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

DE-FE0032058

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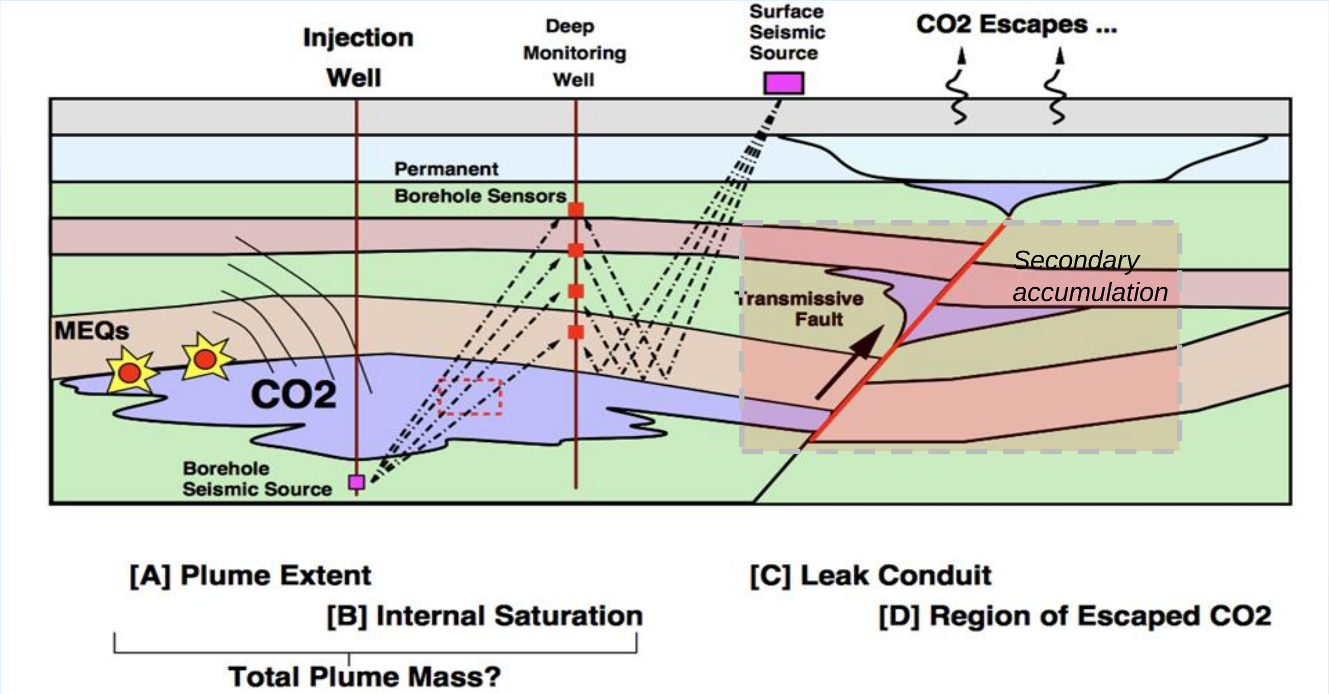
Project Overview

- Funding
  - DOE : 1.19M (over 3 years)
  - Cost-Share: 707K (Rice, SwissTopo)
- Overall Project Performance Dates :
  - July 1st, 2021- July 1st, 2024
- 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.

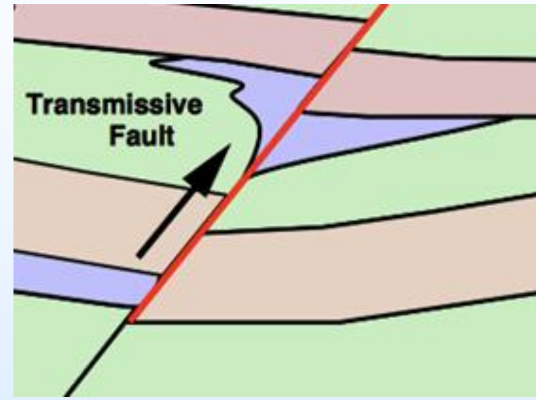
Key Goals for GCS Storage Security

- ***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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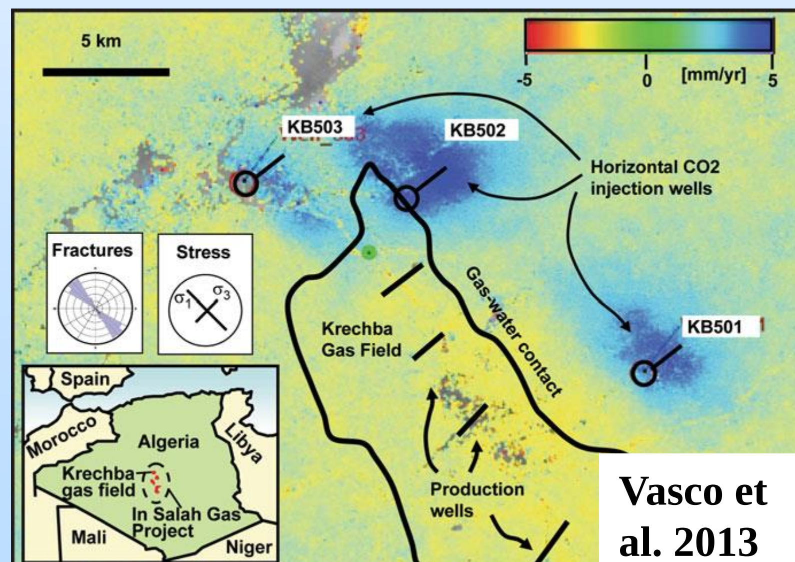
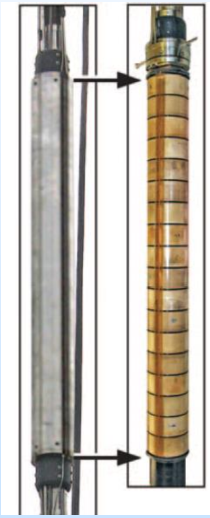


Vasco et al. 2013

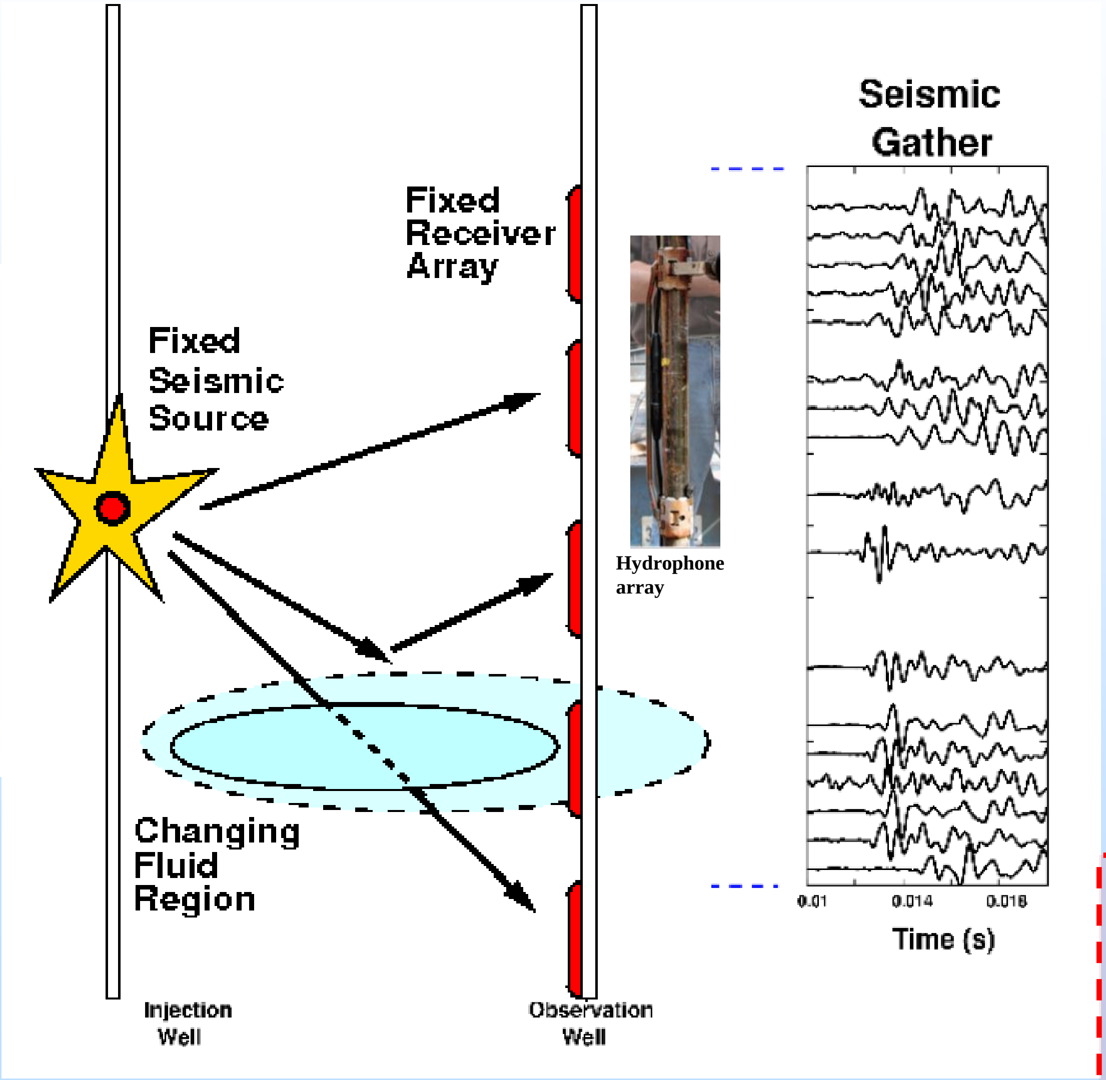
A Useful Technology: CASSM

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]



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

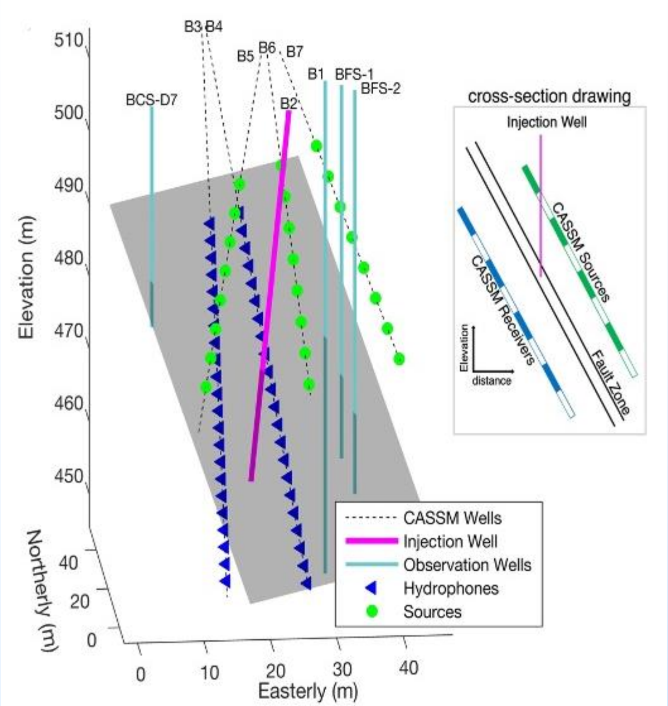
Why CASSM for Monitoring Seals?

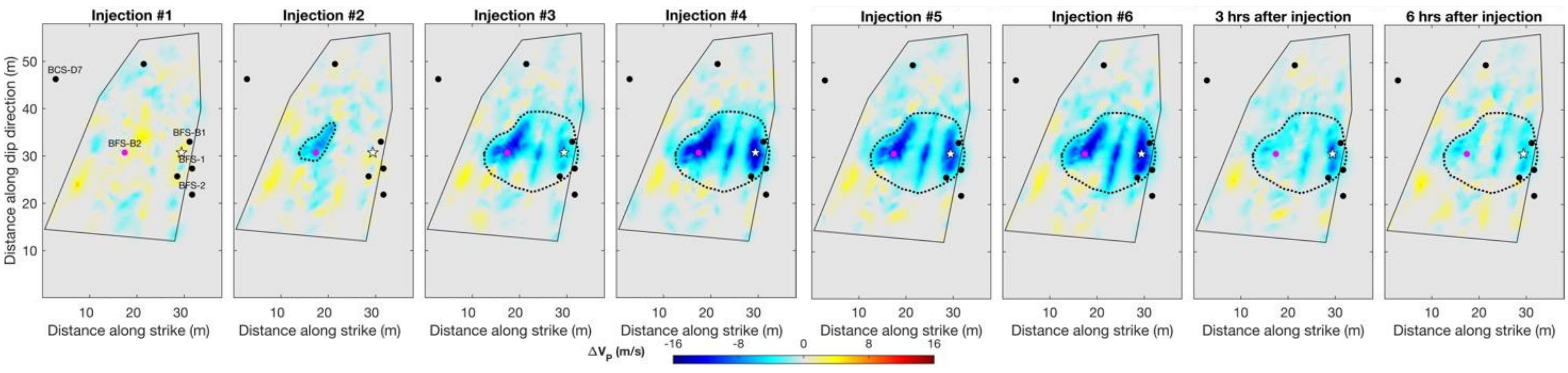
- Microseismic provides constraints on where faults slip (most of the time): not on slow aseismic processes.
- EQs provide no constraints on fault leakage, healing. or creep (long term)

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 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)





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), 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?

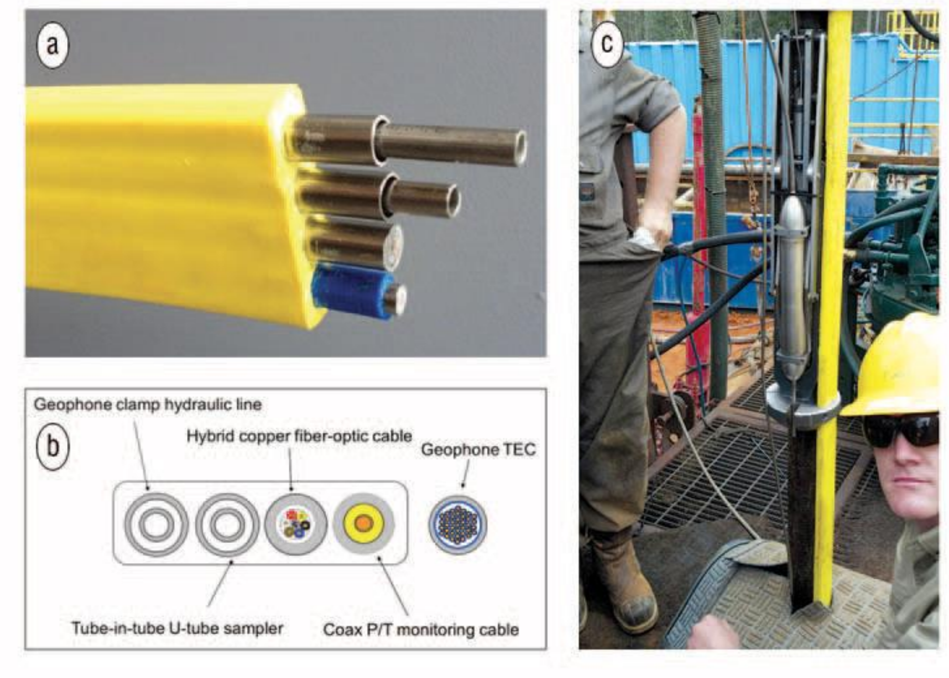
- **Distributed Acoustic Sensing [DAS]** is a rapidly advancing approach for measuring the seismic wavefield using commercial fibers (SM, telecom)

- **Recent** : S/N became sufficient for seismology around 2011. Our work started ~2012/13 out of CO_2 GCS program (borehole applications)

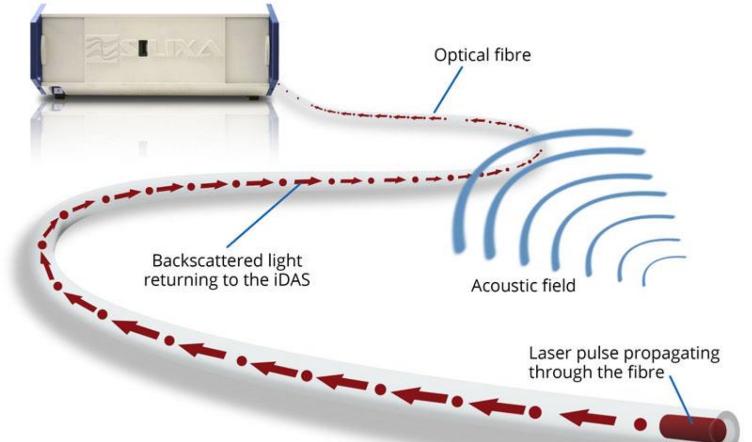
- **Large N** : Easy to deploy in wells, behind casing, 1000s to 100,000s of channels available (big data) over 10+ km (biggest current use is VSP)

- *Very low cost per "sensor"* : \$/ft for cable
- *Rugged* : handles high/low T, high pressures.

- ***The solution for CASSM?***

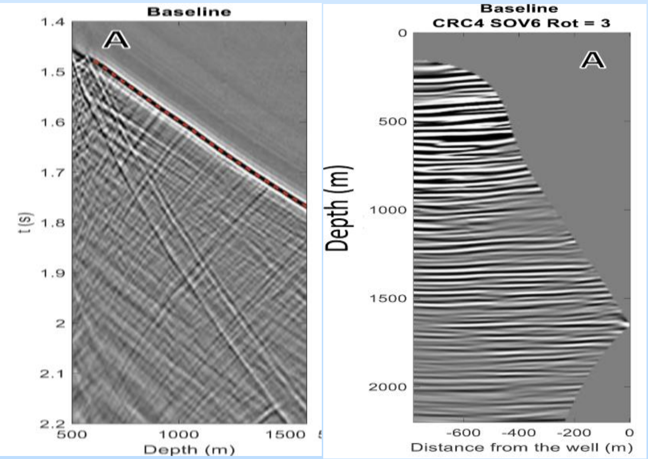


Daley et. al. 2016 (Geop Prosp.), Daley et.al. 2013, (TLE)



Courtesy Silixa LLC

Pevzner et al. 2021 [Otway]



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

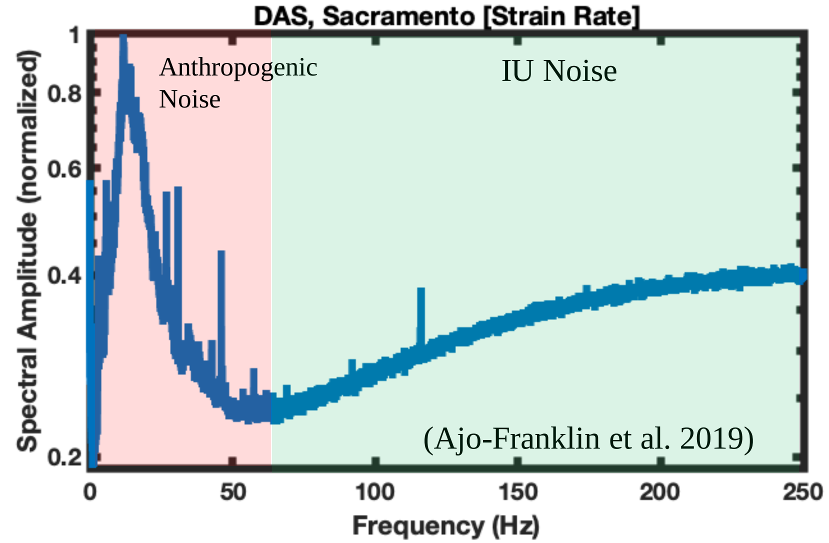
Despite clear advantages, some challenges

Frequency Mismatch:

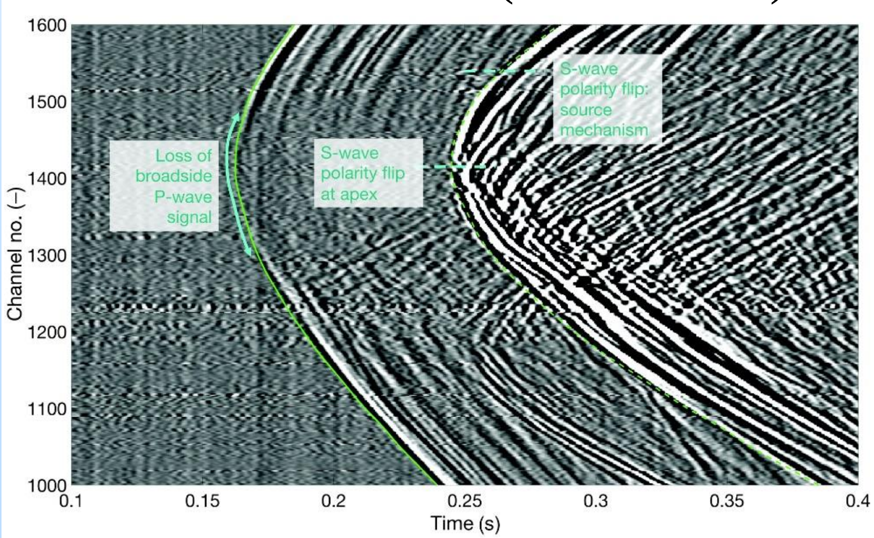
- DAS often exhibits increasing noise at high (kHz) frequencies, presents a mismatch with high F piezoelectric sources (depends on IU). In theory should be flat in strain …..
- Field application will also require longer propagation distances

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.

Technical Approach: Milestones

	Task Number	Deliverable/ Milestone #	Deliverable Title/Description	Deliverable/Milestone Planned Completion	Actual Completion
	1.0/1.3	D1	Data Submitted to NETL-EDX:	90 days after completion	
	1.1	D2	Project Management Plan:	30 days after award.	Jan. 13th, 2022
	1.2	D3	Technology Maturation Plan:	90 days after award.	Jan. 13th, 2022
Source Development (T2)	**2.2**	M1	LF CASSM Source Validated:	Year 1, end of Q4	Jan. 12th, 2023
	2.2	D4	LF CASSM Source Design & Testing Results:	Year 1, end of Q4	Feb. 22nd, 2023
Imaging/ Modeling (T3)	**3.1**	M2	FWI HiEKF Validation:	Year 1, end of Q4	Delayed (est. Q4, 2023)
	3.1/3.2	D5	Report on FWI/Coda Approach:	Year 2, end of Q1	Delayed (est. Q4, 2023)
NS Field Validation (T4)	**4.1**	M3	CASSM/DAS Concept Field Validated:	Year 2, end of Q2	(est. Q4, 2023)
	4.1	D6	Results from Field Testing of CASSM/DAS:	Year 2, end of Q3	(est. Q1, 2024)
	4.3	D7	Inversion Results from RSTF:	Year 2, end of Q4	
Fault Reactivation Experiment (T5)	**5.1/5.2**	M4	Successful Initial Installation and Performance at FSB Testbed:	Year 3, end of Q1	
	5.1/5.2	D8	Preliminary Results from FSB Test:	Year 3, end of Q3	
	5.3	M5	Successful Initial Processing of FSB DAS/CASSM Dataset:	Year 3, end of Q3	
	All	D9	Final Report:	Year 3, end of Q4	

Task 2: Development of a DAS-Oriented CASSM Source

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:

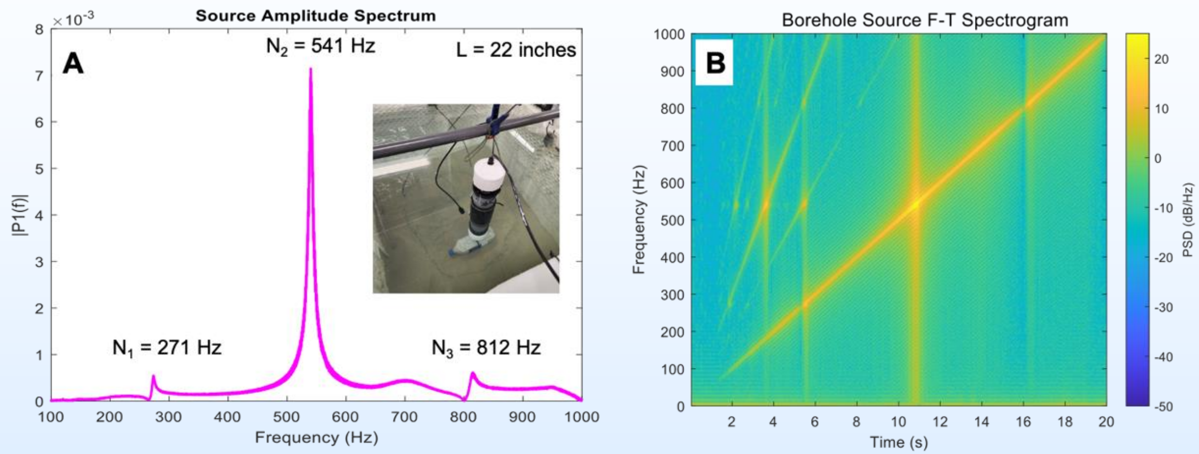
- Fabrication of several prototypes and lab testing in a water tank.
- Reference hydrophones & DAS cables for evaluation.
- Compare to numerical models and extrapolation to field response.

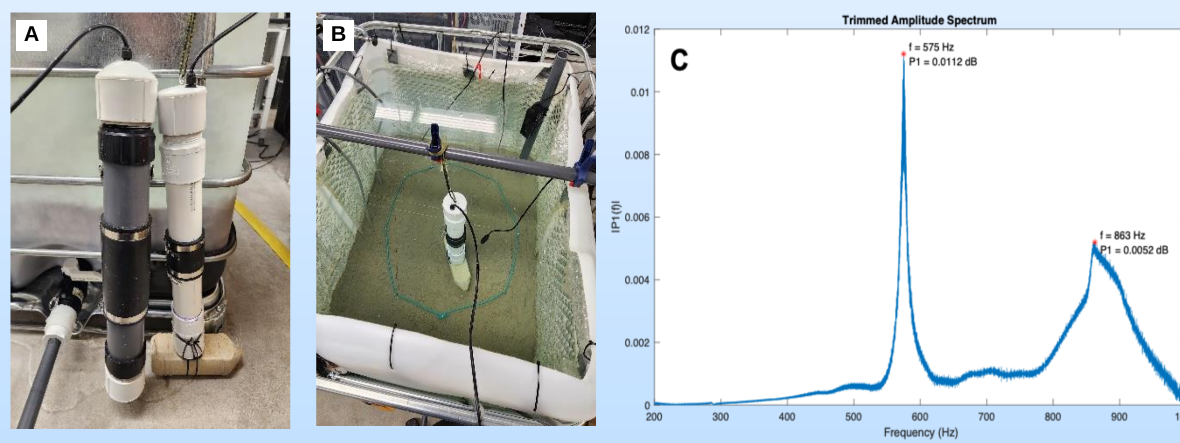
ST 2.3: Fabrication of LF CASSM array for field experimentation

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

Task 2: Third Prototype: Resonant Source

- Third prototype: air-backed simple closed pipe resonator with a rubber membrane to facilitate pressure transfer.
- Active element is a 4-ohm transducer excited by 20 W audio amplifier.
- Linear 20 s sweep: calibrated hydrophone registers first three modes.
- Higher order non-linear modes at nF frequency values (a sign of distortion in the transducer) and broadband energy (mechanical noise?) still observed in the spectrogram.

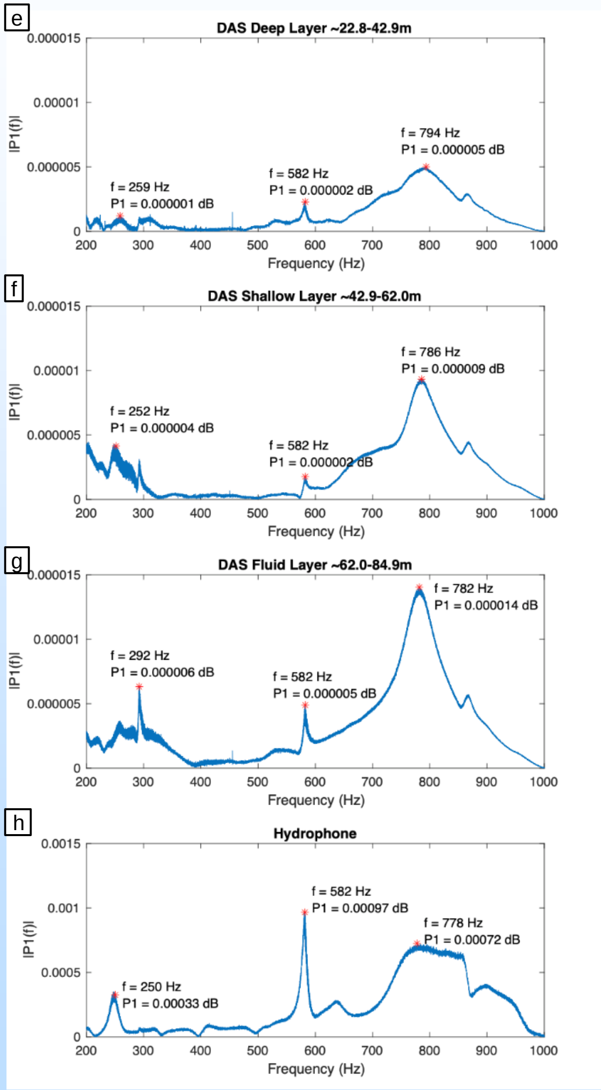


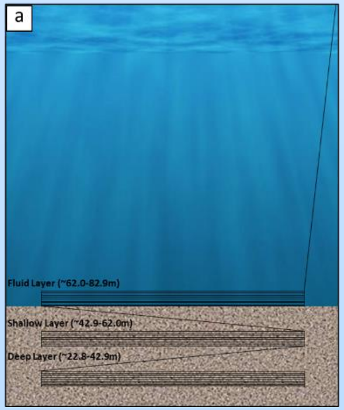


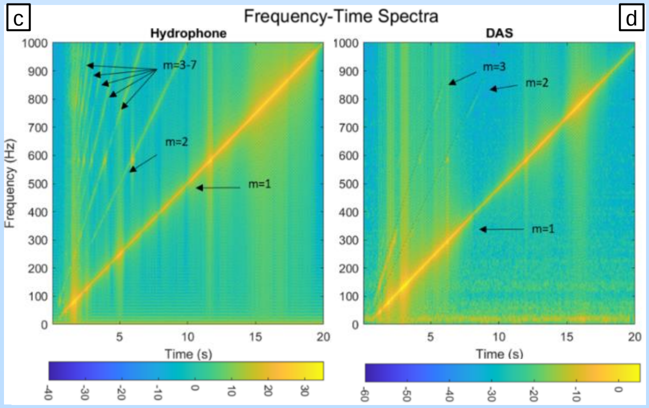
- The next prototype (3.5) was designed similarly but with reduced dimensions to fit into 4" wells at RSTF during the next testing phase.
- The final source 2nd and 3d mode resonance frequencies (575 and 863 Hz) are appropriate for DAS application.

Task 2: Developed Source Tank Test with DAS

- Tank tests using DAS as the receiving sensor to prepare for Task 4.
- Used fluid and sediment-coupled fiber to evaluate the impact of DAS installation on the associated signal.
- ~3x3x4' tank with 100 m of DAS fiber coiled and partially buried in 12" of sand at the bottom.
- The source successfully amplifies acoustic energy in the 200-600 Hz frequency range.
- Both DAS and hydrophone record three relevant resonant modes.
- DAS/hydrophone show different modal strengths – likely related to pressure/strain conversion and sediment coupling.
- Further work is needed to reduce vibrational noise.

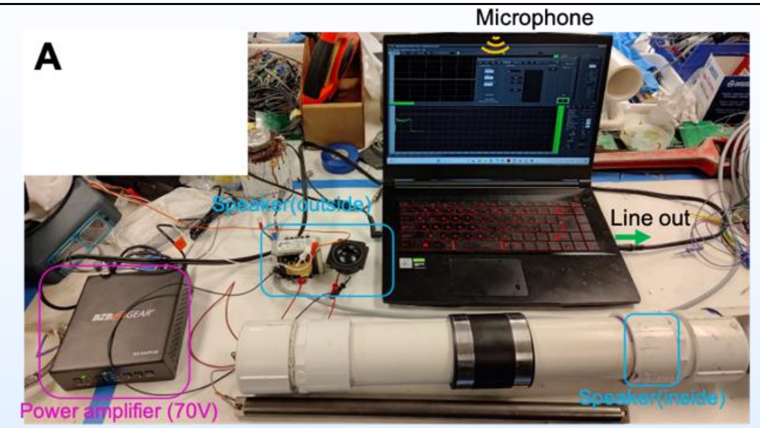


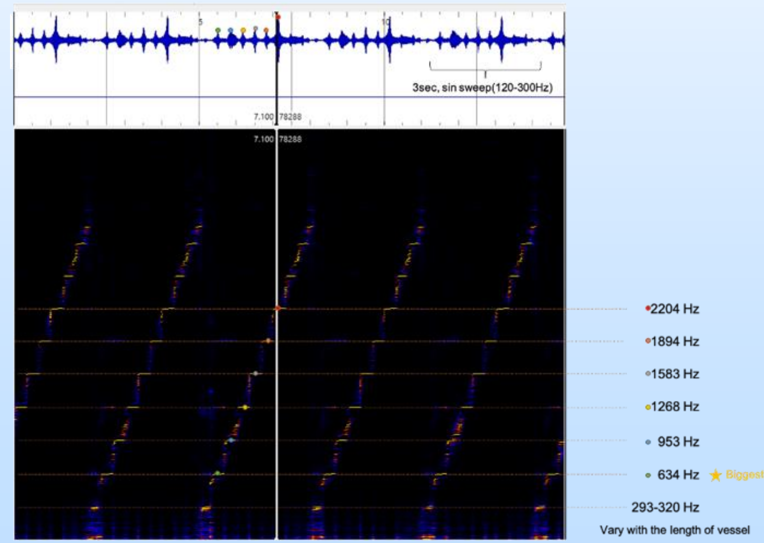


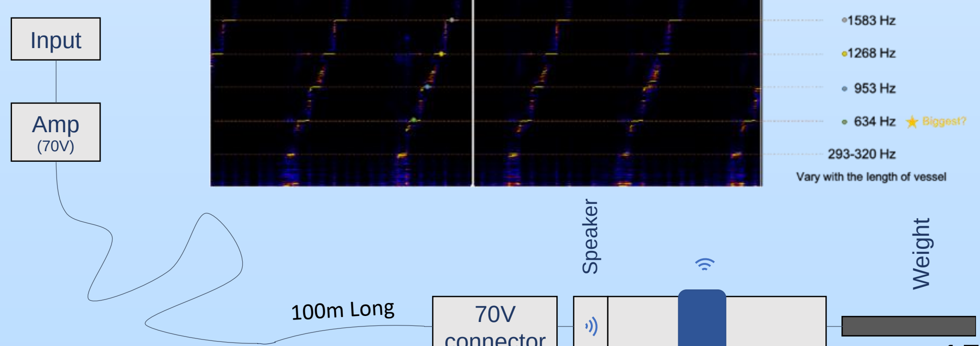


Task 2: Hardened Source Fabrication

- Improved design to minimize leakage risk.
- Added a transformer module to allow power distribution at 70 V with a step-down immediately before the source.
- Air test with 120-3000 Hz sweep excited the first 7 length modes with the 2nd mode (634 Hz) the strongest.
- Slightly higher resonance frequencies due to a reduced effective length.
- Last step – manufacture of a larger number of sources (~5) to allow array deployment.







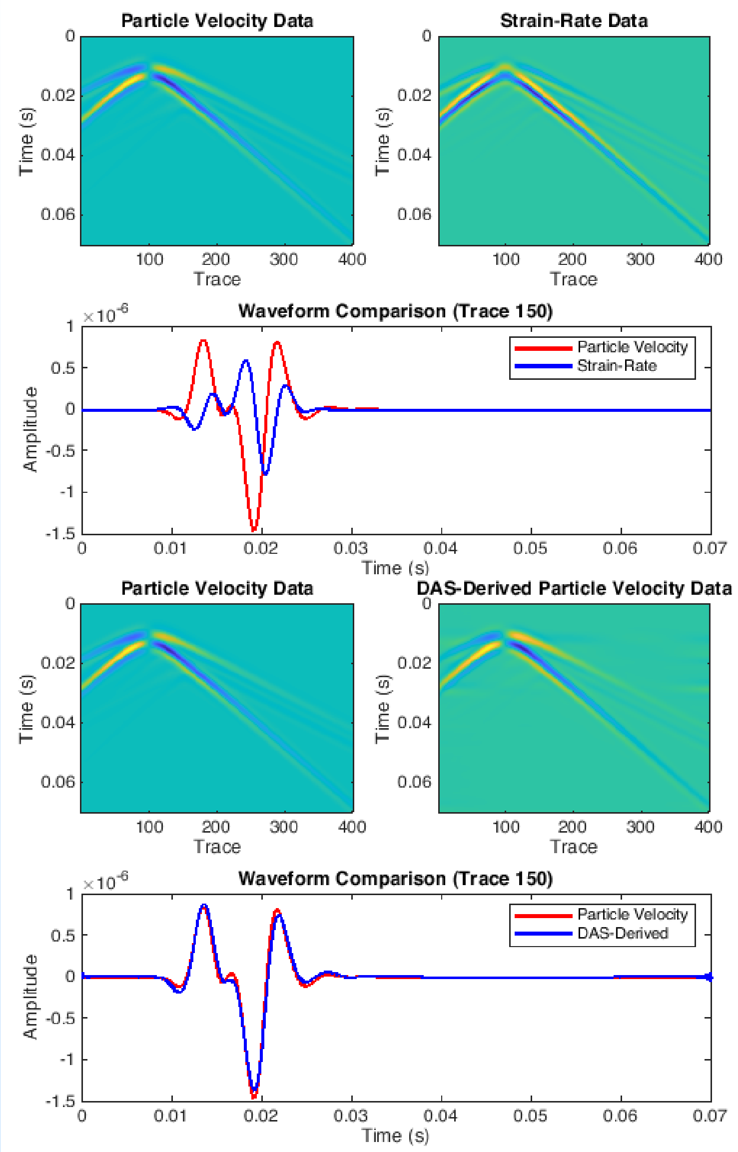
Task 3.1: FWI with CASSM/DAS

- Time-Lapse Full Waveform Inversion (TLFWI) has been used to create high spatio-temporal resolution monitoring model sets from CASSM data. (Liu et al., 2022)
- TLFWI workflows are usually formulated for hydrophone/geophone data, which is fundamentally different from the strain or strain-rate data recorded by DAS.
- Fortunately, it has been shown (Aki and Richards, 2002; Daley et al. 2016) that strain data can be converted to particle velocity by scaling with apparent velocity (c).

$$v = \pm c\varepsilon$$

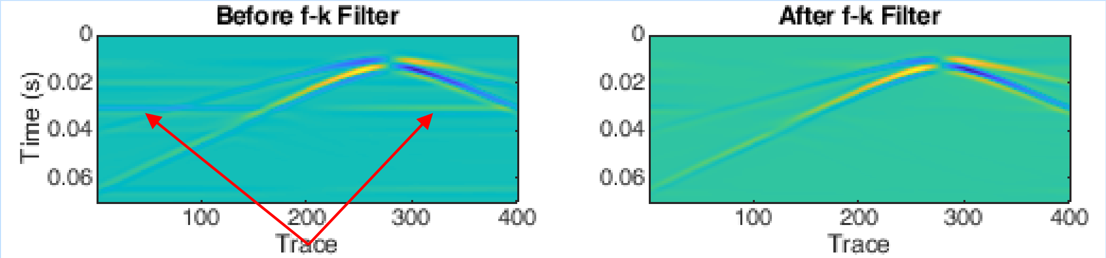
- In practice, the f-k scaling method of Wang et al. (2018) is convenient for cross-well data. This method scales by apparent velocity ($\frac{\omega}{\kappa}$) in the strain f-k domain (E).

$$V(\omega, \kappa) = \frac{\omega + \epsilon}{\kappa + \epsilon} \mathrm{E}(\omega, \kappa)$$

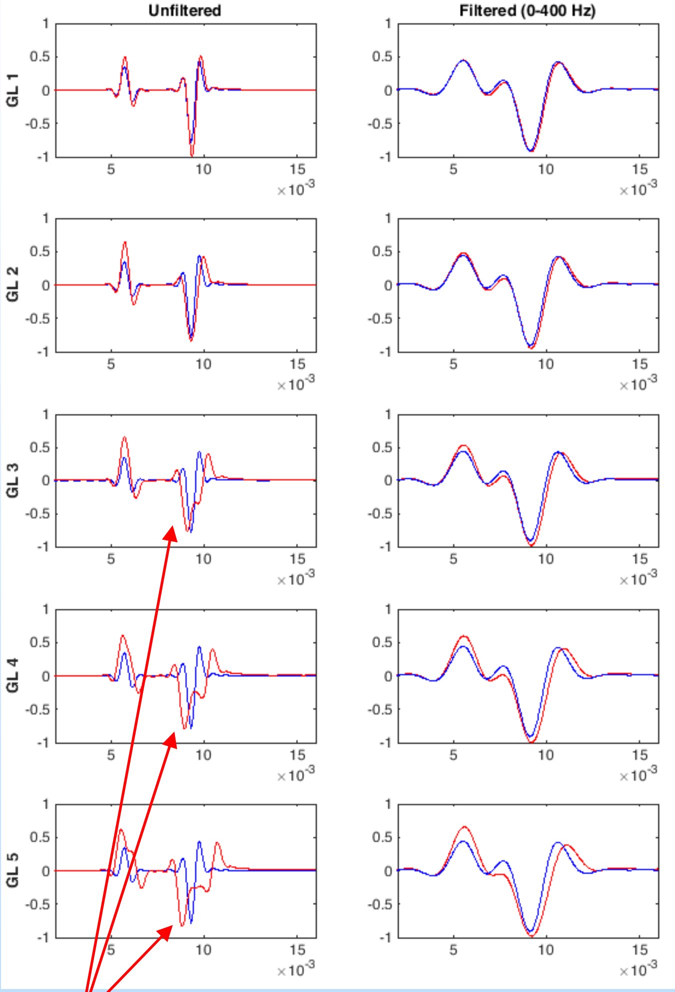


Task 3.1: Limitations of DAS-derived Particle Velocity data

- Two primary considerations must be made to ensure the quality of the DAS-derived particle velocity data.
- First, the spatial wavelength along the fiber must be significantly longer than the gauge length to avoid spatial aliasing issues.
    - Mizuno et al. (2020) recommends a wavelength that is at least 2.5 times longer than the gauge length.
    - Where this criterion is not met, lowpass filtering can lessen the effects of aliasing.
- Second, the f-k scaling method of Wang et al. (2018) tends to introduce low-wavenumber artifacts.
    - High apparent velocities can be removed with f-k filters, and remaining artifacts can be removed through muting.



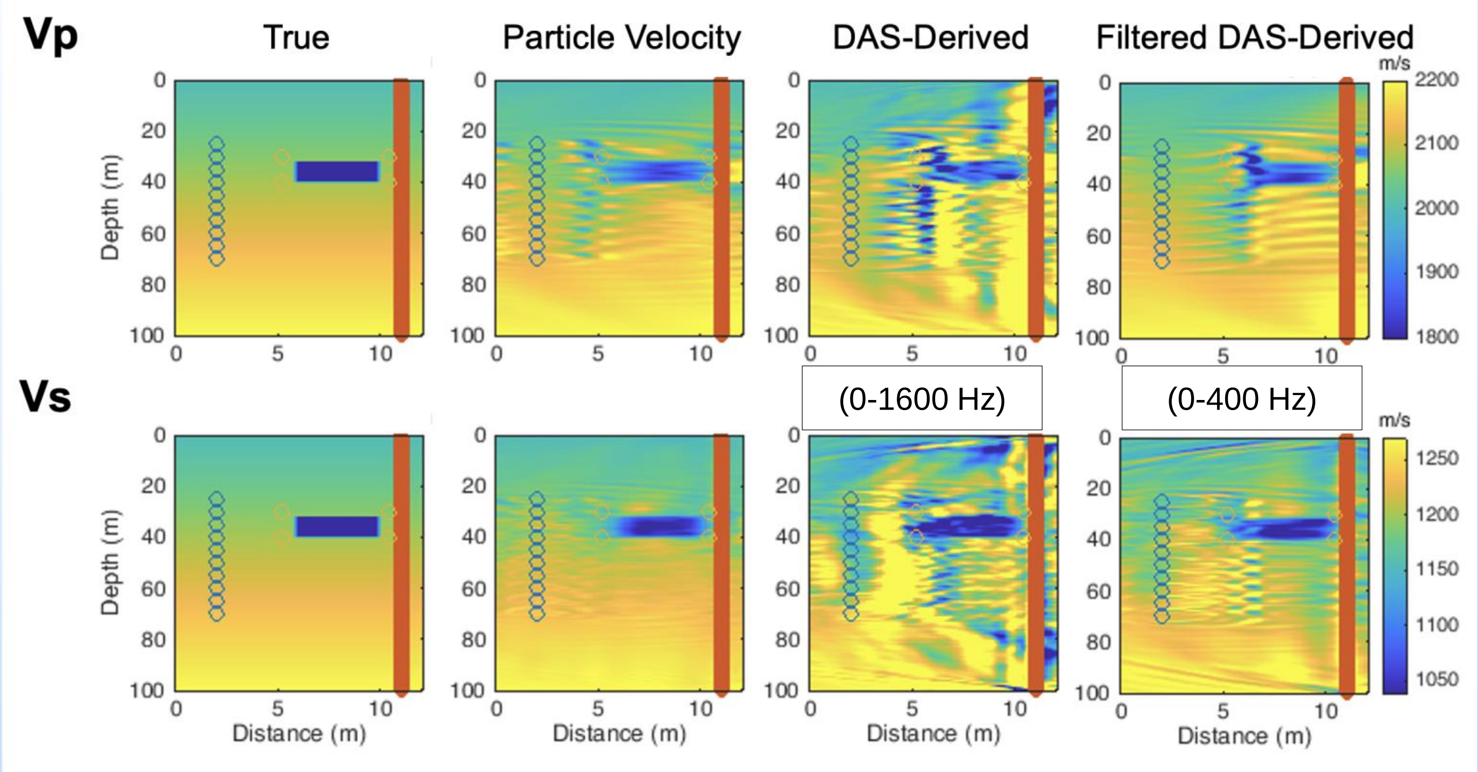
Low-Wavenumber Artifacts



Spatial Aliasing

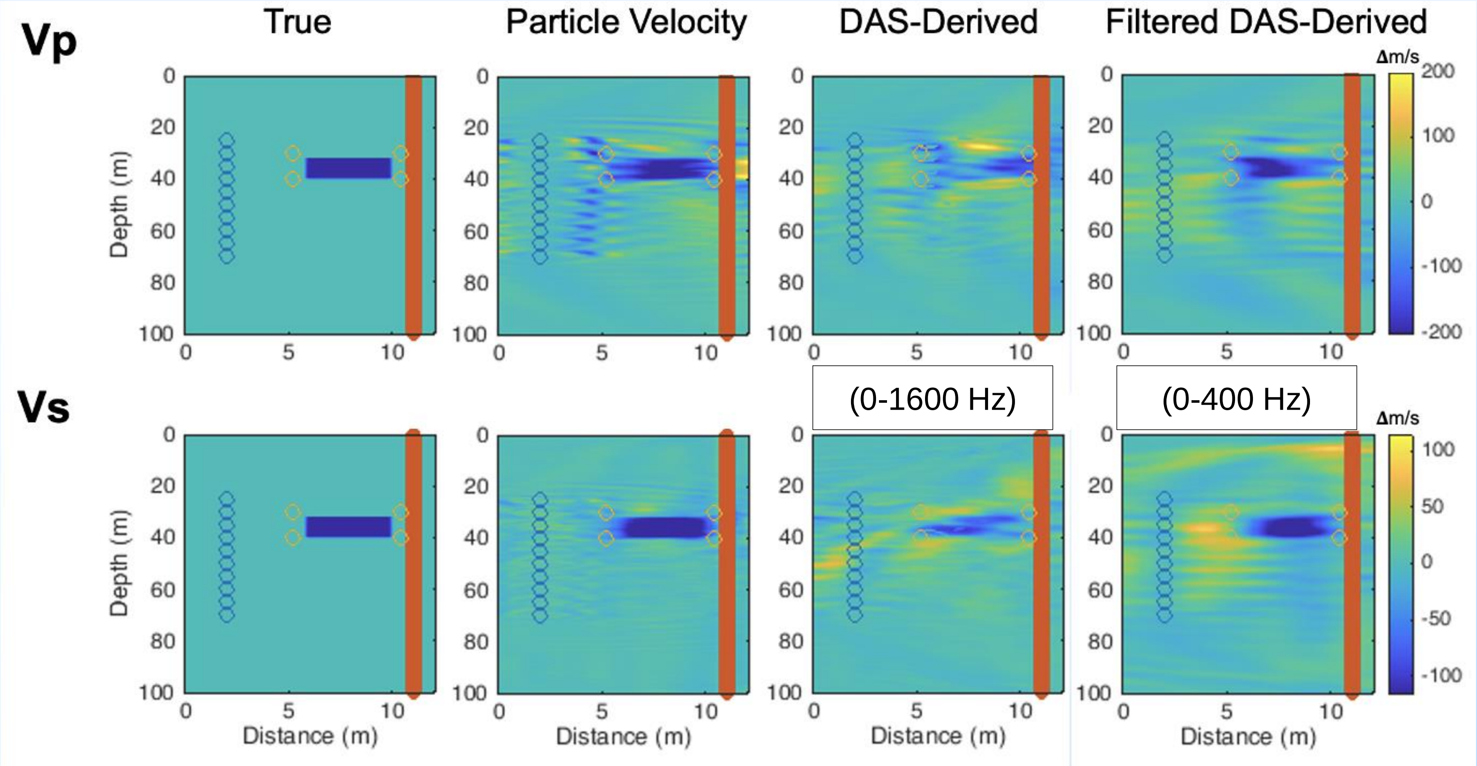
Task 3.1: Cross-well Synthetic Test

- Cross-well synthetic testing of FWI with DAS-derived particle velocity yields good recovery compared with real particle velocity data.
- Here, we use an 800 Hz ricker wavelet as a source.
- The DAS-derived particle velocity data is created using a 2m gauge length.
- We also invert DAS-derived particle velocity data that has been lowpassed (400 Hz), and we observe reduced noise in our models.



Task 3.1: Time-Lapse FWI

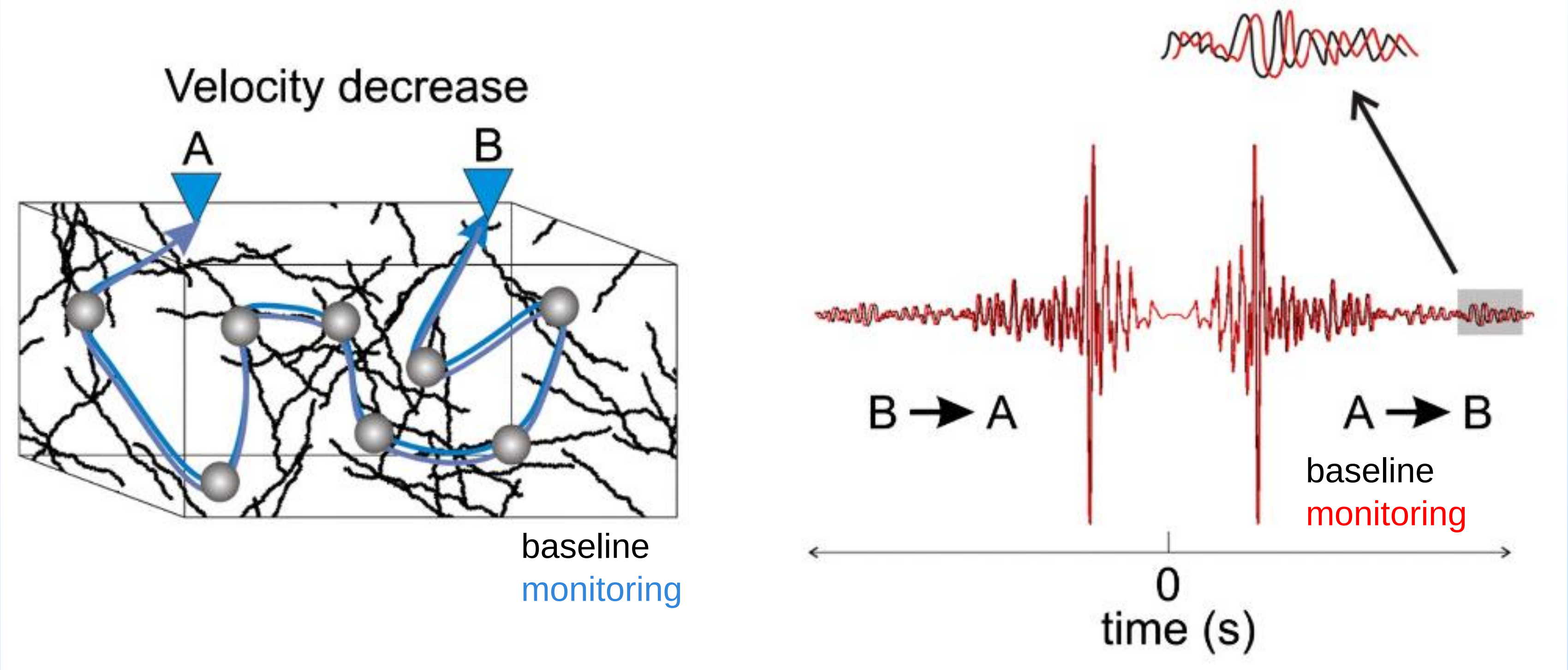
- Taking advantage of the time-lapse nature of CASSM datasets, we can invert data differences to model changes in Vp using the double-difference strategy.
- This method helps to account for errors incorporated during the conversion process.
- More advanced time-lapse FWI workflows (i.e. Hierarchical Matrix-Powered Extended Kalman Filters, HiEKF) could further improve these results by assimilating data from multiple monitoring surveys.



Lower frequency content reduces error, but also reduces resolution (Vp is particularly sensitive).

Future work will aim to determine the maximum viable frequency content that can mitigate the effects of spatial aliasing while minimizing resolution losses.

Task 3.2: Coda-Wave Analysis for Time-Lapse Measurements with DAS



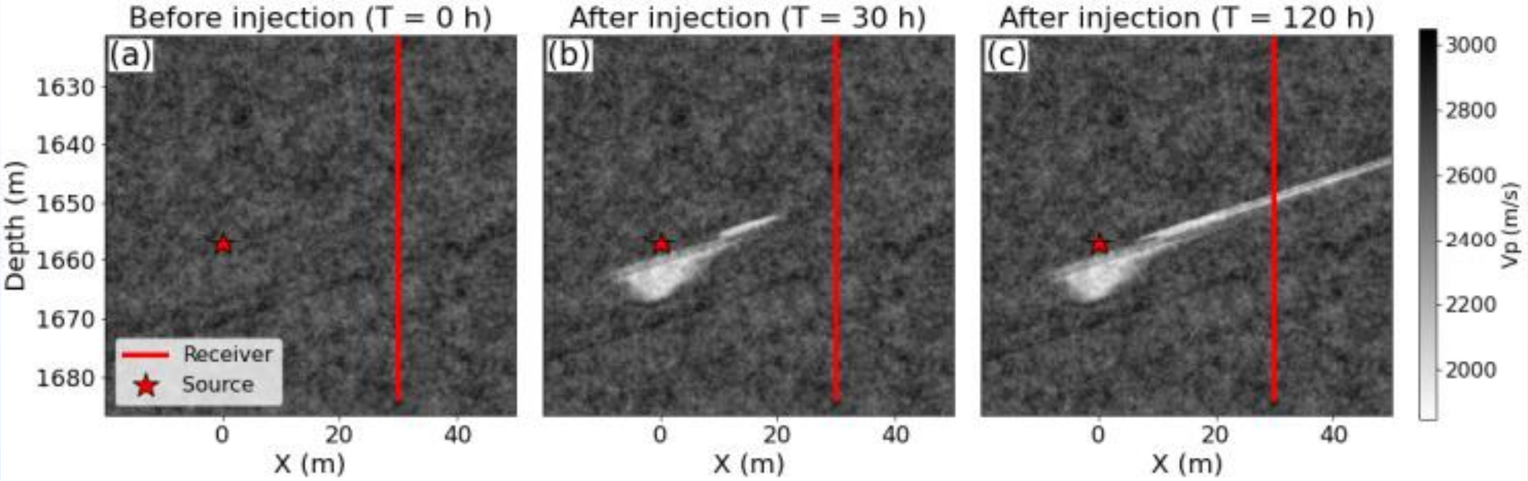
Brenguier, Nakata, et al (2016)

Coda waves, later phases with multiple scattering, are highly sensitive to very small structure changes due to multiple times of sampling of media.

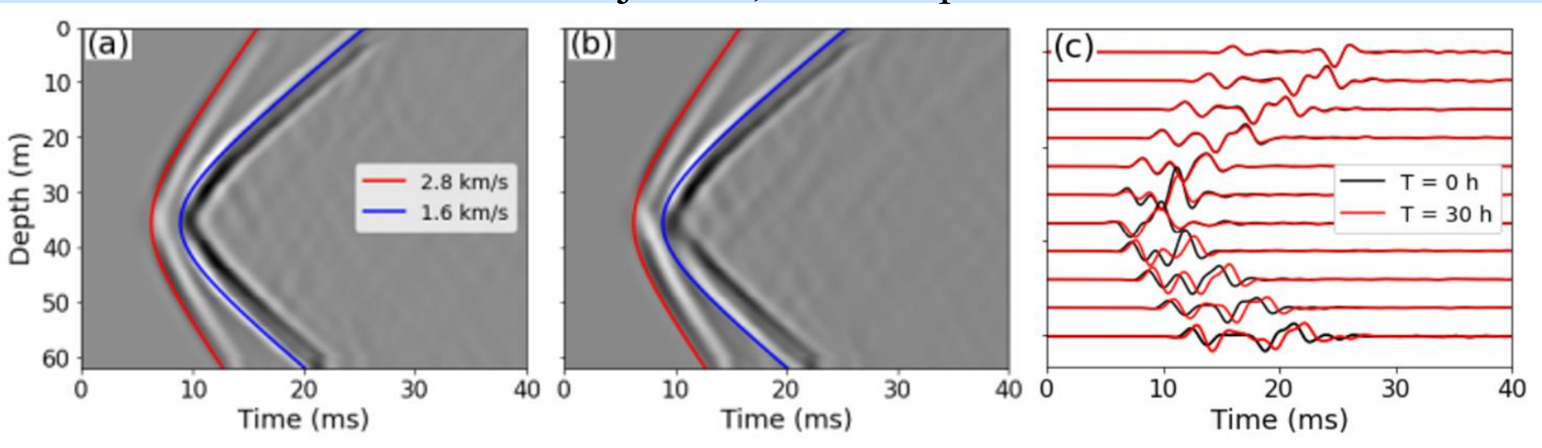
Task 3.2: Coda-Wave Analysis for Reservoir Monitoring

We use synthetic waveform to test capability of coda-wave analysis for reservoir monitoring.

Synthetic velocity model and source-receiver geometry (based on Frio experiment)



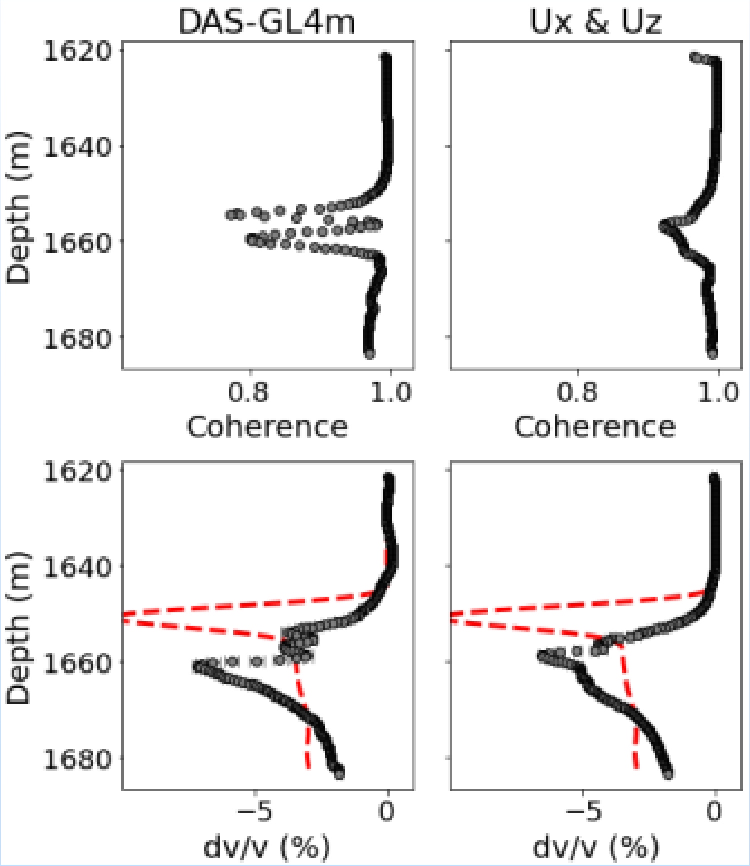
Waveform records before and after injection, and comparison



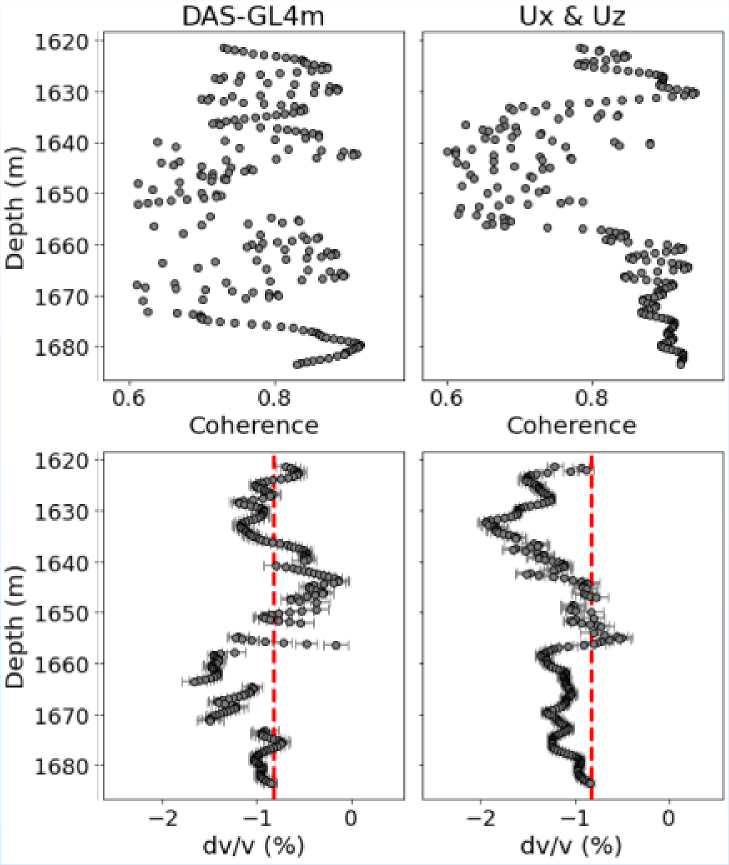
Task 3.2: Coda-Wave Analysis for Reservoir Monitoring

Coda waves are sensitive to the velocity reduction even receivers are not on the reservoir.

Direct waves



Coda waves



Future work: Appling this coda-wave approach to the field data of new CASSM

Task 4 Work Plan:

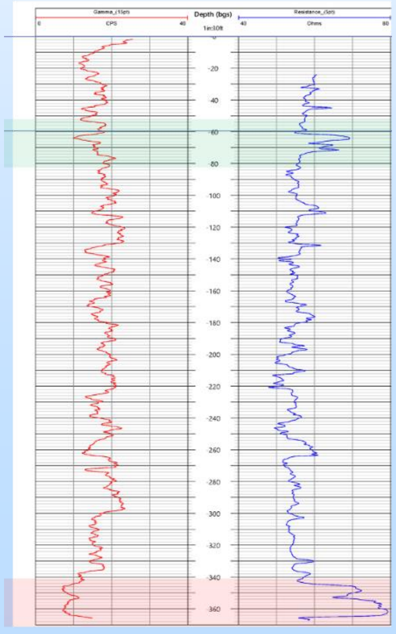
ST 4.1 : Small-Scale validation study of CASSM/DAS combination

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

ST 4.1 : Small-Scale hydraulic test to evaluate time-lapse performance.

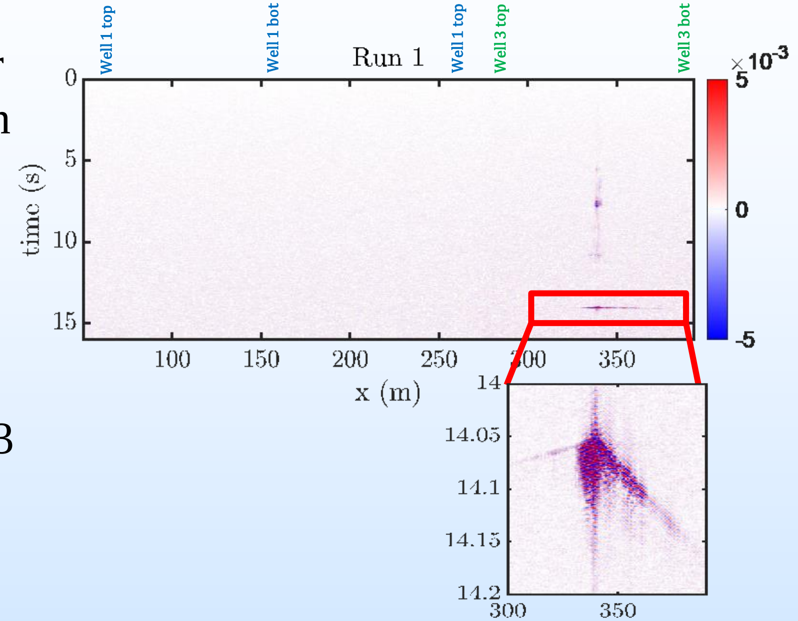
- Conduct hydrogeophysical monitoring test to evaluate sensitivity.
- Depress surficial aquifer by 1m, 9 kPa load forcing. Can we see it?

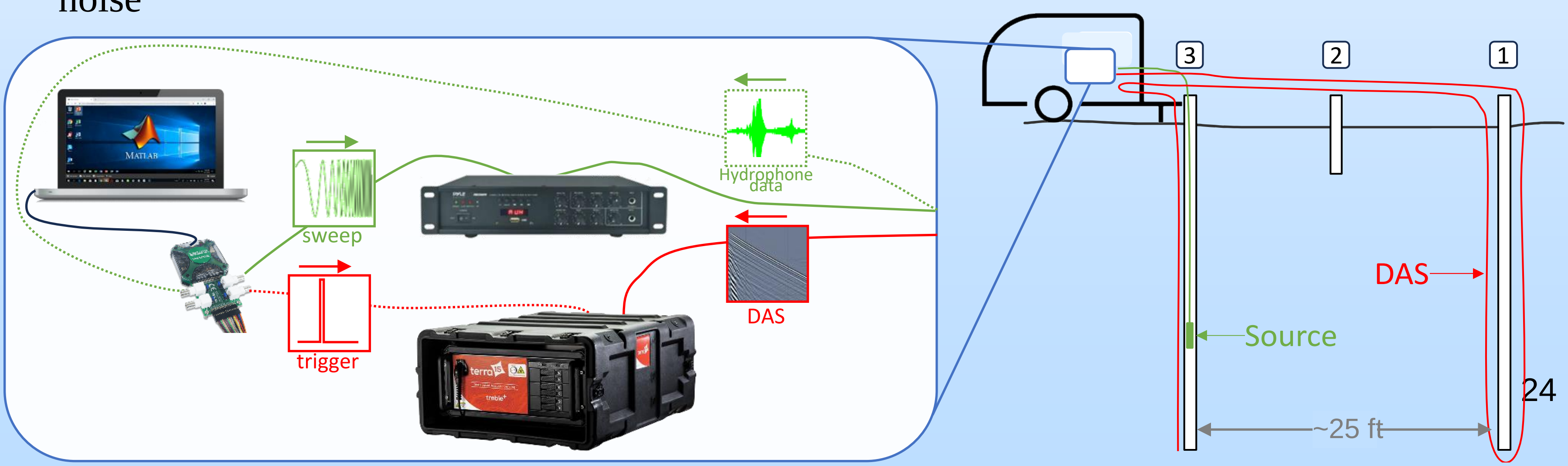
ST 4.2: Analysis of small-scale test using developed monitoring algorithms



Task 4: RSTF Source Test 1

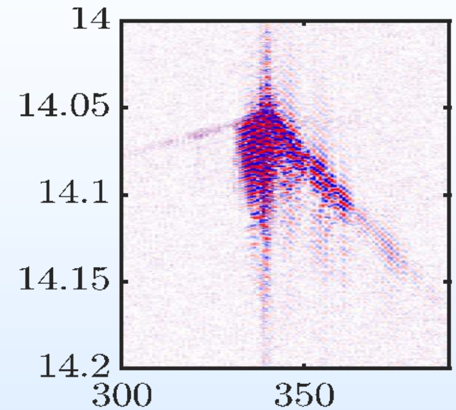
- RSTF: two 375 ft wells (Wells 1 and 3) with optic fiber cables installed behind casing and one 75 ft observation well (Well 2)
- Test 1: source deployed in Well 3 at 200 ft (30 ft below water) while recording in both Well 1 and Well 3
- 100 linear sweeps 0-1000 Hz
- Upgoing and downgoing tube waves observed in Well 3 but no signal in Well 1
- Next step – improve deconvolution to reduce residual noise



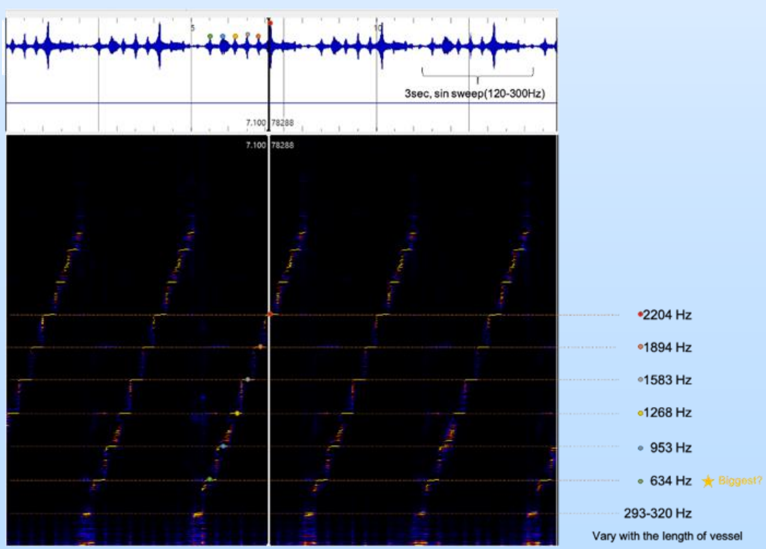


Task 4: RSTF Source Test 1

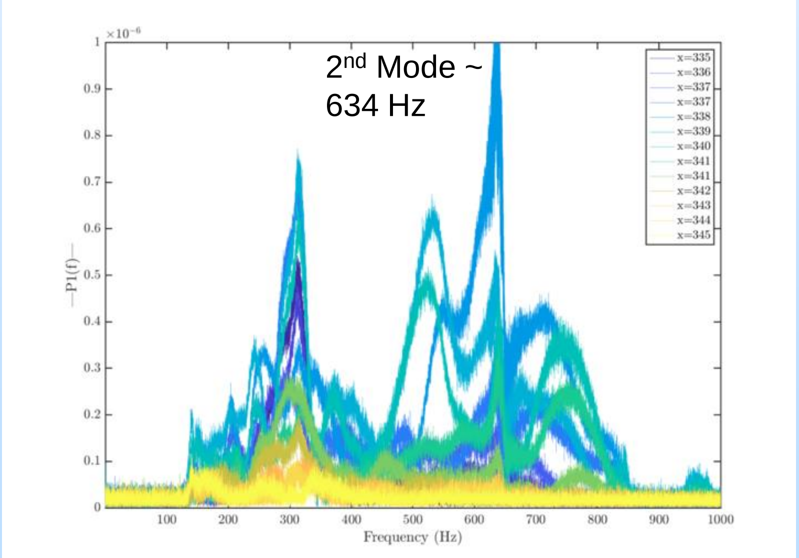
- Frequency content of sweeps measured by DAS in the well similar to lab determined 2nd mode peak (634 Hz).
- First peak (~300 Hz) also observed.
- Still investigating observed borehole modes.



Lab Measurements

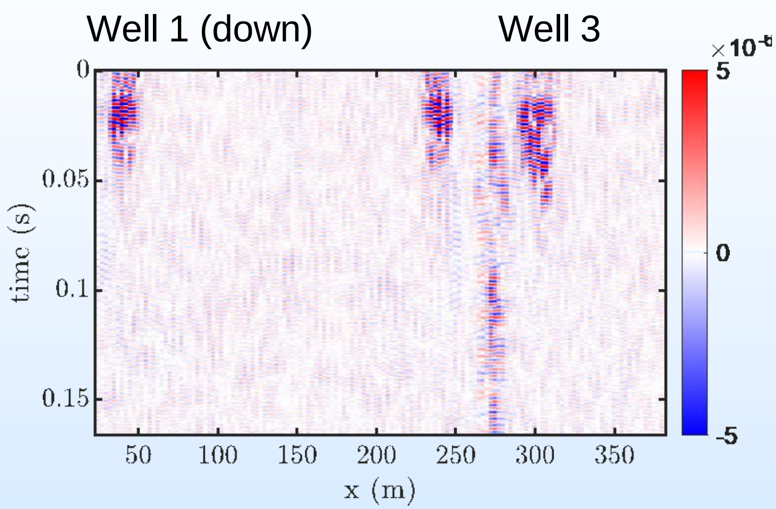


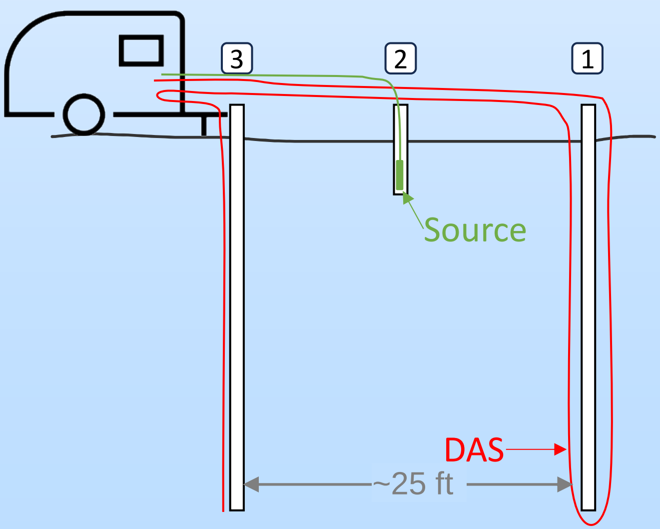
DAS Spectra Near Source



Task 4: RSTF Source Test 2

- Test 2: source deployed in Well 2 at 60 ft (30 ft below water), ~12 ft distance between the source and DAS.
- Increased pulse width to improve S/N: Some energy registered in both wells at the depth corresponding to the source location.
- Next – additional test in Well 2 to optimize signal detection and improve SNR.
- Further tasks include source repeatability and long term stability evaluation, frequency response, SNR and stacking tests, aquifer loading/unloading test
- New processing approach to be developed to remove residual noise.





Plans for future testing/development/ commercialization

- Finish manufacturing the array of source (Task 2)
- Complete field test and optimize data processing (Tasks 4/5).
- Task 6 will involve initial design work to transfer specification more suited for deep borehole deployment (higher TRL).
- Task 6 also involves modeling/inversion tests to evaluate scale-up options for deep borehole CASSM systems.
- With design, will explore DOE or commercialization funds for deeper tool development.

Summary Slide

- Tested and finalized source development and manufactured several hardened sources for field tests.
- Demonstrated FWI approach for DAS processing using strain->velocity conversion approach.
- Demonstrated value of coda analysis strategy for monitoring studies.
- Initiated field testing at RSTF. Preliminary single well/crosswell experiments but analysis on-going.

Organization Chart

Organization Chart

CASSM/DAS Imaging

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


Jonathan

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


Tieyuan

PSU PR/GSRA

Jackson Saftner
Gabriel Santos
Zi Xian Leong
(FWI)


Michelle


Todd

Lawrence Berkeley National Laboratory
Nori Nakata
(co-PI)
(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

Brianna Miranda
Valeriia Sobolevskaia
(CASSM Source Development/Testing)

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


Nader

Gantt Chart

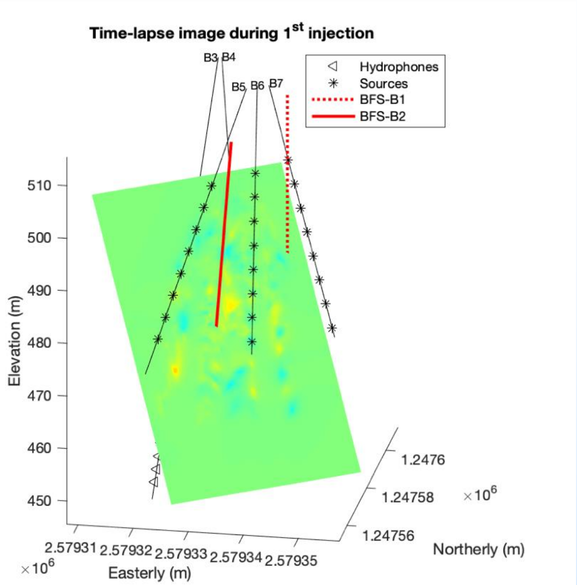
- 3 year project involving 6 tasks
- Spans instrument/method development to field validation
- Two field tests, second involving GCS seal leakage component
- Approximately 1 quarter behind schedule due to delay in funding.

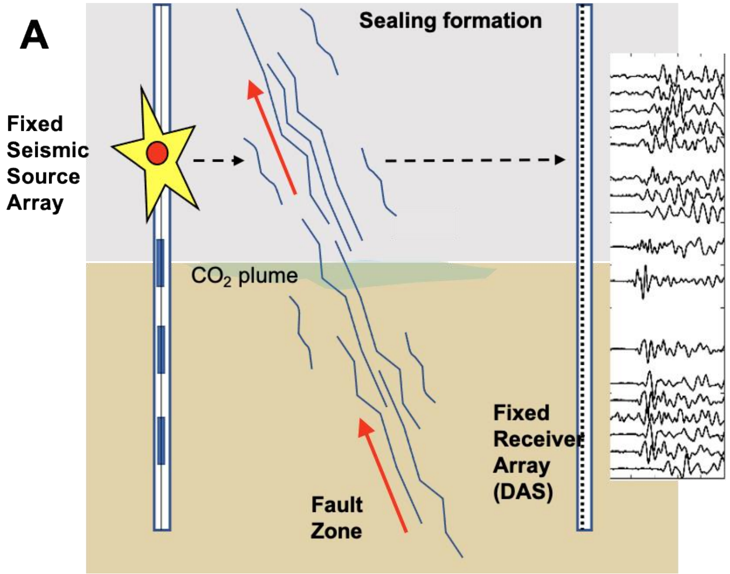
Task	Activity	Lead Organization(s)												
Project Year			1				2				3			
Project Quarter			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1	**Project management and planning**	*Rice*												
ST 1.1	Project management plan development													
ST 1.2	Technology maturation plan													
ST 1.3	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													

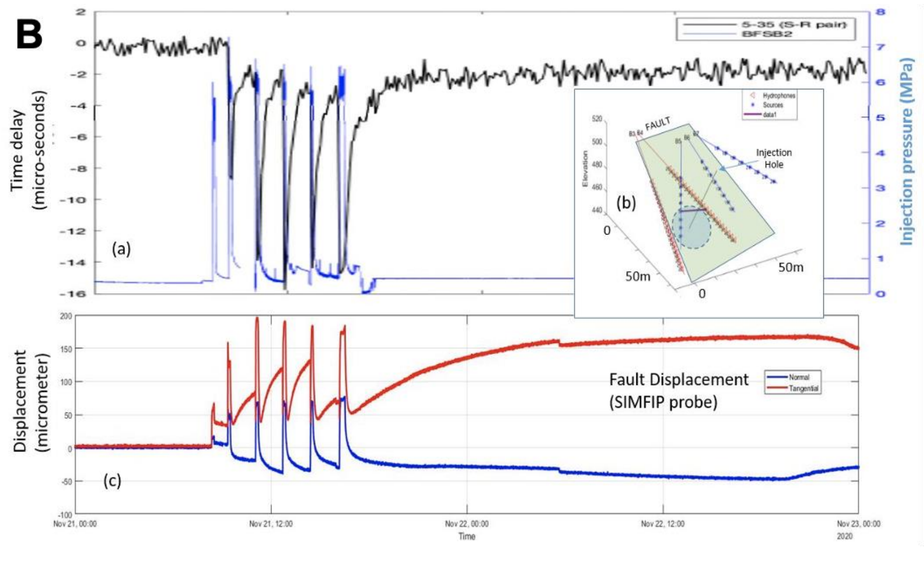
BACKUP

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 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. 2021)



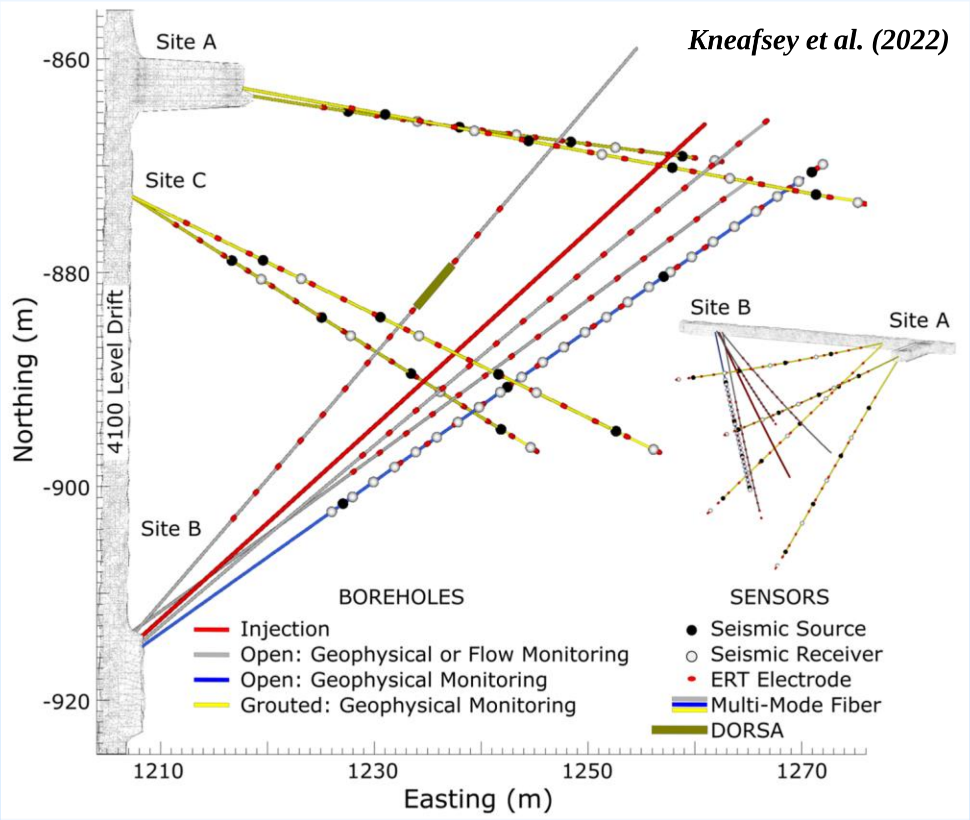


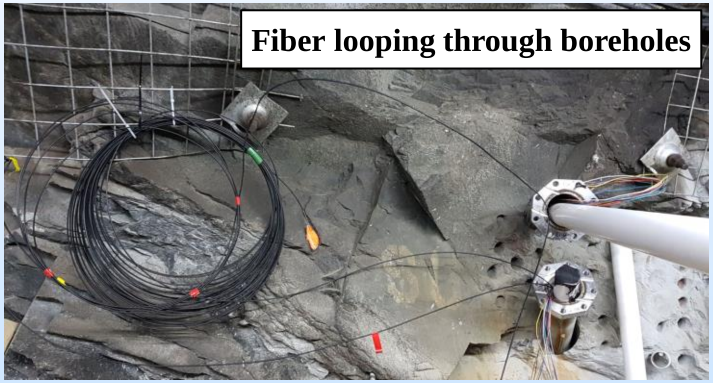


LAST YEAR SLIDES

Test of Opportunity: CASSM-DAS dataset with current generation sources

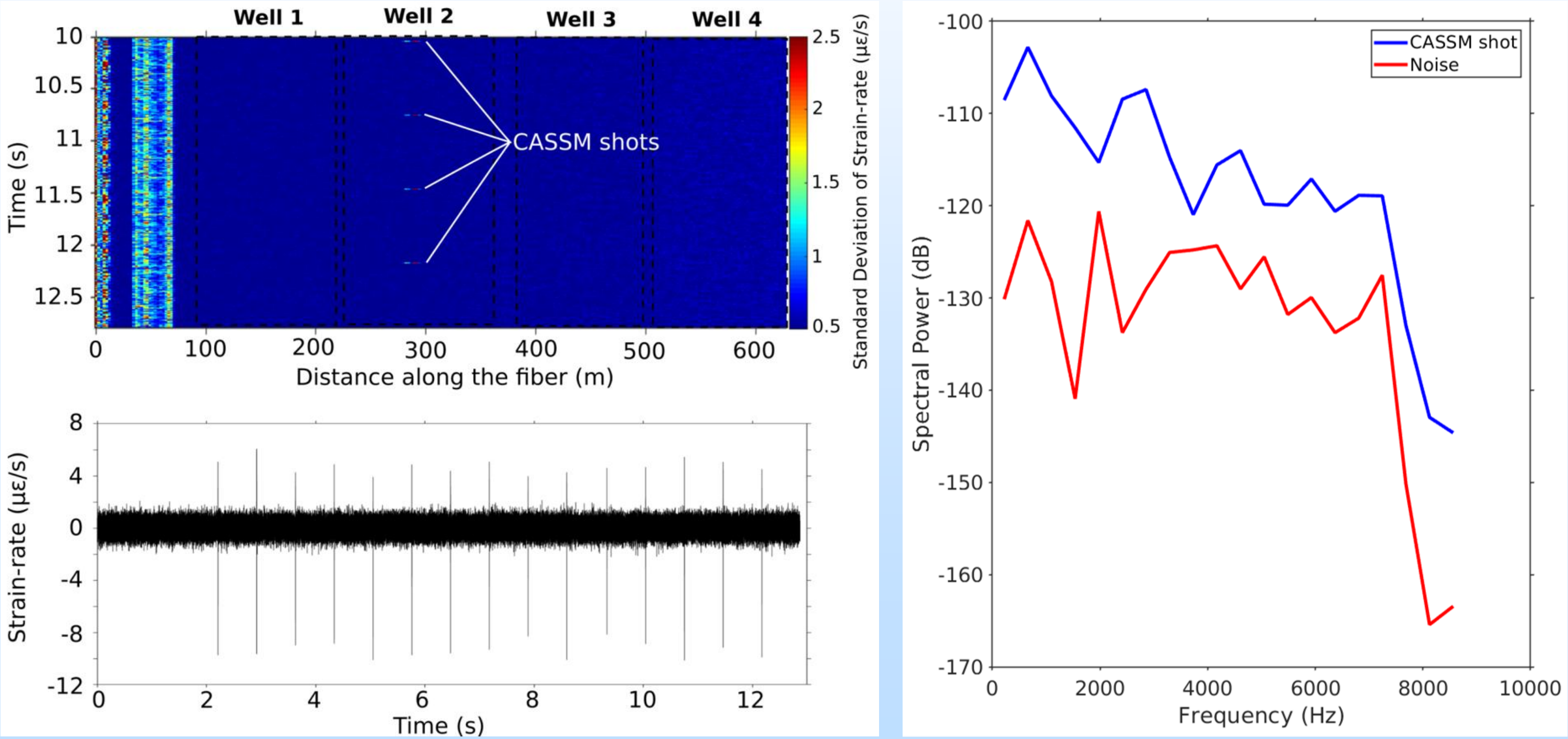
- Had opportunity to evaluate data collected with our chosen IU, grouted fiber, and current CASSM source designs at COLLAB (hard rock, GTO site). Will prior S/N hypothesis be proven correct?
- CASSM sources (~ 1 kHz) in a mesoscale experiment with relevant geometry.
- ~1 km long cable grouted in 4 monitoring wells continuously recording at 36 kHz frequency sampling, spatial sampling of 2.5 m and gauge length of 5 m.





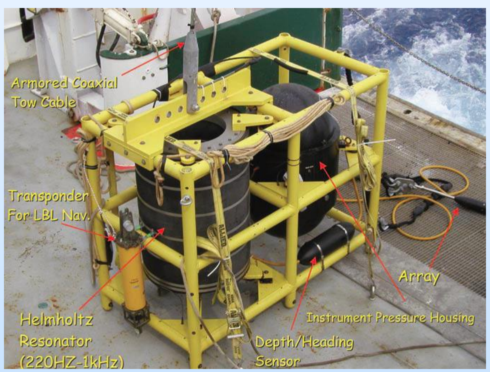
Test of Opportunity: CASSM-DAS dataset with current generation sources

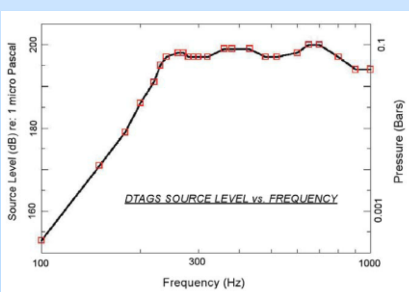
- Data evaluation reveals that DAS records near-source CASSM shots, but signals are below noise floor at reasonable offsets.
- Discrimination based on frequency content is challenging due to broadband optical noise.
- Suggests that more powerful lower F source still required, even with modern DAS units.



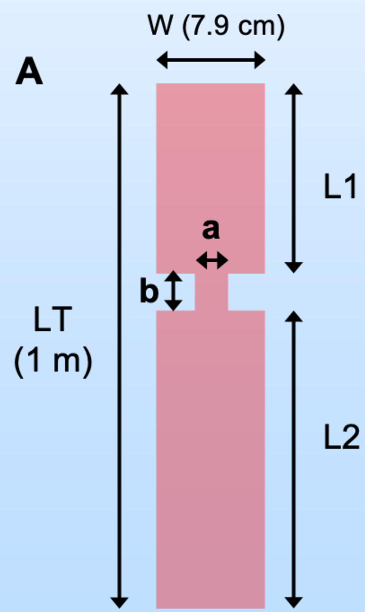
Progress on Task 2:
Development of a DAS-Oriented CASSM Source

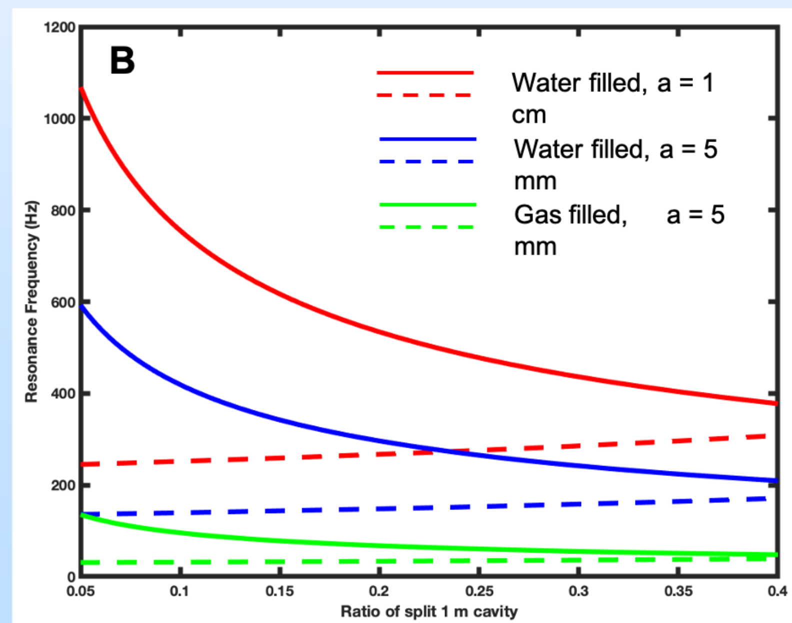
- Bulk of Yr 1 focused on constructing lower frequency resonant CASSM sources and evaluating (a) appropriate cavity shape and (b) transducer for excitation.
- Concept of resonant source not new – systems have been developed for marine oceanographic and seismic studies but few (any?) implemented for borehole arrays.
- Original concept: tuned dual—cavity Helmoholtz resonator. Back of the envelope modeling results for 1m split cavity below which would easily fit in a 4" well (3.11" OD). F_c tuned from 1 kHz to 100s Hz.





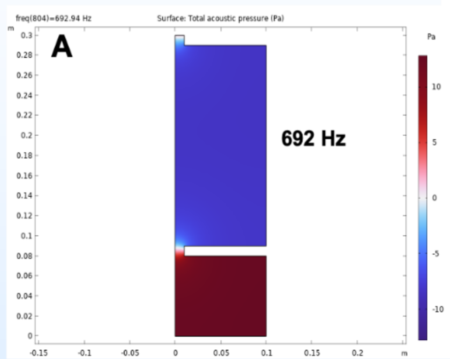
Gettrust, Wood, & Spychalski, 2004

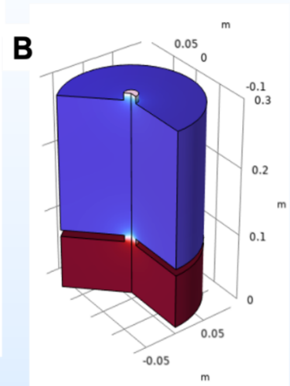


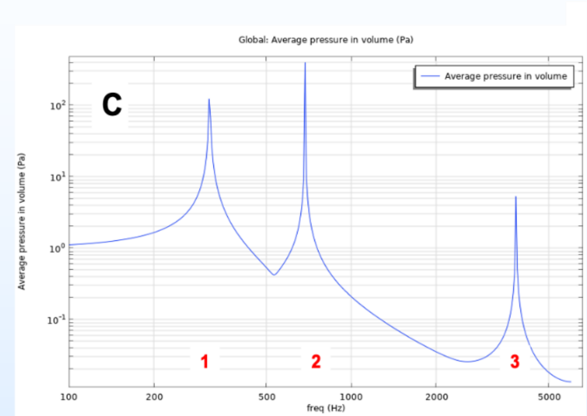


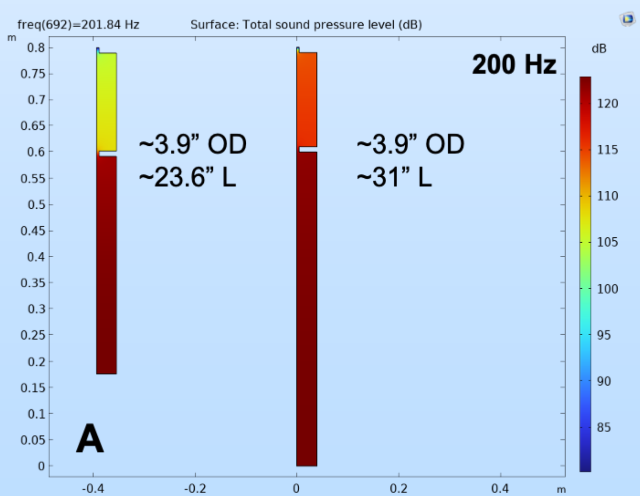
Task 2: Source Modeling Study

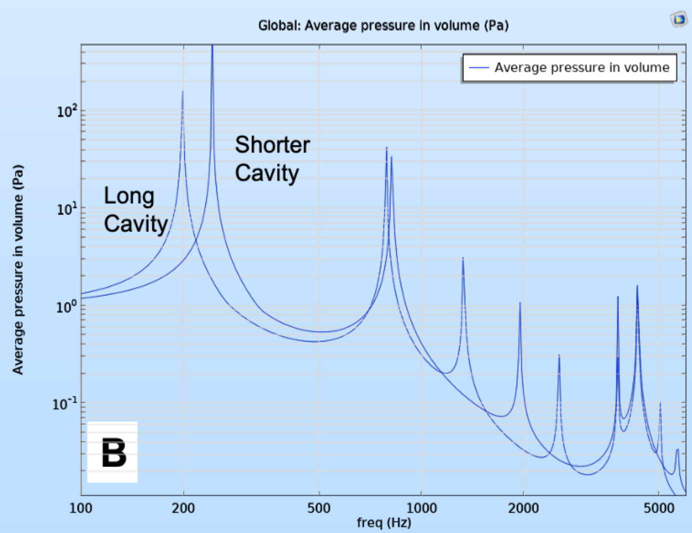
- Before prototyping, conducted series of detailed FEM modeling studies to evaluate realistic geometries (using COMSOL multiphysics).
- Used dual cavity Helmholtz design excited at one end (pressure boundary)
- Designed to fit in 4” well and be of reasonable length for array.
- In model, generated Helmholtz resonance for both cavity components + coupled & length modes.
- Weak modal coupling suggests we can independently spec. lengths
- Can hit appropriate frequencies for DAS exp!





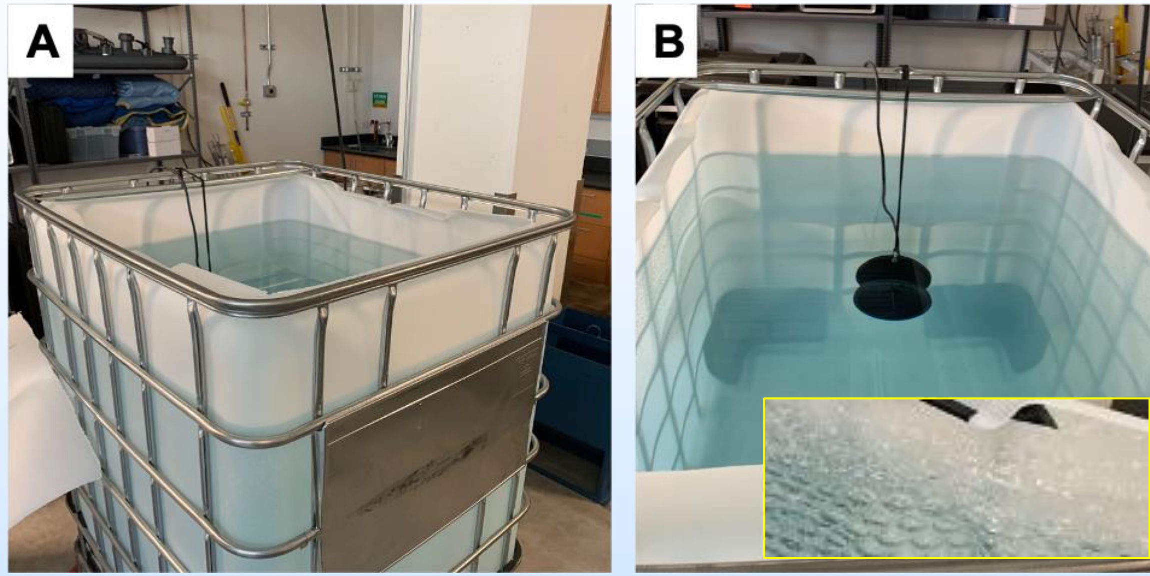


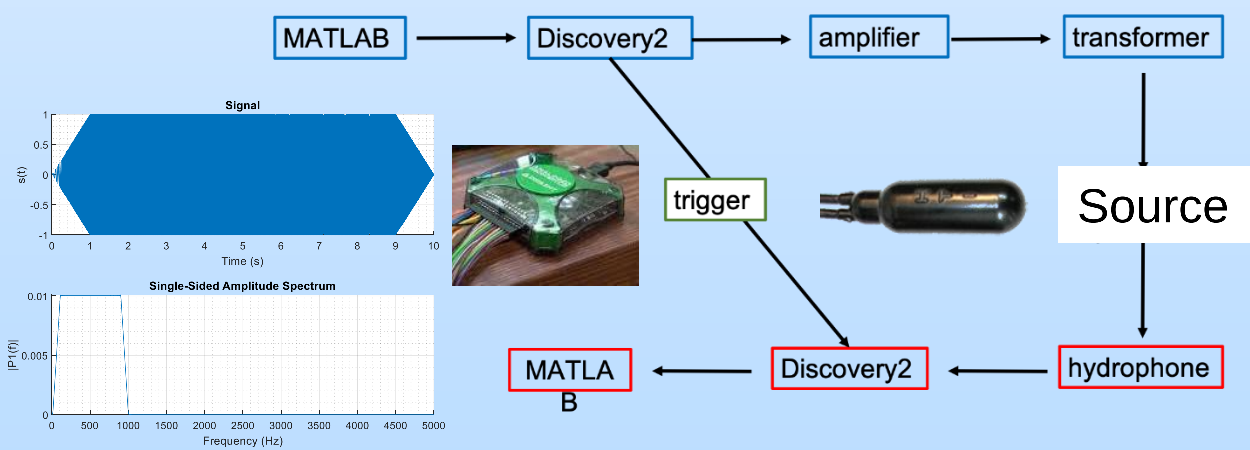




Task 2: Developed Source Testing Tank

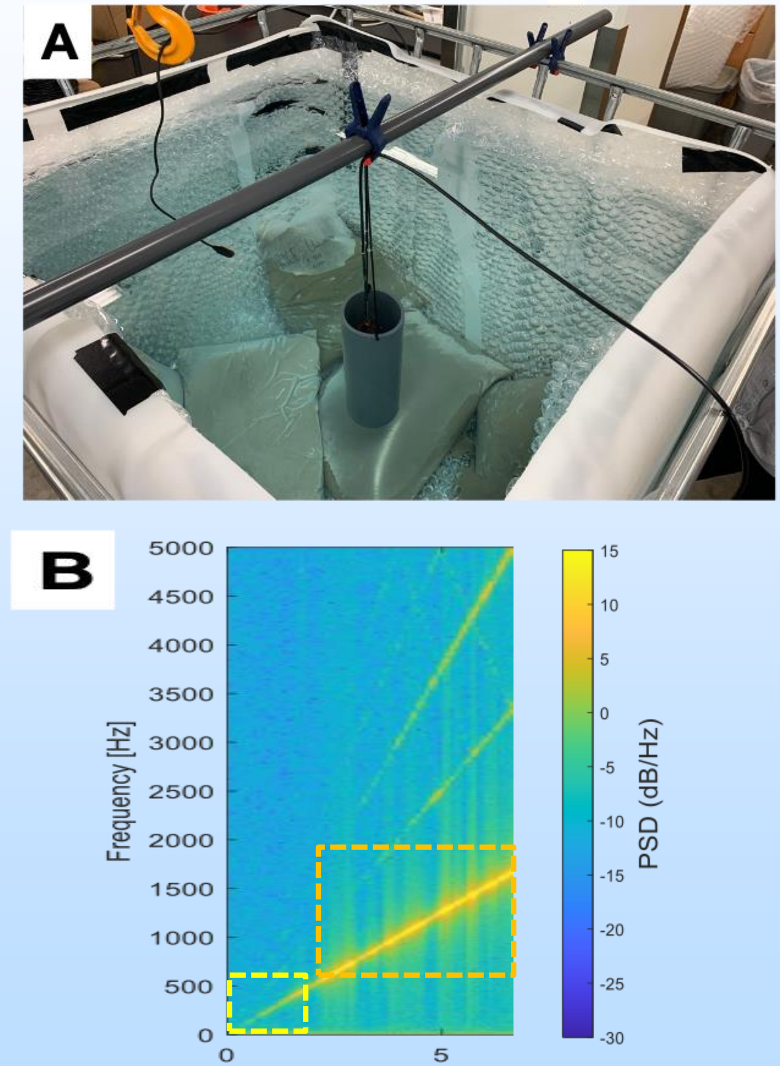
- Developed a lab source testing facility for prototyping.
- ~3’ x 3’ x 4’
- High performance hydrophone, A/D systems, and secondary projector.
- First tests revealed challenges with overall tank resonances.
- Mitigated with bubble wrap (an analog ABC) which reduced reflections by x10.
- Generating good data for controlled projectors.





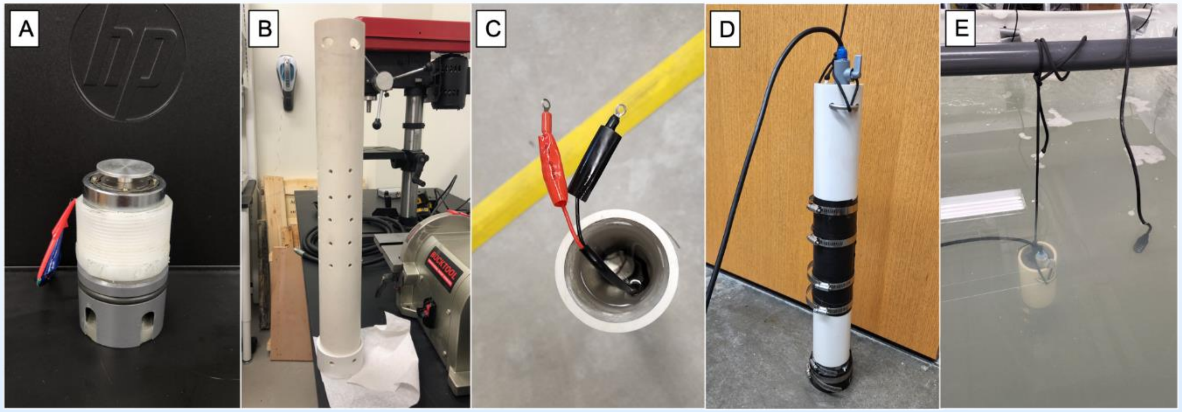
Task 2: First Prototype, Piezo Driven Resonant Tube

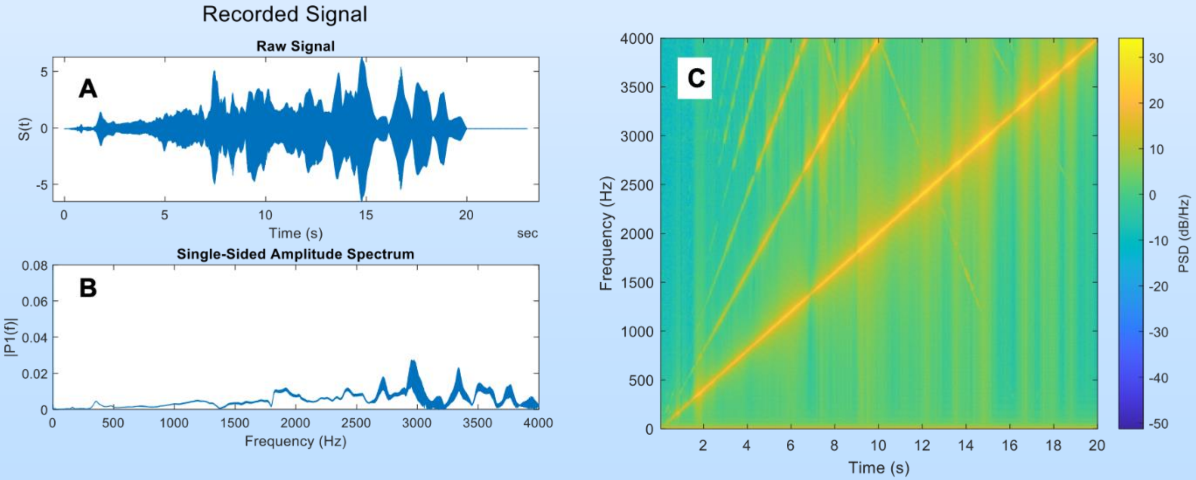
- First protype: a series of coupled "flooded" (open-ended) tubular resonators. Hoping to start with the simplest system.
- Inspired by sources used in oceanographic surveys with compound (pipes of 2 lengths) used to broaden spectrum.
- Driven by our existing 4" CASSM sources (piezoelectric) - cylindrically poled PZT ring assembly, oil-backed. Element ~1.7" OD.
- Driven by HV amplifier at ~700 V pk-2-pk.
- Unfortunately, this piezo assembly not able to generate a clean signal of sufficient amplitude below about 700 Hz, consistent with field experience.
- Higher modes can be excited (n=3)



Task 2: Second Prototype, Electrodynamic Closed Cavity

- Second prototype: a closed resonance cavity with a planned baffle for Helmholtz resonance.
- Rubber boot to facilitate pressure transfer, filled with inert mineral oil.
- Active element is inexpensive 30 W electrodynamic actuator.
- Better low-end excitation but surprisingly high number of NL modes excited.
- Fundamental length mode excited but broad; suggests some departure from pipe resonance.
- ***Third prototype***: planning air-backed Helmholtz resonator with similar transfer membrane.





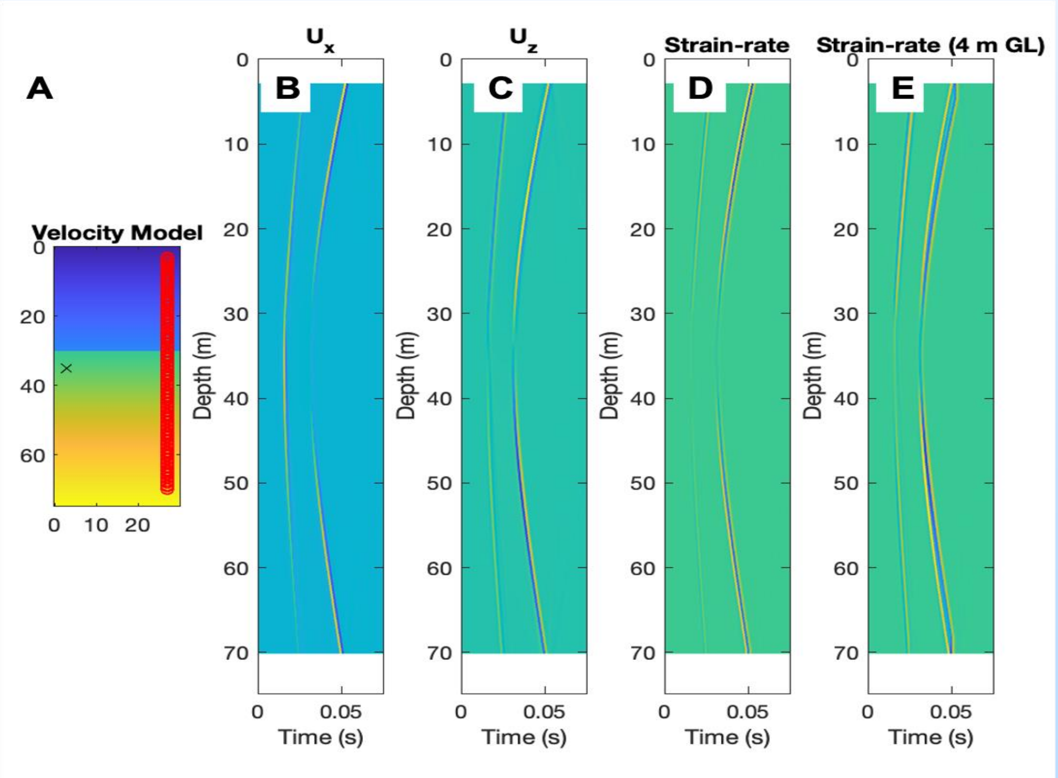
- ***Overall***: Progress on source development but still a little way to go.

Task 4: Modeling Response at RSTF site

- In preparation for first CASSM/DAS tests at RSTF, developed modeling framework for DAS response evaluation.
- Adapted viscoelastic pseudospectral code (K-wave) to generate strain-rate response with selected gauge lengths.
- Used formulation of Binder et al. (2020) for well parallel strain-rate calculation for arbitrary well trajectory – breaks array into short linear segments.
- First model runs (right, 400 Hz) suggest that direct S at intermediate/high angles might be a good wave mode for imaging.
- Will consider FWI and tomographic optimization for non-zero offset paths.
- PSU working on FWI upgrades for next testing sequence (task 3).

$$\Delta\phi(s_i) \propto \sum_j \frac{1}{L_g} \frac{(\mathbf{x}_{j+1} - \mathbf{x}_j) \cdot \left[\mathbf{u}(\mathbf{x}_{j+1}) - \mathbf{u}(\mathbf{x}_j)\right]}{|\mathbf{x}_{j+1} - \mathbf{x}_j|}.$$

L_g = gauge length
$\boldsymbol{u}$ = velocity
$\boldsymbol{x}$ = location



Milestones

- **LF CASSM Source Validated**: LF CASSM source deemed to have sufficient low frequency response to be compatible with DAS measurement [Year 1, end of Q4]

- **FWI HiEKF Validation:** Determination that the proposed FWI HiEKF strategy is appropriate for CASSM/DAS analysis using synthetic test data. This outcome will be documented as part of D5 and hinges on sufficient computational efficiency to handle anticipated multi-epoch CASSM datasets [Year 1, end of Q4]

- **CASSM/DAS Concept Field Validated**: Determination that new LF CASSM/DAS combination yields datasets of sufficient SNR for monitoring. Validated by performing initial data Q/C to examine (a) phase repeatability < 500 ns and (b) amplitude repeatability better 1than 5%. [Year 2, end of Q2]

- **Successful Initial Installation and Performance at FSB Testbed**: Determination that new LF CASSM/DAS combination yields datasets of sufficient SNR for monitoring fault reactivation experiments at Mont Terri. Validated by performing initial data Q/C to examine (a) phase repeatability < 500 ns and (b) amplitude repeatability better than 5%. [Year 3, end of Q1]

- **Successful Initial Processing of FSB DAS/CASSM Dataset**: Successful initial inversions of DAS/CASSM dataset generated during fault reactivation studies. Determined by reasonable misfit of FWI inversions given SNR levels coupled to prior knowledge. [Year 3, end of Q3

Appendix: Funding Tables

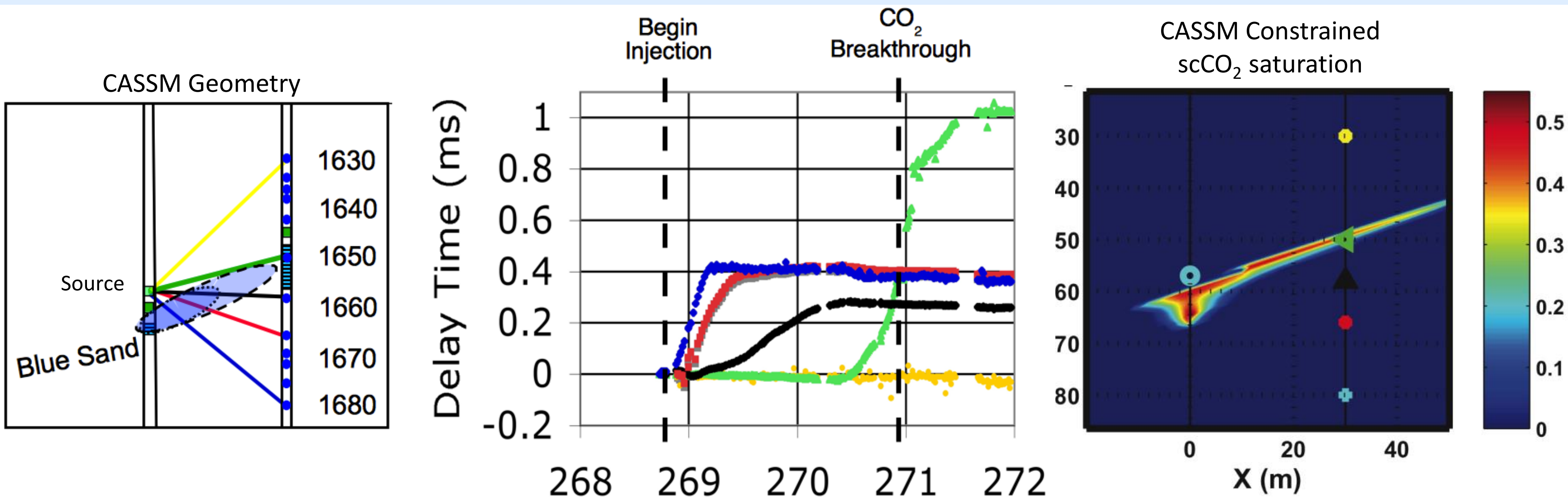
Budget Period No.	Budget Period Start	Government Share $ / %	Recipient Share $ / %	Total Estimated Cost
1	07/01/2021	$417,500 / 82.5%	$88,813 / 17.5%	$506,313
2	07/01/2022	$469,293 / 60.3%	$309,056 / 39.7%	$778,349
3	07/01/2023	$312,802 / 50.2%	$309,780 / 49.8%	$622,582
Total Project	$1,199,595 / 62.9%	$707,649/ 37.1%	$1,907,244	

Risks

Risk #	Risk	Risk Level
R1	CASSM source design cannot achieve spectral performance goals	Low
R2	CASSM source not strong enough for well offsets	Medium
R3	FWI Computational Efficiency Prevents Effective Use	Low
R4	Fault cannot be effectively reactivated	Low

CASSM for GCS Monitoring?

- CASSM concept has now been tested several times in a GCS context (Frio 2, Cranfield)
- Frio 2: Borehole seismic source and receiver array downhole and measured seismic traveltime (and attenuation) as a function of time.
- Observed seismic delay introduced by plume moving between the wells.
- After inverse flow modeling, was able to constrain plume geometry and saturation (needed to make some assumptions).
- Subsequent joint analysis of attenuation (Zhu et al. 2017) improved saturation constraints (in the reservoir). But large changes, utility in the seal?

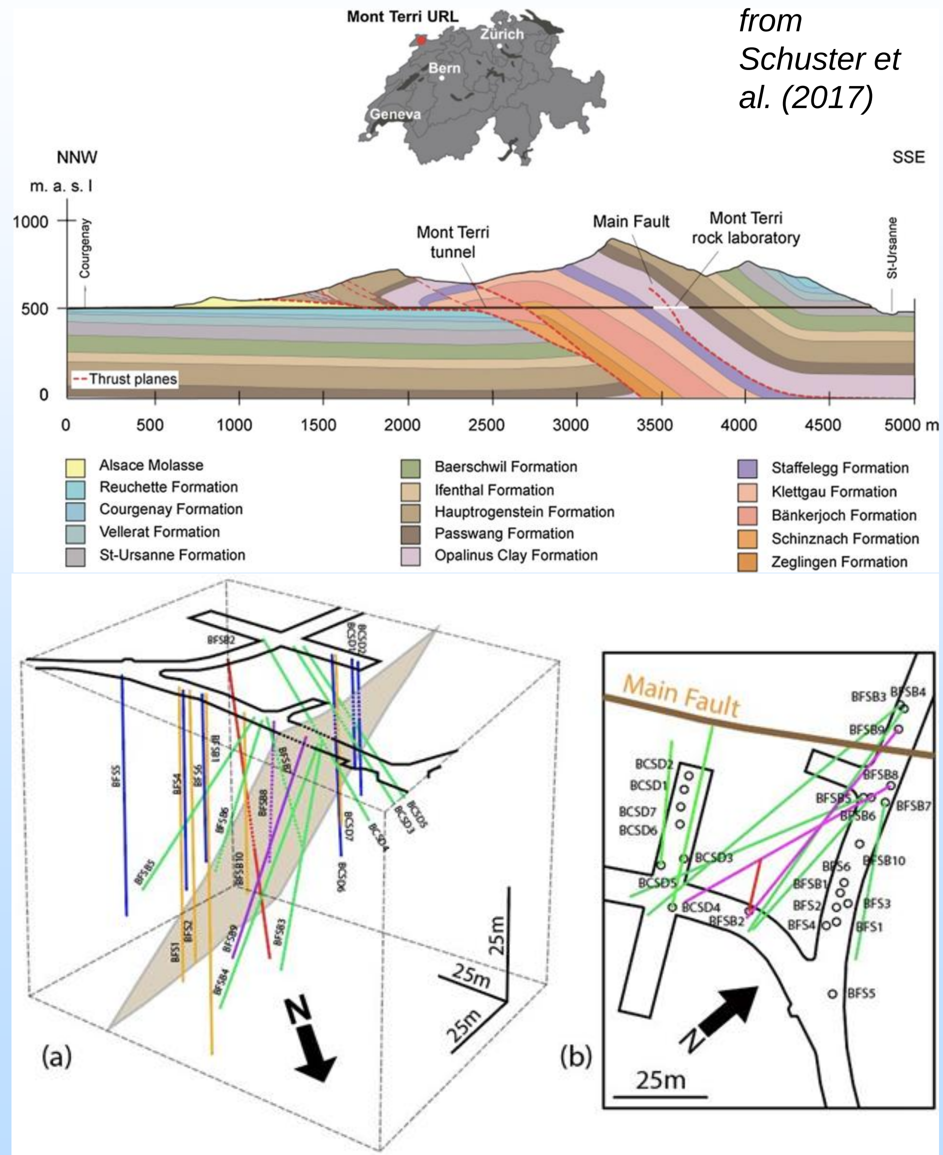


[Daley, Ajo-Franklin et.al. 2007, Daley, Ajo-Franklin et.al. 2011, Zhu et al. 2017]

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.
- Several fault reactivation studies already conducted – will use CASSM/DAS approach to monitor the next sequence.
- Significant cost saving from existing site instrumentation and characterization (piggy back on FSB).

- 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



from Schuster et al. (2017)

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

ST 5.1 : Validation of CASSM/DAS combination at Mont Terri Site

- Evaluate source strength, performance, timing, & repeatability in deep facility.

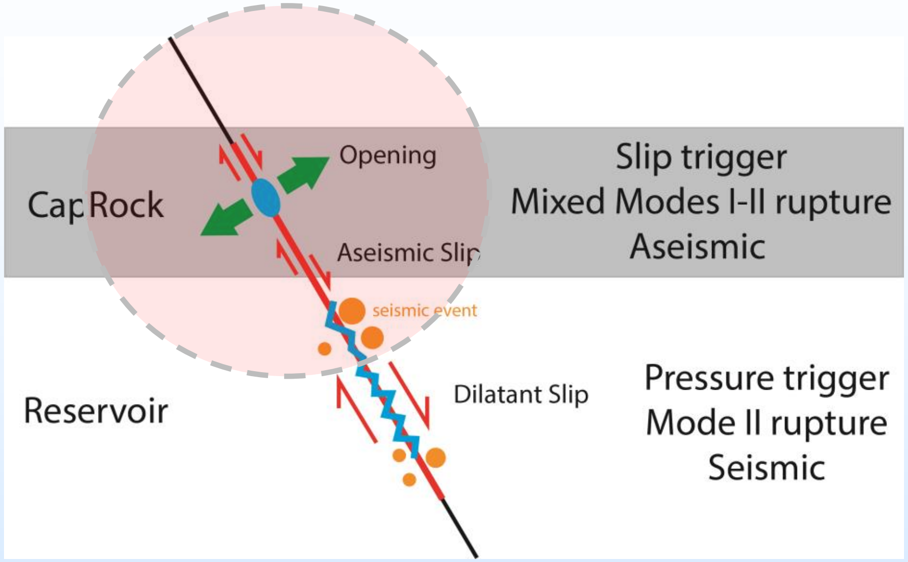
ST 5.2 : Fault reactivation/leakage experiment using brine.

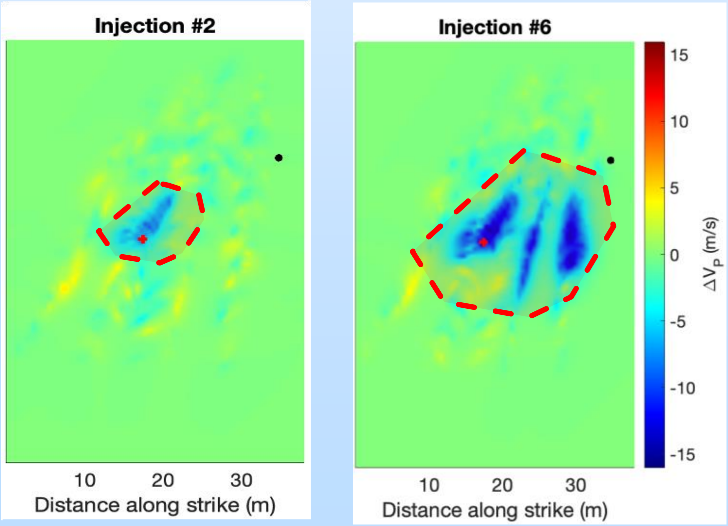
- Monitor zone of fault pressurization, leakage, long-term response.
- Attempt to map spatiotemporal velocity changes across fault plane.

ST 5.3: Fault reactivation/leakage experiment using gas.

- Similar goal but a focus on CO_2 injection, gas migration.

ST 5.4: Processing of fault reactivation experiment datasets.





Task 6: Scale-Up Analysis and System Development

- System described previously target meso-scale experiments, not high P/T reservoir applications.
- Final project task is development of scale-up plan with selected design for deep GCS deployment.
- ***ST 6.1***: Develop a larger (yet still *inexpensive*) LF CASSM source design for deep array deployment. Target 3 km depths, 110 C temperatures.
- ***ST 6.2***: Conduct modeling/inversion tests to evaluate benefits of CASSM/DAS combination at a larger scale.
- Goal is understanding role of technology in industrial GCS.

Mesoscale source

→

Field GCS Source