Energy Geosciences
EARTH & ENVIRONMENTAL SCIENCES AREA

BERKELEY LAB

Field Testing of Emerging Technologies:

Carbon Management Canada (CMC), Containment and Monitoring Institute (CaMI), Field Research Station (FRS)

Project Number ESD14-095 (Task4)

Tom Daley

Lawrence Berkeley National Laboratory

U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 1-3, 2017

Coauthors/Collaborators

B.M. Freifeld*[1], [1]M. Wilt, [1]P. Cook, P. Marchesini[1], D. Lawton[3], Amin Seedfar[3], K. Osadetz[3]

**LBNL Co-PI, [1] Lawrence Berkeley National Laboratory, [3]CaMI*

Acknowledgement:

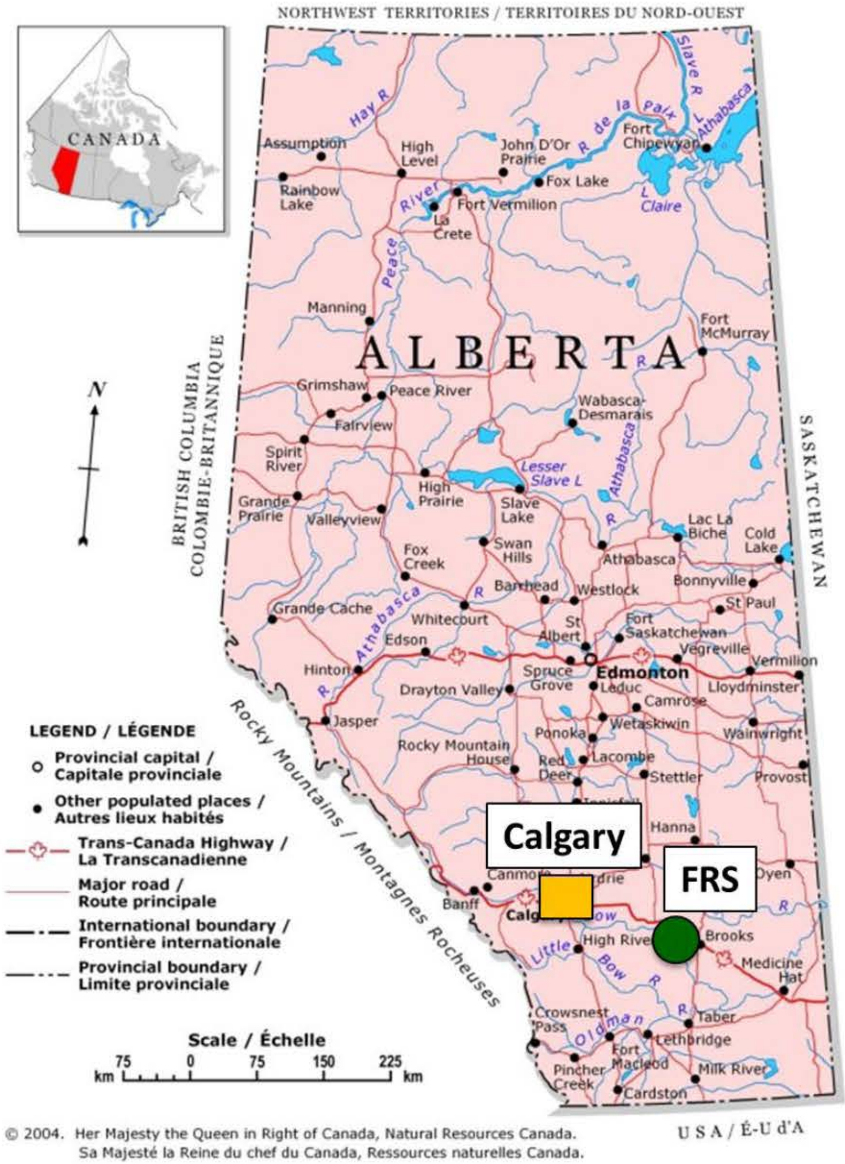
Mark Piercy - Schlumberger

Mark Woitt – RPS Engineering

Presentation Outline

- CaMI Background
- LBNL Activities at CaMI
  - Borehole Geophysical Monitoring, EM and Seismic

Field Research Station (FRS) : Location



Land leased from Cenovus Energy

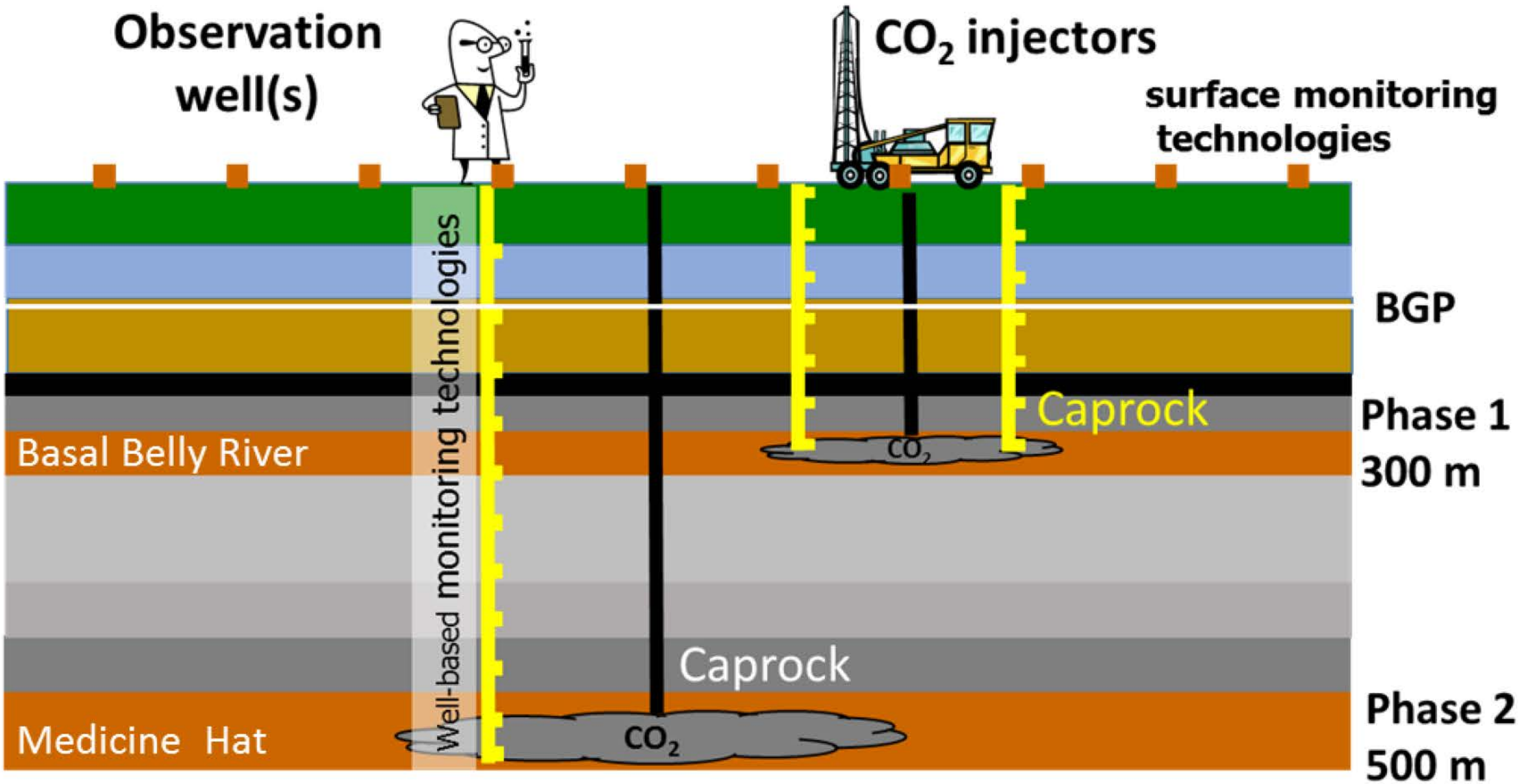
From Lawton, 2016

CaMI/UofC – Field Research Station (FRS)

- A world-leading site for development and demonstration of MMV technologies for fluid containment and conformance
- Undertake controlled CO_2 release at 300 m (Phase 1) & 500 m (Phase 2) depth; up to 1000 t/yr
- Determine CO_2 detection thresholds for different monitoring technologies
- Improve and develop monitoring technologies for tracking the CO_2 plume migration and for cap rock assessment
- Monitor gas migration at shallow to intermediate depths and impacts on intermediate depth groundwater (CO_2 and CH_4)
- Determine fate of CO_2 & CH_4 (trapping/dissolution)
- University & industry field training & research
- Integrating engineering and geoscience
- Public outreach & education

From Lawton, 2016

FRS schematic



From Lawton, 2016

LBNL Activities Supporting CaMI Monitoring

- Electromagnetic (EM) Monitoring
  - crosswell and surface-to-borehole EM
- Crosswell Seismic
- Fiber Optic Sensing
  - Distributed Acoustic Sensing (DAS):
    - Borehole and surface cables deployed;
    - Novel helical wound borehole cable deployed and tested (DAS VSP)
  - Distributed Temperature Sensing (DTS) with Heat Pulse
- Distributed Strain Sensing (DSS):
  - Cable deployment, modeling of geomechanical deformation
- Surface CASSM (Continuous Active-Source Seismic Monitoring)
  - Surface Orbital Vibrator (SOV) source and DAS sensing – design and planning
- U-Tube Fluid Sampler

LBNL/DOE at CaMI

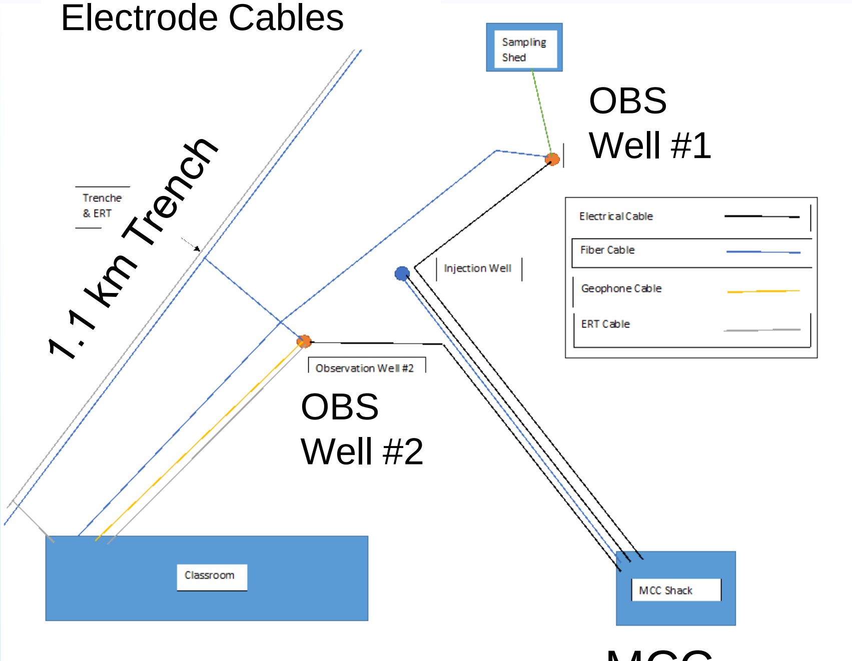
- Applying Higher TRL Tools to Novel Experiment
  - Borehole instrument deployment
    - Integrated DTS – Heat Pulse cable
    - U-tube fluid sampling
    - Pressure-Temperature Gauge
  - Cross-well seismic surveys (LBNL)
- Advancing Lower TRL Tools
  - Cross-well electromagnetic (EM) surveys*
  - *Borehole-to-Surface (BSEM) electrical/EM surveys**
  - Surface helical fiber cable for DAS surface seismic
  - Borehole helical fiber cable for crosswell DAS

*Technology utilizing available fiberglass casing

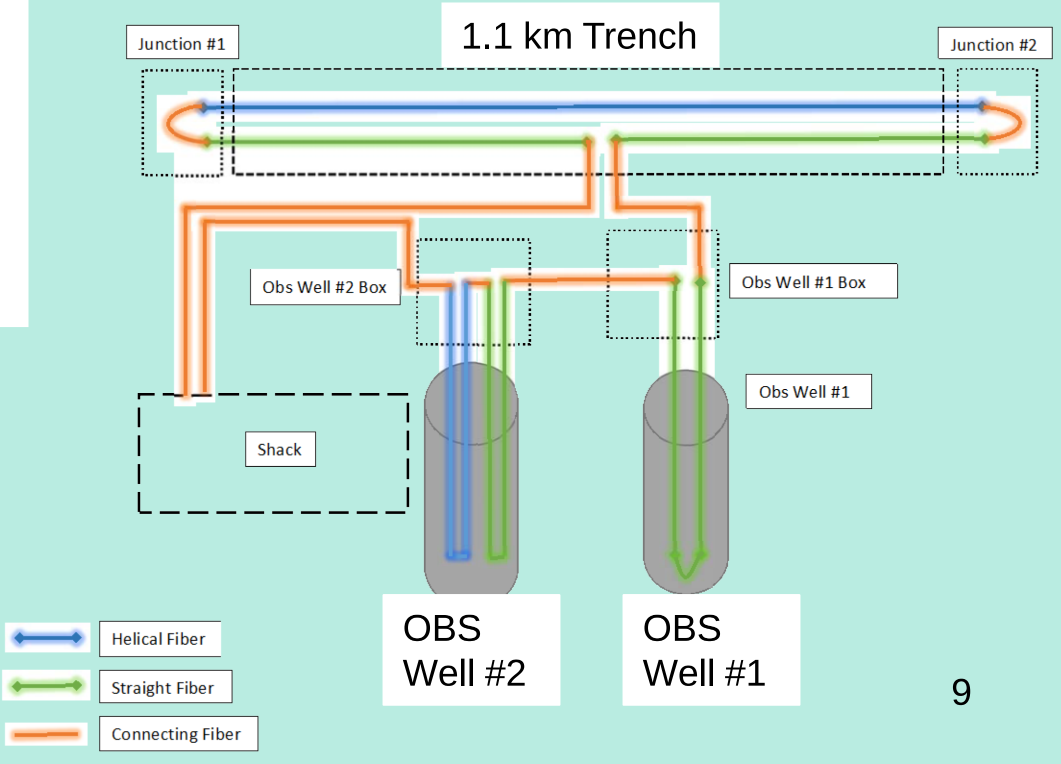
2016-2017 Design and Installation of Monitoring Cables – Fiber and Electrical

Plan View

Trenched Fiber and Electrode Cables



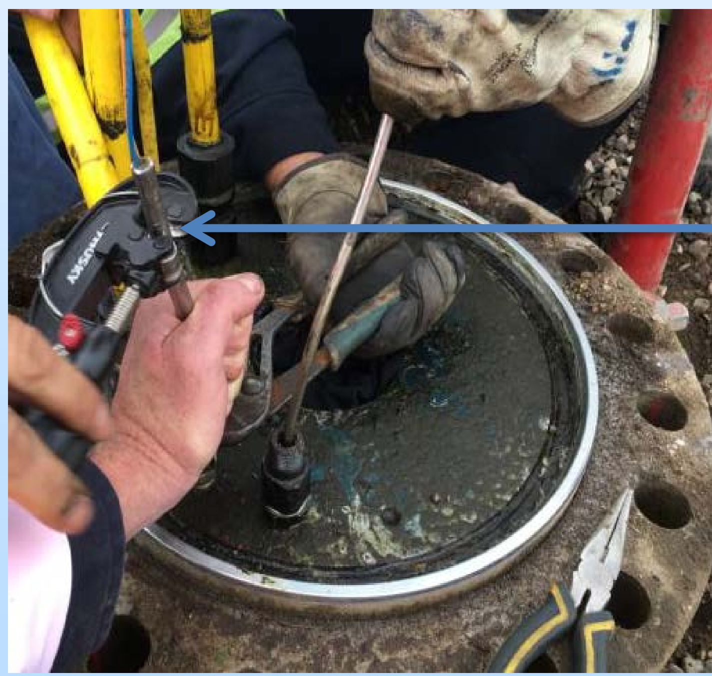
MCC Shack



Three Fiber Optic Cable Types: Spliced into One Continuous Loop

Borehole Sensor Installation

OBS Well #2 Cables for Geophones and Electrodes



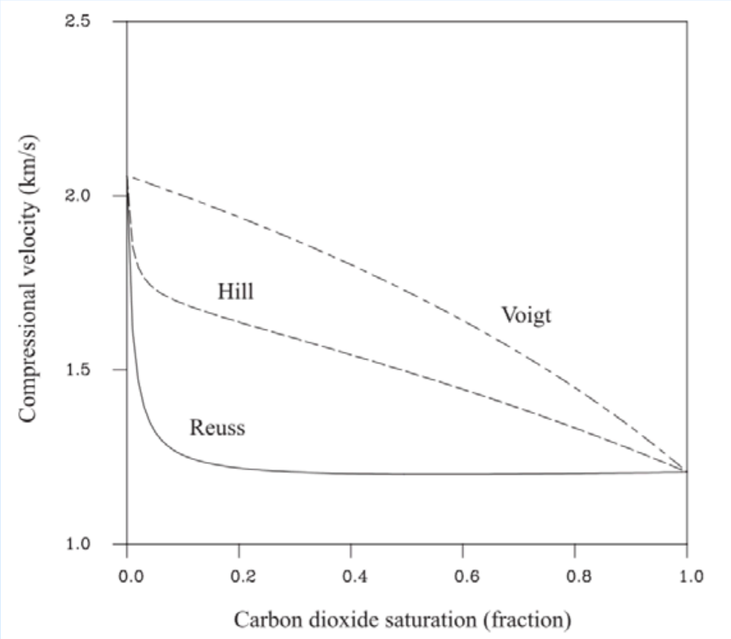
Fiber from HWC (Helical Wound Cable)

Photos: Paul Cook

Multi-Physics - Seismic and EM: Motivation

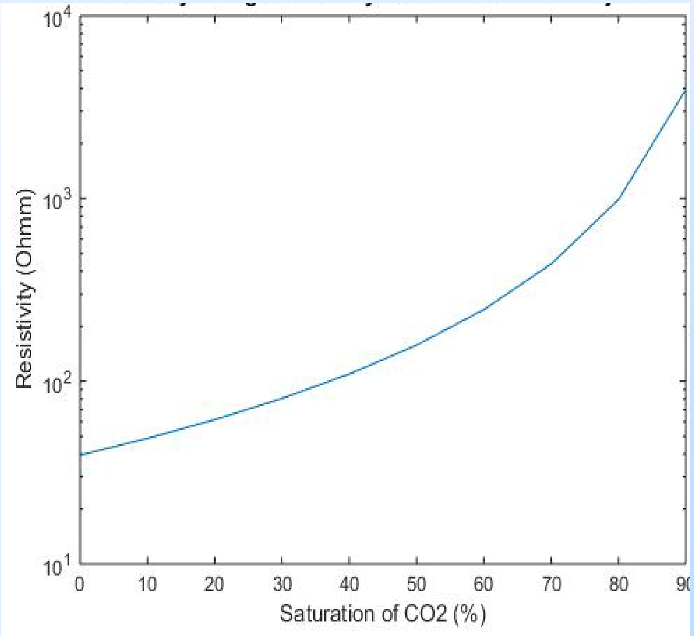
- Seismic alone has uncertainty at high CO2 saturation and uncertainty in rock physics interpretation
- EM has strong sensitivity at all saturations
- Seismic good for initial detection and defining plume edges
- EM good for estimating saturation within plume

Seismic



Vasco, et al, 2014

Electrical

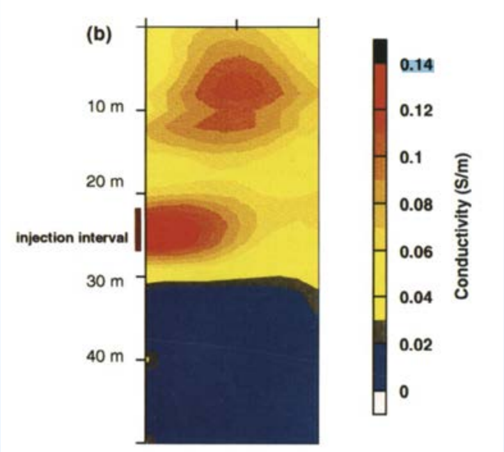


Boerner, et al, 2015

Crosswell EM

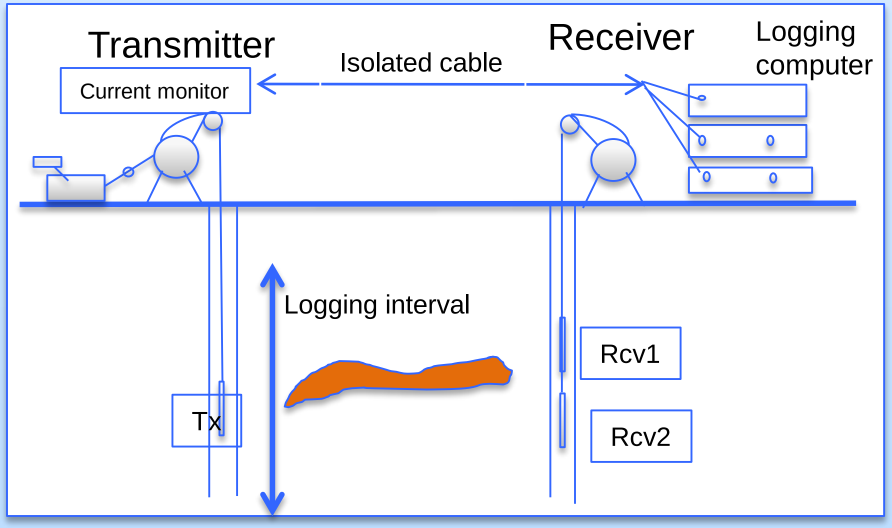
- Moving 'shelved' prototype system to field operation – multi-level sensors
- Obtain 2D resistivity map at depth
- Frequencies from 10 Hz to 20 kHz*
- Well spacing's from 20m to over 500m, and depths to 2km.
- Only one Fiberglass well available for CaMI Phase 1, so frequency is reduced (~200 Hz)

20 m



High Frequency EM Tomography: Developed for EOR monitoring (Wilt, et al, 1995)

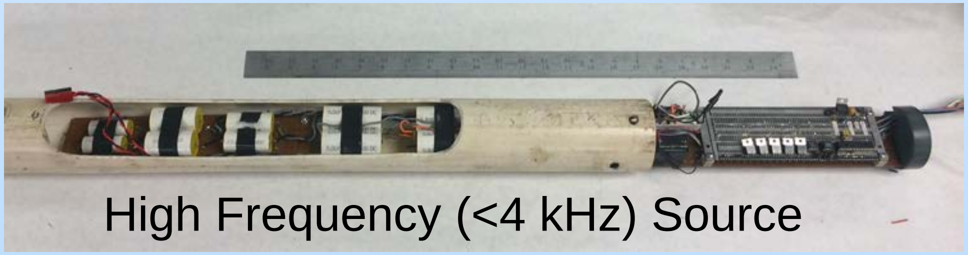
* Higher Frequency than commercially available



Crosswell EM Tools

<u>Transmitter Source</u>

- Size
  - Diameter 3.5” (8 cm)
  - Length ~12 ft (4 m)
  - Weight ~ 120 lbs (50 kg)
- Coil Make up
  - 2.5” Ferrite core 8 ft long
  - 1000 turns of wire on core
  - Tuning capacitors on internal circuit
- Frequency
  - 1- 4000 Hz
    - 1-500 Hz untuned,
    - Tuning 1, 1.5 2 and 4 khz. Selectable by software
- Dipole Moment
  - Maximum moment 1500 A-m^2



High Frequency (<4 kHz) Source

<u>Sensors (1 -5 levels)</u>

- Size 2-level (5 m spacing)
  - Diameter 2.5” (7 cm)
  - Length ~6 ft (2 m)
  - Weight ~ 30 lbs (12 kg)
- Coil Make up
  - 1” mu-metal core 1m long 8
  - 20,000 turns of wire on core
  - Tuning capacitors on internal circuit
- Frequency
  - 1- 10000 Hz; Flat 10-1000Hz
- Sensitivity
  - 0.1 V/nTesla
  - Noise estimated at 10^{-6} nT

Multi-level Sensor Coils

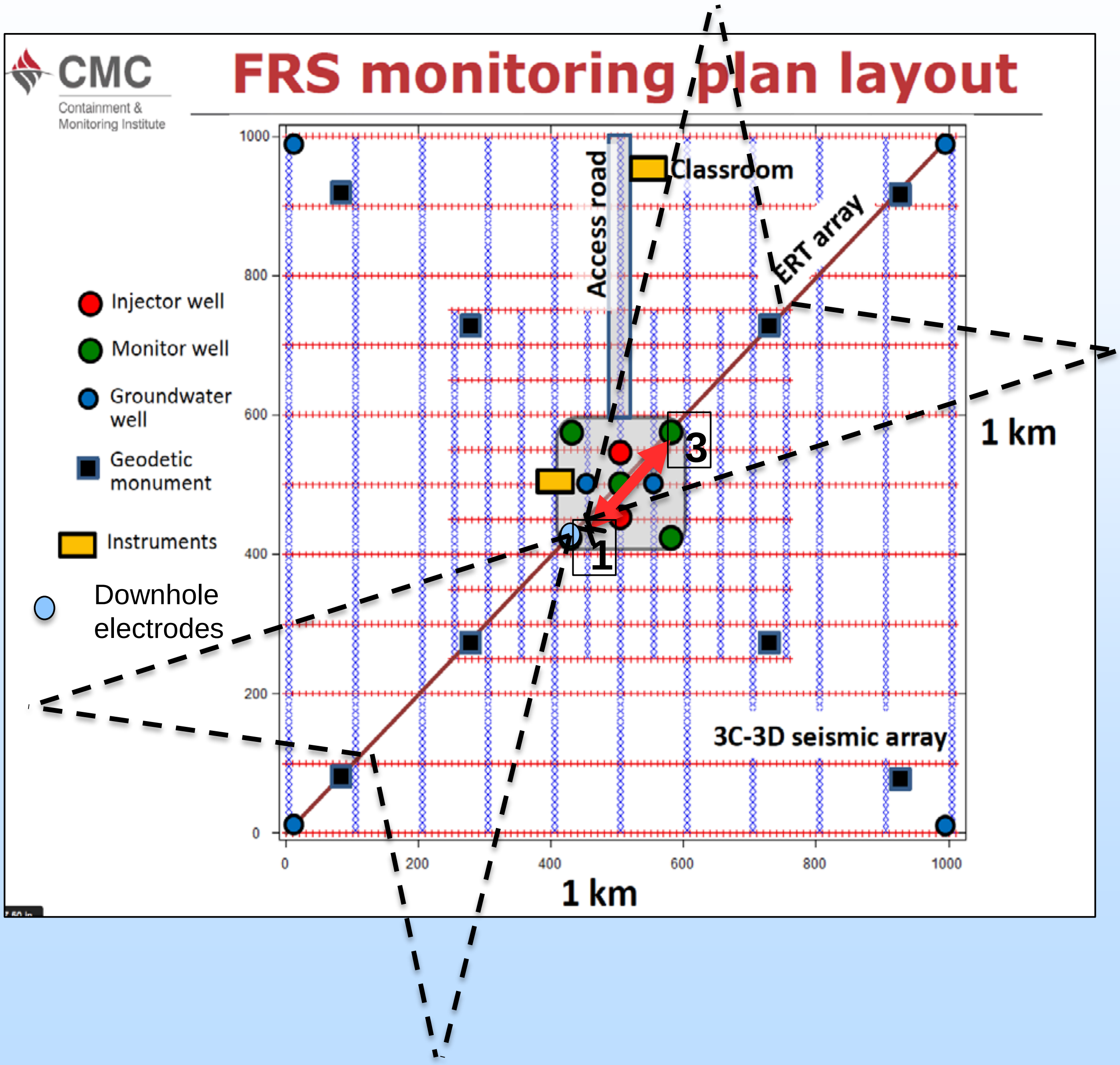
Monitoring Arrays at CAMI

Crosswell EM

BSEM array

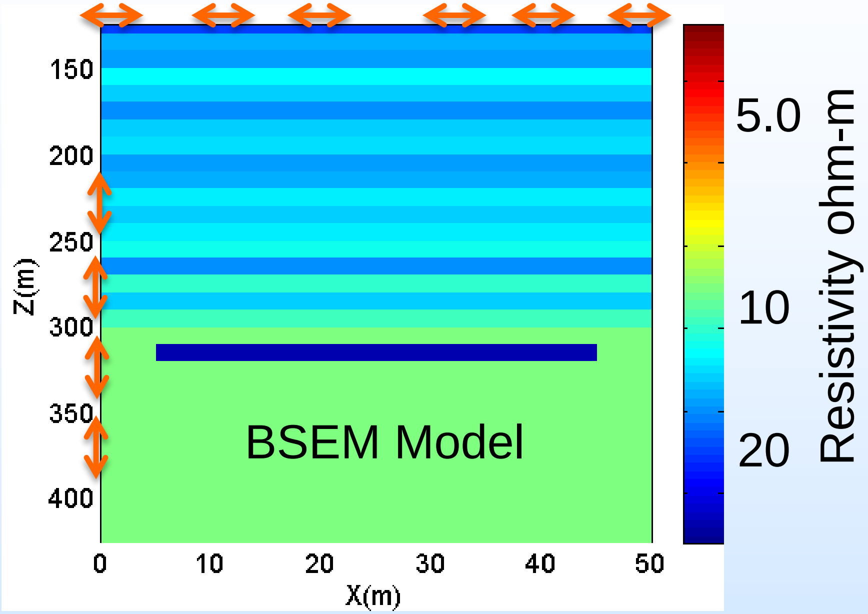
BSEM = Borehole to Surface EM: ~1+km

Crosswell: 50 m

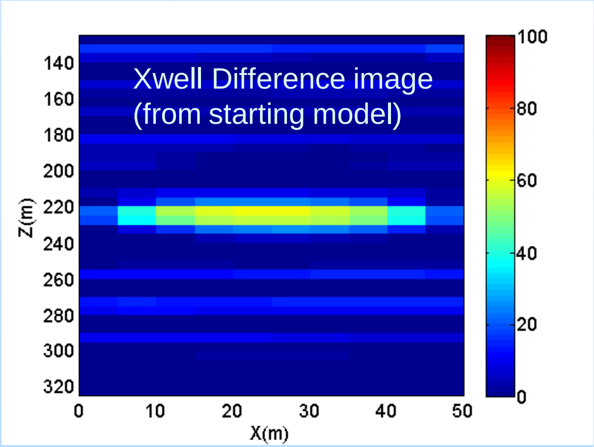


EM Model and Inversion (Xwell and BSEM)

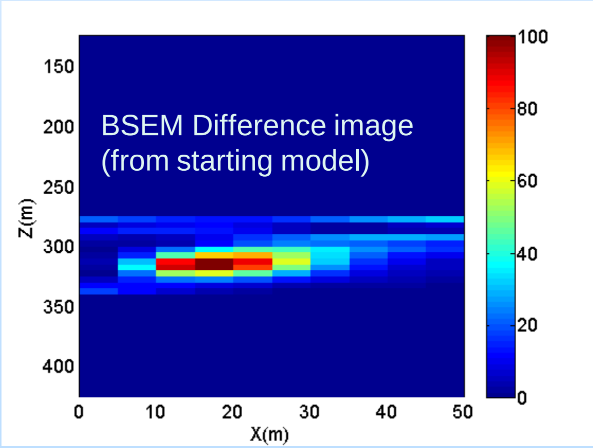
- EM Model:
  - Based on 1 year injection simulation
  - Source 300 Hz, Assume random noise
  - Different injection depths used
- Modeling/Imaging - EMGEO: **3D EM parallel finite-difference code**



- Crosswell: Final image places boundaries and depths properly but slightly underestimates resistivity



- BSEM: Inversion finds leading edge of CO_2 body but has trouble mapping distal edge



Energy Geosciences
EARTH & ENVIRONMENTAL SCIENCES AREA

Baseline Field Surveys 11/16 Successful Acquisition

BERKELEY LAB

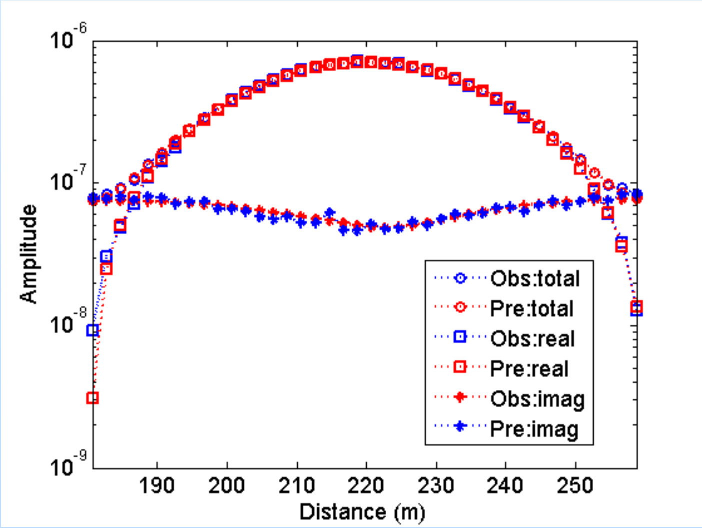
- Crosswell EM
  - good quality data
  - Receiver depths only to 220m due to a cable issue
- Borehole to Survey EM
  - poor data quality due to grounding issue

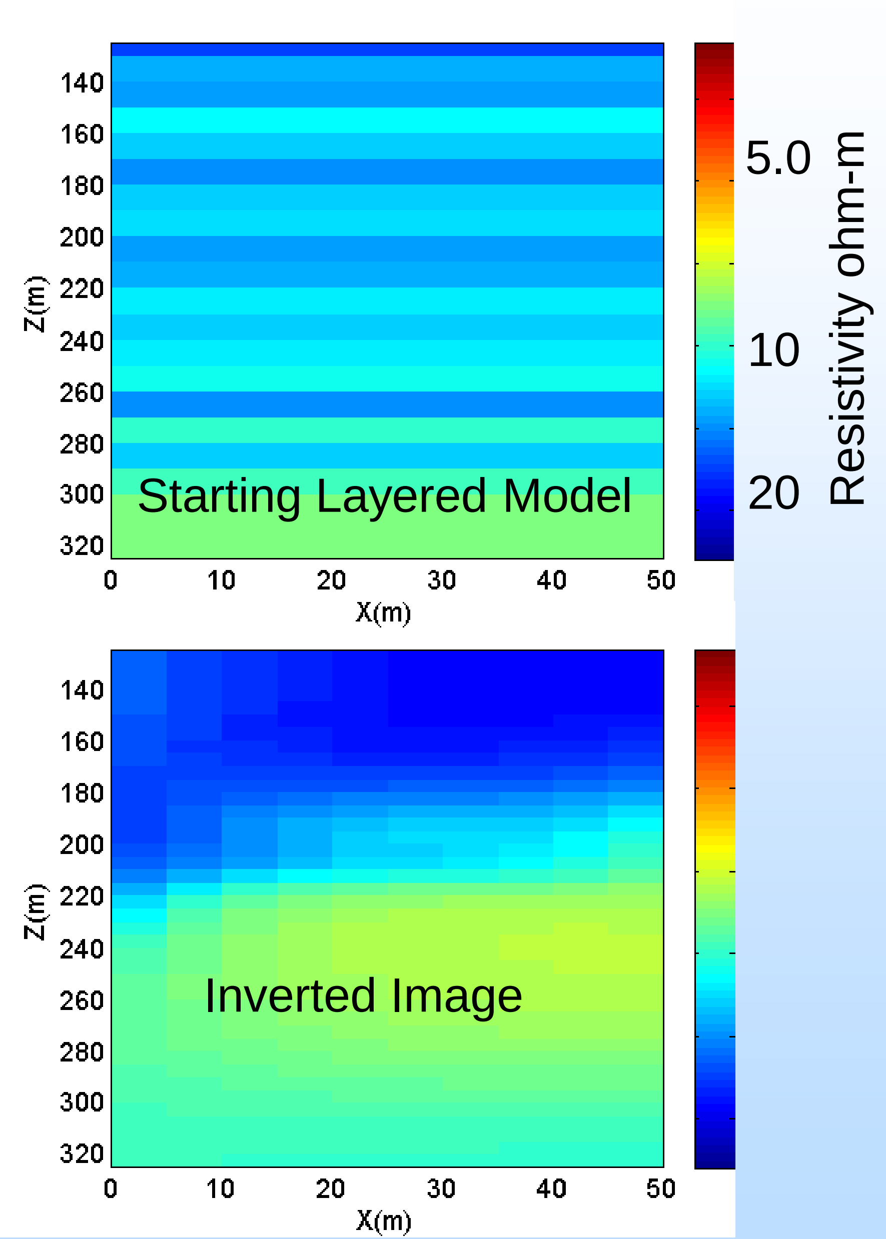
Crosswell EM field data Inversion

- Receivers used: 220,200,190m
  - Estimated noise 3%
  - Inversion domain: z=125 to 325m
- Results are consistent with logs but provide a muddy image
  - Likely due to limited receivers and low frequency (200 Hz)
- BSEM gave poor results due to improper grounding

Conclusion: A new baseline acquisition is recommended and planned

Crosswell data and Model: f= 200 Hz

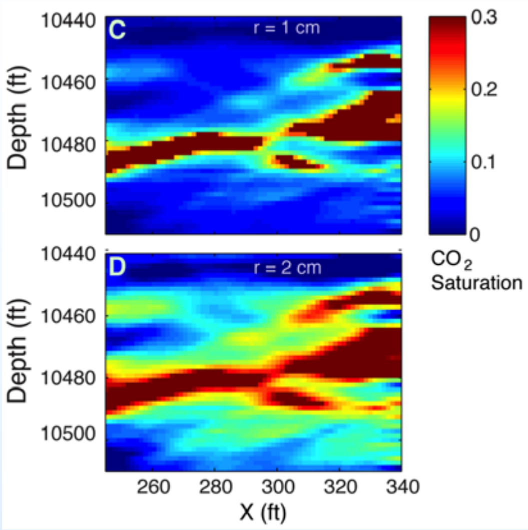




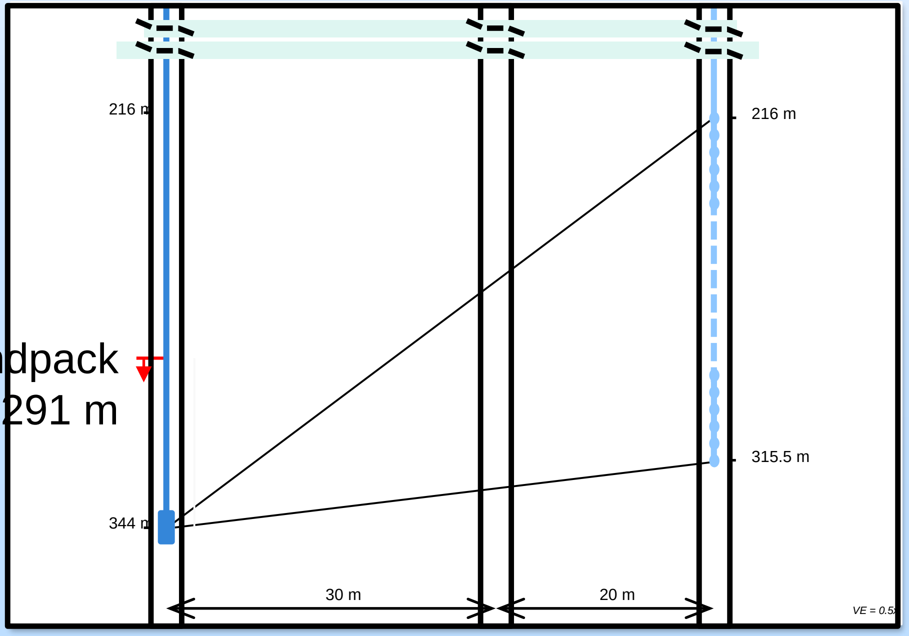
Crosswell Seismic

Initial Baseline Survey (11/16):

- Sensor: Hydrophone array – 20 sensors at 5 m spacing
- Source: piezoelectric
- Source sweep: 300-2500 Hz
- Spatial sampling: 0.5 m



Example Cranfield CO2 Plume, Ajo-Franklin, et al, 2012

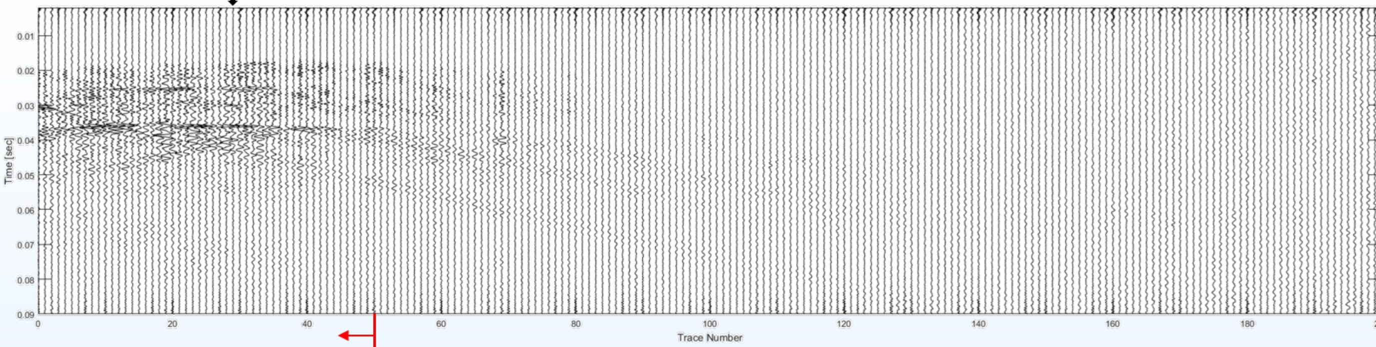


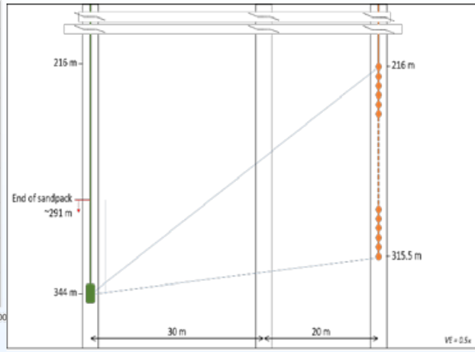
End of sandpack ~291 m

Data quality problems linked to sandpack well completion interval

Crosswell Seismic

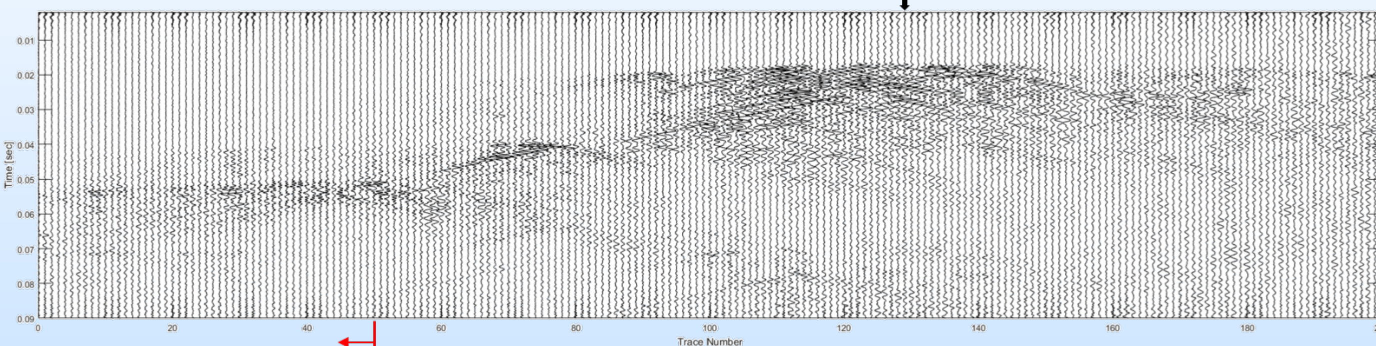
Shot position

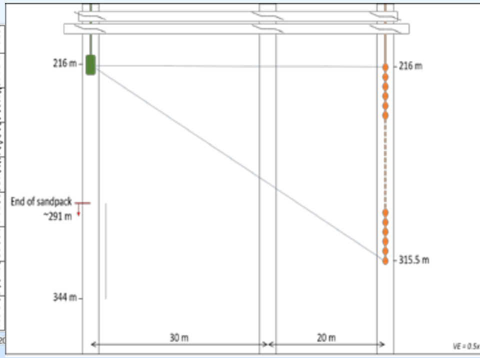




End of sandpack

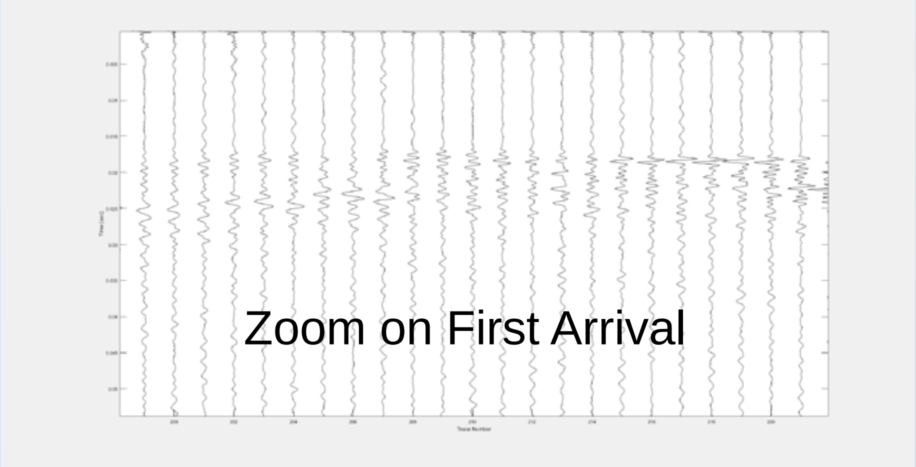
Shot position





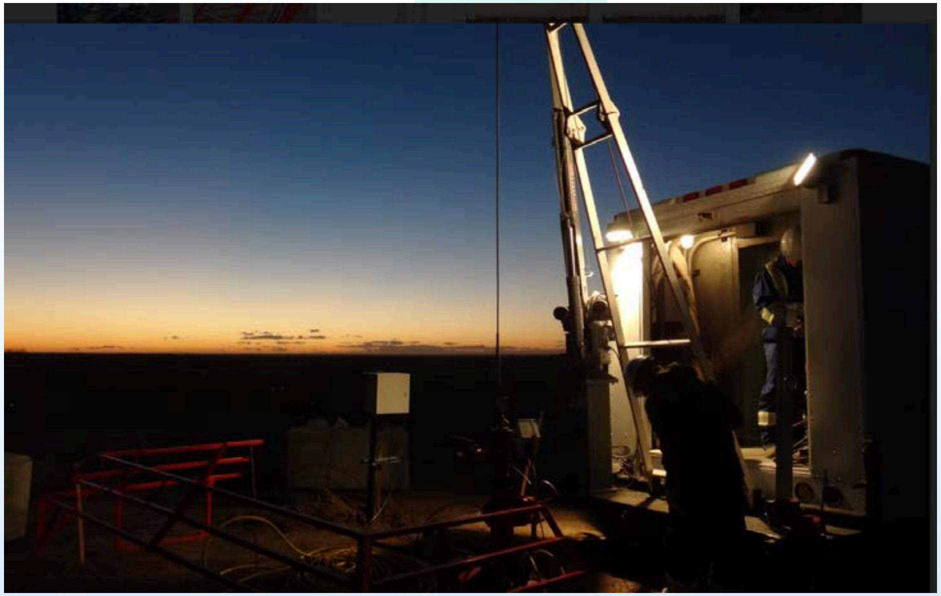
End of sandpack

- First Arrivals are good for travel time tomography, but
- Poor transmission near the sandpack completion interval
  - Gas in sandpack is possible cause



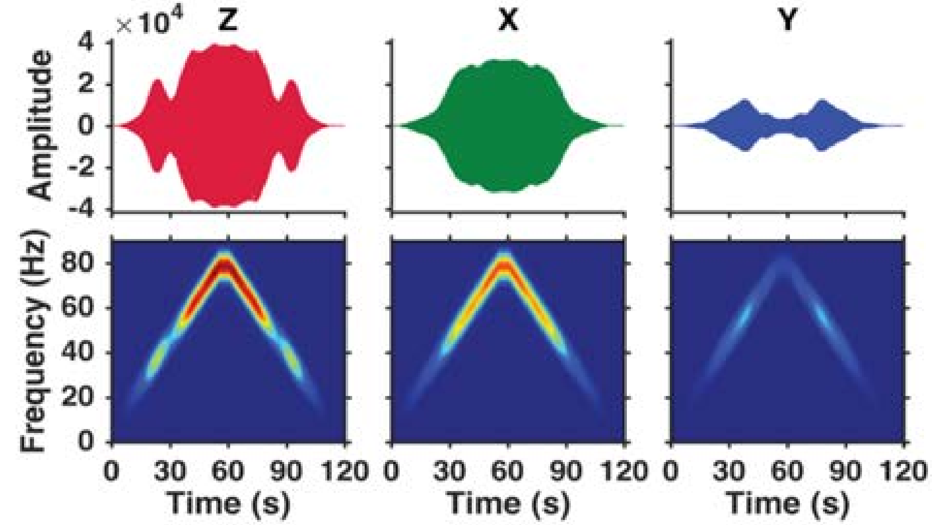
2017 Field Campaign: Improved Baseline

- Plan field acquisition for 9/17
  - Crosswell EM and BSEM
    - Use higher crosswell frequency (450 Hz)
    - Use dual frequency BTS EM, collect data using cable system, borehole electrodes and trench ERT surface array
    - Will jointly process and interpret EM data
  - Crosswell Seismic
    - Increase S/N
    - Demonstrate repeatability

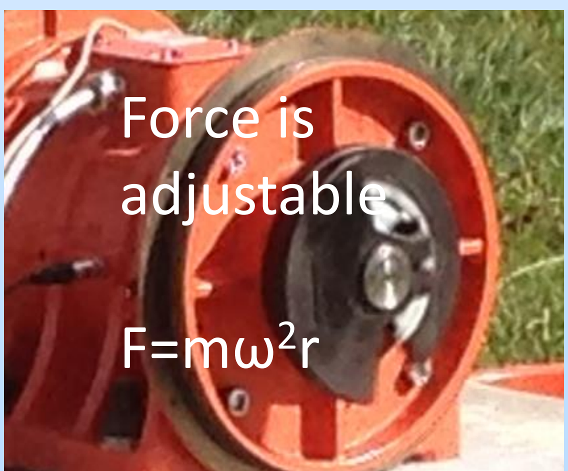


Continuous Seismic Monitoring:

Surface Orbital Vibrator: A Controlled AC Motor w/Eccentric Mass + DAS

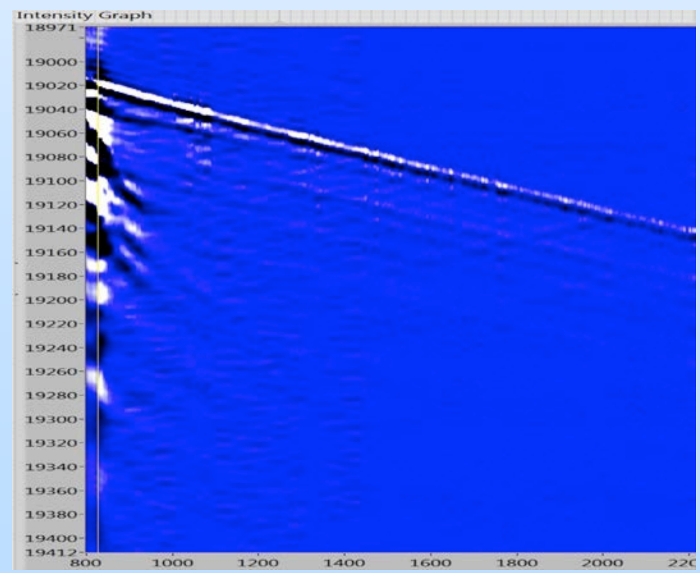


Max Frequency 80 Hz, Force (@80Hz) 10 T-f
Phase stability is not maintained. Operate 2.5 hr/d



- Baseline DAS VSP with novel helical wound borehole fiber cable – field plot

DAS-Vib VSP at CaMI (July 2017)

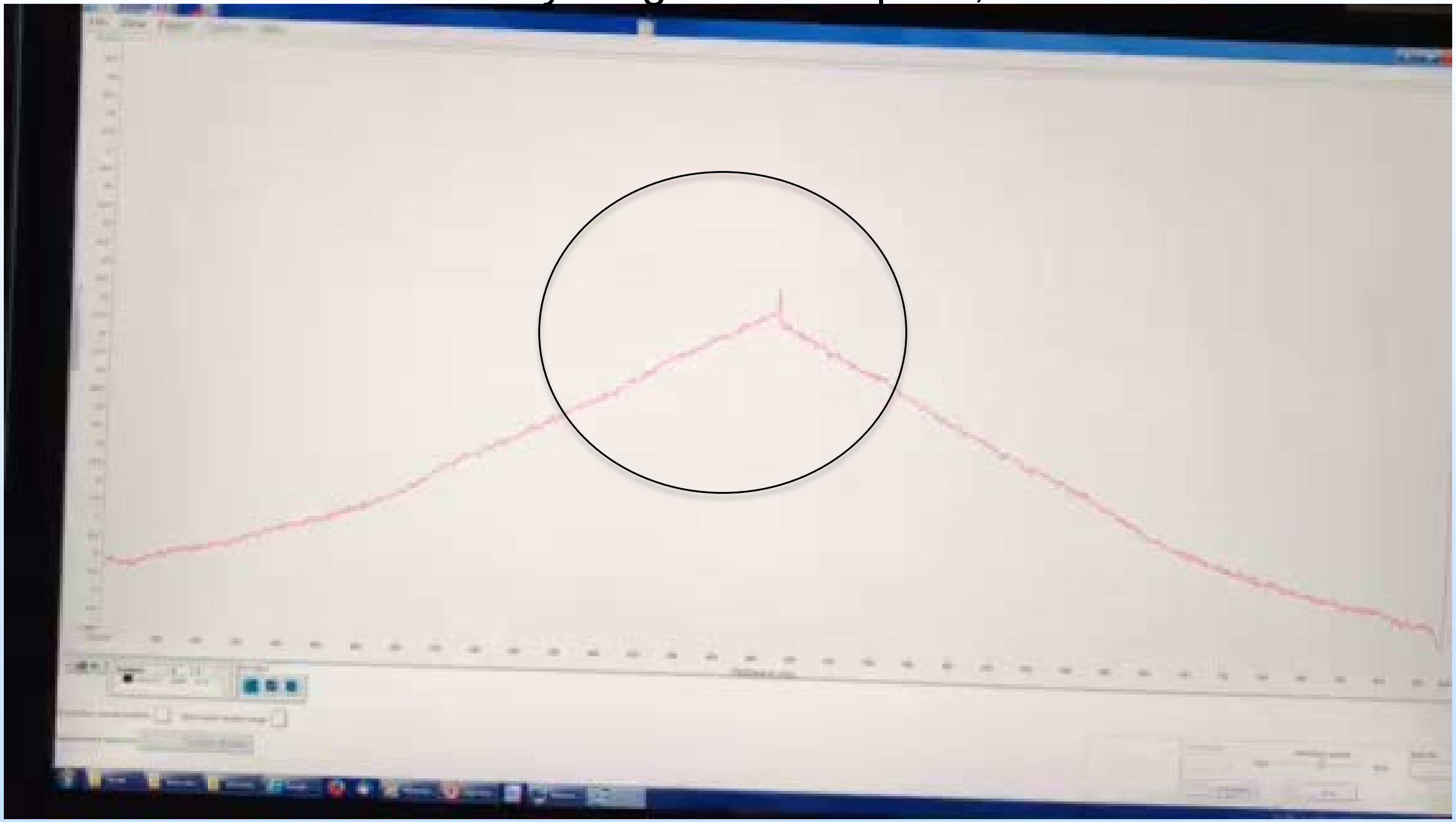


DTS and Heat Pulse

July 2017 Test

Temp

Anomalies may be gas in sandpack, to be confirmed



Depth in Well (down and back up)

Accomplishments to Date

- Collaboration with CaMI on monitoring program
- Development of crosswell EM instrumentation (raise TRL level)
- Deployment:
  - Fiber optics in wells; helical and straight fiber cable in observation wells – first time for helical in well!
  - U-Tube geochemical sampling system in observation wells
  - SOV (surface orbital vibrator) seismic source
- Acquisition of initial data:
  - Crosswell EM and Seismic, BSEM;
  - Heat-pulse, U-tube

Project Summary

- Key Findings
  - CaMI fills an important need in storage R&D: intermediate depth, gas phase detection/monitoring
  - A comprehensive monitoring program is testing higher TRL tools and advancing lower TRL tools
  - Deploying Crosswell EM and seismic; U-Tube sampling; heat pulse monitoring; surface and borehole helical DAS;
- Lessons Learned
  - Plans need to be flexible while project is developing (e.g. change from 2 fiberglass casing to 1 and 1 steel
  - Best to allow for repeat of baseline geophysics to allow for learnings from initial data acquisition
- Future Plans
  - Acquire new baseline data ~ Sep 2017
  - Begin injection
  - Monitor co2 plume

Synergy Opportunities

– Deployment of fiber optic cables in the subsurface allows multiple measurements (Temperature, Acoustics, Chemistry)
– Permanent sensor deployments with semi-permanent sources allows 'continuous' and 'intelligent' monitoring

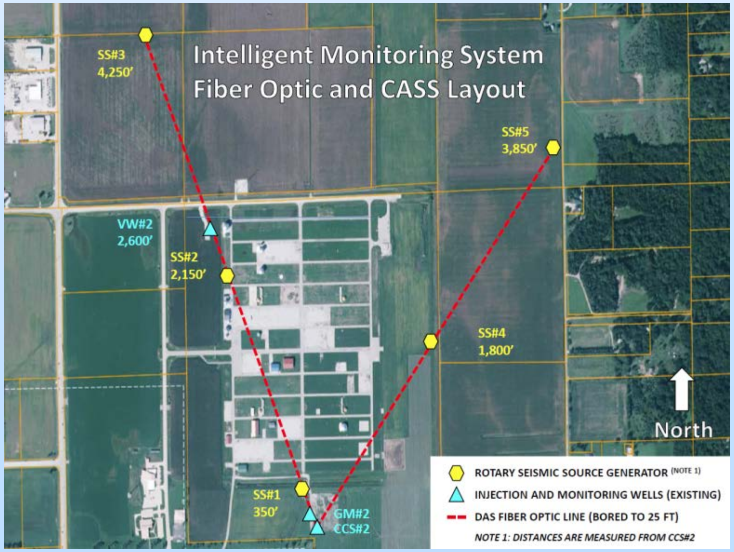
Automated High Power Permanent Borehole Seismic Source Systems for Long-Term Monitoring of Subsurface - GPUSA, Inc. - Howard Wilkinson

Distributed Fiber Optic Arrays: Integrated Temperature and Seismic Sensing for Detection of CO_2 Flow, Leakage and Subsurface Distribution - Electric Power Research Institute Inc. - Robert Trautz

National Risk Assessment Partnership - Strategic Monitoring for Uncertainty Reduction - Lawrence Berkeley National Laboratory - Erika Gasperikova

Robust In Situ Strain Measurements to Monitor Carbon Dioxide (CO2) Storage - Clemson University - Larry Murdock

ADM Intelligent Monitoring System
B. Freifeld



Acknowledgements

- Funding for LBNL was provided through the Carbon Storage Program, U.S. DOE, Assistant Secretary for Fossil Energy, Office of Clean Coal and Carbon Management, through the NETL, for the project "Core Carbon Storage and Monitoring Research" (CCSMR).
- Carbon Management Canada (CMC) Containment and Monitoring Institute (CaMI) Field Research Station (FRS)

Appendix

– These slides will not be discussed during the presentation, but are mandatory.

Geological model: Vertical layers

Combined into one layer

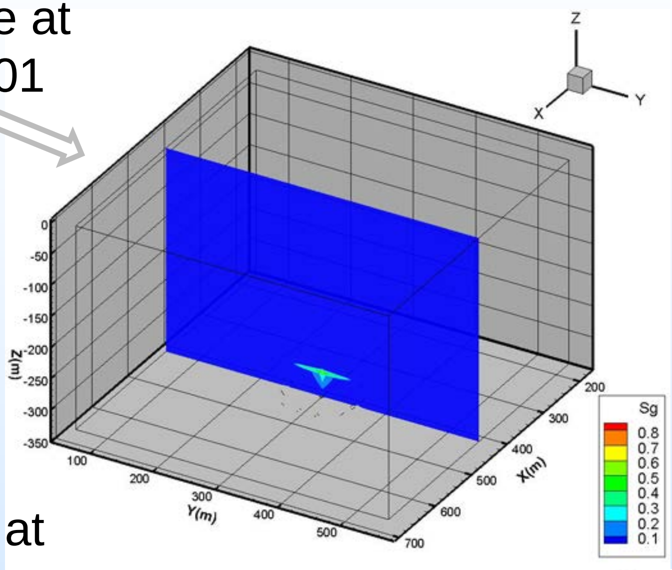
Formation Name	Depth(m)	Lithology	P	K
Overburden	0 –15	Glacial till	0.31	0.09
Bearpaw	15–45	Sandy shale	0.29	0.01
Oldman	45–120	Fine–grained sandstone	0.27	0.00
Foremost	120–264.16	Clayed sandstone with coal, some sand lenses	0.27	0.06
	264.16–264.66	coal	0.23	0.43
	264.66–269.80		0.23	0.04
	269.80–270.30		0.20	0.28
	270.30–271.22		0.22	0.03
	271.22–271.72	coal	0.27	0.83
	271.72–272.90	mudstone	0.26	0.07
	272.90–276.86	Md. Sst Channel, Ironstone Concretion	0.27	0.02
	276.86–277.96	mudstone	0.27	0.07
	277.96–278.46	coal	0.27	0.81
	278.46–278.74	mudstone	0.26	0.06
	278.74–279.24	coal	0.28	0.96
	279.24–284.51	mudstone	0.23	0.04
	284.51–285.01	coal	0.26	0.74
	285.01–286.43	mudstone	0.24	0.05
	286.43–286.93	coal	0.29	1.11
	286.93–289.41	mudstone	0.23	0.04
	289.41–289.91	coal	0.27	0.86
	289.91–293.15	mudstone	0.25	0.06
	293.15–293.65	coal	0.27	0.88
	293.65–295.08	mudstone	0.23	0.04
	295.08–295.65	Fine Sandstone	0.27	0.20
BBR	295.65–301.43	Sandstone	0.28	6.06
Pakowki	301.43–357	Clayed sandstone	0.23	0.03
Milk–river	357–439	Sandy claystone with shale	0.18	0.00
Colorado	439–478	shale	0.21	0.00
Medicine–Hat	478–507	Sandstone chosen for injection	0.19	1.41
Base Medicine–Hat	507–550		0.19	0.00

Energy Geosciences
EARTH & ENVIRONMENTAL SCIENCES AREA

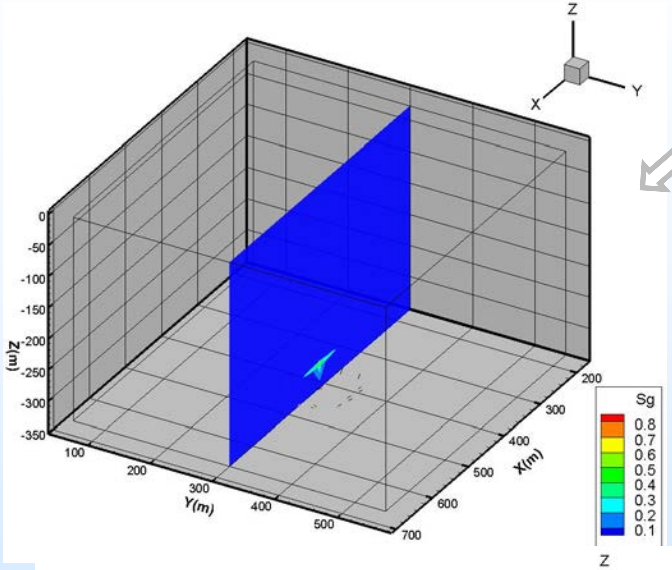
BERKELEY LAB

Geochemical Transport Modeling of CO_2 saturation

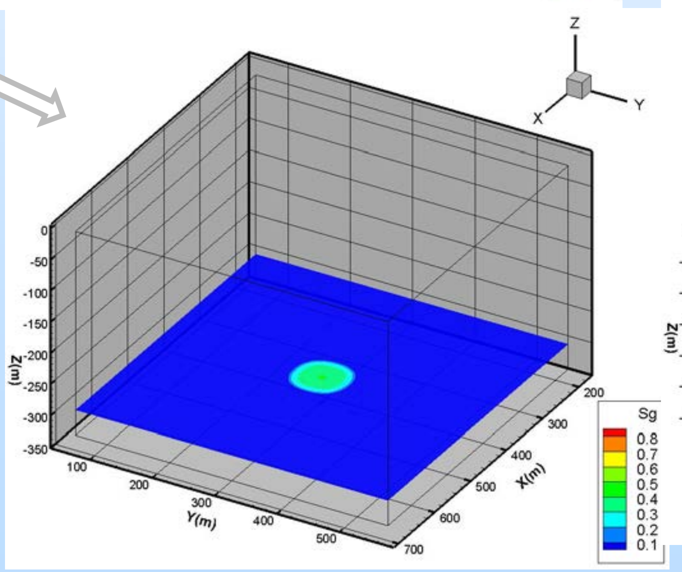
YZ profile at X=438.201 m



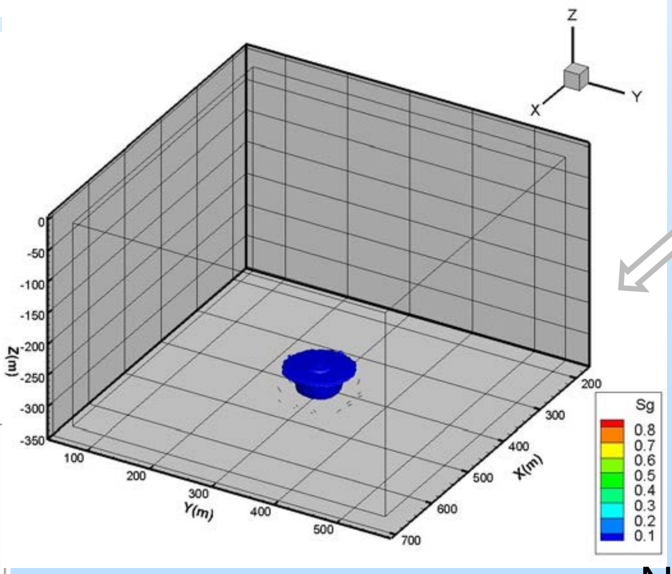
XZ profile at Y=312.634 m



XY profile at Z=-296.18 m

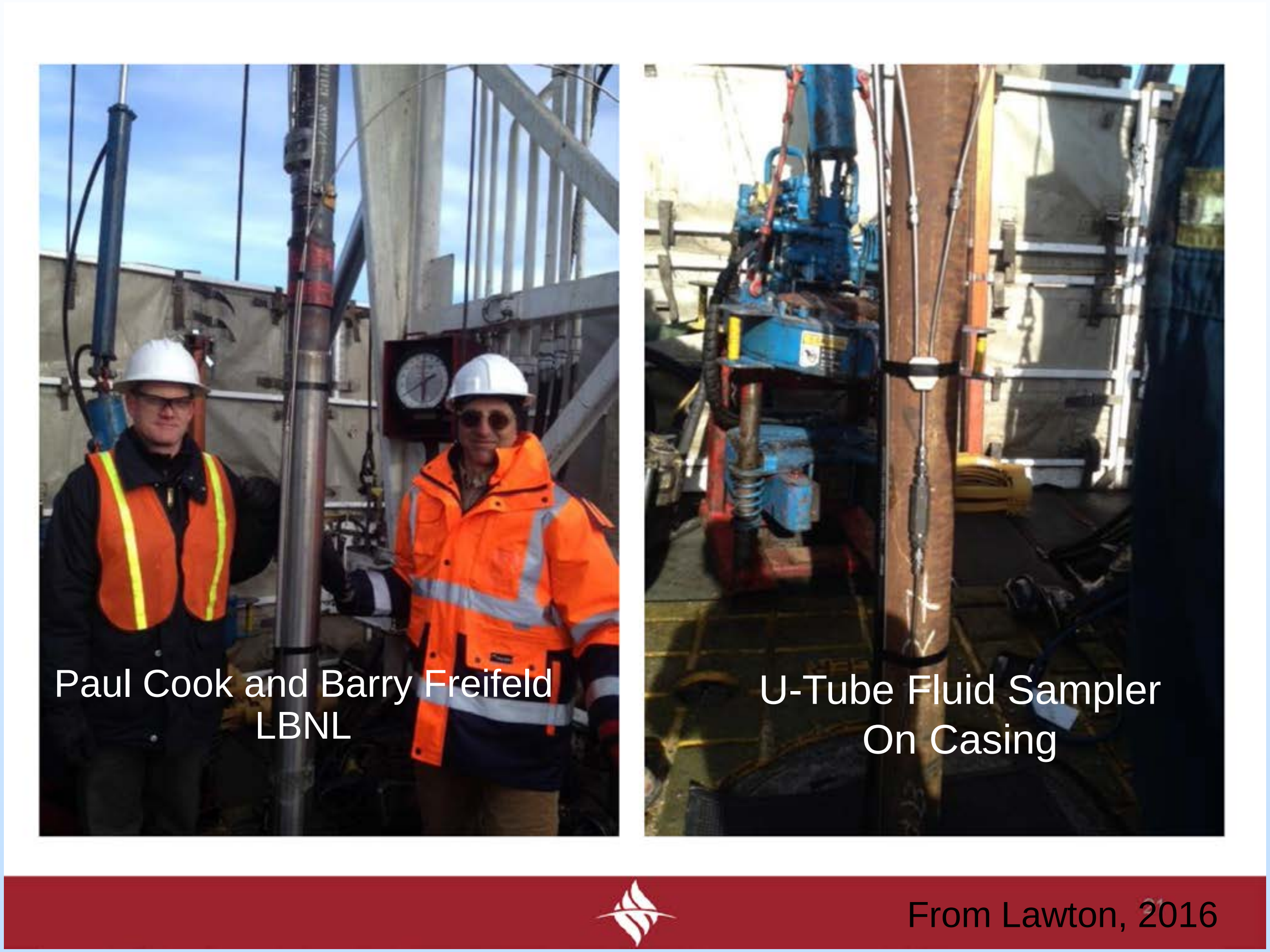


Isosurface at Sg=0.01



NRAP funding

LBNL Geochemical Fluid Sampling: U-Tube Behind Casing



July 2017 test of U-tube indicated gas in OBS well at ~400 psi

Benefit to the Program

- Program goals being addressed:
  - Develop and validate technologies to ensure 99 percent storage permanence.
  - Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness
- Project benefits:
  - Deployment and testing of new monitoring technologies and methodologies.
  - Broader learnings from leveraged international research opportunities
  - Rapid transfer of knowledge to domestic programs

Project Overview: Goals and Objectives

- The Core Carbon Storage and Monitoring Research Program (CCSMR) aims to advance emergent monitoring and field operations technologies that can be used in commercial carbon storage projects. This effort aligns with program goals:
  - Improve estimates of storage capacity and sweep efficiency
  - Develop new monitoring tools and technologies to achieve 99% storage confirmation
- Success criteria is if we are able to advance the technology readiness level (TRL) of targeted technologies from a level of TRL 2 – 3 up to 4 – 5 through leveraged field testing opportunities, with field sites being used as in-situ laboratories.

Organization Chart

- CMC CaMI Project Management: Don Lawton
- CMC CaMI monitoring lead: Don Lawton
- LBNL
  - co-PIs: Tom Daley and Barry Freifeld
  - Field Support, Installation and Instrumentation: Paul Cook
  - EM R&D: Mike Wilt
  - Crosswell Seismic: Pierpaolo Marchesini

- Carbon Management Canada (CMC) organized the Containment and Monitoring Institute (CaMI) which is led by Don Lawton. Mark Piercy of Schlumberger provides in-field logistical support and management at the CaMI Field Research Station (FRS).

Gantt Chart

MILESTONE GANTT CHART

Milestone Reporting accompanies Quarterly report	Q1 FY17			Q2 FY17			Q3 FY17			Q4 FY17		
Subtask Description	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**
Task 1 Project Management and Planning												
Task 2 Otway Project						A						B
Task 3 Aquistore Collaboration			C						D			
Task 4 Carbon Management Canada, FRS						E			F			
Task 5 US-Japan CCS Collaboration on Fiber-Optic Technology			G									H
Task 6 Mont Terri Project						I						J

* A & D are AOP Tracked milestone

TASK 4. Carbon Management Canada FRS Collaboration
Milestone 4-1 (E)
Forward synthetic model to predict 4D seismic response to CO_2 injection
Milestone 4-2 (F)
Baseline cross-hole seismic and EM data collection report

Bibliography

- No Journal Publications, specific to CaMI, as of now