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Core Carbon Storage and Monitoring Research (CCSMR)

Field Testing of Emerging Technologies: Task 3: Aquistore Project

Project Number ESD14-095

Thomas M. (Tom) Daley

Energy Geosciences Division

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

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Coauthors and Collaborators

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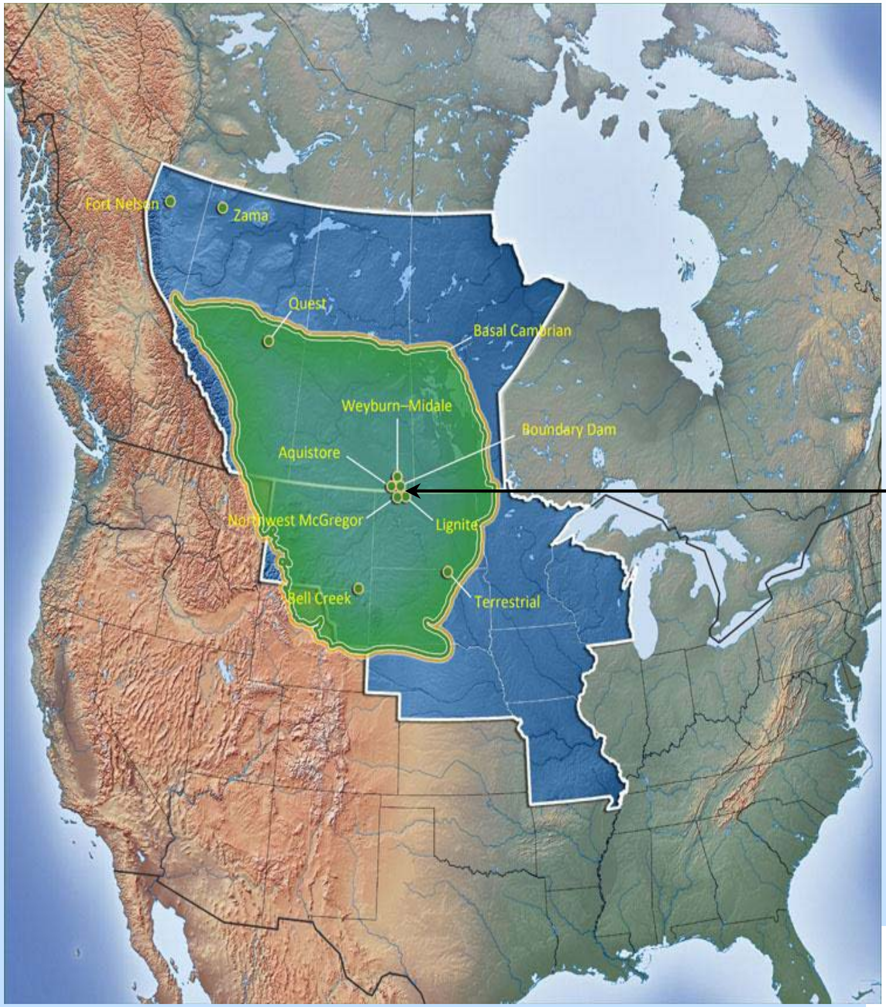
**LBNL Co-PI, [1] Silixa, LLC, [2] Lawrence Berkeley National Laboratory, [3]Geological Survey of Canada-NRCan, [4]Chevron, [5]PTRC, [6]Carleton Univ.*

Presentation Outline

- Aquistore Background/Status
- DAS Technology, DAS Modeling, Geophone Comparison
- DAS Vendor Comparison
- 4D DAS VSP imaging of CO2 plume and comparison to 4D surface seismic
- Other DAS R&D tests at Aquistore

Aquistore Project

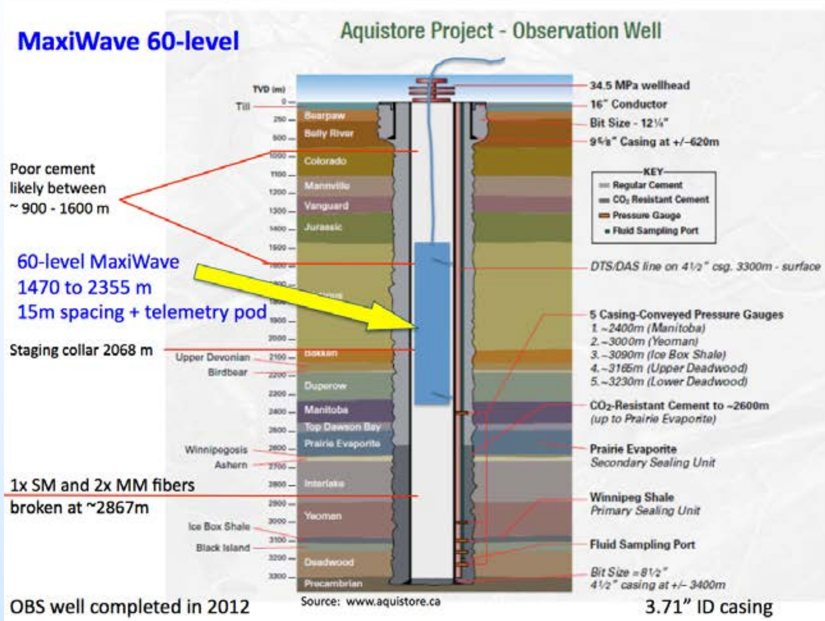
- Integrated CCS:
  - Capture from SaskPower's Boundary Dam Coal-Fired Power Station
  - Transported via pipeline to an injection well at the storage site; over 90% of CO2 for EOR
  - Captured CO_2 stored in a deep (3.2 km) saline aquifer in the Williston Basin
- ~1 Mt/year CO2 capture started in 2014
- Over 100,000 T Injected at Aquistore
- Monitoring Timeline:
  Initial installations 2012
  First Baseline 2013
  Injection 2015
  Monitor Surveys Feb. 2016; Nov 2016

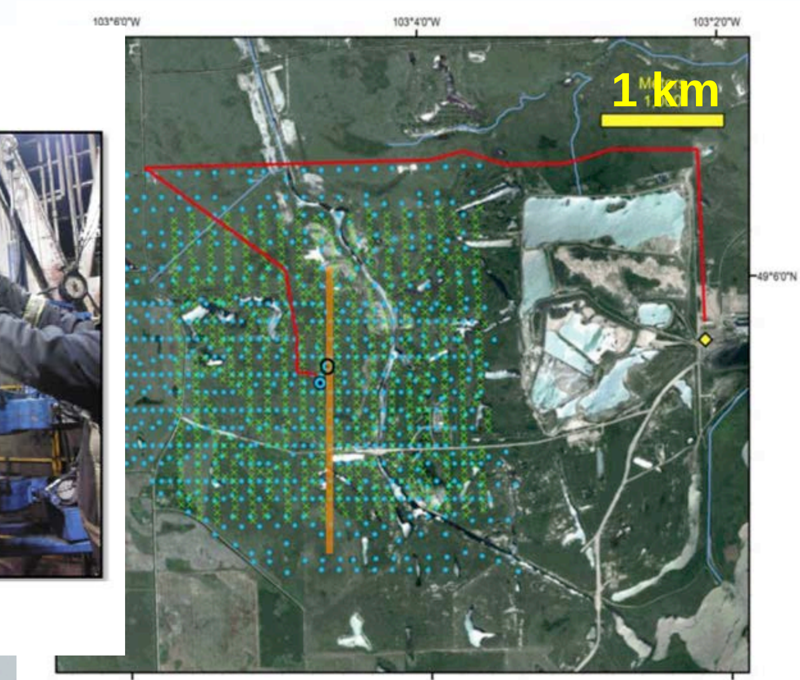


Seismic Monitoring: 3D surface and VSP

Dedicated Monitoring Well with Fiber Cable on *Well Casing (Cemented*)

Instrumented Observation Well

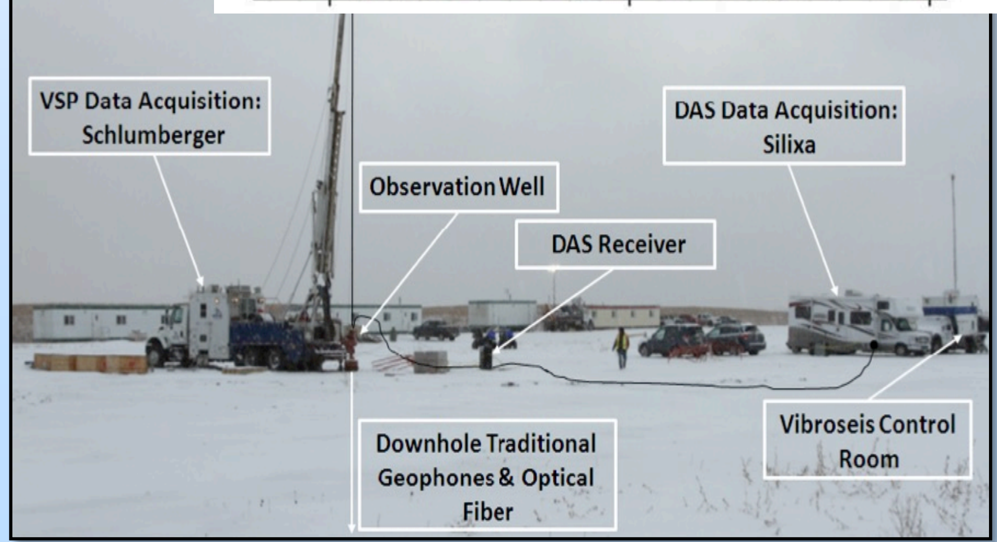




Baseline 3D/VSP surveys in 2013, 2014 and 2015<u>: DAS and Geophone</u>

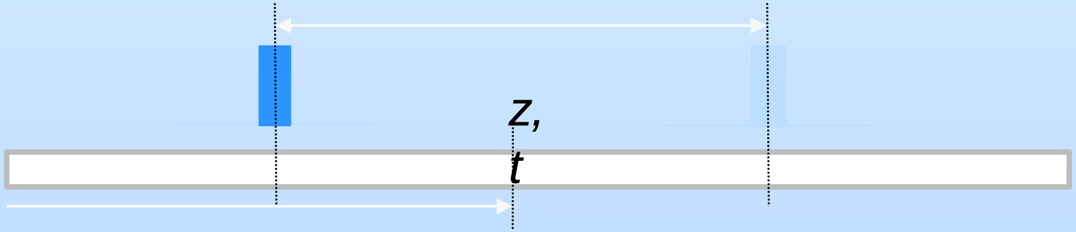
Fiber cable cemented behind casing is a key component of our DAS testing/development program.

Note: Many other non-seismic monitoring activities, not discussed here.



Distributed Acoustic Sensing (DAS) as implemented by Silixa

- Standard optical fibre acts as a sensor array
  - Typical sampling at 10kHz on 10,000+m fibre
  - Standard gauge length of 10m
  - Spatial sampling of 25cm
  - DAS measures change in average elongation per 10m gauge length per 0.1ms acoustic time sample, sampled every 0.25 m in distance

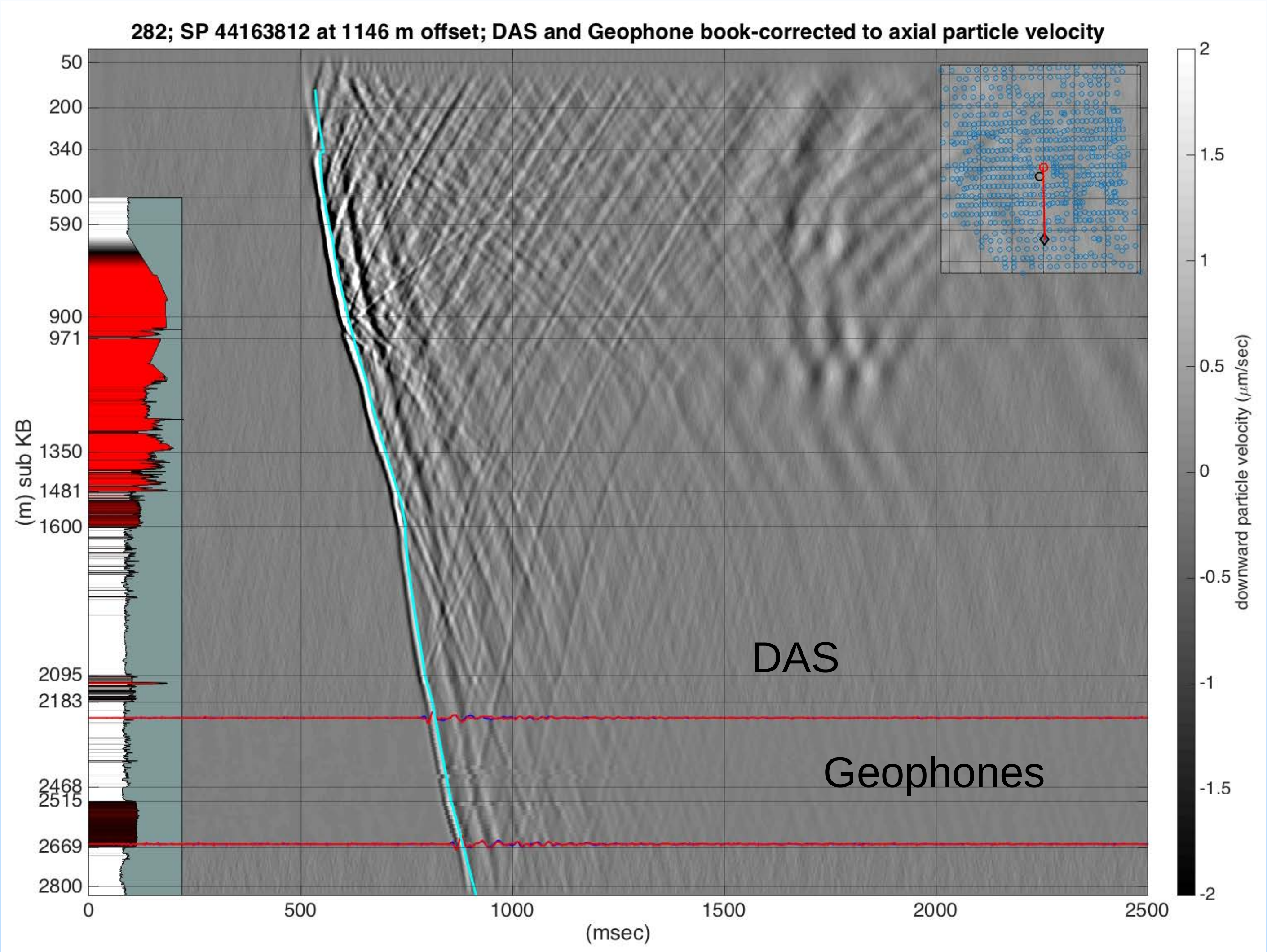


$$\left[u\left(z+\frac{dz}{2},t+dt\right)-u\left(z-\frac{dz}{2},t+dt\right)\right]-\left[u\left(z+\frac{dz}{2},t\right)-u\left(z-\frac{dz}{2},t\right)\right]$$

Property measured by Silixa system is strain-rate

Parker et al., Distributed Acoustic Sensing – a new tool for seismic applications, *first break* (32), February 2014

Previous Work: Equivalence of DAS and Geophone Response

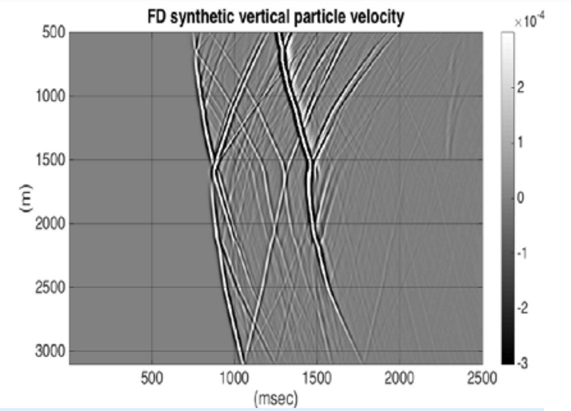


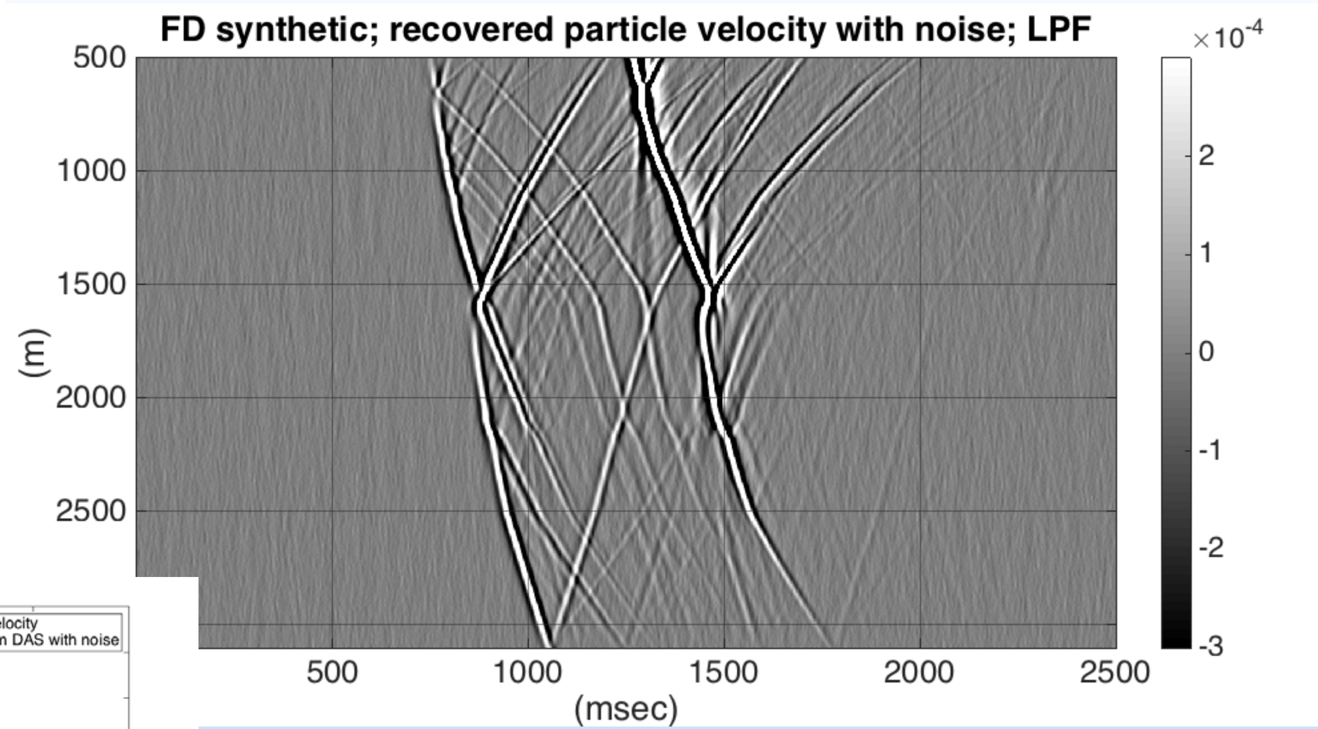
Red traces are DAS, blue are geophone.

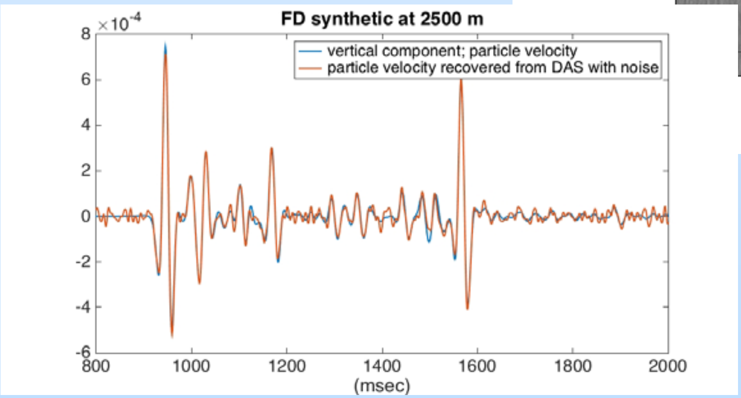
Display between colored traces is geophone; outside is DAS;

Mainly difference is noise from geophone tool slip.

Finite-Difference (FD) Modeling of DAS Data







Strain-rate -> Velocity

Time-integration of numerical strain-rate plus application of an f-k domain velocity rescaling operator yields a particle velocity profile recovered from the synthetic DAS

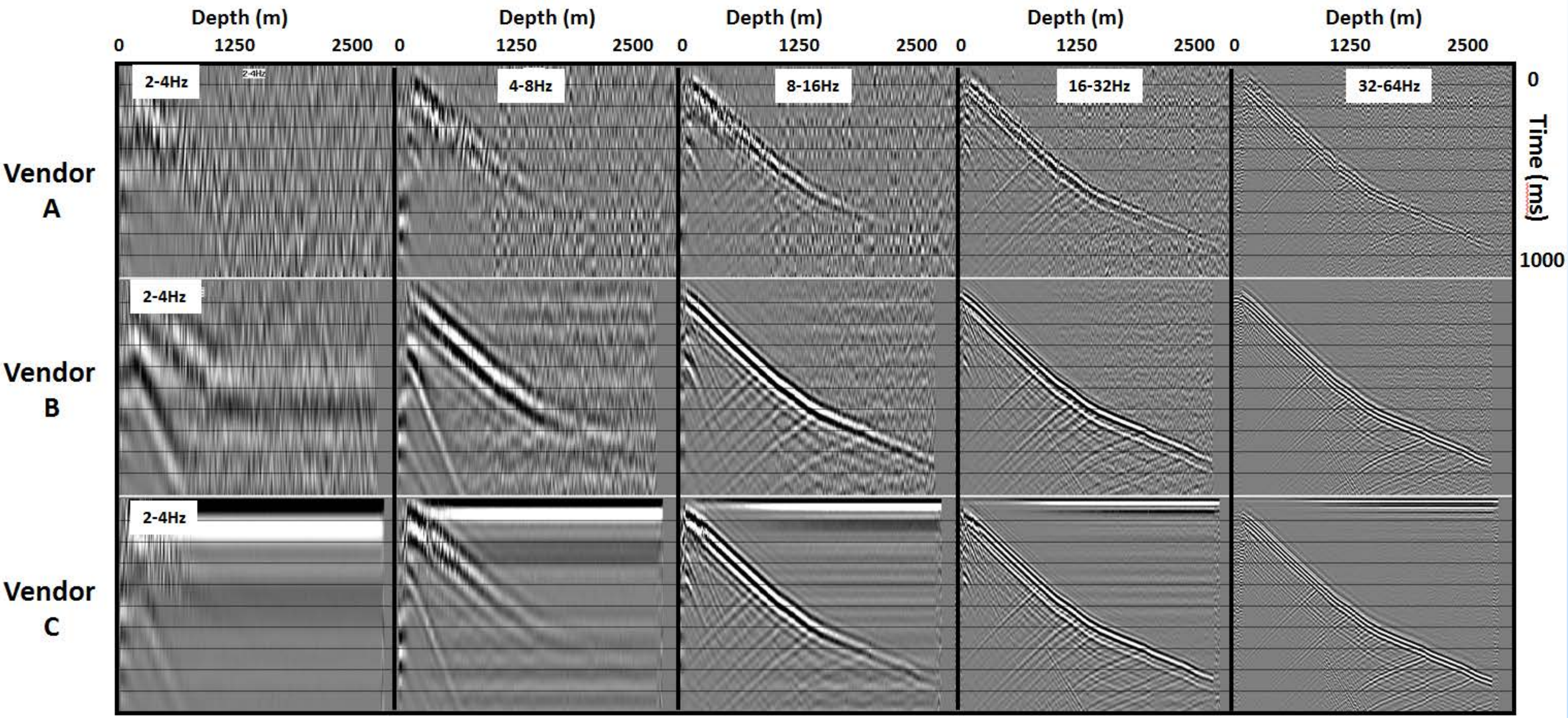
D. Miller

DAS Vendor Test

- 3 Commercial Vendors
- 2D Vibroseis VSP (60 VPs) plus 2 explosive shots (near and far offset) for all 3 vendors
- *Recording parameters specified same for all vendors (Sample Rate, Spatial Sampling, Gauge Length)*
- Same cable loop with connector provided to vendors
  - Same tap test locations for ‘zero’ depth control
- Vibroseis line shot 3 times (once per vendor) over 4 days
- Simultaneous borehole geophone array acquired for all vendors
- Preliminary results: vendors labeled A,B,C at this time

Vendor differences

1kg explosive @ 15m, near offset, “raw” data.



Courtesy Jon Cocker, Mike Craven

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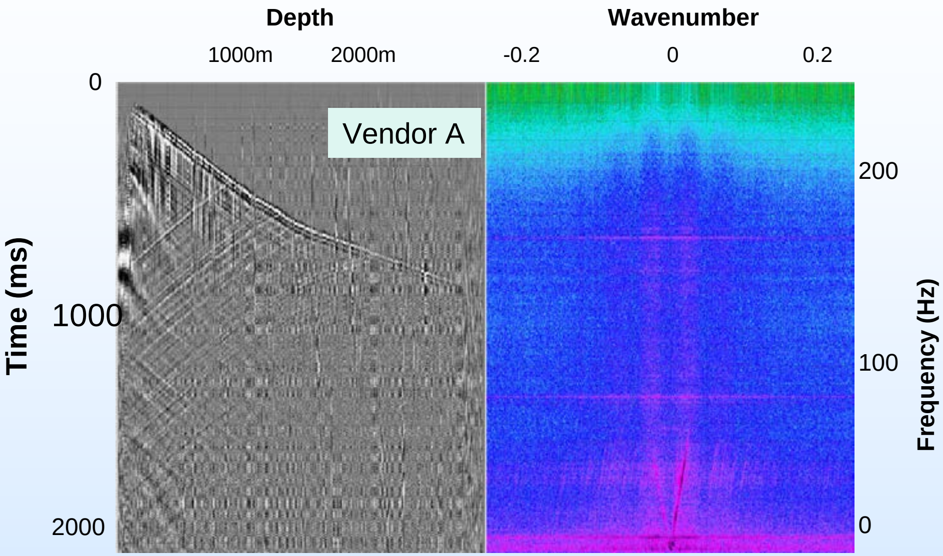
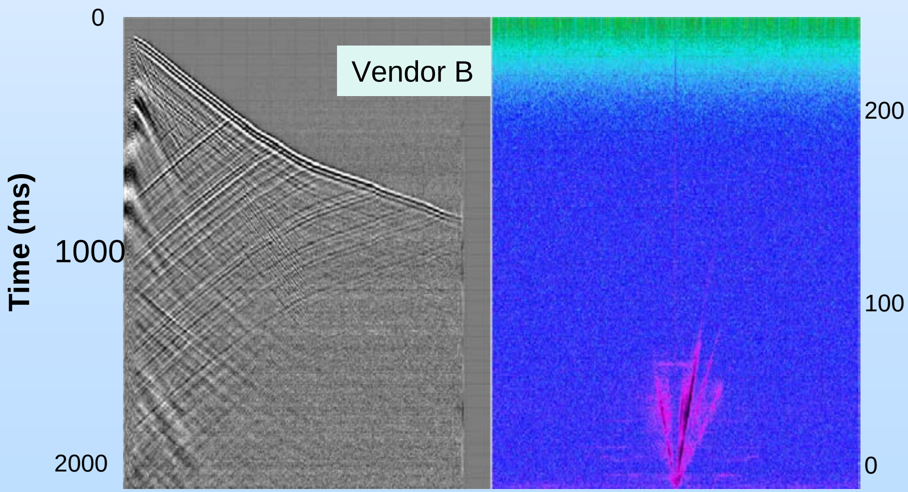
Vendor differences

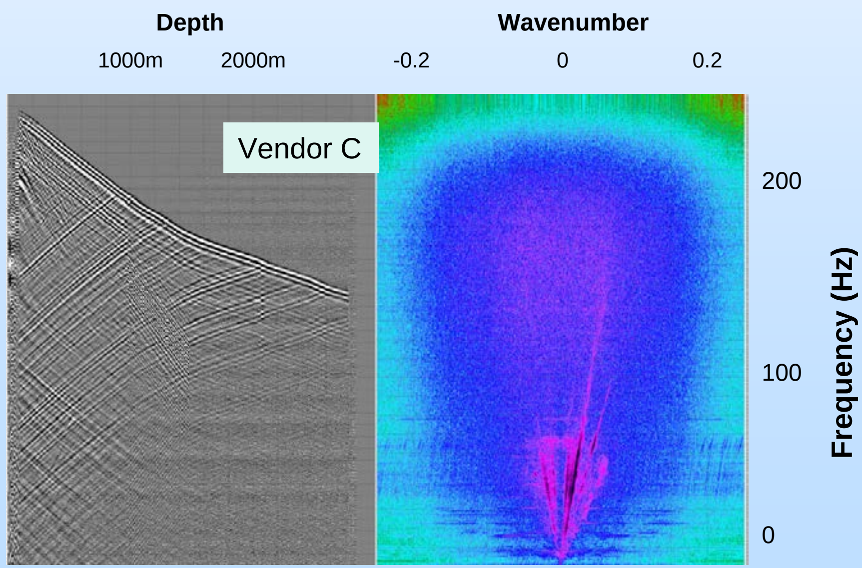
FK spectrums, “field data” + 2000ms AGC



Definitions:
Field data: vendors optimum field deliverable.
Raw data: rawest available digital data stream from the system.

Note: A detailed description of processing steps from ‘raw’ to ‘field’ data is a requirement



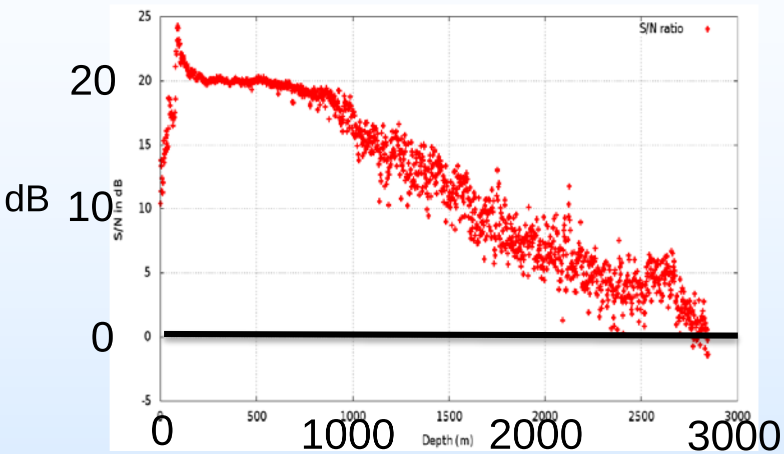


Vendor C clearly has had some filtering applied.

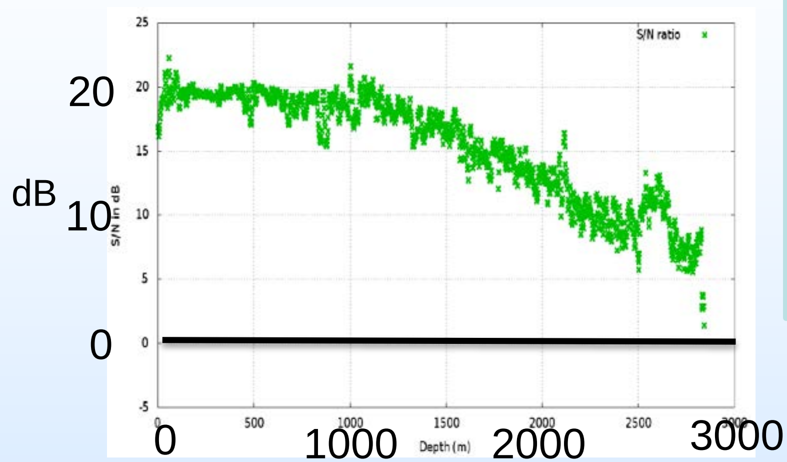
Courtesy Jon Cocker, Mike Craven

DAS Vendor Comparison: Vibroseis Source
Near offset VSP S/N ratio for 64 sweep stack

Vendor B



Vendor C

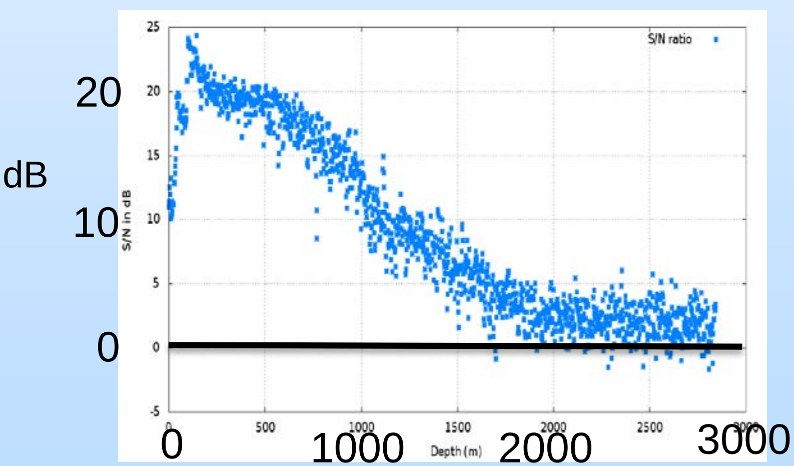


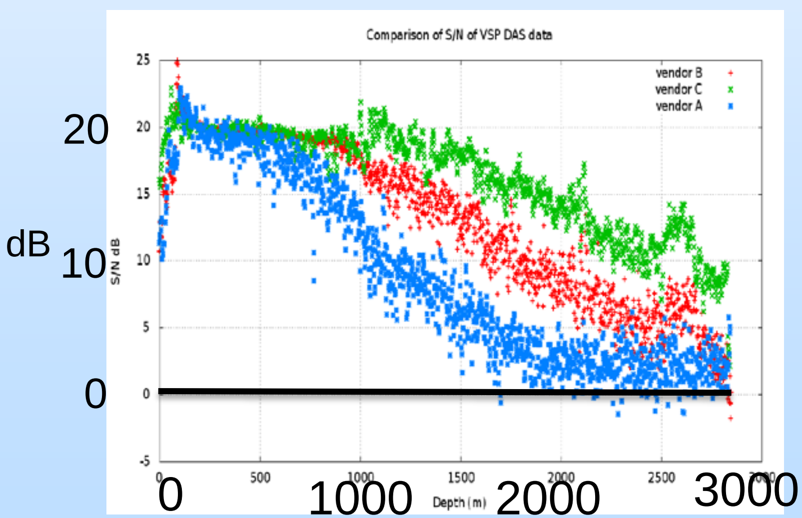
Note:
Geophone S/N ~26 dB (1500-2500 m)

Signal: 100 ms window
Noise: all pre arrival

Depth (m)

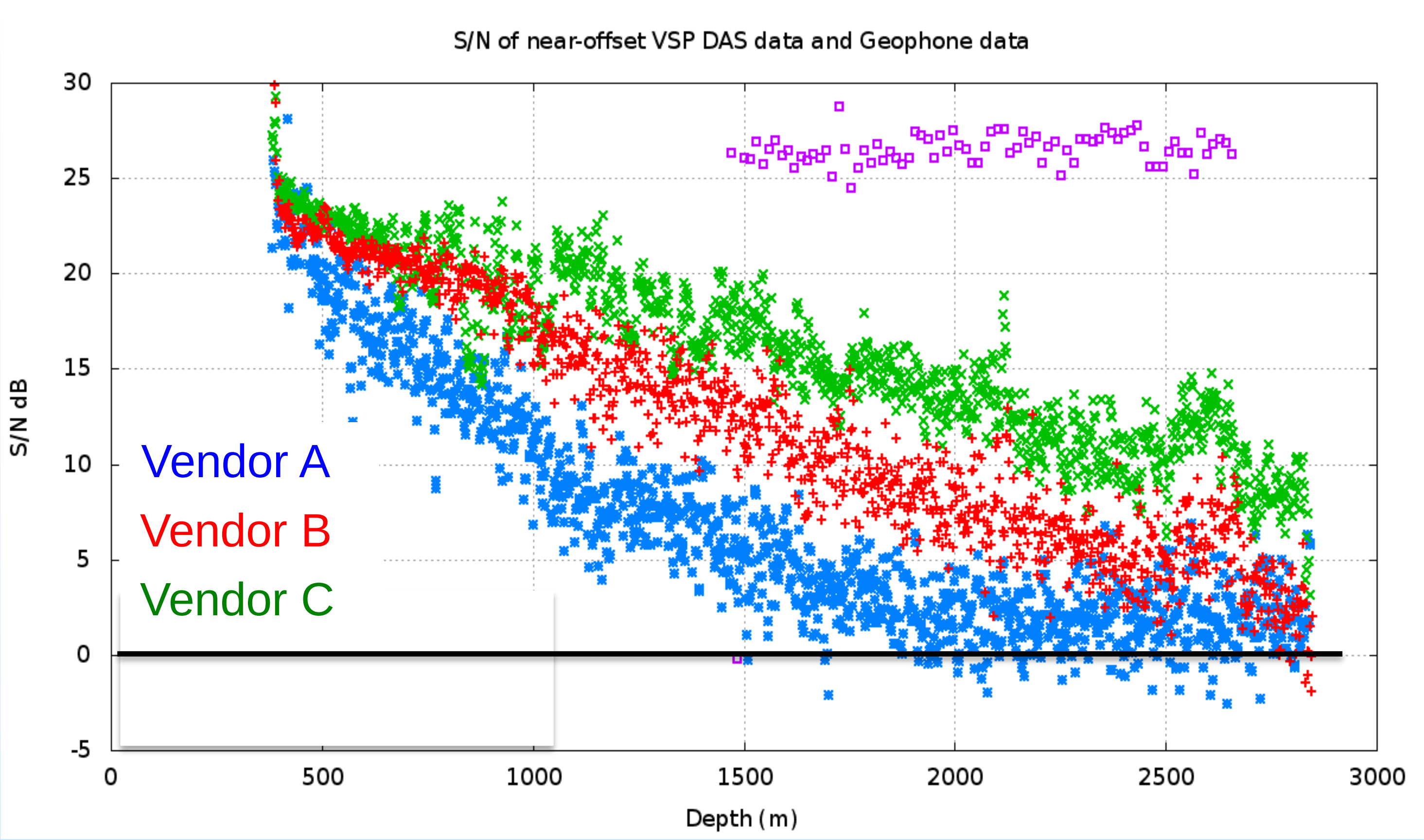
Vendor A





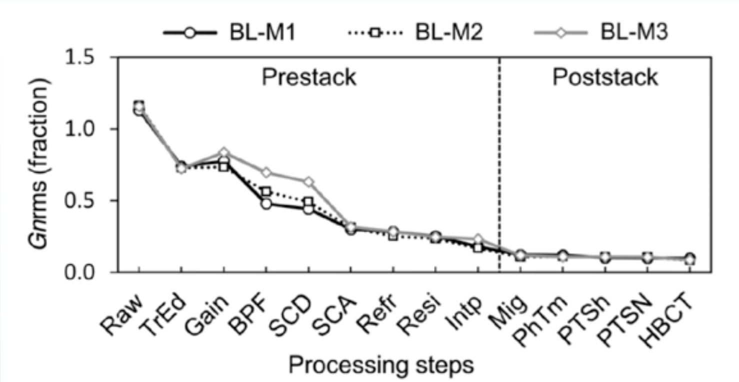
3 Vendors

DAS Vendor S/N Comparison + Geophone

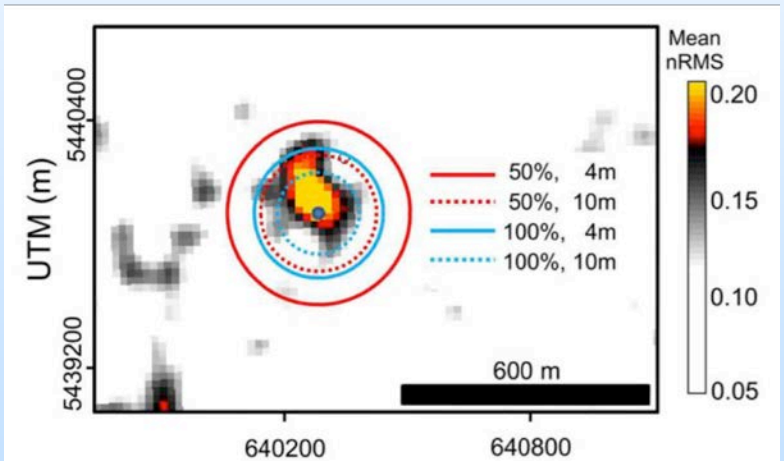


- Vibroseis 128 sweep stack; near offset
- 100 ms window for signal and noise
- Noise window centered 200 ms before signal
- Vertical component of geophone

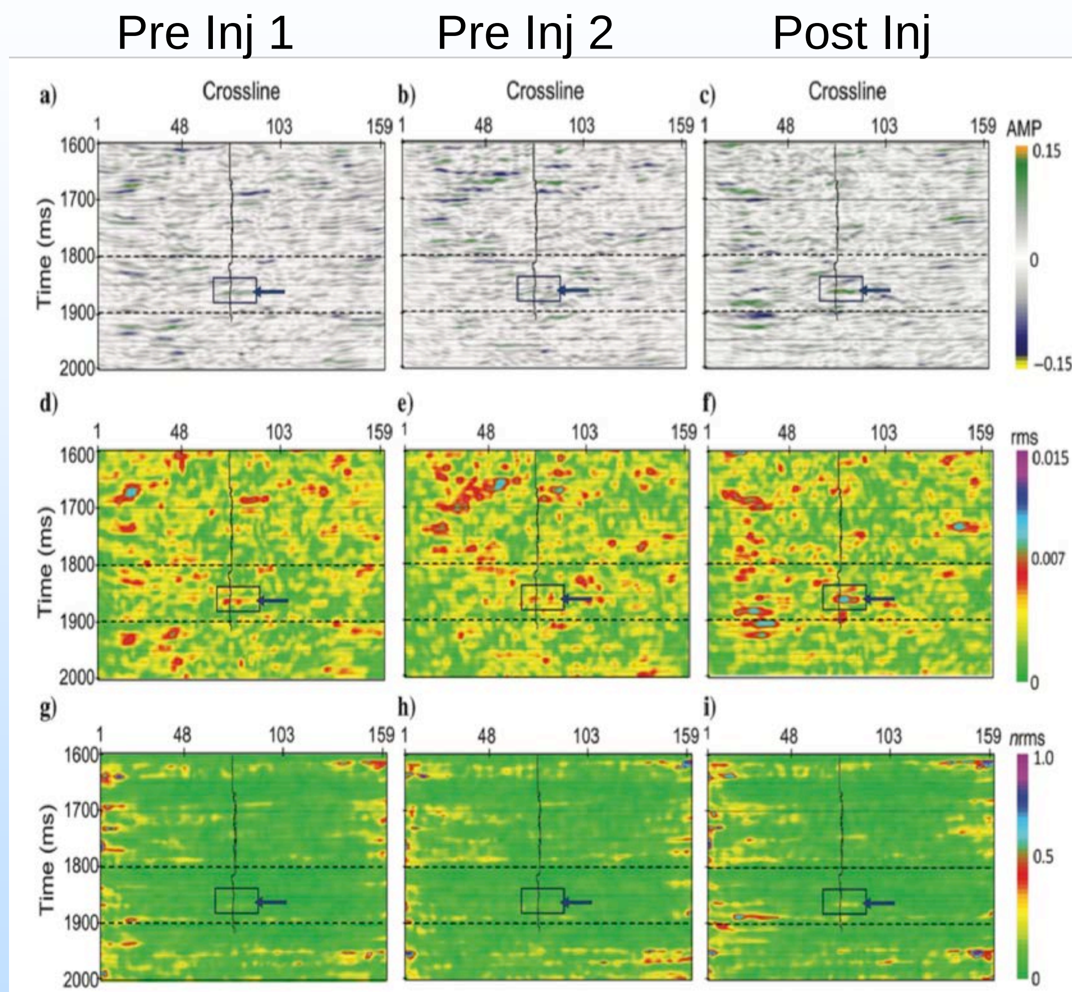
Monitoring the CO2 Plume
4D Surface Seismic: Roach, et al, 2017



The Gnrms computed within the window 700–2000 ms on stacked traces for post- and pre-CO2-injection data sets.



Enlarged portion of the post-injection nRMS map for the upper Deadwood interval. Superposed are circles representing the area of a hypothetical cylindrical CO2 plume for assumed CO2 saturation (50% and 100%) and thickness (4 or 10m) within this zone.



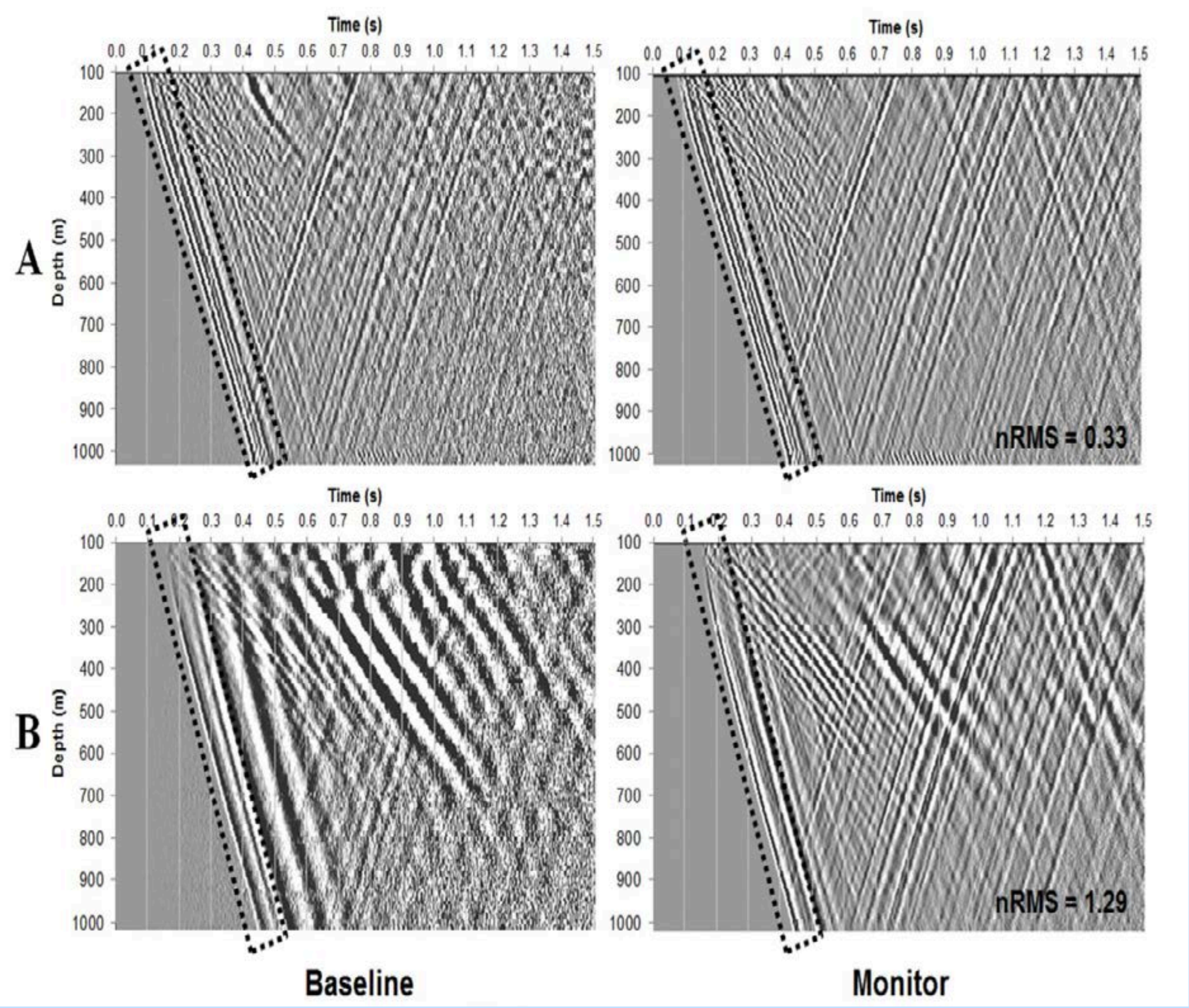
Difference of monitor surveys relative to baseline: Amplitude difference for (a)monitor1,(b)monitor2, and (c)monitor3. The rms amplitude difference for (d) monitor 1, (e) monitor 2, and (f) monitor 3. The nrms amplitude difference for (g) monitor 1, (h) monitor 2, and (i) monitor 3.. Superposed is the V_P log. The reservoir is demarked by the dashed black lines.

4D DAS VSP Repeatability

Shot gathers from the baseline and monitor surveys exhibiting good (A) and poor (B) repeatability.

Values of nRMS were computed by selecting 70 ms
windows around direct waves (box delineated by a dotted lines).

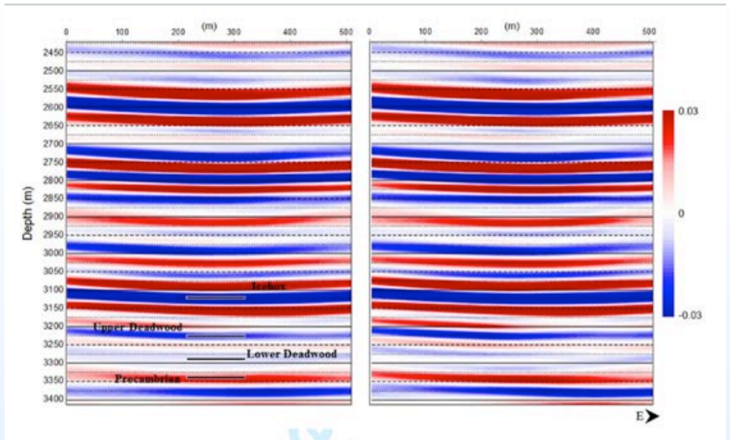
Baseline and monitor
data are scaled by the same shot-based factor for display.



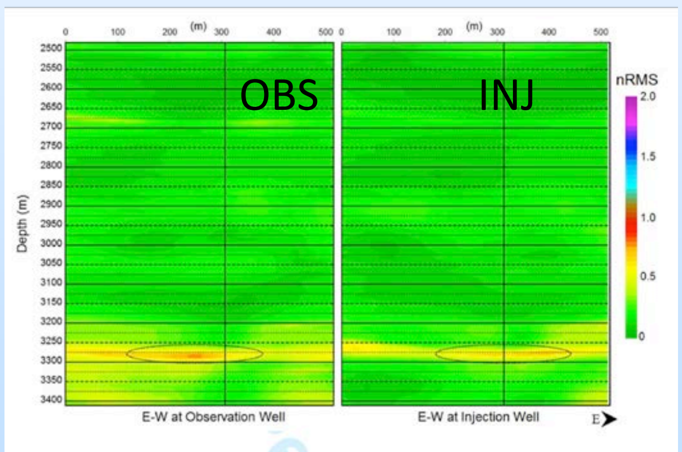
DAS is Repeatable;
Variability in Explosive
Source Affects Repeatability

Harris, et al, Geophysics, in press

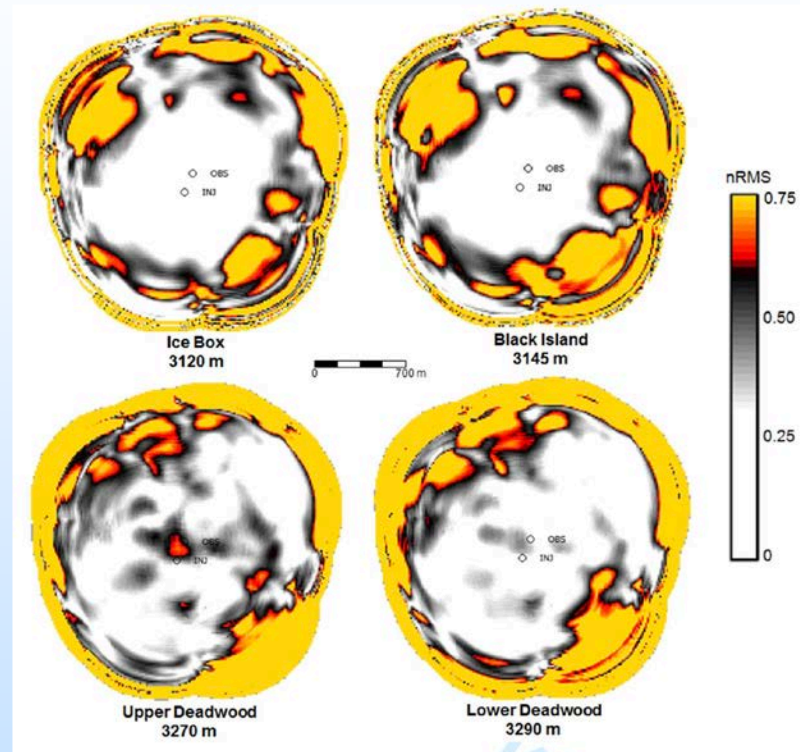
4D DAS VSP; Harris, et al, in press



Amplitude cross-section of baseline (left) and monitor (right) depth-migrated volumes intersecting the observation well. Key reservoir formations labeled on left.



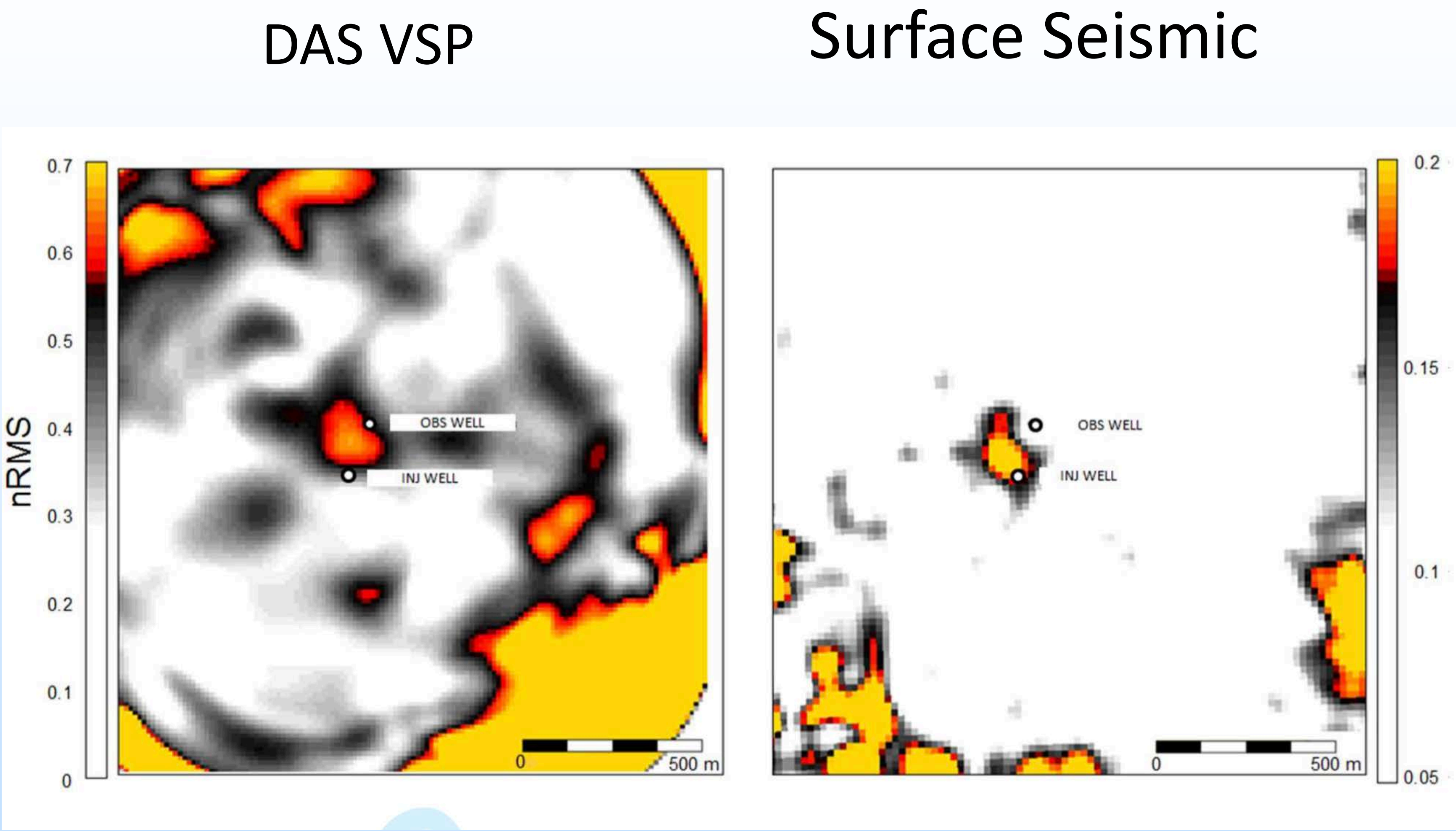
nRMS of monitor-baseline differences for a 75 m window in cross-sections through observation (left) and injection (right) wells. In both difference sections, a nRMS ≈ 0.9 anomaly is present at a depth of ~3275 m (in dashed circle).



Plan view of nRMS difference images for the reservoir caprock (Ice Box formation and 3 intervals where CO2 is injected. nRMS values within a 20 m thick window

Aquistore 4D
Feb 2016

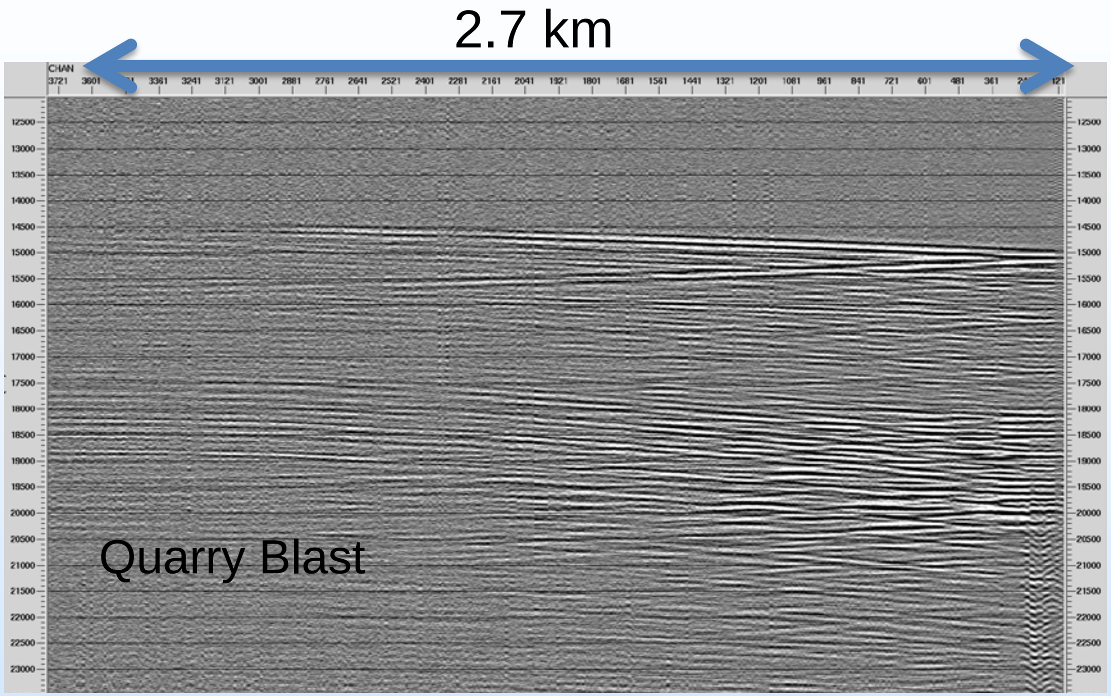
DAS VSP and Surface Seismic for the Upper Deadwood – Agreement!



Plan view of nRMS difference images in the upper Deadwood showing VSP result (left) and surface-based result (right).

Harris, et al, in review
Roach, et al, 2016.

Other DAS Tests: Permanent Monitoring



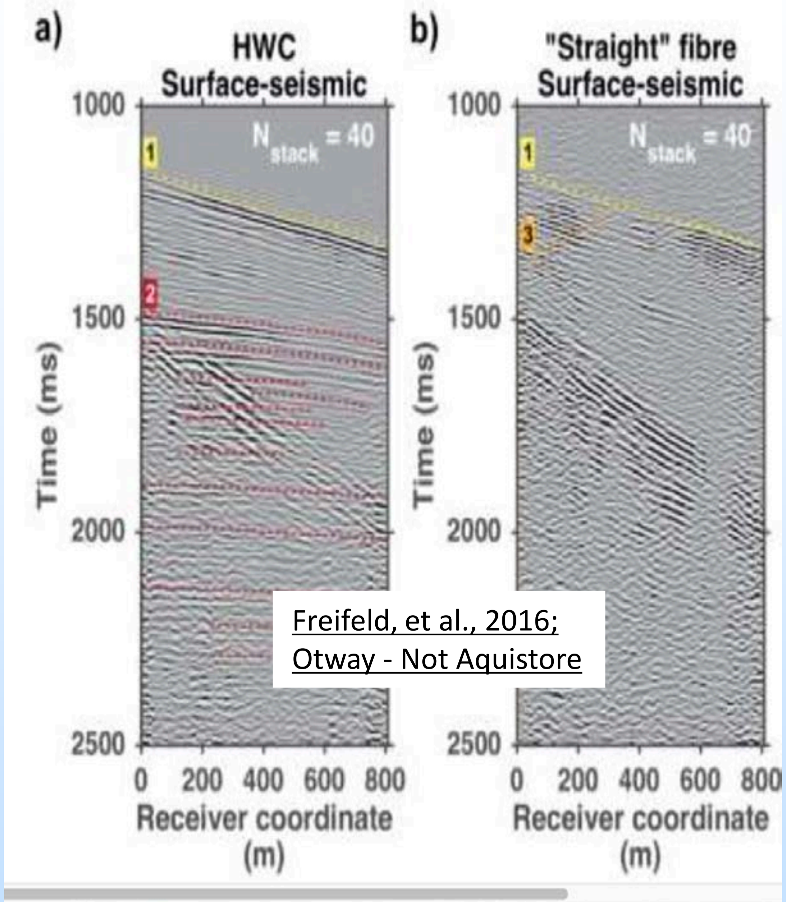
Passive Well Monitoring: Important for Induced Seismicity

- In one month of continuous passive monitoring, no natural events were detected (yet), but local quarry blasts were observed.
- Passive noise monitoring of injection well for ~3 days at start of injection.
- Recording of permanent source operated by JOGMEC (Japan)

LBNL Permanent Surface Source w/DAS:

LBNL 10 T-force SOV source sitting on a 1 m x 2 m x 2 m deep foundation

Other Tests with DAS: HWC

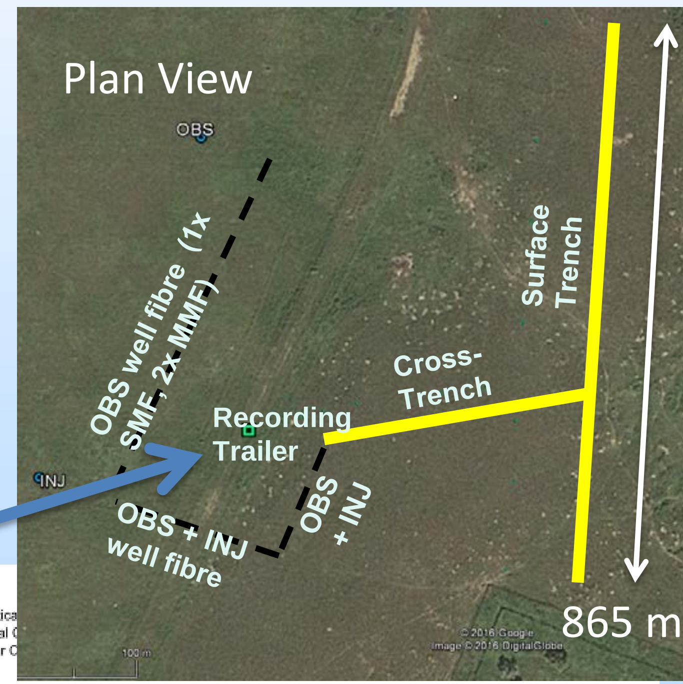


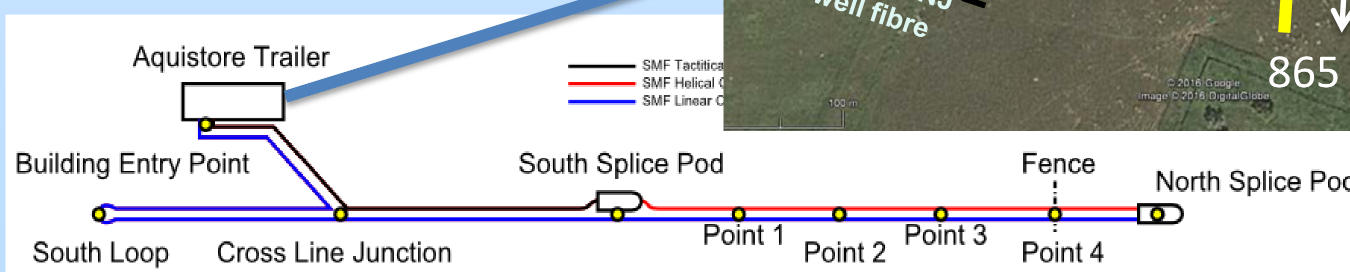
<u>Trenched Surface Cable HWC</u>:

Helical Wound Cable – for angular sensitivity

HWC cable: 30-deg winding, single SMF fibre

Fiber Splice Loop:
Wells and Trenches





Accomplishments to Date

- Fiber Optic Cable Installation
- Baseline DAS VSP (2013, 2014)
  - Comparison of dynamite and vibroseis: both work with DAS, some noise reduction possible with vibroseis
  - Comparison of single mode and multimode fiber recording: equal quality
  - Repeat baseline for for DAS repeatablility
- Injection began 2015; Modeling indicated >30K tonne should be detectable
- First post-injection DAS surveys acquired (Feb 2016) after ~35 K tonne
- 20+ days continuous passive recording using DAS array following injection in 2015
- Recording of permanent JOGMEC ACROSS source into fiber-optic array (2015)
- DAS and Geophone VSP: Data acquired for 4D sensitivity comparison
- Multivendor DAS test
- Trenched surface cable test including helical wound cable
- Demonstration of DAS VSP mapping of CO2 plume at 3.2 km depth

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Lessons Learned

– Key Findings
  - DAS cemented behind casing provides high quality data: this has been an important site for DAS testing
  - Single mode and multi-mode fiber cable can both be used for DAS recording – allows use of more existing cables
  - DAS can operate for long term passive recording
  - DAS can provide VSP data quality comparable to conventional geophones

– Lessons Learned
  - Cables can be damaged when deploying in wells, but…
  - Fiber cable can still be used for DAS above damage point
  - Long term continuous DAS monitoring requires dedicated recording system and large data storage (BIG DATA)

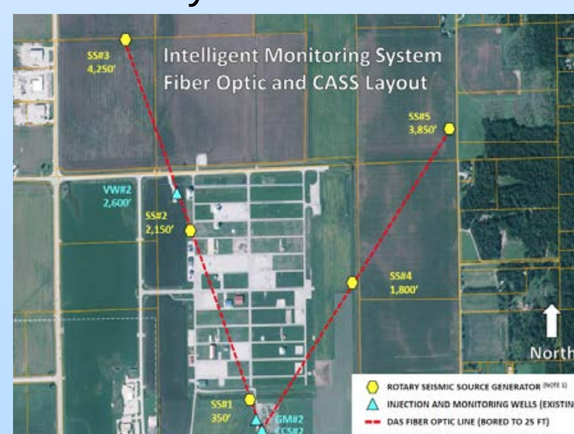
Synergy Opportunities

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

CMC CaMI Field Research talk
Thursday 12:05 PM: T. Daley

Development of Intelligent Monitoring System (IMS) Modules for the Aquistore CO_2 Storage Project - University of North Dakota – Jose Torrez

Intelligent Monitoring Systems and Advanced Well Integrity and Mitigation - Archer Daniels Midland Corporation - Scott McDonald
Wednesday 12:00 PM



Project Summary

- Key Findings
  - DAS cemented behind casing provides high quality data: this has been an important site for DAS testing
  - Single mode and multi-mode fiber cable can both be used for DAS recording – allows use of more existing cables
  - DAS can operate for long term passive recording
  - DAS can provide VSP data quality comparable to conventional geophones
  - DAS VSP can map CO_2 plume
- Next Steps
  - Analysis of DAS data including HWC data
  - Planning for next monitoring repeat

Acknowledgements

- Aquistore: Petroleum Technology Research Council (PTRC); National Resources Canada, Geologic Survey of Canada (GSC); DAS Images Courtesy of Aquistore Project; PTRC/GSC/LBNL/Chevron/ExxonMobil
- Aquistore 4D Seismic Team: Kyle Harris (Carleton University); Lisa Roach (University of Leeds); Claire Samson (Carleton University); Brian Roberts (Geologic Survey of Canada)
- LBNL support from: US DOE: Office of Fossil Energy, Carbon Storage Program, NETL (Program Lead: Traci Rodosta)
- VSP Data Acquisition: Tesla, Reservoir Engineering, Silixa, OptaSense & Schlumberger (in no particular order)

Thank You!

Questions?

Appendix

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

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 at an operational CCS site.
  - 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 3 – 5 through leveraged field testing opportunities.

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Organization

- PTRC: Aquistore Project Management: Kyle Worth
- NR Can., Geol. Survey of Can.: Seismic monitoring: Don White
- LBNL
  - co-PIs: Tom Daley and Barry Freifeld
  - Project Lead: Michelle Robertson

- PTRC is operating the Aquistore storage project with seismic monitoring led by Don White. LBNL is providing DAS acquisition, processing, analysis. Multivendor DAS test included funding from industry consortia.

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 3. Aquistore Collaboration

Milestone 3-1(C)
Title: DAS vendor intercomparison data analysis report
Planned Completion (Reporting) date: Q1 12/31/16 (1/31/17)
Verification Method: Quarterly Progress report and supplement

Milestone 3-2(D)
Title: 4D VSP analysis of Aquistore CO_2 plume and comparison with surface reflection results
Planned Completion (Reporting) date: Q3 6/30/17 (7/31/17)
Verification Method: Quarterly Progress report and supplement

Bibliography

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- Longton, M., A. Strudley, D. White, **T.M. Daley**, D.E. Miller, 2015, Simultaneous Acquisition of Distributed Acoustic Seismic Surveys with Single-mode and Multi-mode Fiber Optic Cables at Aquistore CO2 Storage Site and a Comparison with 3C Geophones, Third EAGE Workshop on Permanent Reservoir Monitoring, 16-19 march 2015, Oslo Norway.