# Autonomous Monitoring of Wellbore Integrity Applying Time-Reverse Nonlinear-Elastic Wave Spectroscopy and Fiber Optic Sensing and Communication

Project Number (FWP-FE-853-17-FY17)

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Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting

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TRIAD Property

# Outline

- Collaborators and Background
- Approach
- Impact
- Technical status
- Accomplishments to date
- Lessons learned
- Synergy opportunities
- Project summary

# Collaborators and Background

## Team

Los Alamos National Lab (project lead)

- **C. Donahue (Co-Pi), P. Johnson (Co-PI),** M. Remillieux, B. Carey, E. Dauson, L. Beardslee
- Acoustics (nonlinearity, time reversal, signals from noise); machine learning; wellbore integrity; lab-scale experiments; project integration

Lawrence Berkeley National Lab

- **K. Nihei**, S. Nakagawa
- Acoustics; fiber optics

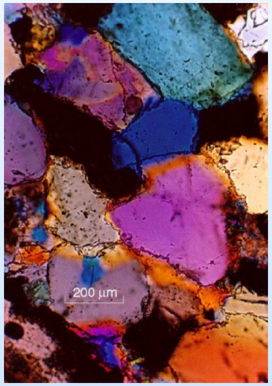
Clemson University

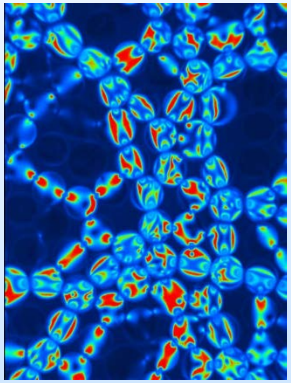
- **L. Murdoch**, L. Hua, H. Xiao, S. DeWolf
- Fiber optics, geomechanics, acoustics

Chevron, ETC

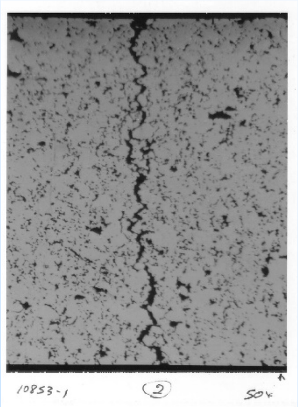
- **H. Goodman**
- Field application needs

Distributed “damage”



“Localized damage”



## Background to Approach

Our previous work has demonstrated:

- Nonlinear acoustical methods probe mechanical damage in complex earth materials;
- Acoustic time-reversal methods used to focus energy (including within earth materials);
- Machine-learning algorithms can extract small seismo-acoustic signatures from noisy backgrounds;
- Fiber optic sensors can be used to monitor strain at high resolution;
- Microwave photonics can measure distributed strain with optical fiber using non-proprietary methods.

# Project Overview

## Goals and Objectives

**Goals and Objective**: **Development of an autonomous system that can be deployed in wells for unattended long-term (e.g., decades) to monitor both wellbore integrity and stress changes near wellbore**

- Need: affordable, robust, autonomous system for monitoring wellbore integrity, especially post closure
- Need: detect leakage signatures for long term $CO_2$ monitoring

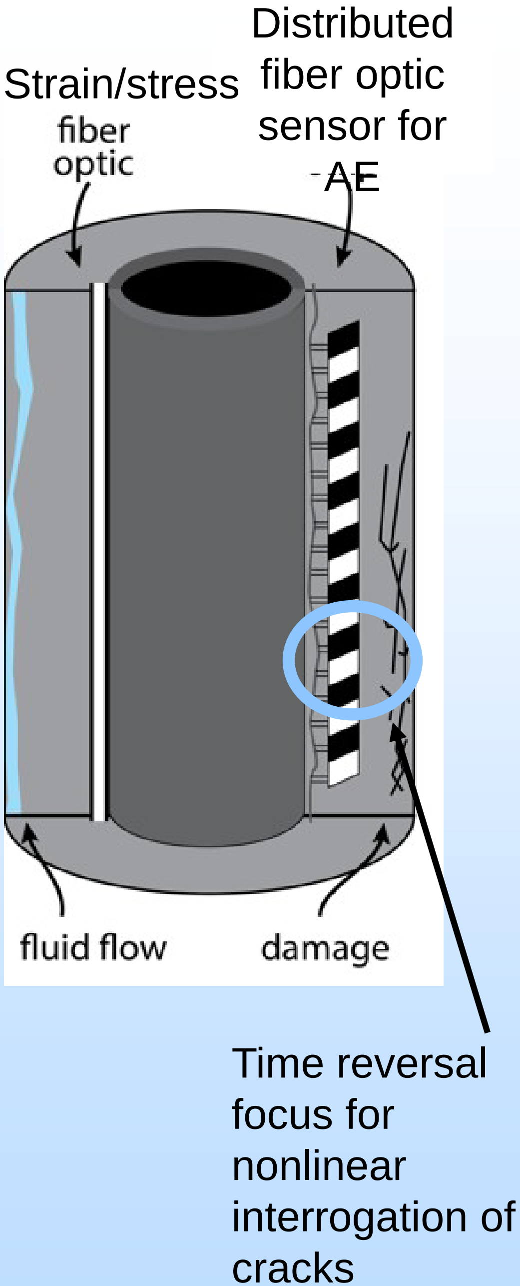
**Innovation**: Combination of:

(i) Fiber optic sensing to track near-borehole anomalous stress evolution associated with damage and to detect acoustic signals

(ii) Supervised machine learning to extract passive seismo-acoustic signals for long term monitoring of associated with leakage;

(iii) Active acoustics using embedded sensors and Time Reverse Nonlinear Elastic Wave Spectroscopy (TR-NEWS) to probe for localized damage

# Approach

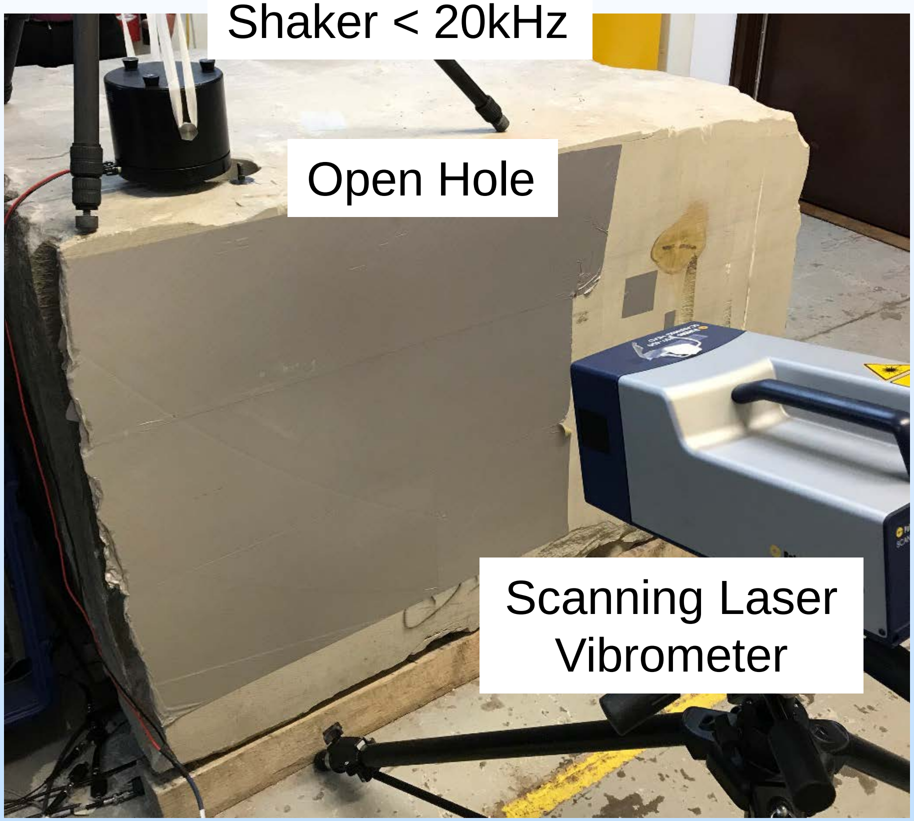


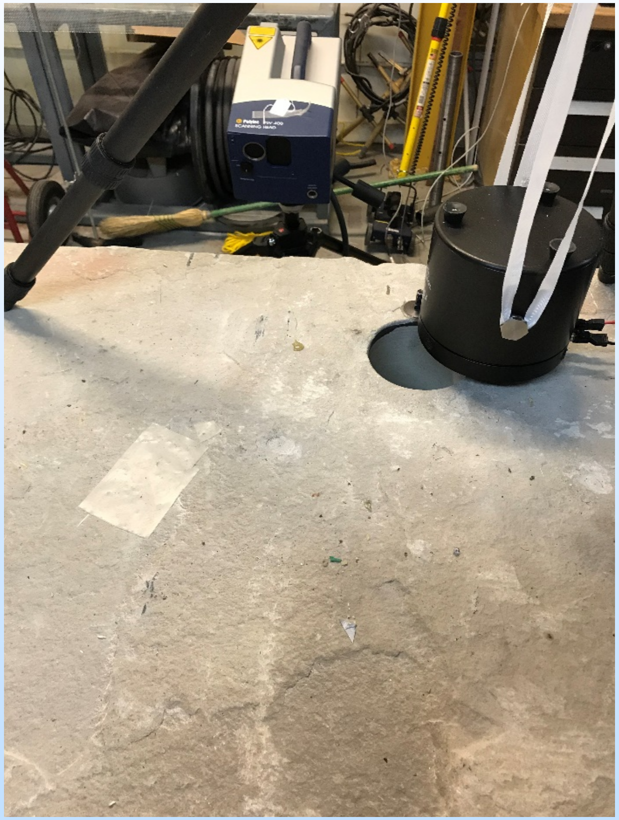

A. Listen for leakage in near-wellbore region using passive acoustic methods (specific objective 1; task 3)
   i. Identify/discover signatures
   ii. Evaluate ability of embedded acoustic sensors to detect signature(s)
   iii. Develop machine-learning algorithms to extract signature(s) autonomously, including the extraction of signal from noise

B. Interogate and locate damage regions with *time-reversal nonlinear elastic wave spectroscopy* (TR-NEWS)
   i. Demonstrate the ability to focus acoustic energy at specific points along a wellbore using time reversal (specific objective 2; task 4)
   ii. Identify/discover nonlinear elastic signatures associated with damage zones and leakage pathways (specific objective 3; task 5)

C. Monitor strain/stress evolution in near-wellbore region using fiber optic sensing
   i. Demonstrate the ability of an embedded fiber optic cable to detect strain tied to loss of integrity in the near-wellbore region (specific objective 4; task 6)
   ii. Evaluate the feasibility of measuring distributed strain and acoustic spectra using non-proprietary fiber optic techniques

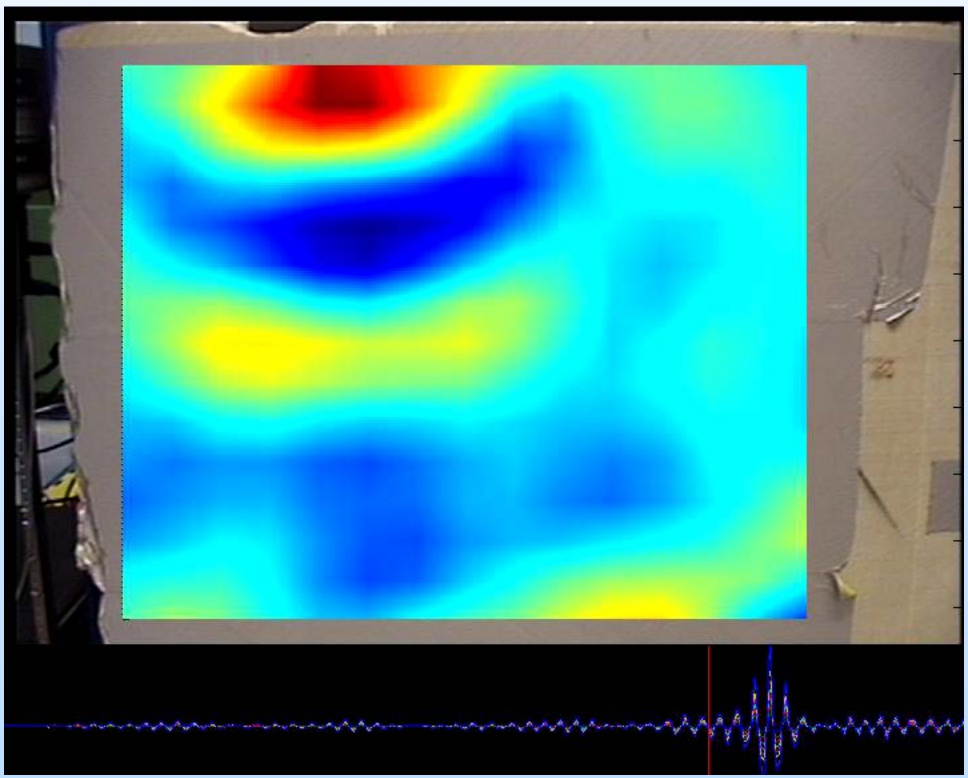
# TR Focusing in open wellbore

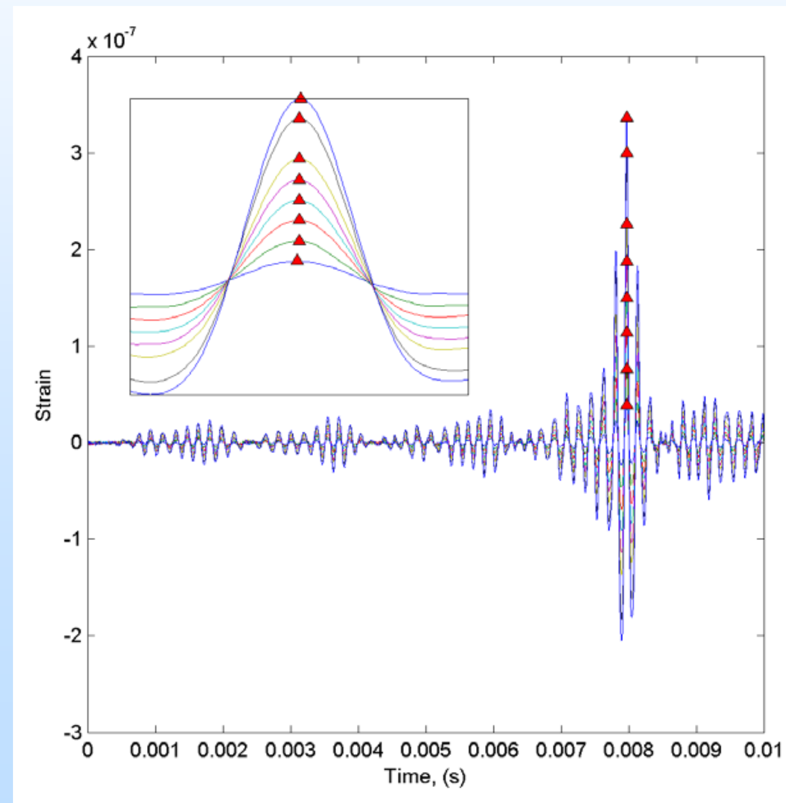


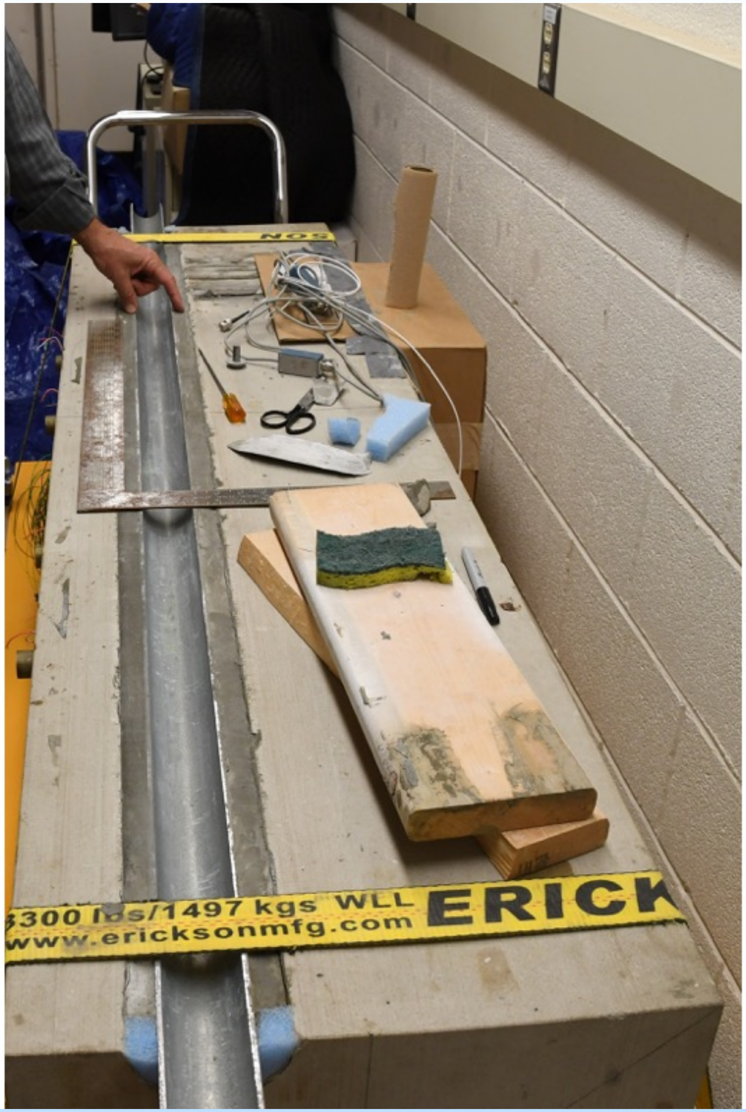
# TR Focusing in open wellbore

- Focuses well in time reasonably well in space





# Half Pipe to Inspect and ground-truth Damage

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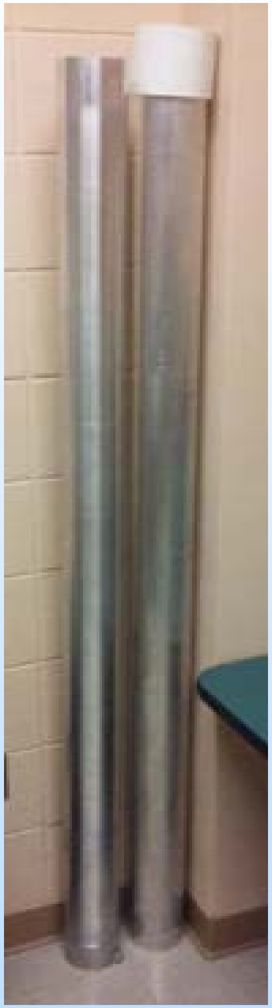
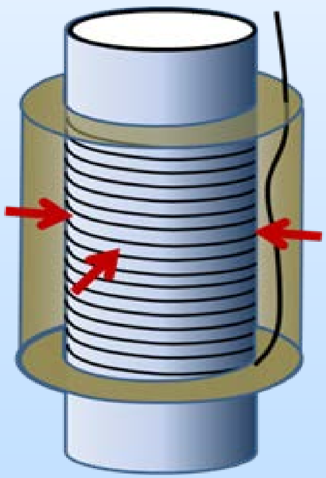
# Smart Casing

## Measuring strain in a wellbore annulus



Prototype smart casing

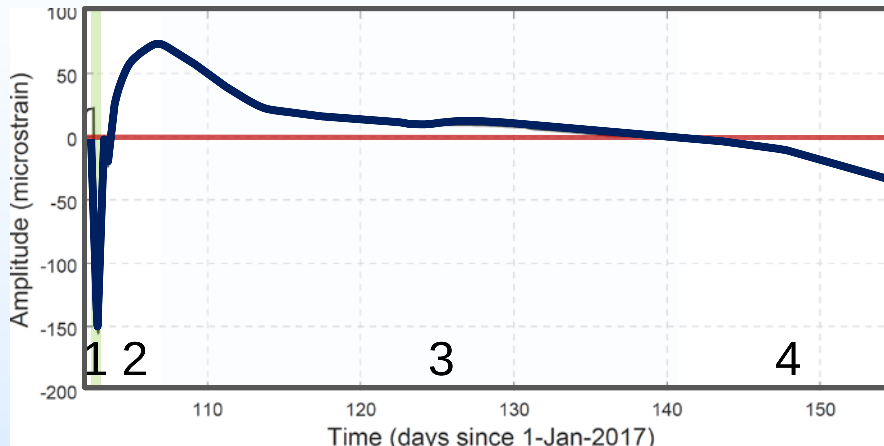
- Tubing wrapped in optical fiber.
- Michelson Interferometer to measure average circumferential strain
- Integrated optical reference

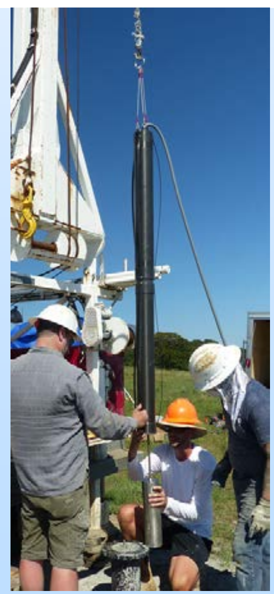


Schematic

Fiber-wrapped casing

Strain in annulus from completion



Field deployment

1. Compression when grout placed, heating during grout cure
2. Tension during grout cooling→net tensile strain
3. Compression from creep
4. Net compressive strain

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# Field Testing Distributed Strain Sensor

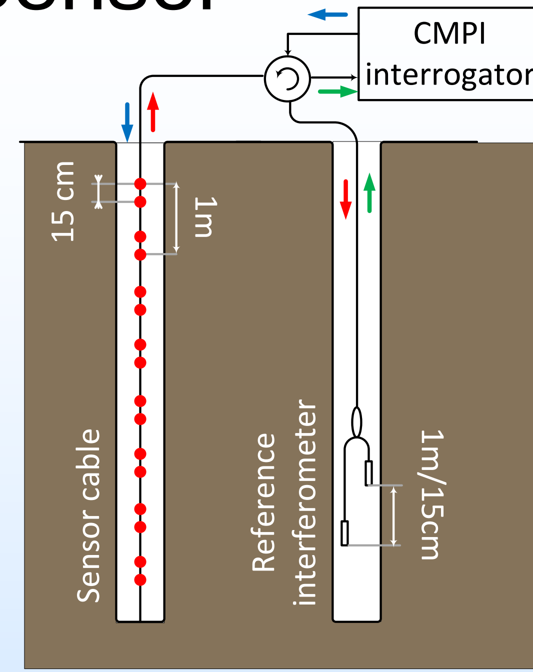
**Sensing**: Microwave photonics for strain and acoustics, CMPI

**Fiber packaging:** strain coupling to formation: high compliance, larger area

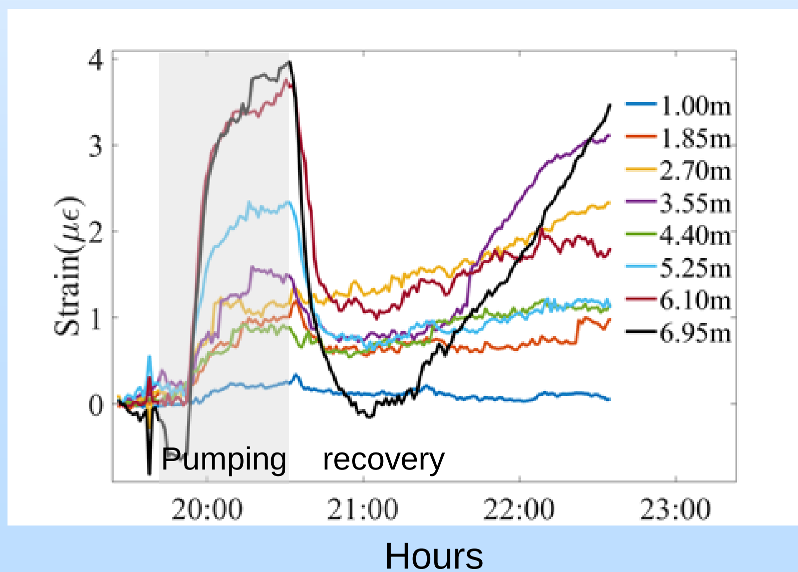
**Field testing**: 8 reflector pairs, pre-strained in a 7.6 m deep borehole. In vadose zone above water table. Field interrogator with telemetry. Tested with static surface loading and pumping tests. **Upgrade VNA for acoustic band.**

Field deployment
High coupling fiber

Interrogator




Field configuration, 15 cm reflector spacing, 1 m apart




Transient strain as function of depth in vadose zone during pumping (shaded) and recovery. No trend filtering

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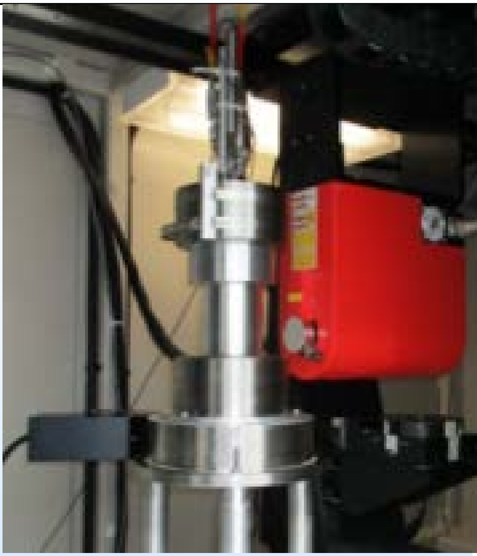
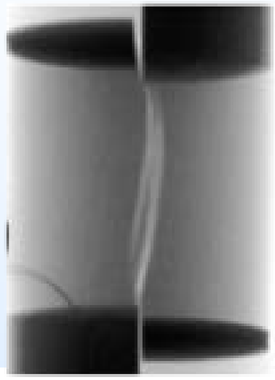
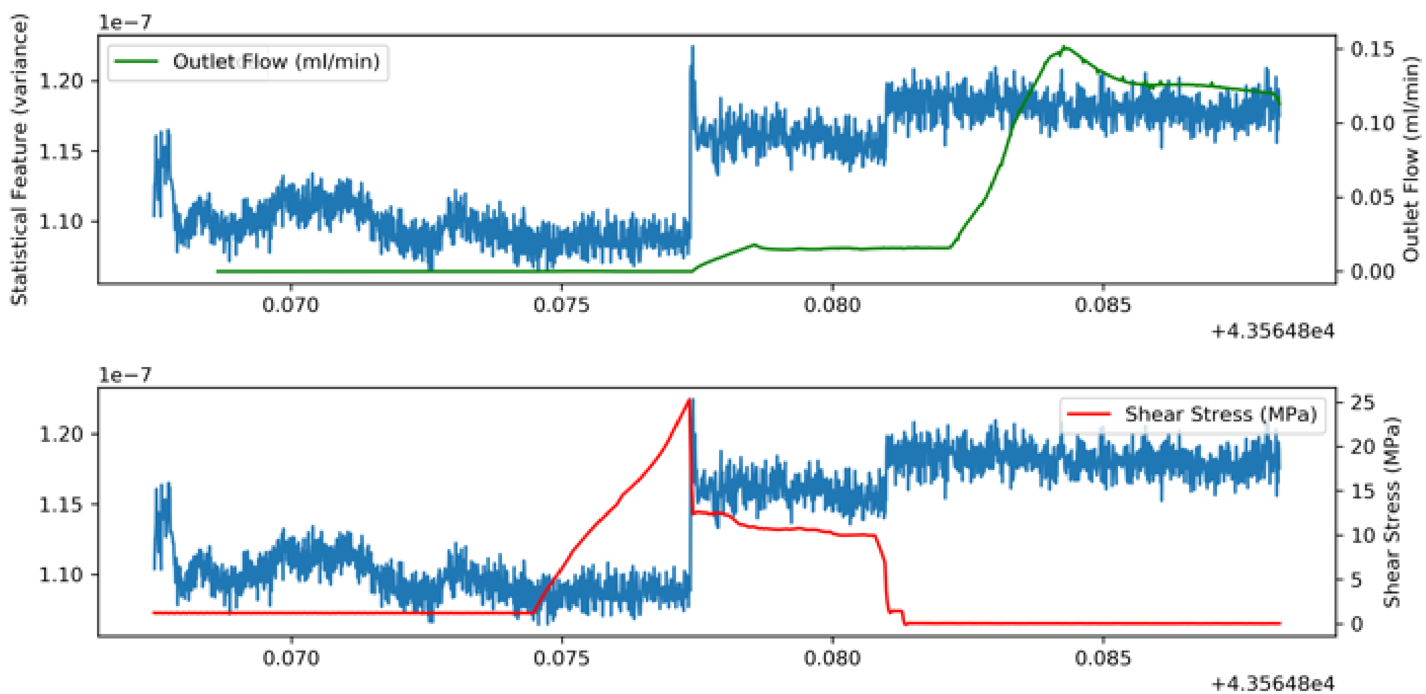
# Monitoring Acoustic Signals with Supervised Machine Learning





**The acoustic signal statistics ‘see’ changes in flow rate.**

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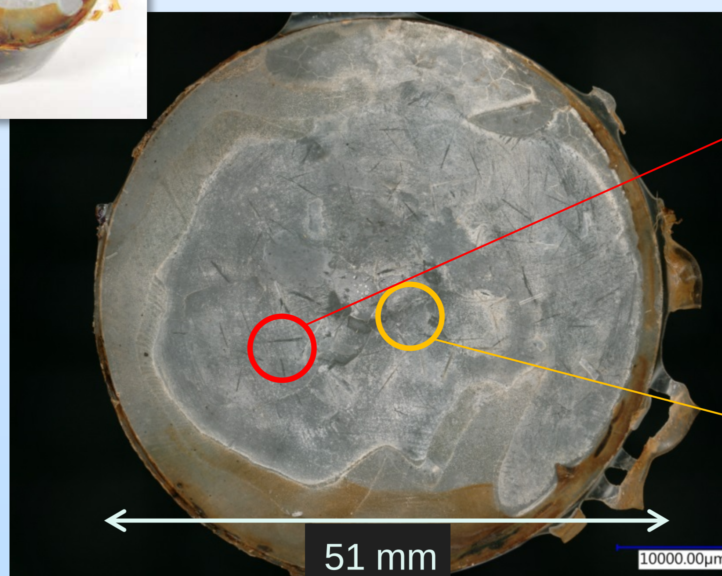
# Nonlinear Elastic Properties of Compliant Defects in Cement

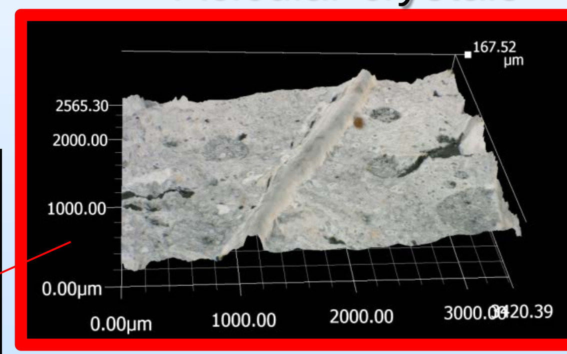
- Dynamic properties of cement-steel interfaces examined in laboratory
- Debonded interfaces created by thermal shock, allowed to undergo chemical changes (corrosion and precipitation) over time

Cement core

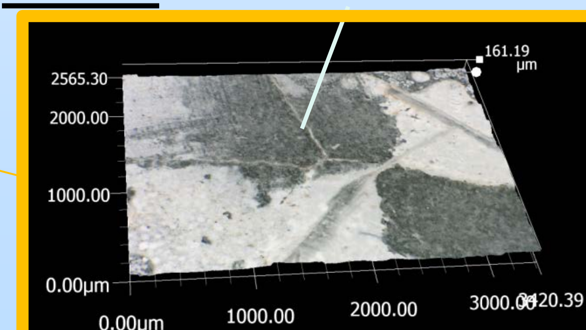
Carbon steel disc




Acicular crystals




**Healed** thermal fractures

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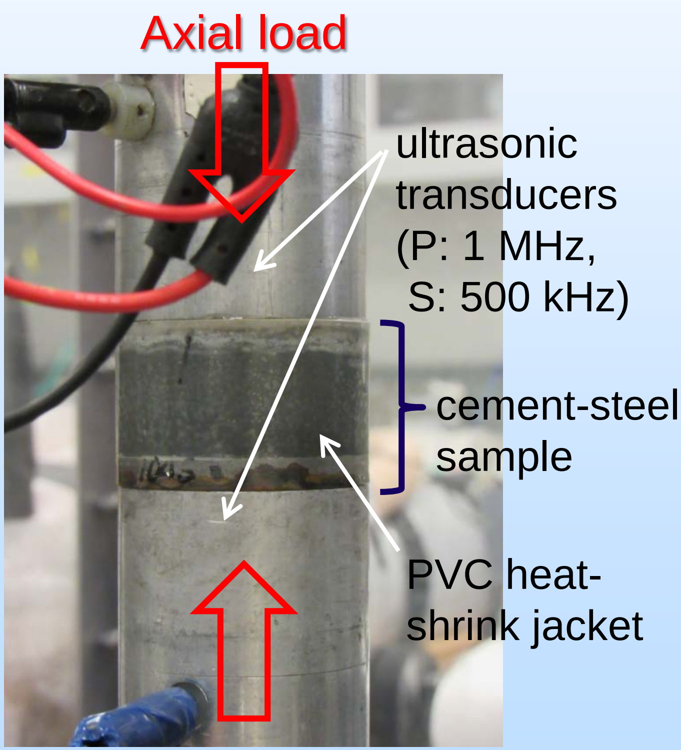
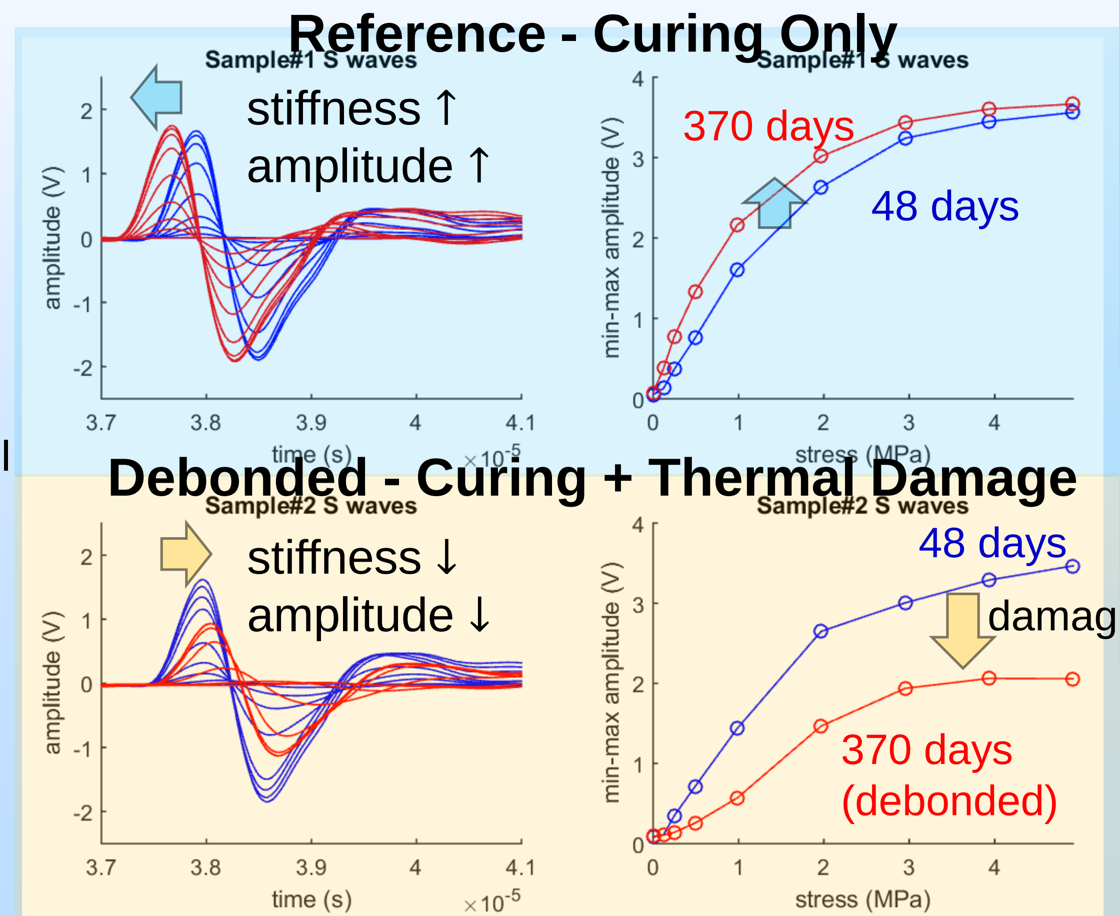
# Nonlinear Elastic Properties of Compliant Defects in Cement

- High-frequency ultrasonic wave tests show increased wave velocity and amplitude with time as the cement **cures**, but decreased wave velocity and amplitude if debonding is introduced.

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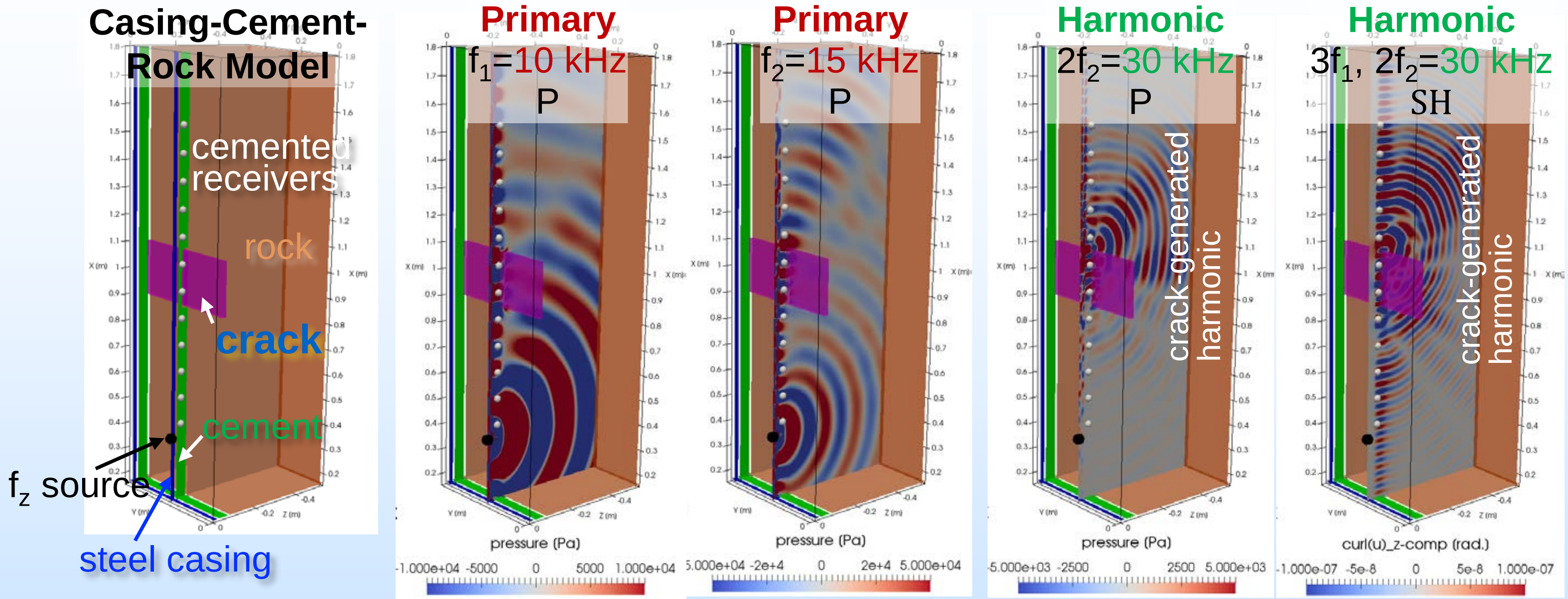
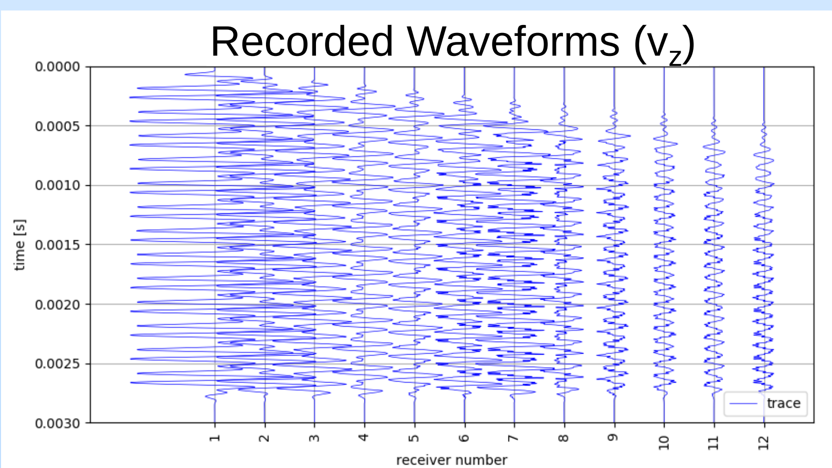
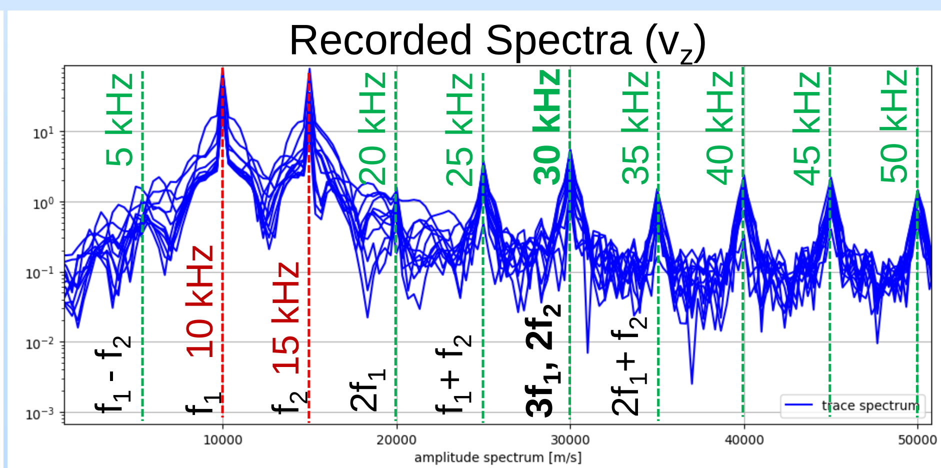
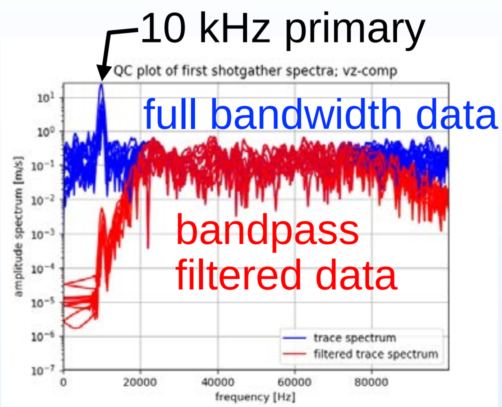
# Simulation of the Nonlinear Seismic Response of Damage (Cracks)

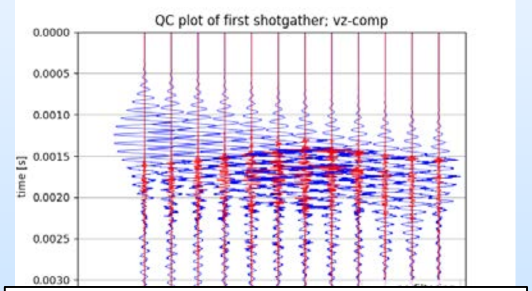


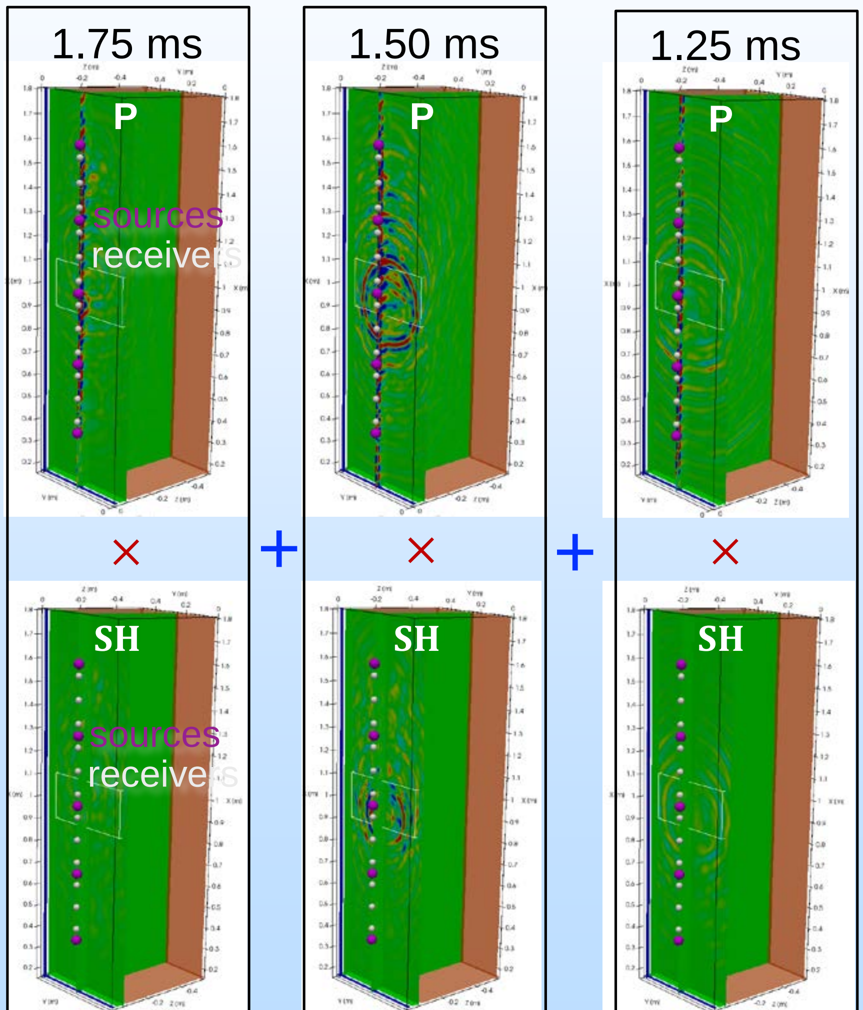
# Imaging Cracks with the Nonlinear Wavefield: 5 sources & 12 receivers



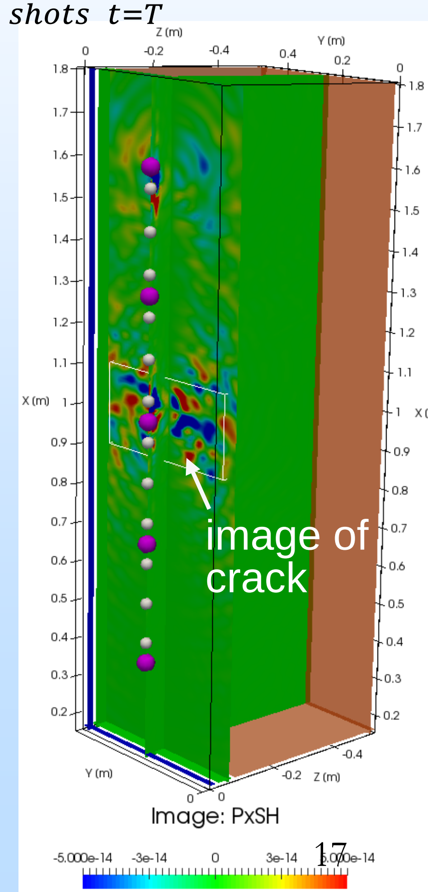

1. Bandpass filter traces
2. Time reverse 1
3. Inject 2 into receivers
4. At each back propagation time step,
   a. Separate P & SH wavefields
   b. Form imaging condition P x SH
   c. Sum b

## Backpropagation →




## Crack Imaging Condition:

$$\sum_{shots} \sum_{t=T}^{0} P(t) \times SH(t)$$



# Accomplishments to Date

- Performed TR in open hole
- Simulated TR in open hole and cased hole
- Cased half-pipe for detecting damage using TR
- Tested two optical fiber systems with TR on large sandstone block
- Created optical fiber system capable of measuring static strain
- Gathered data and applying Machine Learning to acoustic signal generated by flow through a cracked rock
- Simulation of TR-NEWS system show promise

# Lessons Learned

- Team works well together
- Need sufficient reflectors in open hole for time reversal
- Fiber optic distributed seismic sensor is challenging
- Difficult to create damage for evaluation in case wellbore
- Anticipate pieces will be in place at end of project to move to prototype development

# Synergy Opportunities

*DOE-FE Carbon Storage Program*

- Nonlinear Acoustic Methods for the Detection and Monitoring of CO2/Brine Leakage Pathways in Wellbore Systems – Pierre-Yves Le Bas & Carly Donahue. Signatures discovered in this project will be shared with our project to guide discovery of signatures with embedded sensor arrays.
- Novel methods to detect small leaks over large areas – Youzuo Lin. Some signatures discovered and algorithms developed in this effort may be relevant to our project—lessons learned will be shared.
- Robust in situ strain measurements to monitor carbon dioxide storage – Larry Murdoch. Optical methods developed in this effort to measure strain using microwave photonics at higher frequency for acoustic applications will be used by our project
- Characterizing and interpreting the in situ strain tensor during CO2 injection – Larry Murdoch. Strain and changes in in-situ stress resulting from injection evaluated during this project will contribute to understanding wellbore integrity for our project.

*LANL Laboratory Directed Research and Development (LDRD) [internal investment]*

- Critical Stress – Paul Johnson. This project is exploring the physics of systems at a critical state of stress, including many that involve fluid flow. Signatures and insights discovered in this effort are shared with our project.

# Project Summary

**Key Findings:**

– TR NEWS computer simulations show the procedure in full

– The TR Experiments work reasonably in a laboratory borehole and will require optimization

– Fiber optic acoustic sensor progressing

– Static strain sensor working

– Full system still appears feasible

**Next Steps:**

– Advance ‘leak listening’ studies applying machine learning. Laboratory and simulation.

– Advance the acoustic fiber optic sensors for borehole use

– Continue simulations

– Continue tests of TR NEWS in experiment

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# Appendix

# Benefit to the Program

- GOAL: development of autonomous system that can be deployed in wells for long-term (e.g., decades), unattended monitoring both wellbore integrity and associated stress changes (Topic Area 2).
- If successful in achieving the overarching R&D goal, the outcome would be a cost-effective option (hardware and software) for long-term autonomous monitoring of wells.
- This technology would have broad application in subsurface operations, where maintaining and monitoring wellbore integrity is central to reservoir management strategies (including geothermal operations, oil/gas operations, injection operations). However, the largest benefit to national subsurface energy interest likely lies in post-closure monitoring of wellbore integrity, as needed for CO2 storage operations. This system would be a cost-effective autonomous option to provide the data necessary to ensure that wellbore integrity is being maintained, targeting a central need in any CO2 storage.

# Project Overview

## Goals and Objectives

**Goals and Objective**: Development of an autonomous system that can be deployed in wells for unattended long-term (e.g., decades) to monitor both wellbore integrity and stress changes around the borehole

- Need: affordable, robust, autonomous system for monitoring wellbore integrity, especially post closure
- Need: detect leakage signatures for long term $CO_2$ monitoring

**Innovation**: Combination of:

(i) Machine learning to extract passive seismo-acoustic signals for long term monitoring of associated with leakage;

(ii) Active acoustics using embedded sensors and Time Reverse Nonlinear Elastic Wave Spectroscopy (TR-NEWS) to probe for localized damage

(iii) Fiber optic sensing to track near-borehole anomalous stress evolution associated with damage

# Organization Chart

**LANL**:  overall lead

**LANL and LBL**:  TR NEWS simulation and experiment

**LANL:**  Machine learning applied to leak signals, experiment and simulation

**Clemson:**  Fiber optic borehole detection

**Chevron:**  consultation on R and D, and application

# Gantt Chart

(project initiated late Q1 FY18)

Table 1. Timeline for project by task and project year (PY), with two go/no-go (G/NG) decision points.

| Task | Task Description | PY1 | | | | | PY2 | | | | | PY3 | | | | Product | Dependencies |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Q1 | Q2 | G/NG | Q3 | Q4 | Q5 | Q6 | G/NG | Q7 | Q8 | Q9 | Q10 | Q11 | Q12 | | |
| 1.0 | Technical Project Management (200) | | | | | | | | | | | | | | | Quarterly reports; other sponsor requests | |
| 2.0 | Literature Review & Technology Evaluation (250) | | | | | | | | | | | | | | | Briefing with detail to assess 1st go/no-go | |
| 3.0 | Detect Fluid Flow (250) | | | | | | | | | | | | | | | Report documenting lab results on detecting small signals | "Go" at 1st go/no-go |
| 4.0 | Use TR to Focus Energy (200) | | | | | | | | | | | | | | | Report documenting lab results on TR focusing of acoustic energy | "Go" at 1st go/no-go |
| 5.0 | Detect nonlinear Properties (750+ | | | | | | | | | | | | | | | Final report summarizing lab and field results and data | Successful completion of 4.0 |
| 5.1 | Lab-scale Experiments ( | | | | | | | | | | | | | | | Initial report on lab results as needed to assess 2nd go/no-go | Successful completion of 4.0 |
| 5.2 | Field-scale Experiments | | | | | | | | | | | | | | | Data documenting field performance | "Go" at 2nd go/no-go |
| 6.0 | Measure Stress Field | | | | | | | | | | | | | | | Final report summarizing lab and field results and data | |
| 6.1 | Lab-scale Experiments | | | | | | | | | | | | | | | Initial report on lab results as needed to assess 2nd go/no-go | |
| 6.2 | Field-scale Experiments | | | | | | | | | | | | | | | Data documenting field performance | "Go" at 2nd go/no-go |
| 7.0 | Re-assess design criteria | | | | | | | | | | | | | | | Report assessing feasibility of commercial system based system, along with a development pathway | |


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# Bibliography

- In Progress