EERC℠

Critical Challenges. **Practical Solutions.**

Energy & Environmental Research Center (EERC)

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

DE-FE0028659

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Energy & Environmental Research Center

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National Energy Technology Laboratory

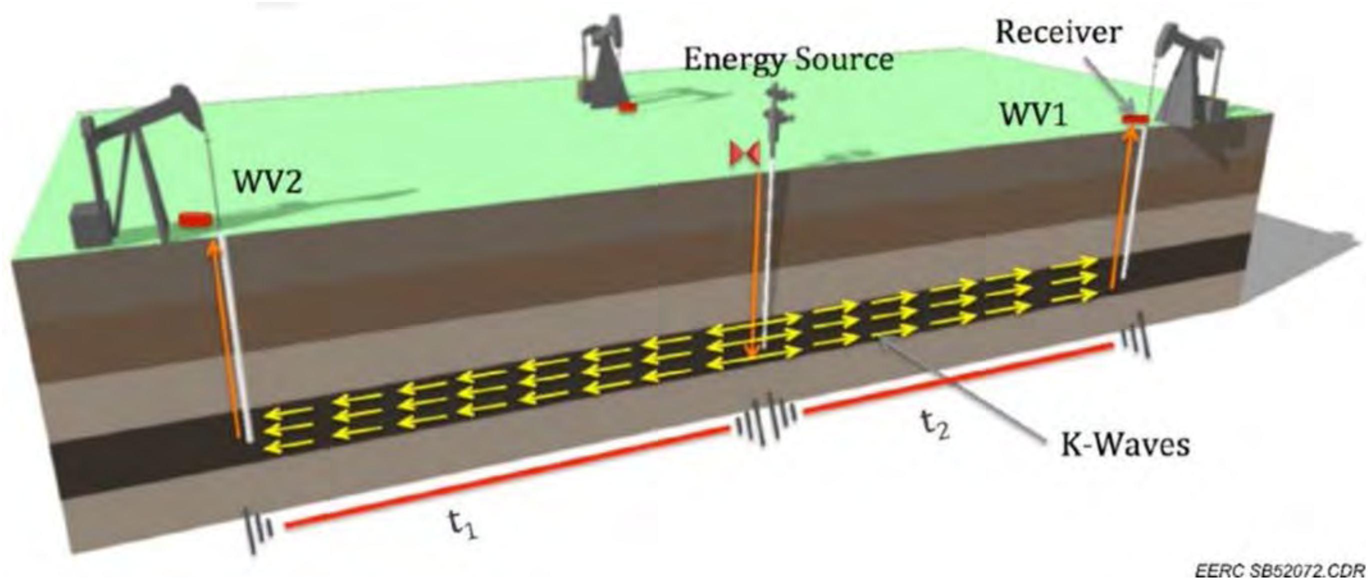
Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 13–16, 2018

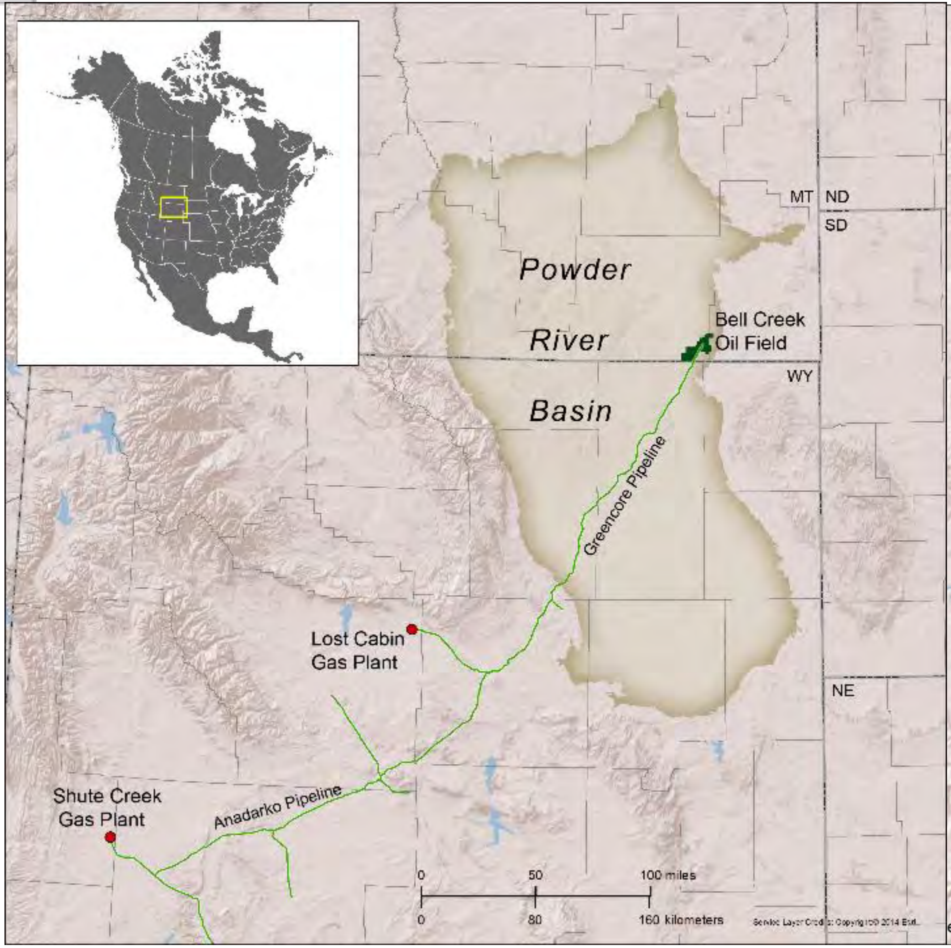
Critical Challenges. Practical Solutions.

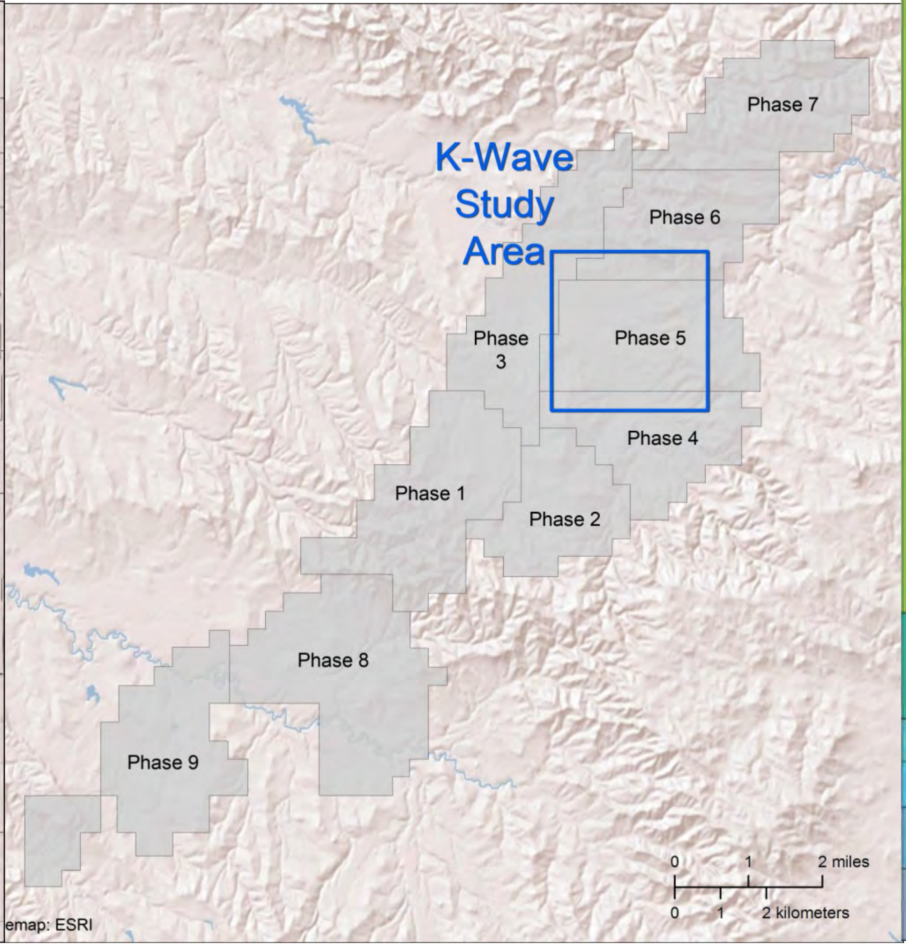
PRESENTATION OUTLINE

- Project Background
  - Study Area
  - Boundary and Guided Waves
  - Guided Wave Monitoring Concept
- Project Plan and Tasks
- Field Hardware Tests
- Accomplishments and Lessons
- Synergy and Summary

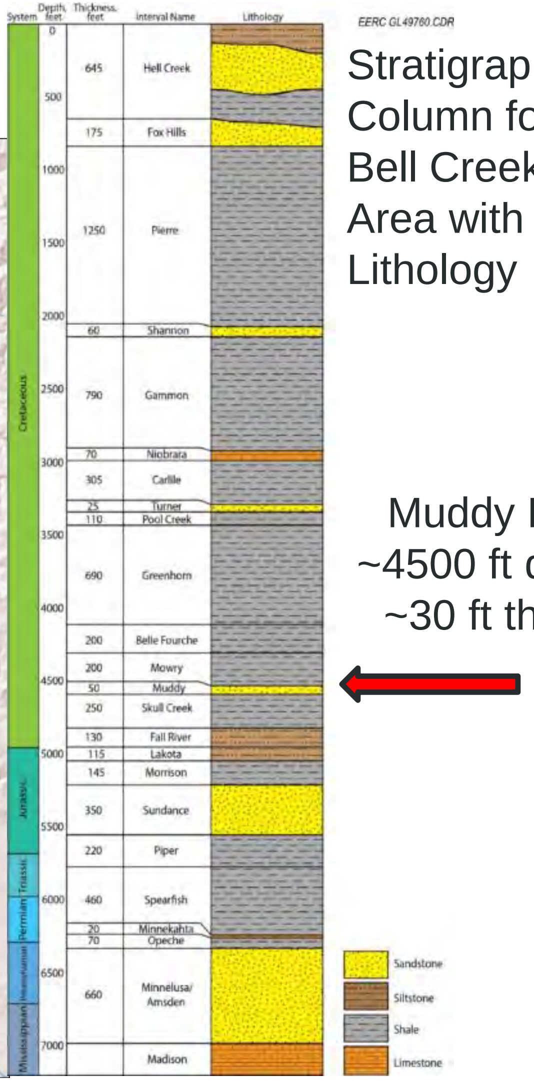


STUDY AREA AND TARGET





Bell Creek Oil Field

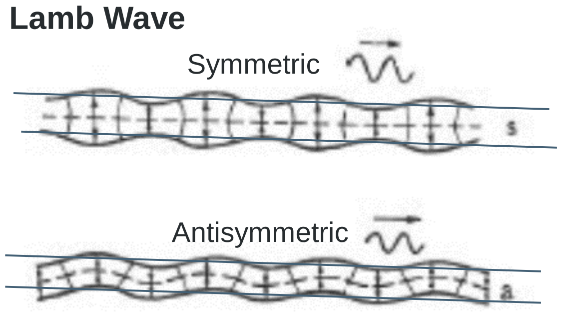


Stratigraphic Column for the Bell Creek Area with Lithology

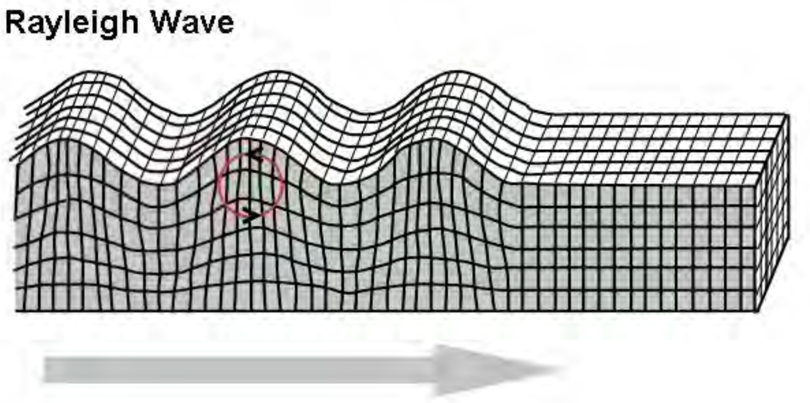
Muddy Fm
~4500 ft deep
~30 ft thick

BOUNDARY AND GUIDED WAVES

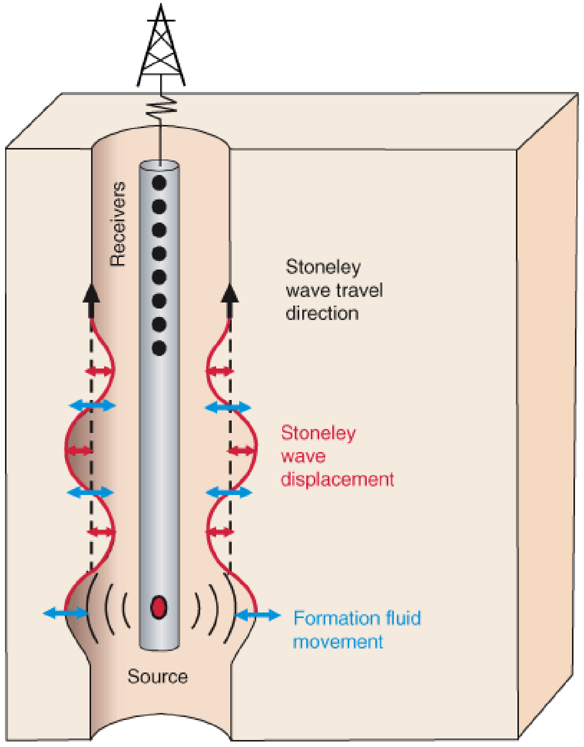
- Rayleigh wave
  - Surface wave.
- Lamb wave
  - Rayleigh wave guided in a layer.
- Stoneley wave
  - Boundary wave guided along a solid–solid interface.
  - Has a large amplitude.
  - Leaky Rayleigh wave.
- Scholte–Stoneley wave
  - Boundary wave guided along a liquid–solid interface.
  - Tube wave is an example.



Muravin.com



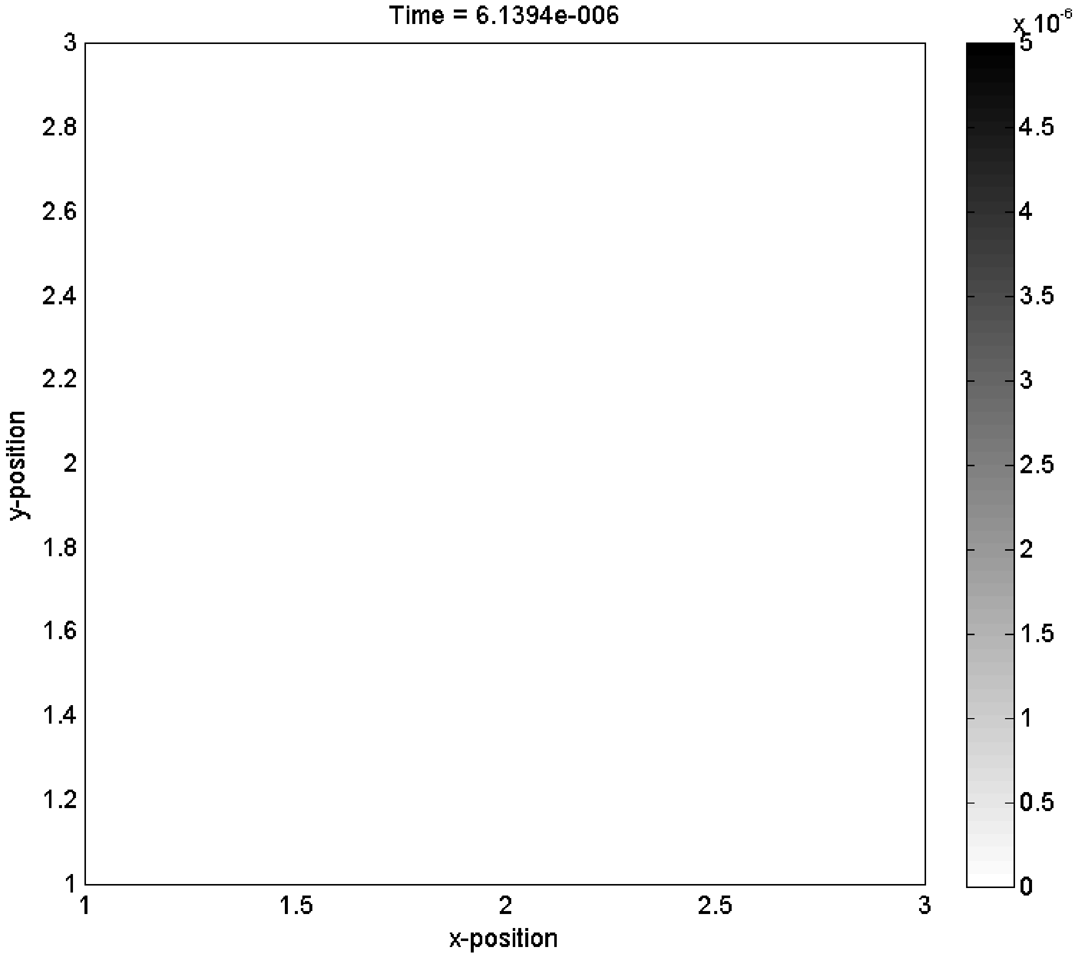
http://www.geo.mtu.edu/UPSeis/rayleigh_web.jpg



Wikipedia.org

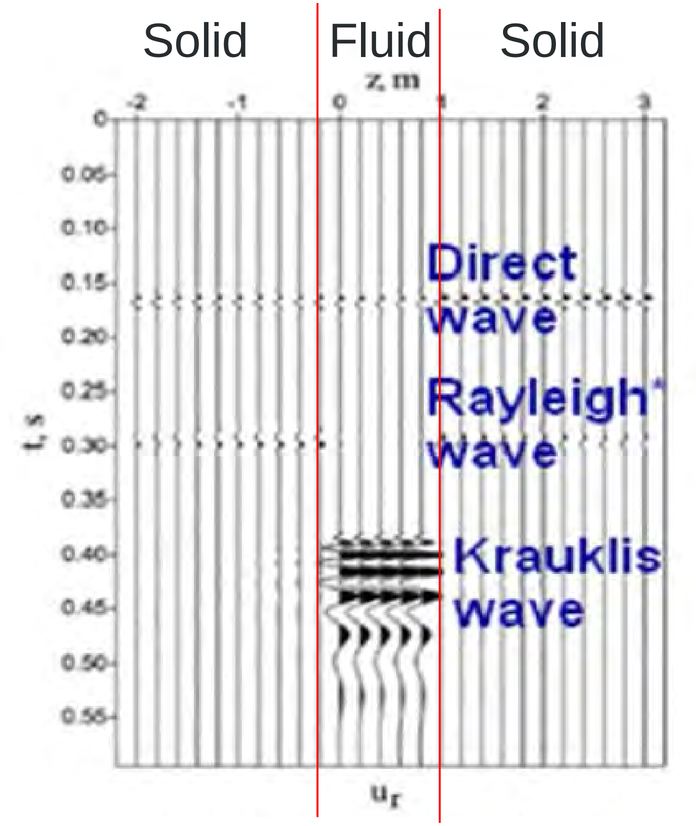
Note:
- Rayleigh wave propagates at a vacuum–solid interface.
- Stoneley wave propagates at a solid–solid interface.
- Scholte wave propagates at a liquid–solid interface.

KRAUKLIS WAVE CHARACTERISTICS



K-Waves in Two Intersecting Fractures

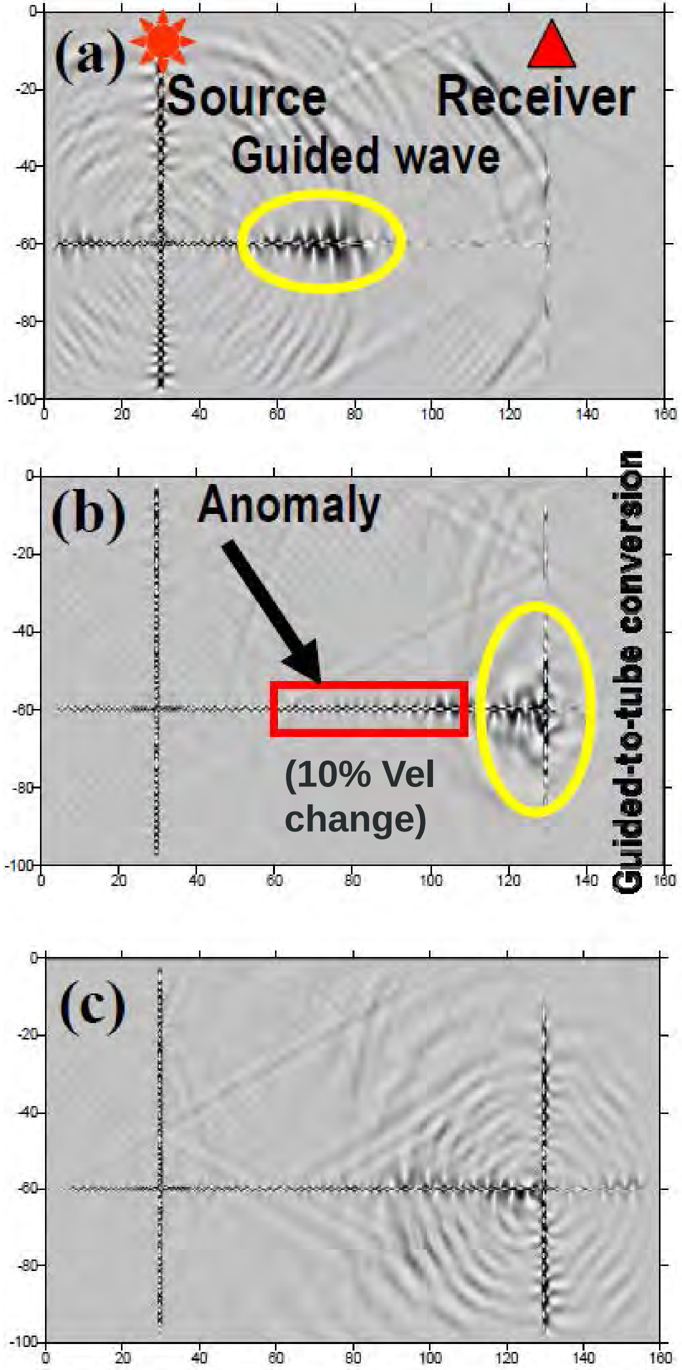
https://www1.ethz.ch/rockphysics/research/krauklis



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

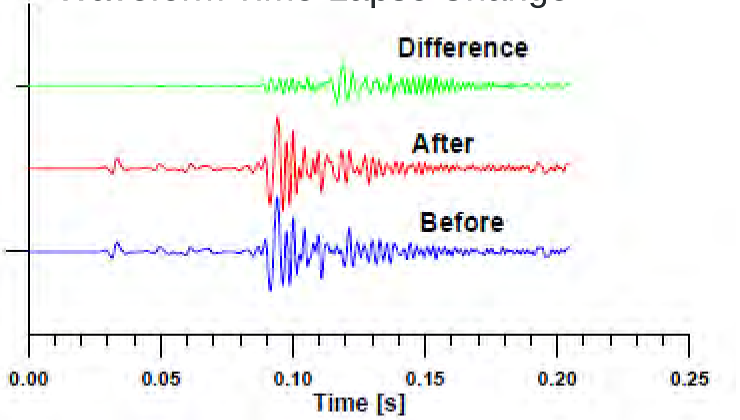
APPLIED GUIDED WAVE MONITORING CONCEPT

- Wellhead-mounted sources and receivers.
- Tube waves induce guided waves in the reservoir, which are recorded at nearby receiver wells.
- Preinjection baseline survey and postinjection monitoring surveys track waveform changes and timing changes due to CO_2 in the reservoir.
- Source on injectors, receivers on producers track CO_2 progress until breakthrough.

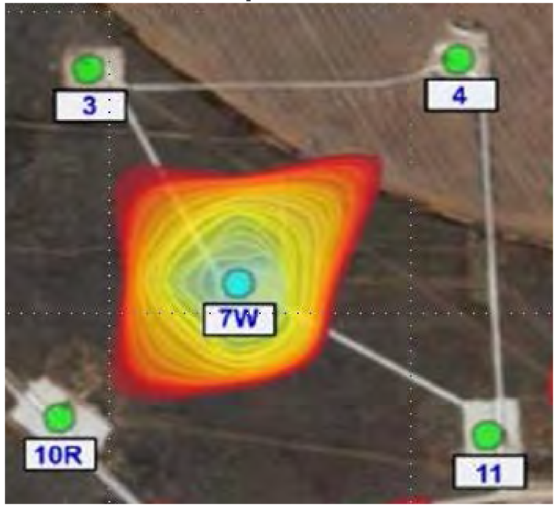


Korneev, V., A. Bakulin, and Ziatdinov, S., 2006, Tube-wave monitoring of oil fields. 76th Annual International Meeting, SEG, Expanded Abstracts, 374-378. http://dx.doi.org/10.1190/1.2370279

Waveform Time-Lapse Change



Five-Spot Pattern



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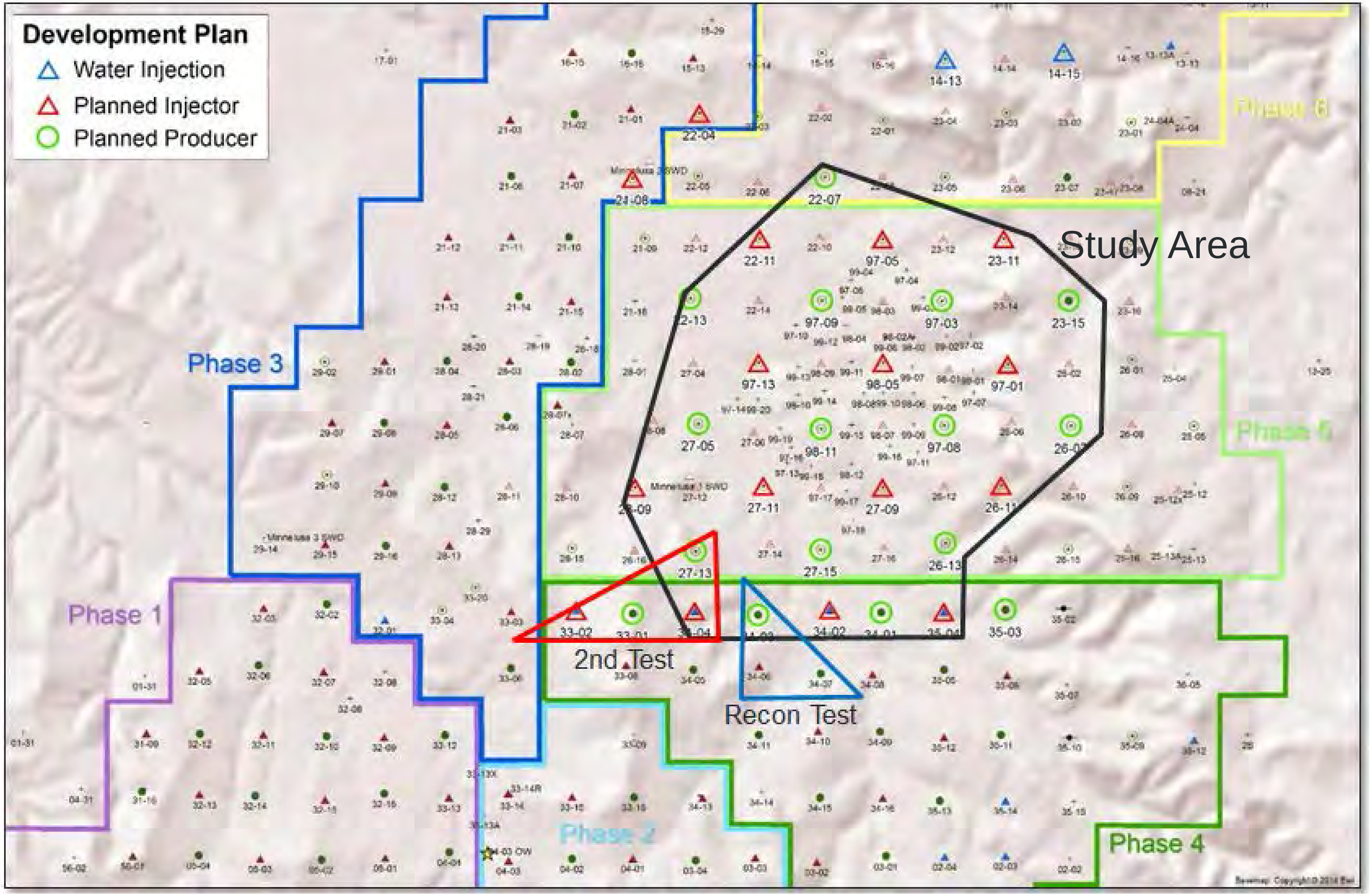
STUDY AREA

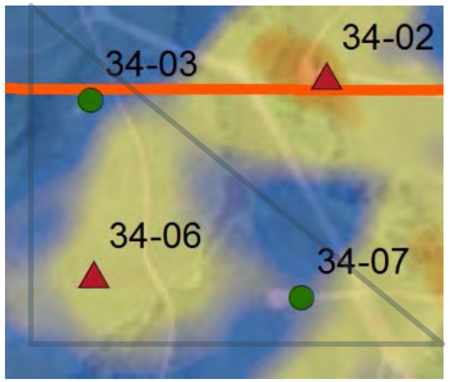
- Project plan
  - New injection area
  - Instrument up to 30 wells with surface sensors
    - Acquire baseline survey
    - Acquire three or more monitoring surveys
  - Acquire two small 3-D surface seismic surveys
    - Before injection (fall 2017)
    - After monitoring (late 2018)
  - Analyze and report

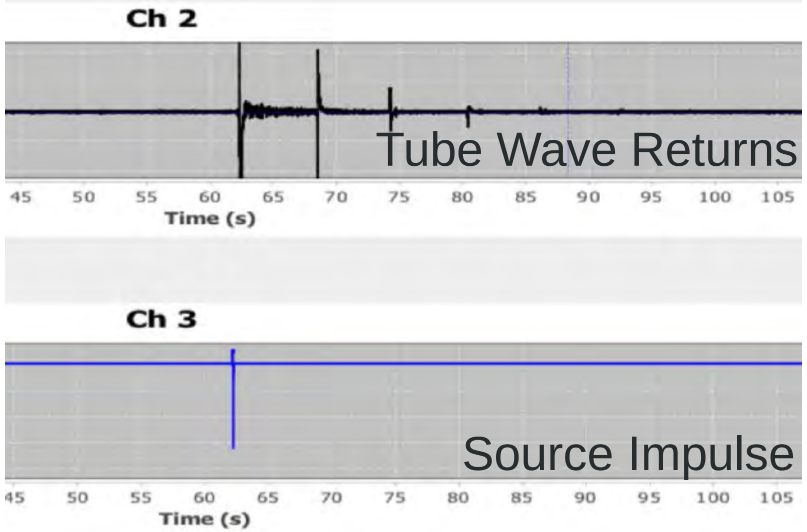


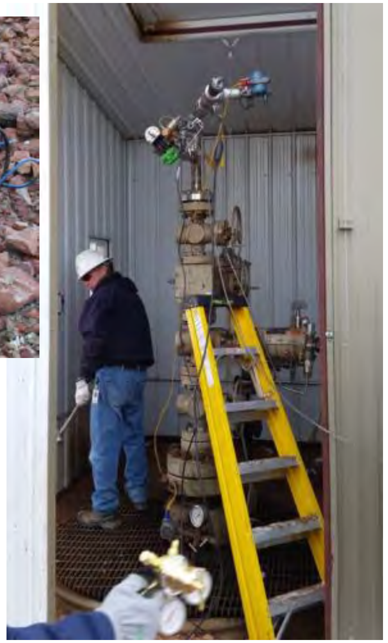
Critical Challenges. Practical Solutions.

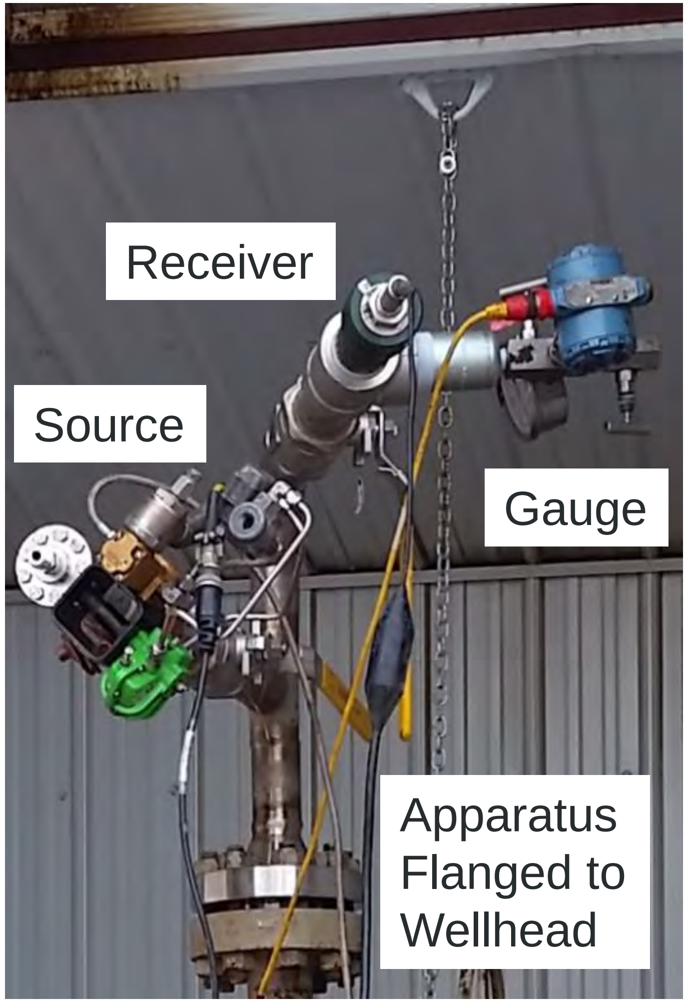
FIRST BELL CREEK TEST – FIRST-GENERATION SOURCE

- December 2016 – three-well test.
- Recon, learn wellhead connections.
- First-generation source.
- Result: No returns seen on neighboring wells.
  – Weak source
  – Gas interference in 34-07







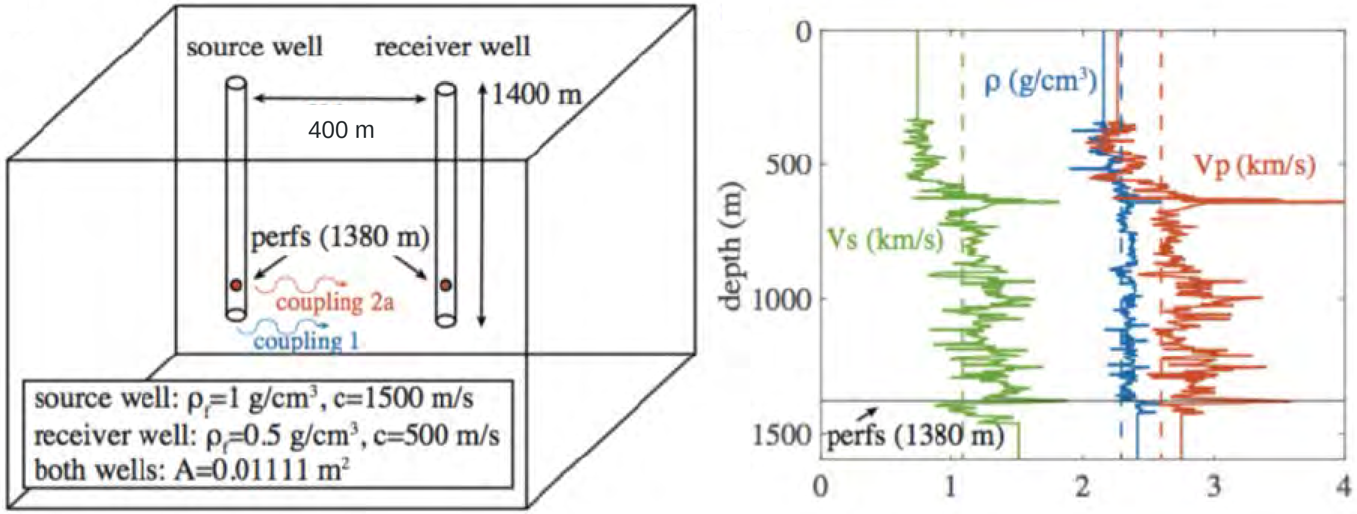


1400 psi
100-ms release

MODELING – SPRING AND SUMMER 2017

- Eric Dunham and Jerry Harris at Stanford University for Seismos
- Objective – numerical simulations to quantify signal amplitudes for conditions relevant to Bell Creek
  - Determine numerical solution(s) to the equations that control conversion from tube waves to seismic waves
  - Code the solution, and include material properties relevant to Bell Creek
  - Quantify the signal amplitudes

Two types of coupling were examined:
1) Through the well bottom
2) Through the perforations

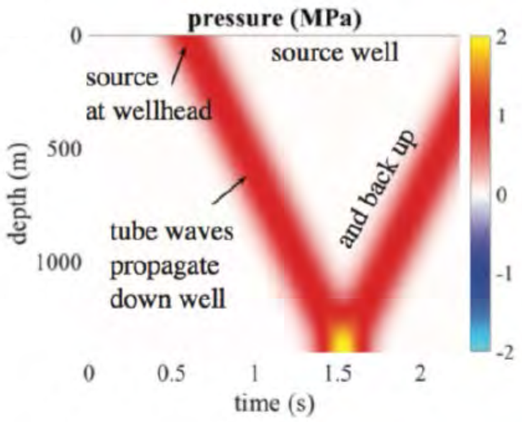


Source: Seismos Modeling Report

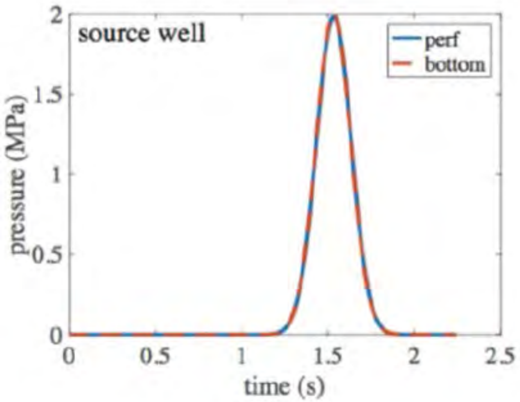
MODELING AMPLITUDE RESULT

Source Well

Space-time plot: tube wave pressure amplitude (MPa, megapascals) in source well propagating down, reflecting, and back up.

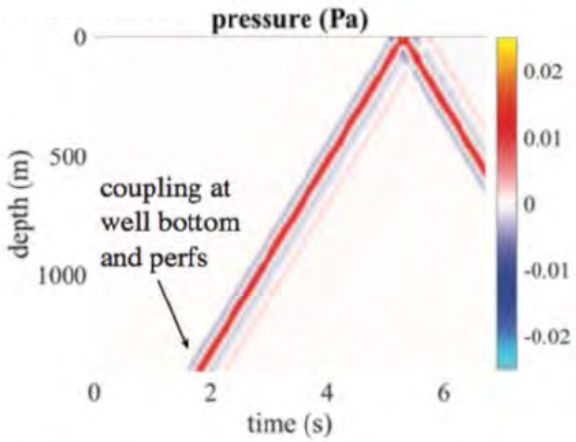


Maximum pressure amplitude at the bottom reflection near the perforations is **2 MPa** (~290 psi).

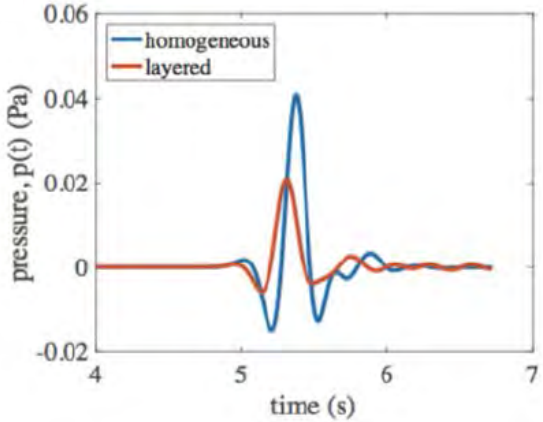


Receiver Well

Space-time plot: coupling pressure amplitude at a well 400-m offset (Pa, pascals) …up, reflecting at the receiver, and back down.



Maximum amplitude at the offset well in the layered model at the receiver is **0.02 Pa** (~2.9 x 10^{-6} psi).



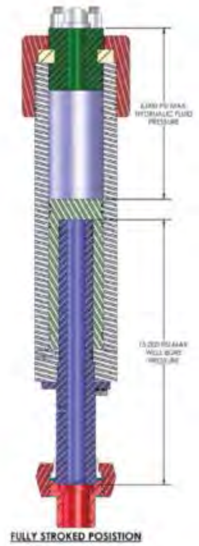
Source: Seismos Modeling Report

10^{-8} attenuation
No guided waves seen, only P & S

NEW SOURCE AND RECEIVERS – SUMMER 2017

Previous Sensor Design

New Sensor Design

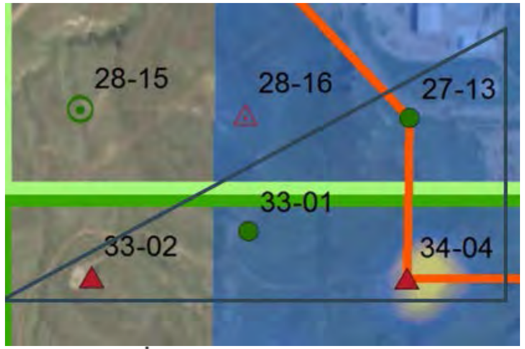


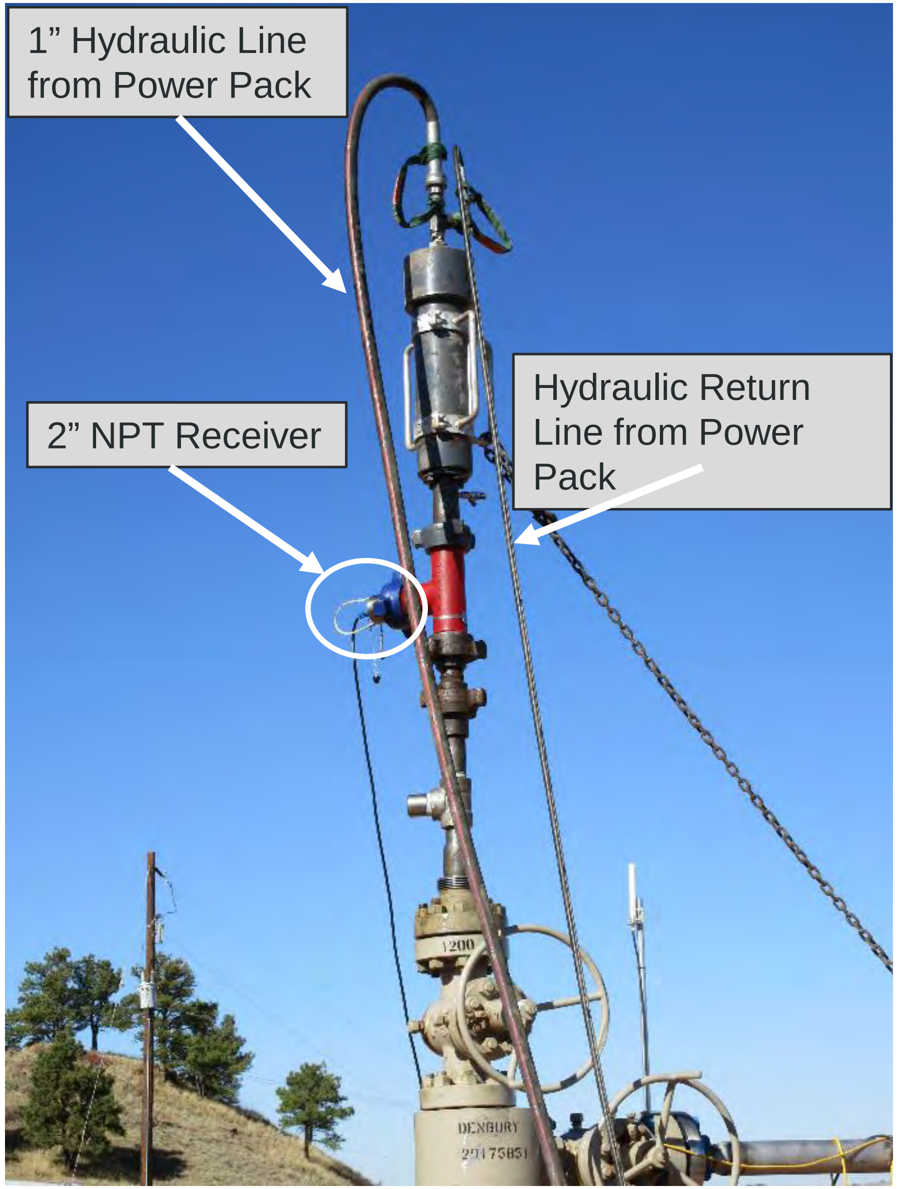
Powerful “Displacement” Source

FIELD TEST – SECOND-GENERATION SOURCE

- Second field test – Fall 2017.
- New "displacement" source.
- Data were analyzed and interpreted.
- Result:
  - No returns were recorded between producers.
  - No returns were recorded between injectors and producers.
  - An anomalous signal was recorded between the two injectors with a long transit time; the path was not resolved.
  - 34-04 CO_2 injection May 2017. 33-01 brekthrough by October.

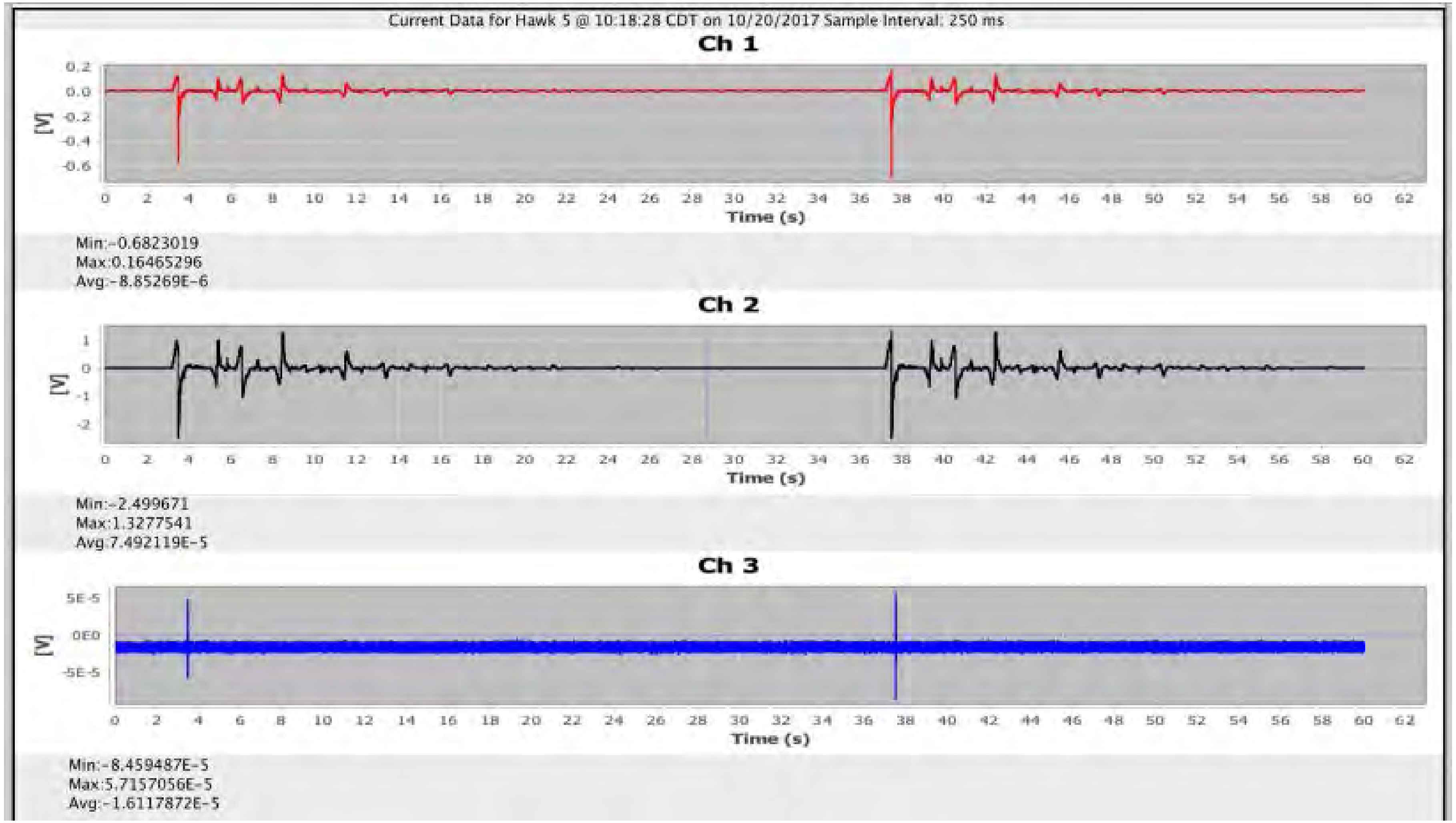
Four Wells





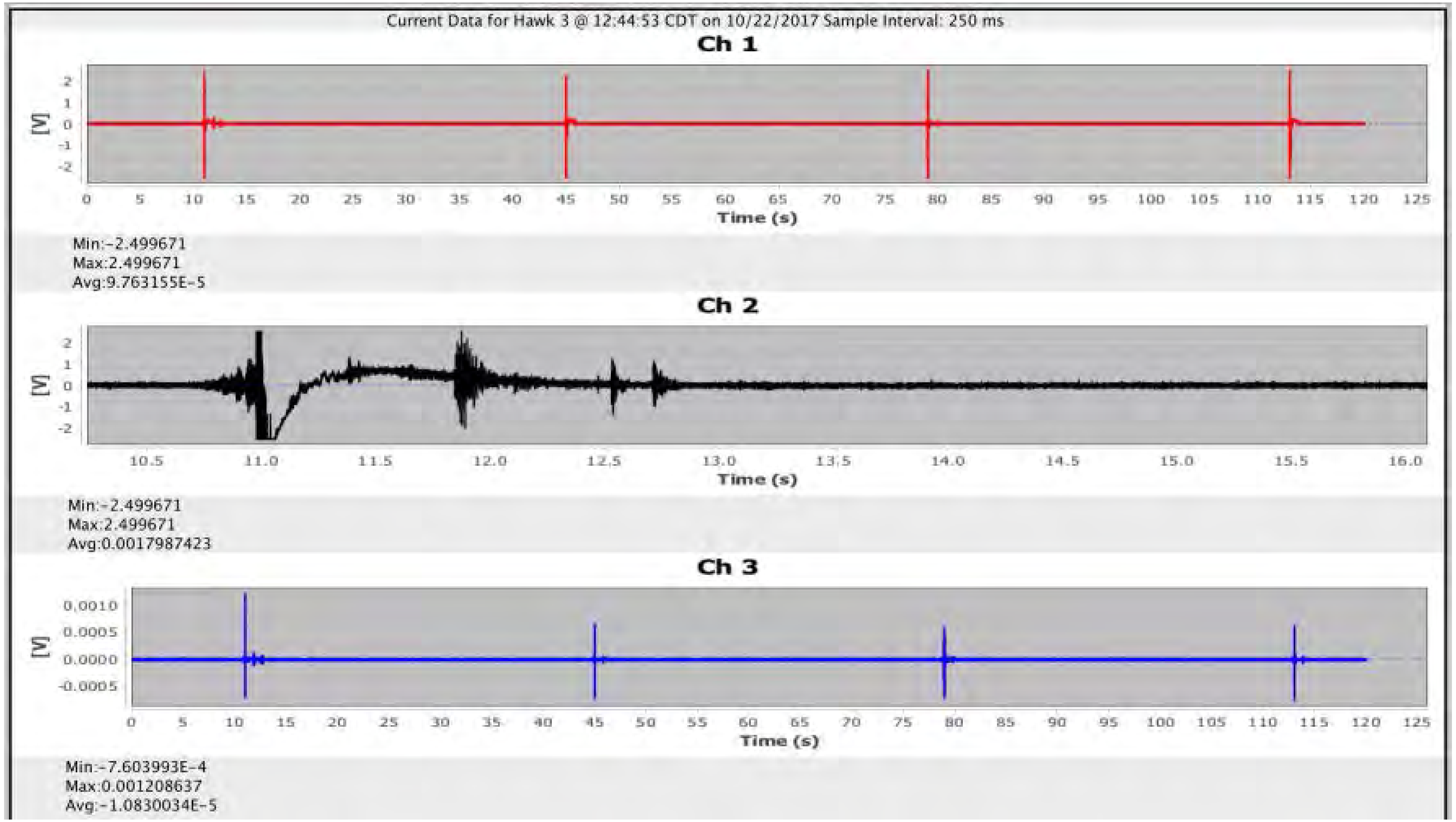
FIELD DATA – PRODUCER 27-13

- Ch. 1 and Ch. 2 show tube wave returns displayed with different gains.
- Ch. 3 is the source impulse.
- Note that tube wave return is 2 seconds, and then a complex echo exists. Returns have alternating opposite polarity and attenuate to the noise level after five or six reflections.

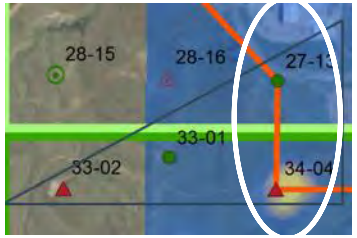


FIELD DATA – PRODUCER 33-01 (CO_2 BREAKTHROUGH)

- Ch. 1 and Ch. 2 show tube wave returns displayed with different gains and different scales.
- The expected tube wave return at 2 seconds is missing. A complex echo or source effect exists. There may be gas coming out of solution (pressure ~500 psi) as early signs of breakthrough were noted at this well.



ANALYSIS: 34-04 (SRC) AND 27-13 (REC)

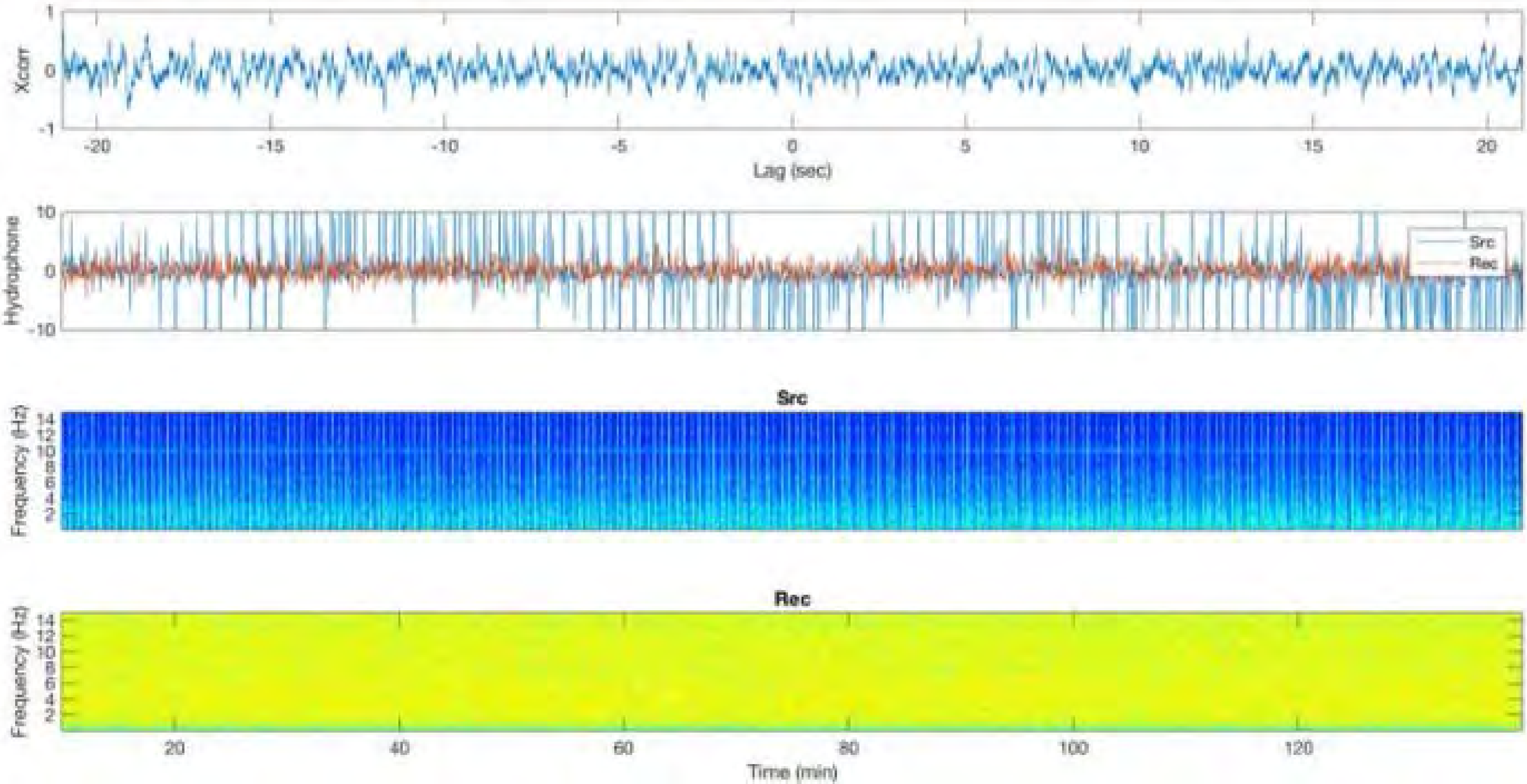


Cross-Correlation

Source and Receiver

Source Spectra

Receiver Spectra

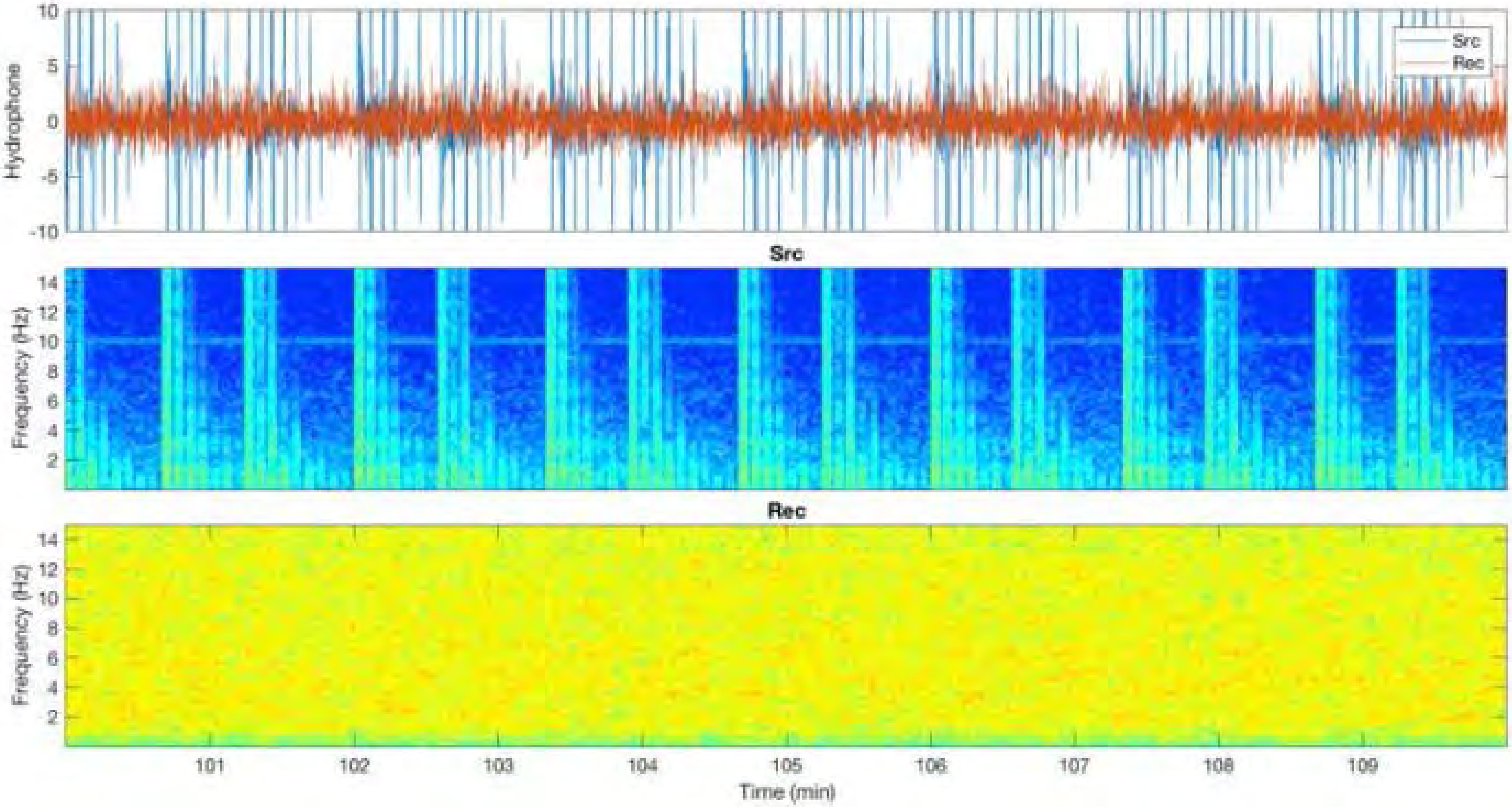


ANALYSIS: 34-04 (SRC) AND 27-13 (REC) – ZOOMED

Source and Receiver

Source Spectra

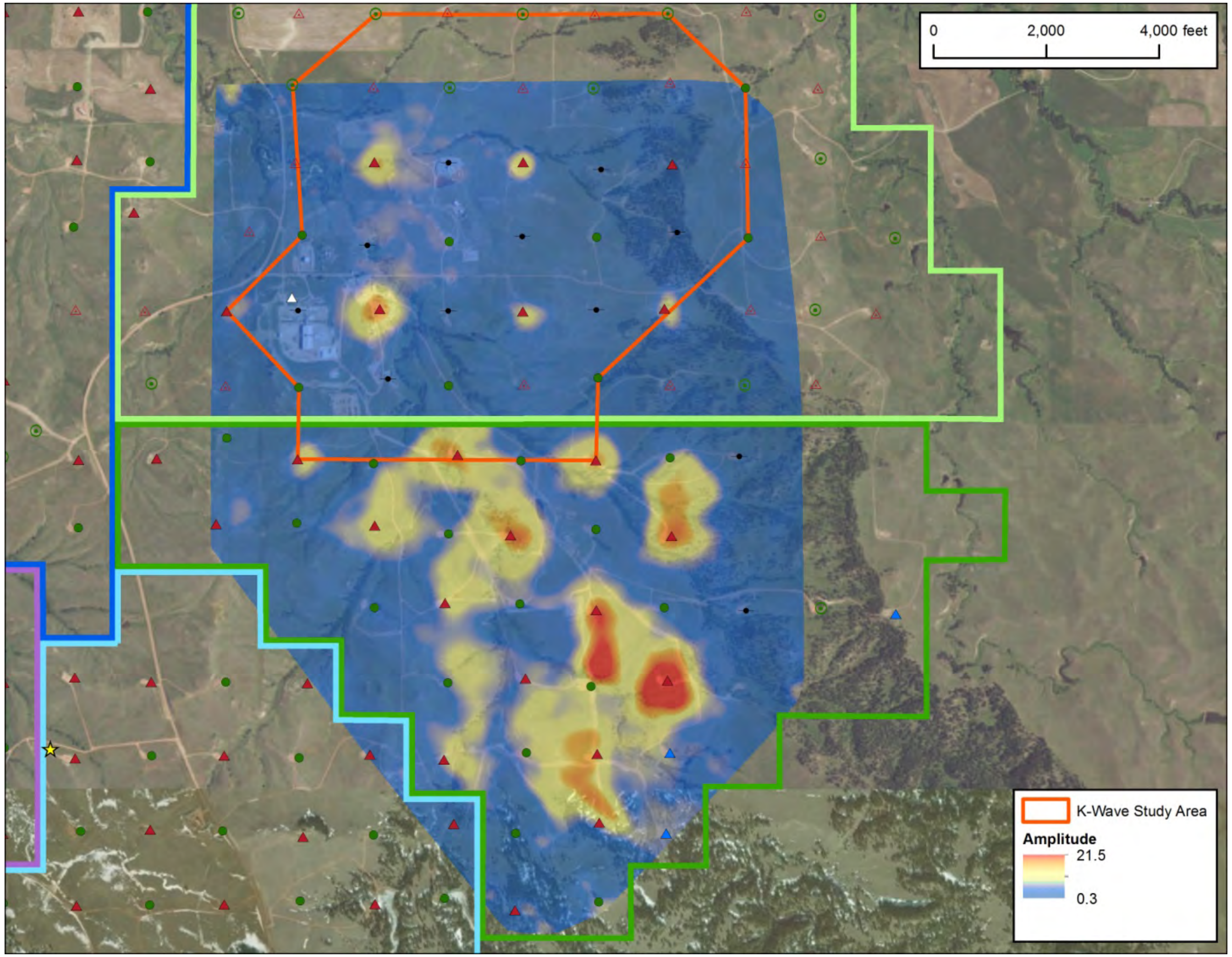
Receiver Spectra



No source energy visible on the receiver.

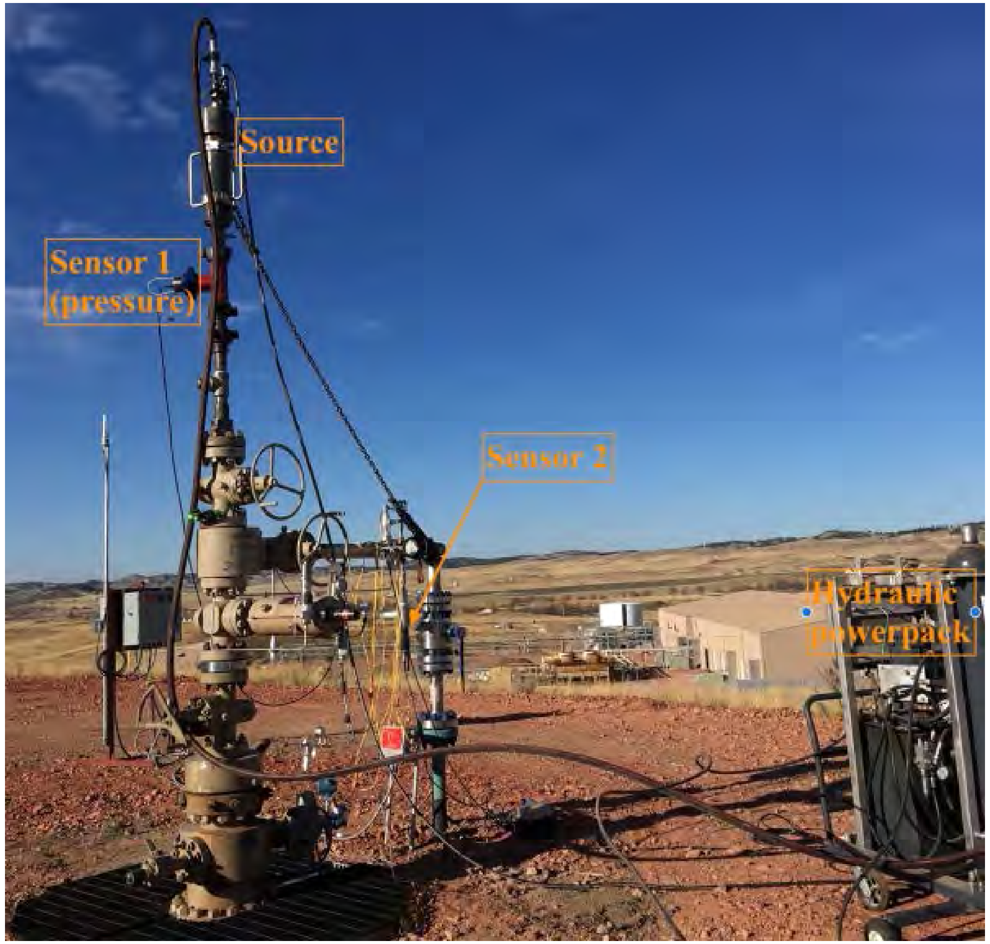
PREINJECTION 3-D SURVEY/4-D DIFFERENCE DISPLAY

- 3-D survey: long lead due to planning, permitting, and procurement.
- Active planning in spring and summer 2017.
- Risk-based decision to include more of Phase 4 to the south in case the study area needed to be moved to an area with closer well spacing. Denbury supplemented part of the additional cost.
- Survey was completed in late October 2017.



ACCOMPLISHMENTS TO DATE

- The initial field test was completed. Data were analyzed and interpreted.
- Modeling and numerical solutions were completed.
  - Three modes of energy coupling were identified.
  - Signal amplitudes for the modes were computed.
  - Solutions to achieve a successful result were defined (but unlikely with current equipment).
- A next-generation source and new receivers were designed, built, and tested in the field.
- Data from the second field test were analyzed and interpreted.
- A 3-D seismic baseline data set was acquired and processed.

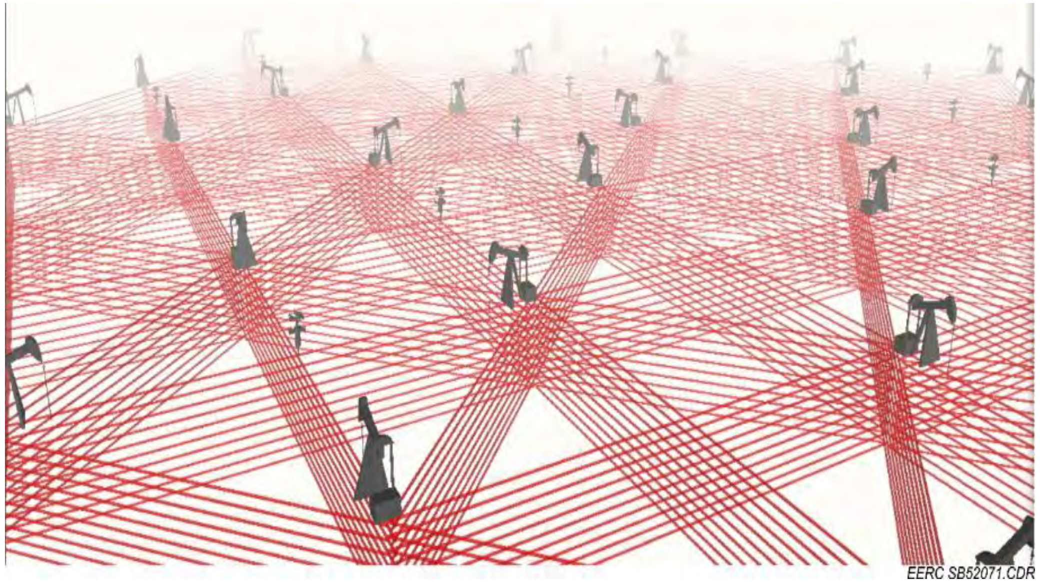


LESSONS LEARNED

- From the modeling:
  - ♦ Attenuation for Bell Creek reservoir characteristics, depth, and 400-m well spacing is on the order of 10^{-8}, largely due to the inefficient conversion of tube wave to seismic wave coupling at low frequencies. Coupling is more efficient at higher frequencies.
  - ♦ Wave guide effects are more likely for wavelengths comparable to the reservoir thickness. Reservoir thickness at Bell Creek is ~10 m, so source frequencies of 100 Hz or greater would be required. Current source has negligible energy above ~15 Hz.
  - ♦ A waveguide for low frequencies requires a velocity inversion, or lower velocity layer enclosed within higher velocity layers. The Bell Creek reservoir is a fast layer.
- From the field testing:
  - ♦ Velocity of H_2O under pressure is ~1500 m/s as expected; CO_2 under pressure is ~600 m/s.
  - ♦ Tube waves generated by the source fail to propagate or do so inconsistently on producing wells after breakthrough, apparently due to gas coming out of solution. Receivers should be mounted someplace other than the highest point on the wellhead.
  - ♦ Viton o-rings do not perform well in high-pressure CO_2/H_2S environments. A wellhead receiver was also damaged by the environment during the second field test.

SYNERGY OPPORTUNITIES

- Geologic and simulation models used for the SASSA project (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 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 deployed and field-tested a prototype MVA (monitoring, verification, and accounting) technology in an operational carbon capture, utilization, and storage (CCUS) field environment.
- The technology employed a new subsurface signal, guided waves, in a novel approach to MVA.
  - As the reservoir was not known to be fractured, K-waves would not be a factor at Bell Creek.
- Field tests of two generations of equipment were completed, but guided wave signals were not identified on nearby wells.
  - A third-generation source is delayed indefinitely because of technical matters.
- A baseline surface 3-D survey planned as part of the monitoring baseline effort was completed.
- Numerical modeling solutions revealed difficult technical challenges…
  1) There is a high degree of signal attenuation on the order of 10^{-8} for a 400-m well spacing.
  2) A source capable of producing frequencies of 100 Hz or more was necessary to produce guided waves in reservoirs with layer dimensions similar to Bell Creek. (Current source has negligible power above 10 to 20 Hz.)
- Lessons learned and a complete summarization of knowledge gained to date are being prepared.
- Currently working with federal project manager on steps to move forward.

ACKNOWLEDGMENT

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Disclaimer

CONTACT INFORMATION

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THANK YOU!

Critical Challenges. **Practical Solutions.**

APPENDIX

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 TRL4 to TRL7.
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

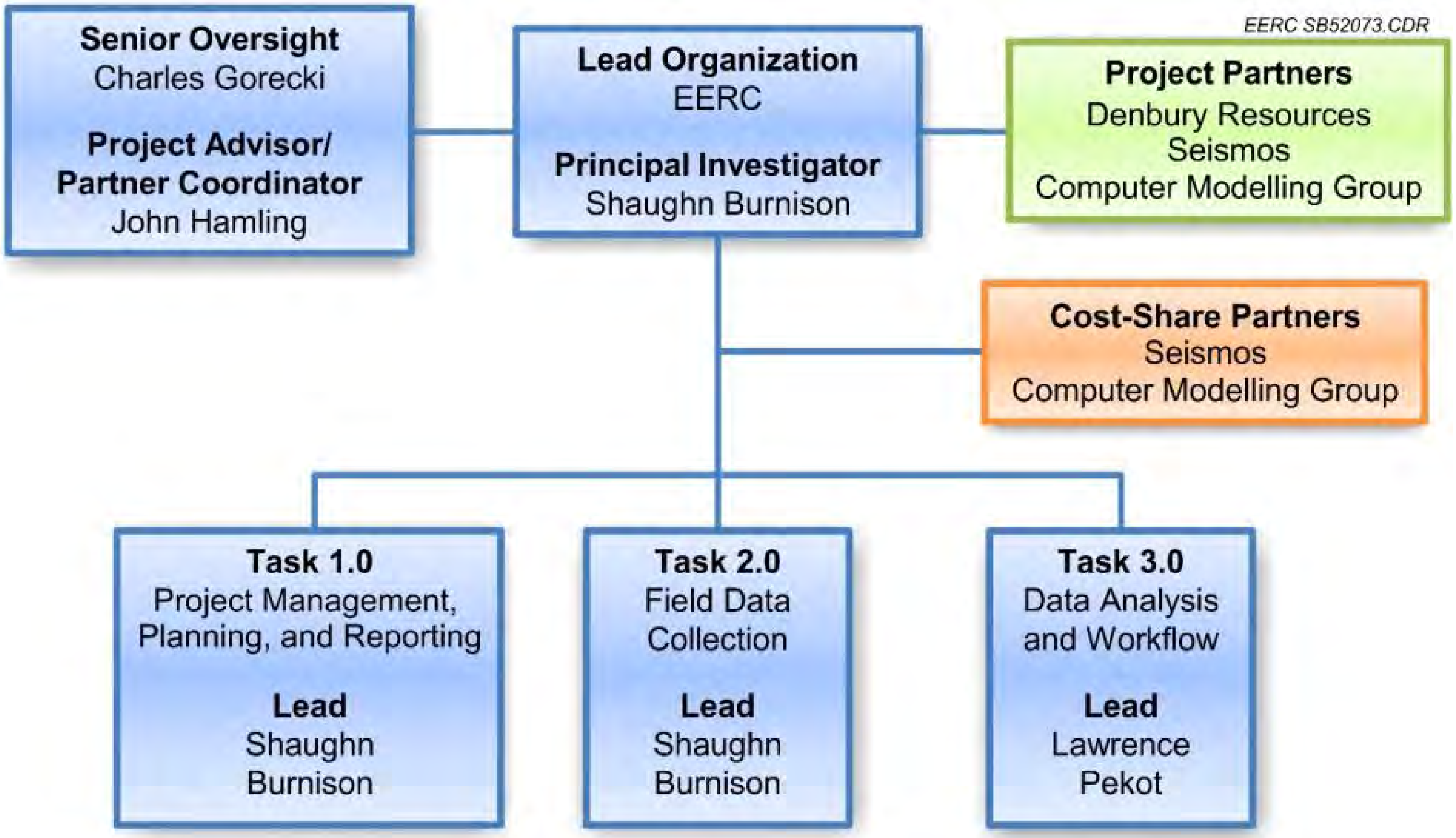
The project will address Area of Interest 1, “Field Demonstration of MVA Technologies,” by deploying and validating a prototype carbon storage monitoring, verification, and accounting (MVA) technology in an operational field environment. The method employs a new subsurface signal, the K-wave, to monitor 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

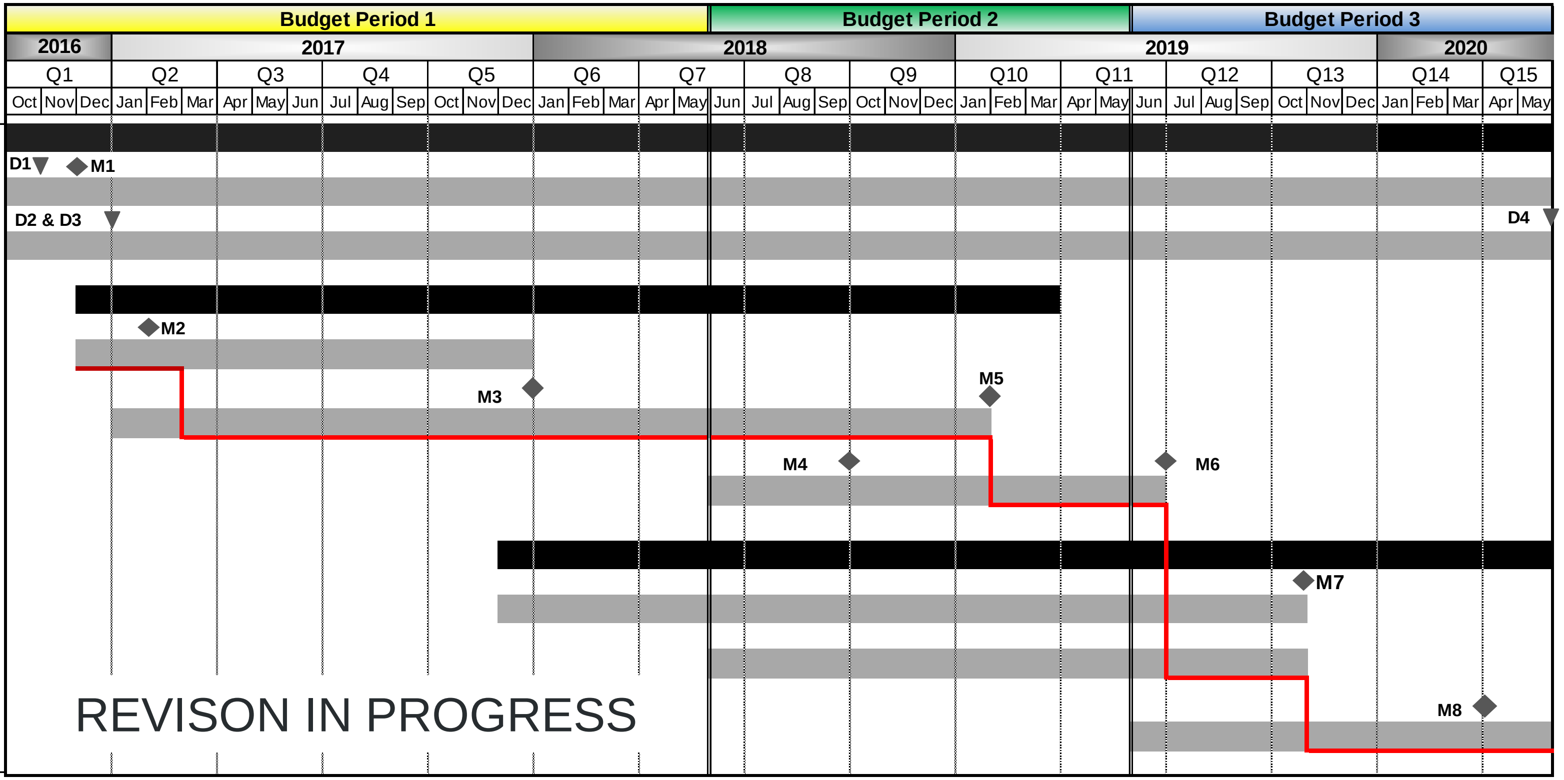
- Objectives: Deploy to demonstrate, validate, and evaluate a new method of monitoring the morphology and extent of subsurface CO_2 injection plumes from the surface in a manner that has low impact, is noninvasive, and is nondisruptive to normal operations.
  - The method leverages a new way of transmitting 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 TRL4 (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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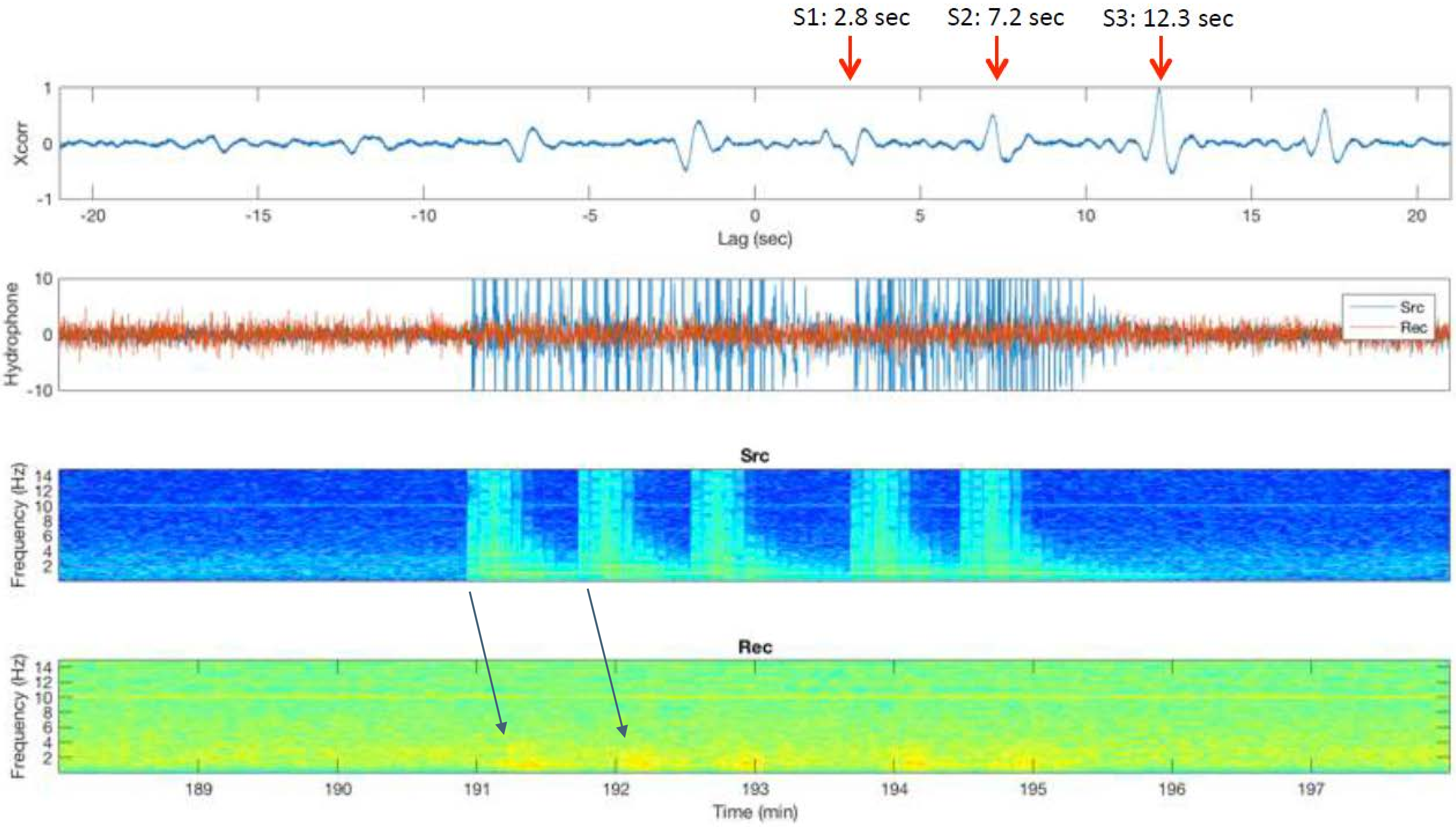
DISCUSSION

ANOMALY BETWEEN INJECTORS 1/2

Correlation indicates a 12.3 sec lag between source and receiver signal.

Much too long for reservoir communication or along CO_2 pipelines.

Path unresolved.



ANOMALY BETWEEN INJECTORS 2/2

Pipeline Info

Distances between wells

From	To	Distance (feet)	Distance (miles)
33-02	33-01	1293.63	0.245
33-02	34-04	2506.68	0.475
33-02	27-13	2819.49	0.534
34-04	33-01	1318.65	0.250
34-04	27-13	1273.80	0.241
27-13	33-01	1564.27	0.296

Distance from Phase 4 manifold to respective well

33-02 (B)		9721.31	1.841
34-04 (C)		6951.64	1.317
33-01 (A)		8472.58	1.605

Two possible wave paths

Wells B -> C: Tube wave – Formation guided wave – Tube wave

0.3048*(4475/1500+2500/2300+4408/1500) -> 2.14 sec

Wells B -> C: Pipelines

0.3048*(9721/1500 + 6952/1500) -> 3.4 sec