AOI [1]: Charged Wellbore Casing Controlled Source Electromagnetics (CSC-CSEM) for Reservoir Imaging and Monitoring: FE0028320

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U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 1-3, 2017

Full Project Team: Original

Colorado School of Mines

- Yaoguo Li
- Richard Krahenbuhl
- Jiajia Sun
- Andy McAliley

University of Utah

- Trevor Irons
- Nathan Moodie

Southwest Regional Partnership on Carbon Sequestration (SWP)

- Brian McPherson (also Univ. Utah)

United States Geological Survey

- Andy Kass

New Mexico Institute of Mining and Technology

- William Ampomah

Full Project Team

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- Yaoguo Li
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- Trevor Irons
- Brian McPherson
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United States Geological Survey
- Ben Bloss

New Mexico Institute of Mining and Technology
- William Ampomah

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

Presentation Outline

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

Project Overview: Proposed

- Production-scale verification of CWC-CSEM as MVA technology
  - Multi-phase system, fluid content-sensitive electrical conductivity
  - Dynamic system with WAG cycles, time-lapse monitoring
  - Low-cost 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 regional partnership and EOR monitoring

- Field site: FWU

Project Overview: Updated

- Production-scale verification of CWC-CSEM as MVA technology
  - Multi-phase system, fluid content-sensitive electrical conductivity
  - Dynamic system with CO_2 cycles, time-lapse monitoring
  - Low-cost 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 regional partnership and EOR monitoring

- Field site: Bell Creek, Montana

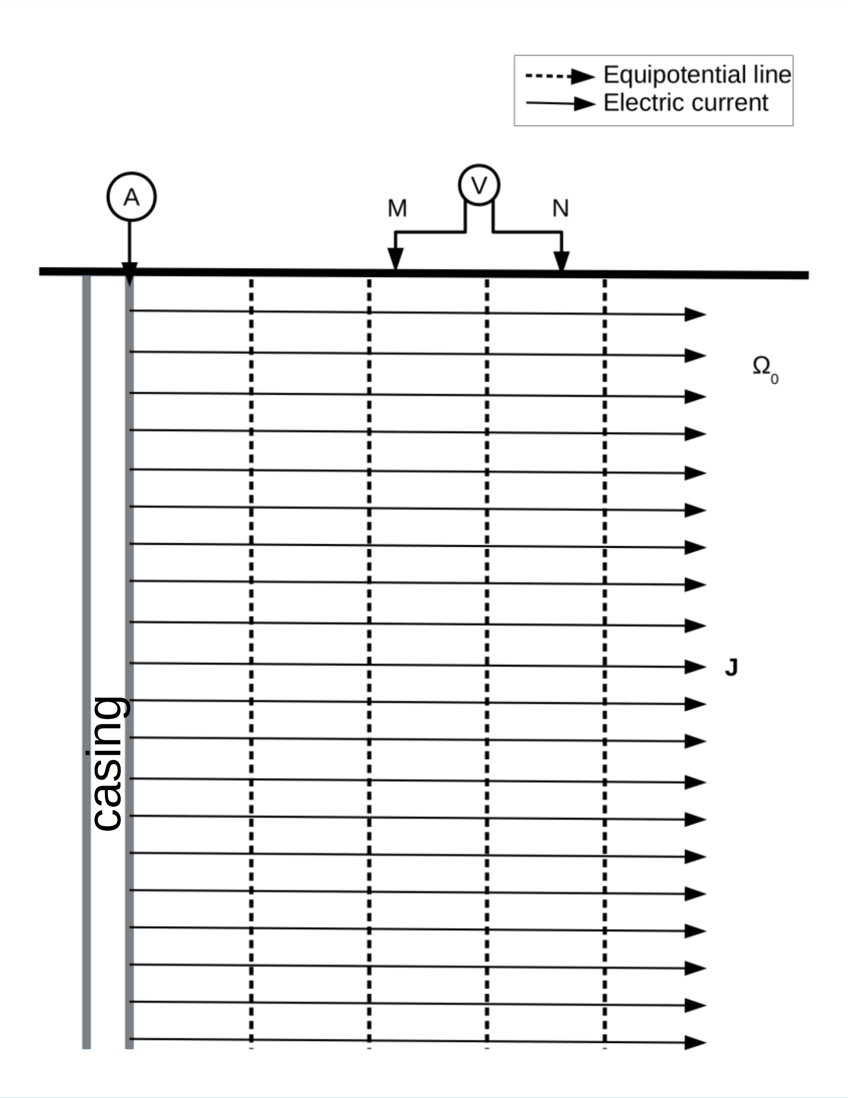
Methodology

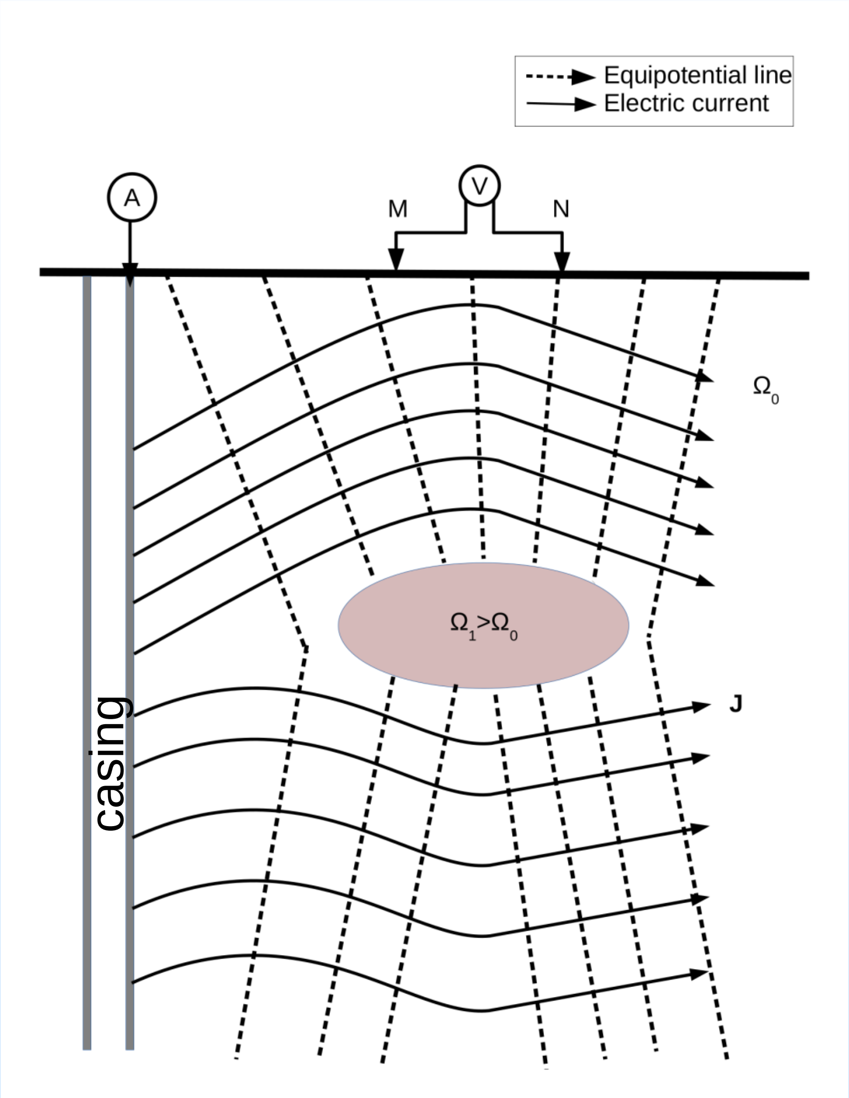
Charged wellbore casing controlled source electromagnetics

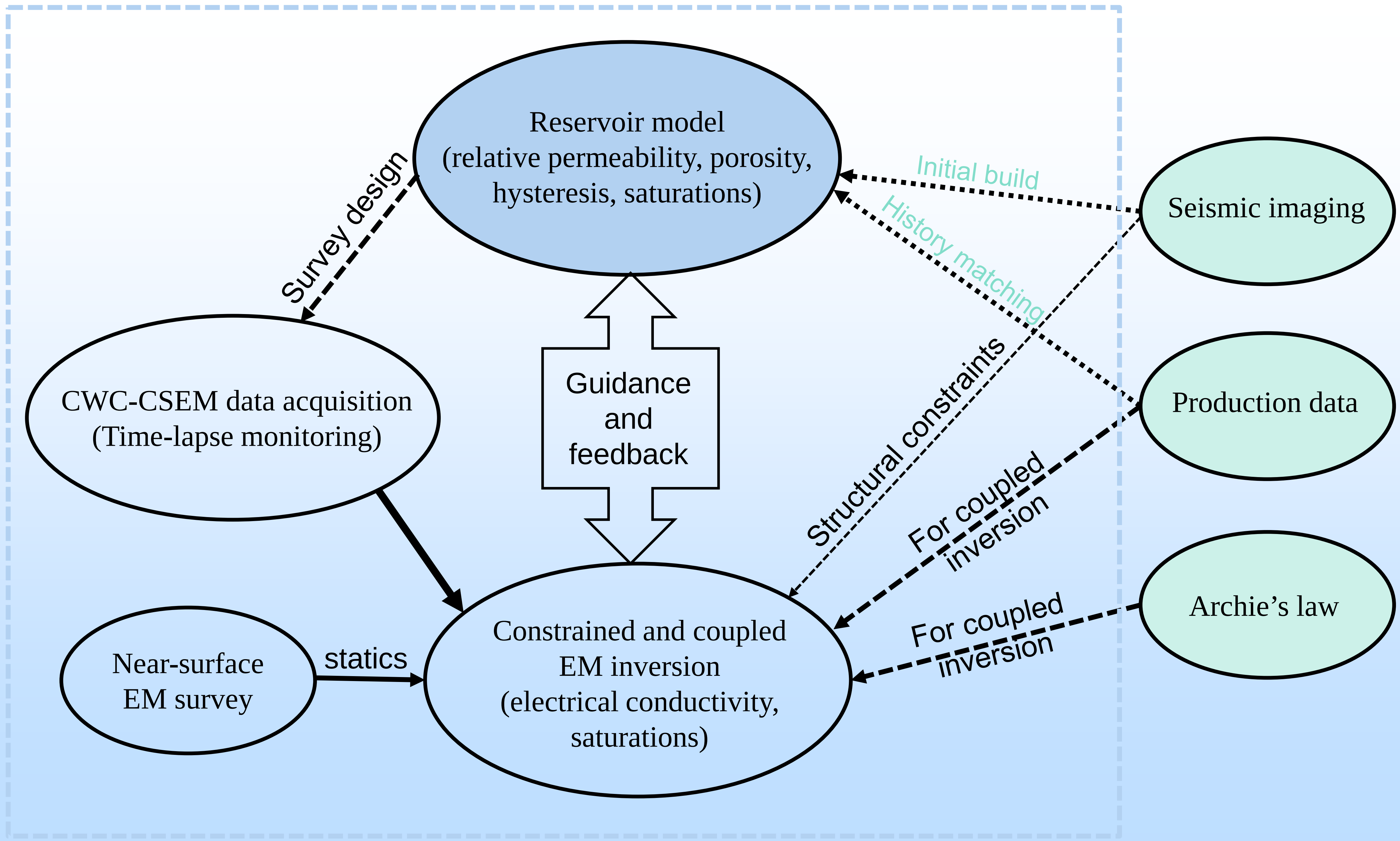
1. Electrical conductivity depends on reservoir fluid phase (oil / CO_2)
2. Validation at active CCS-EOR project
3. Constrained inversion using existing characterization
4. Static near-surface correction from TEM data
5. Integration with reservoir simulation
6. History matching for validation

CWC-CSEM: Concept

- Grounded transmitter
- Sub-hertz frequencies
- Electric fields as data
- Magnetic field as auxiliary data



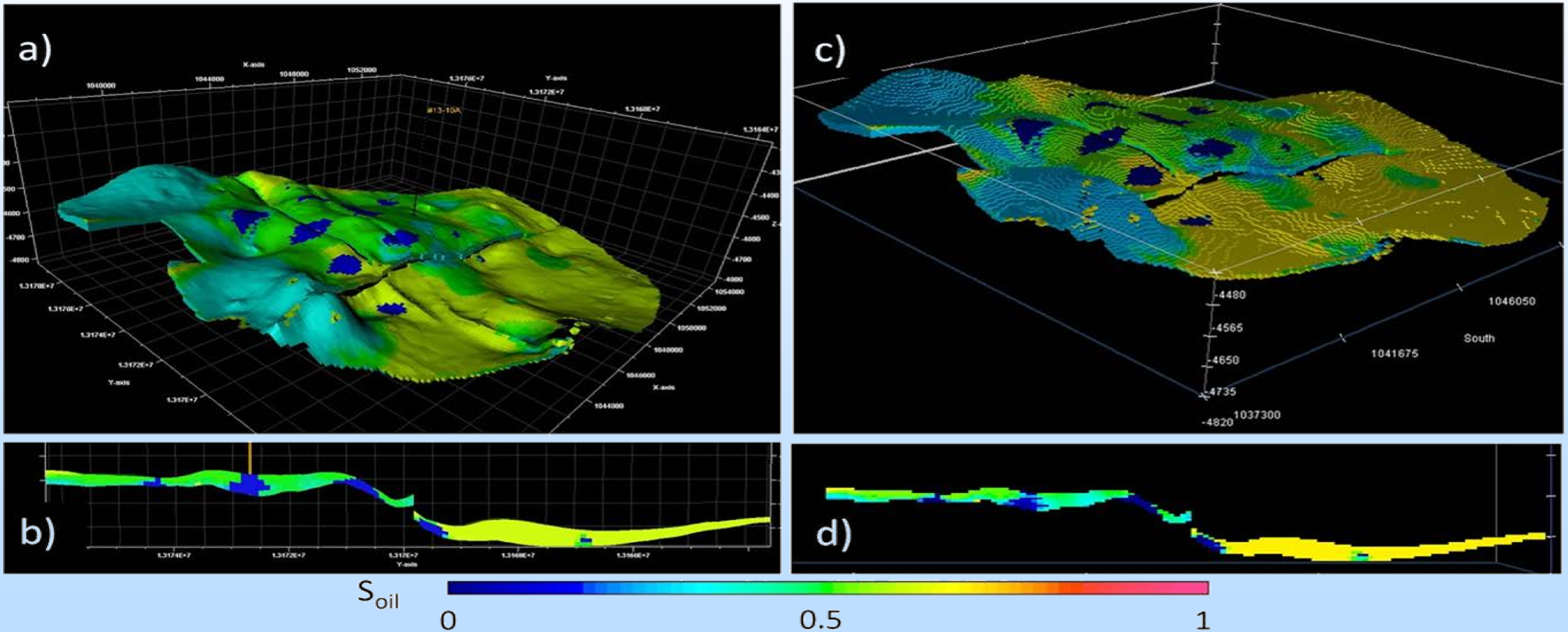



Reservoir model
(relative permeability, porosity,
hysteresis, saturations)
Survey design
Initial build
History matching
Seismic imaging
Production data
Archie's law
CWC-CSEM data acquisition
(Time-lapse monitoring)
Guidance
and
feedback
Structural constraints
For coupled
inversion
For coupled
inversion
Near-surface
EM survey
statics
Constrained and coupled
EM inversion
(electrical conductivity,
saturations)

Technical Status

Link between reservoir model and EM software

Original reservoir model - S_{oil} | Converted for EM simulation



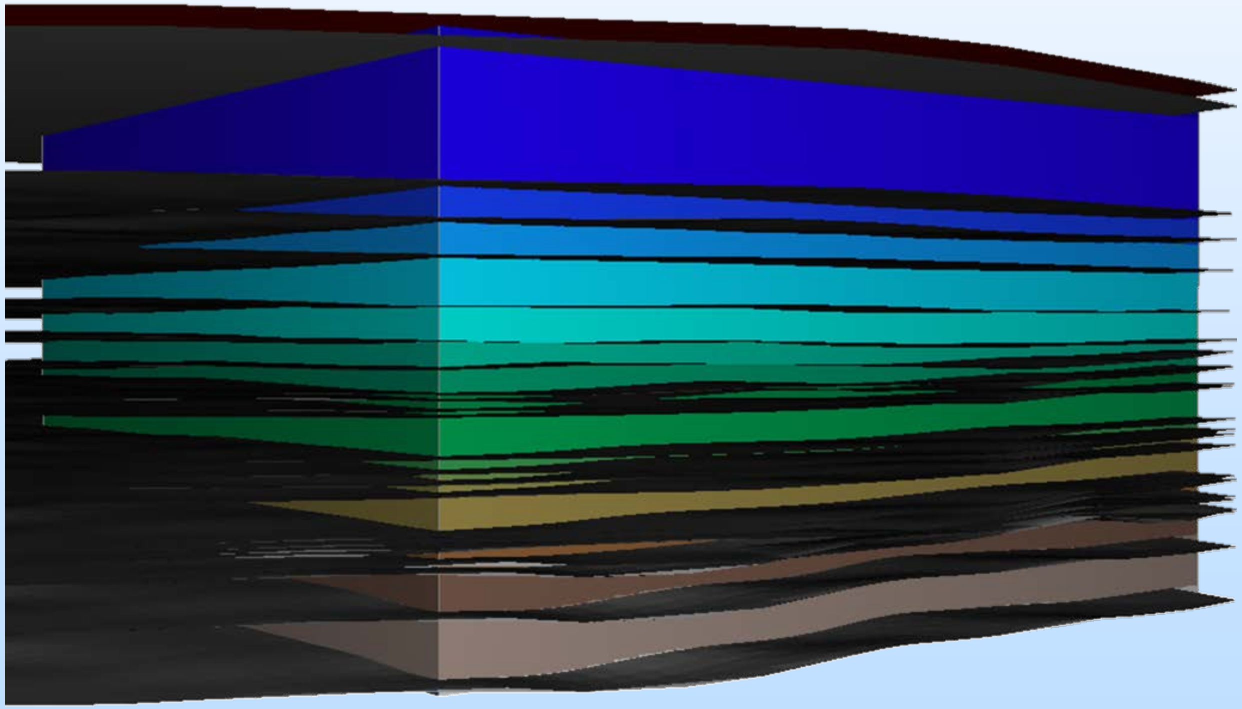
Technical Status

Full 3D geobody model for EM simulations must:

- Extend from surface to basement
- Capture significant geologic/conductive layers
- Incorporate reservoir model at appropriate depth
- Extend laterally beyond reservoir area

Technical Status

Seismic Horizons to 3D Geobody Model



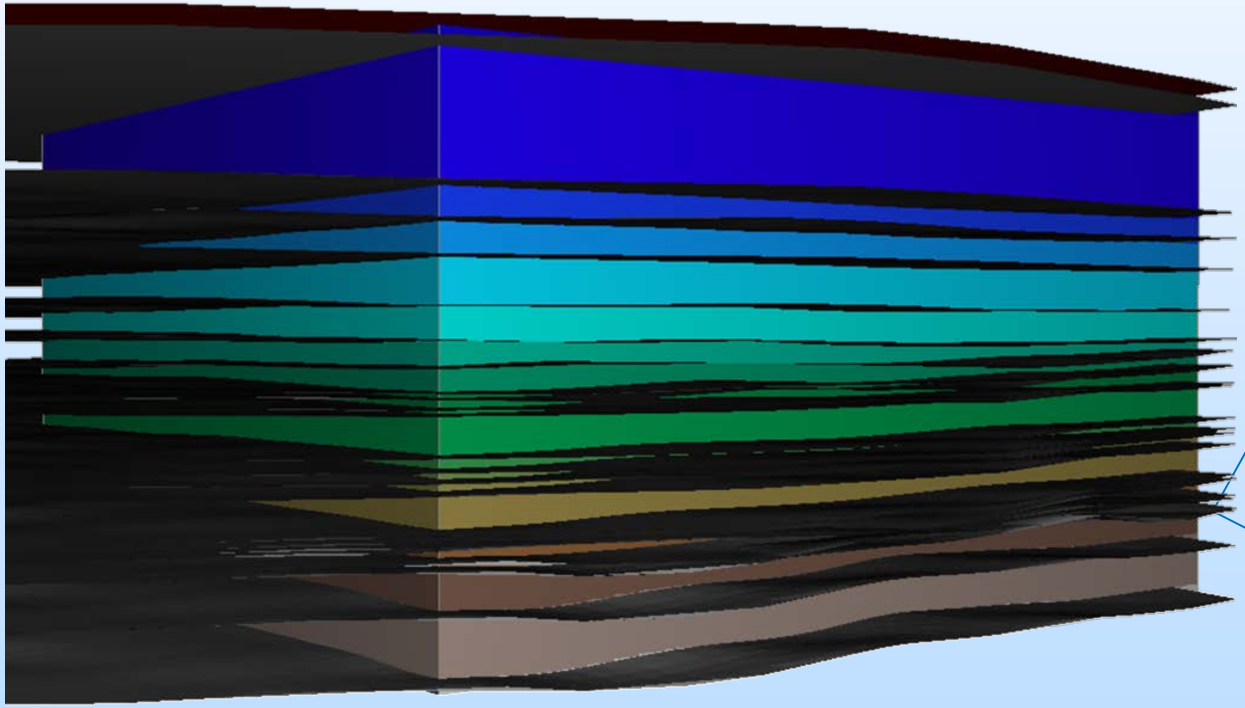
Significant Layers

Air = 1;
Shallow = 2;
RedCave = 3;
UpWell = 4;
LowWell = 5;
UpChase = 6;
LowChase = 7;
UpVirg = 8;
LowVirg = 9;
Doug = 10;
Coffee = 11;
Tonk = 12;
Missourian = 13;
Kansas = 14;
Espresso = 15;
Marmat = 16;
UpCherokee = 17;
LowCherokee = 18;
Thirteen = 19;
MorrowShale = 20;
MorrowB = 21;
SubMorrow = 22;
MUMorrow = 23;
Mississ = 24;
Basement = 25;

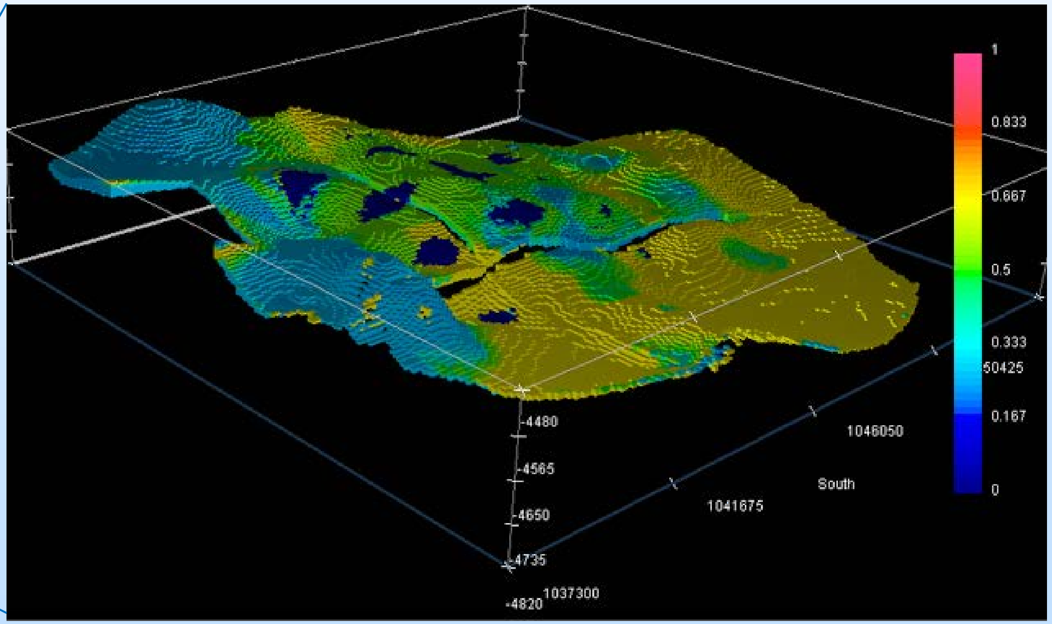
Technical Status

full 3D geobody model

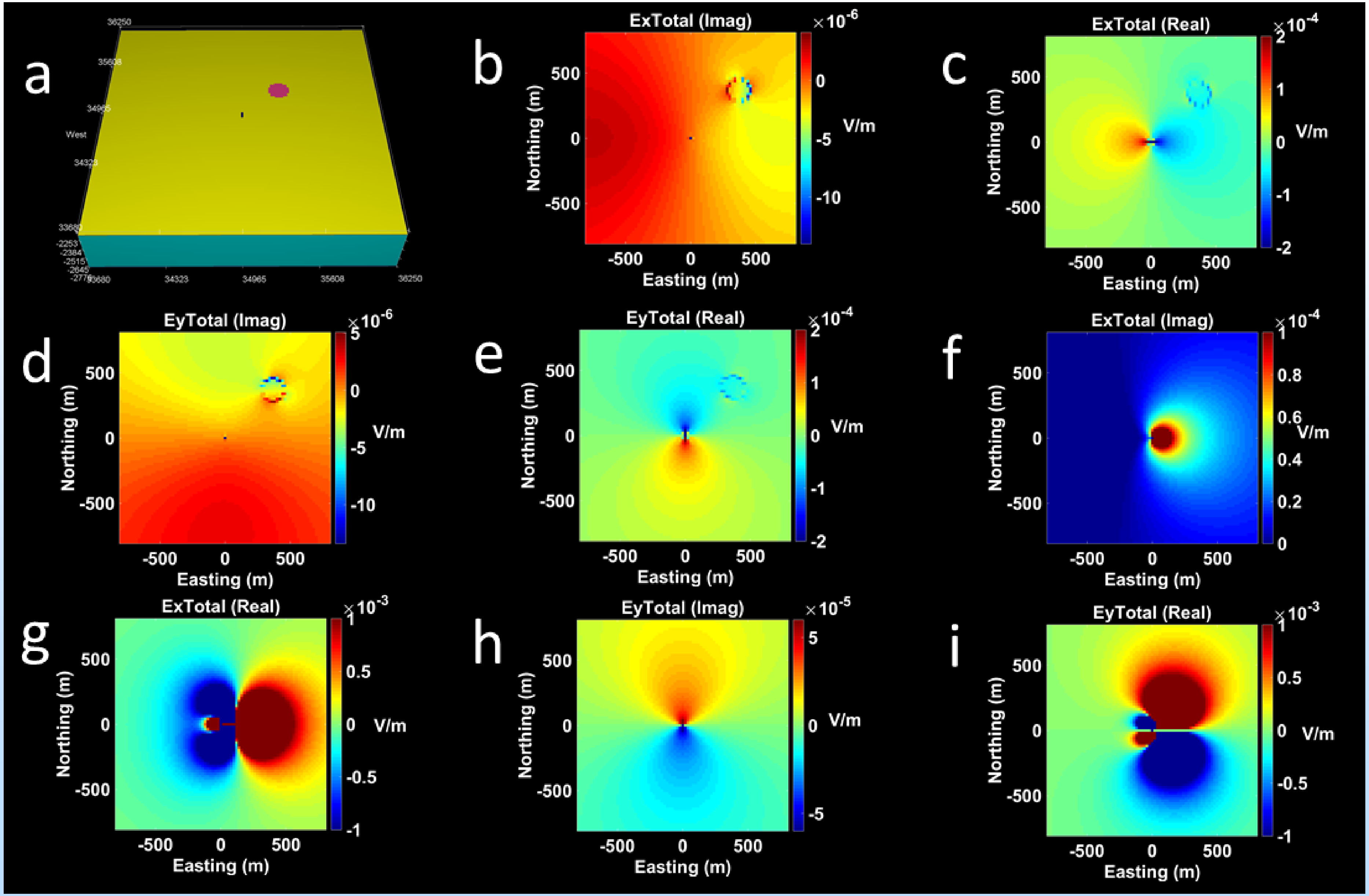
Seismic Horizons to 3D Geobody Model



Insert reservoir model



Preliminary CWC-CSEM modeling at FWU



Technical Status

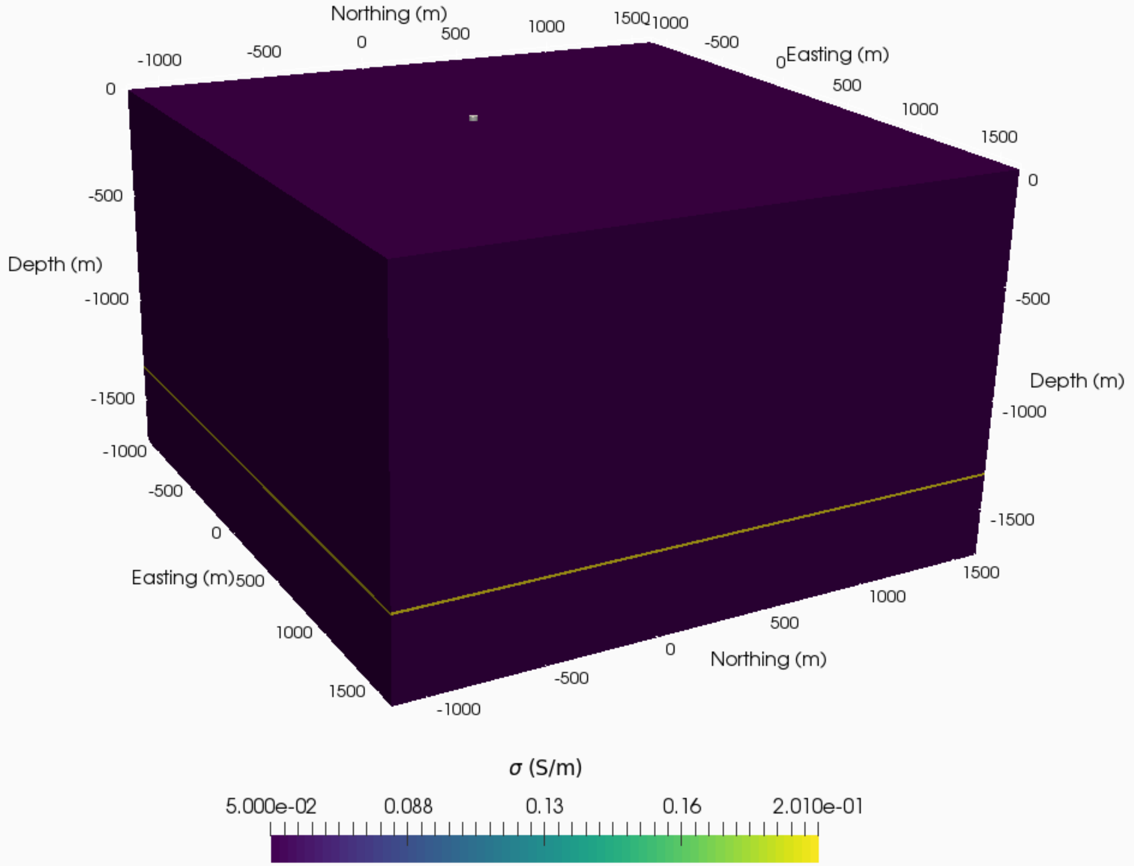
New field site: Denbury and EERC

- Interested in research project
  - Support new and cost-effective monitoring technologies
  - Will provide full access to field site, boreholes, and reservoir model
- Candidate Site: Bell Creek, Montana
  - Phase 5 area has not seen CO_2 yet, ideal for baseline data
  - CO_2 injection starts between mid-August and end of September
  - Significantly shallower reservoir
  - Large collection of boreholes (casings) available
- Requested approval from NETL to change sites: Approved!

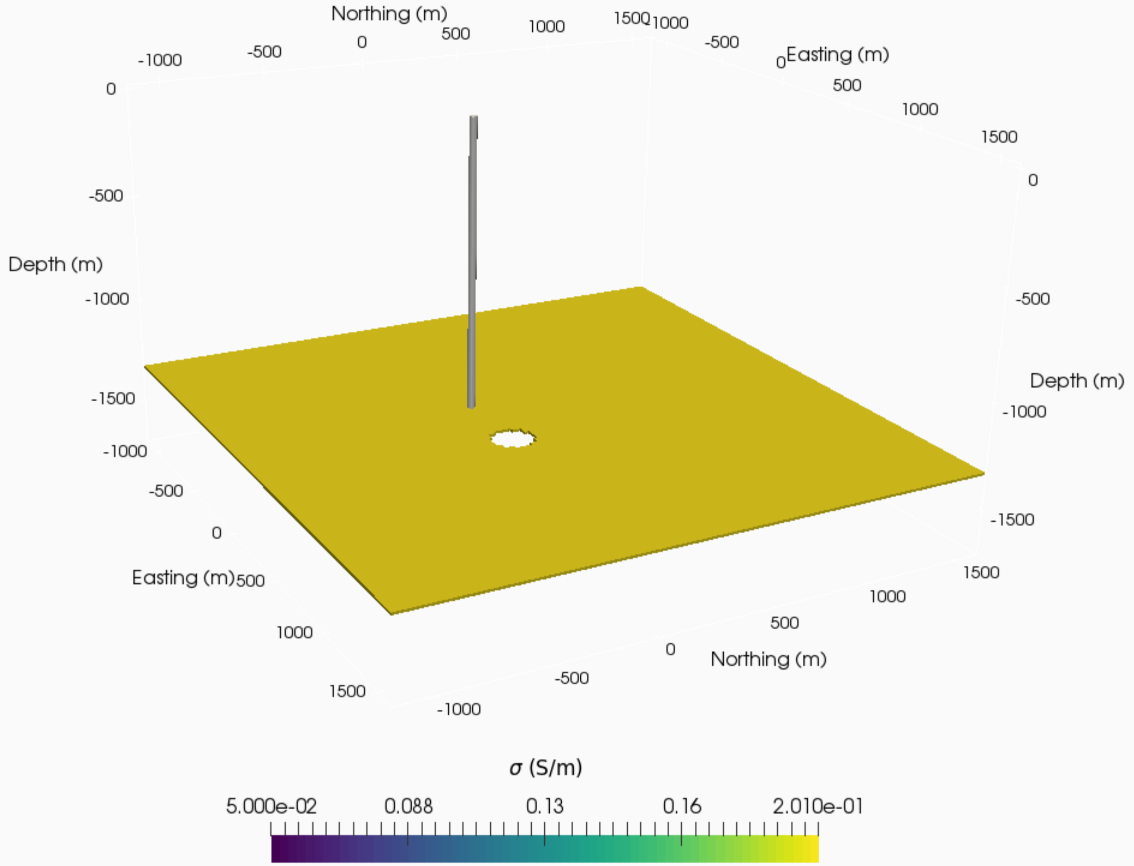
Technical Status

CWC-CSEM Simulations for Bell Creek Depths

CWC-CSEM Modeling Domain (core)

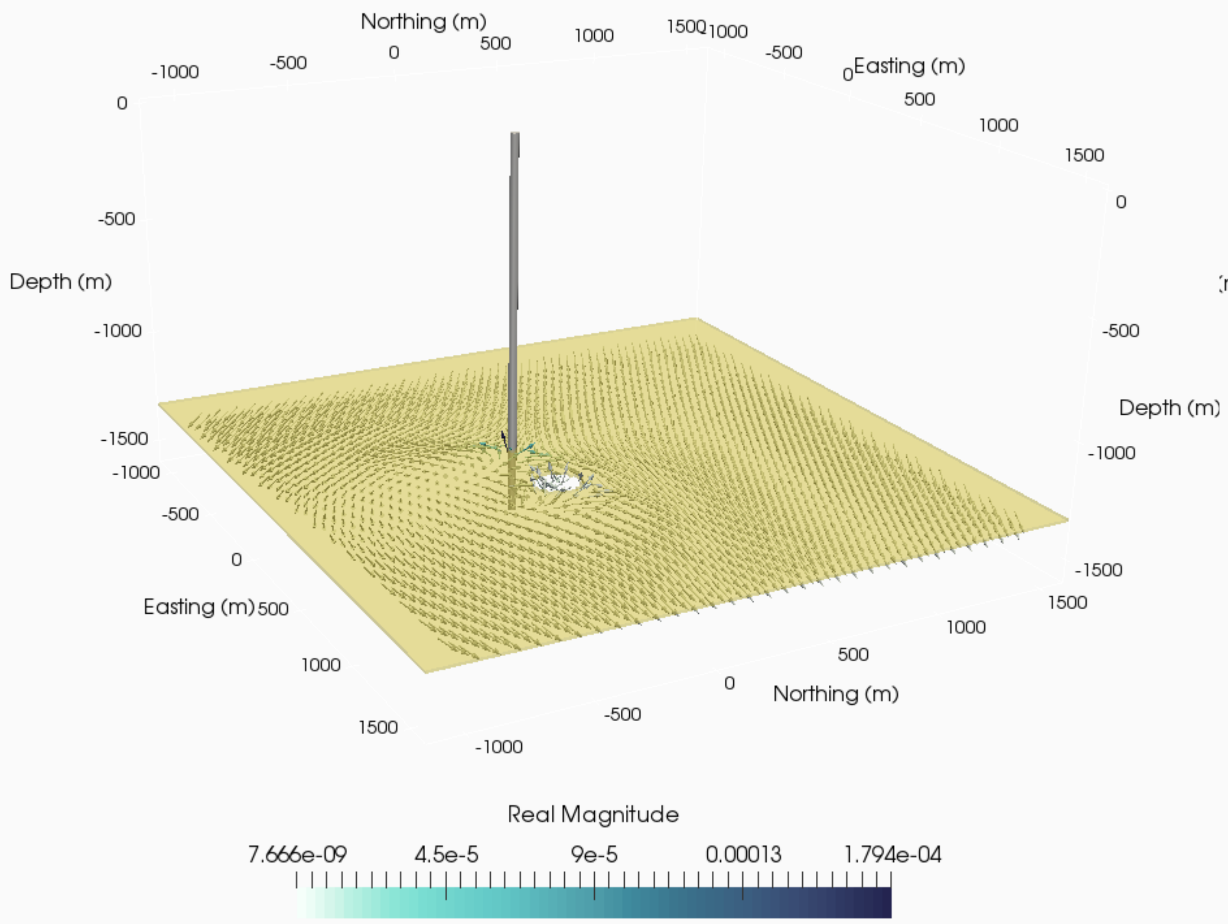


Reservoir/CO_2 Depth

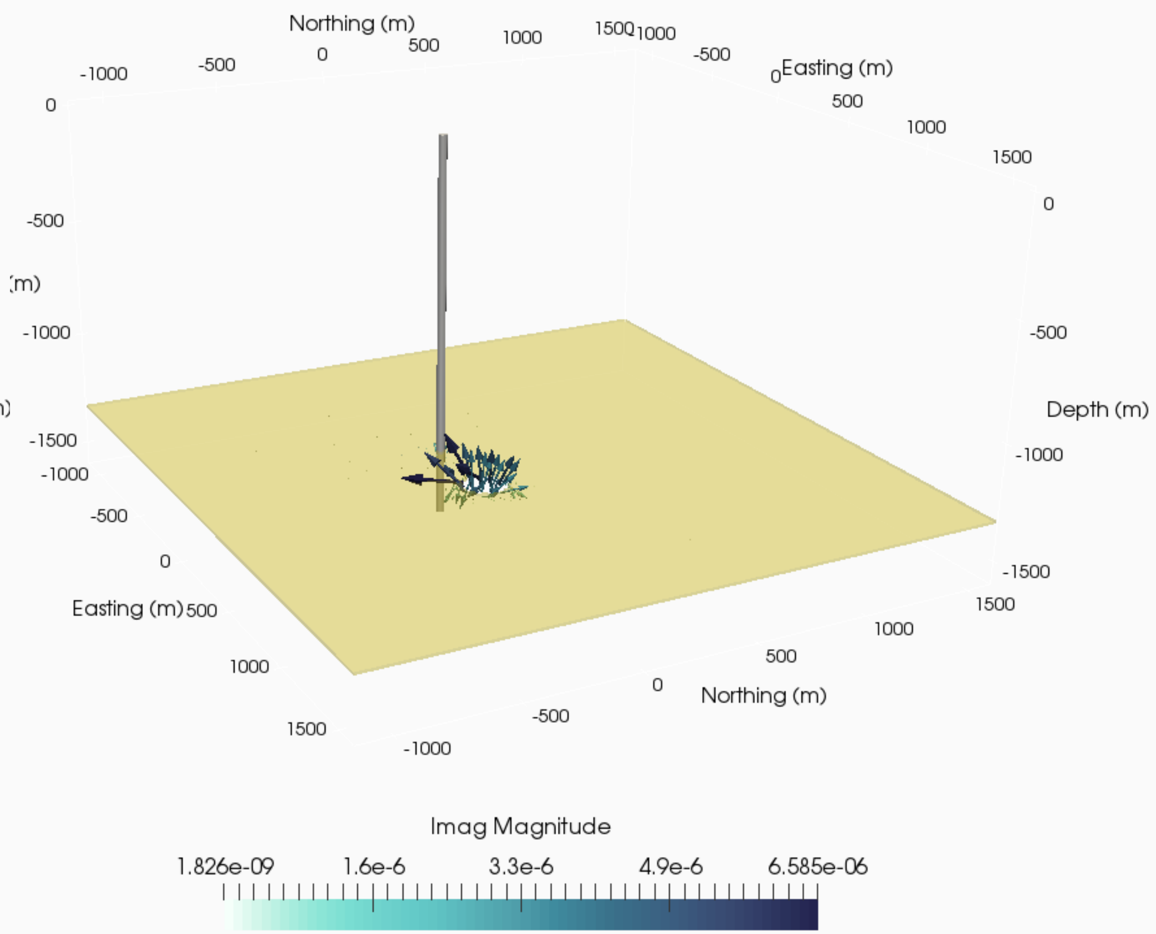


Technical Status

Real component

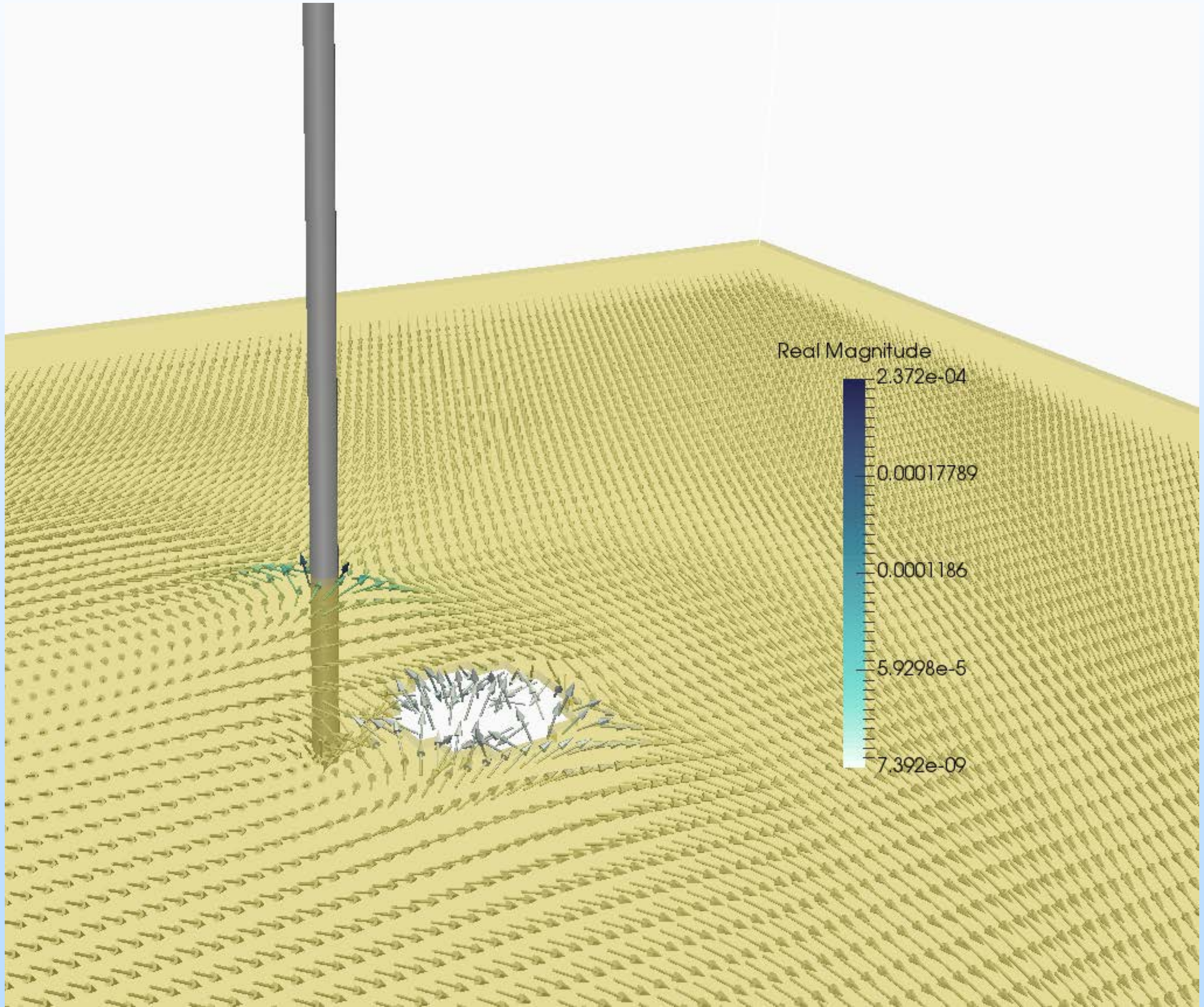


Imaginary component

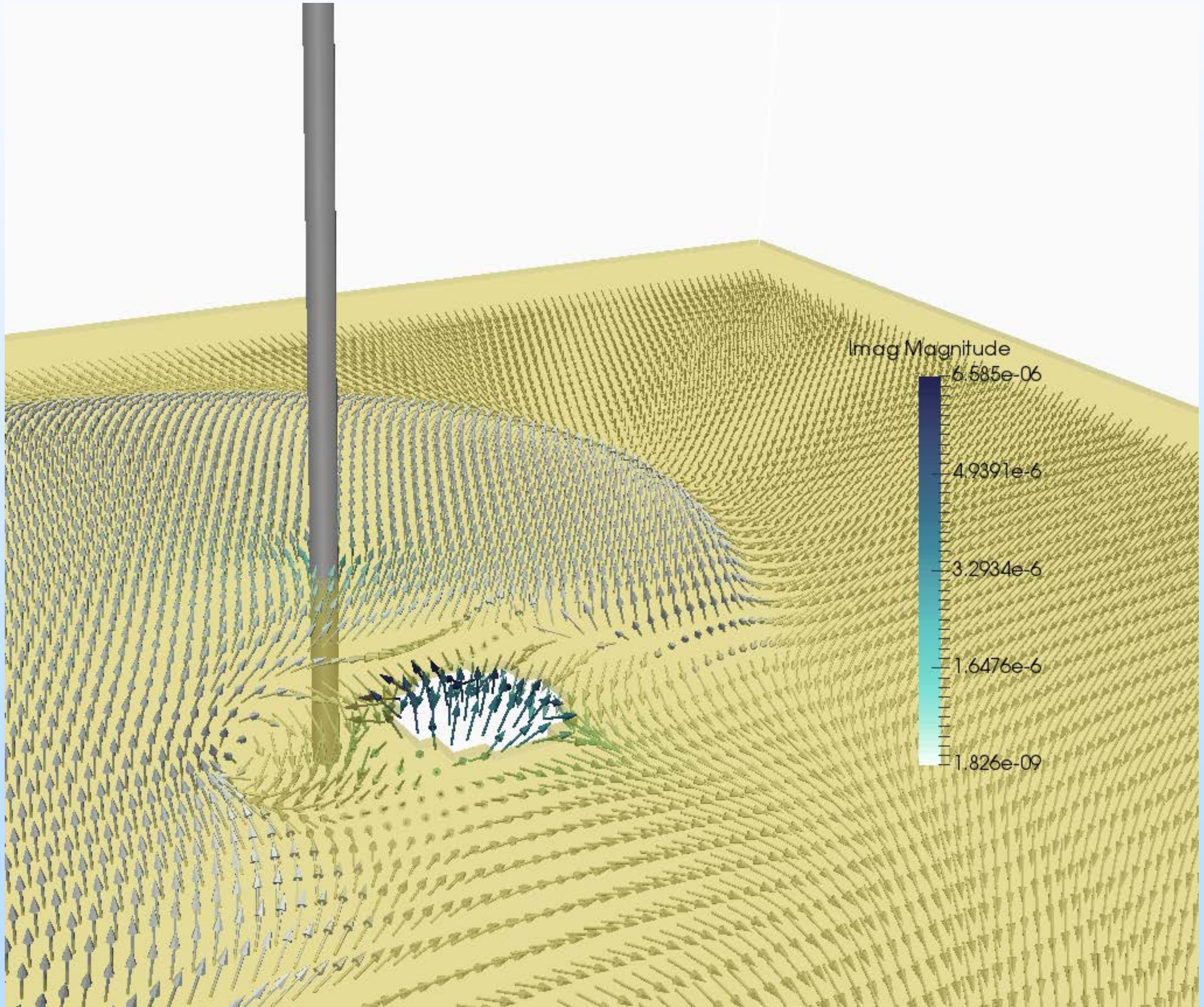


Technical Status

Real component



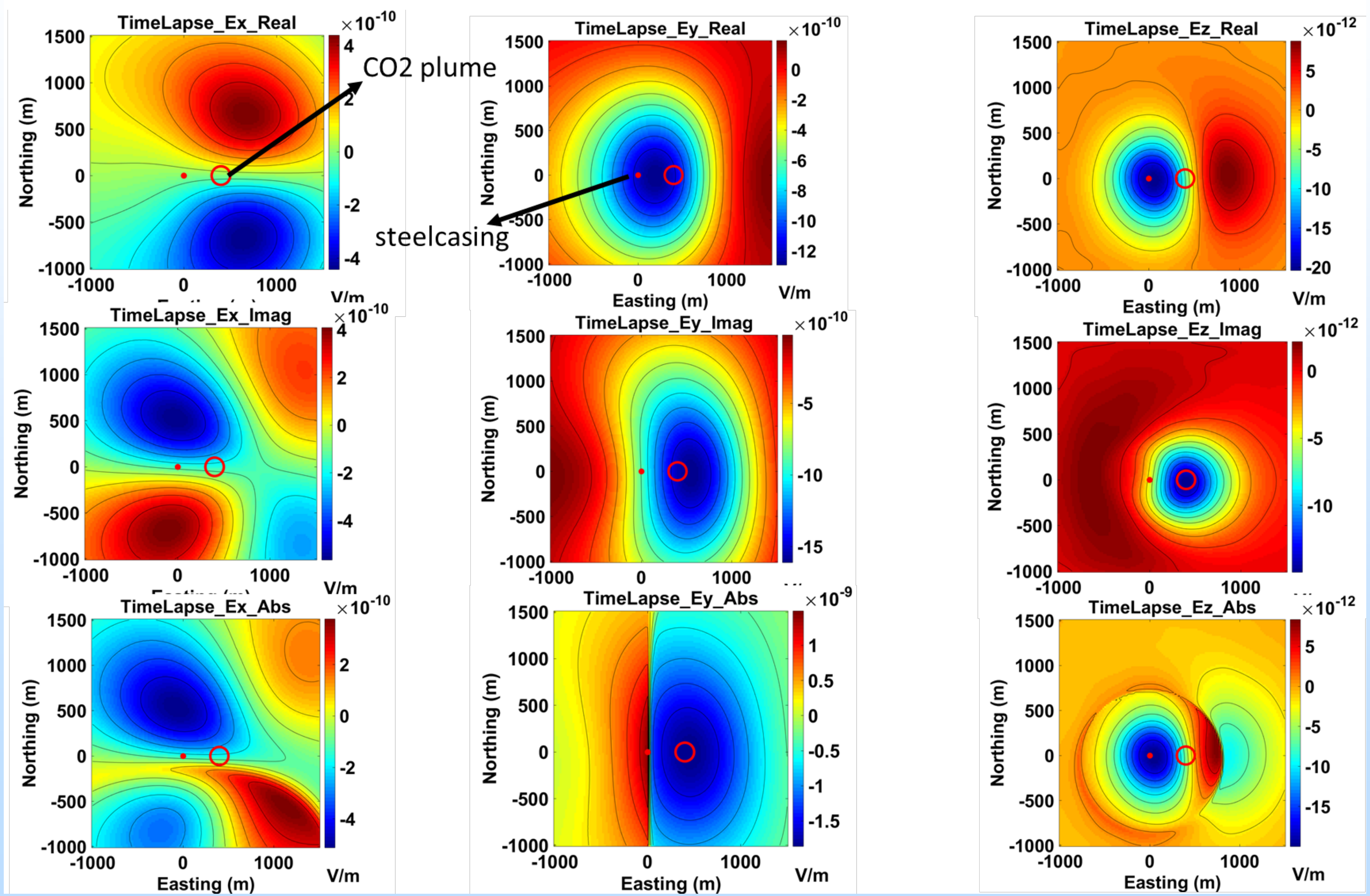
Imaginary component



CWC-CSEM Simulations for Bell Creek Depths

Electric field on surface:

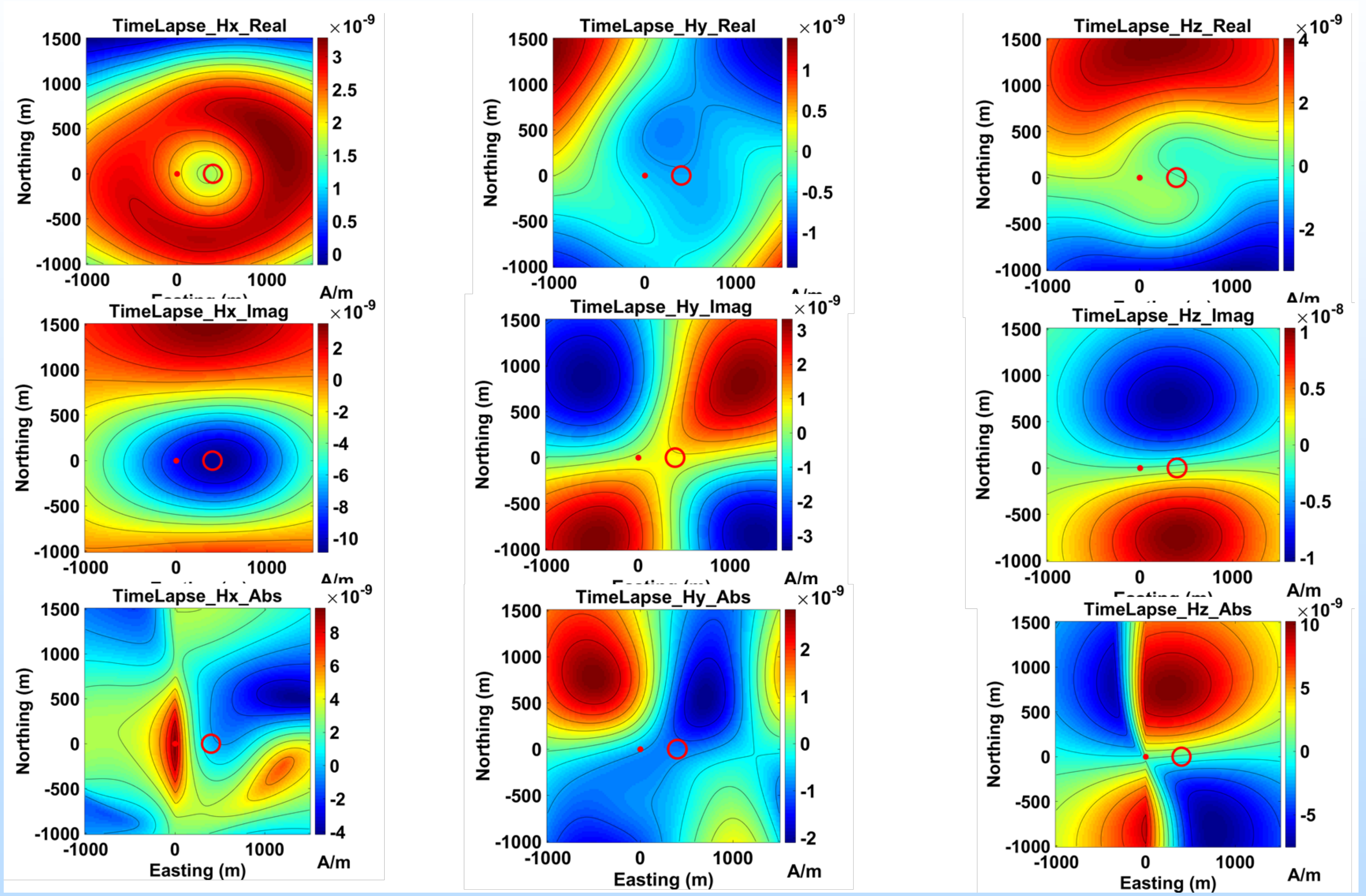
- Time-lapse response
- Thee components



CWC-CSEM Simulations for Bell Creek Depths

Magnetic field on surface:

- Time-lapse response
- Thee components



Field Surveys

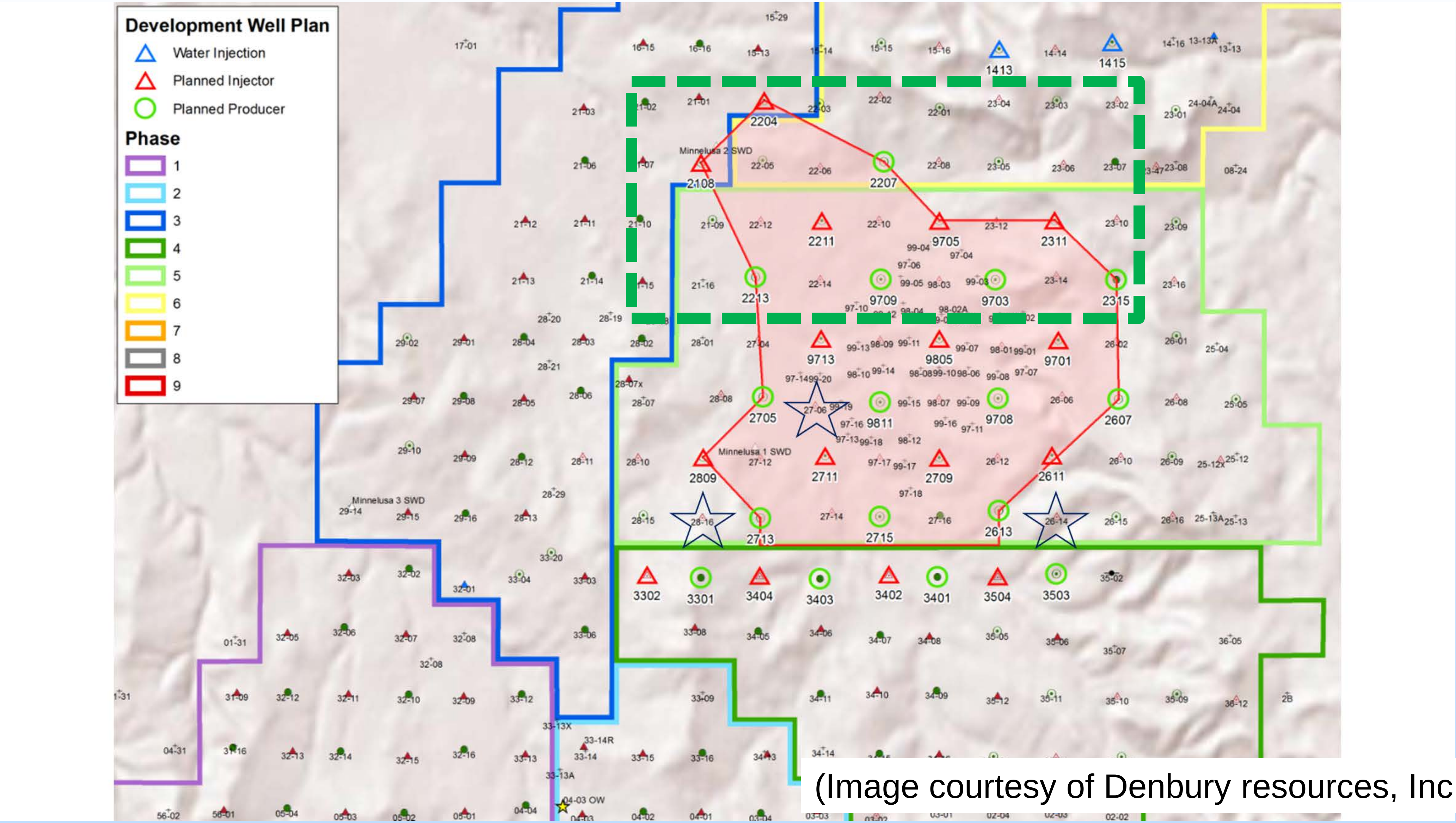
Field site: Bell Creek

- First EM Survey: August 13 – 19, 2017
- Immediately prior to the Phase-5 CO_2 injection

Reservoir model

- CSM/UU working closely with EERC

Planned Field campaign: August 12-19, 2017



(Image courtesy of Denbury resources, Inc.

Accomplishments to Date

Algorithmic and modeling developments

- All tasks on track
- Reservoir model
  - Software to link reservoir model to CWC-CSEM algorithm
  - Successful application to FWU model; will translate 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 CSM code made more robust and flexible
  - CSM code successfully run on UU high performance computing resources

Accomplishments to Date

Dissemination of information

- Web-site development
  - multiphysics-mva.org & cwc-csem.org
  - Limited content at moment
  - Will be updated throughout project
- Presentation at 2017 AIChE Annual Meeting
  - Topical conference: Advances in Fossil Energy R&D
  - Title: Monitoring carbon sequestration using charged wellbore controlled sources electromagnetics and integrated reservoir models

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

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 can be challenging

Summary: Overall Project Status

Field site, reservoir modeling, field campaigns

- Reservoir modeling and initial simulations started at original site, procedures and algorithms in place
- Combining field campaigns into four
- Back on track with a new field site at Bell Creek
- First field data acquisition campaign: August 12-19, 2017

Acknowledgements

– DOE/NETL: FE0028320

– Kylee Rice (PM)

– Chaparral

– Regional Partnership on Carbon Sequestration (SWP)

– Denbury Resources, Inc.

– Energy and Environmental Research Center (EERC)

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 carbon storage 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 geothermal exploration.

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

Organization 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

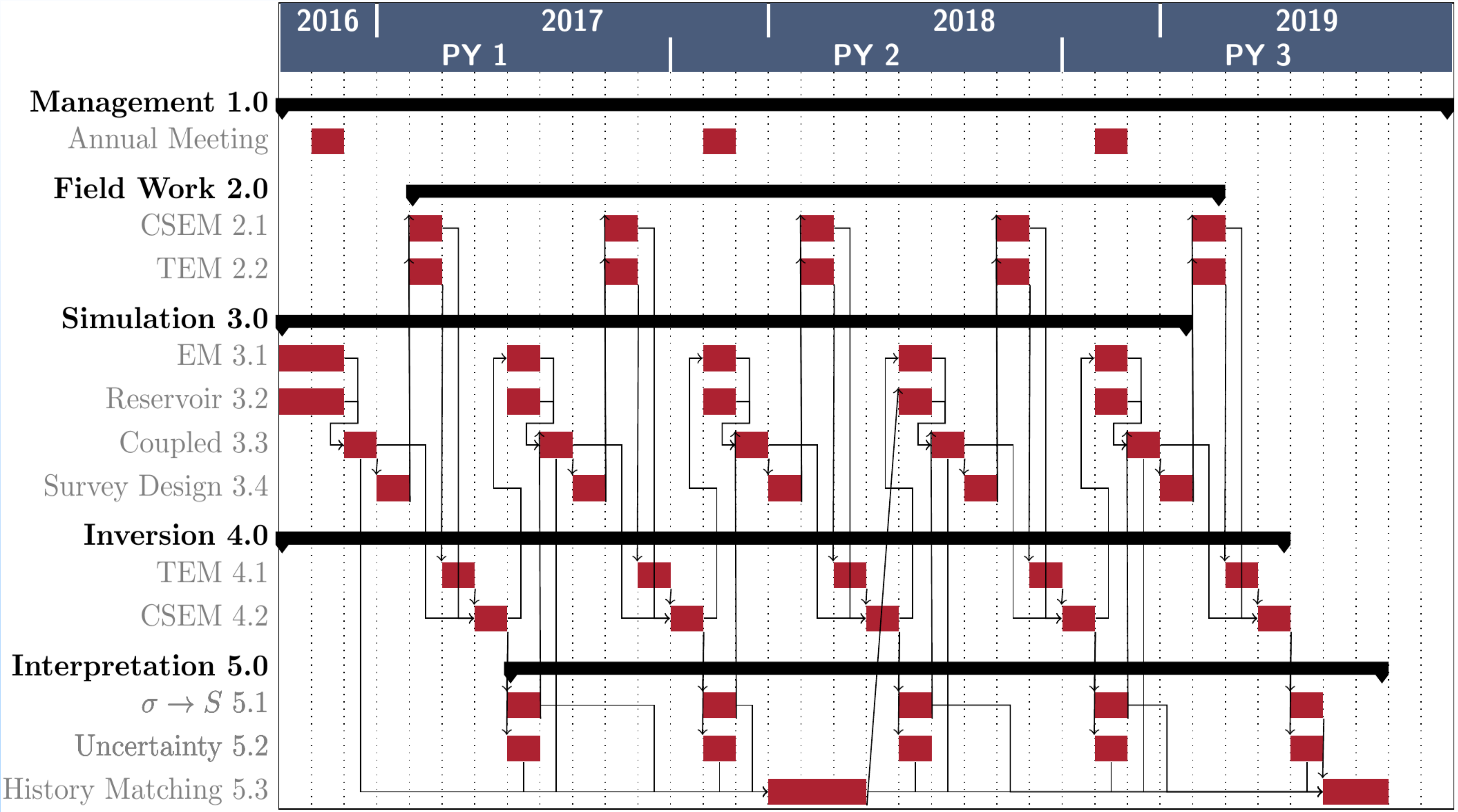
Communication plan

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

Project website

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

Proposed Schedule



Revised Statement of Project Objectives (SOPO)

Task 2.0 – Field Work (previous version)

Field work entails any collection of data that is performed directly as part of this proposal. We had proposed five campaigns of data acquisition, primarily focused on acquiring CWC-CSEM data, with a smaller component of supporting TEM data. The acquisition of data at multiple time instances are essential for time-lapse monitoring of the dynamic process in the active CCS-EOR site.

Revised Statement of Project Objectives (SOPO)

Task 2.0 – Field Work (revised)

Field work entails any collection of data that is performed directly as part of this proposal. We have proposed four campaigns of data acquisition, primarily focused on acquiring CWC-CSEM data, with a smaller component of supporting TEM data. The acquisition of data at multiple time instances are essential for time-lapse monitoring of the dynamic process in the active CCS-EOR site. Since Denbury does not plan to use a water alternating gas (WAG) cycle, the field will be somewhat less dynamic and the reduction in field campaigns should have minimal impacts on the project goals.

Bibliography

- No publications yet