CCSMR Task 2
(FWP-ESD14095)

SOV/DAS for Continuous Seismic Monitoring of a CO_2 Injection

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U.S. Department of Energy

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Project Overview: Goals and Objectives

- Project Goal:
  - To build a cost-effective technology for long-term timelapse seismic acquisition using autonomous seismic sources and receivers (SOV-DAS).
  - To improve the performance of SOV-DAS by trialing new field hardware and data processing methodologies. Develop best practice and guidance for incorporating SOV-DAS into permanent reservoir monitoring programs.
  - Leverage from active seismic and passive seismic components of the DAS acoustic data.
- This project will be considered a success if it is able to improve SOV-DAS performance such that it provides equal or better quality data as compared to current state-of-the-art approaches to seismic acquisition.

Contributors

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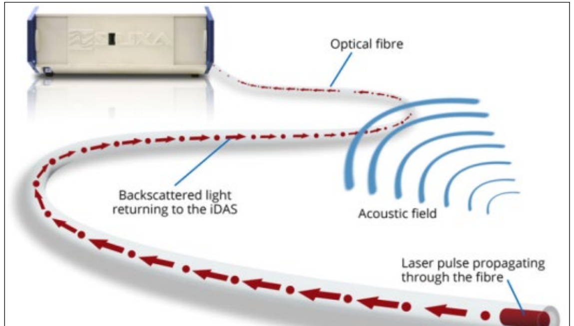
Subsurface Monitoring with SOV-DAS

Conventional campaign-based systems
Temporally sparse / **Spatially** dense

SOV-DAS permanent monitoring system
Temporally dense / **Spatially** sparse

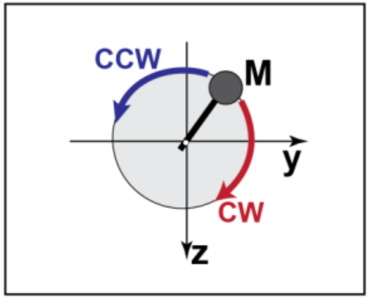
Surface orbital vibrator (SOV)



Distributed acoustic sensing (DAS)

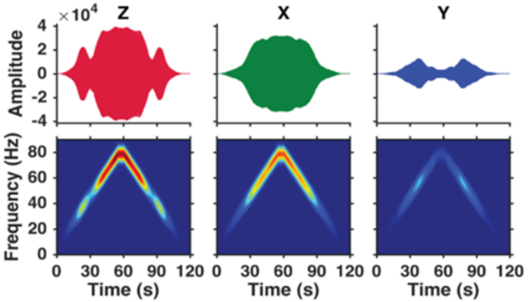
What is a surface orbital vibrator (SOV)?

Rotation of eccentric mass
=> force ~ f^2



An SOV can rotate clockwise (CW) or counter-clockwise (CCW)

1st generation SOV
8-80 Hz



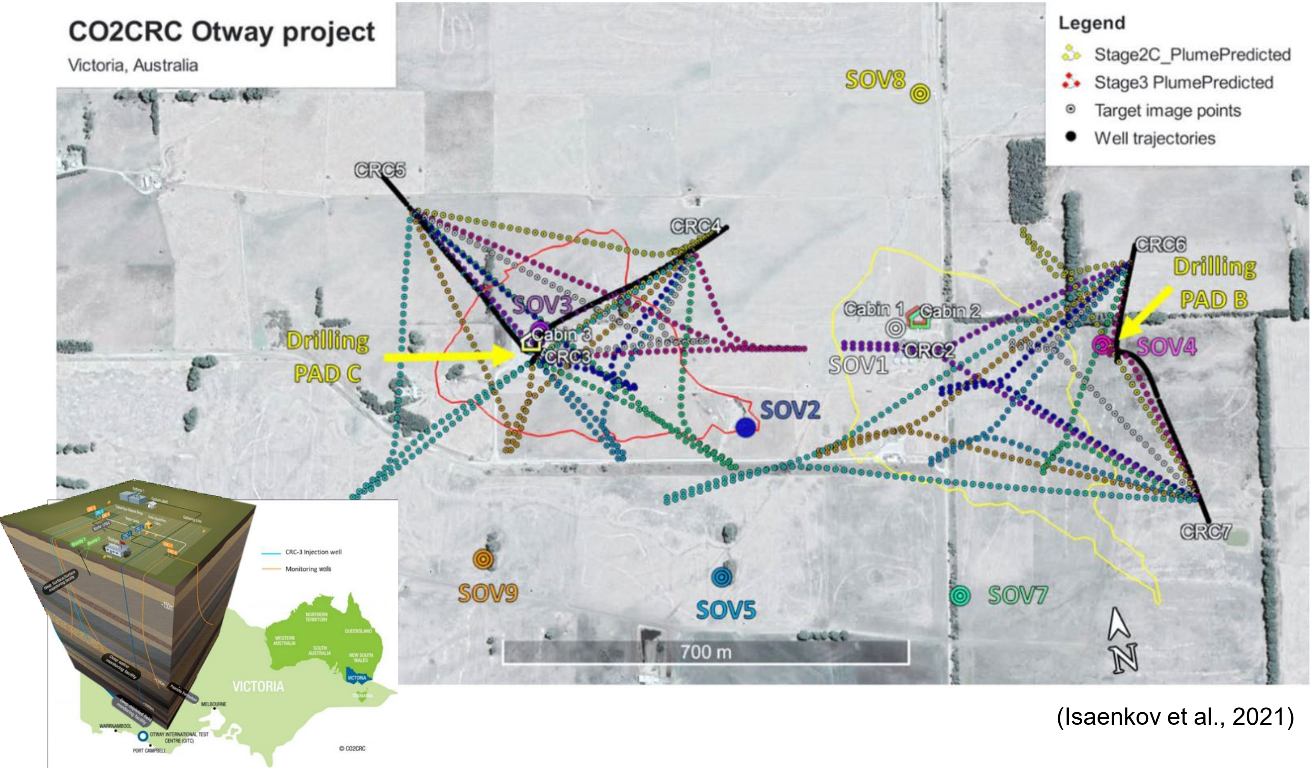
3C Reference geophone buried 3 m below records a sweep

2nd generation SOV
8-105 Hz

[Correa et al 2021, Geophysics]

SOV/DAS demonstration: Otway Project Stage 3

Seismic coverage from DAS/SOV permanent system



(Isaenkov et al., 2021)

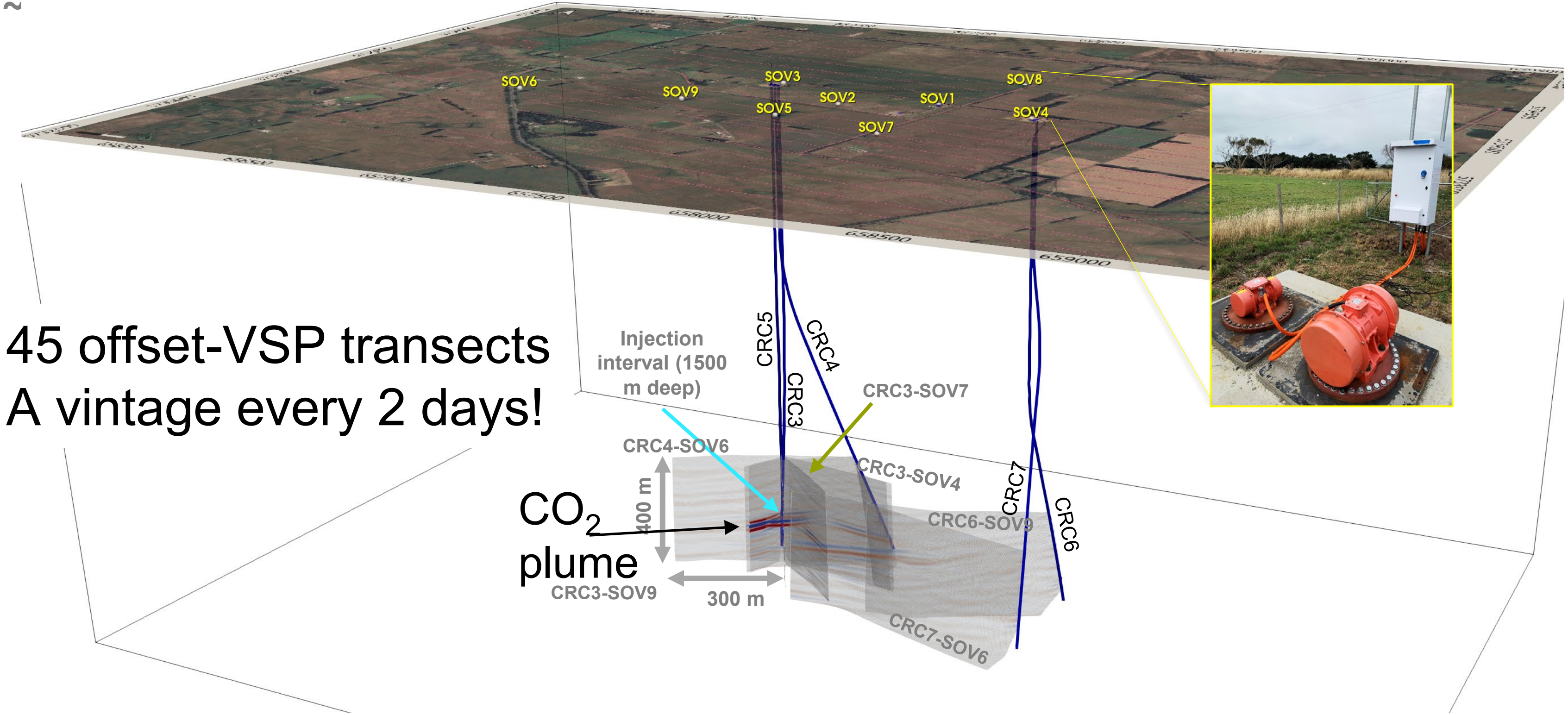
Objectives of experiment:

- Demonstrate **continuous and automated seismic acquisition** using DAS/SOV system
- Demonstrate automated seismic processing for **rapid plume evaluation**
- **Decrease acquisition footprint and societal impact** from seismic acquisition

CO_2 monitoring using SOV/DAS: Otway Project Monitoring

24/08/2021
~

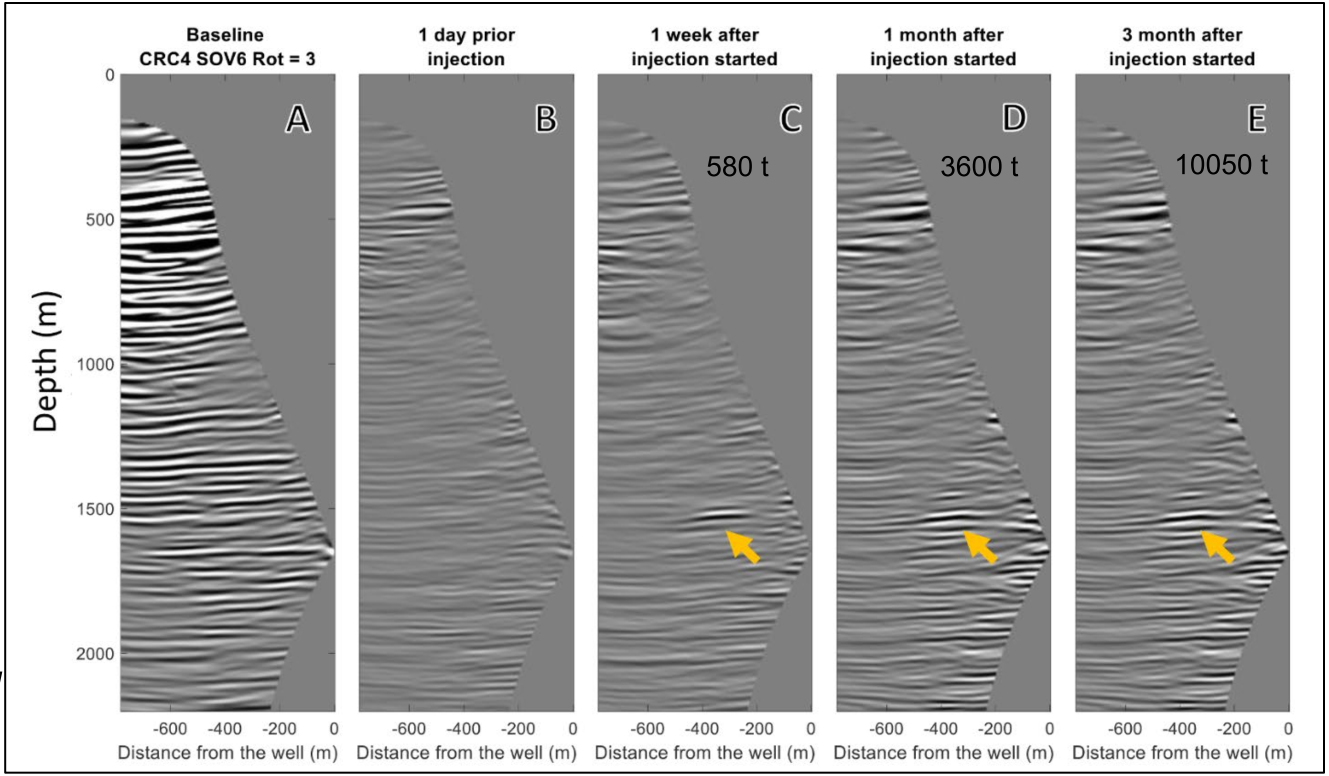
45 offset-VSP transects
A vintage every 2 days!



[Pevzner et. al. 2021]

Baseline and difference seismograms after migration

Detection of CO_2 plume after 580 t injection



[Pevzner et. al. 2021]

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Current Status of Project and Accomplishments

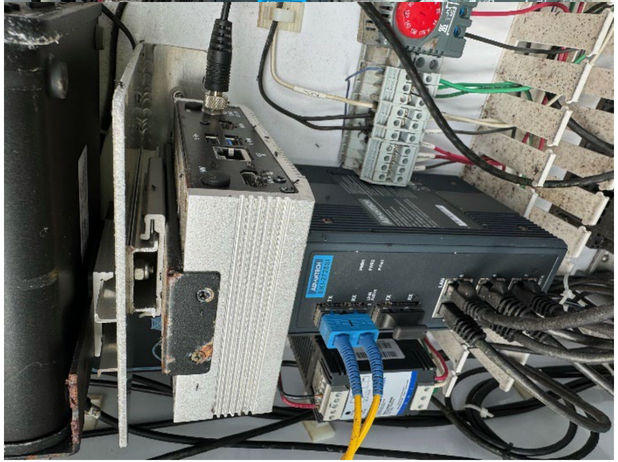
Leakage detection and cap integrity monitoring using DAS/SOV

- Otway planned a shallow release experiment through a known fault to understand the viability of different monitoring methods for detecting leakage

- In preparation to the experiment, we assisted remotely our collaborators with the maintenance of the SOVs – some locations had ant infestation inside the electronic board which caused the power to trip

- VSP data was acquired with DAS and SOVs – in the next FY we plan to analyze the surface waves generated by the SOVs to look for changes in velocity due to the CO_2 leakage

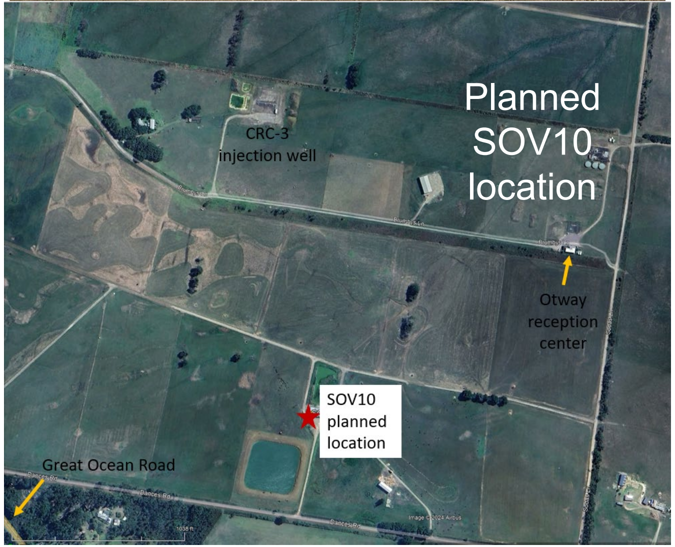
SOV8 computer with ants infestation.



Current Status of Project and Accomplishr

Otway Project Stage 4 preparation

- **The Otway Project plans to inject an additional 10 kt in December 2024 as part of Stage 4 of the project**
- **LBNL is installing one more SOV location – field work for installation starts on the third week of August 2024**
- **LBNL sent three motors to the site (2x 10 tf and 1x 15 tf) and one electronic board/VFD**
- **SOV10 location will be towards the south of the field site to monitor the plume migration, which current monitoring techniques suggests its movement towards SE**



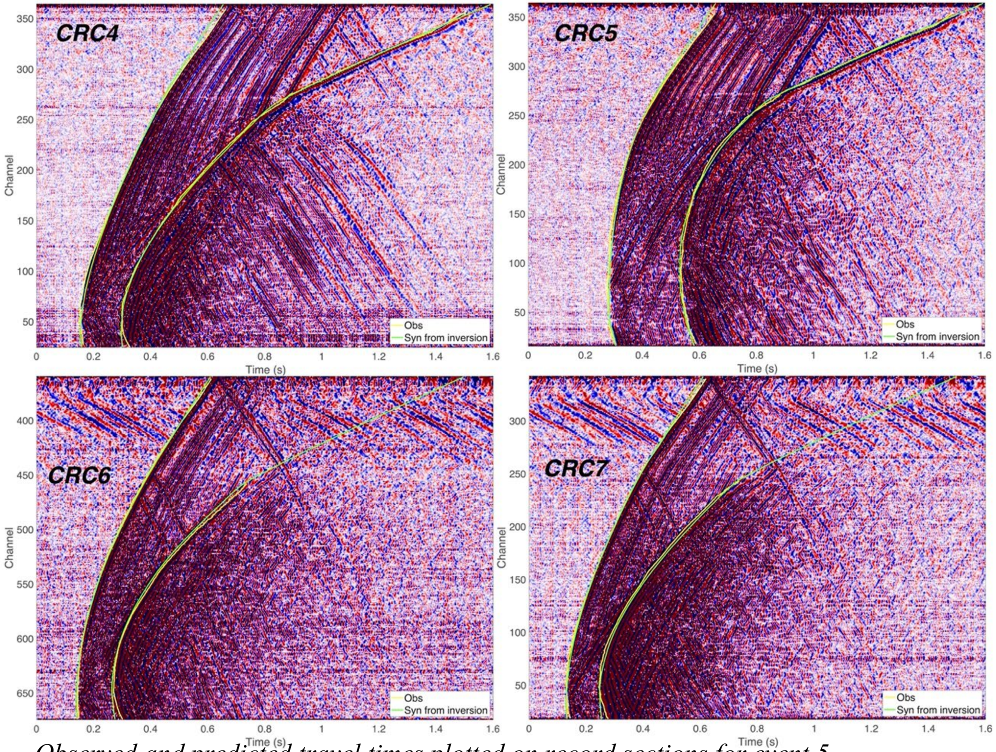
Current Status of Project and Accomplishments

Feasibility of subsurface imaging using injection induced microseismic events

- Over 20 microseismic events were detected with DAS (Glubokovskikh et al. (2023))

- Most events occurred at injection interval – we wanted to understand if we could use MEQs as imaging sources for the CO_2 plume

- Previous work on using MEQ during hydraulic fracturing for imaging has shown successful results on delineating fractures (Ma et al., 2024)

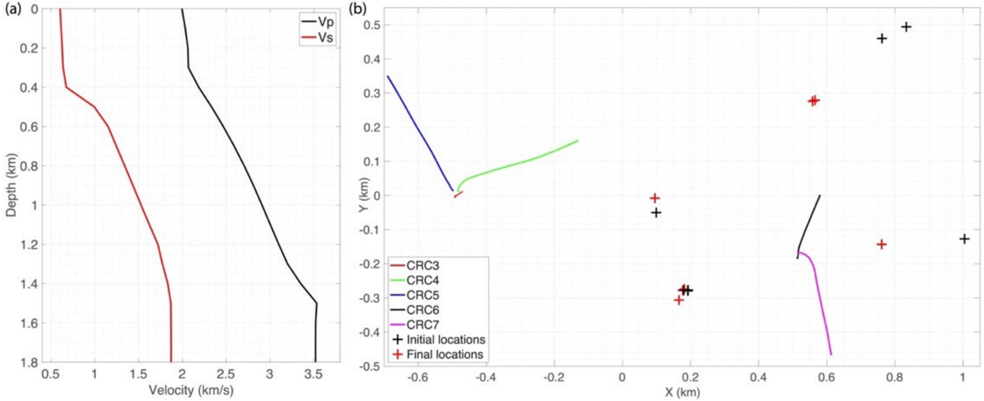


Observed and predicted travel times plotted on record sections for event 5.

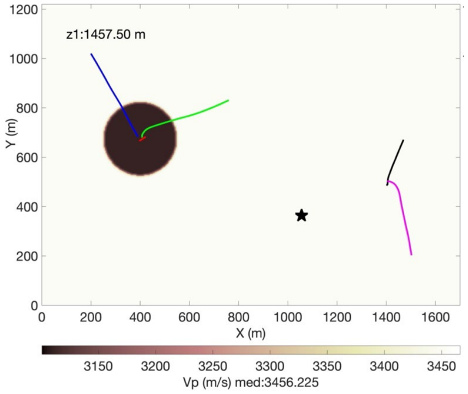
Current Status of Project and Accomplishments

Feasibility of subsurface imaging using injection induced microseismic events

- **Update observed P- and S-wave picks for microseismic events with ID 5, 6, 7, 11, 13, 20 and 21 described in Glubokovskikh et al. (2023)**
- **Inversion of the observed arrival times using tomoDD (Zhang and Thurber, 2003). The initial 1D model was assumed to be a smooth version of the model used in Glubokovskikh et al. (2023)**
- **Forward modeling using the 4th order accurate finite difference based seismic wave propagation software SW4 (Sjogreen and Petersson, 2012)**
- **We perform two sets of forward modeling – one for the background 1D model and one for a model with a circular disc shaped seismic anomaly centered on the CRC3 well representing the CO_2 plume**



(a) Final 1D velocity model. (b) Initial and final microseismic event locations.

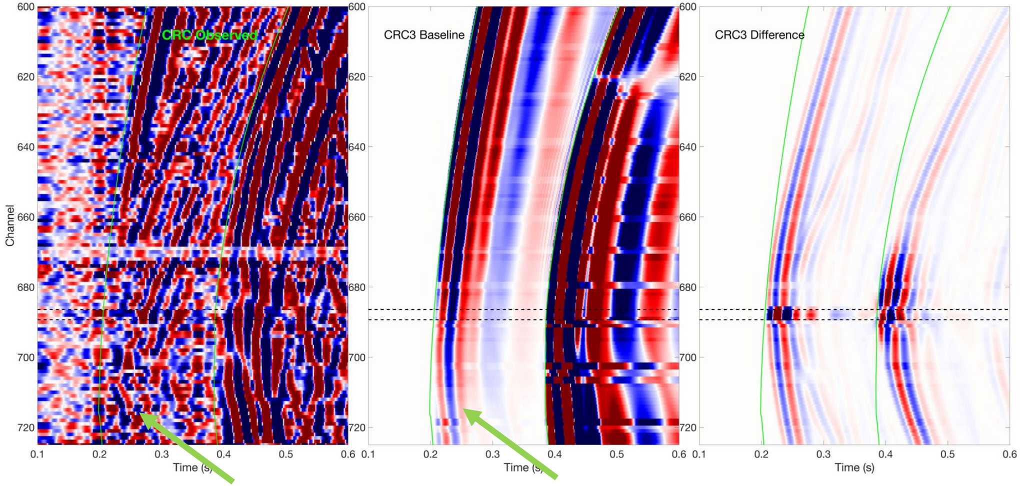


Computational domain showing a hypothetical negative Vp anomaly around CRC3 at depth 1457 m. Black star marks event 5.

Current Status of Project and Accomplishments

Feasibility of subsurface imaging using injection induced microseismic events

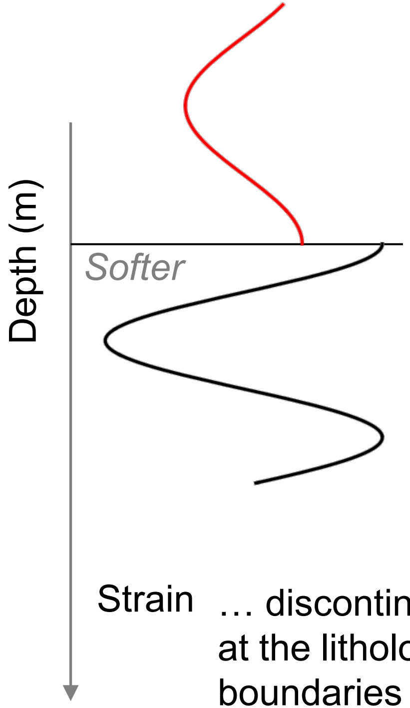
- We compare the real event with the simulation
- The difference plot (right panel) shows reflected PP and PS, demonstrating we can potentially use these reflections for imaging the CO_2 plume
- The real event (left panel) is considerably noisier, which makes it difficult to identify which reflection is associated with the plume
- However, we can see reflection on the real event close to the plume interval which could be potentially used for imaging



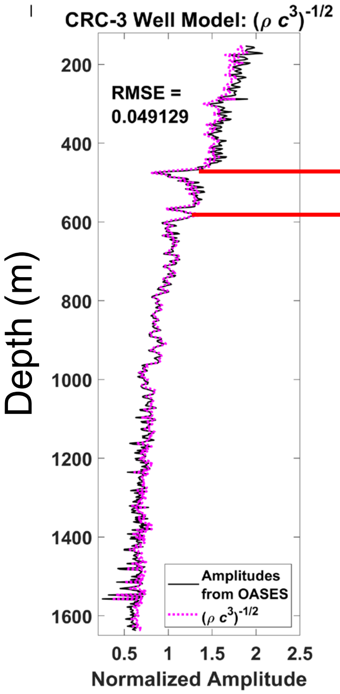
On the left, real MEQ event as observed on DAS in CRC3 well. On the middle, the simulated seismogram shows the baseline response using the background 1D model. The right panel shows the difference plot between the simulations of the baseline and after plume. The green curves are P and S travel time predictions from ray-tracing. Waveforms are filtered 10-40 Hz.

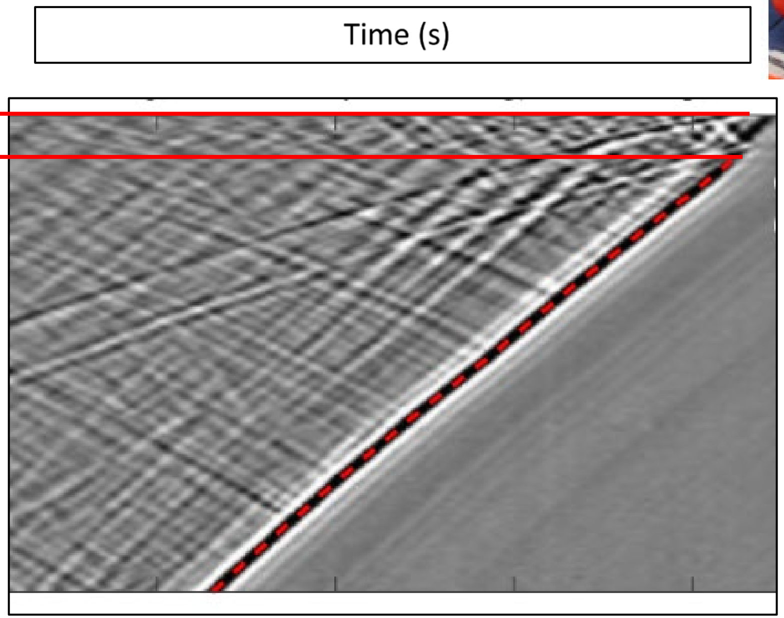
Current Status of Project and Accomplishments

SOV/DAS amplitude response to the repeated seismic signals *in-situ*



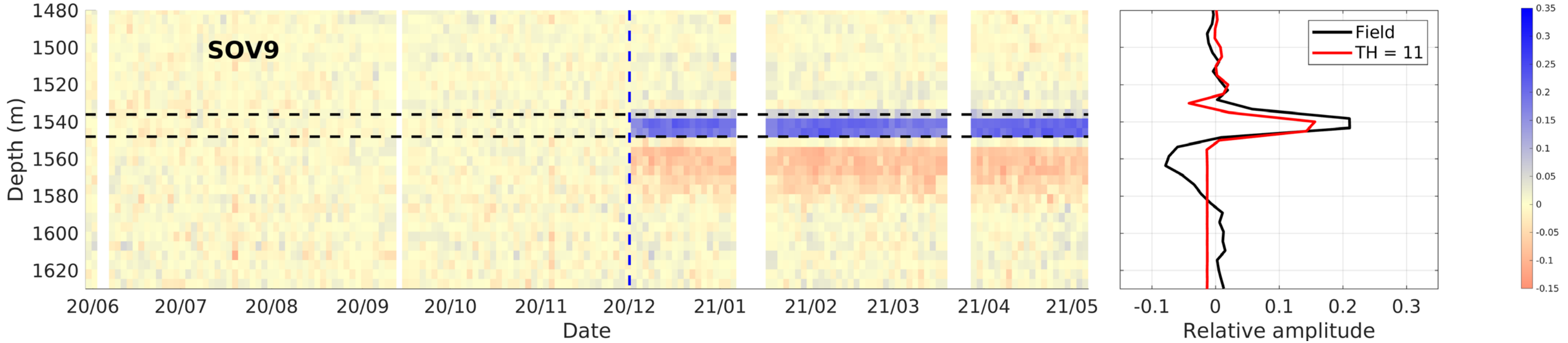
… discontinuous at the lithological boundaries



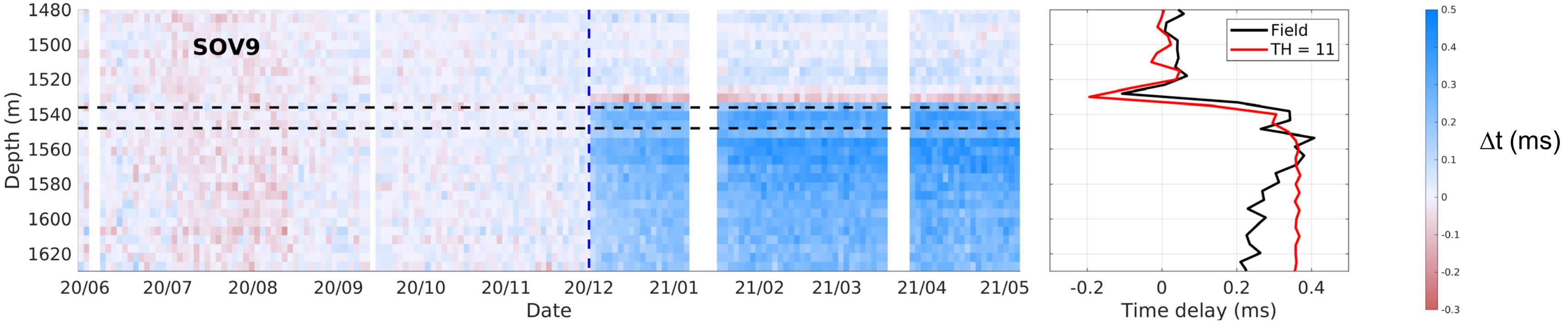


Repeat Logging: SOV/DAS amplitude vs Rock Stiffness

DAS anomalies are clear in the direct wave



After time-lapse deconvolution the difference seismograms have a strain anomaly in the plume

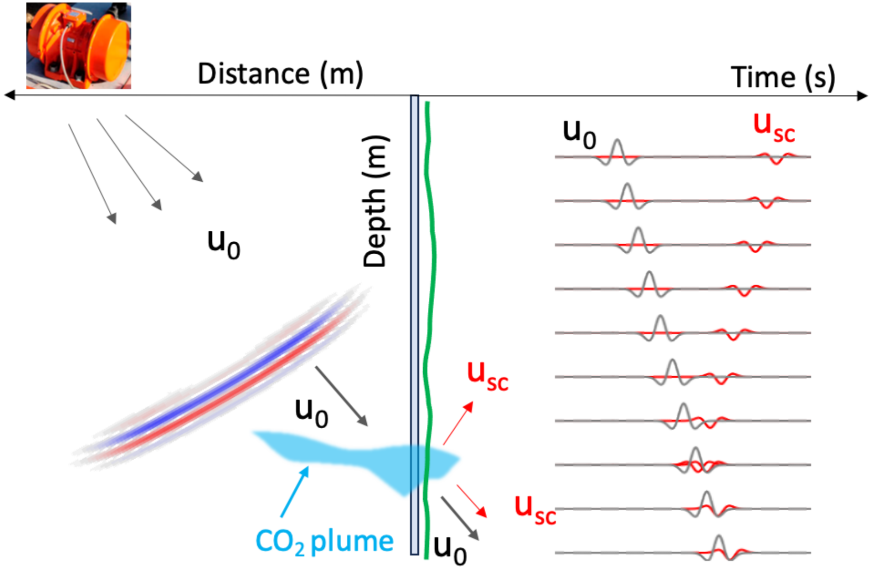


[Pevzner et. al. 2021, https://doi.org/10.1190/geo2021-0404.1]

Repeat Logging: SOV/DAS amplitude vs Rock Stiffness

Scattering integral formalism to model DAS amplitude anomalies

$$\boldsymbol{u}_{sc}(\boldsymbol{r}) = \omega^2 \int_{\Omega_i} \delta\rho(\boldsymbol{r}')\mathbf{G}_0(\boldsymbol{r},\boldsymbol{r}') \cdot \boldsymbol{u}_0(\boldsymbol{r}')d\Omega - \int_{\Omega_i} [\mathbf{G}_0(\boldsymbol{r},\boldsymbol{r}') \otimes \nabla'] : \delta\mathbf{C}(\boldsymbol{r}') : \epsilon_0(\boldsymbol{r}')d\Omega$$

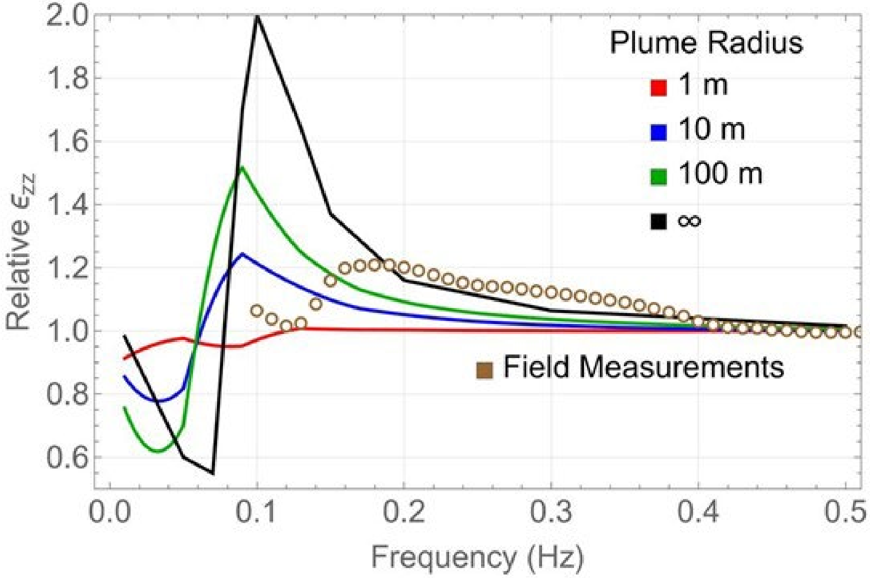


Benefits of the scattering integral (Born)

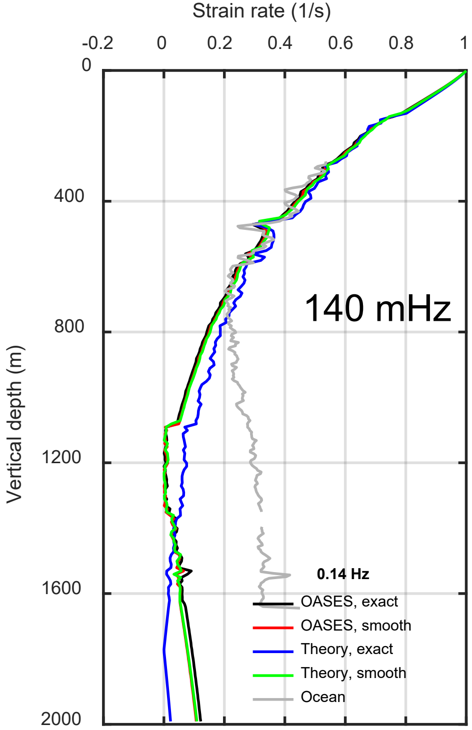
- Valid for the majority of subsurface scenarios
- DAS does not need calibration
- Easy to compute using BEM
- Easy to approximate analytically
- Underlies conventional imaging, so can do a joint inversion

Repeat Logging: Microseisms vs Rock Stiffness

Modeling the baseline wavefield is challenging!!!



Incident Rayleigh wave
Model vs Reality



- Not 1D for a 10-km range
- Averaging out multiple sources/locations
- Accurate deeper crust?

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[Glubokovskikh et al. (2024) SRL, submitted]

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Key findings

- Maintenance of SOV-DAS involves tightening bolts on the motors and keeping up with pest control
- Forward seismic modeling of MEQ event during injection shows a PP and PS reflection due to plume, which can be potentially used for imaging
- At the Otway Project, we saw a clear change of DAS amplitudes within the CO_2 plume
- DAS amplitude analysis within the plume enable repeat sonic logging for free

Lessons Learned and Accomplishments to Date

- *Take away message*: Cost-effective, long-term and continuous seismic monitoring of a CO_2 injection can be successfully achieved with SOV/DAS
- Detection of the injected CO_2 plume with volume as low as 580 ton using the SOV/DAS data)
- Continuous operation for over 3 years with minimum down-time
- Remote operation and acquisition of SOV/DAS for quasi-real time monitoring
- Simultaneous passive monitoring for joint active/passive interpretation

Next Steps

Continuous seismic acquisition with SOV/DAS

- Field work for SOV10 installation beginning in two weeks
- Injection of 10 kt starting on December 2024
- Continue to provide assistance with SOV maintenance and continuous operation
- Leakage detection test: analysis of velocity variation through surface waves on SOV/DAS
- Use reflections identifies on MEQ event for imaging

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Questions?

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