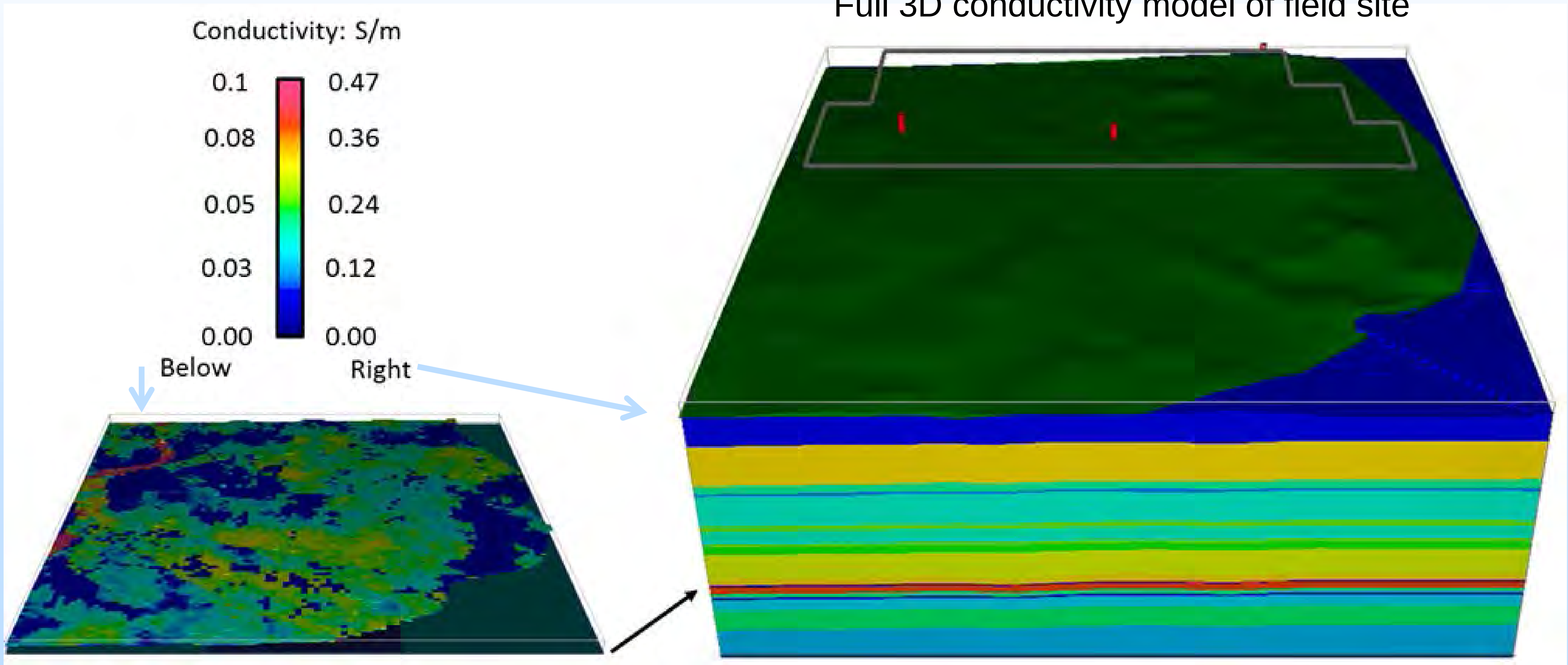
Reservoir model: Expanding to conductivity for EM



Accomplishments: Data Integration

Reservoir model: Expanding to conductivity for EM

Full 3D conductivity model of field site



Accomplishments: Summary

Algorithmic and modeling developments

- All tasks on track
- Reservoir model
  - Software to link reservoir model to CWC-CSEM algorithm
  - Successful application to Bell Creek
- CWC-CSEM algorithm
  - Modified to work with new reservoir model format from above
  - EM simulation codes enhanced: flexibility and interoperability
  - User interface for CESM code made more robust and flexible
  - CESM code successfully run on high performance computing resources

Accomplishments: Summary

Dissemination of information

- Web-site development
  - multiphysics-mva.org & cwc-csem.org
  - Limited content at moment
- 2017 AIChE Annual Meeting, Presentation
  - Topical conference: Advances in Fossil Energy R&D
  - Title: Monitoring carbon sequestration using charged wellbore controlled sources electromagnetics and integrated reservoir models
- 2018 American Geophysical Union (AGU)
  - Two abstracts submitted for poster presentation
  - Reservoir simulation modeling; CWC-CSEM Field campaign at Bell Creek

Lessons Learned

– The need for efficient EM simulation algorithms
– The need for high performance computing facility

– The site access was a known risk, but the actual need to change the field site did consume time and energy

– Need site-specific relationship between reservoir parameters and electrical conductivity

Synergy Opportunities

- Bell Creek Field site serves as the field laboratory for previous SubTER seismic array presentation (EERC)
  - Joint inversion of seismic and EM datasets a natural opportunity
  - Overlapping survey areas of investigation
- EM methods can provide de-risking of exploration projects
- Monitoring of CO_2-EOR projects has wide application
- EM methods can enhance seismic data in karst, subsalt, and anhydrite locations where seismic interpretation may be challenging

Summary: Overall Project Status

Field site, reservoir modeling, field campaigns

- Procedures and algorithms in place for reservoir modeling and simulations
- Reservoir model expanded to electrical conductivity model

- Two field campaigns completed at Bell Creek; two remaining
- Next field data acquisition campaign: October 2018

Acknowledgements

- DOE/NETL: FE0028320
- Traci Rodosta, Kylee Rice

- Denbury Resources, Inc.
- Energy and Environmental Research Center (EERC)

Thank You!

Appendix

- Benefit to the program
- Project overview
- Methodology
- Organizational chart
- Schedule

Benefit to the Program

SubTER Program Goals

1) **Ensure storage permanence for injected CO_2**
   - **[AOI-1]: Deploy and validate prototype <u>carbon storage</u> Monitoring, Verification, and Accounting (MVA) technologies in an operational field environment.**

2) Advancing state of knowledge in geothermal exploration
   - [AOI-2]: Identify and validate new subsurface signals to characterize and image the subsurface advancing the state of knowledge in <u>geothermal exploration</u>.

Benefit to the Program

SubTER Pillars

1) Wellbore integrity - New sensors and adaptive materials are needed to ensure sustained integrity of the wellbore environment.
2) Subsurface stress and induced seismicity - Radically new approaches are needed to guide and optimize sustainable energy strategies and reduce the risks associated with subsurface injection.
3) Permeability manipulation – Greater knowledge of coupled processes will lead to improved methods of enhancing, impeding, and eliminating fluid flow.
4) **New subsurface signals - DOE seeks to transform our ability to characterize subsurface systems by focusing on four areas of research: new signals, integration of multiple data sets, identification of critical system transitions, and automation.**

Benefit to the Program

Project Benefits Statement

- Currently, there is a lack of cost-effective tools that are able to
  - Probe to the required depths, and
  - Be sensitive to changes in the makeup of the reservoir fluids
- Responsive technologies need to be sensitive to both
  - Distribution of CO_2 within reservoir, and
  - Overburden where leakage may occur
- The proposed project is designed to address these requirements

Benefit to the Program

Project Benefits Statement

The project will benefit the monitoring and tracking the fate of CO_2 in a storage site by advancing the state of art through the following three components:

1) Time-lapse monitoring using charged wellbore casing controlled-source EM (CWC-CSEM) method
   - data are to be interpreted through constrained coupled inversions using reservoir models
   - electrical conductivity changes mapped to the reservoir properties, fluid saturations (phase)

Benefit to the Program

Project Benefits Statement

The project will benefit the monitoring and tracking the fate of CO_2 in a storage site by advancing the state of art through the following three components:

2) Improved characterization of reservoir properties such as relative permeability and dynamic states such as fluid saturations
   - Integrate static and dynamic properties from time-lapse EM monitoring
   - Improve existing reservoir models for long-term monitoring and tracking
   - Characterize the distribution and migration of CO_2

Benefit to the Program

Project Benefits Statement

The project will benefit the monitoring and tracking the fate of CO_2 in a storage site by advancing the state of art through the following three components:

3) Development of a responsive technology capable of imaging CO_2 migration within the whole overburden

Benefit to the Program

Project Benefits Statement

- Proposed technology relies upon
  - Legacy infrastructure
  - Minimal hardware installation

- It will be possible to install sensors permanently with minimal additional effort

- The field site was selected in order to:
  - Validate the method at a WAG site that should provide a distinct target
  - Leverage existing efforts by DOE-NETL in this area

Project Overview:
Goals and Objectives

Goals

- Production-scale verification of CWC-CSEM as MVA technology
  - Three phase system, fluid content-sensitive electrical conductivity
  - Dynamic system with WAG cycles, time-lapse monitoring
  - Low cost through use of legacy wellbores

- Integrated reservoir MVA
  - Coupled simulation
  - Constrained inversion
  - History matched with time lapse CWC-CSEM and production data

Project Overview:
Goals and Objectives

Objectives

1. Develop software capabilities
   - 3D CWC-CSEM simulations at reservoir scale
   - Forward looking survey design, informed with reservoir simulations
   - Constrained 3D inversion with a priori reservoir knowledge and near surface statics

2. Development of best practice recommendations for CWC-CSEM
   - Survey frequencies
   - Data and inversion uncertainty
   - Validation through CCS-EOR production data

Methodology

Charged wellbore casing controlled source electromagnetics

1. Electrical conductivity tied to reservoir fluid phase (oil / CO_2 / water)
2. Validation at active CCS-EOR project
3. Constrained inversion from existing characterization
4. Static near surface correction from TEM data
5. Integration with reservoir simulation
6. History matching for validation

Organizational Chart / Communication Plan

Colorado School of Mines

- Project lead
- Survey design
- EM inversion/modeling lead

University of Utah

- Reservoir simulation lead
- Coupled modeling

United States Geological Survey

- Field logistics lead
- Statistical data analysis

New Mexico Tech

- History matching

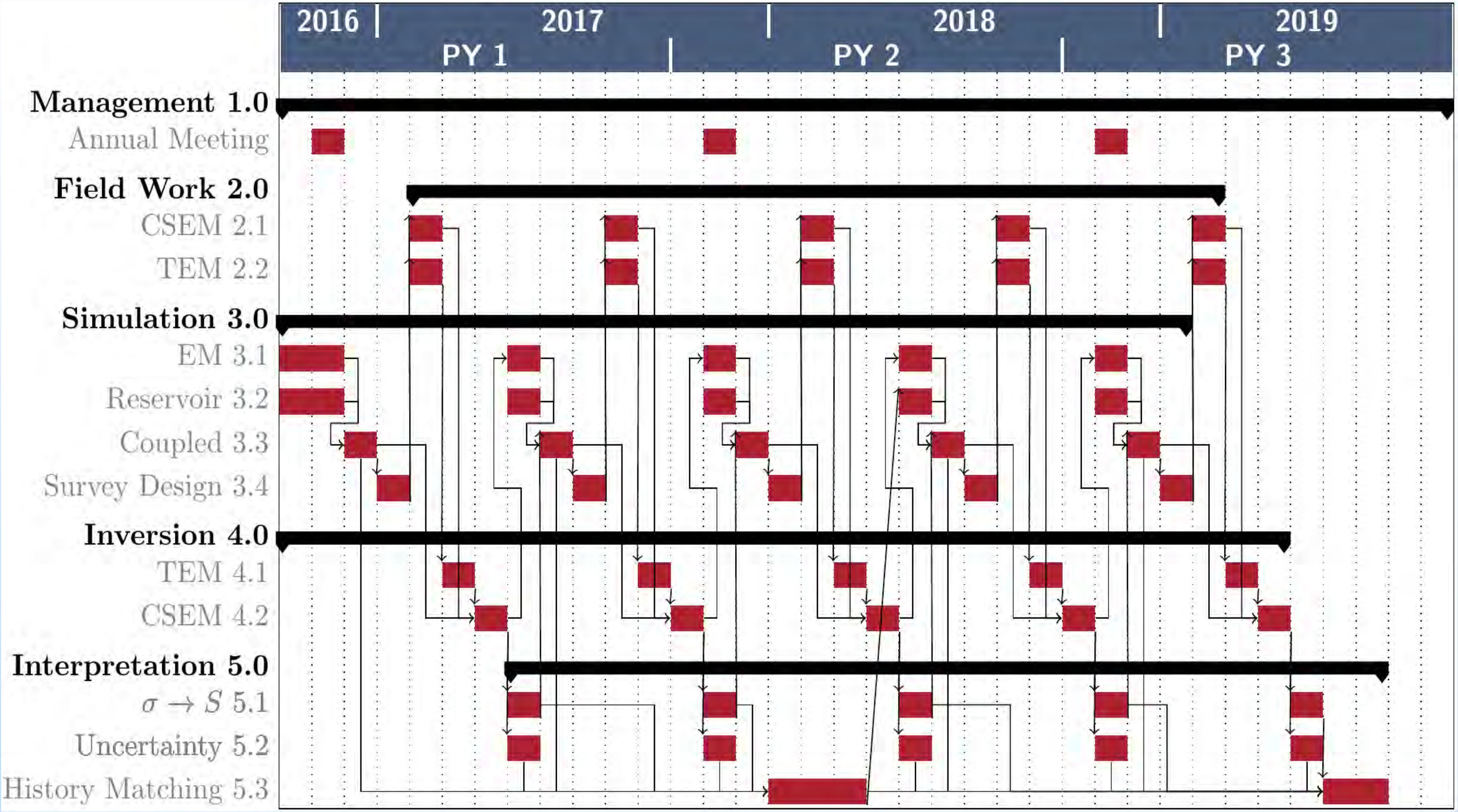
Communication plan

- Bi-monthly virtual meetings (GOTO Meeting, etc.)
- Annual project meetings

Project website

- http://multiphysics-mva.org
- Outreach and collaboration

Proposed Schedule



Bibliography

No journal publications yet