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

DE-FE0032058

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U.S. Department of Energy

National Energy Technology Laboratory

Carbon Management Project Review Meeting

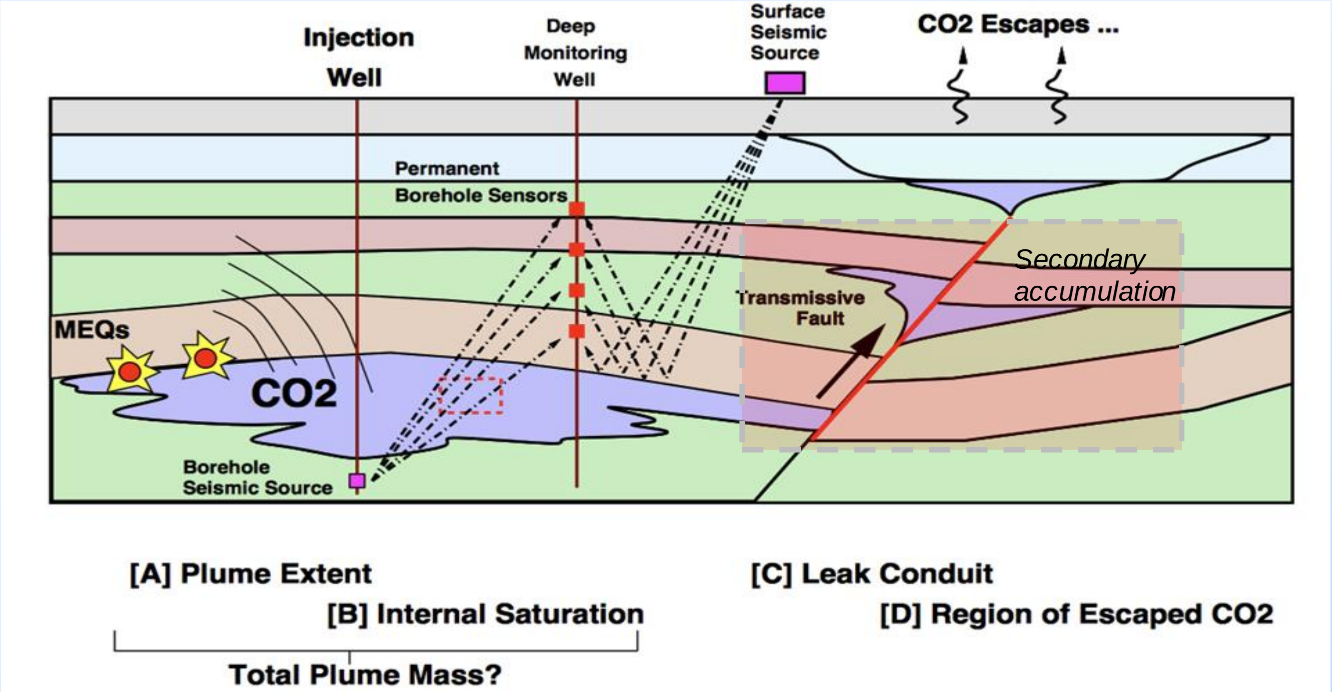
August 15 - 19, 2022

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 (Veronica Rodriguez-Tribaldos, Yves Guglielmi, Michelle Robserston)
  - 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.

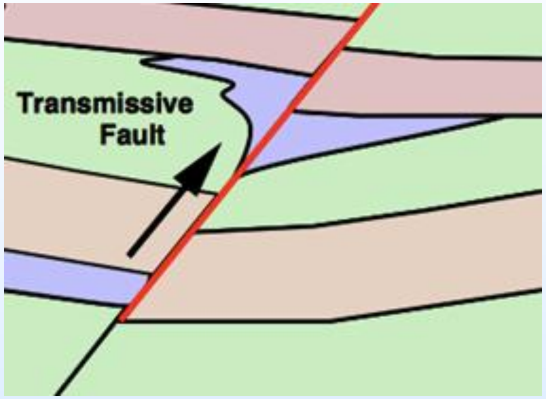
Key Goals for GCS Storage Security

- ***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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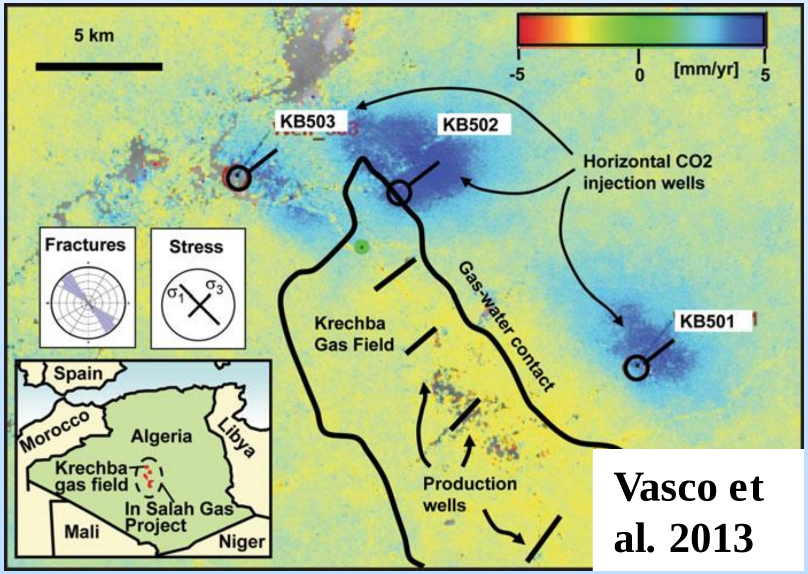
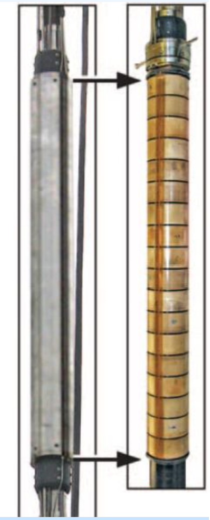


Vasco et al. 2013

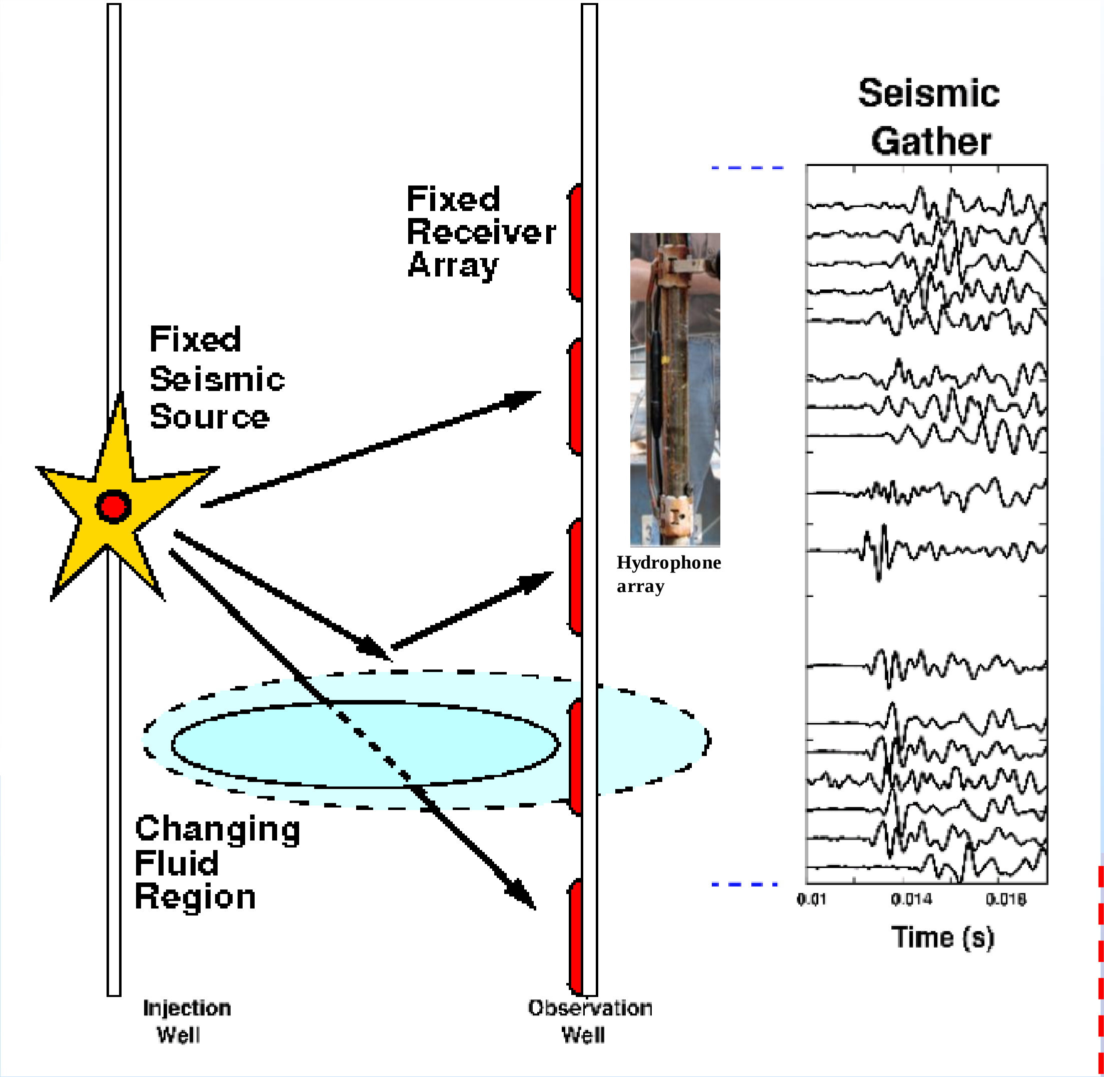
A Useful Technology: CASSM

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

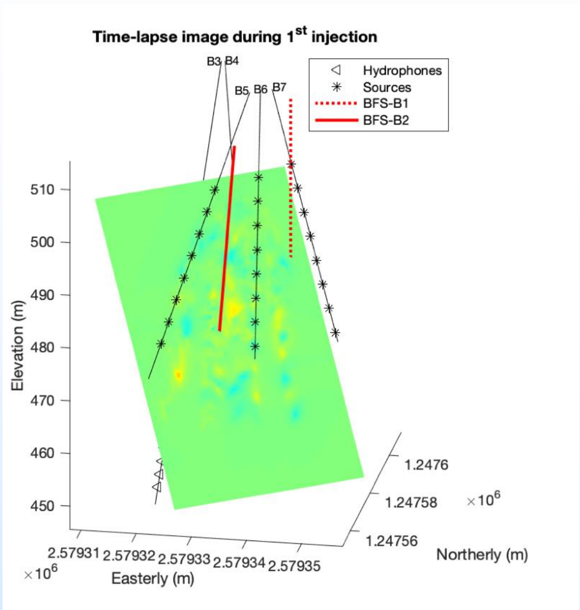
Why CASSM for Monitoring Seals?

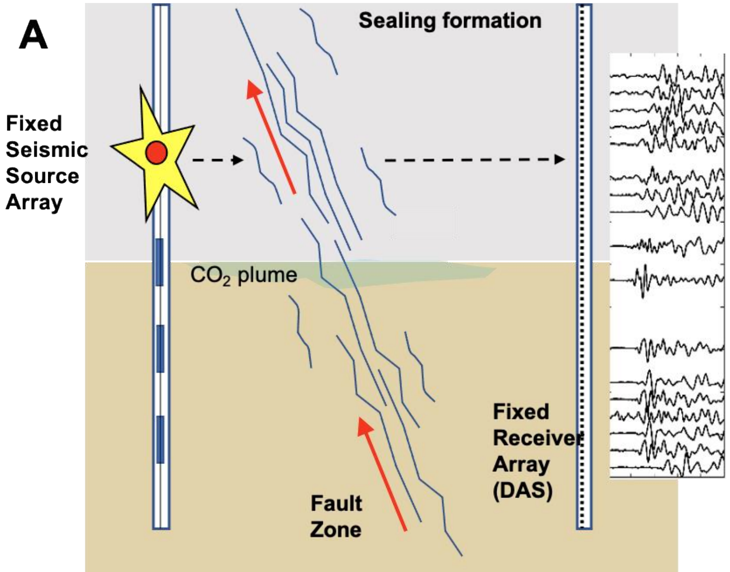
- Microseismic provides constraints on where faults slip (most of the time): not on slow aseismic processes.
- EQs provide no constraints on fault leakage, healing. or creep (long term)

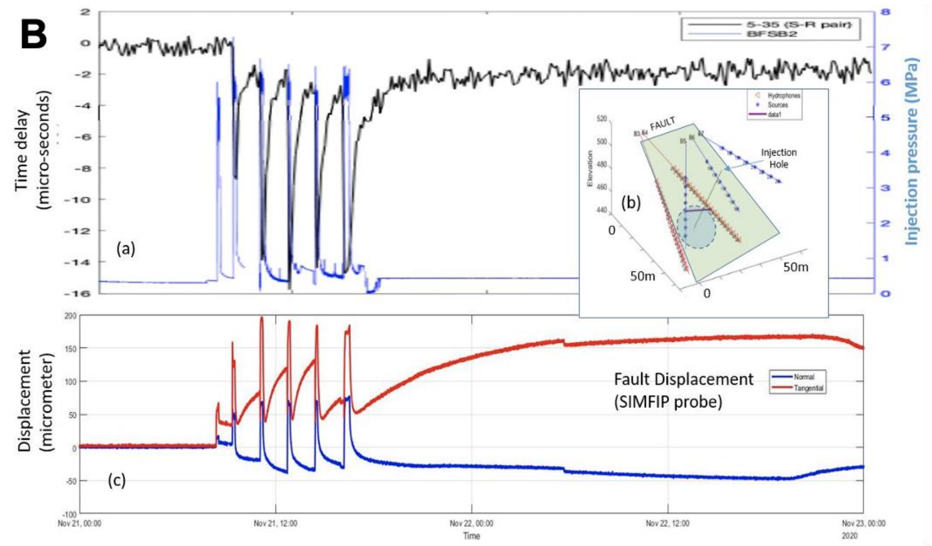
Elastic moduli are locally sensitive to micro-fracture density, stress state; CASSM might access aseismic fault zone evolution

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. 2021)







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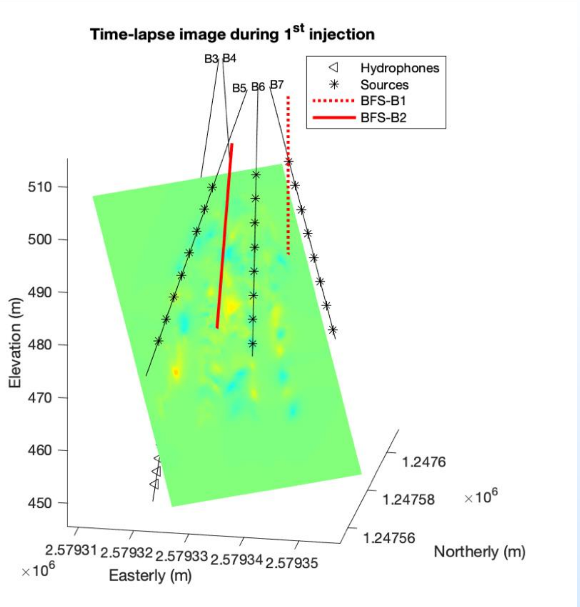
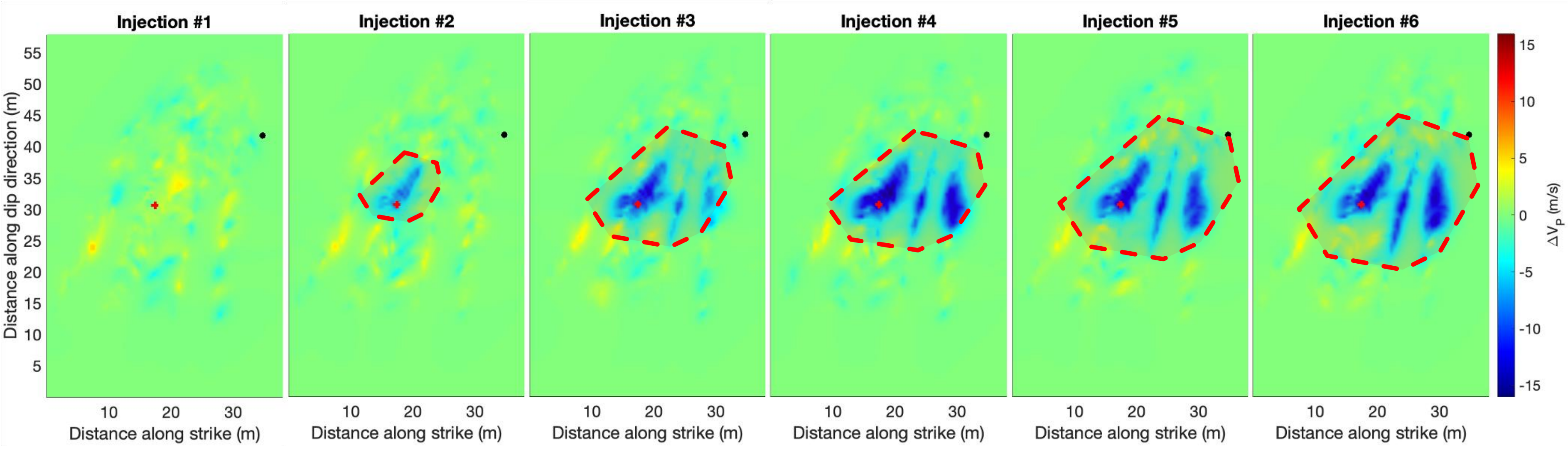




Limitations of CASSM for Long-Term Seal Monitoring

- 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?

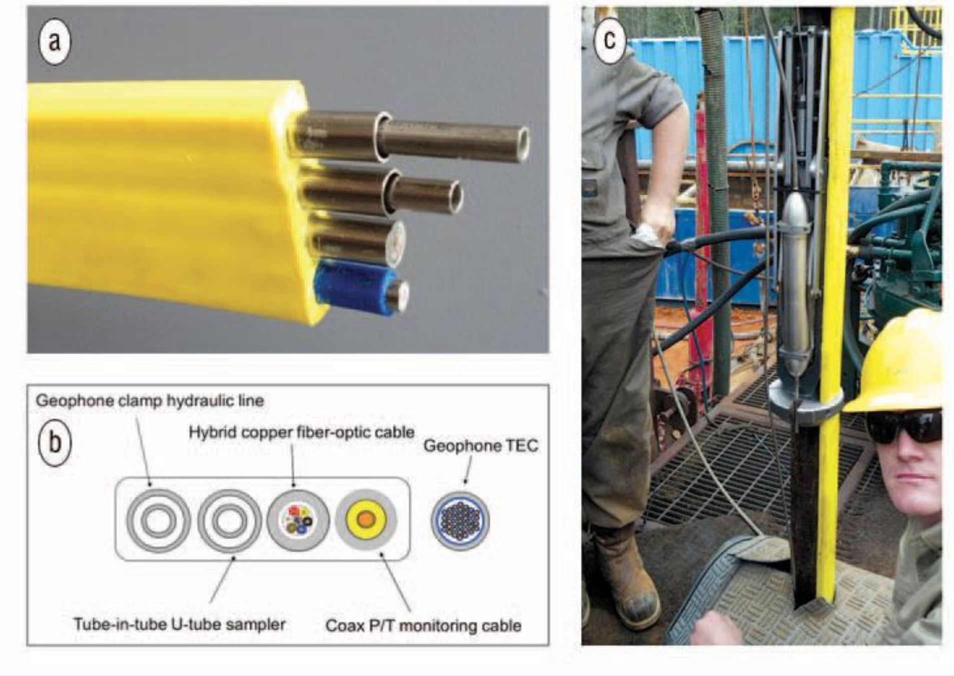
- **Distributed Acoustic Sensing [DAS]** is a rapidly advancing approach for measuring the seismic wavefield using commercial fibers (SM, telecom)

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

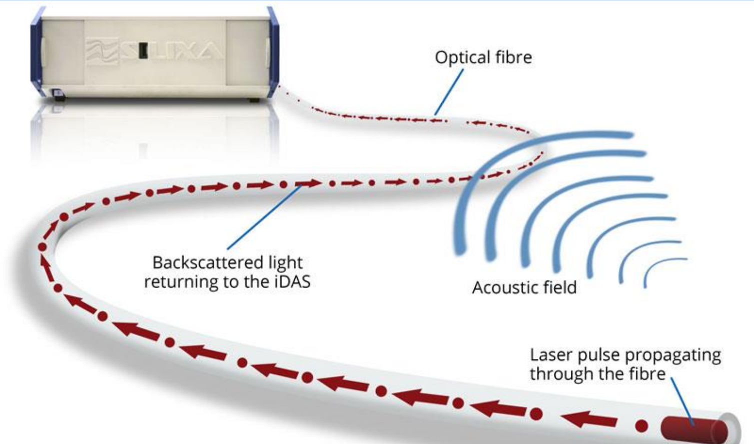
- **Large N** : Easy to deploy in wells, behind casing, 1000s to 100,000s of channels available (big data) over 10+ km (biggest current use is VSP)

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

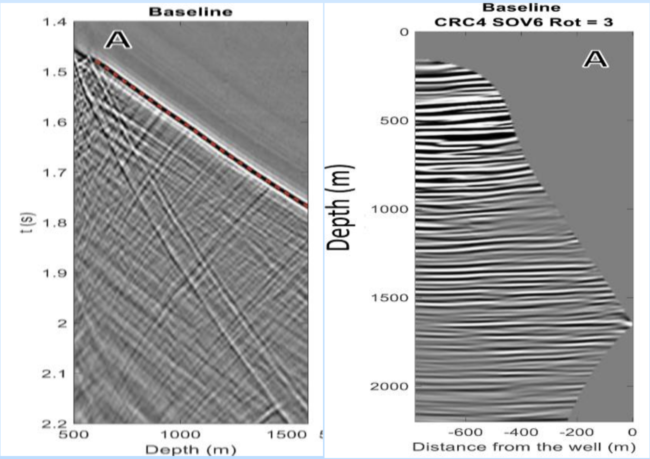
- ***The solution for CASSM?***



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

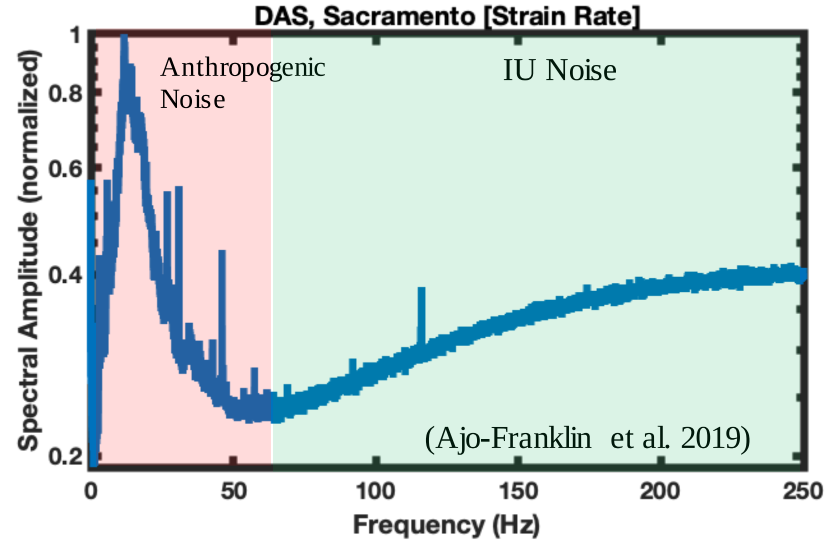
Despite clear advantages, some challenges

Frequency Mismatch:

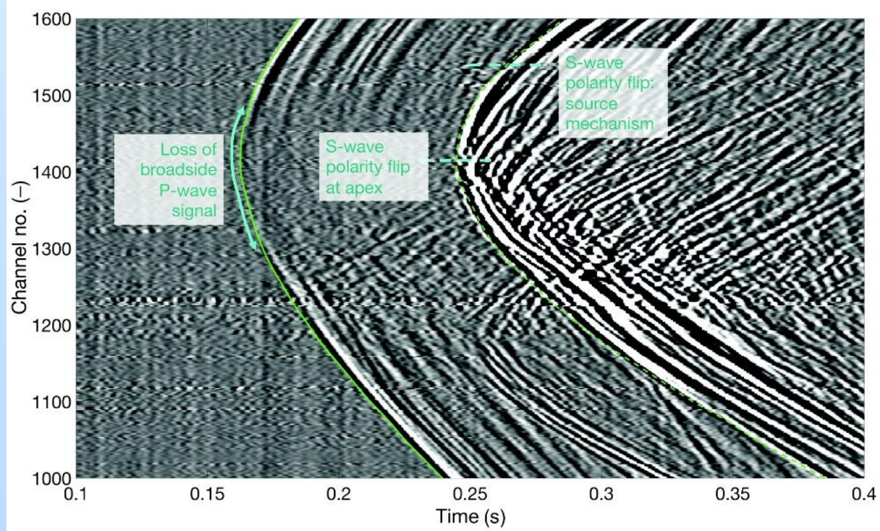
- DAS often exhibits increasing noise at high (kHz) frequencies, presents a mismatch with high F piezoelectric sources (depends on IU). In theory should be flat in strain …..
- Field application will also require longer propagation distances

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:

T1: Develop and validate a new low frequency CASSM source to improve DAS response.
(should be small, inexpensive, and suitable for array deployment)

T2: Develop an improved processing flow using FWI and coda wave analysis tailored to the measurement combination (evaluate optimal geometries).

T3: Test this combination for CASSM monitoring at a well-characterized shallow test site (Rice test facility)

T4: Demonstrate efficacy as part of a fault reactivation experiment at Mont Terri underground laboratory.

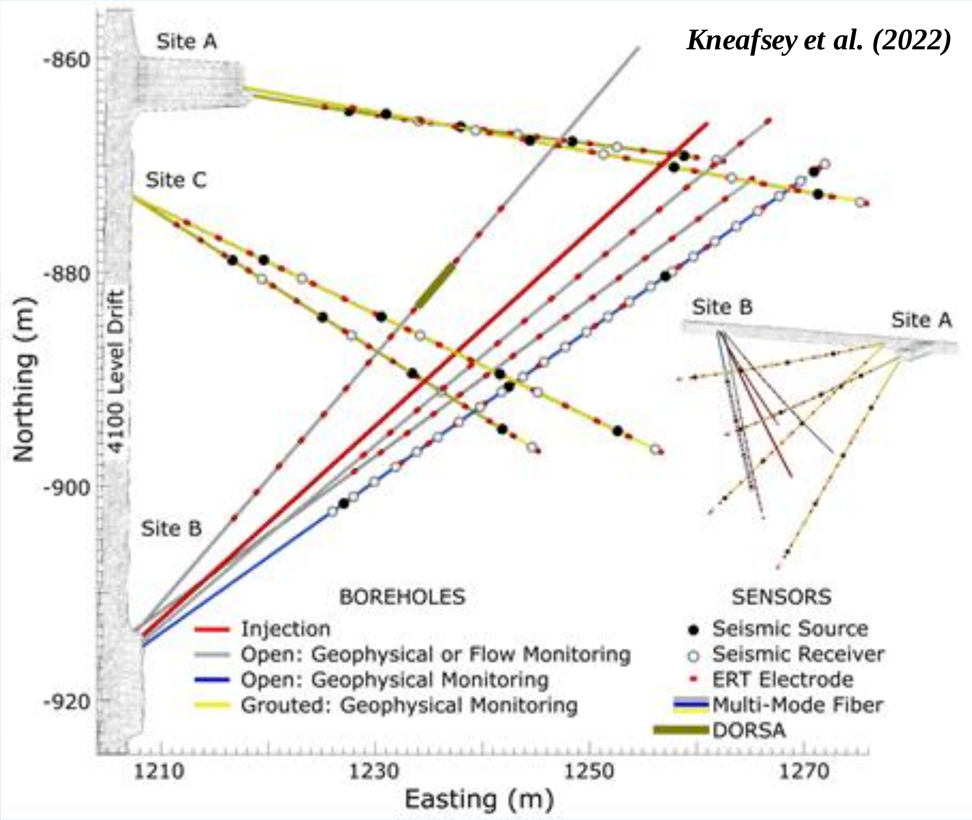
T5: Develop scale-up plan for future deep GCS targets.

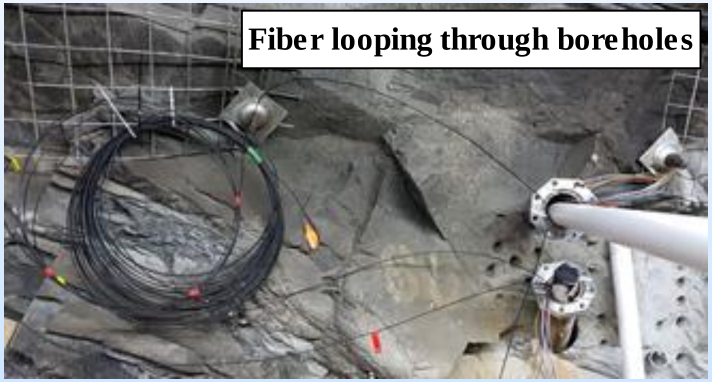
Technical Approach: Milestones

	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 aw ard.	Jan. 13th, 2022
	1.2	D3	Technology Maturation Plan:	90 days after aw ard.	Jan. 13th, 2022
Source Development (T2)	**2.2**	M1	LF CASSM Source Validated:	Year 1, end of Q4	
	2.2	D4	LF CASSM Source Design & Testing Results:	Year 1, end of Q4	
Imaging/Modeling (T3)	**3.1**	M2	FWI HiEKF Validation:	Year 1, end of Q4	
	3.1/3.2	D5	Report on FWI/Coda Approach:	Year 2, end of Q1	
NS Field Validation (T4)	**4.1**	M3	CASSM/DAS Concept Field Validated:	Year 2, end of Q2	
	4.1	D6	Results from Field Testing of CASSM/DAS:	Year 2, end of Q3	
	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	

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

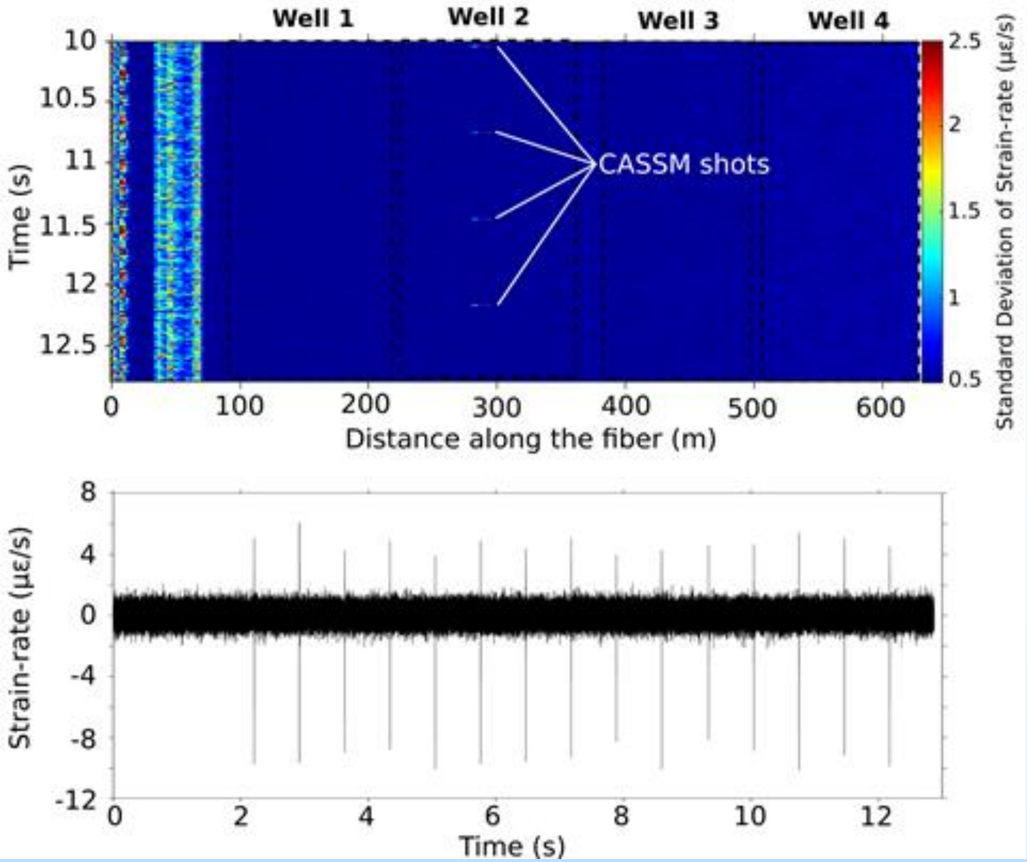
- Had opportunity to evaluate data collected with our chosen IU, grouted fiber, and current CASSM source designs at COLLAB (hard rock, GTO site). Will prior S/N hypothesis be proven correct?
- CASSM sources (~ 1 kHz) in a mesoscale experiment with relevant geometry.
- ~1 km long cable grouted in 4 monitoring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

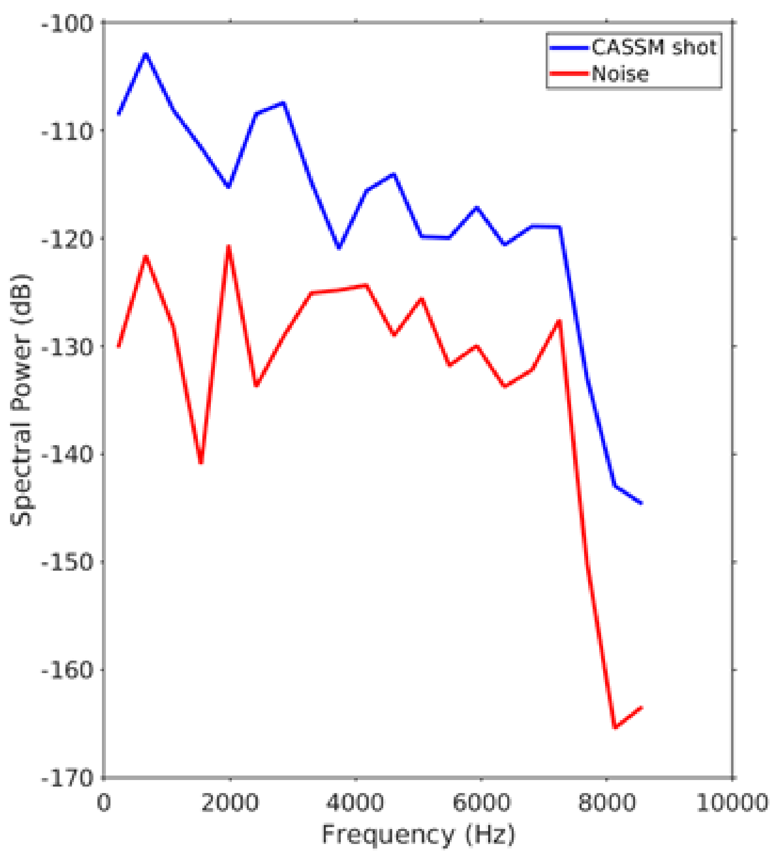




Test of Opportunity: CASSM-DAS dataset with current generation sources

- 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.





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:

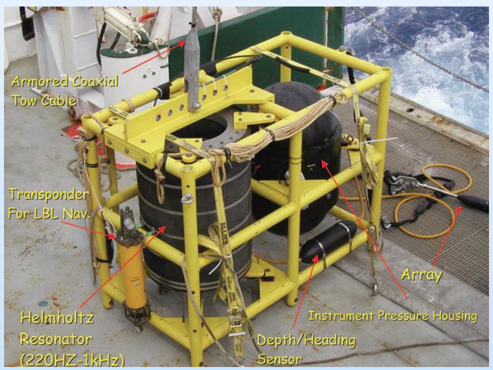
- Fabrication of several prototypes and lab testing in a water tank.
- Reference hydrophones & DAS cables for evaluation.
- Compare to numerical models and extrapolation to field response.

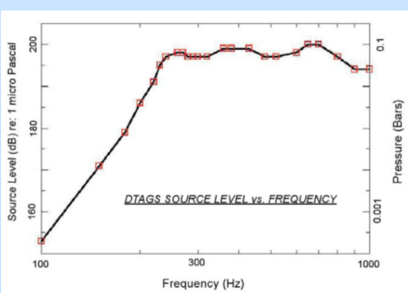
ST 2.3: Fabrication of LF CASSM array for field experimentation

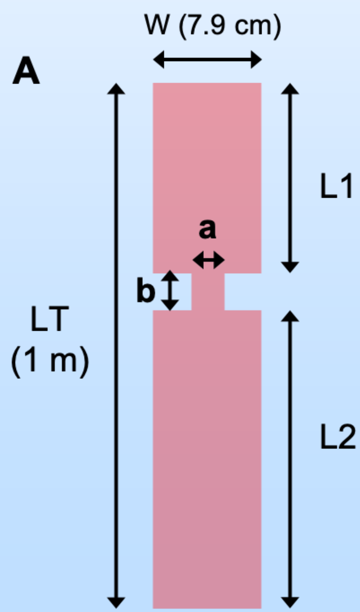
- Once a good design is developed, fabrication of larger array (~20) for tests
- Plan is to reuse array for tasks 4 & 5.

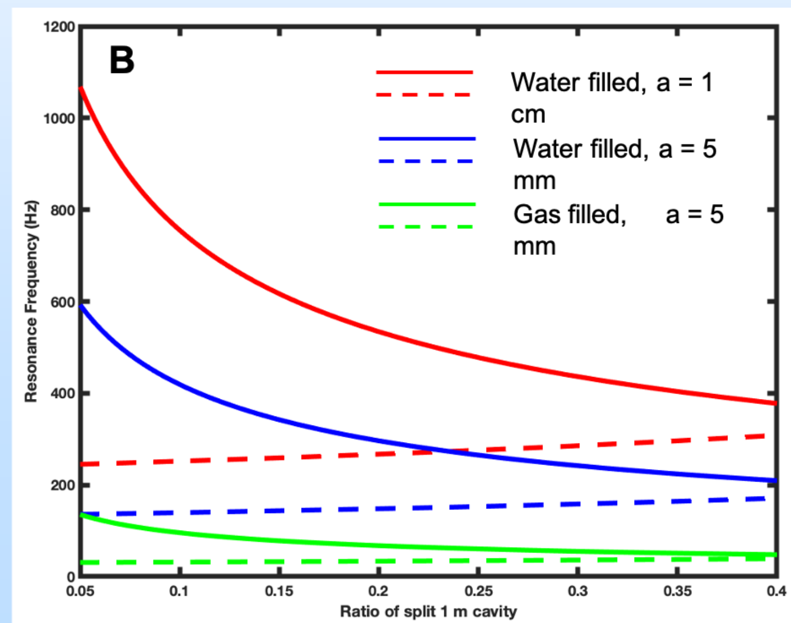
Progress on Task 2: Development of a DAS-Oriented CASSM Source

- 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.





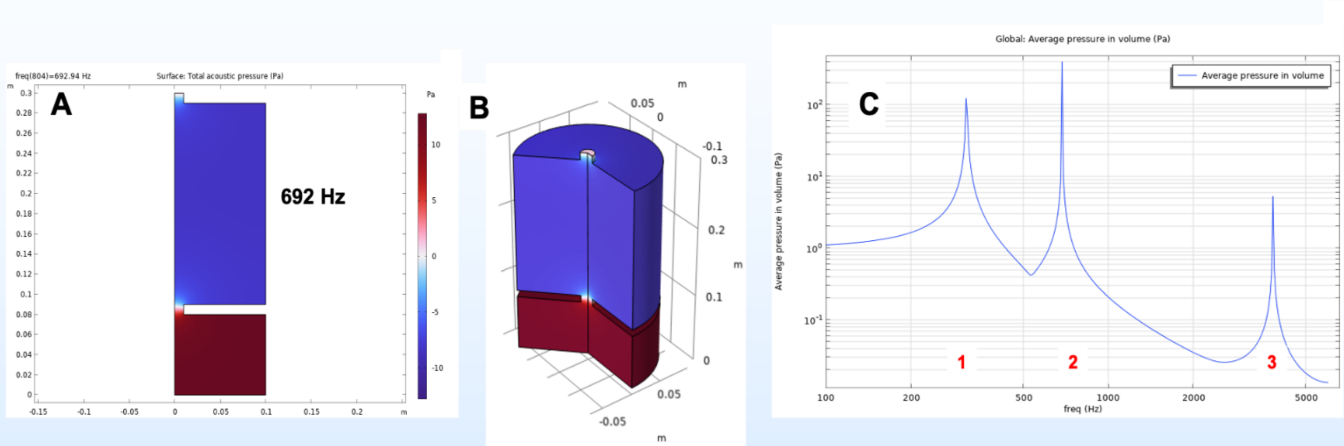


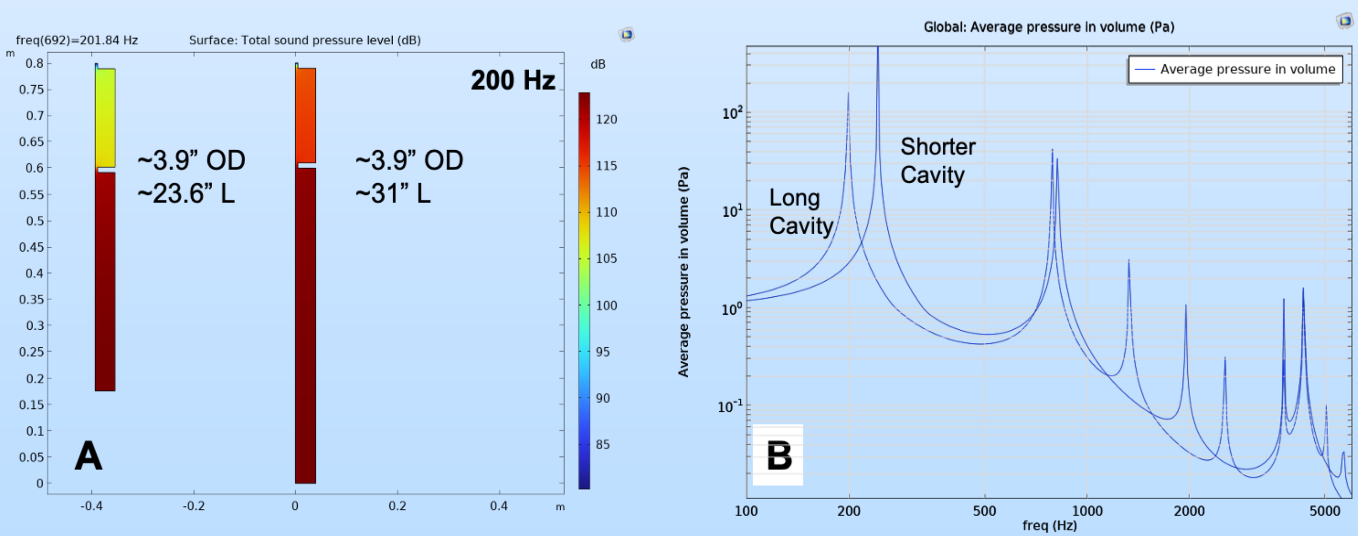


Gettrust, Wood, & Spychalski, 2004

Task 2: Source Modeling Study

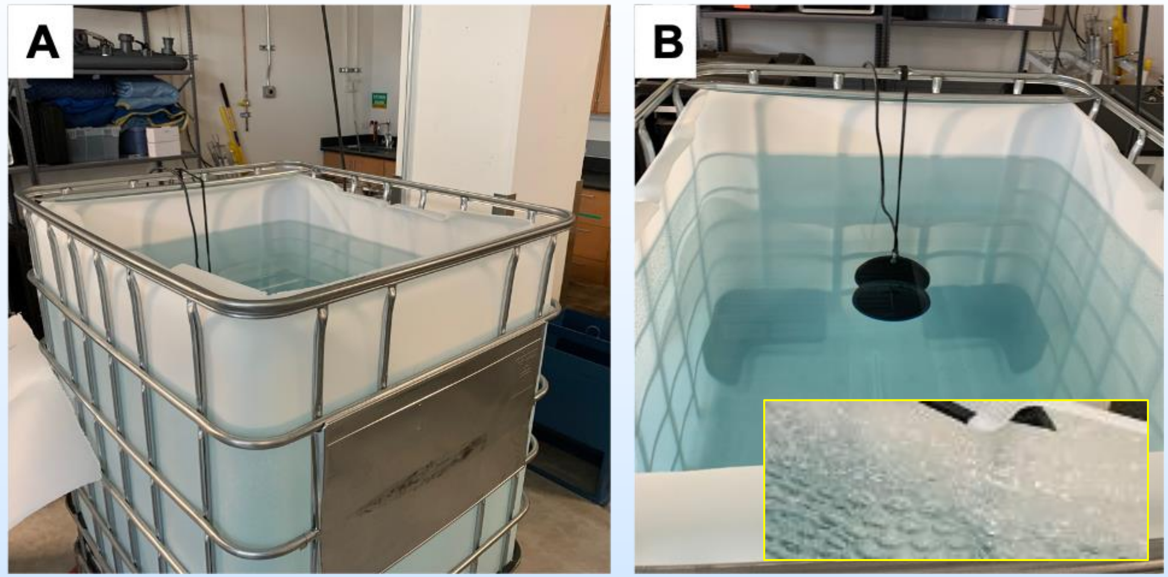
- Before prototyping, conducted series of detailed FEM modeling studies to evaluate realistic geometries (using COMSOL multiphysics).
- Used dual cavity Helmholtz design excited at one end (pressure boundary)
- Designed to fit in 4” well and be of reasonable length for array.
- In model, generated Helmholtz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

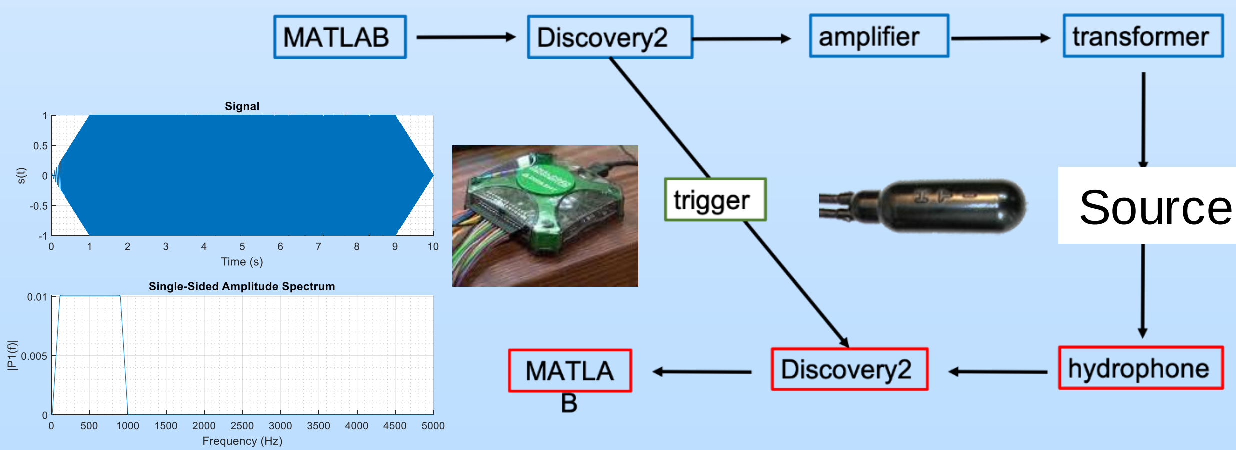




Task 2: Developed Source Testing Tank

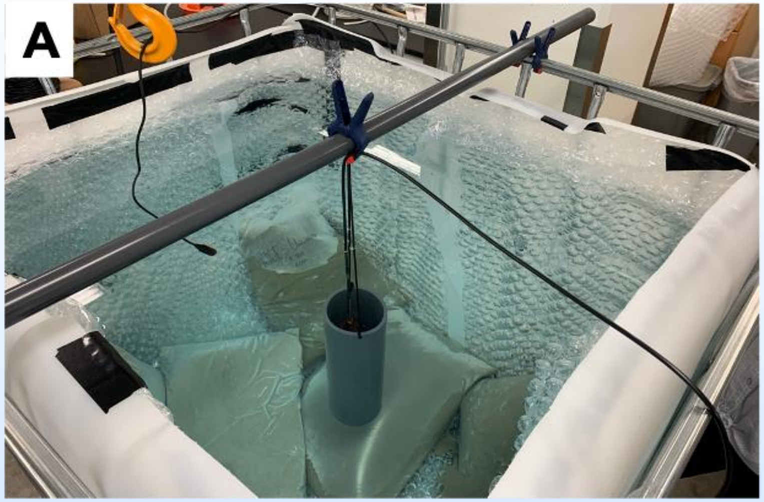
- Developed a lab source testing facility for prototyping.
- ~3’ x 3’ x 4’
- High performance hydrophone, A/D systems, and secondary projector.
- First tests revealed challenges with overall tank resonances.
- Mitigated with bubble wrap (an analog ABC) which reduced reflections by x10.
- Generating good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

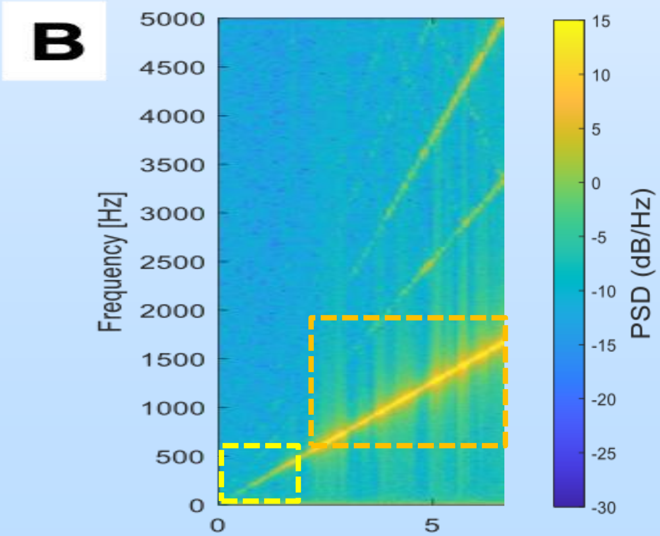




Task 2: First Prototype, Piezo Driven Resonant Tube

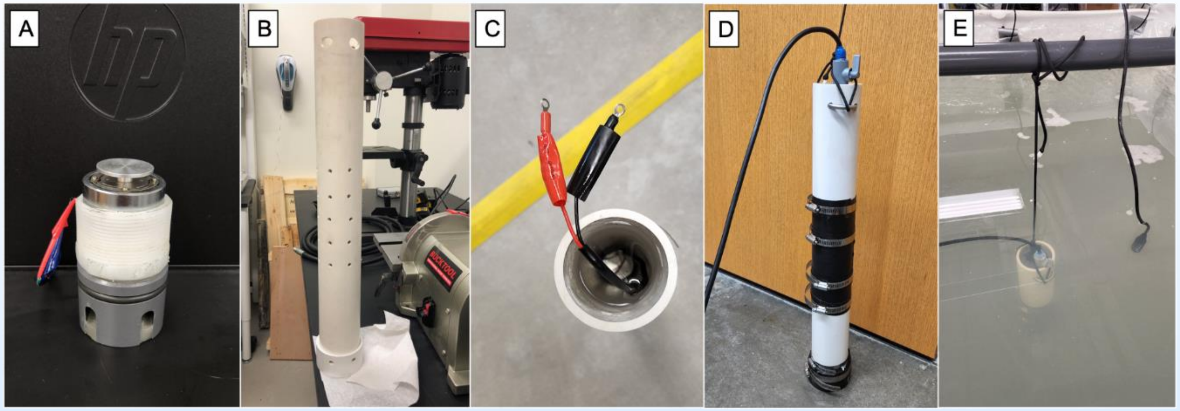
- First protype: a series of coupled "flooded" (open-ended) tubular resonators. Hoping to start with the simplest system.
- Inspired by sources used in oceanographic surveys with compound (pipes of 2 lengths) used to broaden spectrum.
- Driven by our existing 4" CASSM sources (piezoelectric) - cylindrically 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)

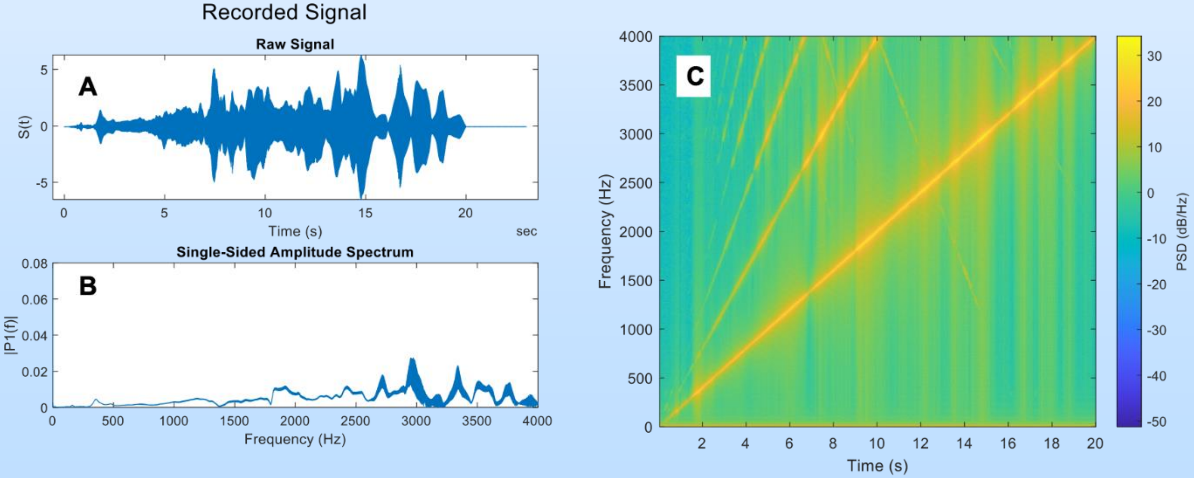




Task 2: Second Prototype, Electrodynamic Closed Cavity

- 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.





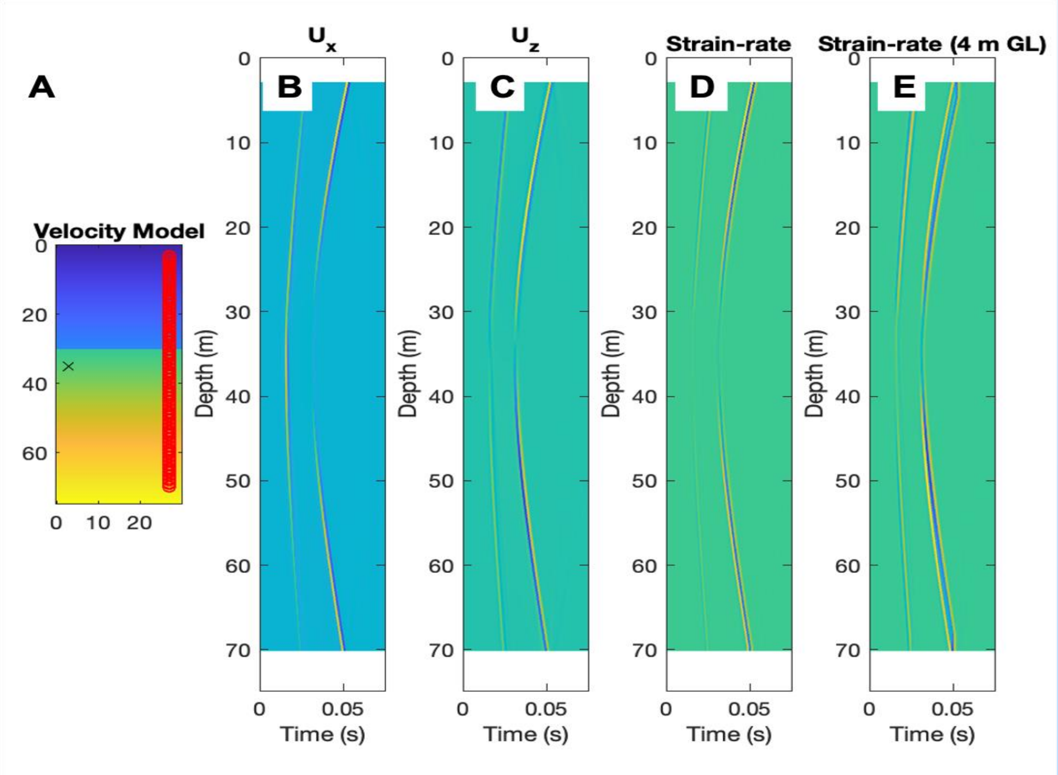
- ***Overall***: Progress on source development but still a little way to go.

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



Plans for future testing/development/ commercialization

- Still in prototyping phase, but current scope involves continued laboratory (Task 2) & field testing (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

- Verified challenges with current generation CASSM sources recorded by DAS using dataset of opportunity (COLLAB)

- Initiated source development process with more realistic modeling runs, verified coupled Helmholtz concept.

- Developed testing tank and two prototype sources based on simple resonance. Still refining details; 3rd prototype is in development.

- Initiated modeling to support Task 4 experiments at RSTF.

- Slow start due to retroactive start date (funds arrived Oct. 2021) and subcontracting snafus.

- Now making rapid progress (several students starting in the fall)

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)

PSU GSRA (TBD)

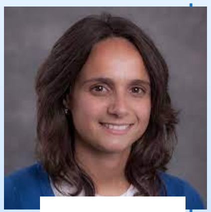
Tieyuan

Lawrence Berkeley National Laboratory
Veronica Rodriguez-Tribaldos
(co-PI)
(Coda wave imaging)

Yves Guglielmi
(Co-I)
Fault Zone Monitoring

Michelle Robertson
LBNL/GMF Field Operations

Todd Wood
LBNL/GMF Engineering



Veronica

Yves

Rice GSRA (TBD)

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

Nader

Michelle

Todd

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

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
2.2	M1	LF CASSM Source Validated:	Year 1, end of Q4	
2.2	D4	LF CASSM Source Design & Testing Results:	Year 1, end of Q4	
3.1	M2	FWI HiEKF Validation:	Year 1, end of Q4	
3.1/3.2	D5	Report on FWI/Coda Approach:	Year 2, end of Q1	
4.1	M3	CASSM/DAS Concept Field Validated:	Year 2, end of Q2	
4.1	D6	Results from Field Testing of CASSM/DAS:	Year 2, end of Q3	
4.3	D7	Inversion Results from RSTF:	Year 2, end of Q4	
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	

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]

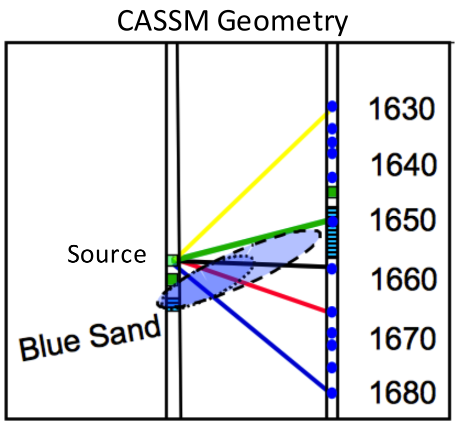
- **Successful Initial Processing of FSB DAS/CASSM Dataset**: Successful initial inversions of DAS/CASSM dataset generated during fault reactivation studies. Determined by reasonable misfit of FWI inversions given SNR levels coupled to prior knowledge. [Year 3, end of Q3

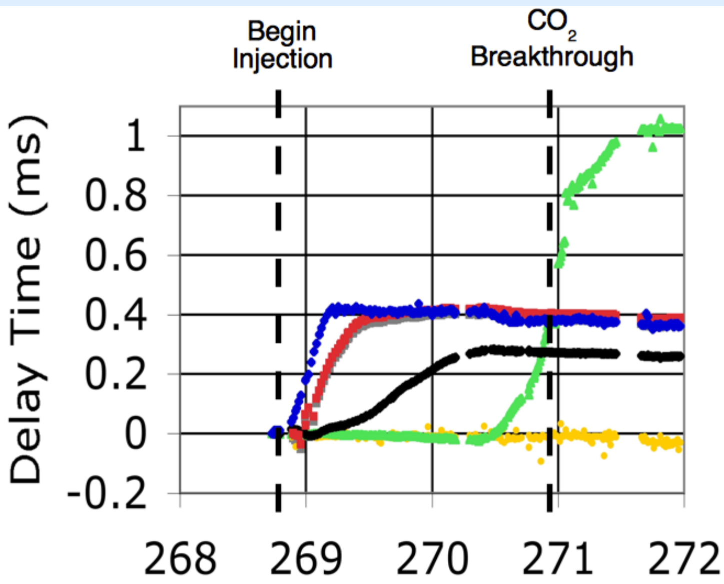
Appendix: Funding Tables

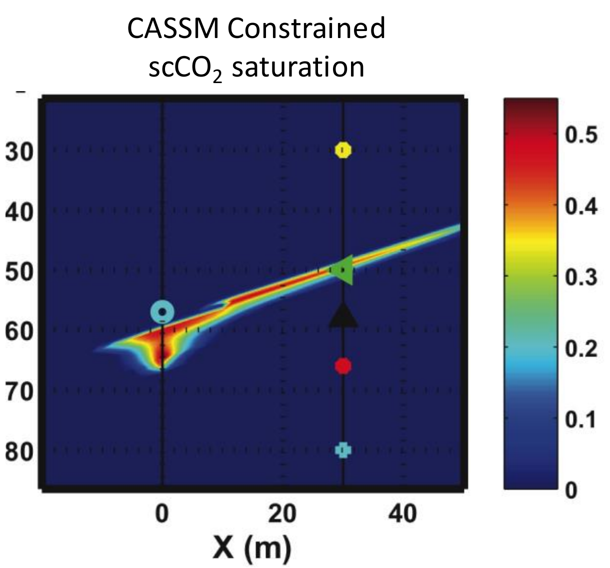
Budget Period No.	Budget Period Start	Government Share $ / %	Recipient Share $ / %	Total Estimated Cost
1	07/01/2021	$417,500 / 82.5%	$88,813 / 17.5%	$506,313
2	07/01/2022	$469,293 / 60.3%	$309,056 / 39.7%	$778,349
3	07/01/2023	$312,802 / 50.2%	$309,780 / 49.8%	$622,582
Total Project	$1,199,595 / 62.9%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

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]

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

Task 4 Work Plan:

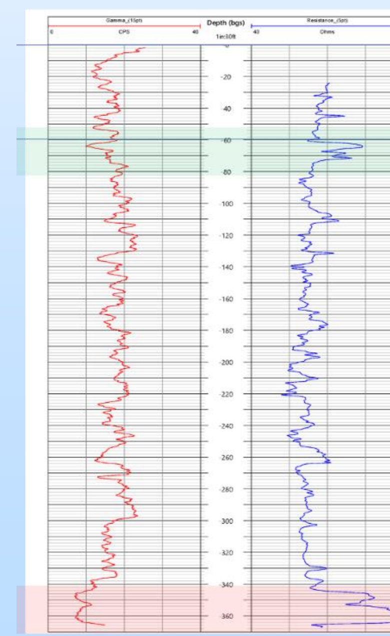
ST 4.1 : Small-Scale validation study of CASSM/DAS combination

- 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?

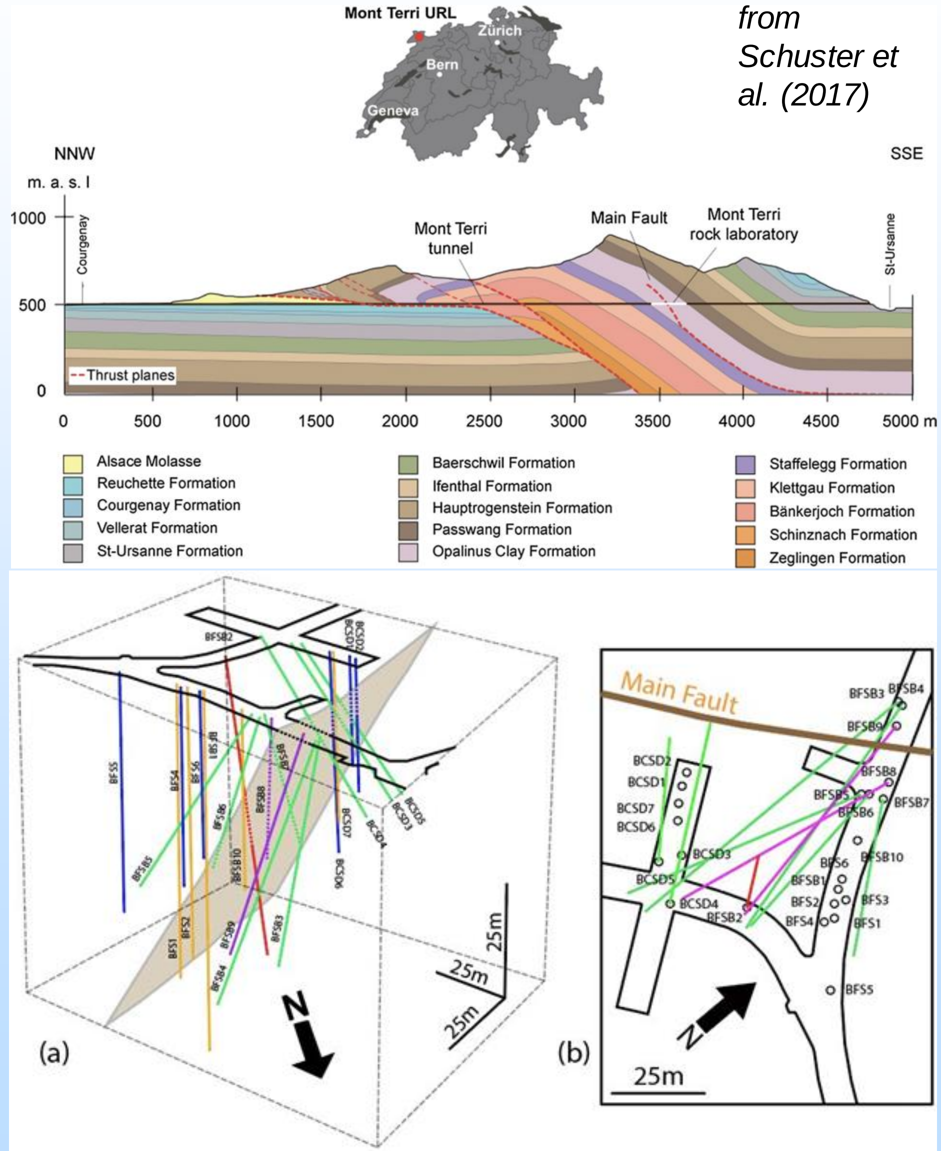
ST 4.2: Analysis of small-scale test using developed monitoring algorithms



Task 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.

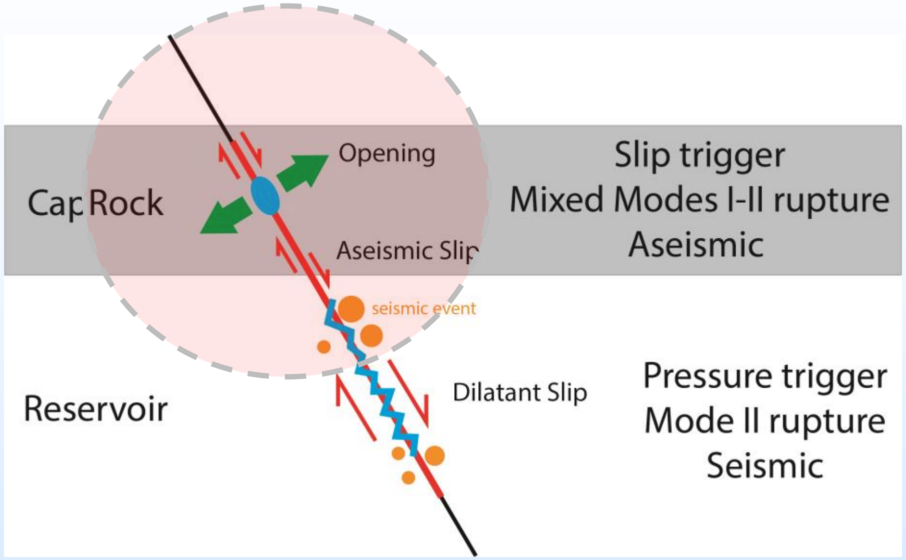
ST 5.2 : Fault reactivation/leakage experiment using brine.

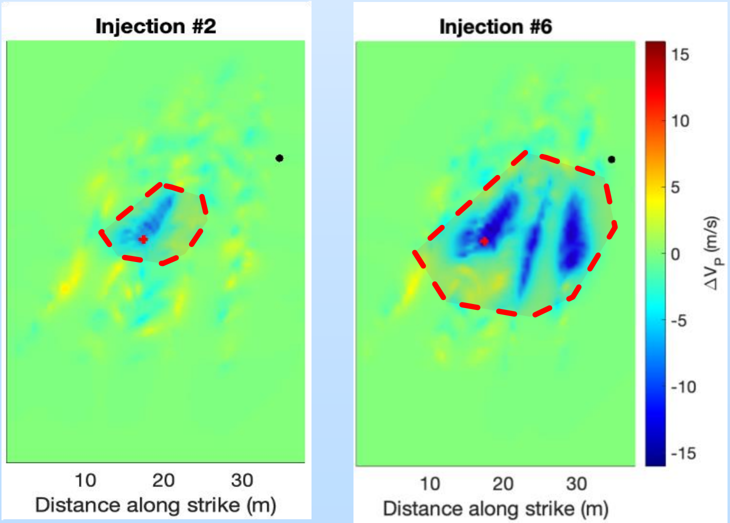
- Monitor zone of fault pressurization, leakage, long-term response.
- Attempt to map spatiotemporal velocity changes across fault plane.

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