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Critical Challenges. **Practical Solutions.**

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FIELD DEMONSTRATION OF CO_2 INJECTION MONITORING USING KRAUKLIS AND OTHER GUIDED WAVES

DE-FE0028659

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Energy & Environmental Research Center

U.S. Department of Energy

National Energy Technology Laboratory

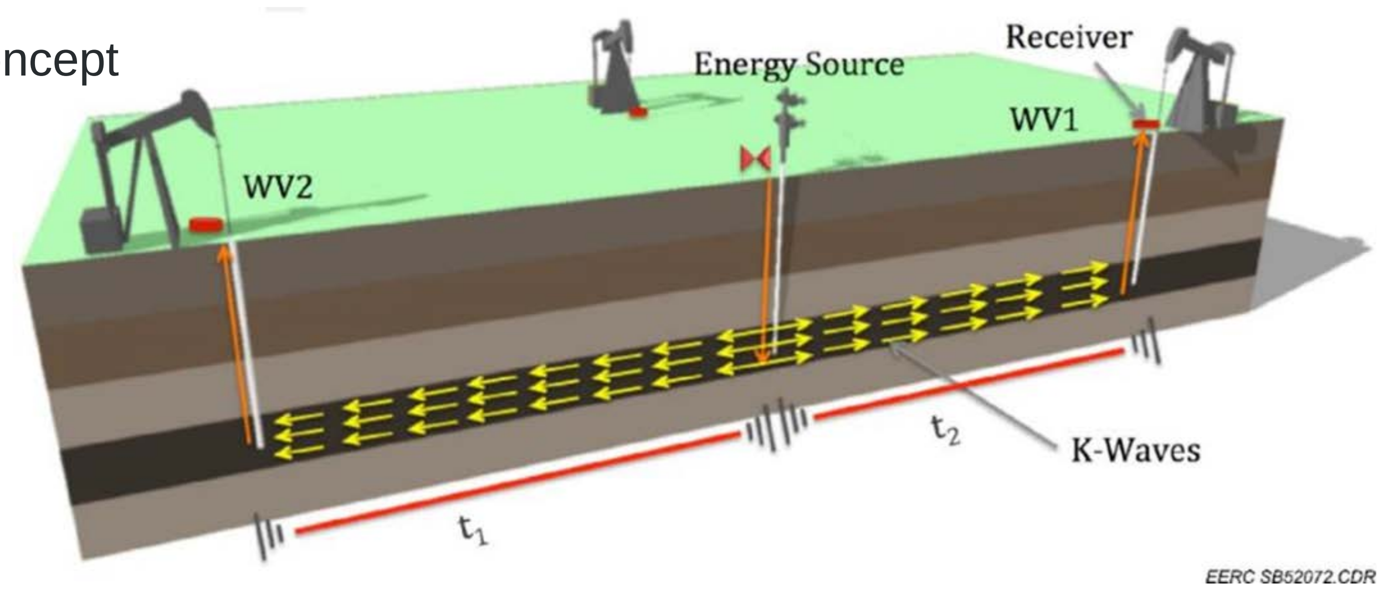
Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 1–3, 2017

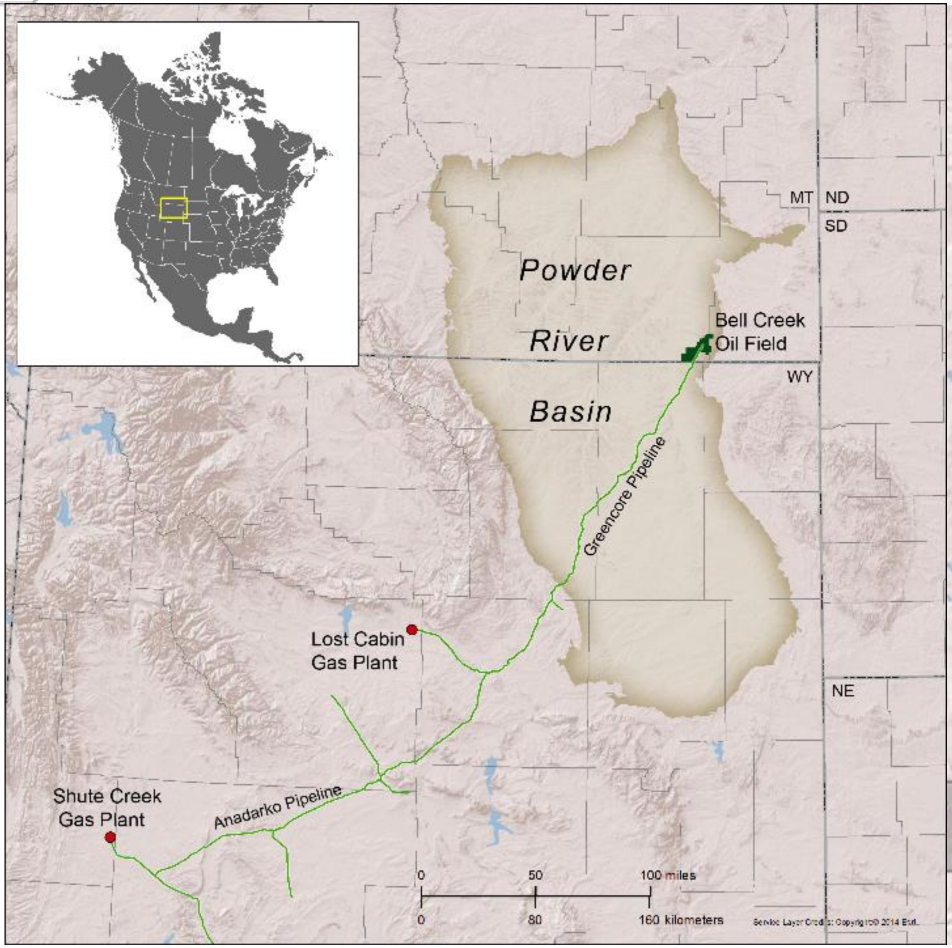
Critical Challenges. **Practical Solutions.**

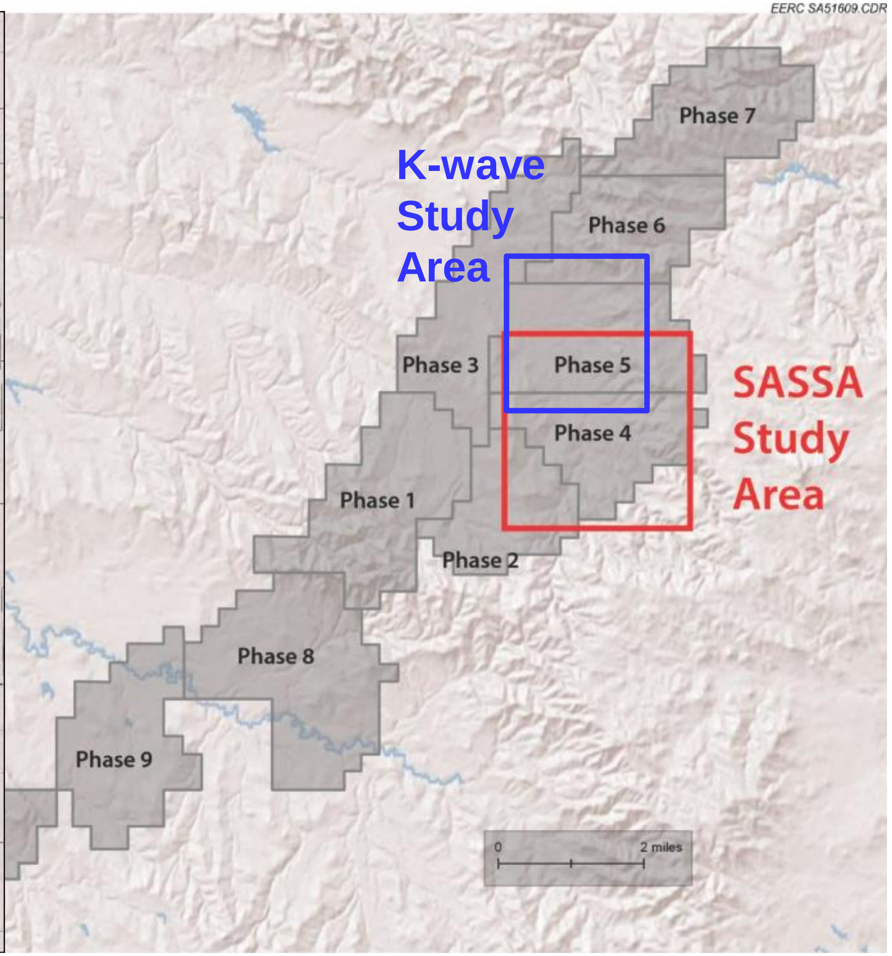
PRESENTATION OUTLINE

- Project Background
  - Study Area
  - Boundary and Guided Waves
  - Krauklis Wave (K-wave) Monitoring Concept
- Project Plan and Tasks
- Field Hardware Test
- Accomplishments and Lessons
- Synergy and Summary

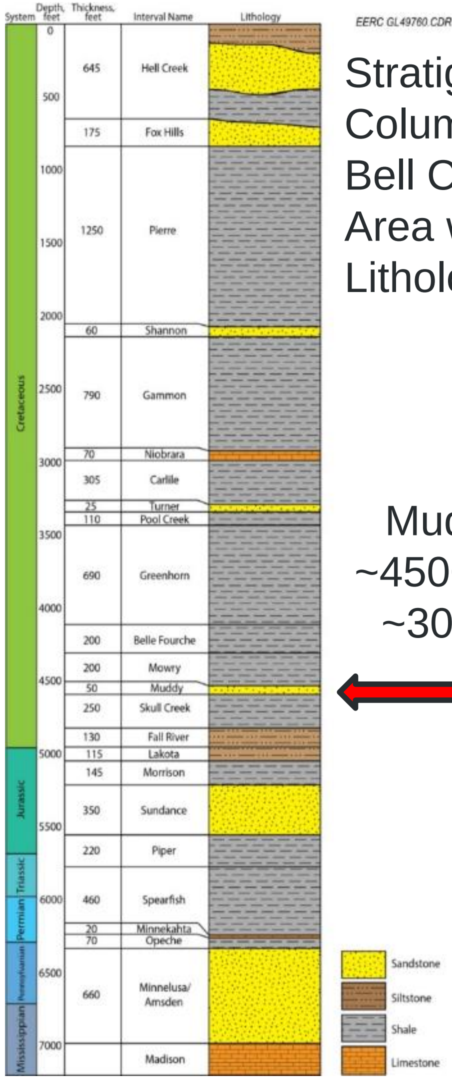


STUDY AREA AND TARGET





Bell Creek Oil Field

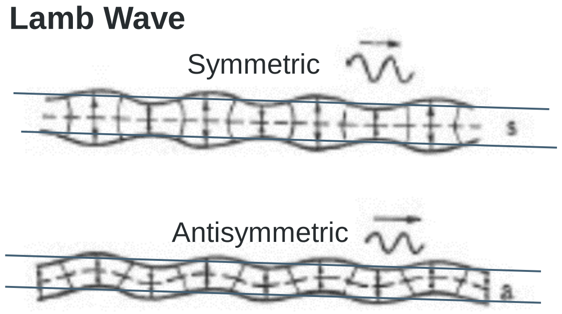


Stratigraphic Column for the Bell Creek Area with Lithology

Muddy Fm
~4500 ft deep
~30 ft thick

BOUNDARY AND GUIDED WAVES

- Rayleigh wave
  - A surface wave
- Lamb wave
  - A Rayleigh wave guided in a layer
- Scholte wave
  - A boundary wave guided along a liquid–solid interface
  - A tube wave
- Stoneley wave
  - A boundary wave guided along a solid–solid interface
  - Has a large amplitude
  - Leaky Rayleigh wave



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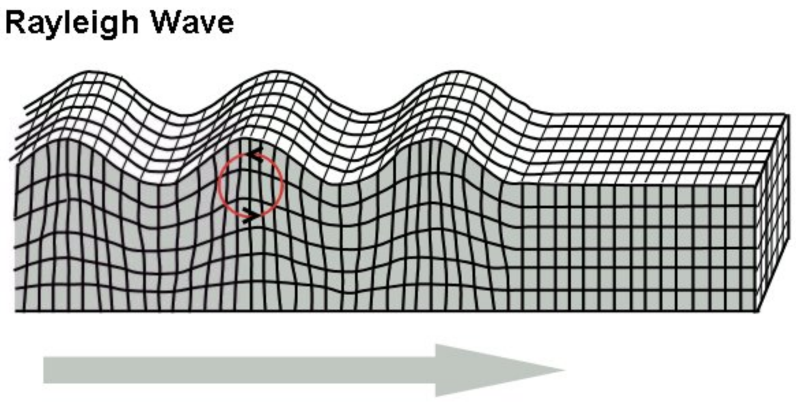
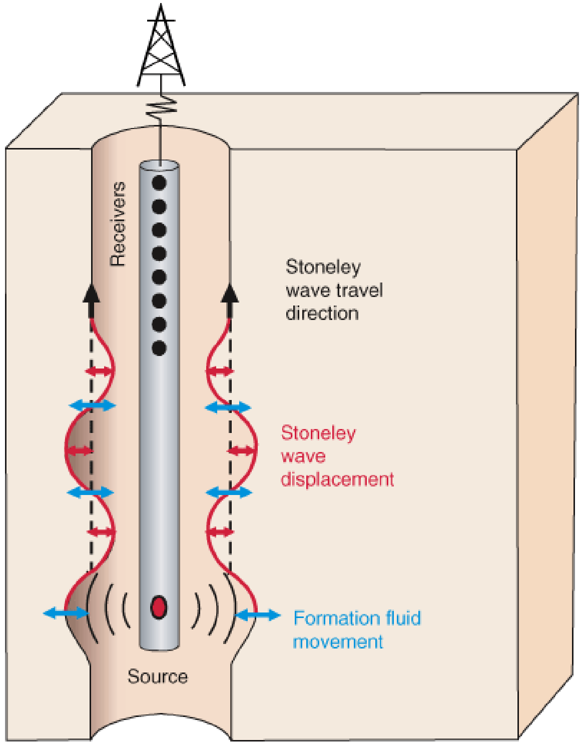


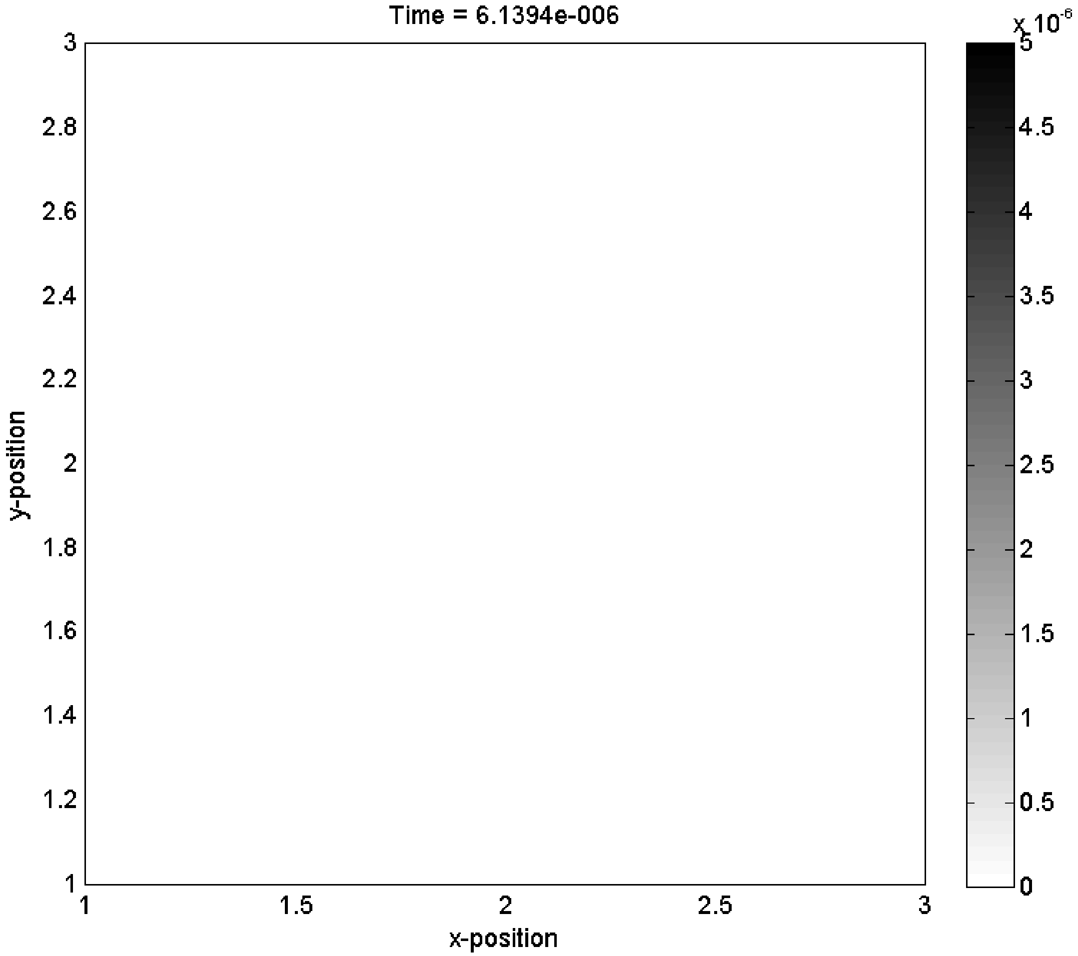
http://www.geo.mtu.edu/UPSeis/rayleigh_web.jpg



Wikipedia.org

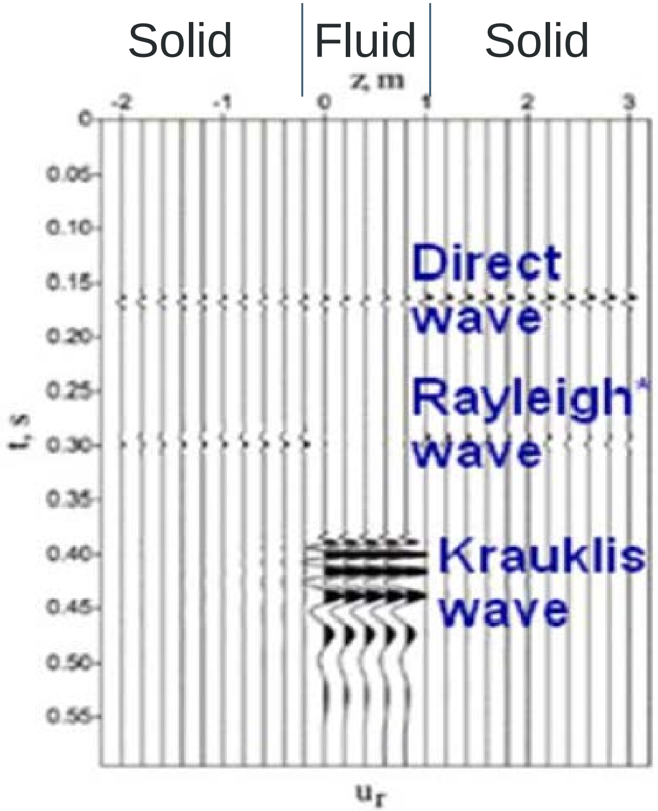
Note:
- Rayleigh wave propagates at a vacuum–solid interface
- Stoneley wave propagates at a solid–solid interface.
- Scholte wave propagates at a liquid–solid interface.

K-WAVE (1962)



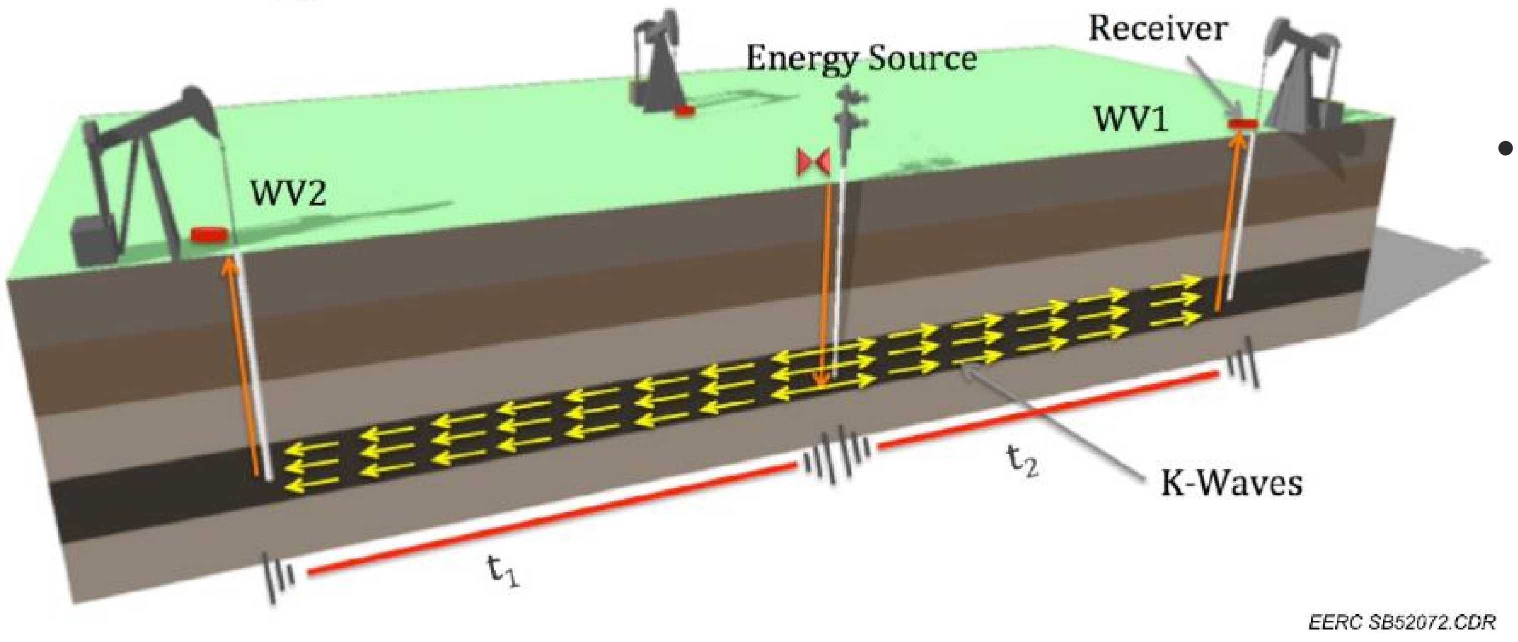
K-Waves in Two Intersecting Fractures

https://www1.ethz.ch/rockphysics/research/krauklis



Shigapov, R., and Kashtan, B. [2011] Oscillations of a Fluid Layer Sandwiched between Different Elastic Half-spaces. 73rd EAGE Conference, P046, Vienna, Austria.

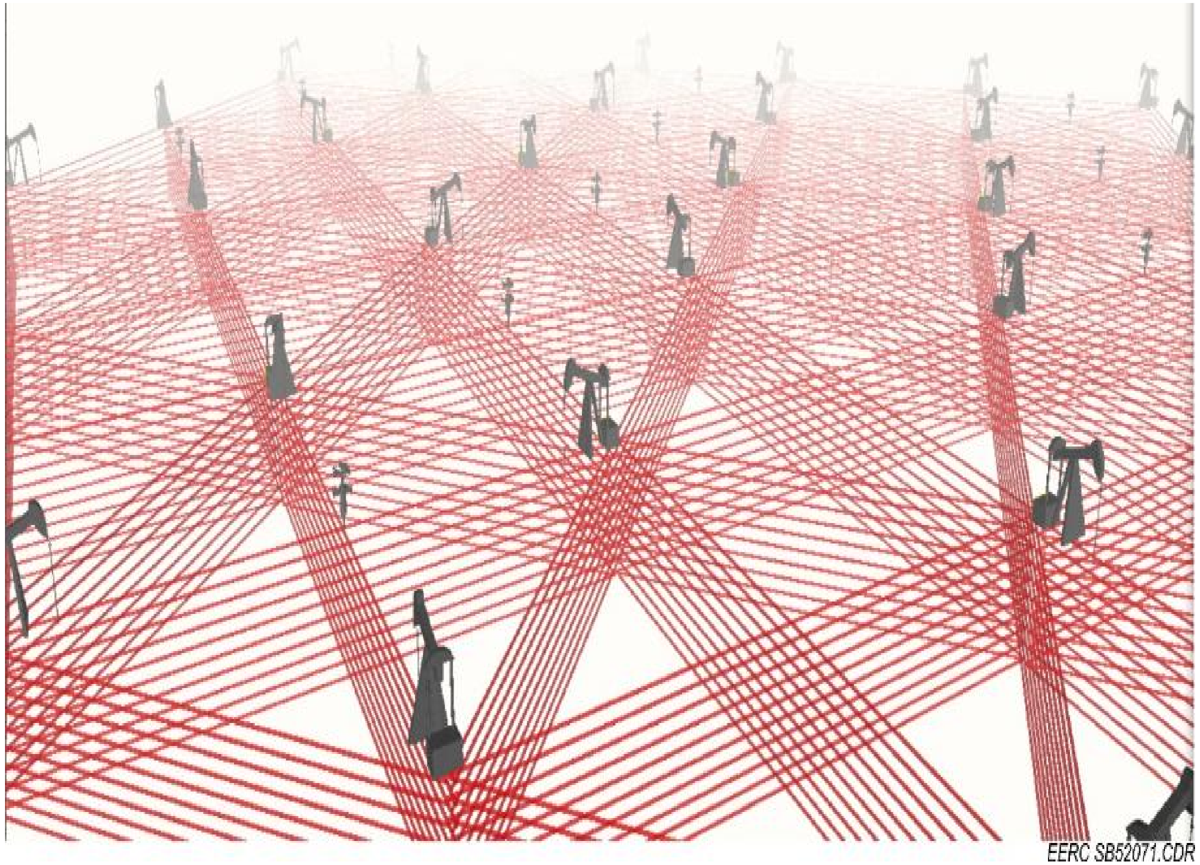
K-WAVE CONCEPT



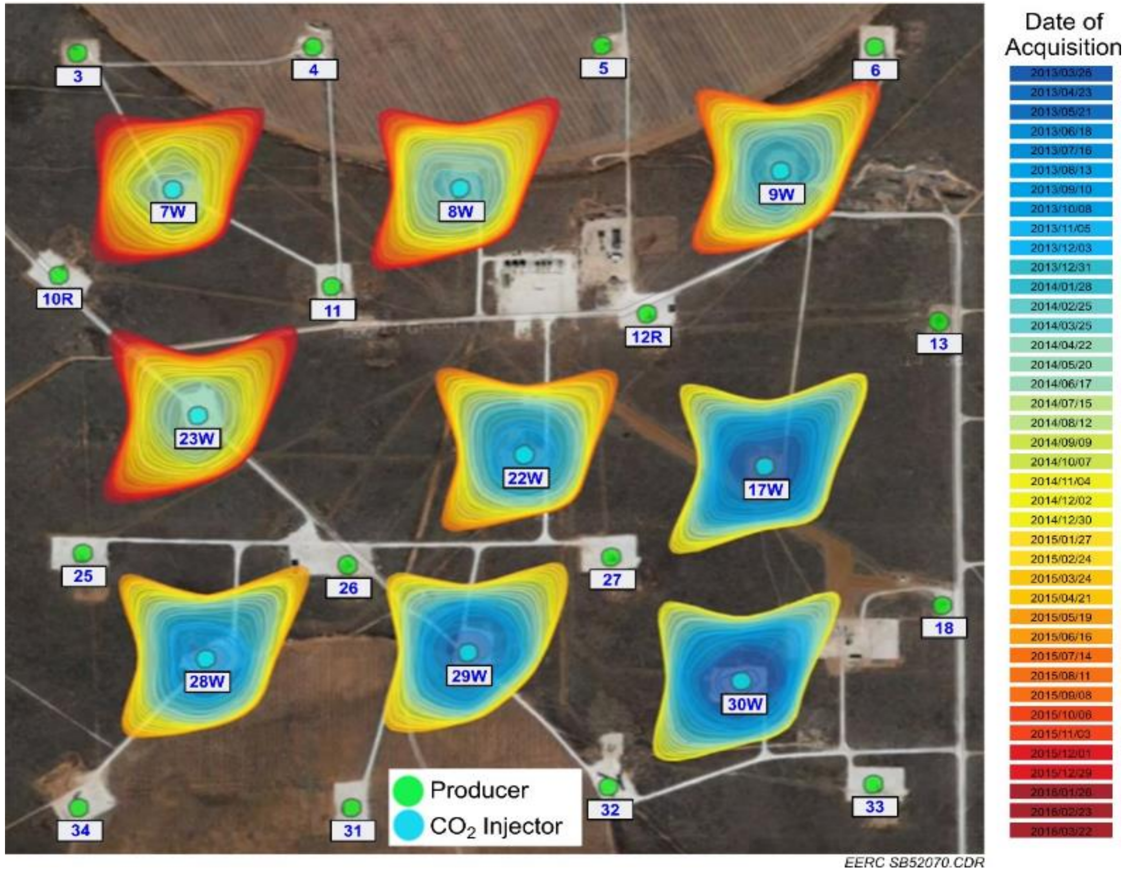
Simplified K-wave system illustration showing two well pairs (one “source” well and two “receiver” wells) (image courtesy of Seismos, Inc.).

- Question: If K-waves travel in liquid-filled fractures, how does it work in a clastic reservoir that is not fractured?
- Answer: All guided waves that propagate laterally through the reservoir are monitored.
  - Includes Stoneley, Sholte, Lamb, etc., that travel in the waveguide (the reservoir), and K-waves.
  - In the enhanced oil recovery (EOR) application, an engineering approximation is used… a mix of guided waves, including K-waves.

K-WAVE COVERAGE MESH AND VISUALIZATION



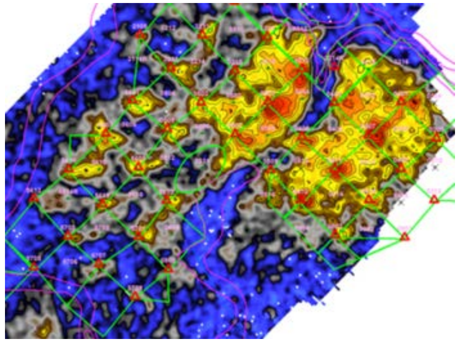
K-wave ray paths monitored in a hypothetical well pattern (image courtesy of Seismos, Inc.).

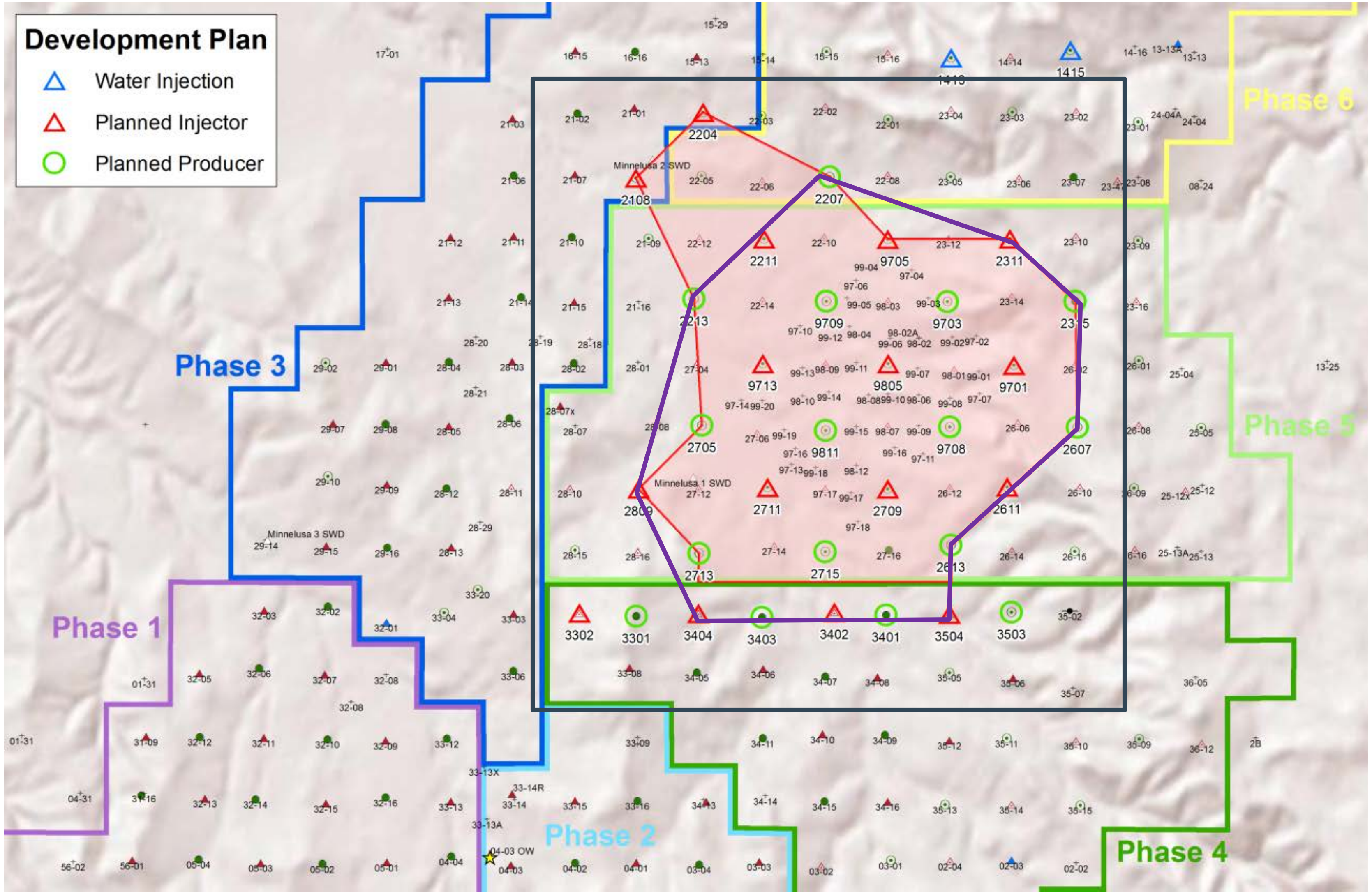


Idealized CO_2 saturation evolution generated by the K-wave system (image courtesy of Seismos, Inc.).

K-WAVE STUDY AREA

- Project plan
  - Up to 30 wells with passive surface hardware
  - Perform ~four formal data collections
  - Acquire two small 3-D surface seismic surveys
    - Before: summer 2017
    - After: summer 2018
  - Analyze and report

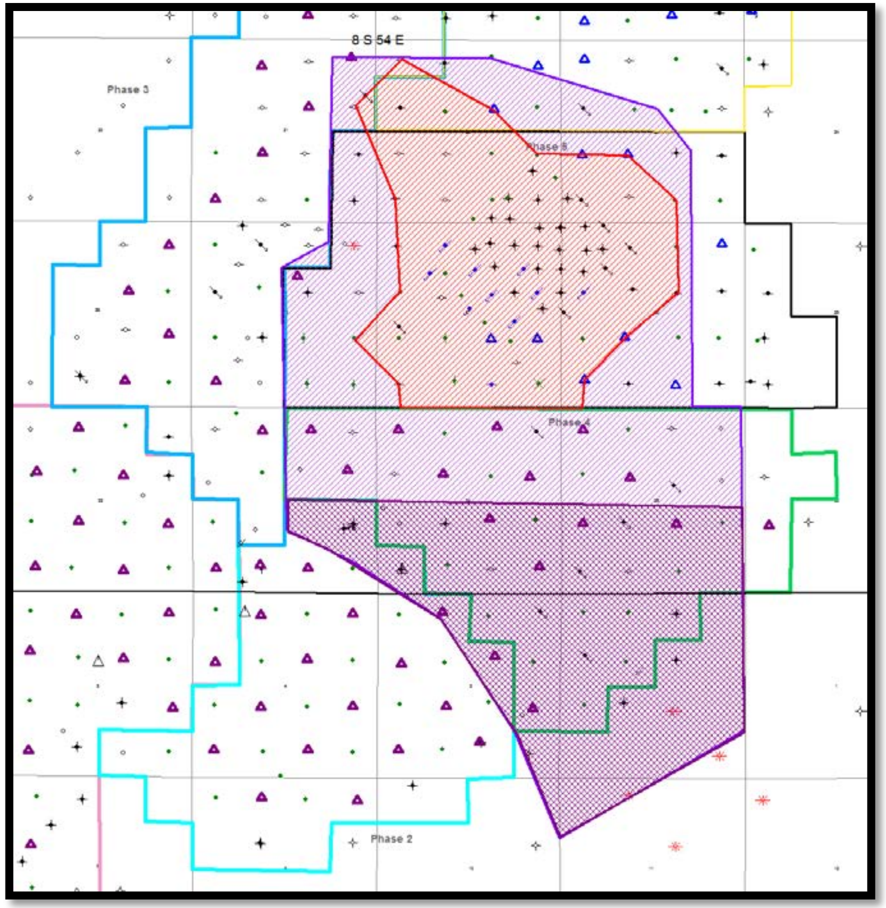




TASK BREAKDOWN

- Task 1 – Project Management
  - Planning, Oversight, Reporting
- Task 2 – Field Data Collection
  - 2.1 Prestudy 3-D survey –
    - ♦ Timestamp image of CO_2 and pressure before K-wave monitoring
  - 2.2 K-Wave Monitoring –
    - ♦ Baseline and three periodic monitoring surveys
  - 2.3 Poststudy 3-D survey –
    - ♦ Timestamp image of CO_2 saturation after K-wave monitoring.
- Task 3 – Data Analysis and Workflow
  - 3.1 Seismic Data Interpretation and Geologic Model Refinement
  - 3.2 Predictive Simulations and Comparisons to K-Wave Surveillance
  - 3.3 Review of Results, Integration Workflow Development, and Report Generation
    - ♦ Develop a workflow that integrates the K-Wave data with 4-D seismic and dynamic simulations

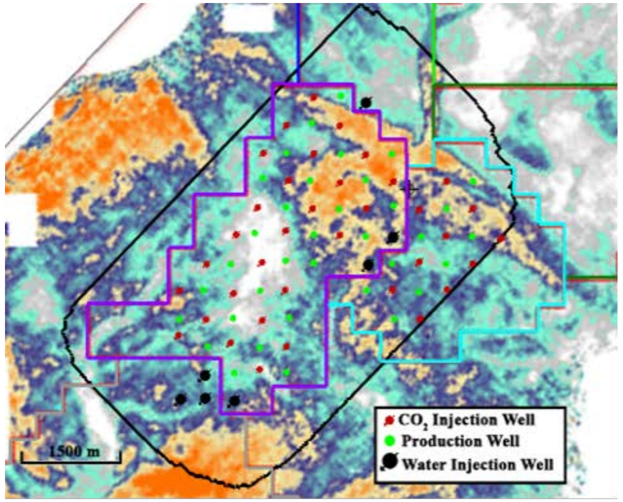
Proposed Field Plan



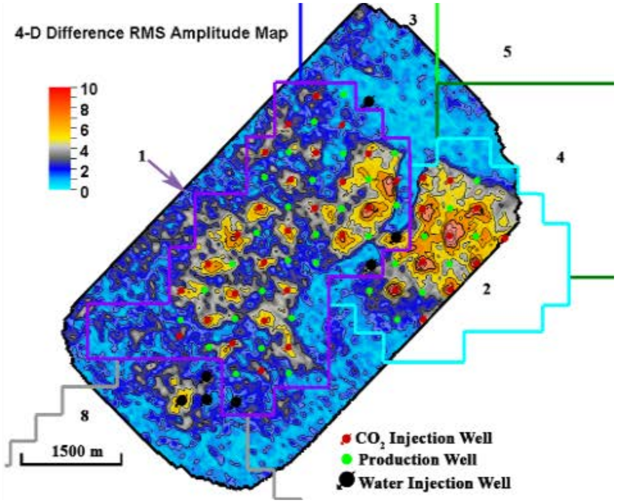
DATA ANALYSIS: 3-D AND 4-D SEISMIC

- Task 3.1 – Seismic Data Interpretation and Geologic Model Refinement
  - 3-Ds – before and after K-wave.
  - 4-D images of CO_2. Compare to the K-wave results.
  - Calibrate where there was injection prior to the K-wave survey.
  - Improve the geologic model – input for dynamic reservoir modeling with CMG software.

Baseline



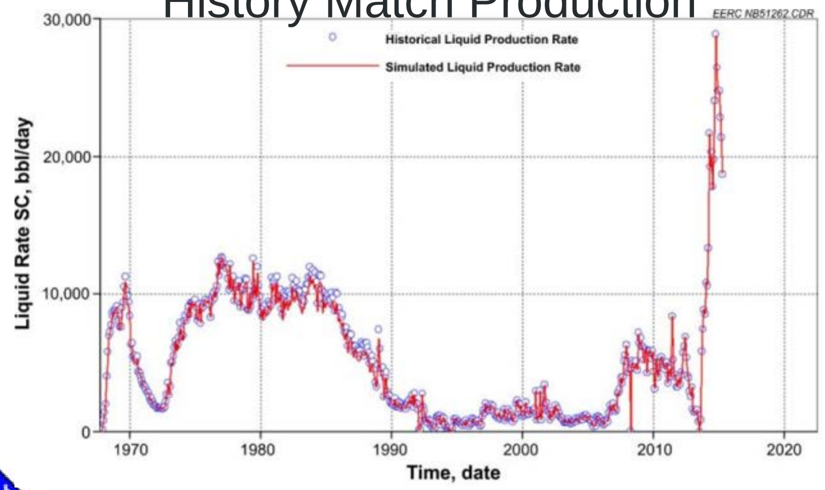
4-D Difference



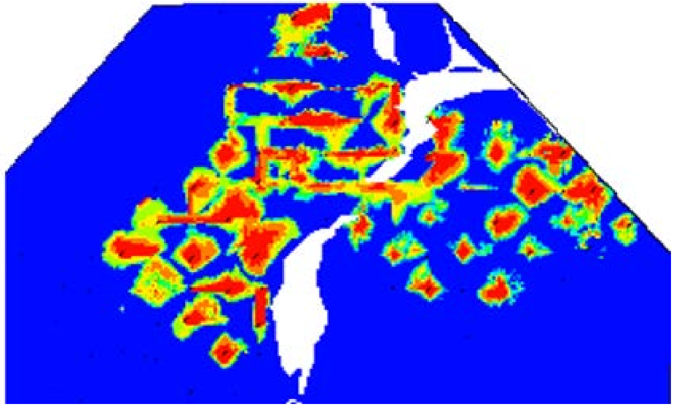
DATA ANALYSIS: PREDICTIVE SIMULATIONS

- Task 3.2 – Predictive Simulations and Compare to K-Wave Results
  - Refine the geologic model
  - History match to known production and CO_2 injection volumes
  - Model CO_2 saturation
  - Compare to K-wave images

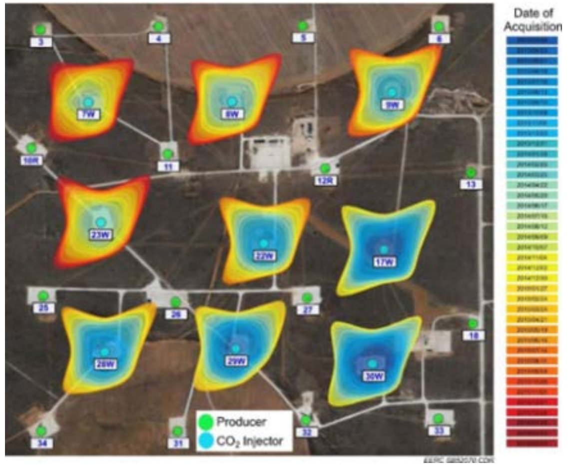
History Match Production



CMG Simulation CO_2 Map

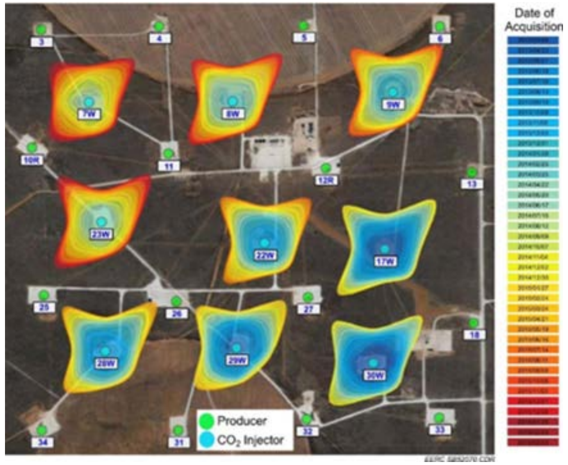


K-Wave CO_2 Map

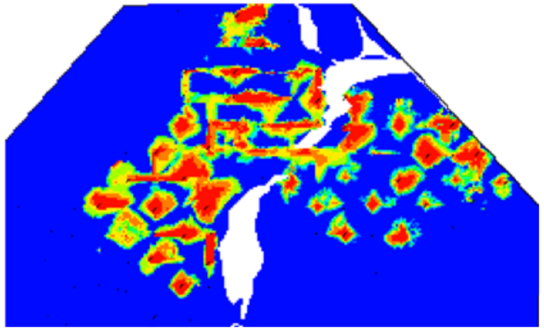


DATA ANALYSIS: WORKFLOW DEVELOPMENT

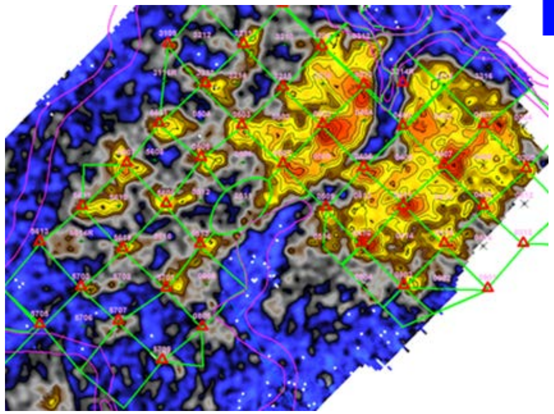
- Task 3.3 – Review and Integrate Workflow
  - Develop a workflow to integrate the K-wave data with 4-D seismic and dynamic simulations.
  - Look-ahead – integrate the K-wave system into an intelligent monitoring system.
  - Leverage efforts that are currently being developed in a separate project.



K-Wave CO_2 Map



CMG Simulation CO_2 Map



4-D Seismic CO_2 Map

K-WAVE WELL SENSORS

Injector

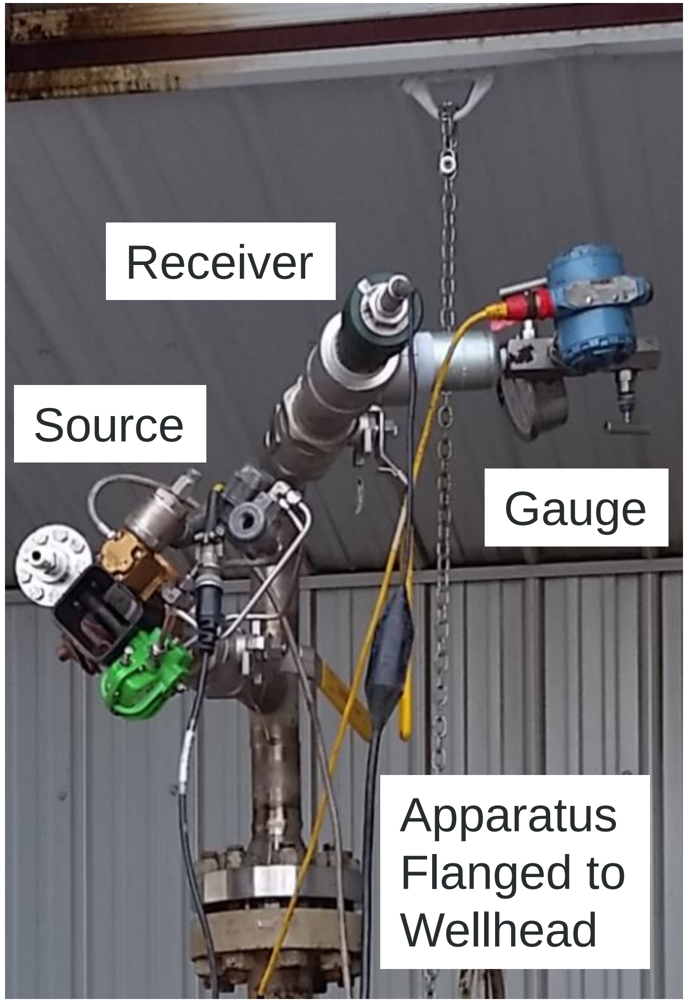
Producer

BELL CREEK WELLHEADS

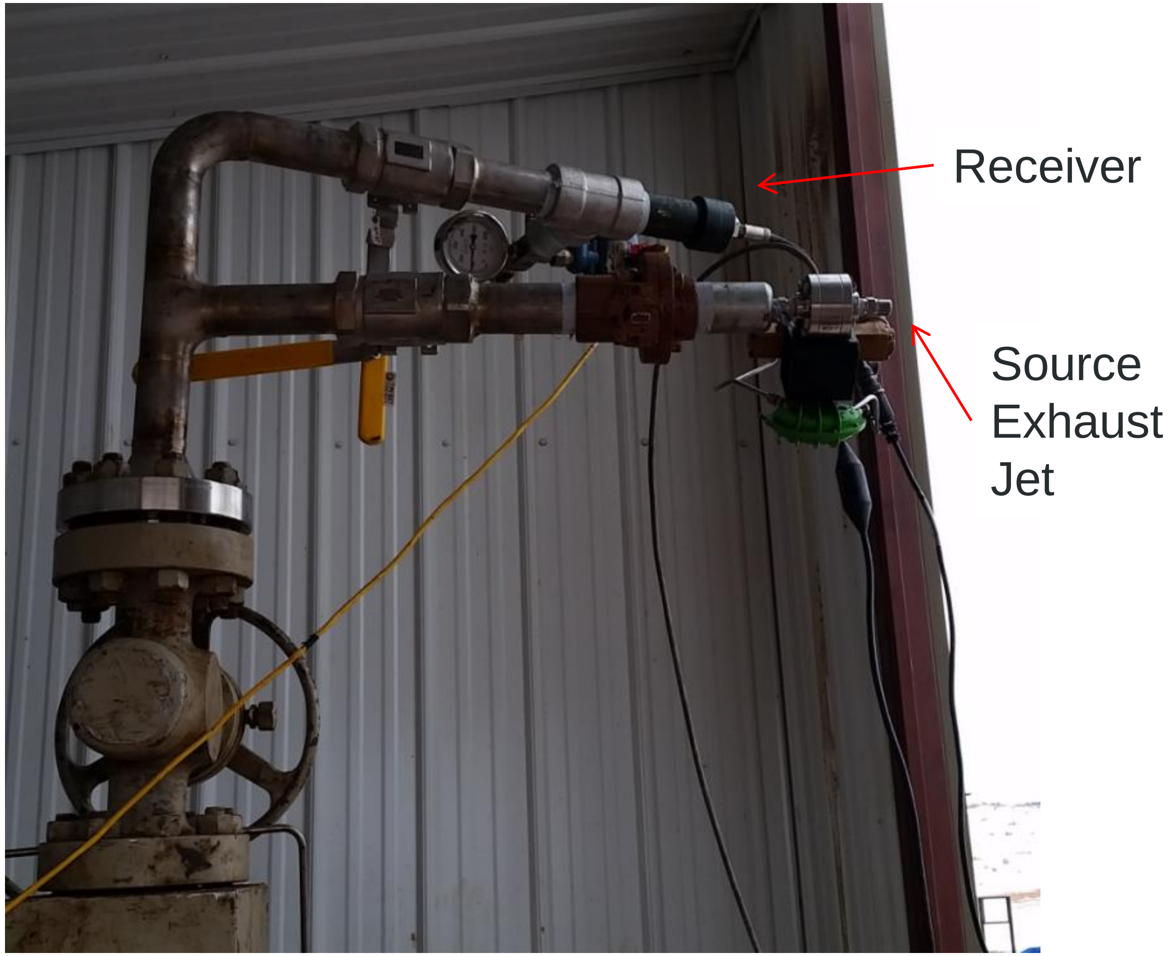
TESTING AT BELL CREEK – TEMPORARY MOUNT

Hammer Union

Flange



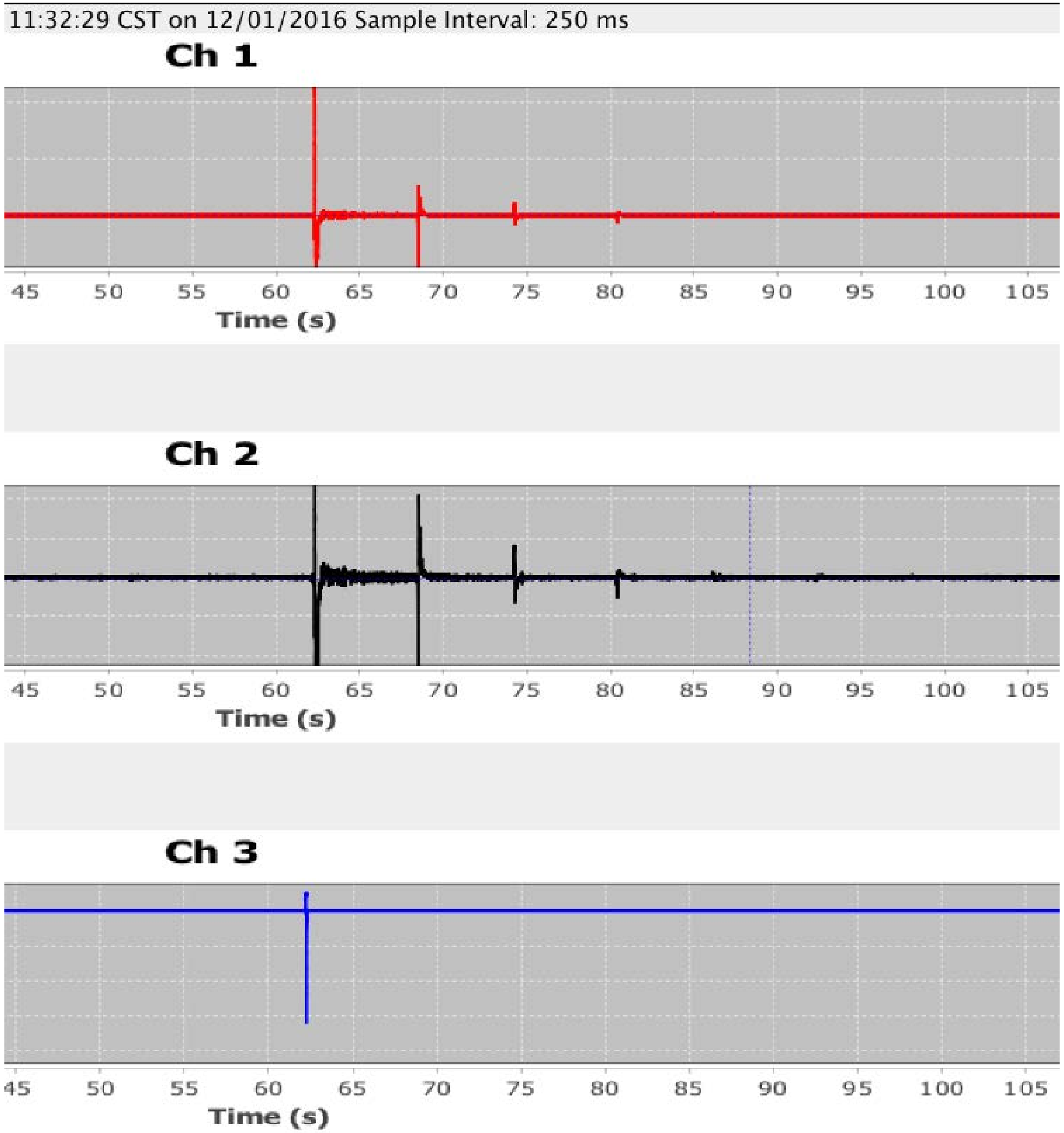
INJECTOR SETUP



Source actuation is powered by compressed nitrogen. The injector operates at ~1400 psi, so a 100-ms release of CO_2 from the well induces the pulse in the well.

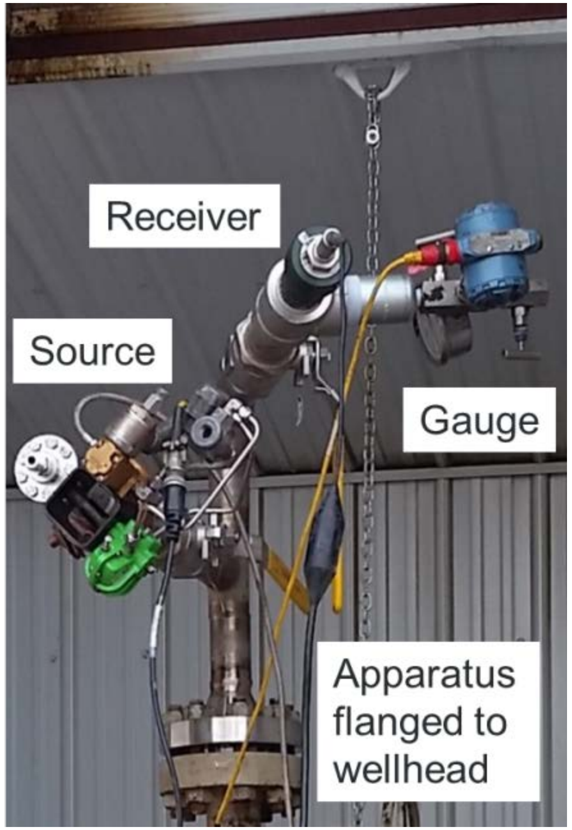
TEST SHOT

- Ch 1 and Ch 2 show a test shot showing tube wave returns, displayed with different gains.
- Ch 3 is the source impulse.
- Note the tube wave returns have alternating opposite polarity and attenuate to the noise level after five or six reflections.



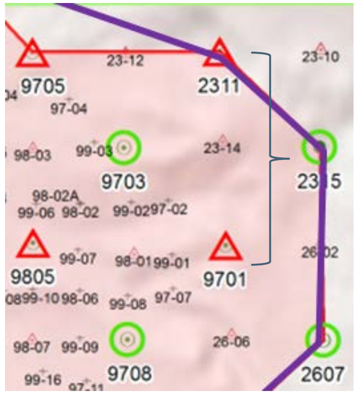
ACCOMPLISHMENTS TO DATE

- Kickoff meeting with DOE completed.
- Contracts are in place with partners: Denbury, Seismos, and CMG.
- Field reconnaissance trip with Seismos and Denbury engineers; instrumenting of three wells and acquiring test shots were completed.
- Main study area, wells to be instrumented and project time line are firmed up.
- Attachment points for sensors and source to wellheads are engineered.
- Modeling of guided wave energy in the Bell Creek reservoir is under way.
- Design, permitting, and contracting for both prestudy and poststudy surface 3-D surveys are under way.



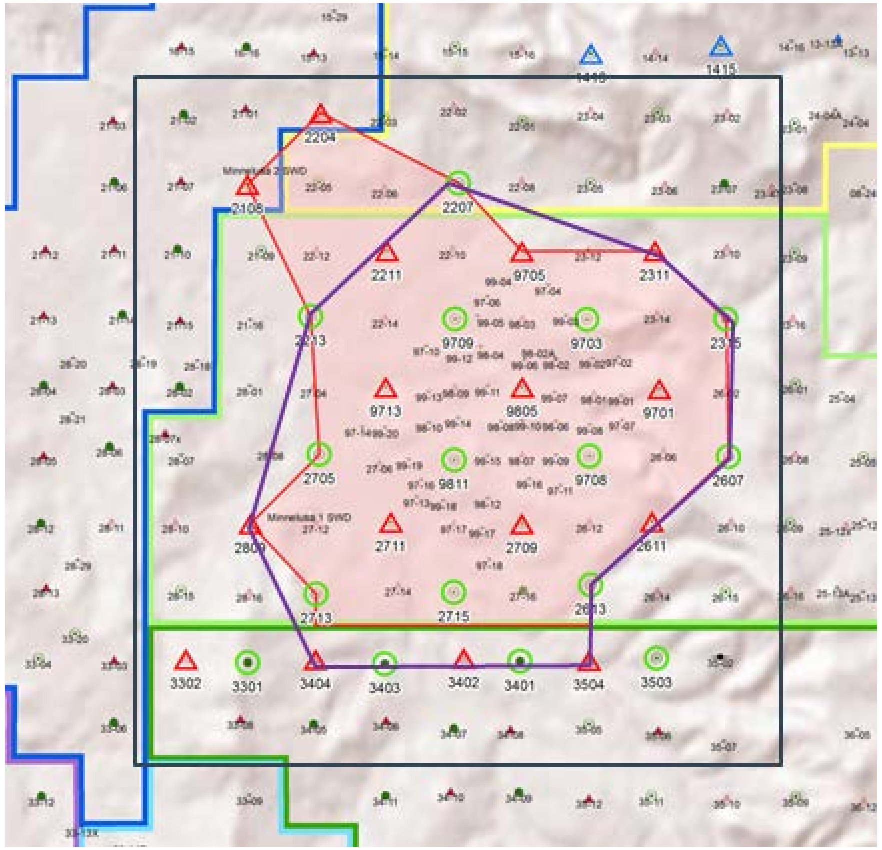
LESSONS LEARNED

- Buildout plan for Phase 5 has well spacing twice the distance as previous phases.
  - A new, stronger "positive displacement" source has been developed, but has not yet been tested in the field.
  - Unknown if the source signal can be detected at the new distances.
  - Modeling is under way which will provide an indication.
  - A second field test will be scheduled based on modeling results.
- Field test showed that production wells operate at significantly lower pressure than injection wells.
  - If CO_2 has broken through at the well, a gas bubble may form at the top of the wellhead.
  - Bubbles interfere with the receiver signal.
  - Receivers need to be lower on the flow line.



SYNERGY OPPORTUNITIES

- Geologic and simulation models used for SASSA (scalable, automated, semipermanent seismic array) can be extended into the K-wave study area.
- Reservoir characterization data gained from other Bell Creek projects can be input to the K-wave modeling.
- Colorado School of Mines project, *Charged Wellbore Casing–Controlled Source Electromagnetics (CWC–CSEM) on Reservoir Imaging and Monitoring*.
  - Same Phase 5 study area for K-wave.
  - Reservoir characterization information can be shared.
  - Results of the K-wave monitoring 4-D surface seismic results can also help validate the CWC–CSEM method.
- A joint inversion project that uses the 3-D surface seismic and CSEM data together is a future possibility.



PROJECT SUMMARY

- The EERC and its project partners will deploy and validate a prototype MVA (monitoring, verification, and accounting) technology in an operational carbon capture, utilization, and storage (CCUS) field environment.
- Employs a new subsurface signal, the K-wave, and other guided waves in novel approach.
- 3-year project, with ~15 months of data collection at Bell Creek Field.
  - Up to 1 year of K-wave monitoring involving up to 30 wells.
  - Validation by two surface 3-D surveys – before and after K-wave monitoring.
- Raise the technology from the current TRL 4 to TRL 7.
- The implementation is entirely surface-based and is not invasive or disruptive to operations.
- May be suitable for long-term or permanent placement.
- Expected to provide temporal and spatial monitoring of the CO_2 distribution within the reservoir.
- Could eventually be cost-effective for monitoring future CO_2 storage facilities and incorporated into an intelligent monitoring system.
- A “go/no go” decision point for project continuation: determine viability after the baseline and first monitor survey.
- Contracts in place – field recon complete – modeling in progress – first 3-D pending.

APPENDIX

Benefit to the Program
Project Overview – Goals and Objectives
Organization Chart
Gantt Chart
Bibliography
Acknowledgment
Contact Information

BENEFIT TO THE PROGRAM

PROGRAM GOALS ADDRESSED

1. Deploy and validate a prototype CCUS MVA technology in an operational field environment.
2. Employ a new subsurface signal.
3. Raise the current TRL 4 to TRL 7.
4. Implementation is not invasive or disruptive to operations.
5. May be suitable for long-term deployment or permanent placement.
6. Provides temporal and spatial monitoring of the CO_2 distribution within the reservoir.
7. Could eventually be cost-effective for monitoring future CO_2 storage facilities and incorporated into an intelligent monitoring system.

BENEFITS STATEMENT

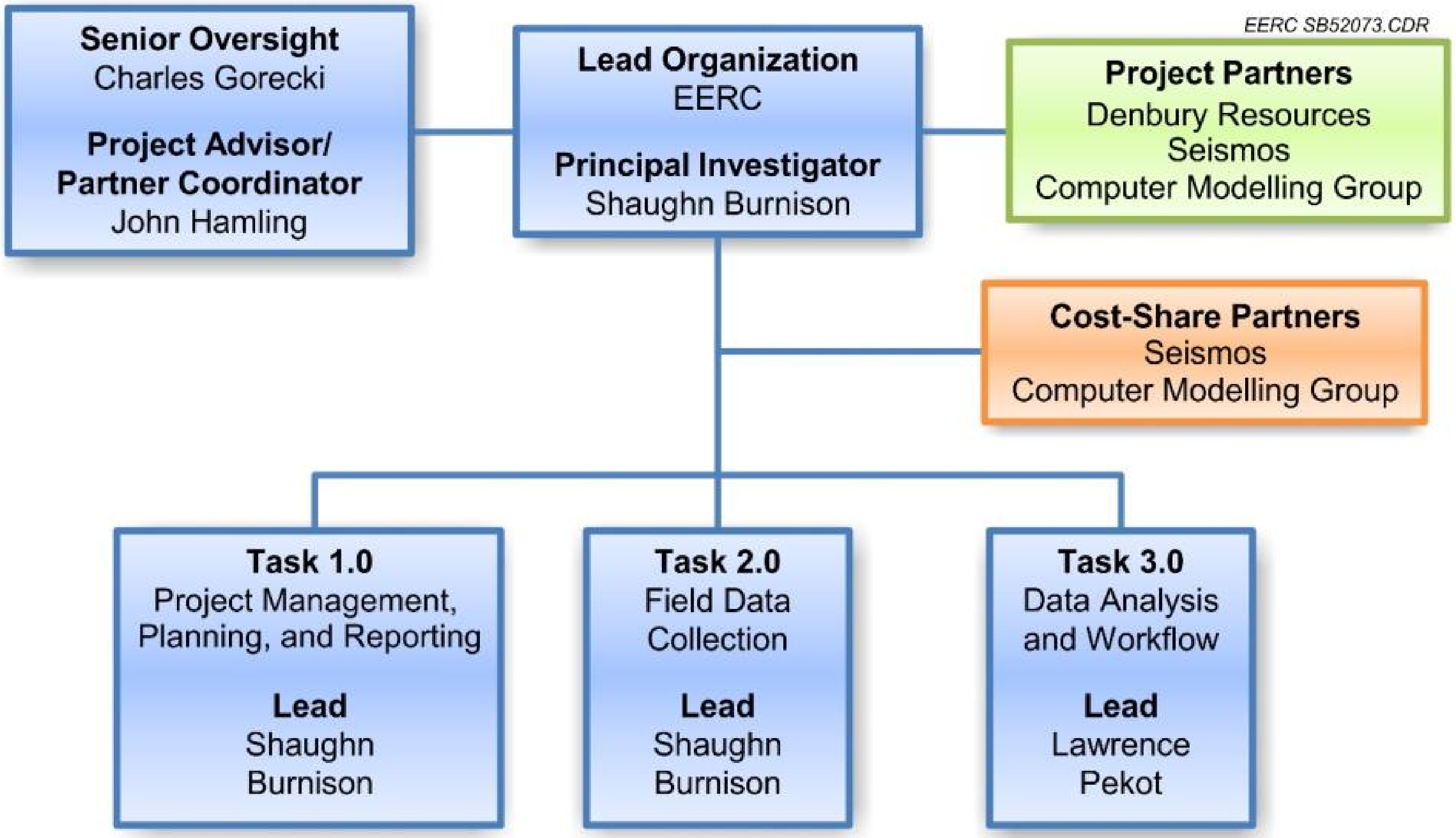
The project will address Area of Interest 1, "Field Demonstration of MVA Technologies," by deploying and validating a prototype carbon storage monitoring, verification, and accounting (MVA) technology in an operational field environment. The method employs a new subsurface signal, the K-wave, to monitor the migration of injected CO_2 in a cost-effective, noninvasive way that is not disruptive to injection operations. Project goals will be accomplished by applying the technology, currently at TRL4, to an appropriately scaled subset of wells within a commercial-scale CO_2 enhanced oil recovery project with associated CO_2 storage and validating the resulting data with conventional seismic monitoring methods and dynamic reservoir simulation results, bringing the K-wave technology to TRL7. Potential exists for future upgrades to real-time monitoring that could feed data to an intelligent monitoring system. The proposed research supports the U.S. Department of Energy (DOE) Carbon Storage Program's goal to "Develop and validate technologies to ensure 99 percent storage permanence." Other DOE program goals supported by the proposed research include "develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness" and "support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent." Information produced will be useful for inclusion in DOE's Carbon Storage best practices manuals for MVA, the development of which is also a DOE program goal.

PROJECT OVERVIEW – GOALS AND OBJECTIVES

Ties to program goals noted in blue

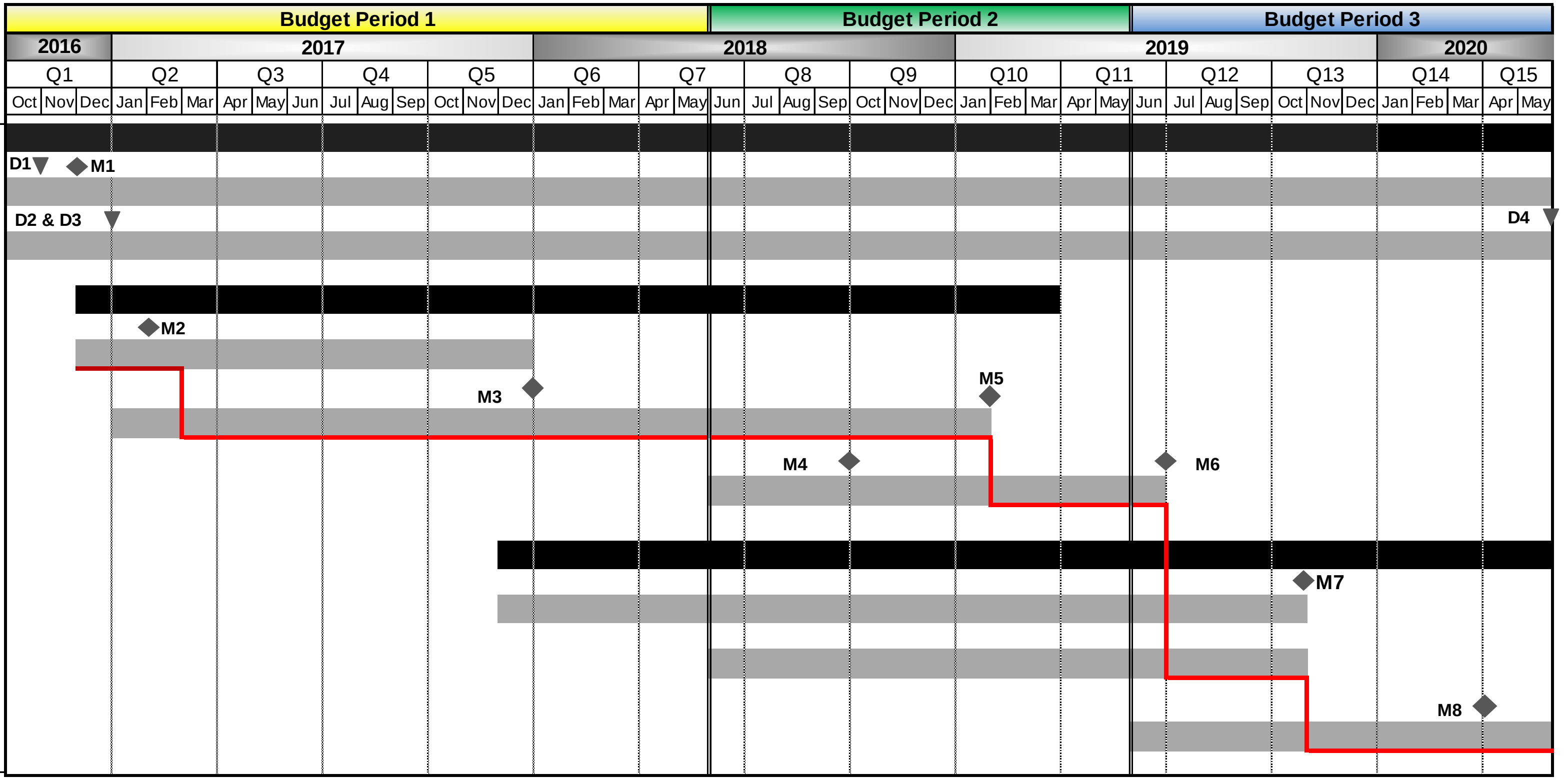
- Objectives: Deploy to demonstrate, validate, and evaluate a new method of monitoring the morphology and extent of subsurface CO_2 injection plumes from the surface in a manner that has low impact, is noninvasive, and is nondisruptive to normal operations.
  - The method leverages a new way of transmitting energy from the surface to the reservoir and employs a new subsurface signal called the Krauklis wave (K-wave) and other guided wave energy for injection monitoring that may be applicable to other CCS and CCUS applications.
  - Currently at a TRL of 4 (basic technology components integrated and validated in a laboratory environment), the first-year objective is to install the system to a significant subset of a field's wells and acquire a baseline data set and one or more major repeat/monitor data sets to evaluate the system for viability.
    - ♦ A go/no-go assessment will occur after the first monitoring data are acquired to assess the likelihood of success before proceeding with the remainder of the project.
  - Assuming viability, the objective of the project will be to validate and evaluate the method as a temporal and spatial MVA method for CCS and CCUS applications as a fully integrated prototype technology tested at a field site, thus advancing the technology to TRL7 (system prototype validated in an operational system).

ORGANIZATION CHART



GANTT CHART

Task	Start Date	End Date
Task 1.0 – Project Management, Planning, and Reporting	**10/1/16**	**5/31/20**
1.1 – Project Management and Planning	10/1/16	5/31/20
1.2 – Project Reporting	10/1/16	5/31/20
Task 2.0 – Field Data Collection	**12/1/16**	**3/31/19**
2.1 – Prestudy 3-D Survey Planning, Acquisition, and Processing	12/1/16	12/31/17
2.2 – K-Wave Monitoring: Installation, Calibration, Baseline, and Surveillance	1/2/17	1/31/19
2.3 – Poststudy 3-D Survey Planning, Acquisition, and Processing	6/1/18	6/30/19
Task 3.0 – Data Analysis and Workflow	**12/1/17**	**5/31/20**
3.1 – Seismic Data Analysis and Geologic Model Refinement	12/1/17	10/31/19
3.2 – Predictive Simulations and Comparisons to K-Wave Surveillance	6/1/18	10/31/19
3.3 – Review of Results, Integration Workflow Development, and Report Generation	6/1/19	5/31/20



Deliverables ▼	Key for Milestones (M) ◆
D1 – Project Management Plan (updated)	M1 – Formal Kickoff Meeting Held
D2 – Technology Maturation Plan (updated)	M2 – Prestudy 3-D Survey Planning Initiated
D3 – Data Management Plan (updated)	M3 – K-Wave Surveillance Initiated
D4 – Data Submitted to NETL EDX	M4 – Poststudy 3-D Survey Planning Initiated
	M5 – K-Wave Surveillance Completed
	M6 – Field Data Collection and Processing Completed
	M7 – Seismic Data Analysis Completed
	M8 – Integration Workflow Completed

6.29.17 hmv

Note: Critical path passes through sub-subtasks.

BIBLIOGRAPHY

Note: These publications provide technical background. No publications have originated from the project at this time.

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- Korneev, V., A. Bakulin, and Ziatdinov, S., 2006, Tube-wave monitoring of oil fields. 76th Annual International Meeting, SEG, Expanded Abstracts, 374-378. http://dx.doi.org/10.1190/1.2370279

ACKNOWLEDGMENT

This material is based upon work supported by the U.S. Department of Energy National Energy Technology Laboratory under Award No. DE-FE0028659.

Disclaimer

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THANK YOU!

Critical Challenges. **Practical Solutions.**


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