High-resolution Reservoir Seal Integrity Monitoring Using Optimized Borehole Sources and Distributed Acoustic Sensing

DE-FE0032058

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Aug. 6th, 2024

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Management Project Review Meeting
August 5 – August 9, 2024

Project Overview

– Funding
  - DOE : 1.19M (over 3 years)
  - Cost-Share: 707K (Rice, SwissTopo)

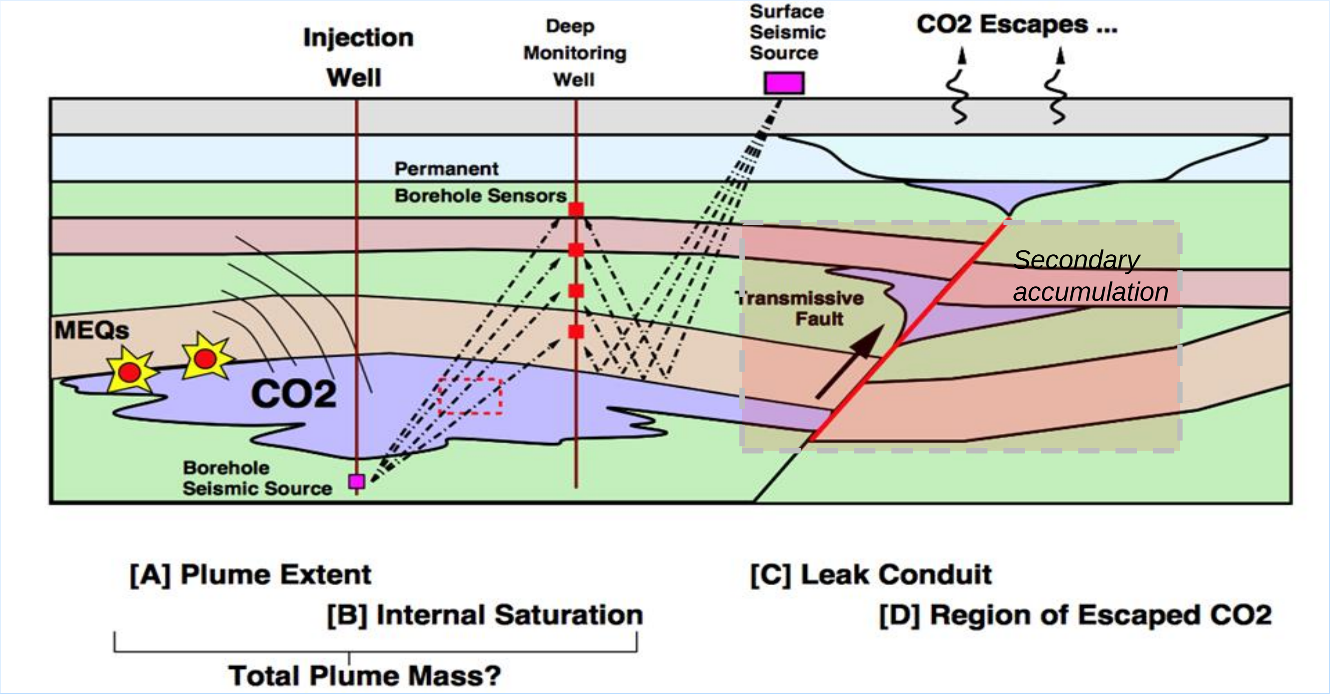
– Overall Project Performance Dates :
  - July 1st, 2021- July 1st, 2025

– Key Participants:
  - Rice University (Jonathan Ajo-Franklin)
  - LBNL (Nori Nakata , Yves Guglielmi, Michelle Robertson)
  - Penn State University (Tieyuan Zhu)
  - Terra 15 LLC (Nader Issa)

– Overall Project Objectives
  - Develop and test approaches for integrating CASSM & DAS for reservoir seal integrity monitoring.

Key Goals for GCS Storage Security

- ***Goal***: Ensure that sealing formations retain integrity for the lifetime of the project, prevent transport of CO_2 outside of the storage reservoir.
- If seal integrity is compromised, provide information on the location of the breach (spatial resolution) in a timely manner (early in the process = good time resolution).
- Provide enough information to allow formulation of intervention (leaky fault? Zone of higher perm in seal? Opening tensile fractures?)



The Challenges of Monitoring Seal Integrity

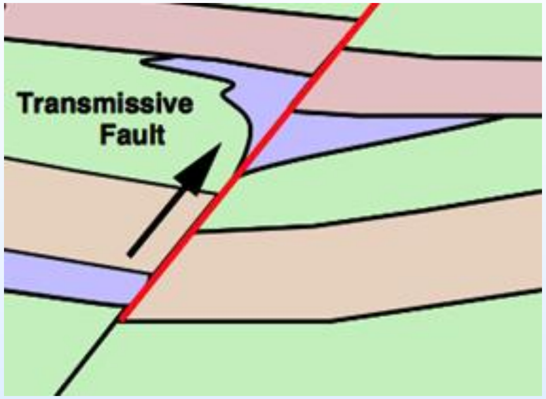
- In contrast with CO_2 movement in the reservoir, small leaks in sealing units due to reactivation of faults & tensile fracture opening are a challenging imaging target.

- Clay-rich sealing units can fail aseismically; no microseismic signature of opening.

- Potentially no surface 4D seismic signature until large CO_2 volumes have leaked + accumulated in shallower units.

- Need a technique which can ”see” small localized changes in seismic properties.

- Don’t want to see large scale opening via geodesy (sign big alteration is happening)



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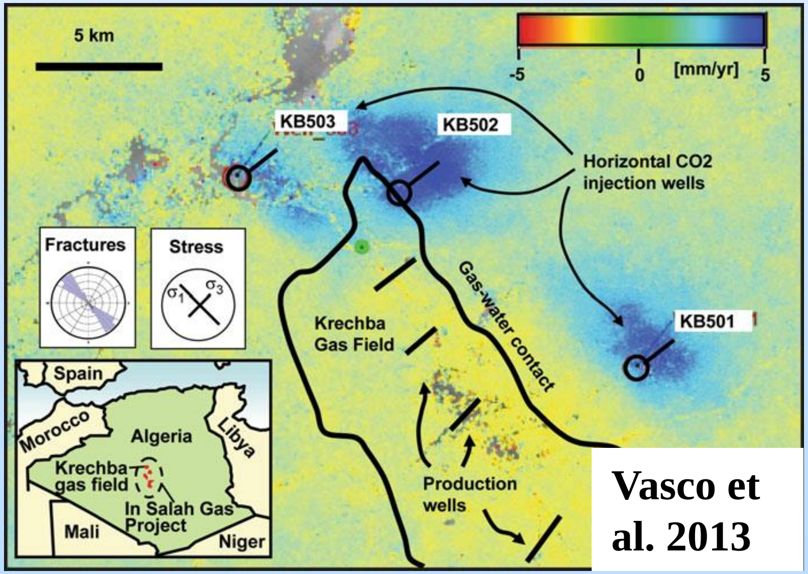
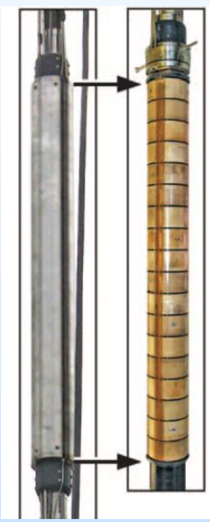


Vasco et al. 2013

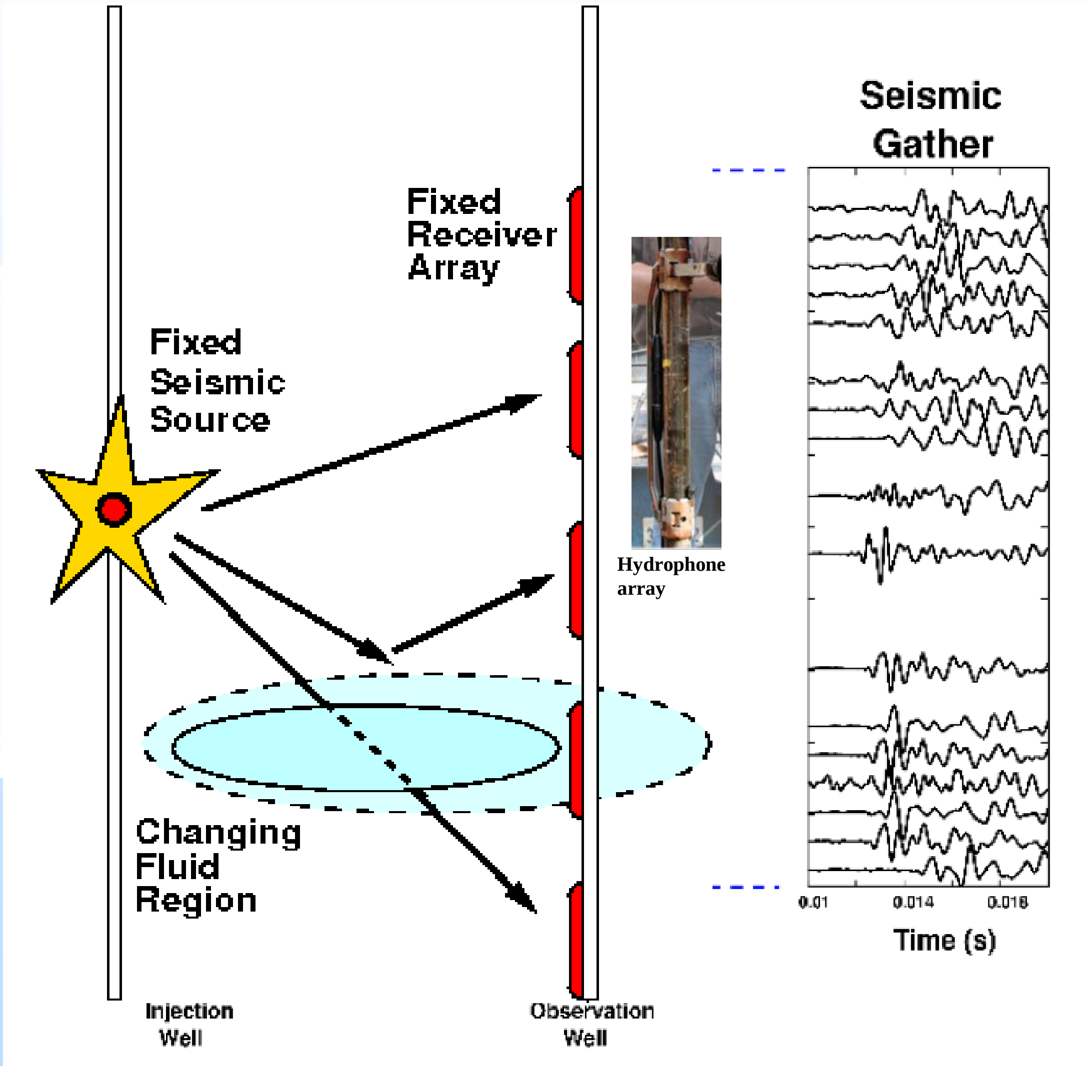
A Useful Technology: CASSM

CASSM = Continuous Active Source Seismic Monitoring



Custom piezoelectric borehole source

[Daley et.al. 2007]
[Silver et al. 2007]
[Ajo-Franklin et al. 2011]
[Marchesini et al. 2017]
[Shaddoan et al. 2023]



Fixed repeatable source & receiver array.

- Excellent temporal Resolution (< 5 min)
- Precise repeatability (~10-100 ns)
- Stacking -> Excellent S/N
- Moving towards real-time seismic tomography

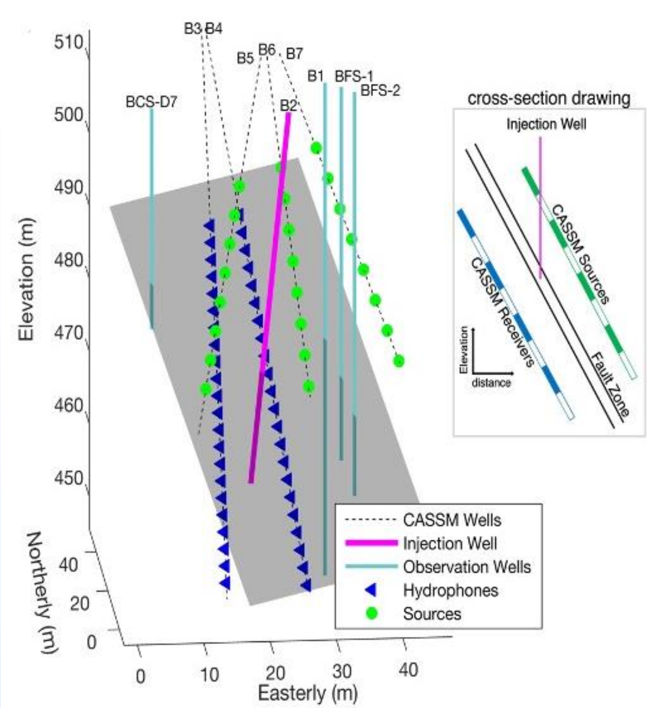
Why CASSM for Monitoring Seals?

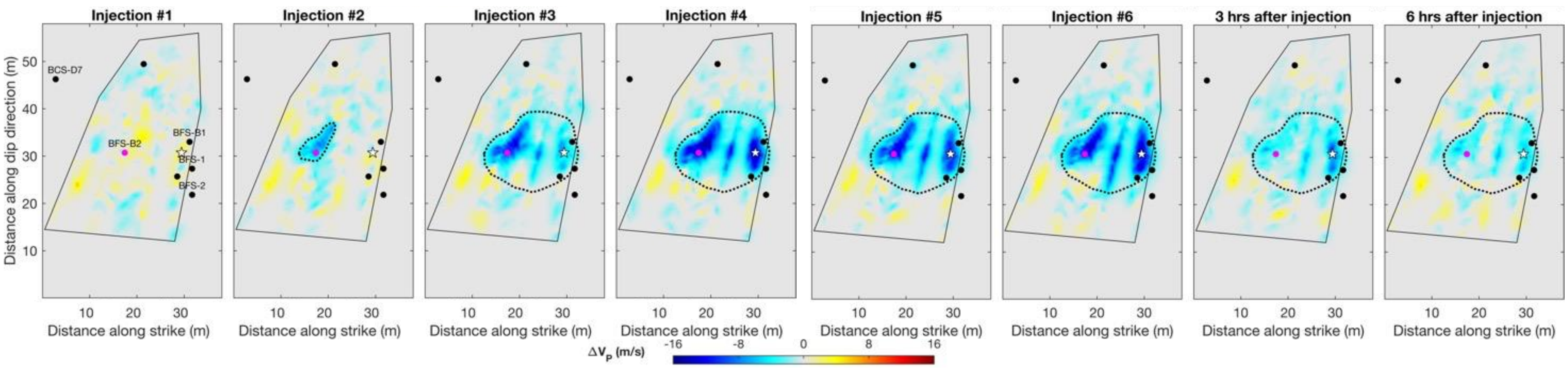
- Microseismic provides constraints on where faults slip (most of the time): not on slow aseismic processes.
- EQs provide no constraints on fault leakage, healing. or creep (long term)

Elastic moduli are locally sensitive to micro-fracture density, stress state; CASSM might access aseismic fault zone evolution

CASSM for Seal Monitoring? FSB at Mont Terri

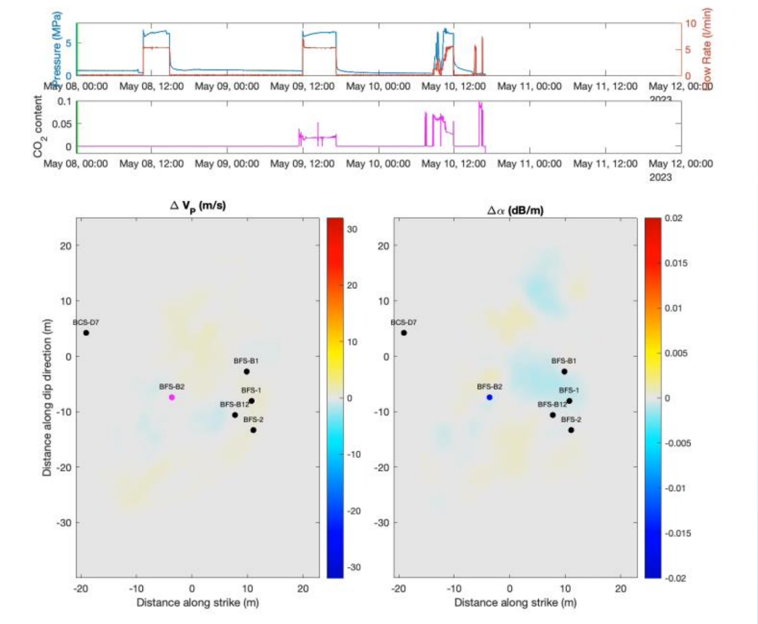
- High repeatability/sensitivity makes CASSM ideal for monitoring small velocity changes associated with fault pressurization/reactivation.
- Example from Mont Terri FSB experiment: CASSM monitoring of fault reactivation experiment (w. FSB/C effort, PI. Y. Guglielmi)
- 5 wells, 24 sources, 48 hydrophones - 570 epochs of data acquired over 3 day experiment, 6 minute temporal resolution.
- Fault patch reactivated through series of brine injections, slip patch imaged through V_p reduction (Shadoan et al. 2023)

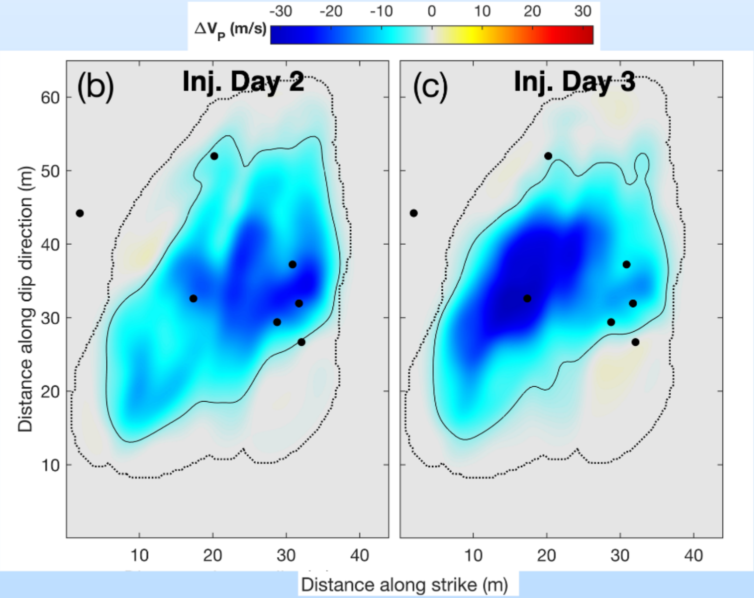


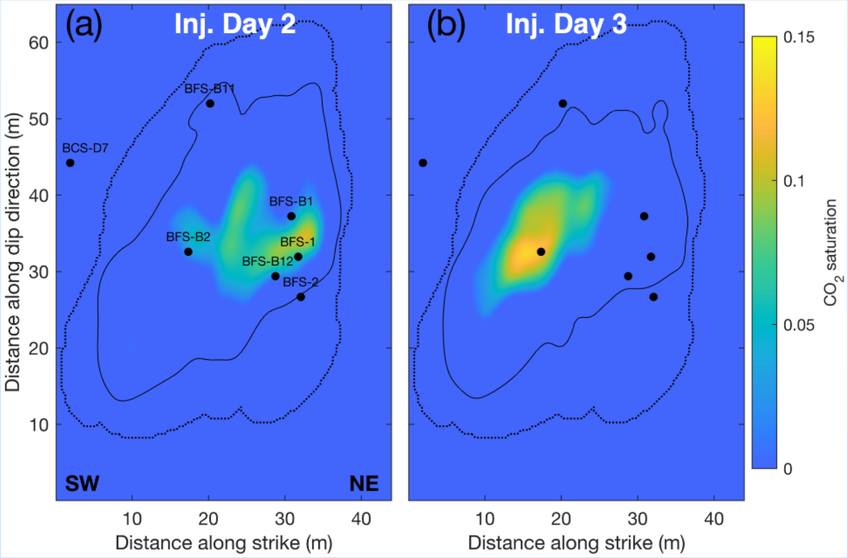


CASSM for Seal Monitoring? FSC at Mont Terri

- Most recent results from FSC (LBNL/Rice collaboration, 2023), demonstrate that conventional CASSM can effectively detect/quantify multiphase CO_2 movement within reactivated faults!
- Small but detectable Vp and attenuation signatures (10s of m/s perturbations) – convolved fracture compliance/saturation effects.
- Not topic of this talk – see Y. Guglielmi's presentation next but seems like a powerful tool for seals.







Limitations of CASSM for Long-Term Seal Monitoring

- So what's missing?

- To achieve good quality data, need semi-permanent dense borehole receiver arrays (as well as sources!).

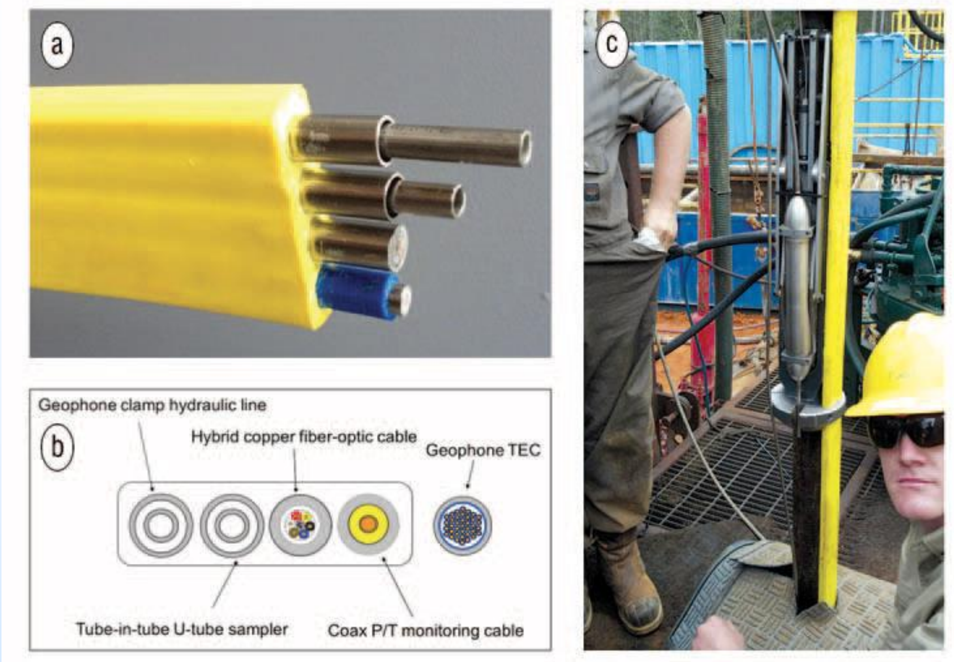
- Past experiences have shown us that this is challenging with conventional sensors (expensive, large cables), particularly in harsh environments (problems scaling hydrophone arrays, point sensors).

- GCS CASSM hydrophone arrays used in past studies (Frio 2, Cranfield) were effective (Daley et al. 2007, Marchesini et al. 2017) but failed during different stages of operation.

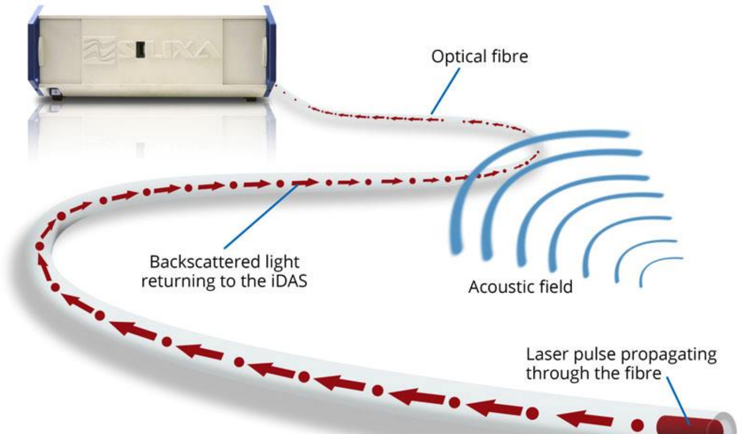
- For CASSM to be broadly applicable, need rugged, cost-effective, high density receiver arrays – how?

DAS to the Rescue?

- **Distributed Acoustic Sensing [DAS]** is a rapidly advancing approach for measuring the seismic wavefield using commercial fibers (SM, telecom)
- **Recent** : S/N became sufficient for seismology around 2011. Our work started ~2012/13 out of CO_2 GCS program (borehole applications)
- **Large N** : Easy to deploy in wells, behind casing, 1000s to 100,000s of channels available (big data) over 10+ km (biggest current use is VSP)
- *Very low cost per "sensor"* : $/ft for cable
- *Rugged* : handles high/low T, high pressures.
- ***The solution for CASSM?***

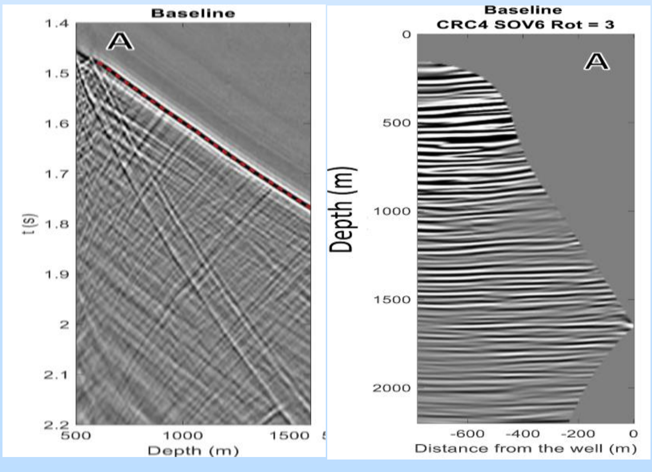


Daley et. al. 2016 (Geop Prosp.), Daley et.al. 2013, (TLE)



Courtesy Silixa LLC

Pevzner et al. 2021 [Otway]



Challenges of X-well CASSM + DAS for Seal Integrity Monitoring

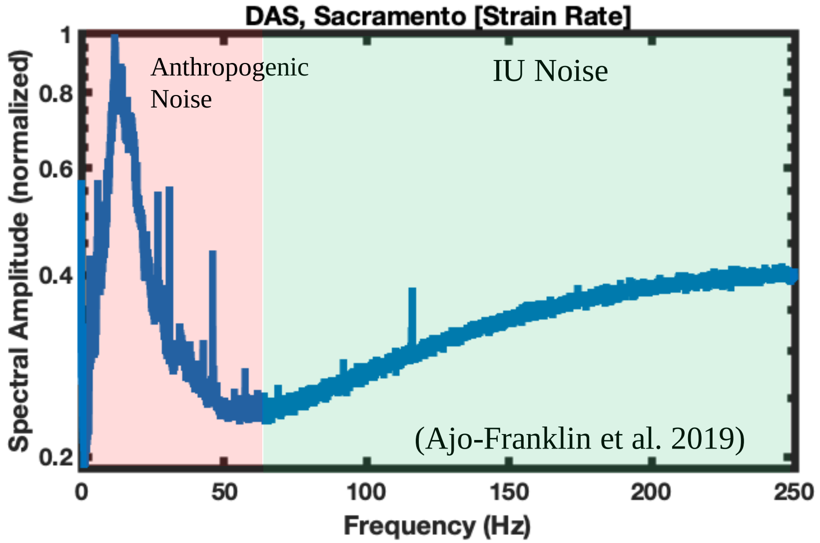
Despite clear advantages, some challenges

Frequency Mismatch:

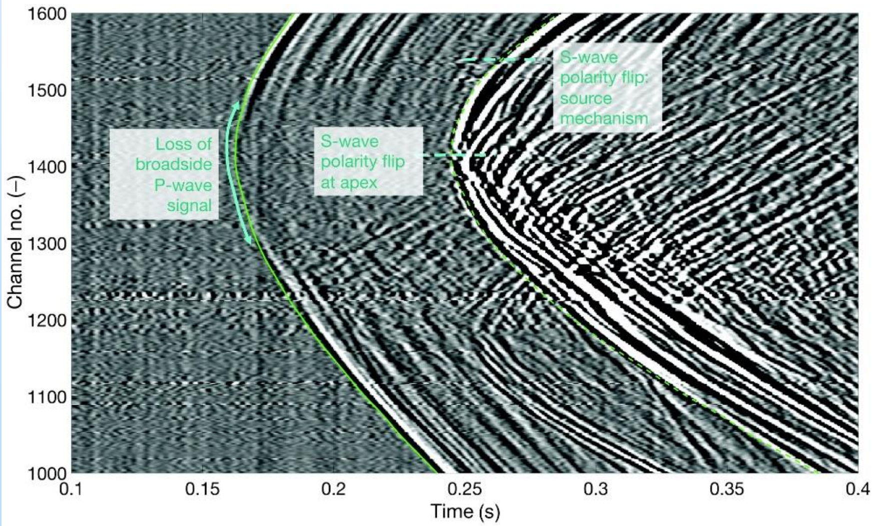
- DAS often exhibits increasing noise at high (kHz) frequencies, presents a mismatch with high F piezoelectric sources (depends on IU). In theory should be flat in strain …..
- Field application will also require longer propagation distances

Angular Response:

- DAS measures extensional strain (or strain-rate), yields a $\cos^2$ theta response pattern.
- Fluid-coupled CASSM sources radiate in the null of conventional receiver sensitivity at S/R offsets.



Verdon et al. 2020 (microseismic)



Technical Approach

Our Goal:
Demonstrate that the novel combination of CASSM & DAS can be utilized for monitoring seal integrity for GCS.

Process:

T2: Develop and validate a new low frequency CASSM source to improve DAS response.
(should be small, inexpensive, and suitable for array deployment)

T3: Develop an improved processing flow using FWI and coda wave analysis tailored to the measurement combination (evaluate optimal geometries).

T4: Test this combination for CASSM monitoring at a well-characterized shallow test site (Rice test facility)

T5: Demonstrate efficacy as part of a fault reactivation experiment at Mont Terri underground laboratory.

T6: Develop scale-up plan for future deep GCS targets.

Task 2: Development of a DAS-Oriented CASSM Source

Challenge: *Development of a source (or source set) appropriate for CASSM/DAS recording? Task 2 – lab scale prototyping/evaluation.*

ST 2.1: Design of resonant source matched to DAS:

- Initial analytical & numerical modeling to develop some plausible source geometries and driving elements.
- Design should allow tuning with small system modifications.

ST 2.2: Prototyping of CASSM source and laboratory testing:

- Fabrication of several prototypes and lab testing in a water tank.
- Reference hydrophones & DAS cables for evaluation.
- Compare to numerical models and extrapolation to field response.

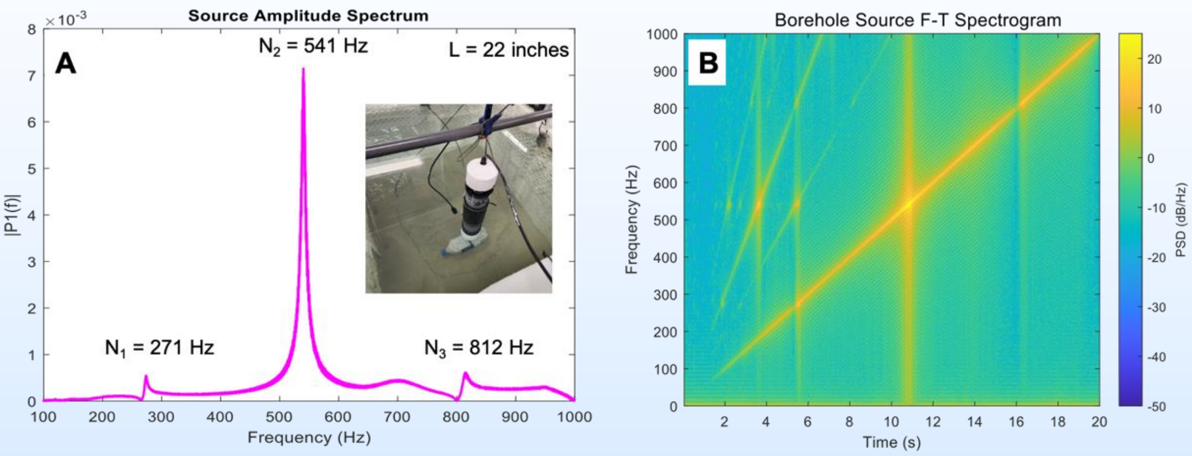
ST 2.3: Fabrication of LF CASSM array for field experimentation

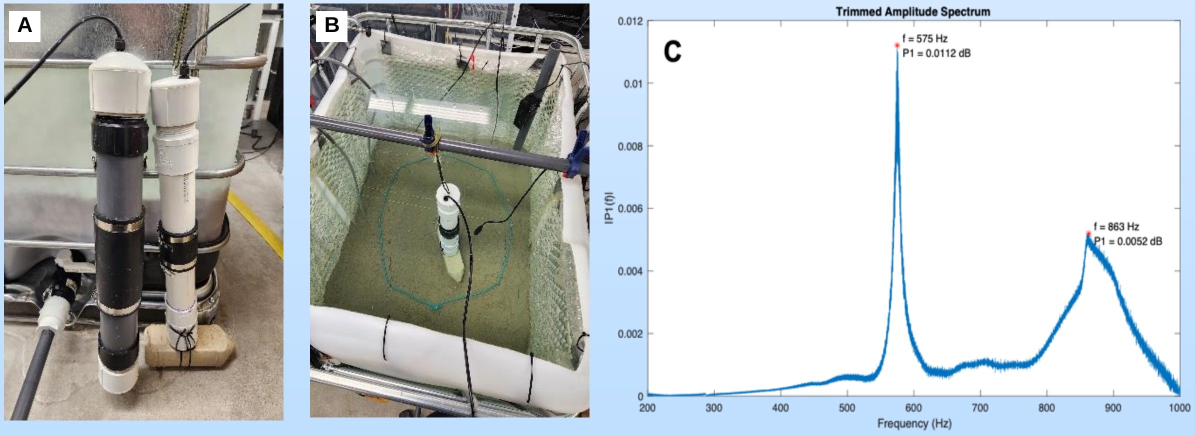
- Once a good design is developed, fabrication of larger array for tests
- Plan is to reuse array for tasks 4 & 5.

Task 2: Prototype Resonant Source

Context:

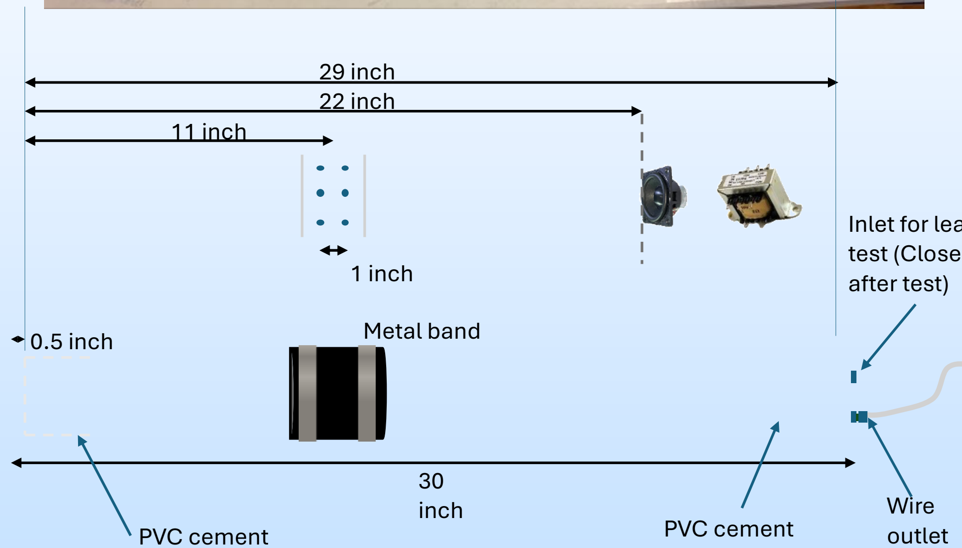
- For DAS-oriented source, target is 400-800 Hz frequency range; a good mix for DAS response, propagation distance, and source mechanics.
- Performed preliminary work on a range of single/dual cavity Helmholtz and simple resonators.
- Several generations of designs tested using both fiber and conventional sensors in lab.
- Settled on air-backed simple resonance source with membrane coupling to fluid.

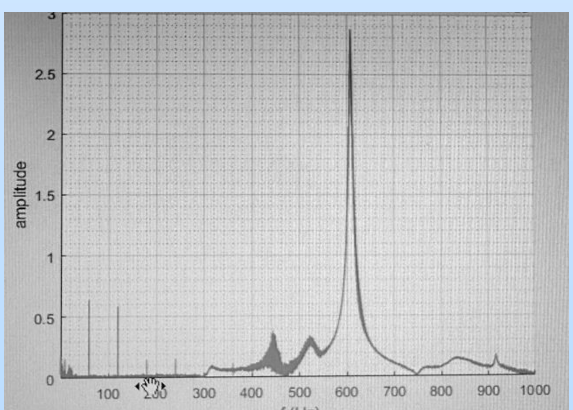


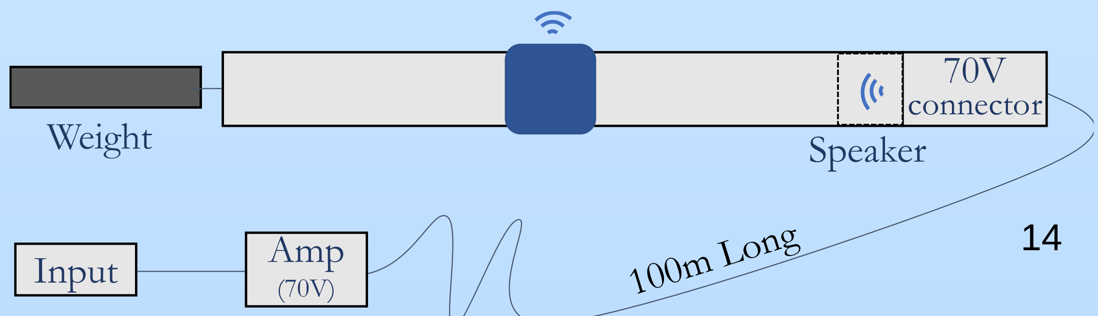


Task 2: Resonant Source Design Iteration

- Fourth iteration of source design improvements after field tests to minimize leakage risk and enhance overall performance.
- ***The final design***: a single chamber resonator with two separate internal housings for the 70 V transformer and excitation transducers.
- Overall geometry remained largely unchanged to maintain the same resonance frequencies .
- Water tank tests (hydrophone) Sweep, 15 s long 0-1,000 Hz excited the first 2 length modes with the 2nd mode (605 Hz) the strongest. Appropriate for field tests.

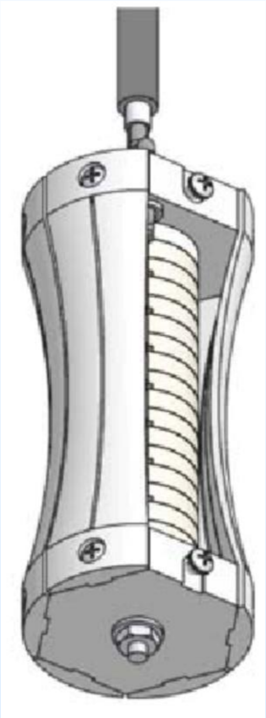






Task 2: Barrel-Stave Piezoelectric Source

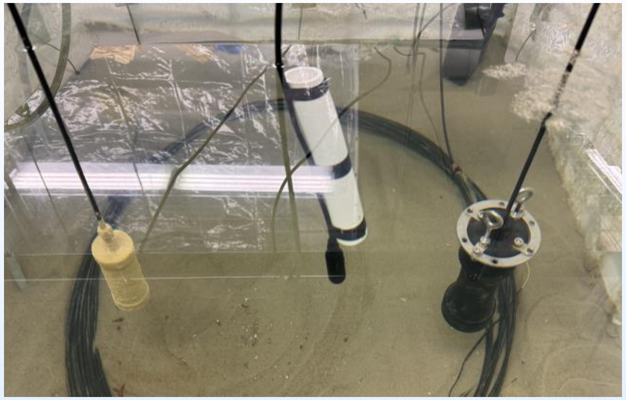
- ***A new alternative source***: a barrel-stave (flextensional transducer.
- Piezoelectric stack inside: designed to deform a concave shell to improve low frequency response when compared to radially poled cylindrical crystals.
- Concept out of the sonar community, designed for transmission with lower resonance frequency.
- Commercial vendor fabricated custom source for testing.
- Remedies some issues with resonance source (membrane pressure dependence, size).

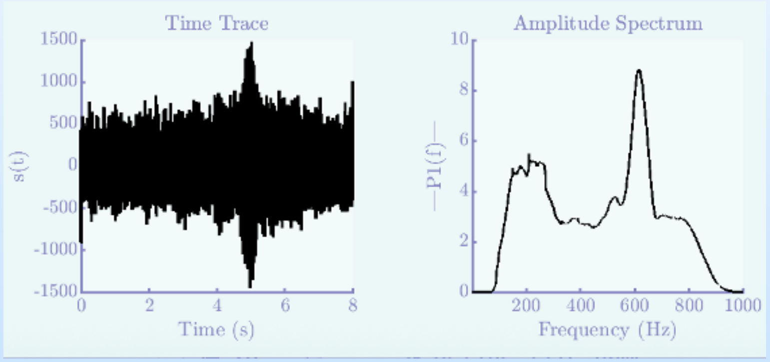


Somayajula et al. 2018

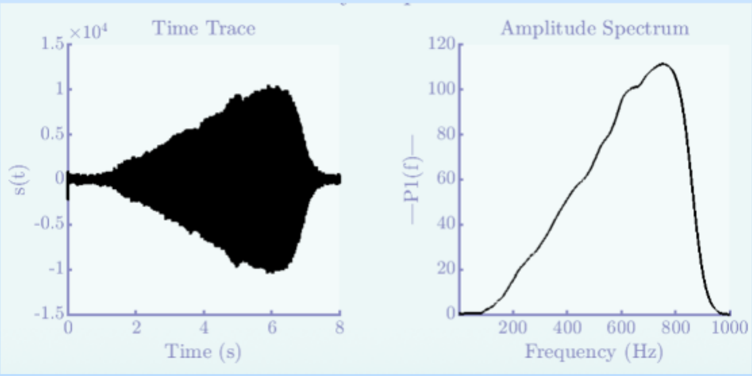
Task 2: Barrel-Stave Piezoelectric Source

- Laboratory tests in a water tank comparing the response of the traditional 4 in piezoelectric transducer and the barrel-stave source.
- Conventional CASSM source (used in prior FSB/FSC examples) is a 4” radially poled PZT ceramic.
- For a linear 8 s 0-1,000 Hz sweep, the custom source showed a peak frequency of about 840 Hz with amplitudes an order of magnitude higher than the traditional piezoelectric source with a peak frequency of 610 Hz (same driving voltage).
- Quite promising for lower frequency measurements – worth field testing.





4” piezoelec. transducer



Barrel-stave transducer

Task 4: Shallow CASSM/DAS Study at RSTF

Tank tests only go so far: Validating CASSM/DAS concept at a shallow field site. Sufficient S/N? Repeatable?

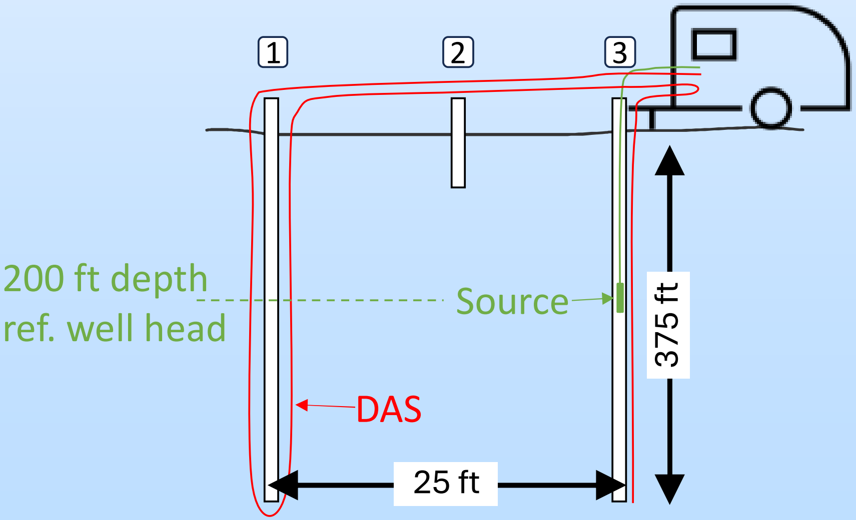
ST 4.1 : Small-Scale validation study of CASSM/DAS combination

- Evaluate source strength/performance
- Evaluate timing/repeatability
- Evaluate response on reference sensors for DAS modeling.

ST 4.2 : Small-Scale hydraulic test to evaluate time-lapse performance.

- Conduct hydrogeophysical monitoring test to evaluate sensitivity.
- Depress surficial aquifer by 1m, 9 kPa load forcing. Can we see it?

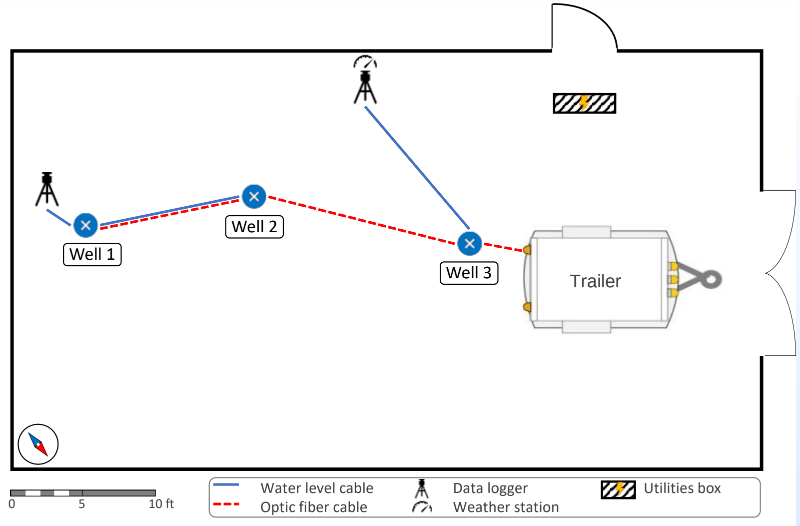
ST 4.3: Analysis of small-scale test using developed monitoring algorithms

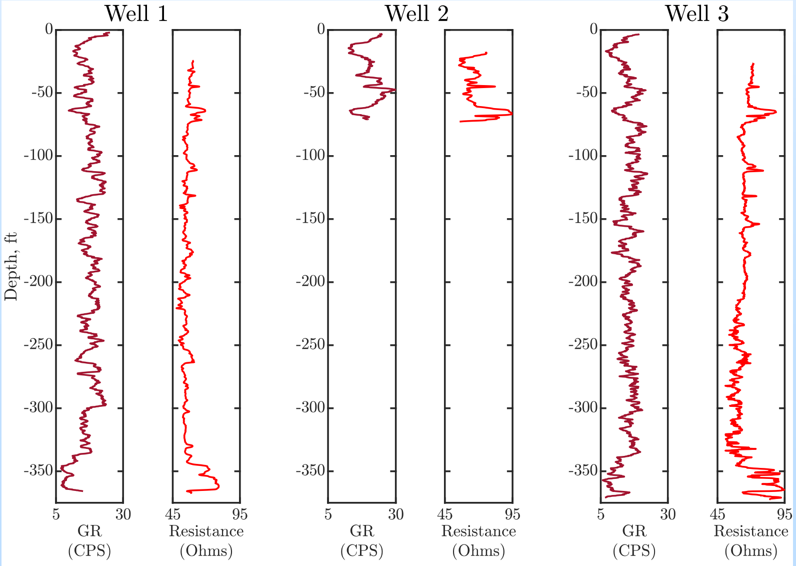


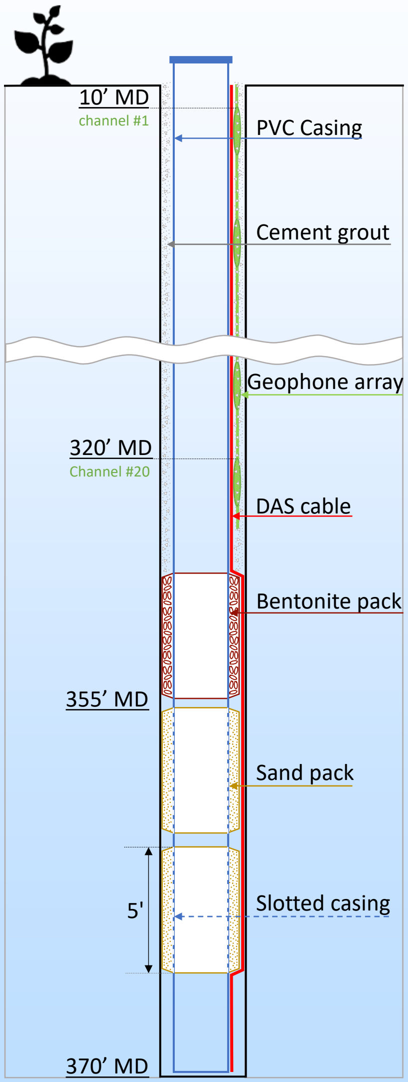
Task 4: Rice Subsurface Test Facility

RSTF Site = Rice Subsurface Test Facility
(on Rice Campus, Houston, TX)

- 3 instrumented shallow wells (2 x 375 ft bgs, 25 ft spacing), completed in shallow aquifer.
- Fiber optics (4 SM & 2 MM) behind casing to facilitate DAS and DTS measurements. One well with 24 vertical geophones
- Trailer for housing DAS IU and secondary electronics.
- Well logs and hydraulic monitoring for pump/slug tests.



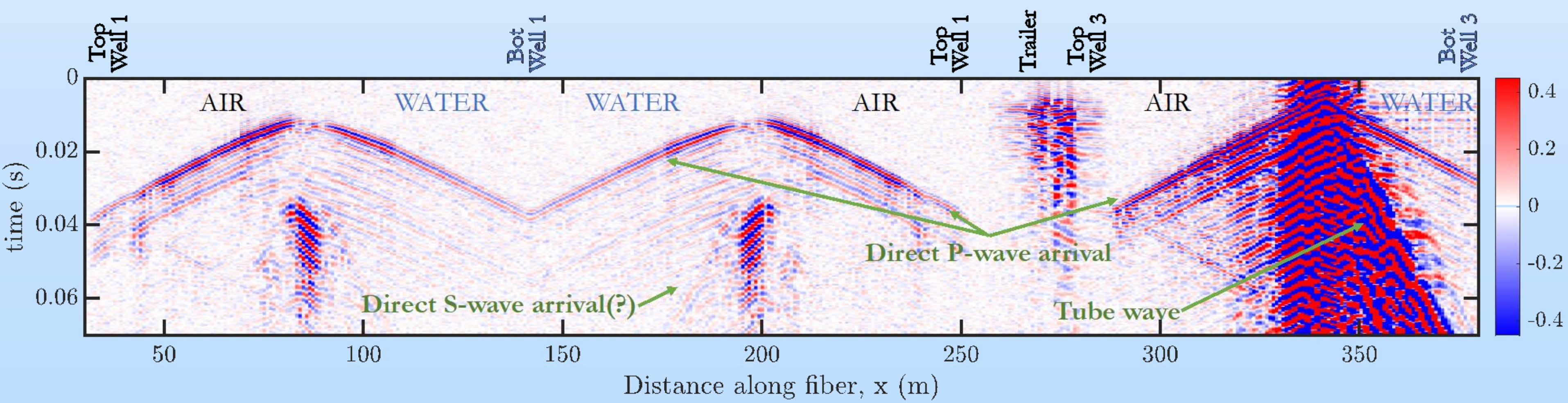




Task 4.1: Validation study at RSTF: Resonance Source

Challenge: Does the resonant CASSM source "work" well enough in the field for imaging? Preliminary results last year but difficult to interpret (not usable).

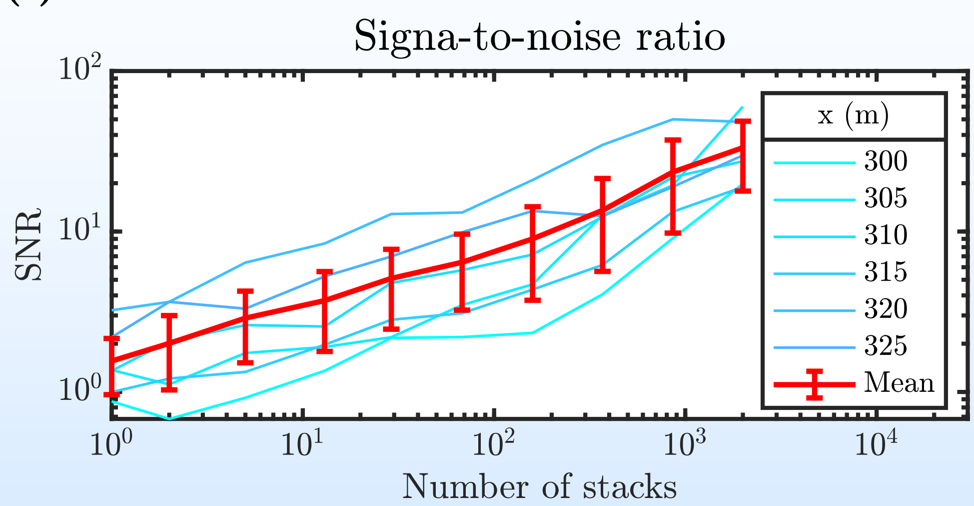
- Source deployed in Well 3 at 200 ft (30 ft below water table). DAS data collected in Wells 1 & 3.
- Updated processing workflow resolved inconsistent triggering issues and improved S/N ratio.
- Direct P-wave detected in both the source and receiver wells: consistent with expected average sediment velocity of 1,650 m/s. Strong tube wave dominates in the source well.
- Low amplitudes observed at near-zero vertical offsets (80-90 and 190-200 m) are consistent with the expected DAS angular response (maximum sensitivity to coaxial stress).
- Results **confirm** that the proposed combination of the resonance source and DAS can be used for continuous data acquisition.



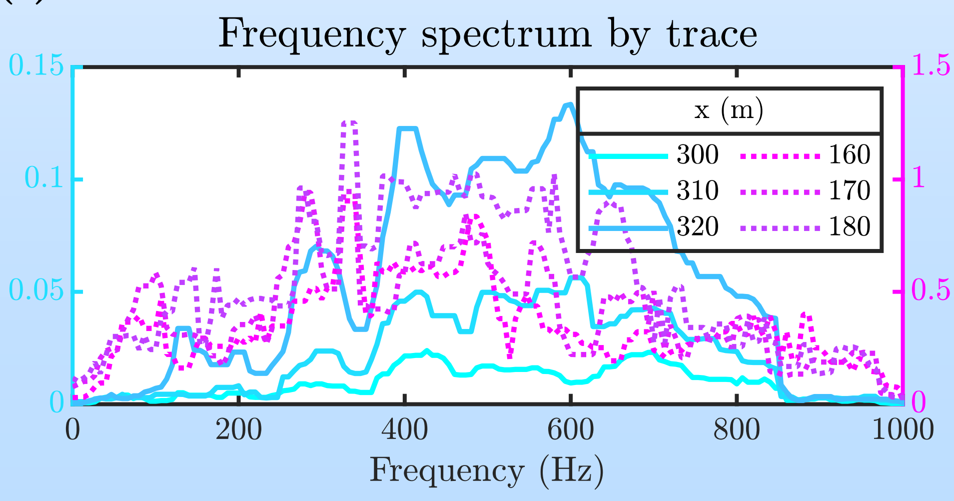
Task 4.1: Validation study at RSTF: Resonance Source

- **Challenge**: Is the source/IU combination sufficiently repeatable for CASSM experiments?
- Signal-to-noise ratio improves over 2,000 stacks, $\sqrt{N}$ stacking suggesting excellent source repeatability.
- Frequency spectra in the source well peaks at resonance frequencies of the source (around 300 and 600 Hz) while remains flatter overall in the receiver well.
- Both attributes key for CASSM/DAS experiments.

(a)

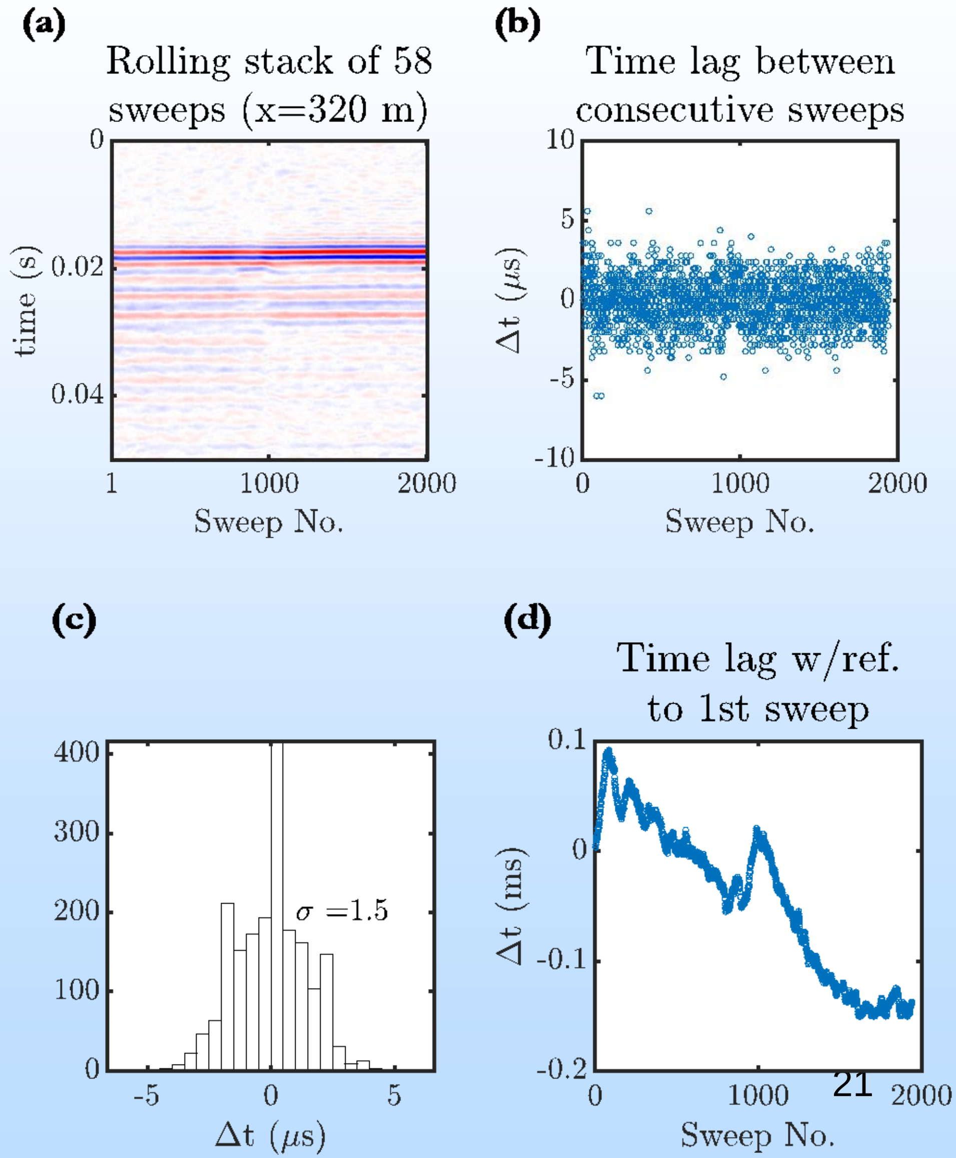


(b)



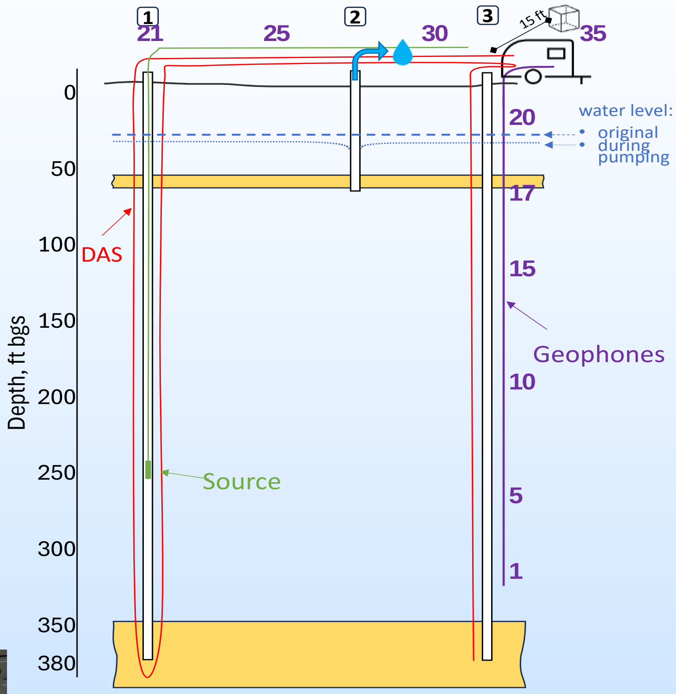
Task 4.1: Validation study at RSTF: Resonance Source

- **Challenge**: Is the source/IU combination sufficiently repeatable for CASSM experiments?
- Source repeatability estimated using a rolling stack of 58 sweeps (~30 min of data) shows an average time lag between consecutive sweeps of 0 μs with a standard deviation of **1.5 μs.**
- Smallest velocity change that can be detected with the current setup is 0.2 m/s over 30 min.
- Slow drift still to solve ….
- Only slightly below the temporal resolution required for the next phase of the project.



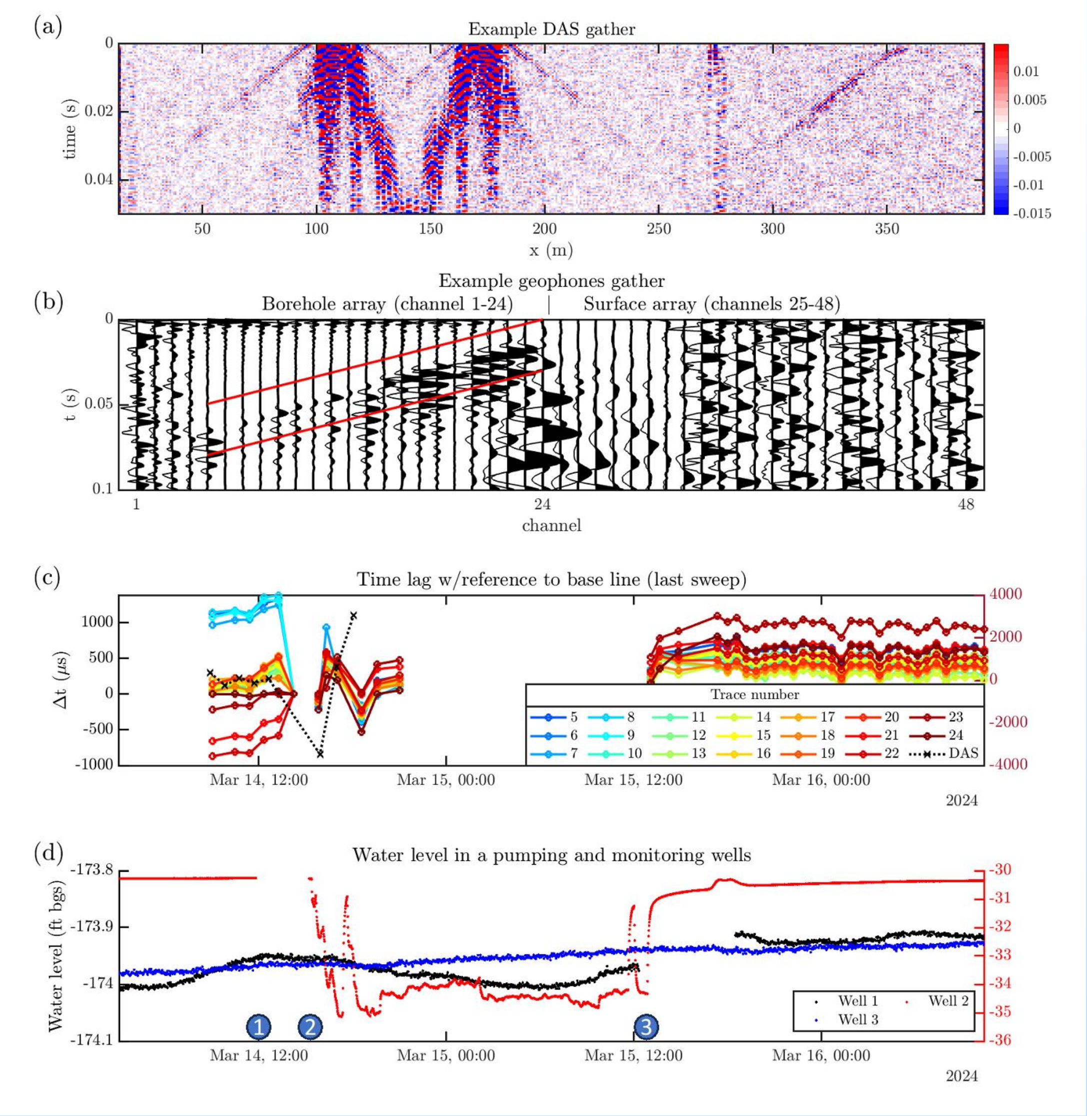
Task 4.2: Hydraulic test at RSTF

- Two-day experiment to evaluate the timelapse performance of CASSM/DAS using NS hydraulic forcing as a target.
- Source deployed in Well 1 and an additional electromechanical surface source 15 ft away from Well 1; recording using DAS and geophones.
- Total 4 ft drawdown in Well 2 maintained over 22 hours.
- The sources run sequentially suing 70 sweeps in each set.



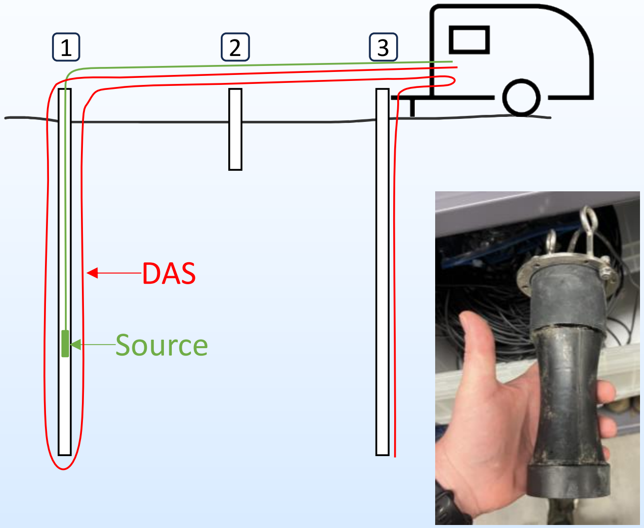
Task 4.2: Hydraulic test at RSTF

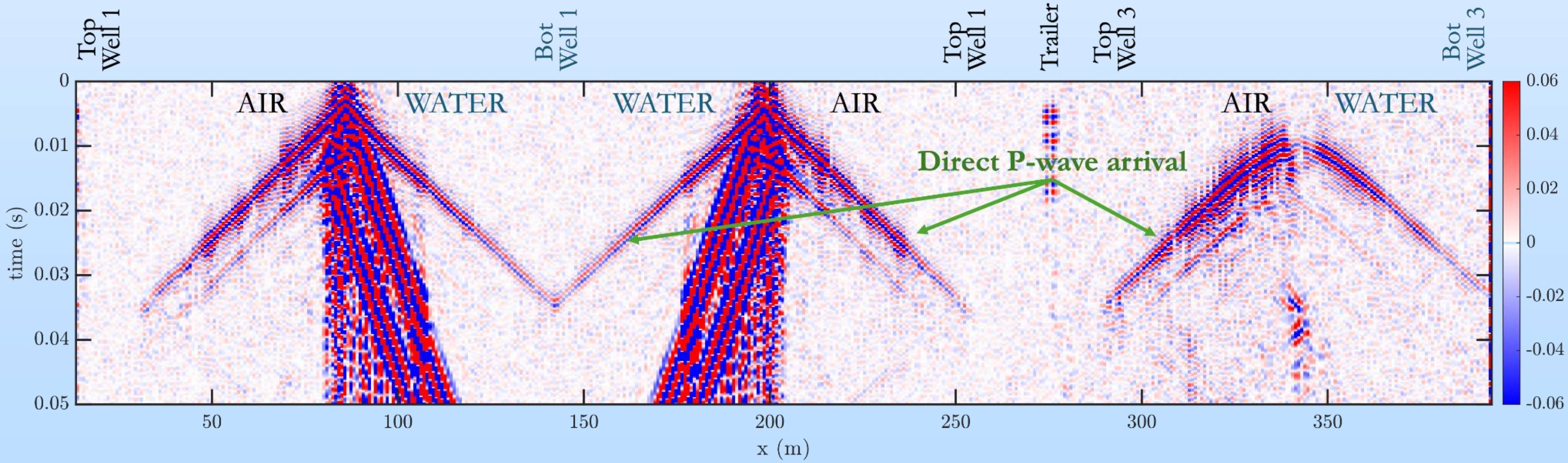
- Unfortunately, the resonance source transducer failed at the beginning of the experiment (transducer failure).
- The geophone + surface source dataset shows correlation between the water level and velocity change over time.
- This indicates that a decreasing water level in the shallow aquifer causes an increase in recorded P-wave velocity.
- Replicating this experiment soon.



Task 4.1: Validation study: Barrel-Stave Source

- **Challenge**: Resonant source, while functional, has suffered from power, leakage, and transducer reliability issues. Decided to field test barrel-stave source discussed previously.
- Source placed in Well 1 at 200 ft depth (25 ft below water). Data recorded using DAS and geophones over 30 h period.
- Strong temperature dependence initially observed in DAS data was traced back to the interrogator software flaw and corrected.
- Excellent data quality. Equivalent S/N to resonance source at mid-frequency band with much shorter stacking time (~2 minutes).



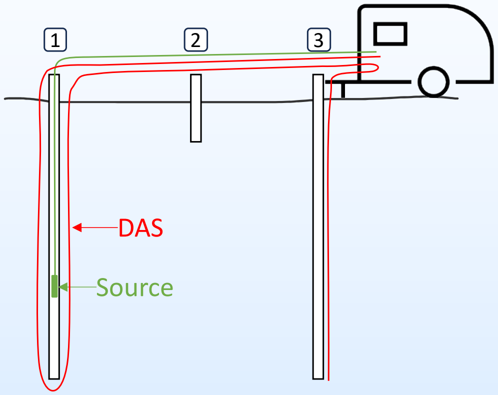


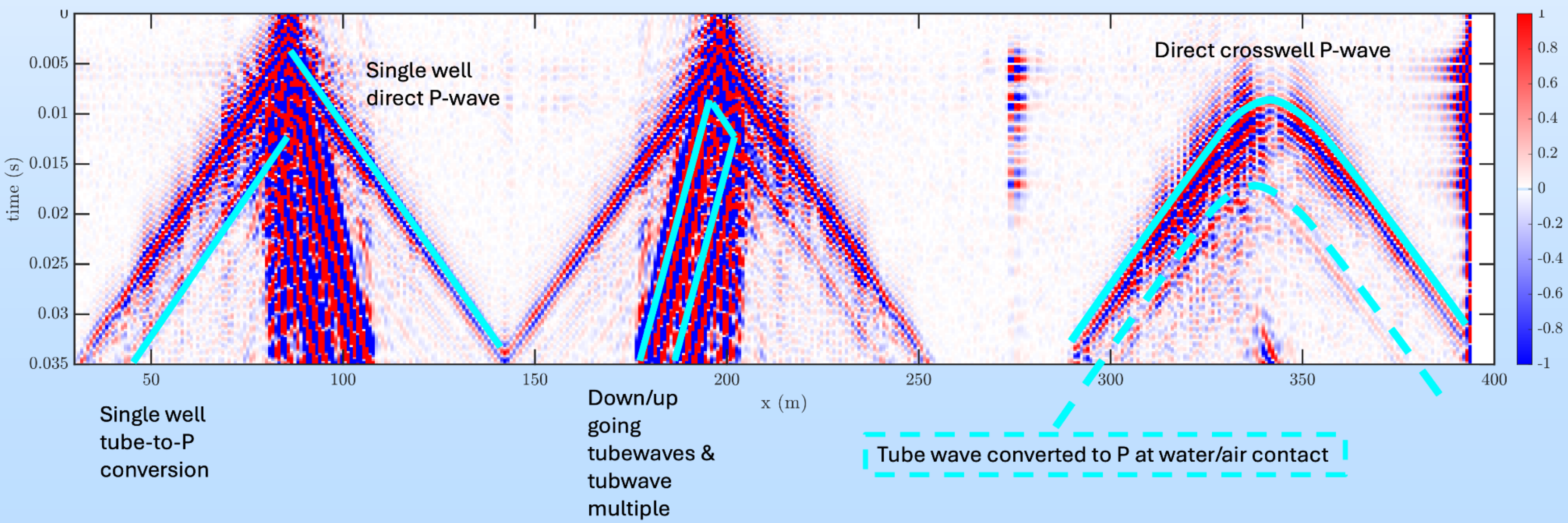
Task 4.1: Validation study: Barrel-Stave Source

- Some interesting phases observed …..
- Tube wave multiples
- Tube-to-P wave conversions in both single and crosswell geometries

Why does this matter?

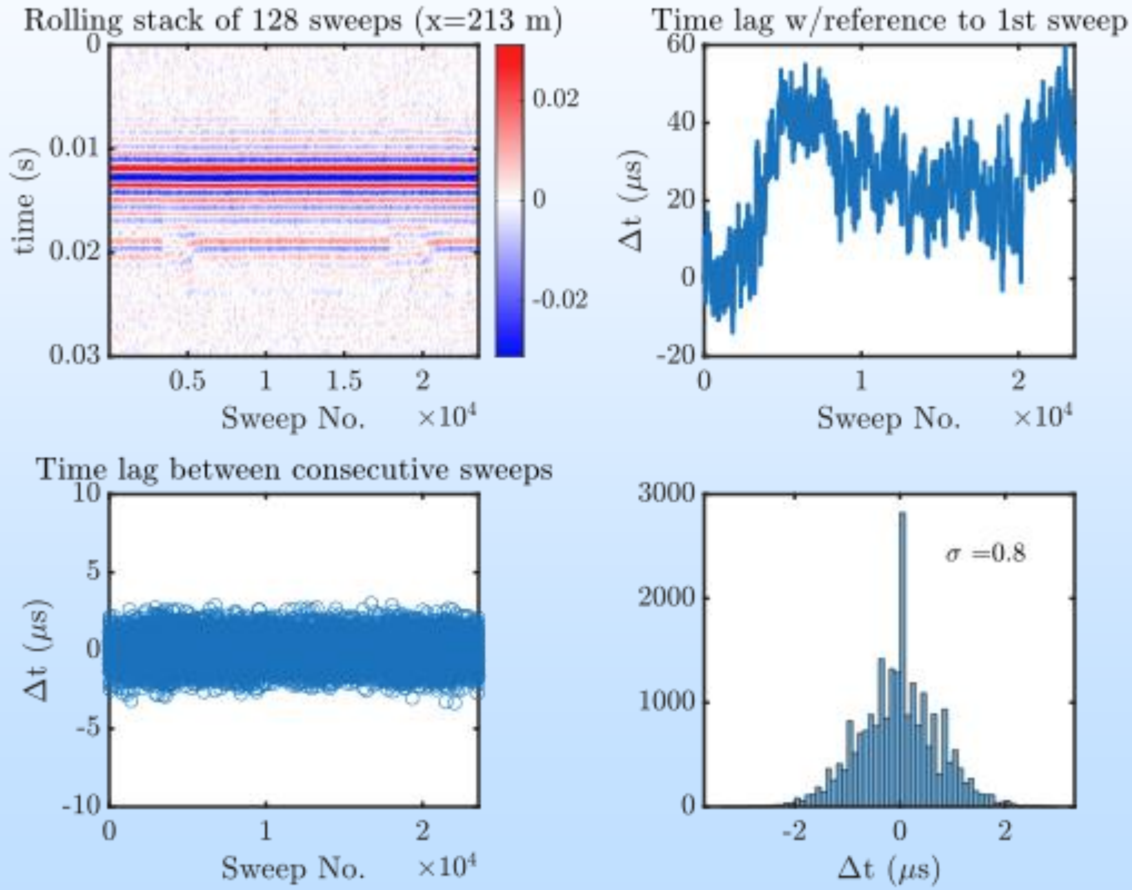
- These phases have potential for a variety of monitoring modalities in GCS (pseudo-logging, secondary sources).





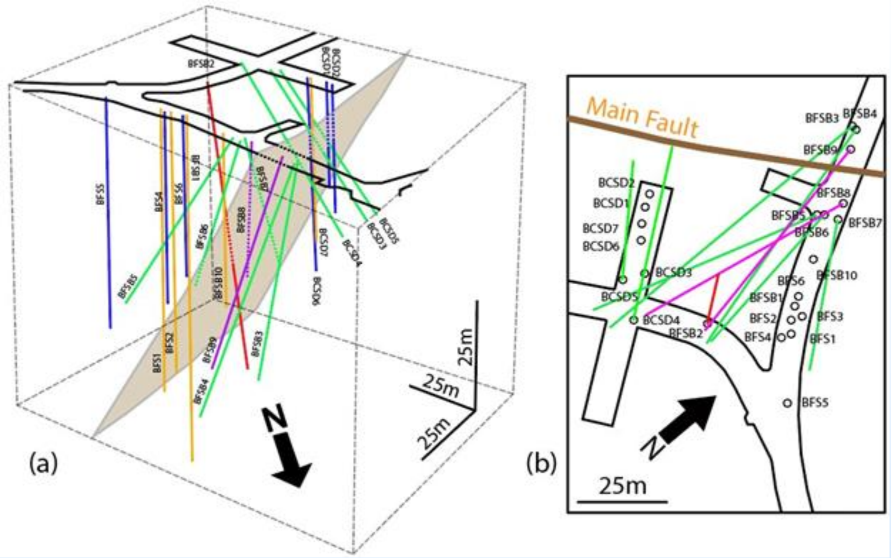
Task 4.1: Validation study: Barrel-Stave Source

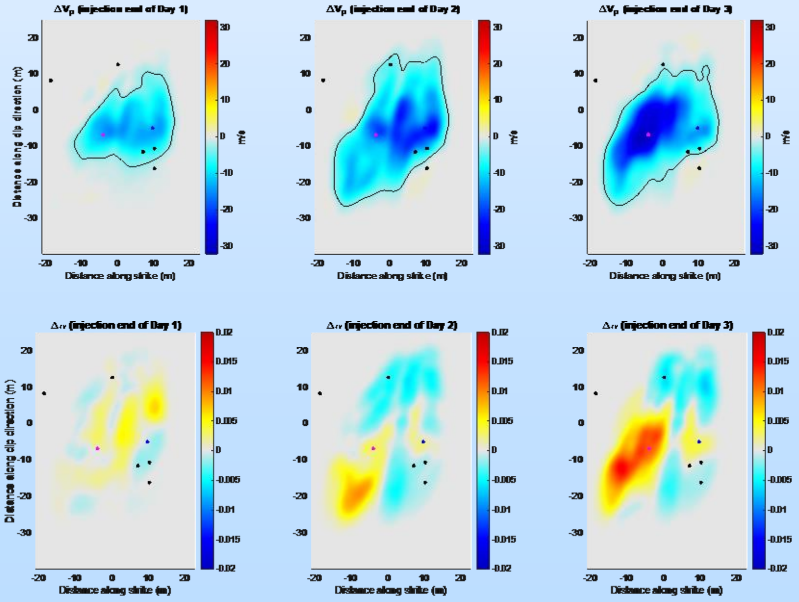
- For DAS data, source repeatability using a rolling stack of 128 sweeps (~2.5 min of data) shows an average time lag between consecutive sweeps is 0 μs with a standard deviation of 800 ns!
- Smallest velocity change that can be detected with the current setup is 0.16 m/s over 2.5 min. Definitely sufficient for next monitoring stage.
- ***Next step***: Recently acquired larger multi-source dataset at RSTF for evaluating FWI algorithms for CASSM/DAS analysis (last week – no slides, ST 4.3). Will use results to refine Task 5 effort.



Task 5: Field Deployment of CASSM/DAS at the Mont Terri Facility

- **Crucial evaluation** is application to seal integrity experiment.
- Will test integrated approach using new LF source array at the Mont Terri site in Switzerland (5.1)
- Several fault reactivation studies already conducted – will use CASSM/DAS approach to monitor the next sequence (5.2/5.3)
- Significant cost saving from existing site instrumentation and characterization – recently completed CO_2 injection experiment.

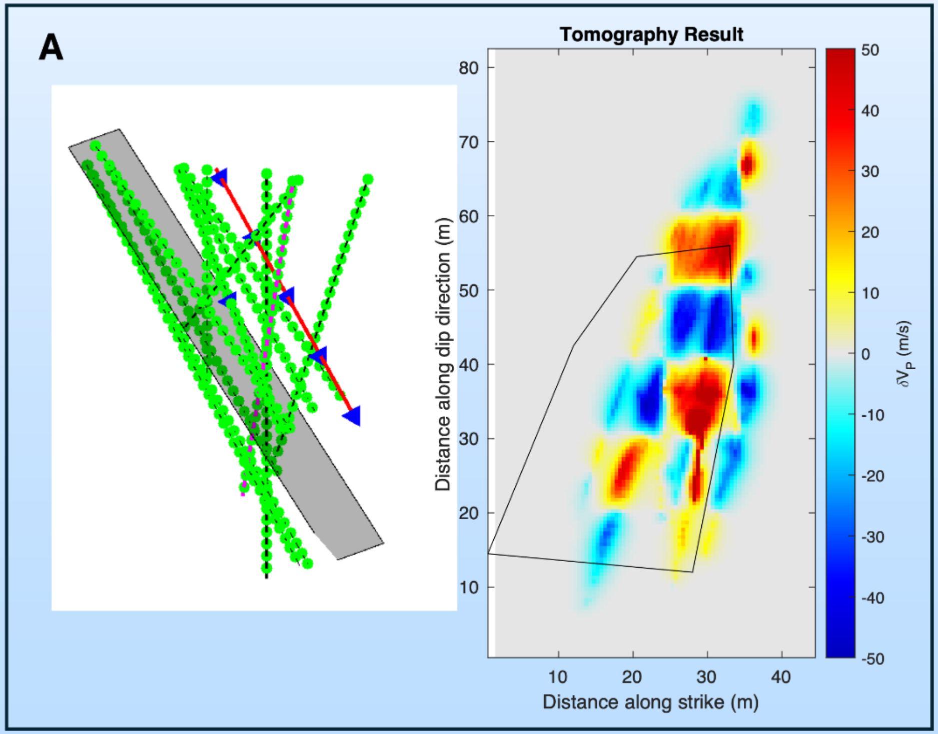


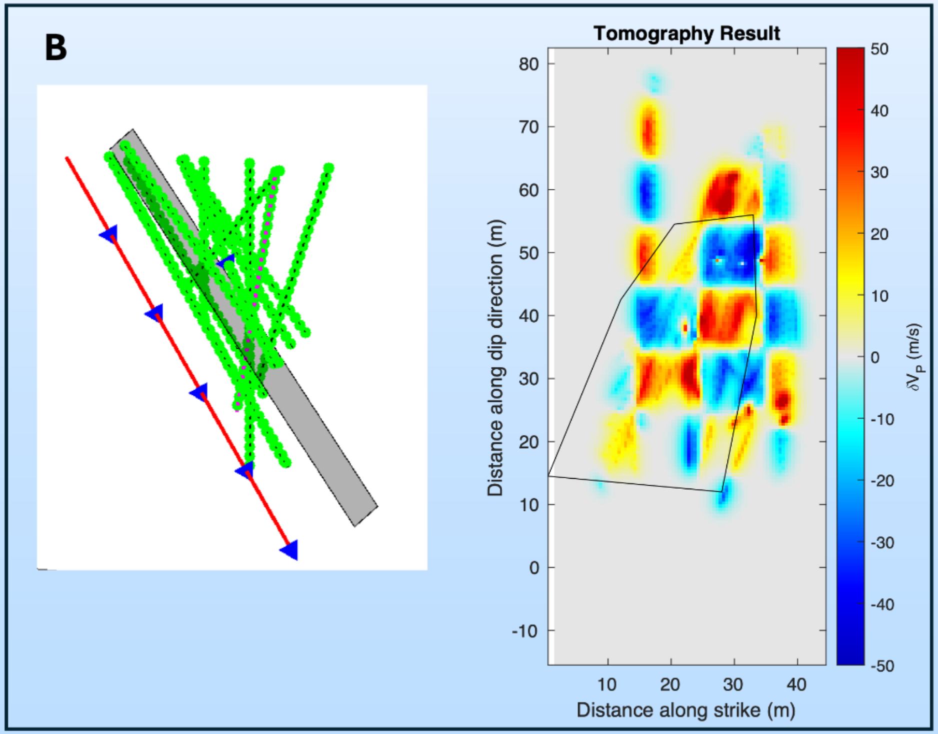


- 5 monitoring wells, all with SM/MM fiber
- Bracket fault – can be taken to failure.
- Reference hydrophone arrays (48 ch.)
- Existing 24 source HF CASSM array
- Comprehensive geomechanical monitoring

Task 5: Mont Terri

- **Question**: Where to place upcoming LF-CASSM sources for fault imaging experiment?
- **Challenges**: Large number of fiber instrumented wells for DAS recording but highly non-uniform distribution.
- Conducted forward modeling/inversion study to evaluate choice of fault footwall vs. hanging wall for new CASSM well.
- Assume 2 m DAS channels for analysis, 5 CASSM sources, various depths.
- Tending towards footwall deployment but still trying to optimize to improve lower regions.



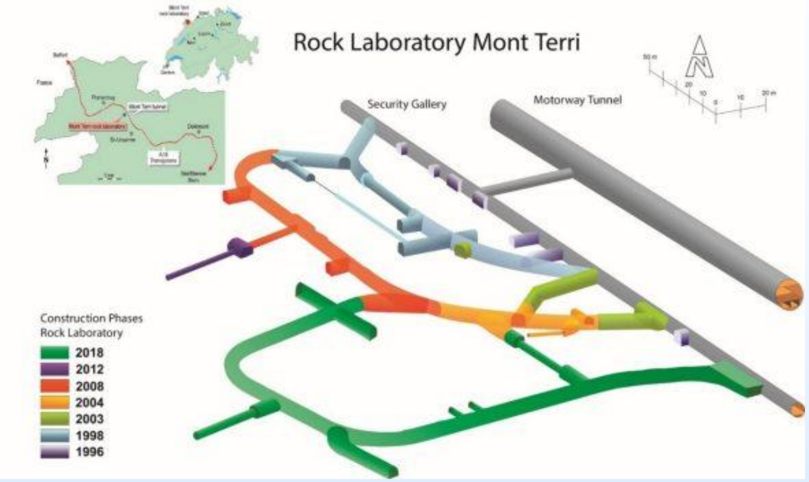


Task 5: Mont Terri: Next Steps

- **Next Steps**: Drill/complete new CASSM source well(s) at Mont Terri underground lab for monitoring experiment.
- Wells will be PVC cased with multiple fibers (SM/MM) components behind casing, permanent LF CASSM sources fluid-coupled.
- Planning source testing at MT (5.1), short fault reactivation (5.2), and longer-term mixed-phase injection (5.3).

- **Preliminary Schedule:**

Aug. 24:	Complete design
September 24:	Well(s) drilled/completed
Nov/Dec 24:	CASSM/DAS field campaign [5.1/5.2/5.3]
Dec. 24:	Data distribution [5.4]
Spring 25:	Analysis/inversion [5.4]



Summary & Next Steps

- Conducted extensive testing of 4th-generation resonant source and barrel-stave flextensional piezoelectric sources in the laboratory.
- Field-validated both sources at RSTF; both sources meet needs for high repeatability (< 1.5 microsecond phase repeatability) and S/N sufficient for CASSM/DAS tomographic imaging.
- Now generating high S/N single well/crosswell CASSM/DAS datasets and replicating hydraulic tests.
- Conducting modeling studies to determine Mont Terri CASSM geometry
- ***Next***: 2024/2025 conducting a sequence of fault reactivation and CO2 injection experiments at Mont Terri + further refinement of FWI and coda wave analysis RSTF results.

Acknowledgements

Thanks!

Support from US DOE, Office of Fossil Energy and Carbon Management through DE-FE0032058 under DE-FOA-0002401

Questions?

Organization Chart

Organization Chart

CASSM/DAS Imaging

Rice University
Jonathan Ajo-Franklin
(PI)
(CASSM Source Development)

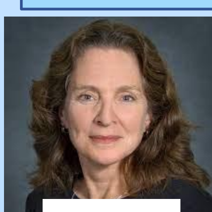
Jonathan

Tieyuan

Pennsylvania State Univesity
Tieyuan Zhu
(co-PI)
(FWI approaches)

PSU PR/GSRA

Jackson Saftner
Gabriel Santos
Zi Xian Leong
(FWI)



Michelle

Todd

Lawrence Berkeley National Laboratory
Nori Nakata
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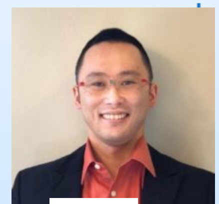
(Coda wave imaging)

Yves Guglielmi
(Co-I)
Fault Zone Monitoring

Michelle Robertson
LBNL/GMF Field Operations

Todd Wood
LBNL/GMF Engineering



Nori

Yves

Rice GSRA

Valeriia Sobolevskaia
(CASSM Source Development/Testing)

Terra 15 LLC
Nader Issa
(co-I)
(DAS System Performance)

Nader

Gantt Chart

- 3 year project involving 6 tasks
- Spans instrument/method development to field validation
- Two field tests, second involving GCS seal leakage component
- Approximately 1 quarter behind schedule due to delay in funding.

Task	Activity	Lead Organization(s)												
Project Year			1				2				3			
Project Quarter			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1	**Project management and planning**	*Rice*												
ST 1.1	Project management plan development													
ST 1.2	Technology maturation plan													
ST 1.3	Team coordination and outreach													
Task 2	**Development of a DAS-Oriented CASSM Array**	*Rice (w. LBNL)*												
ST 2.1	Design of resonant CASSM source													
ST 2.2.	Prototyping of CASSM source													
ST 2.3	Scale up and array fabrication													
Task 3	**Development of CASSM/DAS Processing**	*PSU (w. LBNL)*												
ST 3.1	Timelapse FWI													
ST 3.2	Coda wave interferometry													
Task 4	**Proof-of-concept field test at RSTF**	*Rice (w. LBNL, PSU)*												
ST 4.1	Small scale CASSM/DAS validation study													
ST 4.2	Hydraulic forcing experiment													
ST 4.3	Initial test analysis (FWI & Coda)													
Task 5	**Field Deployment at Mont Terri**	*LBNL (w. Rice, PSU)*												
ST 5.1	Installation/evaluation of test array at Mont Terri													
ST 5.2	Fault reactivation/leakage experiment w. brine													
ST 5.3	Fault reactivation/leakage experiment w. gas													
ST 5.4	Processing of experiment datasets													
Task 6	**Scale-up Analysis and System Development**	*PSU (w. Rice, LBNL)*												
ST 6.1	Source modification for deep GCS deployment													
ST 6.2	Modeling/inversion experiments for scale-up													