Core Carbon Storage and Monitoring Research:

Task 3: Advancing Monitoring Technology

Project Number LBL-15-ESD14095

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U.S. Department of Energy
National Energy Technology Laboratory
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Transforming Technology through Integration and Collaboration
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LAWRENCE BERKELEY NATIONAL LABORATORY

Presentation Outline

- Benefit
- Goals and Objectives
- Overview
- Technical Status
  - – Continuous Seismic Monitoring Technology
  - – EM monitoring Technology
- Accomplishments to Date
- Synergy Opportunities

Benefit to the Program

- Support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
- Develop and validate technologies to ensure 99 percent storage permanence.
- Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness.
- This research project is investigating continuous seismic and EM monitoring technologies and subsurface instrument tools that range from the conceptual/lab scale to pilot scale. The technology, when successfully demonstrated, will aid in mapping the CO2 plume, physical property changes, and potential migration pathways in storage reservoirs. This technology contributes to the Carbon Storage Program's effort of ensuring 99 percent CO_2 storage permanence (Goal).

Project Overview: Goals and Objectives

– This project will provide core R&D support for carbon storage and monitoring. The aim of the research is to develop and test technologies ready for field deployment while supporting the Carbon Storage Program goal of developing and validating technologies to ensure 99 percent storage permanence.

– Success criteria

  • Conduct technology tests at field sites of opportunity where collaborative learning can add to the DOE Carbon Storage

  • Investigate new monitoring technology from the 2nd generation (currently in R&D) and advance it to 1st generation (being demonstrated)

Task Description

- **Task 3: Advancing Monitoring Technology**
  - Support Task 2: Field Testing of Emerging Technologies
    - » Technology deployment at international sites
  - Explore monitoring tools that range from conceptual/lab scale to pilot scale
  - Goal to aid in mapping the CO2 plume, monitoring physical property changes, and detecting potential migration pathways in storage reservoirs.
  - Monitoring technologies at the TRL 2-4 level will advance through further engineering and development activities up to a TRL level 4-6.
  - Technologies that are less ready to move up to field testing than the technologies identified under Task 2 and will need until 2020 to advance to a TRL 6-7.

Technical Status

- **Advancing Monitoring Technology: Project Tasks**
  - a. Continuous Monitoring
    - *a-1. Electrical and Electromagnetic monitoring*
    - *a-2. Seismic*
  - b. Subsurface Instrument Development and Deployment
    - *b-1. Electrical and Electromagnetic monitoring*
    - *b-2. Geochemical*

Project Status

- Full funding received mid 2015, so some subtasks have not yet started
- Early start tasks:
  - Continuous Seismic Monitoring
    - Permanent Surface Seismic Source
    - Surface fiber optic cables
  - Electromagnetic borehole instruments
    - Electromagnetic acquisition geometry modeling
      - Borehole-to-surface

New Technologies for Continuous Monitoring

- Our project will use and advance commercial developments where available and develop new technology where needed:
- Fiber optic sensing:
  - Distributed Acoustic Sensing (DAS)
- Semi-Permanent Seismic Sources
- EM
  - Continuous EM crosswell (i.e. CASEM)
  - Borehole-to-Surface EM (BSEM)

Continuous Surface Seismic/VSP

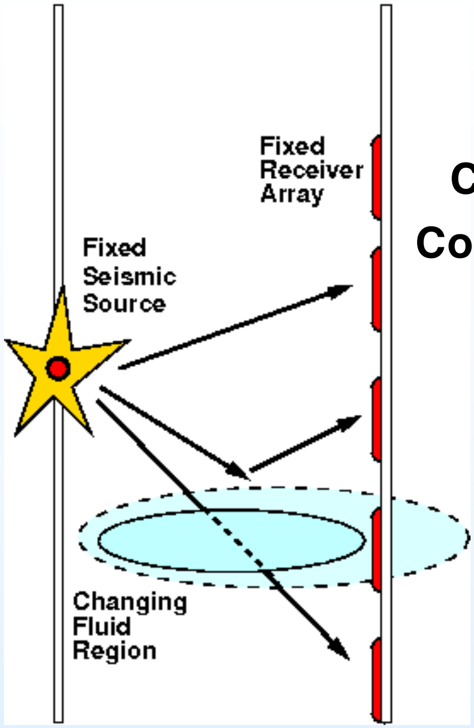
- What is continuous?
  - Discrete temporal sampling at rate which accurately captures processes of interest.
- Why continuous?
  - CO_2 storage is long term process with long term monitoring requirements;
    - initial high costs for installation of permanent instrumentation can be recovered when saving cost of discrete redeployment
  - Unexpected events can be detected in a timely manner
  - Processes can be more accurately modeled and understood; models can be constrained
  - Data quality can improved:
    - Often lower noise levels for permanent sensor deployment
    - Allow optimal temporal filtering of non-aliased time series

Continuous Monitoring: Background

- Building on development of Continuous Active-Source Seismic Monitoring (CASSM) with crosswell acquisition geometry
  - Proved valuable for CO_2 monitoring
  - Rich data set addressing rock physics impacts
    - Daley, et al: velocity change -> CO2 saturation
    - Zhu, et al: - attenuation change

Continuous Active-Source Seimsic Monitoring (CASSM) Background

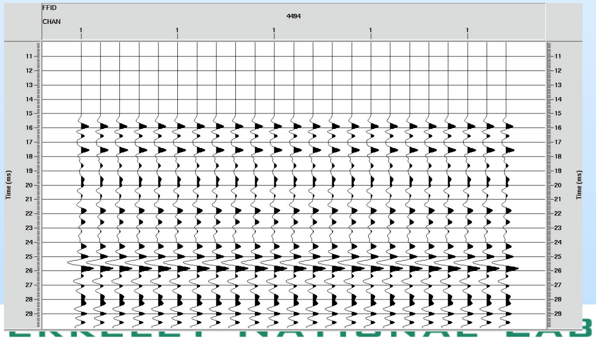
- Goal: Advancing the precision *in situ* monitoring of seismic properties
  - Current: crosswell geometry
  - Planned: surface – borehole

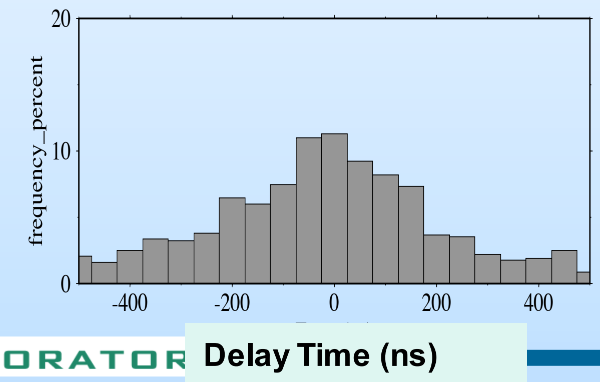


Crosswell Configuration

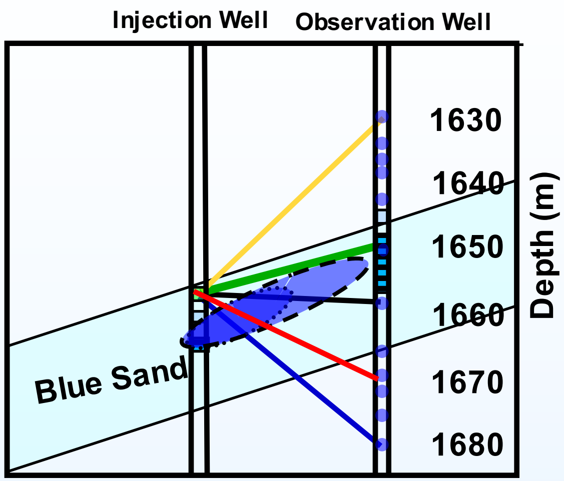
- Motivation:
  - Monitoring of In-Situ Processes
  - Monitoring of CO2 sequestration
    - Monitoring for plume dynamics and 'leakage'
    - Reservoir dynamics and petrophysics
      - Velocity/Saturation (fluid effects)
    - Monitoring for groundwater remediation

Piezo-tube Source

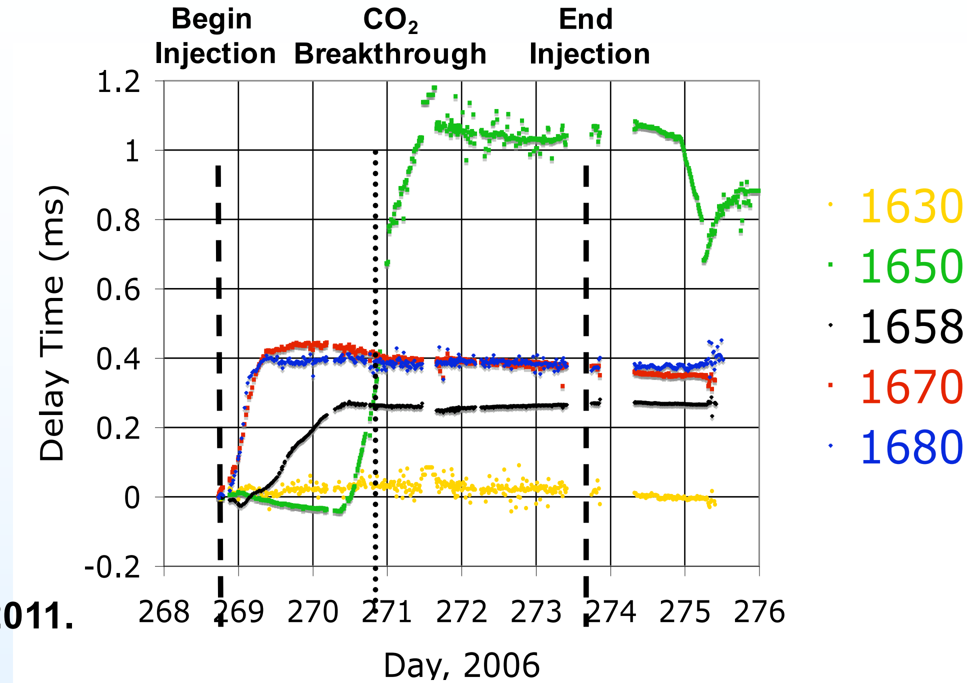


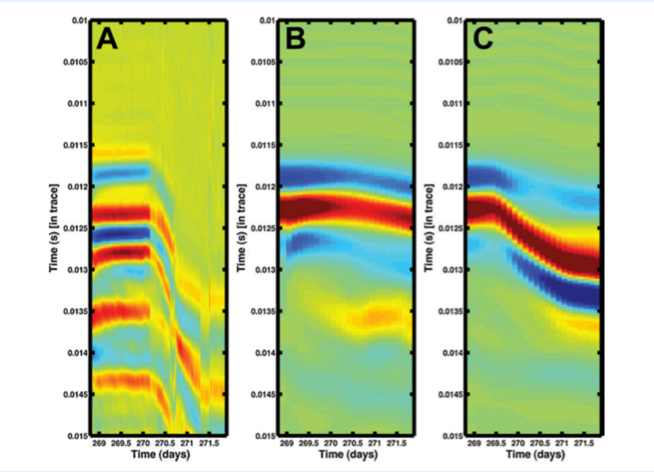


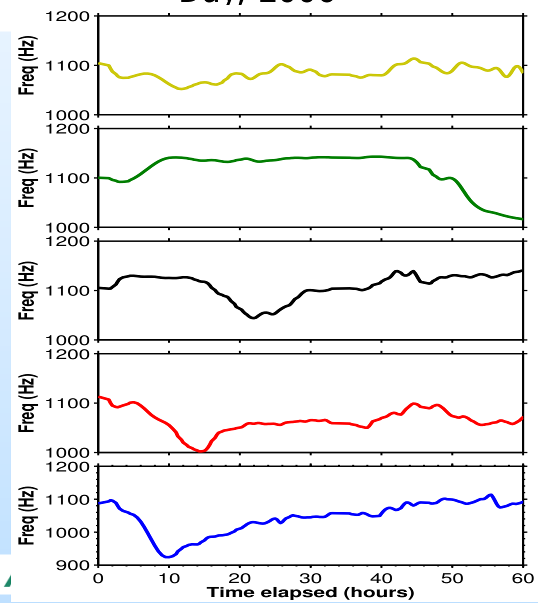
Background: Frio-II CASSM Results



Daley, et al, Geophysics, 2007; IJGCC, 2011.







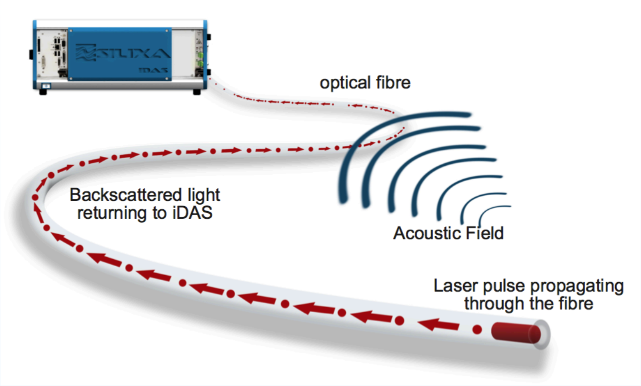
Attenuation

Centroid frequency
T. Zhu, et al;
AGU,2014

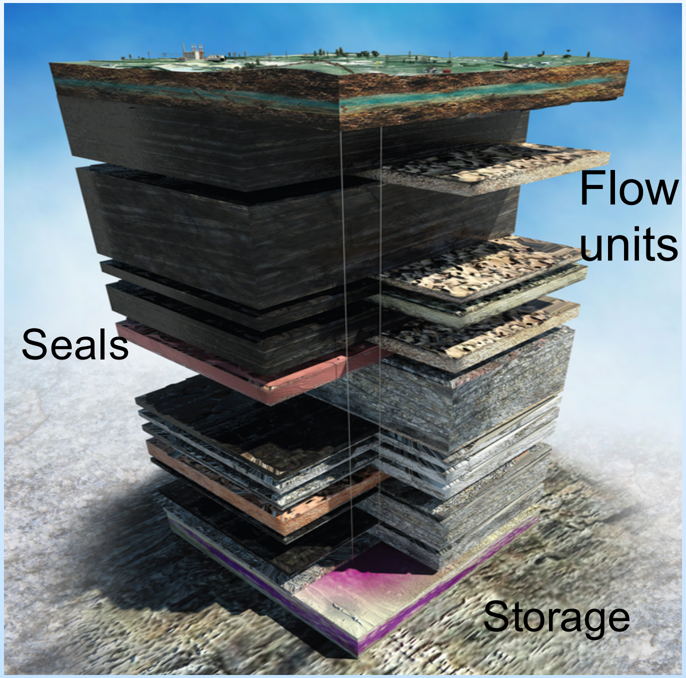
Background: Distributed Acoustic Sensing (DAS)

Aquistore

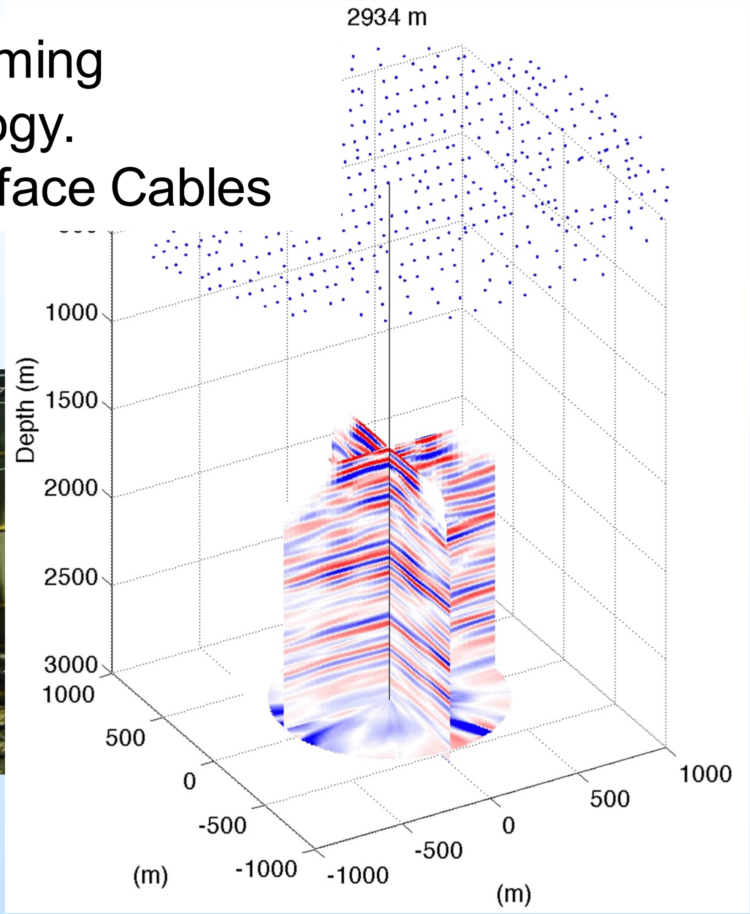
DAS Baseline 3D-VSP



DAS VSP is becoming accepted technology.
New Frontier: Surface Cables



Casing Deployment Of Fiber Optic Lines



Otway Stage 2C Experiment (CO2CRC)

Permanent 3D Surface Seismic Sensor Array

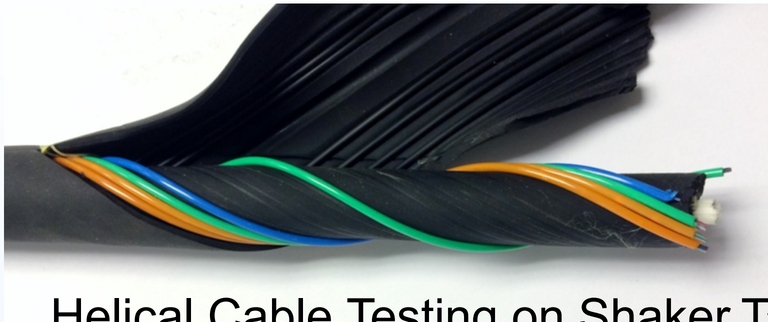
LBNL: 2 Permanent Sources and surface DAS fiber cables in trenches

Planned:

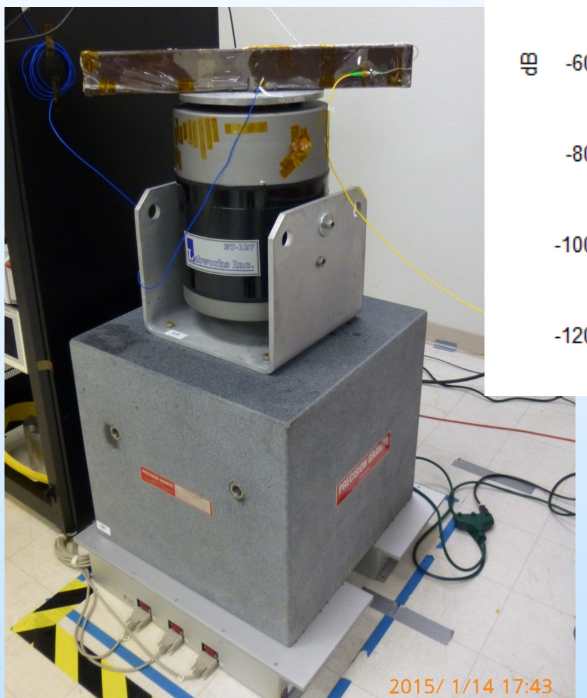
- 3 5k Tonne Injections with full monitoring of each
- 1500 m depth
- Saline aquifer

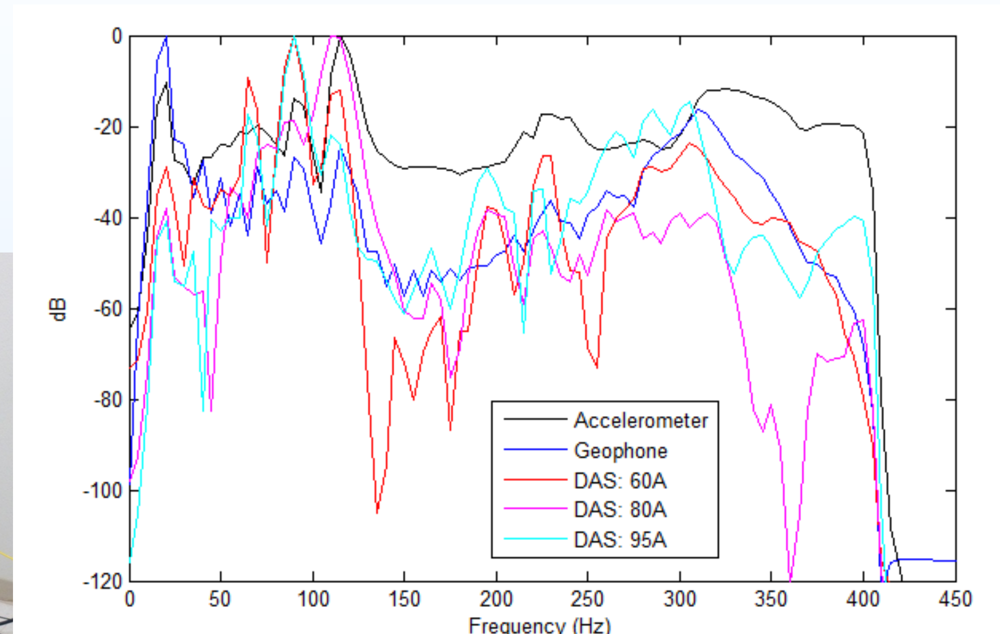
Courtesy R. Pevezner, Curtin Univ, CO2CRC

Problem: Standard DAS Fiber Cable is not good for surface seismic geometry
Development: Helical Wound Cable Cable



Helical Cable Testing on Shaker Table

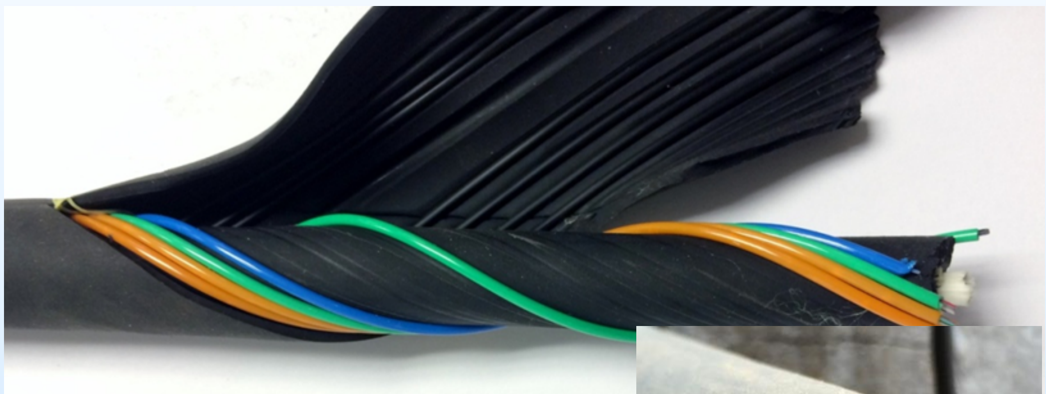




Multi cable frequency response
10-410 Hz Sweep

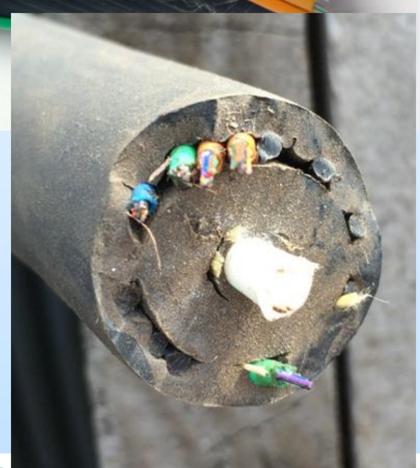
Latest Helical Cable: ‘FAT’ Wound Cable

- Based on results of Hornman et al. (2013 EAGE) for deployment of a broadside sensitive cable we deployed our own design
- Initial testing of spiral wound cable with hard plastic showed strong attenuation of seismic signal and a new design was developed.

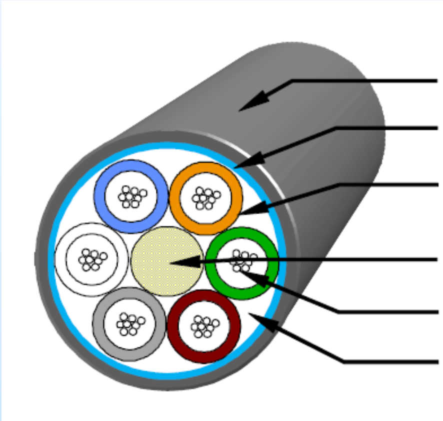


30° spiral wound on 58 Shore A rubber mandrel.

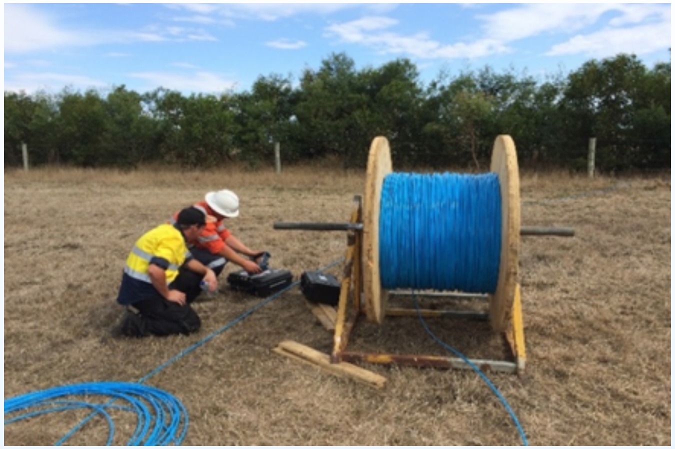
Used in one trench.

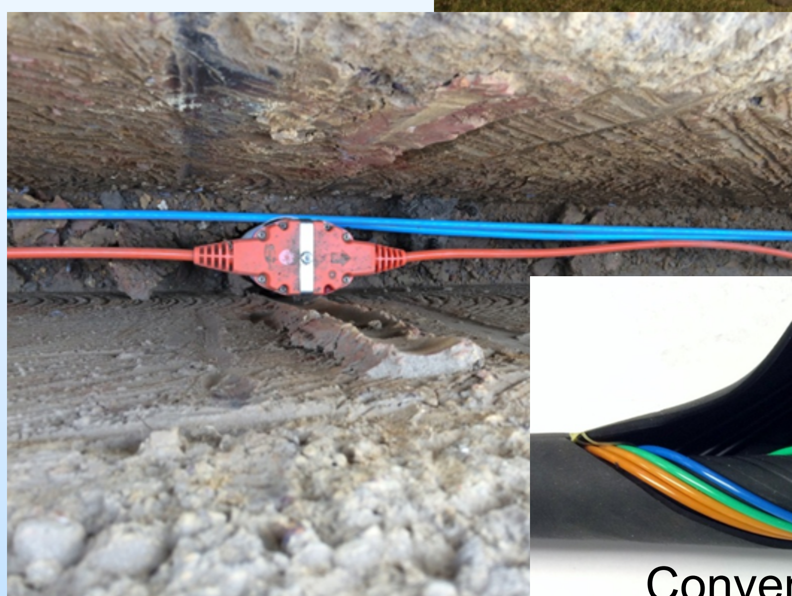


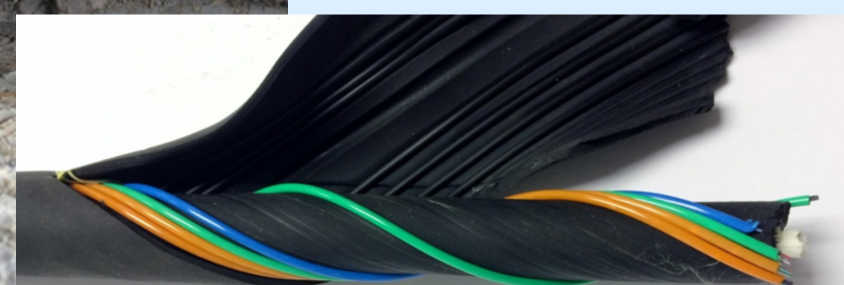
Normal Telcom Cable used in all trenches



March 2015 Otway ~15+ km Cable Installation



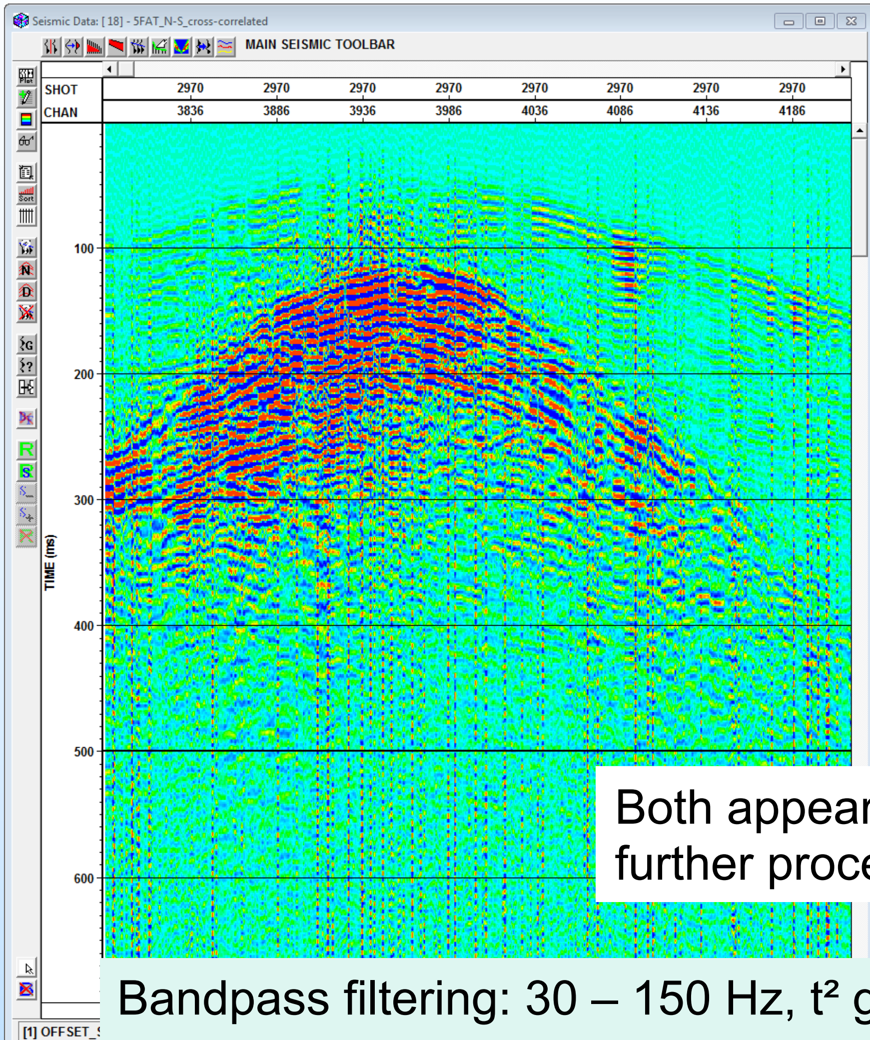




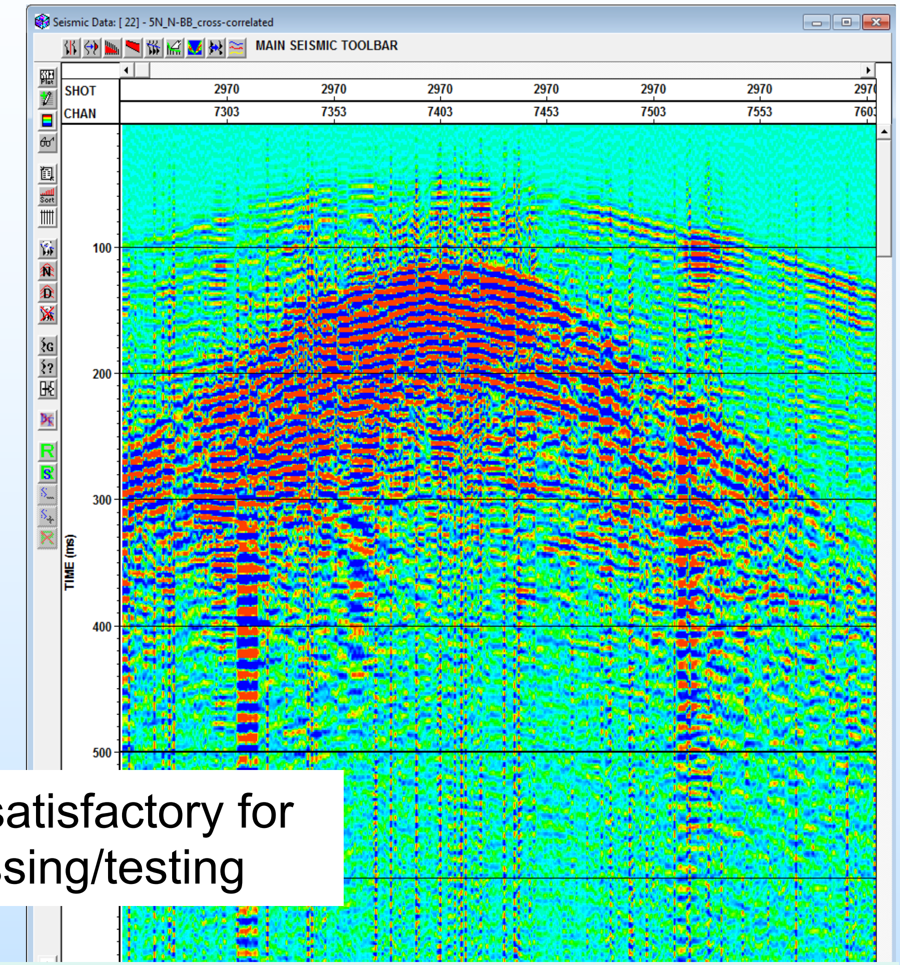
Conventional and FAT cable

Otway: Comparison crosscorrelated shot gathers at S29VP70; Conventional Vibroseis Source Helical and Conventional Fiber Surface Cables

5-N FAT Helical



5-N Conventional



Both appear satisfactory for further processing/testing

Bandpass filtering: 30 – 150 Hz, t^2 gain applied, true amplitude comparison.

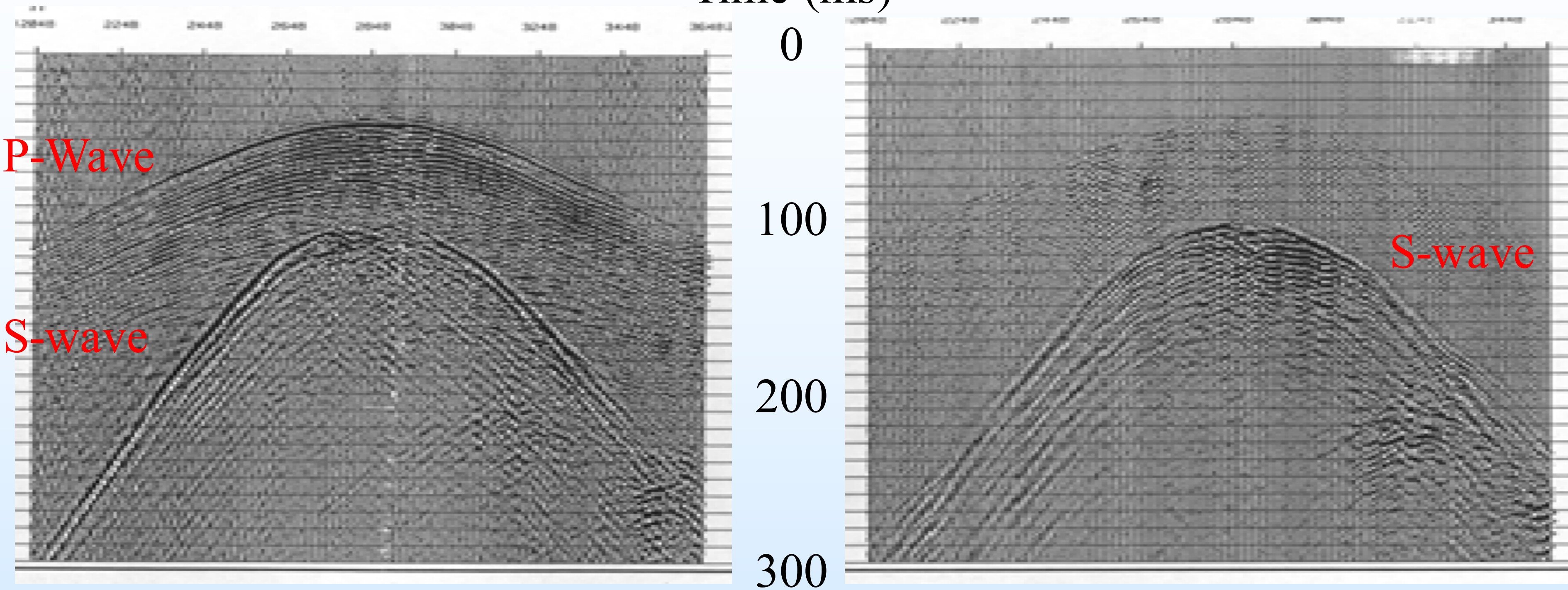
Next Step in CASSM Development
Continuous Surface Seismic

- What is an optimal permanent surface source?
- Orbital Vibrator? Background:
  - Orbital Vibrator (rotary eccentric mass) sources proposed/developed in 1970s-1980s
  - Initial success with borehole source in 1990s
  - Attributes/Advantages
    - Generates P- and S-waves
    - Output (Force) increases with frequency
    - Conventional electric motor drive
- Surface Source
  - 1980's truck mounted (Conoco Research)
  - 1990's – 2000's ACROSS source (Japan, JOGMEC)
    - used for tectonic/crustal and reservoir studies

O.V. Background: Crosswell Data
In-Line source has P and SV-waves
Cross-Line source minimizes P-wave coda

In-Line Source (X) | Cross-Line Source (Y)

Time (ms)

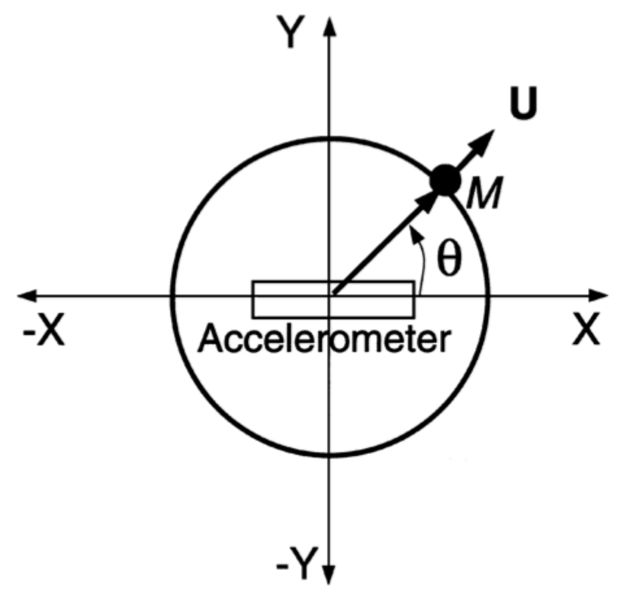


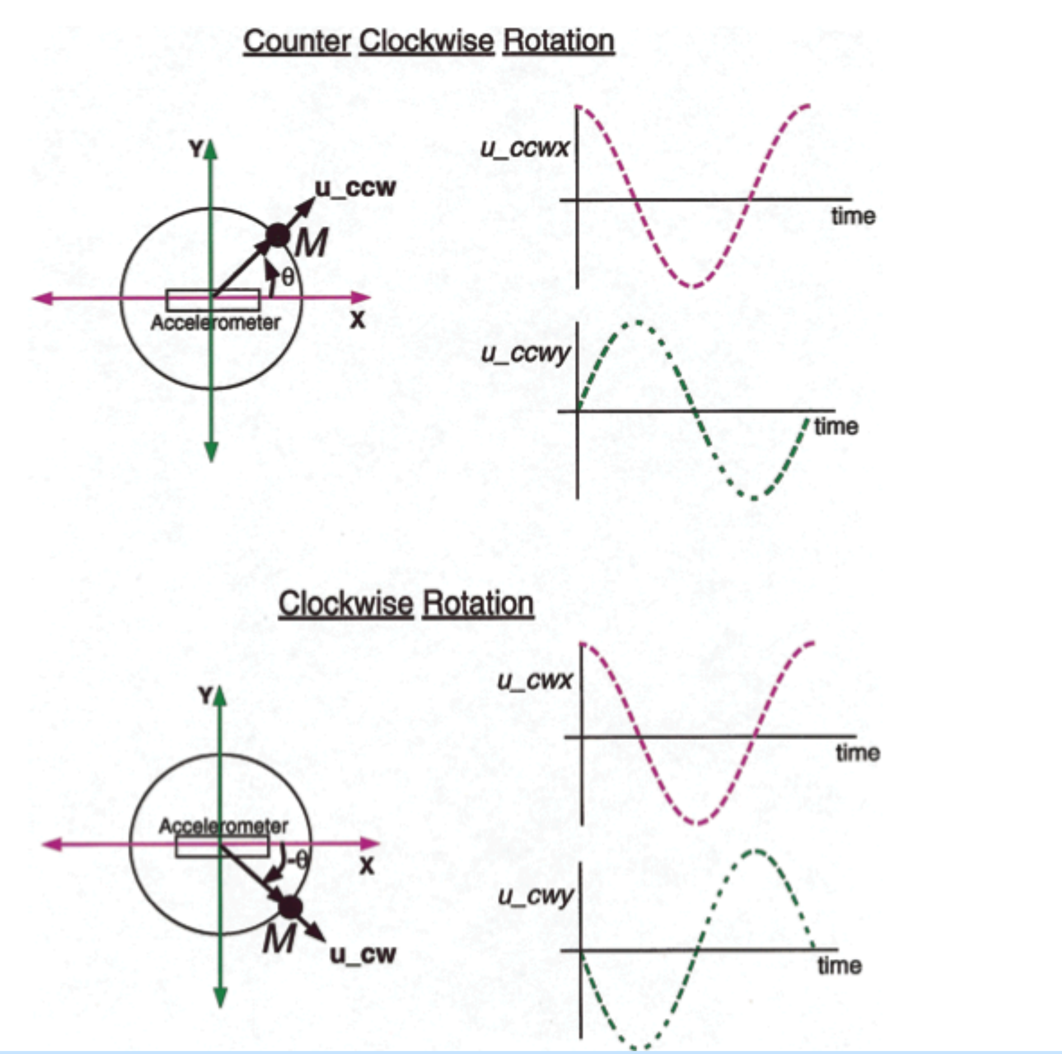
ACOV Source at 2864 ft; Sensors 2048 – 3648 ft. at 8 ft intervals

Well Spacing ~ 250 ft.

Data from Bayou Choctaw, La (Daley, et al, SEG 2002)

O.V. Operating Principle



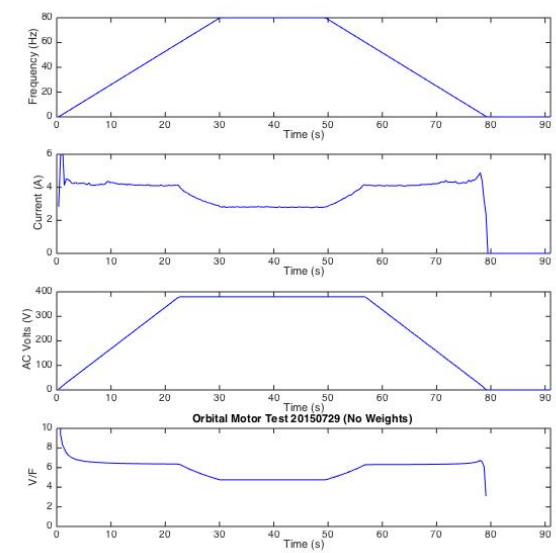


Daley and Cox, 1999

EM-01C

Surface Orbital Vibrator Permanent Seismic Source for 4D Monitoring

With Eccentric Weights



Electrical Response

Swept frequency fixed rotary source –

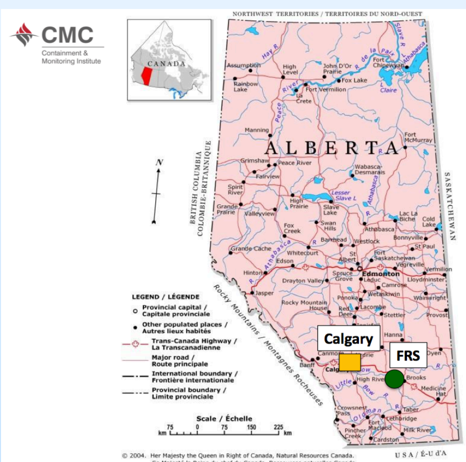
- Design for extended periodic seismic excitation (e.g. 1 hr/day)
- 20 to 80 Hz sweep
- Reverse motor direction each sweep
- F_{peak} = 10 Tons at 80 Hz

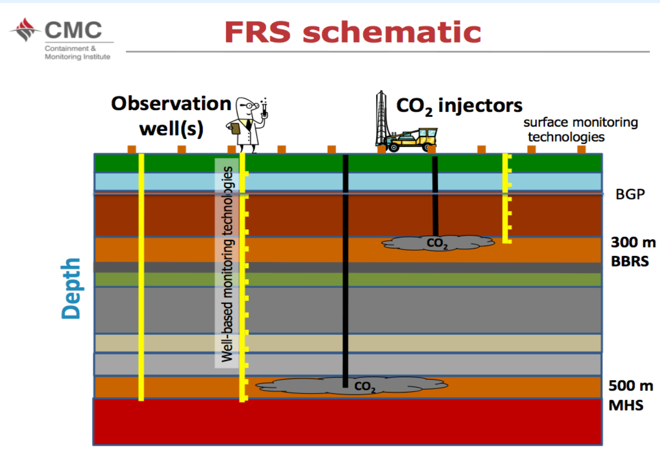
Continuous Seismic Monitoring

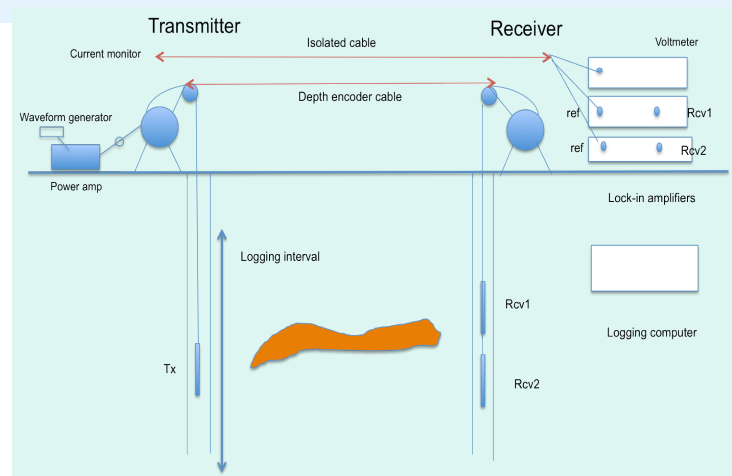
- Solution: Combination of permanent fiber optic sensing (DAS) in trenches and wells with permanent surface sources
  - To be tested at Otway Stage 2C: Late 2015
- Time sampling and spatial sampling as needed to monitor subsurface processes
- On-demand subsurface surveillance

Electro-Magnetic (EM) Instrumentation

- Developing high-frequency (10+ Khz) crosswell EM system
- Planned field test at Carbon Management Canada, Field Research Station
- Goal: Continuous active-source electromagnetic monitoring (CASEM)
- Initial test likely: borehole-to-surface (BSEM) monitoring

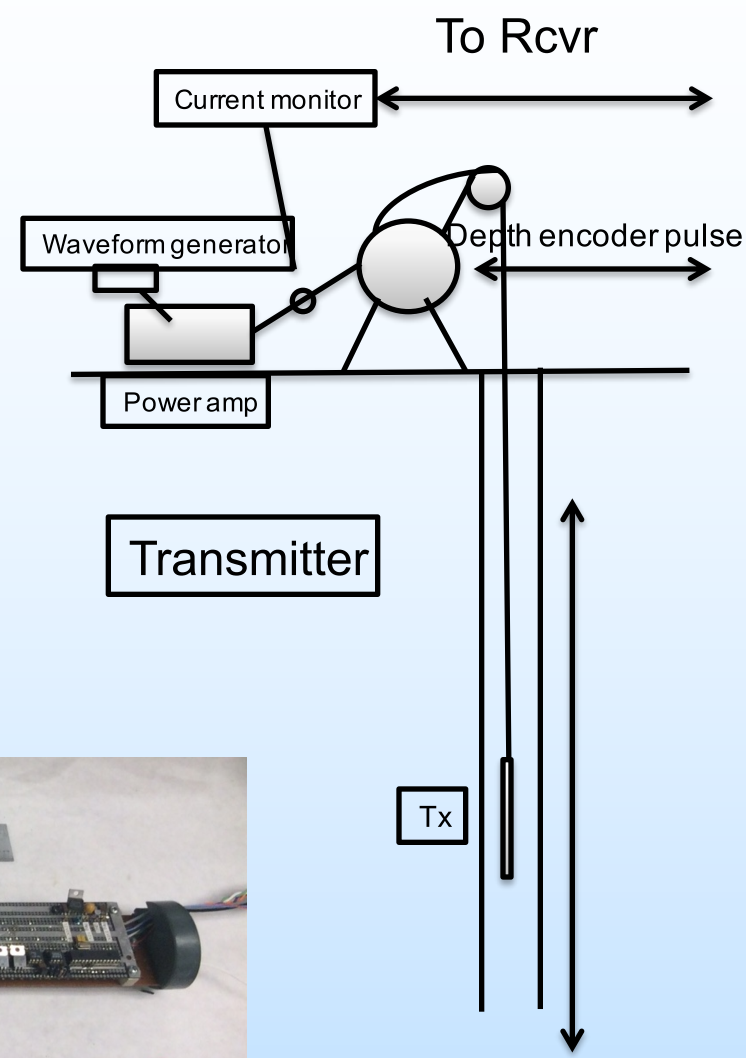


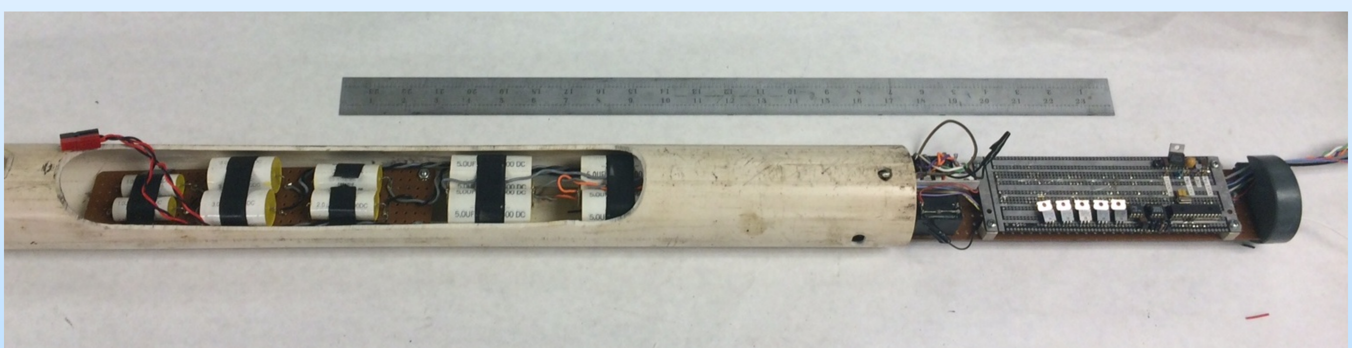




Transmitter side

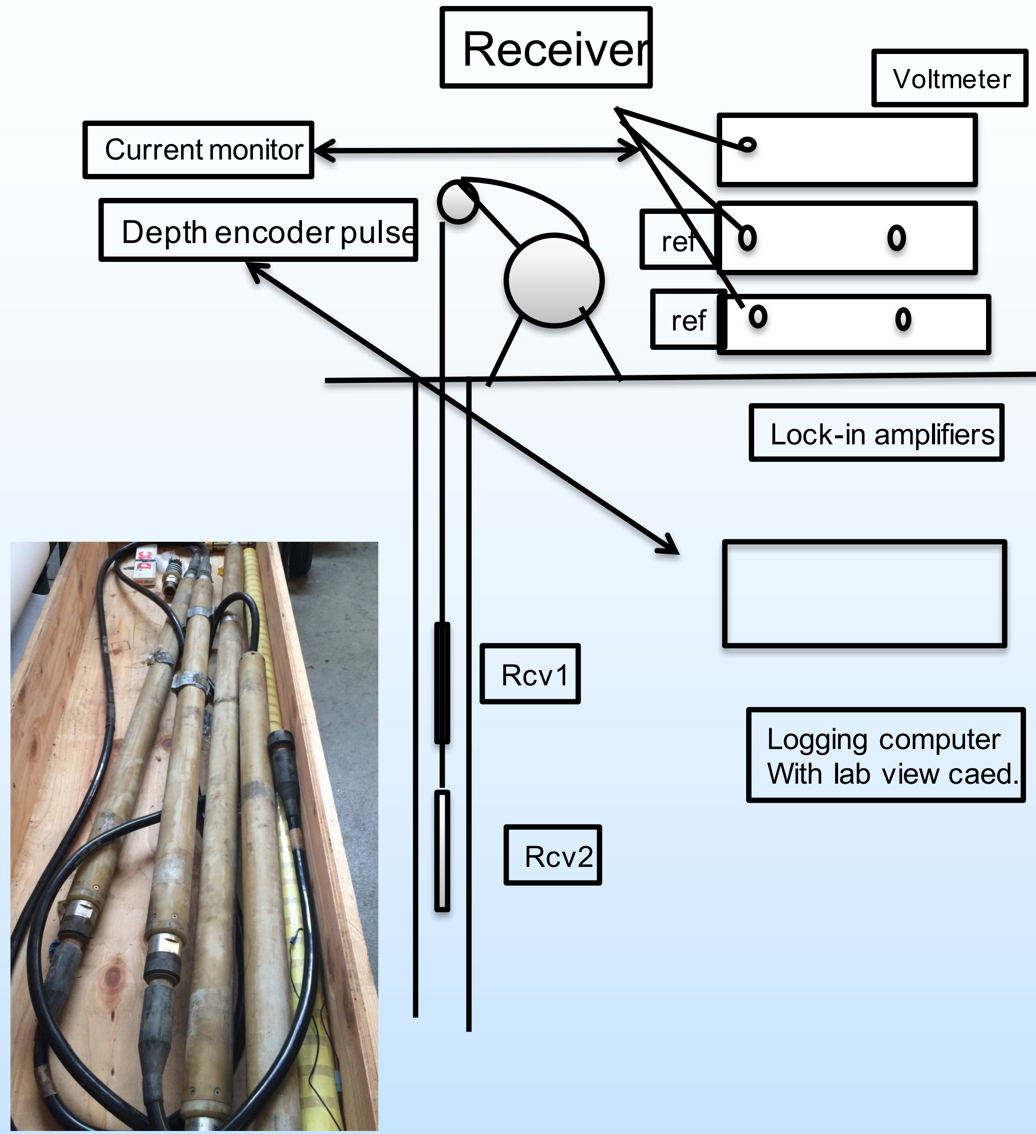
- Transmitter
  - Sine wave signal generated at Tx site
  - Signal amplified by power amp (techron)
    - 150V about 5 amp
  - Signal transmitter down 7 cond wireline cable (analog)
    - Use 6 conductors of the cable,
  - Amplified signal is measured with inductive current monitor
    - Signal is sent via twisted pair wire to receiver station, 200-300m away
    - This may need to be optically isolated





Receiver side

- Receiver
  - Downhole receiver signal sent to surface via wireline cable
    - 2 receiver stations on string
  - Signal connected to lock-in amps in logging truck
    - Lock-in reference signal comes from inductive monitor at transmitter
    - One lock in for each receiver
  - Inductive current monitor measured with a digital voltmeter



Accomplishments to Date

- Begin this program leveraging previous continuous monitoring experience
  - Bringing new technology to CO_2 storage projects
- Development of fiber optic surface seismic using DAS technology – initial field deployment
- Development of orbital surface source for continuous monitoring – moving technology to field deployment
- Beginning development of high frequency crosswell EM system – lab testing underway
- Collaboration on international pilots brings learning to DOE program and storage community

Synergy Opportunities

- Development of DAS technology at partnership sites (Citronelle) and international collaboration (e.g. Aquistore) is brought to other storage programs (e.g. CO2CRC/Otway; new FOA project at ADM site)
- Technology can be licensed to commercial sector (e.g. CASSM PiezoTube source)

Summary

– Key Findings
  - Continuous permanent monitoring provides improved data for long-term storage at potentially lower cost
  - Fiber optics, e.g. DAS, ideally suited to continuous monitoring

– Lessons Learned
  - Technology development coupled with field testing can provide rapid advancement of new techniques

– Future Plans
  - Continuous surface seismic monitoring (Surface CASSM)
  - Continuous Crosswell EM (CASEM)

Questions?

Surface Fiber Cable Deployment
Otway Stage 2C – March 2015

Appendix

– The Following slides will not be discussed during the presentation, but are mandatory

Organization Chart

- CCSMR Task Leads
  - Barry Freifeld (Field Testing Emerging Technologies)
  - Tom Daley (Advancing Monitoring Technology)
  - Jens Birkholzer (Optimization Framework)
- Key Staff
  - Michelle Robertson, Paul Cook, Todd Wood (Field testing and support)
  - Mike Wilt, Abdullah Cihan, Jonathan Ajo-Franklin, Kevin Knauss, Valeri Korneev, John Peterson, Jonny Rutqvist, Nic Spycher, Don Vasco, Qualin Zhou (Scientific support)
- Collaborators:
  - Aquistore Pilot: Kyle Worth (PTRC), Don White (GSC, NRCan)
  - Otway Pilot: Rajindar Singh (lead CO2CRC), Roman Pevezner (lead Curtin Univ., CO2CRC)
  - CMC FRS: Don Lawton (Lead, Univ. Calgary, CMC)

Gantt Chart

	Q1 FY15			Q2 FY15			Q3 FY15			Q4 FY15		
Subtask Description	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**
Task 1 Project Management and Planning												
Task 2 Field Testing of Emerging Technologies												
Subtask 2.1 Aquistore Project												
Subtask 2.2 Otway co-contaminant injection				B								
Subtask 2.3 Carbon Management Canada										A*		
Subtask 2.4 Mont Terri URL							C					
Subtask 2.5 Industry and international field site development												
Task 3 Advancing Monitoring Technology												
Subtask 3.1 Continuous monitoring				D*								E
Subtask 3.2 Instrumentation Development										F		
Task 4 Optimization Framework							G					H

Milestone 2-1 (A)	Report on current monitoring design and proposed LBNL supplement for Carbon Management Canada Field Research Station
Milestone 2-2 (B)	Report on Installation plan for CO2CRC Otway Stage 2c fiber-optic monitoring system and integration into continuous network.
Milestone 2-3 (C)	Review of coupled-models for application to the Mont Teri geomechanical investigation
Milestone 3-1 (D)	Test results of a prototype helical wound fiber-optic cable for improved broadside sensitivity
Milestone 3-2 (E)	Design and testing plan for coupled U-tube and Gas Membrane fluid sampler
Milestone 3-3 (F)	Application of Stoneley-wave and P-wave data for well integrity monitoring using distributed acoustic sensing
Milestone 4-1 (G)	Identify suitable field sites/partners for demonstration of optimization toolset
Milestone 4-2 (H)	Develop methodology for adaptive CO2 storage management with dynamic model updating based on continuously measured field data

Bibliography

- **Journal Publications (FY15)**
  - Freifeld, B, **T Daley**, P Cook, R Trautz, K Dodds, 2015 The Modular Borehole Monitoring Program: a research program to optimize well-based monitoring for geologic carbon sequestration, Energy Procedia 63, 3500-3515.
  - White, D.J., L.A.N Roach, B. Roberts, **T.M. Daley**, 2015, Initial Results from Seismic Monitoring at the Aquistore CO_2 Storage Site, Saskatchewan, Canada, Energy Procedia 63, 4418-4423.
  - Zhang, R., **Daley, T.M.**, Vasco, D., 2015 (in review), Application of sparse layer inversion on 3D seismic at the In Salah carbon dioxide storage project for improved thin-bed resolution, International Journal of Greenhouse Gas Control.

- **Conference Presentations, Invited Talks, Non-Peer Reviewed Publications and Abstracts (FY15)**
  - **Daley, T.M.,** 2015, Comparison of Fiber Optic Monitoring with Conventional Geophone Detection Systems at Aquistore, 10th Monitoring Network Meeting, International Energy Agency Greenhouse Gas Program, Berkeley, CA, June 10-12, 2015.
  - **Daley, T.M.,** 2015, Induced seismicity from CO_2 storage: monitoring and risk assessment, Stanford Center for Carbon Storage Annual Meeting, Workshop on “Induced Seismicity due to CO_2 injection”, Palo Alto, Ca, May 27-28.

Extra Slides

Frio-II: Change in Reservoir/Plume Model with CASSM Constraints

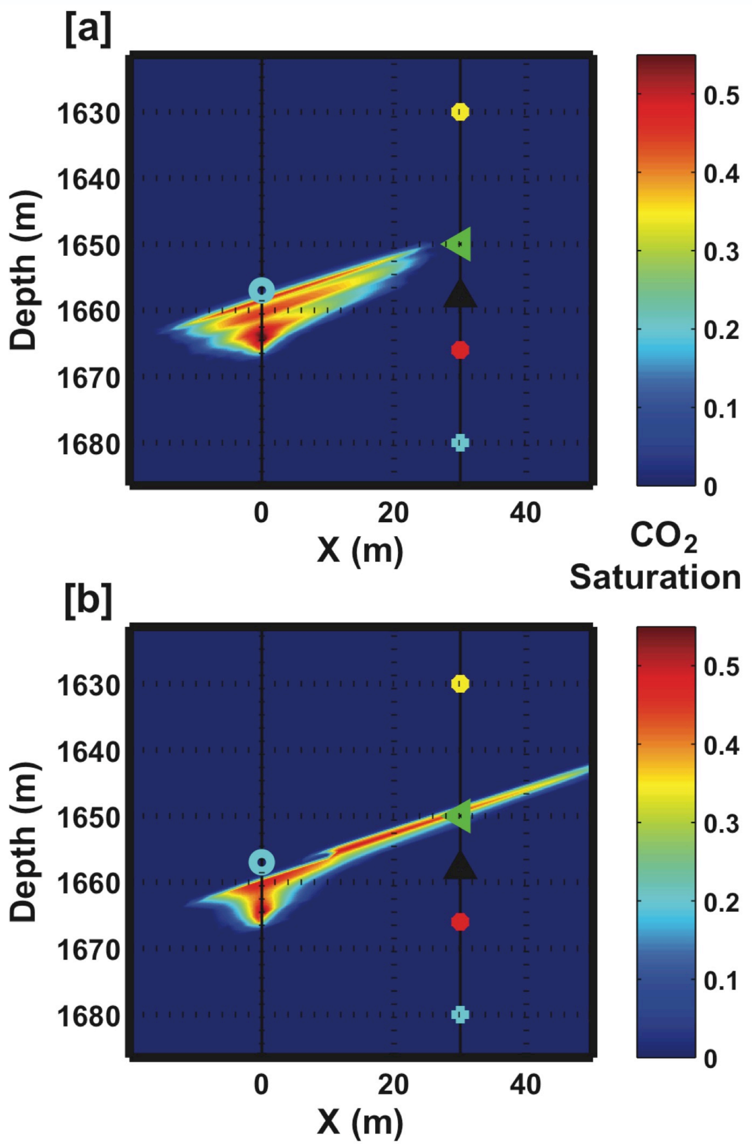


Figure 10

Initial model
Well Logs and Core

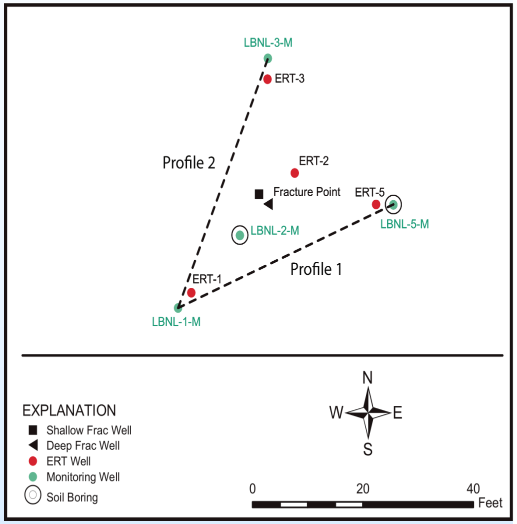
Updated model:
CASSM Constrained

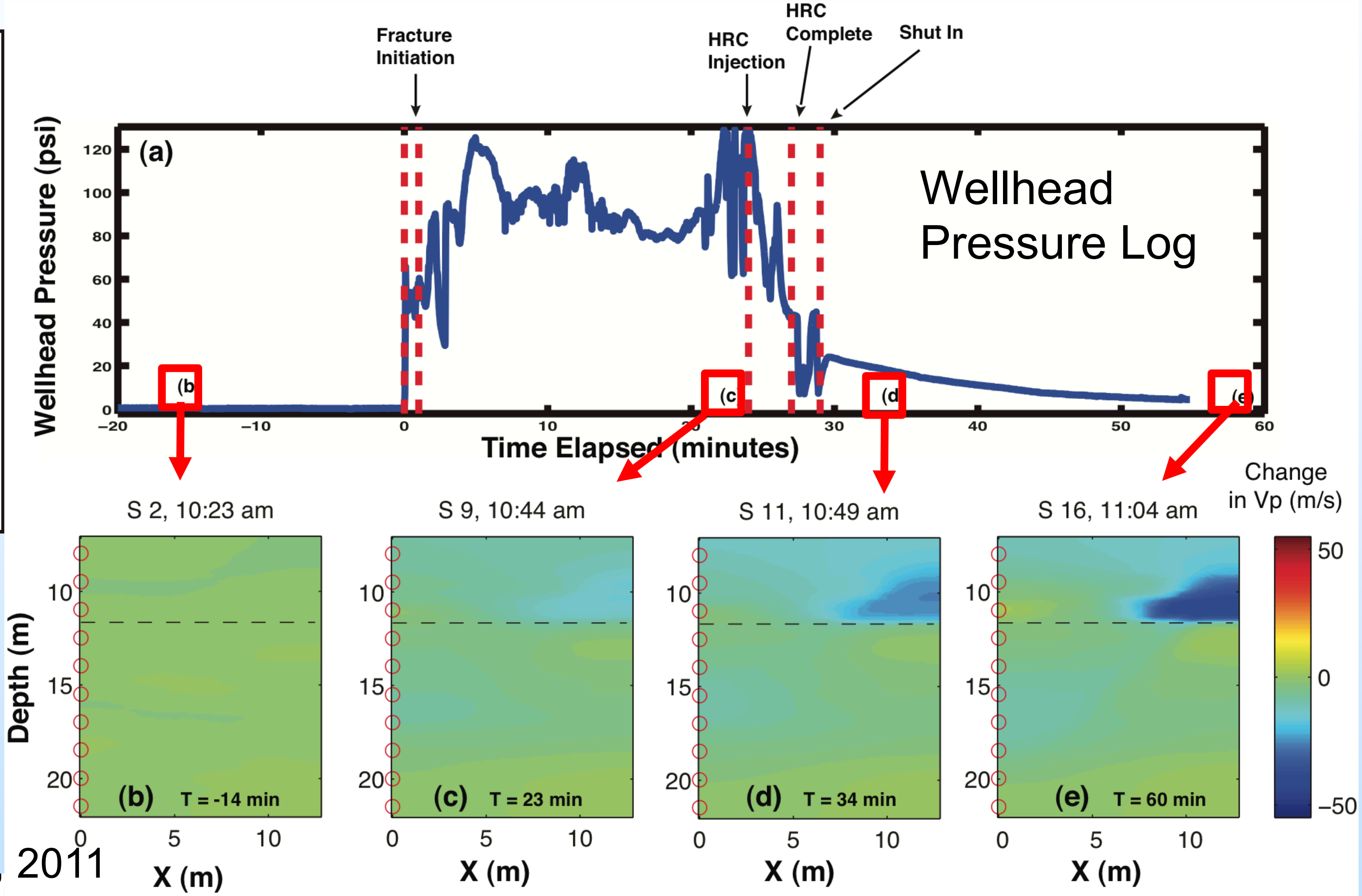
Daley, et al, IJGCC, 2011.

CO2 plume is more affected by buoyancy near injector;
thinner and longer than original estimate;
with 'step' between wells.

CASSM : Continuous Monitoring of a Hydraulic Fracture

Target : Monitor shallow hydrofrac emplacement (33 ft)
Goals : Capture dynamics of fracture propagation with high time resolution
Notes : First-of-kind seismic tomography system with fully automated acquisition, 3 minutes to acquire a multiwell dataset
Results : Successfully imaged fracture extension (thin low Vp zone)

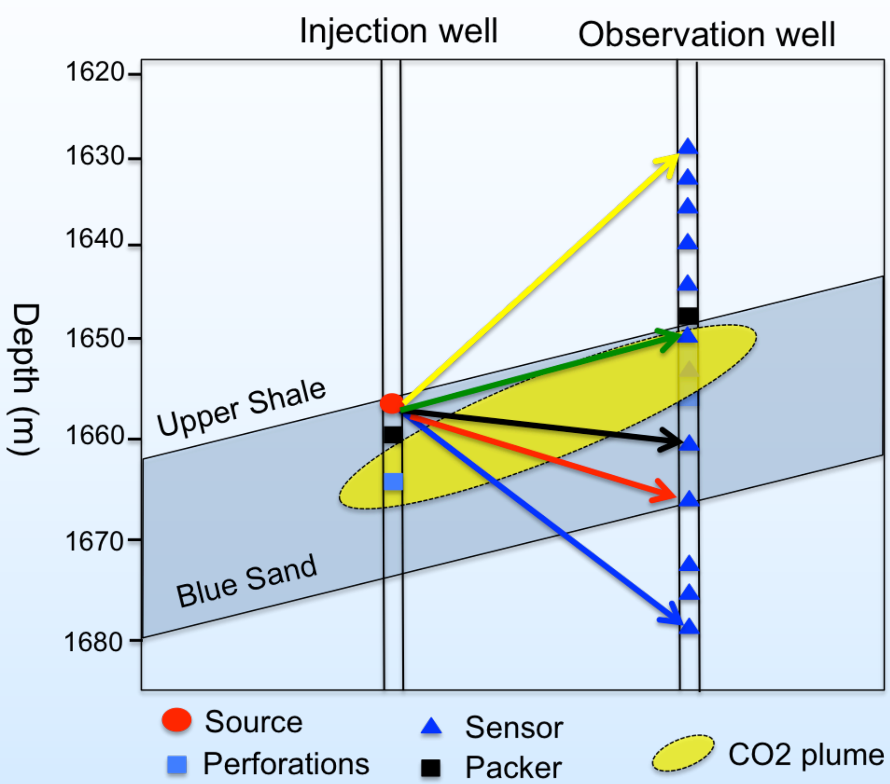


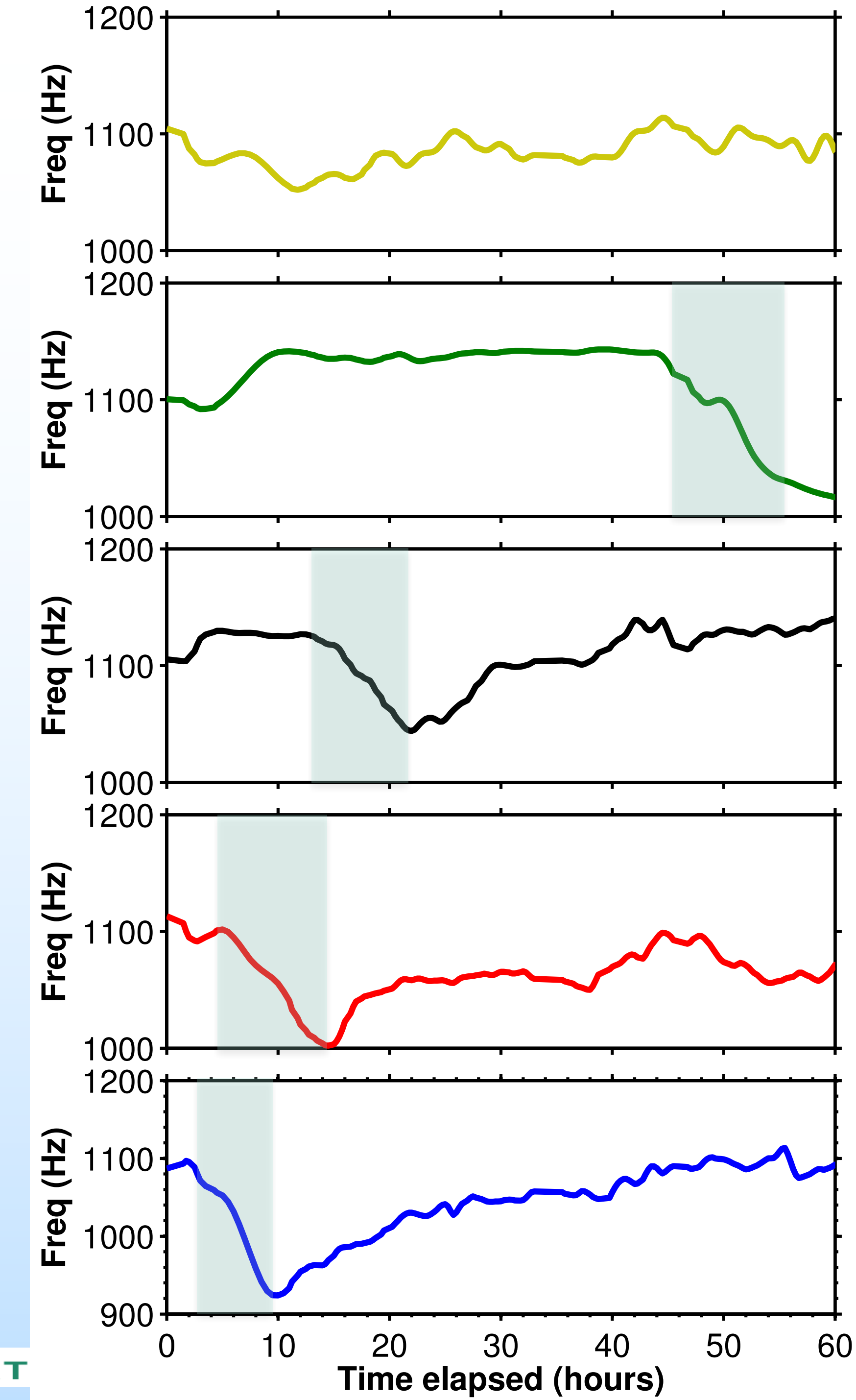


Velocity Tomography

Ajo-Franklin, et al, SEG, 2011

Centroid frequency T. Zhu, et al; AGU,2014





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