Borehole Based Monitoring of CO_2 Storage: Recent Developments in Fiber-Optic Sensing

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contributions from many project participants

2014 RITE CCS Workshop, Tokyo
January 23, 2014

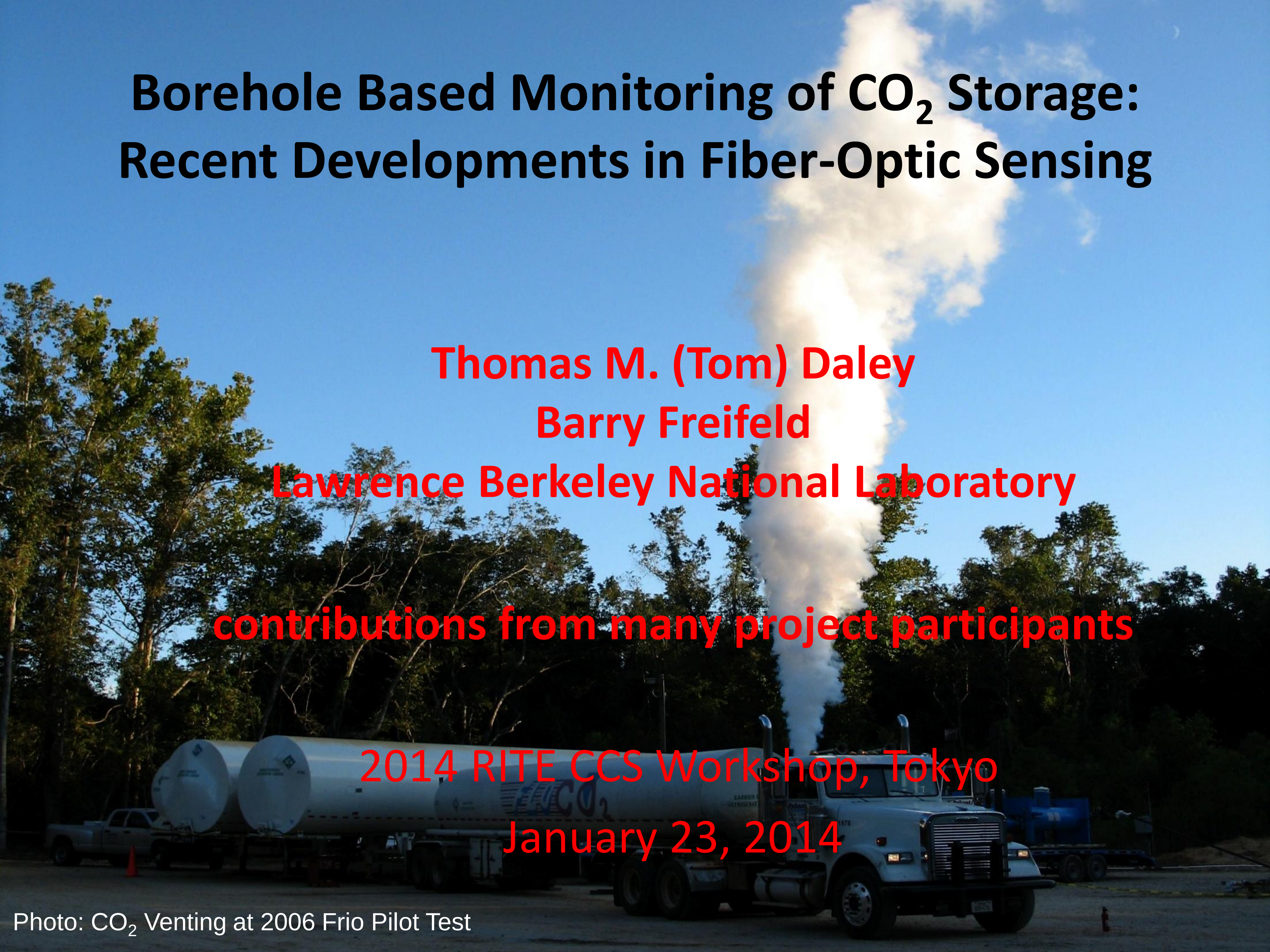


Photo: CO_2 Venting at 2006 Frio Pilot Test

Outline

- CO2 Monitoring – Brief Review
  - 1950-2000s:
    - Early Enhanced Oil Recovery (EOR) Tests
    - Development of reservoir monitoring
    - First CO_2 Sequestration Specific Tests
- Importance of monitoring wells
    - Look Forward: Large Scale Sequestration
    - Need for 'adaptive' monitoring well program
- Fiber optic technology for monitoring wells
  - Background
  - Field testing and applications (CO_2 monitoring)
    - Citronelle, Alabama, USA
      - Repeat with improvement
    - Otway, Australia
      - With surface cable testing
    - Ketzin, Germany
      - Multiple wells
    - Aquistore

1950s – 1960s

- Early EOR Tests: Laboratory and Field Studies
  - Torrey, 1951: Oil recovery by carbonic acid injection
  - Beeson and Ortloff, 1959, Laboratory investigation of the water-driven CO2 Process for Oil Recovery
  - Budde, 1959, Geoph. Prosp.: Detection of CO2 in ground water (mineral water) via atmospheric measurements: (uses heat conductivity variation of CO2 vs N2/O2)

Carbon Dioxide Solvent Flooding for Increased Oil Recovery

L. W. HOLM
MEMBER AIME

THE PURE OIL CO.
CRYSTAL LAKE, ILL.

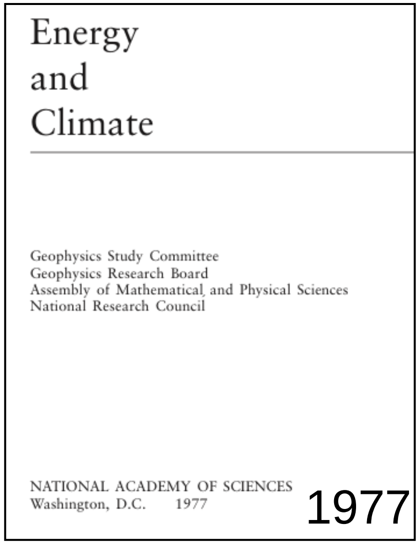
ABSTRACT

Laboratory flooding experiments on linear flow systems indicated that high oil displacement, approaching that obtained from completely miscible solvents, can be attained by injecting a small slug of carbon dioxide into a reservoir and driving it with plain or carbonated water. Data are presented in this paper which show the flood. Oil recoveries of 6 to 15 per cent of the original oil in place were obtained during this blowdown period. This additional recovery was found to be a function of oil remaining after the flood, decreasing with decreasing oil saturation. It was also noted that highest oil recoveries by blowdown were obtained when carbonated water rather than plain water followed the CO_2 slug.

Holm, 1959, SPE.

1970s

- **Large Scale CO2-EOR Field Tests - SACROC Field**
  - Crameik and Plassey, 1972, API: Carbon Dioxide Injection Project SACROC Unit, Texas
    - Plan 37 Mton injection over 9 years in 202 injection wells; 220 mile pipeline
  - Farr, 1978, SPE: ".. Seismic as a reservoir analysis technique"
    - Until recently …pore fluid identification was considered … beyond the resolving power of the seismic reflection method"
  - Richardson, 1979, JPT: Monitoring with Induction Logs: " using the technique on a CO2 pilot flood"
- **Early Climate Change Concern in U.S.**
  - National Academy Report 1977


Energy
and
Climate

Geophysics Study Committee
Geophysics Research Board
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1977

1977

1980-90s

- **Beginning of Subsurface Monitoring**
  - Goodrich, 1980, SPE/DOE: Review of past and ongoing CO_2 injection field tests
    - 19 projects - abstract has no mention of monitoring
  - Svor and Globe, 1982, SPE: "..Quantitative Monitoring for CO_2 Floods"
    - Pulsed Neutron logging for co2 saturation
  - Widmyer, 1987, JPT: **Use of Monitor Observation Wells** For fluid sampling
  - **Wang and Nur, 1989, SPE: Rock Physics - Effect of CO_2 on Wave Velocities**

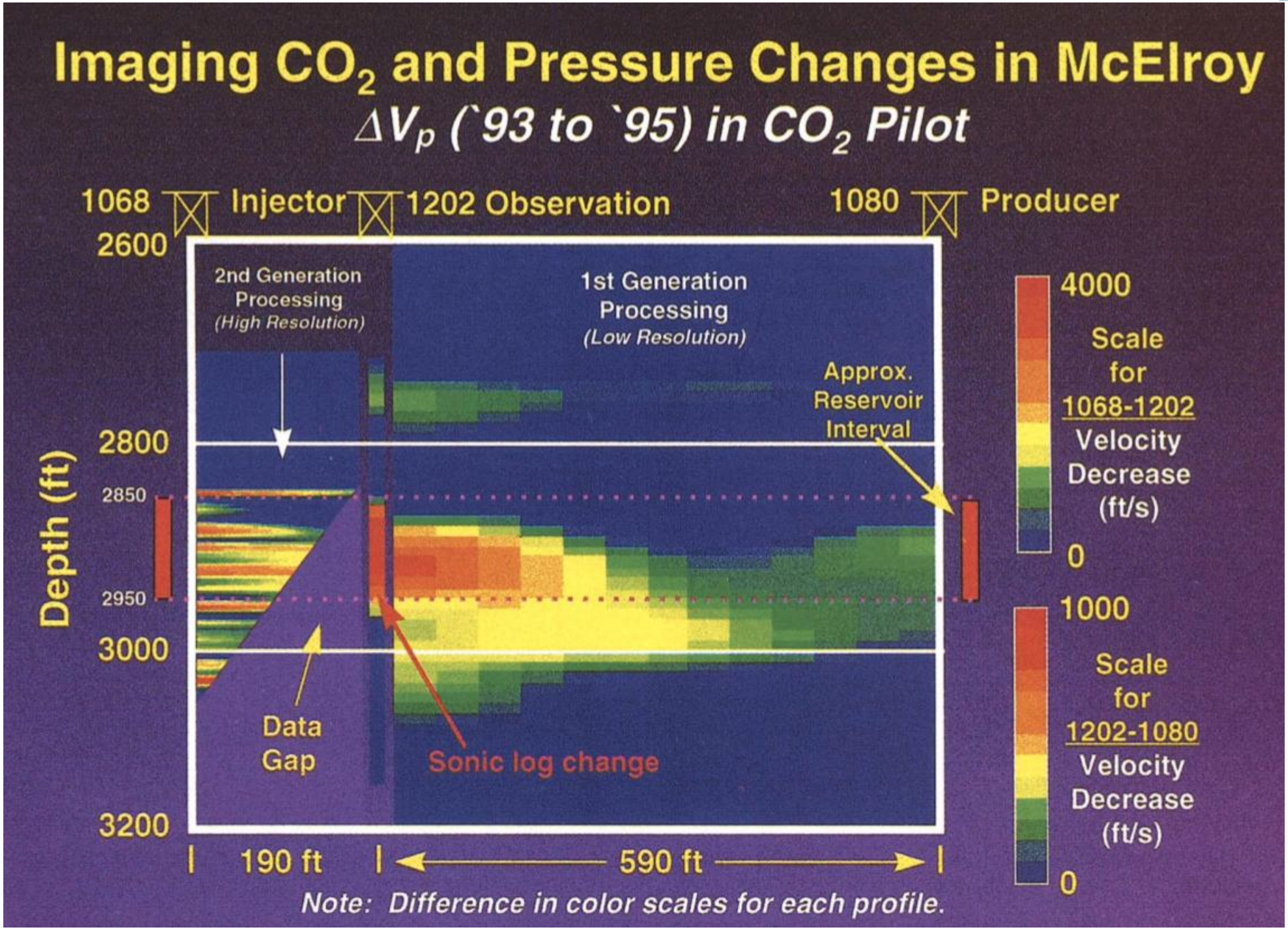
- **Maturing Monitoring Tools**
  - Wang, et al, 1998: McElroy CO_2 Flood – Imaging w/Rock Physics
  - Huang, et al, 1998, TLE: Integrating reservoir model and seismic monitoring
  - Lumley 2001, Geophysics: 100 total and 75 active reservoir monitoring projects (4D seismic)

1990s-2000s

- **Initial Sequestration Field Tests – All With Monitoring Program**
  - Industrial
    - Sleipner (4D marine seismic)
    - Weyburn-Midale (also EOR)
    - In Salah (success of InSAR)
    - Snohvit (2008 – marine seismic)
  - Research Pilots
    - Frio (crosswell, continuous fluid sampling)
    - **Nagaoka (crosswell, multiple well logging)**
    - Otway (multi-level continuous fluid sampling)
    - CO2Sink (Ketzin) (ERT, 4D seismic)

    - US DOE Partnerships (e.g. Cranfield, Decatur, etc.)
      - Wide range of monitoring tools tested

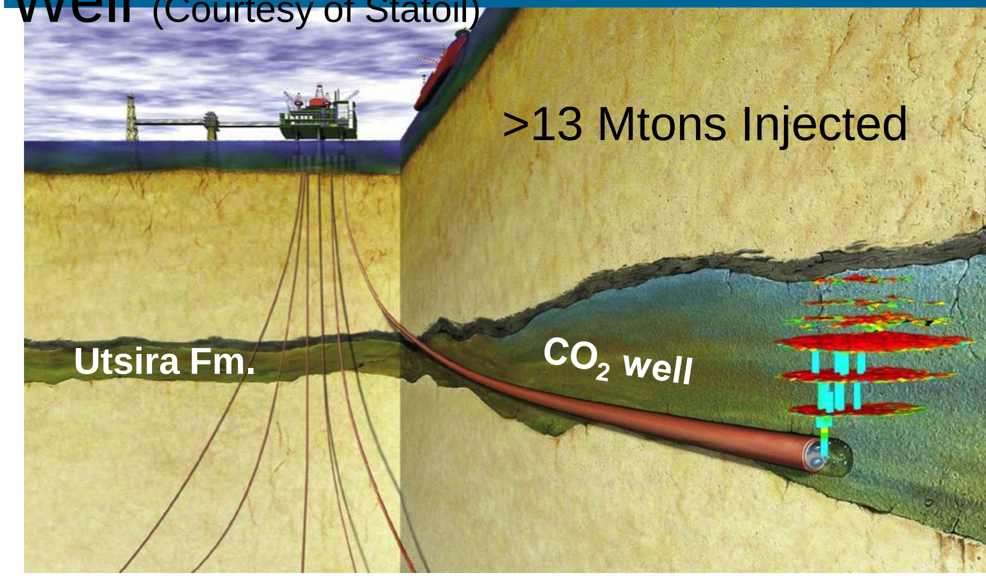
Early Success at Borehole Monitoring McElroy Pilot Test 1995



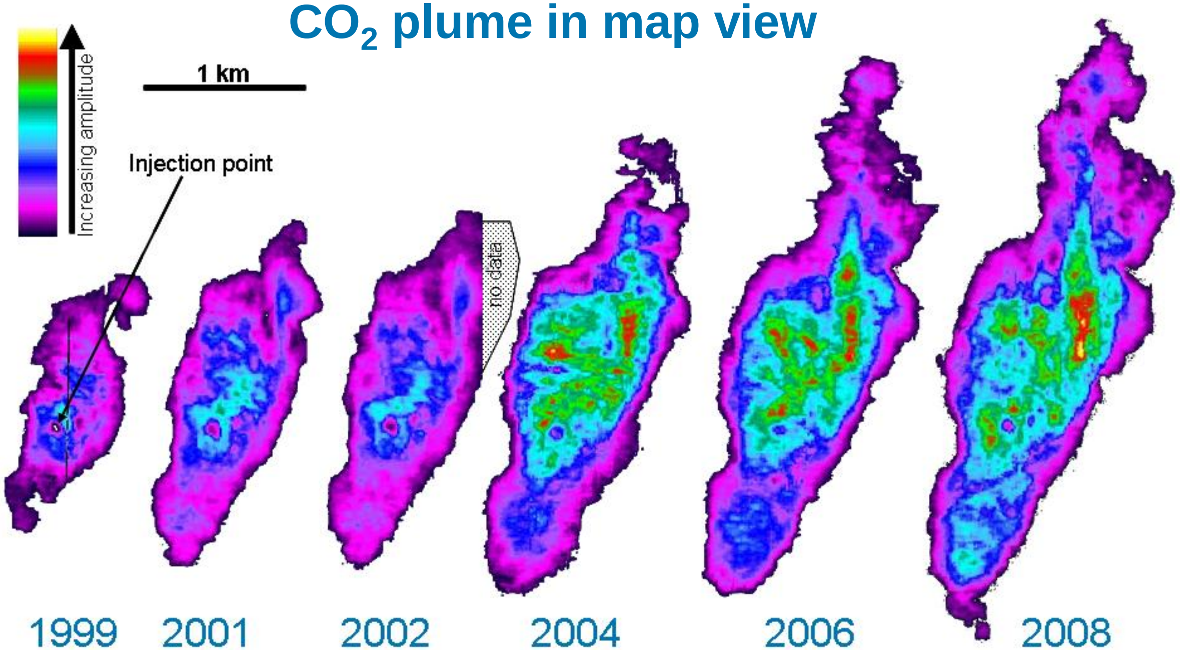
Wang, et al, 1998;

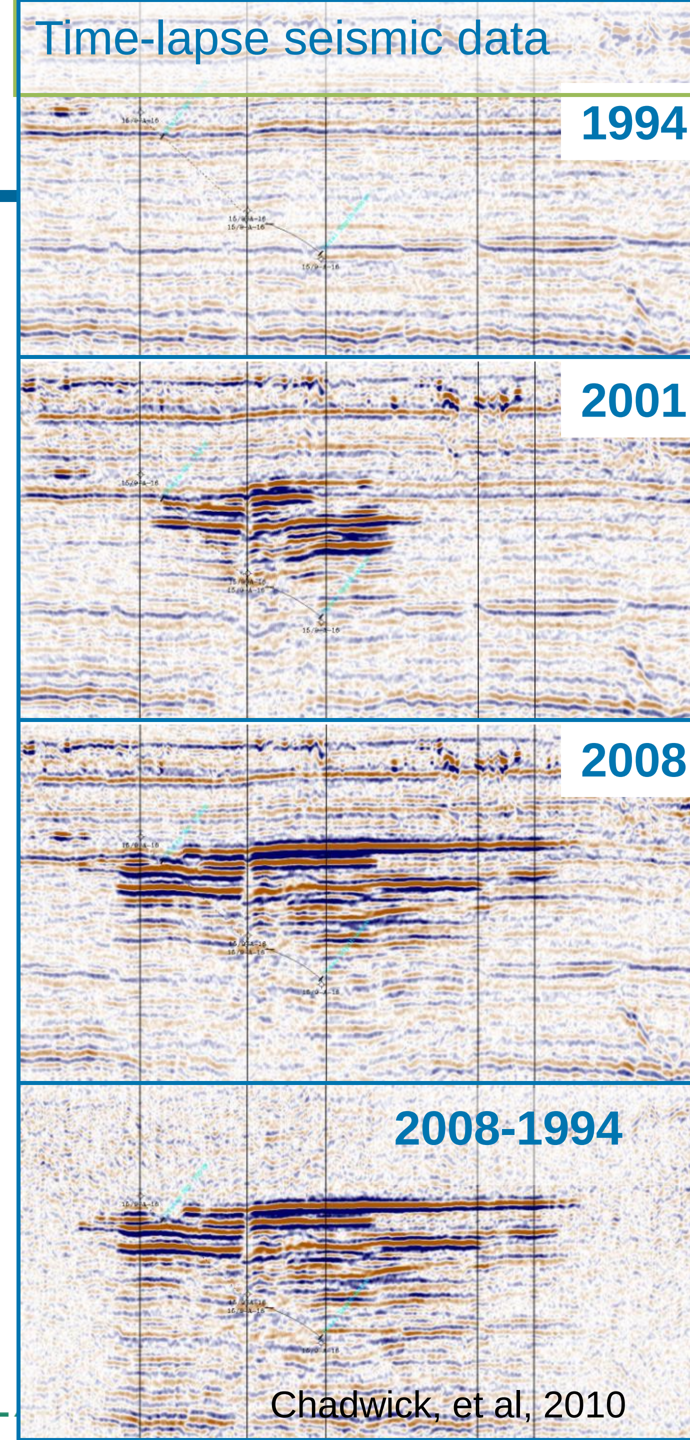
Harris, et al, 1995

1996-?: Sleipner CO_2 Injection: Seismic Monitoring Success – No Mon. Well (Courtesy of Statoil)



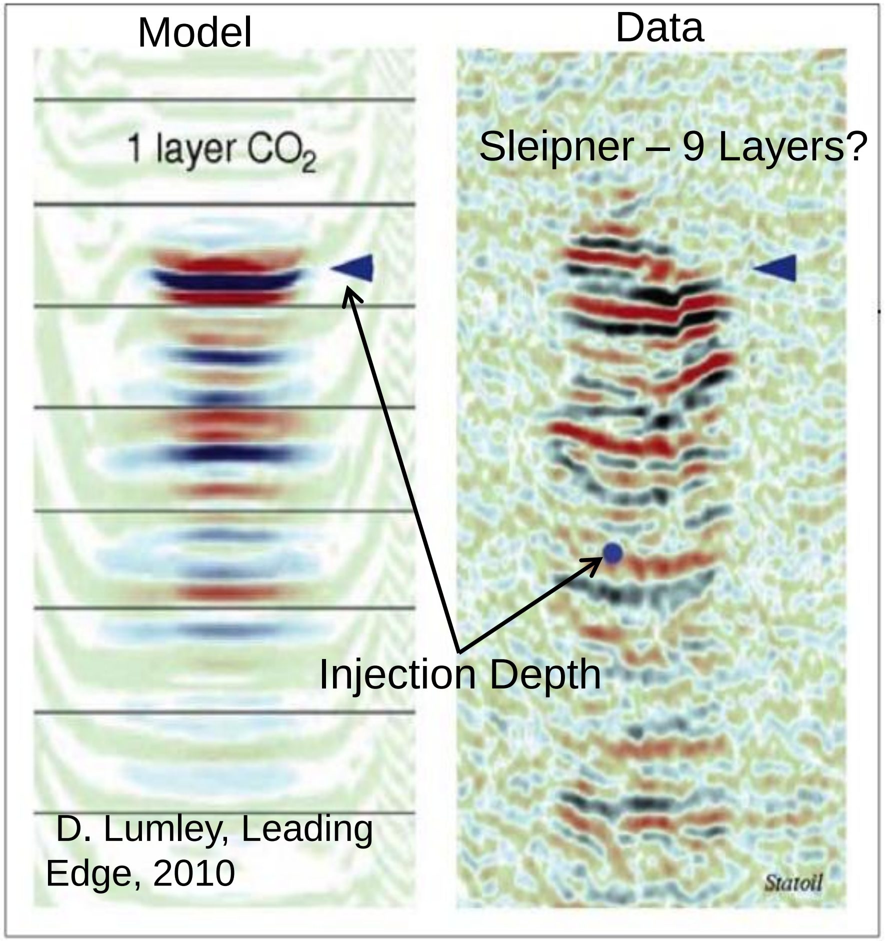
CO_2 plume in map view





Issues with Seismic Imaging:

Quantitative interpretation without other data may be difficult:



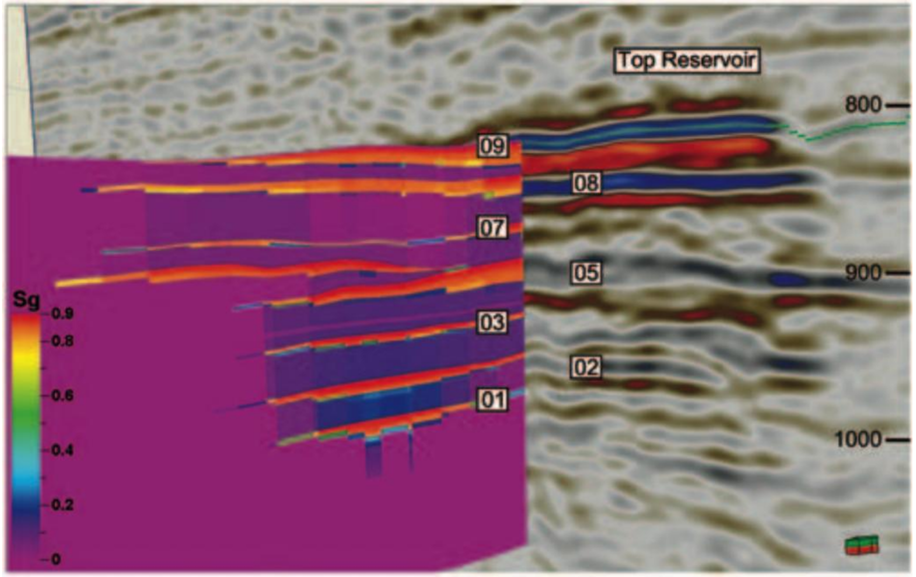
Synthetic PSDM 4D seismic difference

Real PSTM 4D seismic difference

How many layers at Sleipner?

No monitor well to aid interpretation!

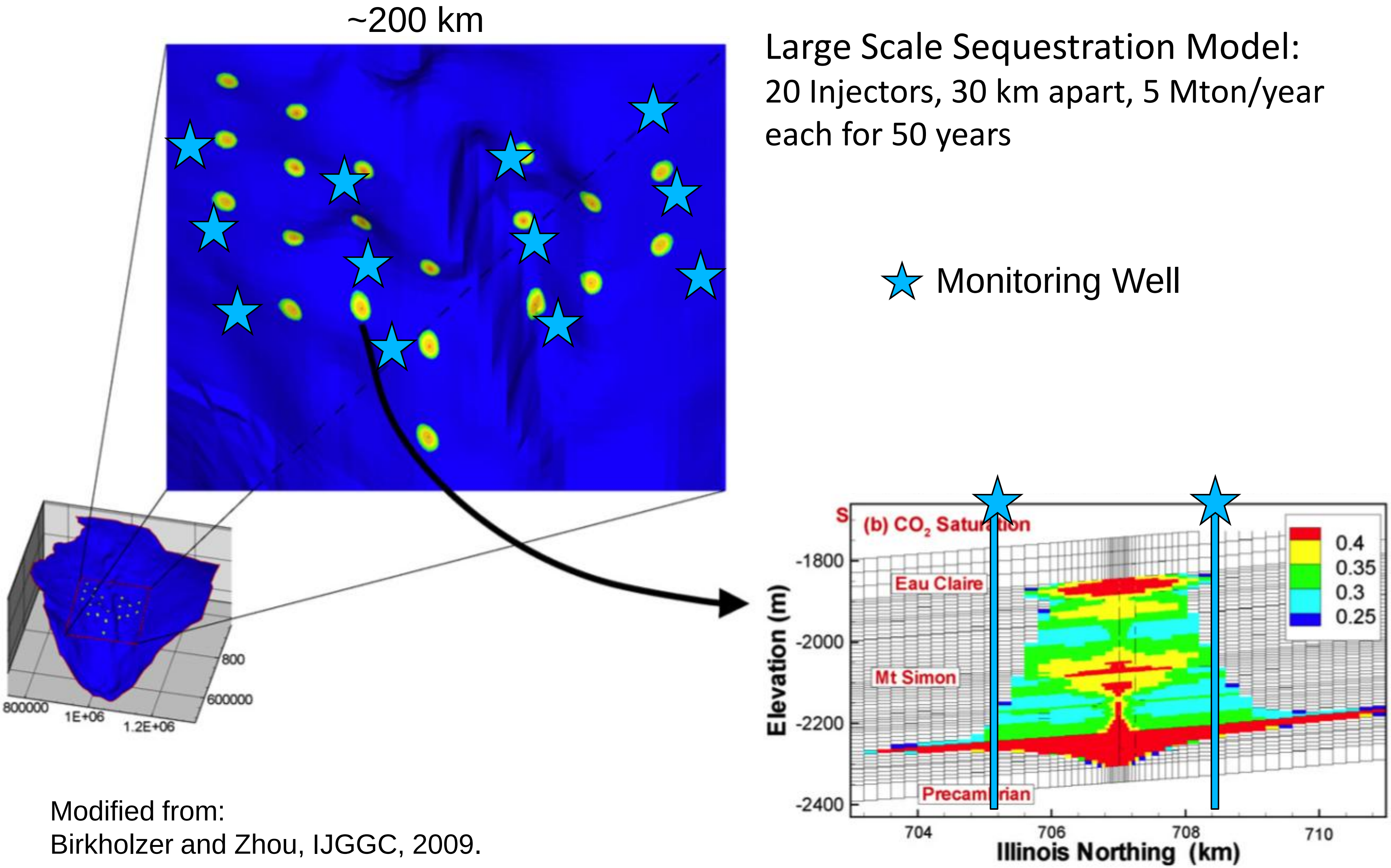
Reservoir Model (Sg) & Seismic Data



Arts and Vandeweijer, Leading Edge, 2011

Large Scale Storage – Multiple Injectors

Need to Optimize Utilization and Location of Monitoring Wells



Large Scale Sequestration Model:
20 Injectors, 30 km apart, 5 Mton/year each for 50 years

★ Monitoring Well

Modified from:
Birkholzer and Zhou, IJGGC, 2009.

Advances in Borehole Monitoring Methods are Needed for CCS Projects

Motivation: Deep monitoring wells are expensive to drill and complete and have limited space available for instrumentation

- ✓ Monitor CO_2 plume location
- ✓ Reservoir pressure and temperature
- ✓ Fluid sampling
- ✓ Leak detection
- ✓ CO_2 saturations

Goal: Develop a rugged, cost effective, multi-sensor monitoring platform designed for a single-well

- **Distributed fiber optic sensor arrays**
- **Modular Borehole Monitoring (MBM)**

Advanced Borehole Monitoring Tool: Fiber Optic - Distributed Sensor Arrays

- Benefits:
  - Operate in harsh downhole environments
  - long potential life span, high data sampling rates,
  - high spatial resolution, adaptive to changing measurement technologies

Applications include:

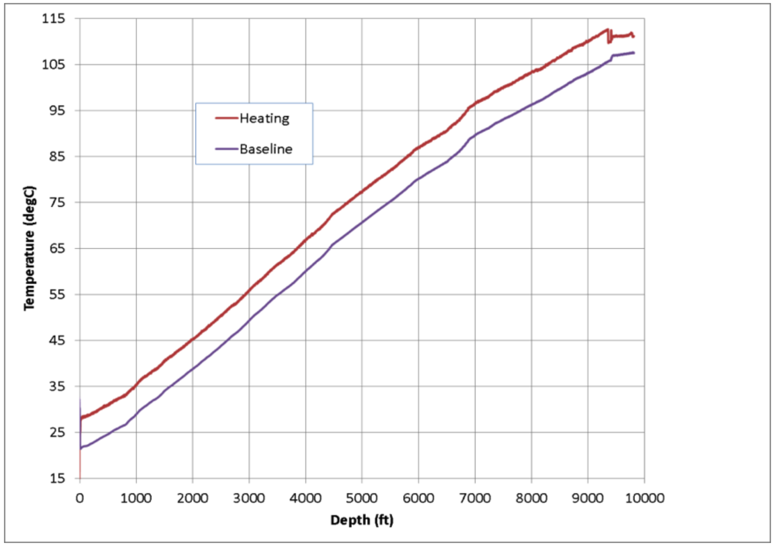
- Distributed temperature sensing (DTS)
- Borehole strain measurements
- Direct chemical detection
- High density seismic arrays (DAS)
  - Leak detection
  - Compliance monitoring
- Heat-pulse monitoring
  - Leak Detection
  - CO_2 distribution behind casing
  - Flow monitoring and allocation

Subsea Fiber optic cable assembly

Citronelle Deployment

Distributed Temperature Sensing (DTS)

- DTS:
  - DTS used for past 20 years
  - Measurement of Raman backscattering, combined with Optical Time-Domain Reflectometry (OTDR), determines temperature along fiber length
- Specifications vary with stacking time and length:
  - ~10 km fiber: spatial resolution 25 cm, temperature resolution 0.01°C
    measurement time 1 s

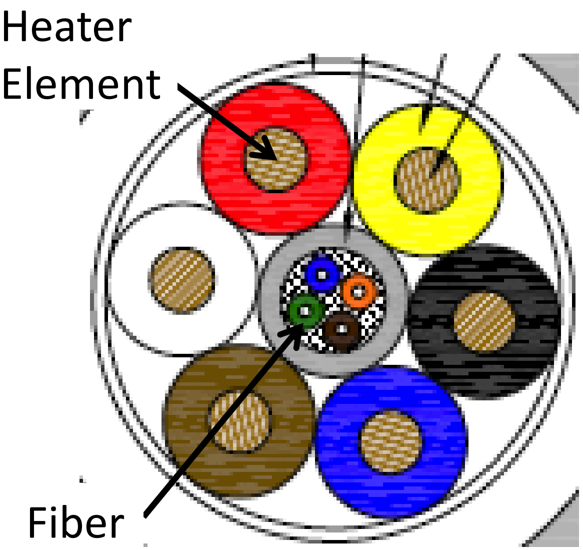


3 km DTS Temperature

DTS Heat-Pulse Monitoring

- Heat Pulse:
  - Copper heater elements (wire) integrated with DTS fiber in the same cable provide distributed pulse of heat
  - time-lapse measurement of temperature during/after heating
- Fluid substitution in well or pore space changes thermal properties detected by heat pulse measurment

Heat-Pulse Cable



Multiple heater elements and fibers are integrated into a 3/8" OD stainless steel control line

Distributed Acousting Sensing (DAS)

- DAS acquisition allows seismic monitoring with fiber optic cable
- DAS has received great interest and development in recent years –
  - from Petroleum Technology (2012) to The Economist (2014)
  - Early adoption for CCS monitoring (2011)

The Economist

Acoustic sensing

The ear underground

How fibre-optic cables can work like microphones

Jan 4th 2014 | From the print edition

Field Trials of Distributed Acoustic Sensing for Geophysical Monitoring

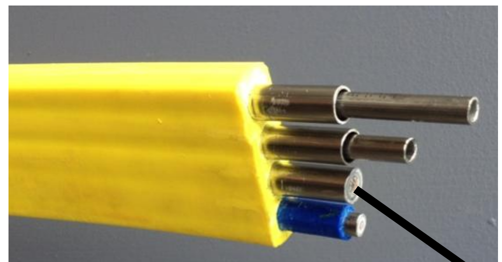
J. Mestayer, B. Cox, P. Wills, D. Kiyashchenko, J. Lopez, M. Costello, Shell International E&P Inc.; S. Bourne, G. Ugueto, R. Lupton, G. Solano, Shell Upstream Americas; D. Hill, A, Lewis, QinetiQ OptaSense®*

© 2011 SEG

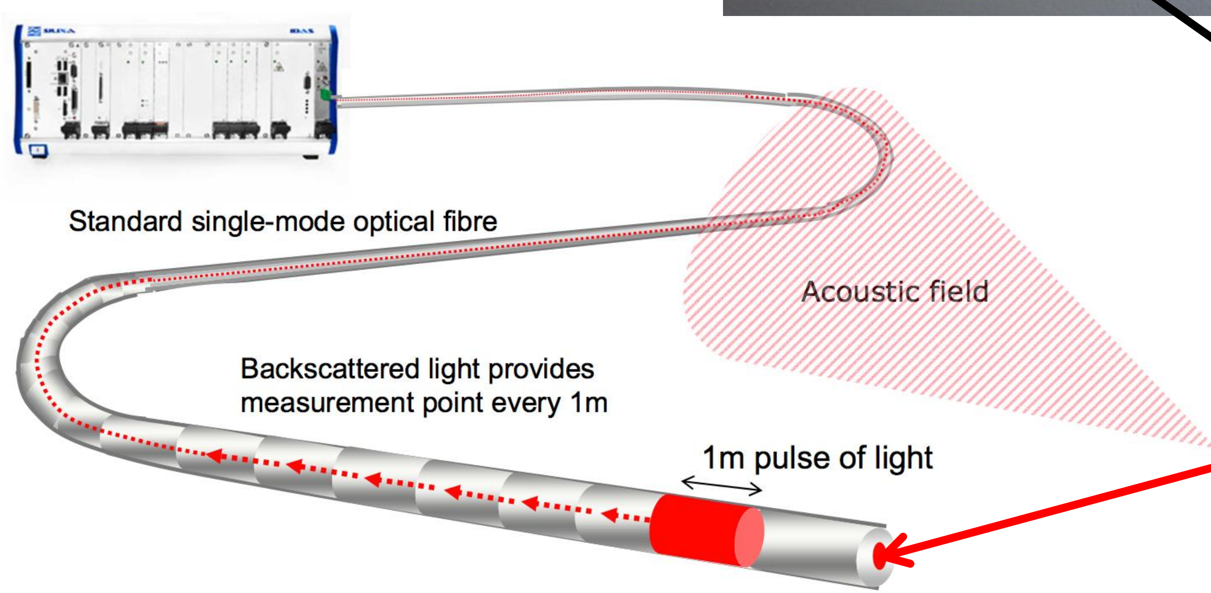
SEG San Antonio 2011 Annual Meeting

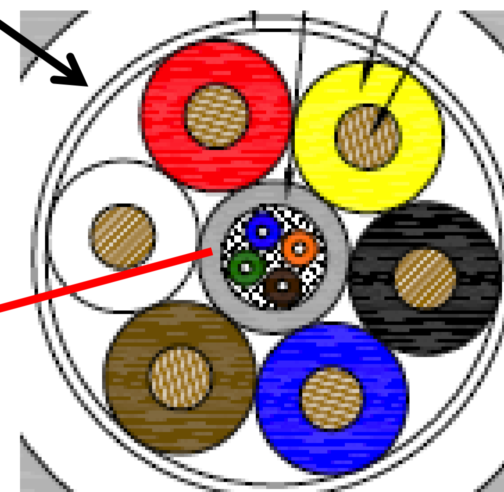
DAS

- DAS acquisition
- Sensitivity currently less than standard geophone, but…
  - Spatial sampling and ease of deployment much greater
- Easy deployment of DAS with other lines



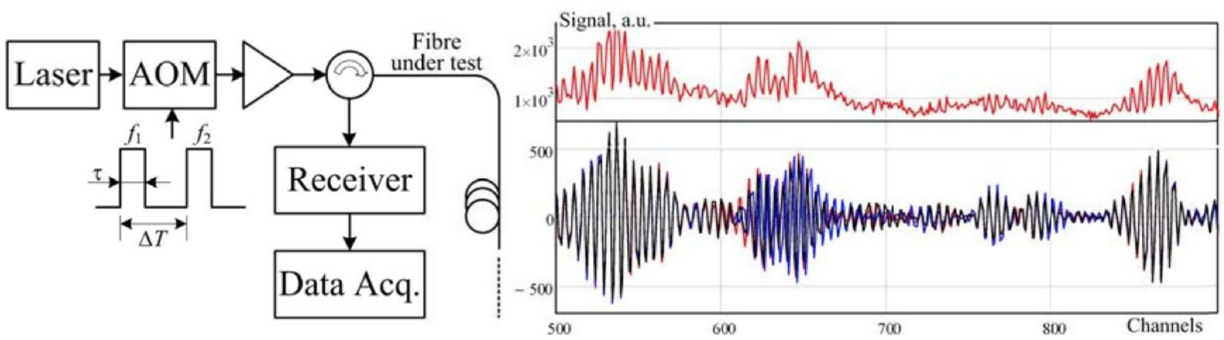
Same cable as DTS Heat-Pulse





DAS Theory

- Light pulse is reflected throughout fiber's length by Rayleigh scattering
- DAS system measures changes of the backscattered light
- An acoustic field around the fiber causes pressure/ strain on the fiber, resulting in changes to the backscattered light
- The DAS measures these changes by generating a repeated light pulse at e.g. 100 µs and continuously processing the returned optical signal
- Up to 10 km in length, up to 10 kHz sample rate, and up to 1 m resolution



Single Pulse

Multiple Filtered Pulses

From Hartog, et al, EAGE, 2013

A 3 km single mode fiber becomes an acoustic array with up 3,000 sensors!

Deployment: Modular Borehole Monitoring

- Motivation: Maximize efficient use of available boreholes for semi-permanent monitoring
- Measurements of Interest
  - Pressure*
  - Temperature
  - Fluid Sampling*
  - Wireline logs
  - Geophysical Monitoring
    - Seismic: active source and passive monitoring
    - Electrical

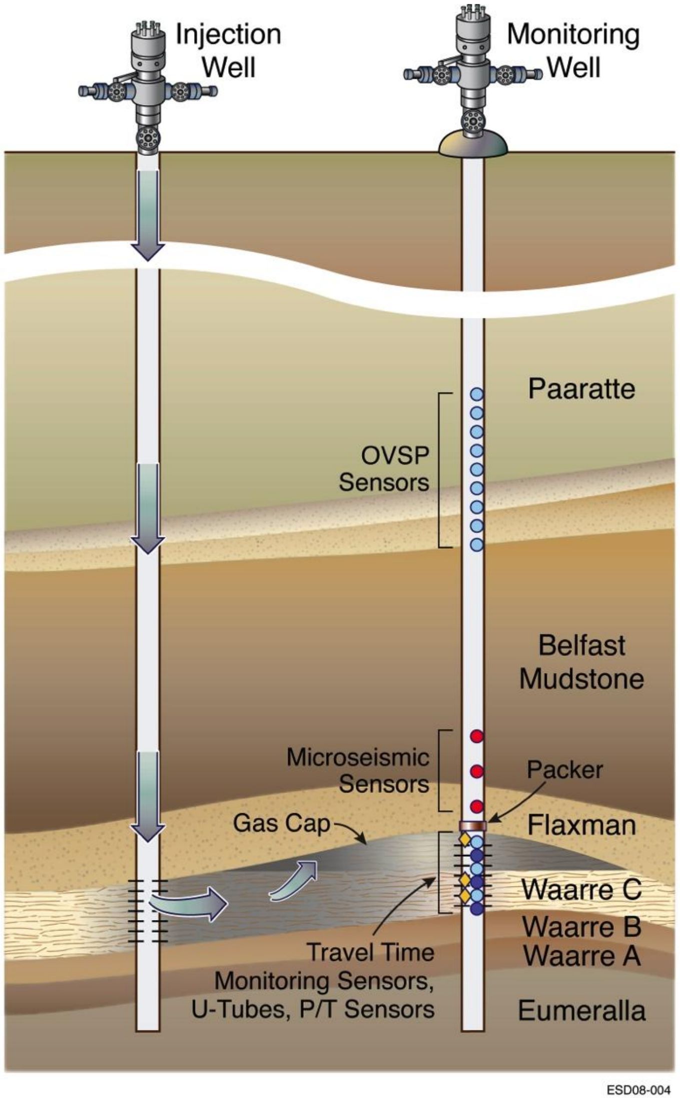
* Requires Packer for zonal isolation

The Previous Way:
6 Separate Lines

Modular Borehole Monitoring (MBM) Conceived at Otway Pilot (Australia) 2007

- Concept: A package of redeployable borehole monitoring instruments
- Example: Otway 2007
  - Dedicated Monitoring well
  - Fluid sampling was main monitoring success (not seismic)

Light blue circle	Geophone with clamp (VSP)
Red circle	3c Geophone with clamp (Microseismic)
Dark blue circle	Hydrophone (seismic)
Yellow diamond	Pressure &Temperature
Yellow diamond	Fluid Sampling: U-tube Inlet



Freifeld and Daley, LBNL & CO2CRC

Otway 2007:
Naylor-1 Monitoring well – 11 Lines

Problem: Deploying many instruments and cables in small well was challenging.

Modular Borehole Monitoring (MBM)

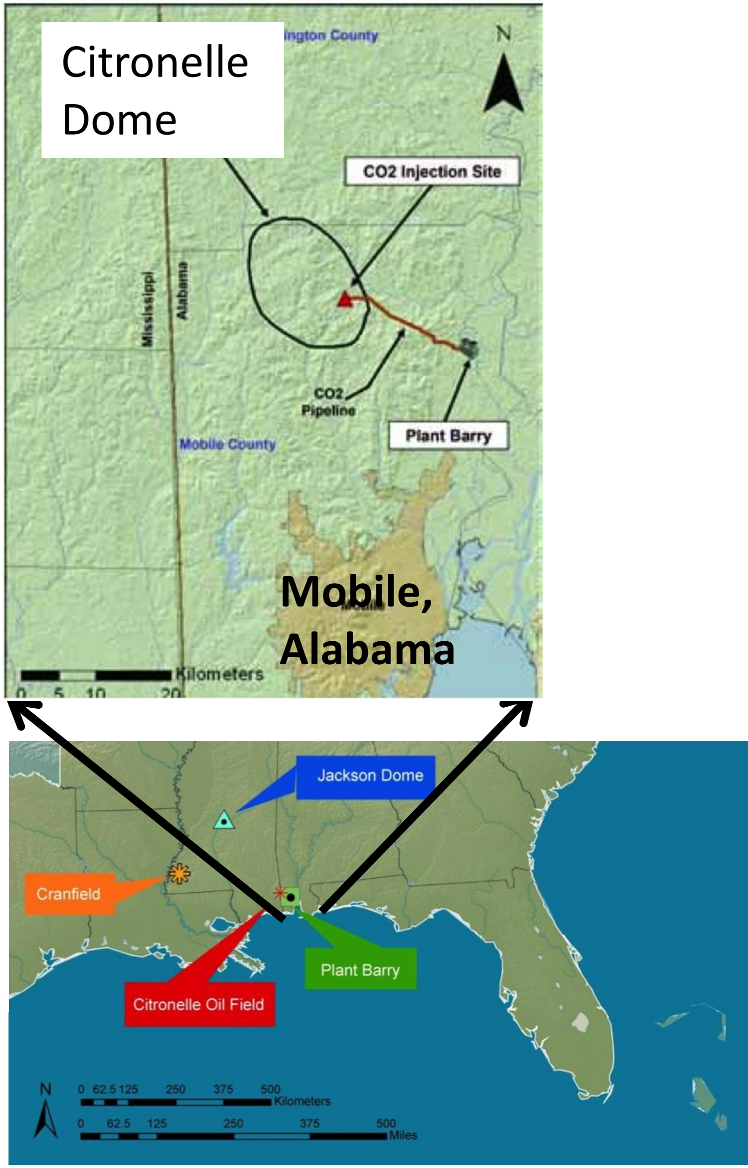
- Tools Deployed with MBM
  - Discrete Pressure & Temperature (2 Quartz Gauges)
  - Distributed Temperature Sensing (DTS) with Heater (Heat-Pulse)
  - Fluid Sampling (U-tube)
  - Seismic monitoring
    - 18 clamping geophones
  - Distributed Acoustic Sensing (DAS)

The MBM Improvement:
Flatpack and Geophone Cable

CO2 Capture Project®

SECARB Anthropogenic Test

- Integrated Capture, Transmission, Storage
  - CO_2 Capture began June 2011
  - Transportation via 19 km pipeline
  - Saline Storage at Citronelle Oil Field began August 2012



SECARB Anthropogenic Test
Citronelle, Alabama

- First integrated CO_2 capture, transportation and storage project on a coal-fired power station using advanced amines
- Southern Co. and MHI have captured over 200,000 metric tonnes of CO_2 to date
- Denbury Resources has transported, injected and stored over 100,000 tonnes
- Injecting CO_2 into the Paluxy Formation, which has excellent storage capacity of regional significance

SECARB
Southeast Regional Carbon Sequestration Partnership

Citronelle Storage

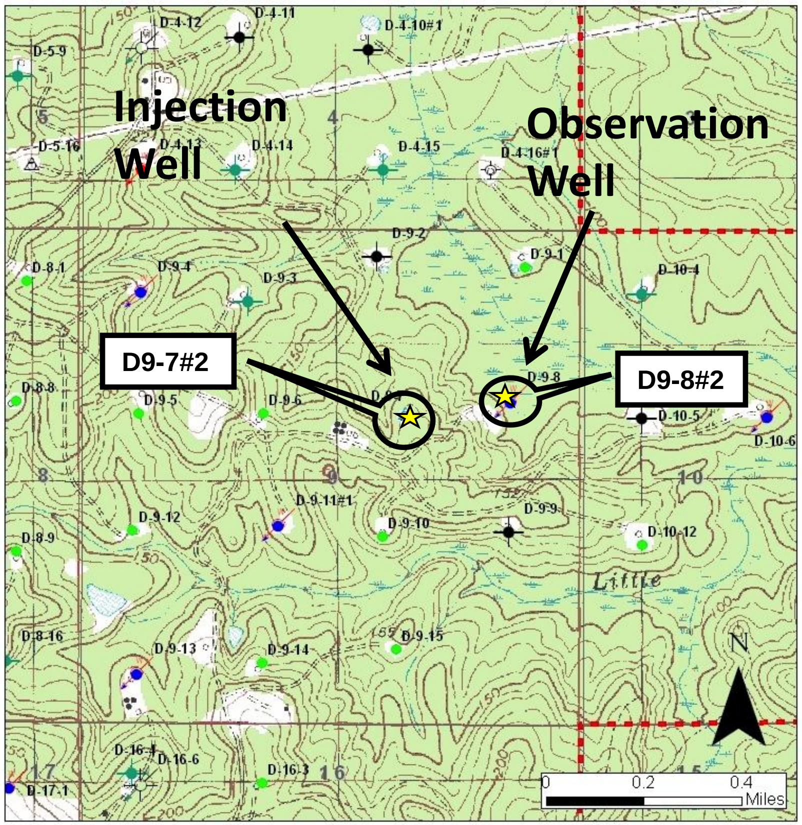
Elements of the MVA Program

- **Shallow MVA**
  - Groundwater sampling (USDW Monitoring)
  - Soil Flux
  - PFT Surveys
- **Deep MVA**
  - Reservoir Fluid sampling
  - Crosswell Seismic
  - Mechanical Integrity Test (MIT)
  - CO_2 Volume, Pressure, and Composition analysis
  - Injection, Temperature, and Spinner logs
  - Pulse Neutron Capture logs
  - Vertical Seismic Profile
- **MVA Experimental tools**

Courtesy of ARI

Advanced Resources International, Inc.

R&D Effort Focused on the MBM System in Observation Well



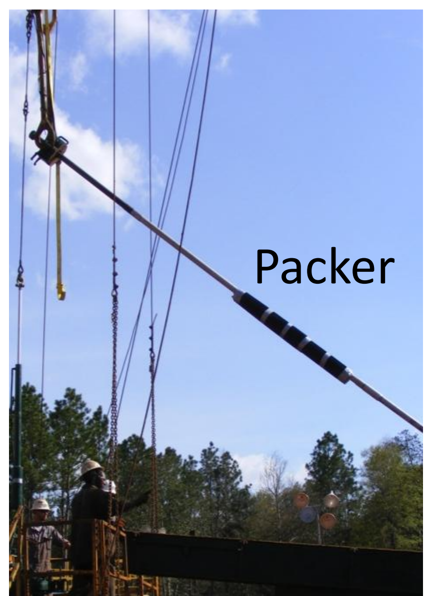
CO_2 injection well D9-7#2 and observation well D9-8#2

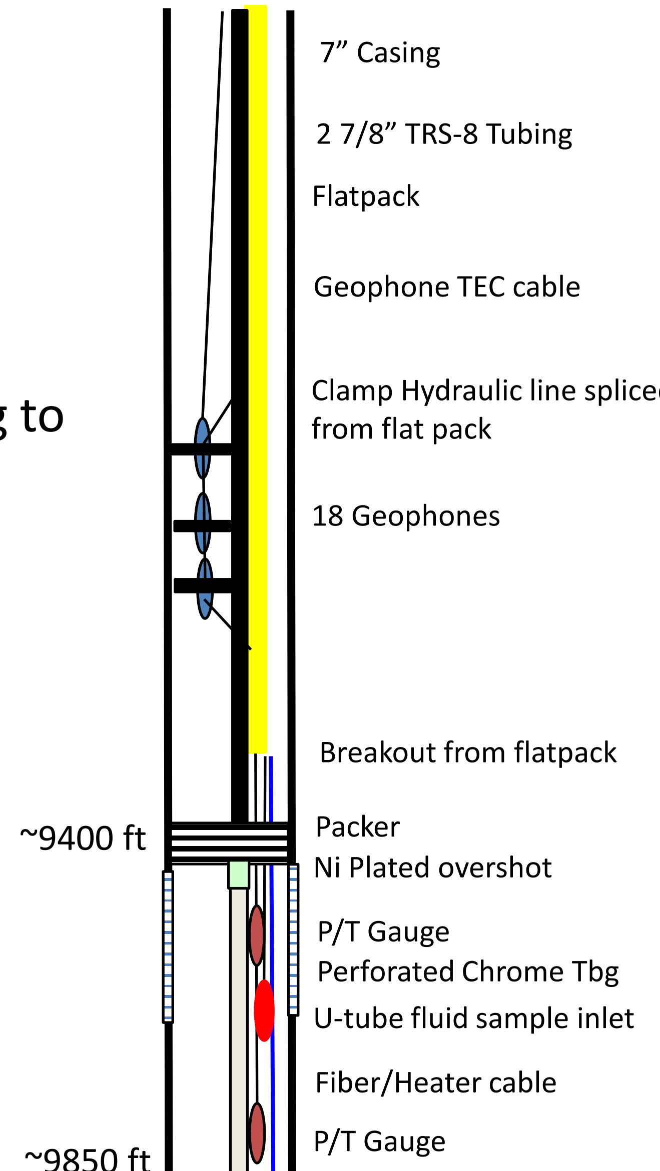
- Observation well (D9-8#2):
  - ~250 m east of the CO_2 injection well
  - Perforated at a depth of ~2.8 km in Paluxy Formation

Deployment of MBM

- Tubing Deployed (allows wireline access)
- 4-element flatpack and sealed geophone cable
- 18-level Geophone array
  - Hydraulic clamps for Geophones
  - Clamp in tubing/casing annulus
- Dual mandrel hydraulic packer
  - Non-rotating overshot connection for coupling to 450’ bottom assembly
    - Avoids splices at packer

Geophone in clamp with flatpack





MBM System Sensor Configuration

- **Fiber optic cable for distributed temperature and acoustic measurements**
  - **Heat-pulse monitoring for CO_2 leak detection**
- Tubing deployed geophone array (6,000-6,850 ft)
- Two in-zone quartz pressure/ temperature gauges (~9400 - 9500 ft)
- U-tube for high frequency, in-zone fluid sampling (tube-in-tube design)
- 2 7/8" production tubing open for logging

Geophone pod and clamping assembly and yellow flat pack containing fiber cable

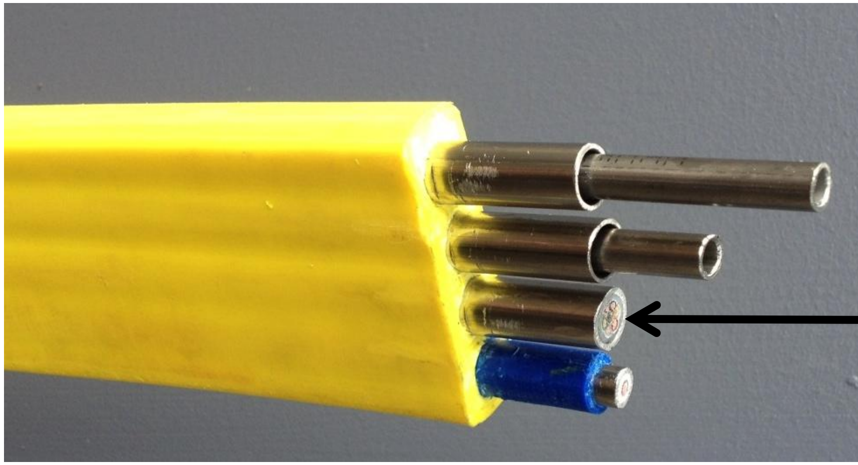
CO2 Capture Project

SECARB Southeast Regional Carbon Sequestration Partnership

CO₂ Capture Project

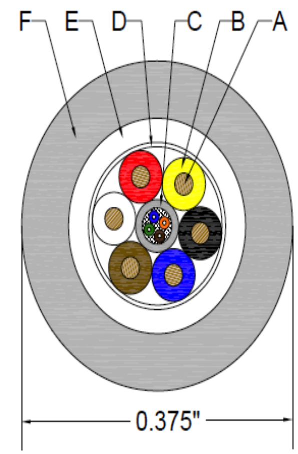
MBM Design: Flat-Pack and Geophone

Flatpack replaces 7 lines



DTS, Heater, DAS
Hybrid 6-copper, 4-fiber-optic cable

SIX 20 AWG CONDUCTORS & FOUR FIBER FIMT STAINLESS STEEL TUBE



Components

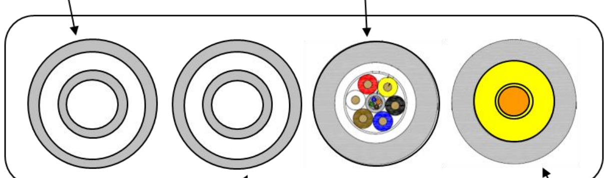
A: 6 x 20 AWG 7/28 Tin Coated Copper; O.D.: 0.96 mm (0.037") Nominal

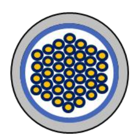
B: Colored T-01 (FEP); O.D.: 1.73 mm (0.068") Nominal;

Geophone clamp hydraulic line

Hybrid copper fiber-optic cable

Geophone TEC





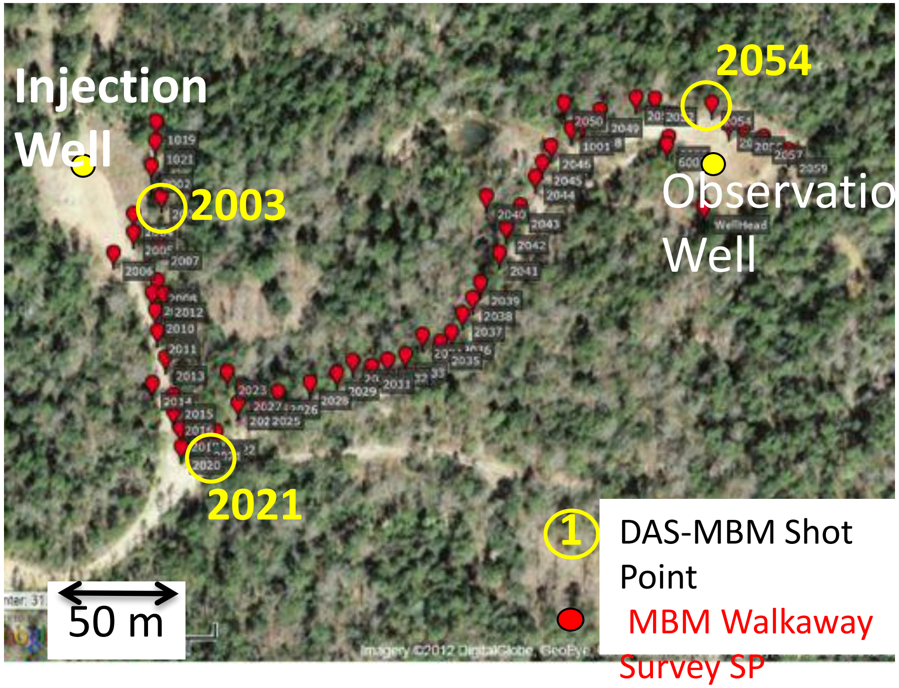
Welded Geophone Line

Tube-in-tube U-tube sampler

Coax P/T monitoring cable

Citronelle DAS VSP (Vertical Seismic Profile):

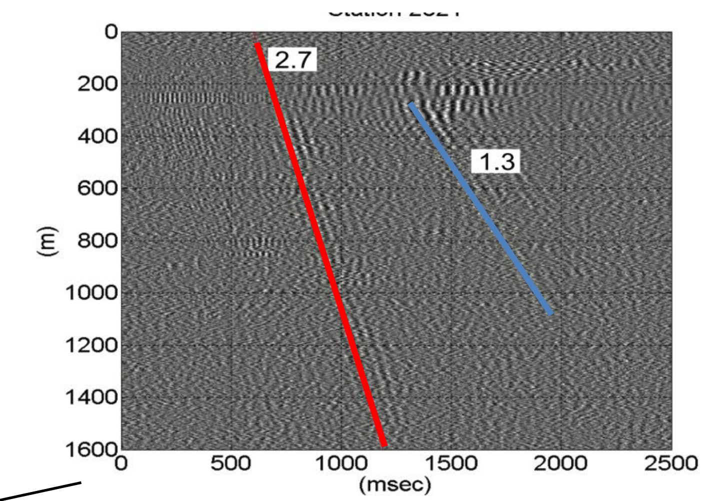
- June 2012 and August 2013
- Citronelle Offers an Opportunity to Compare Seismic Methods to Monitor CO_2
- Seismic monitorling at Citronelle:
  - Cross-well seismic surveys
  - Geophone VSP surveys using
    - 80-160 level 3C arrays in the injector and D9-8#2
    - 18 geophone MBM array
  - DAS and MBM Geophone:
    - Source: vibroseis truck
    - ~60 shot points
    - 4–64 sweeps per location
    - Sweep: 16 s, 10–160 Hz



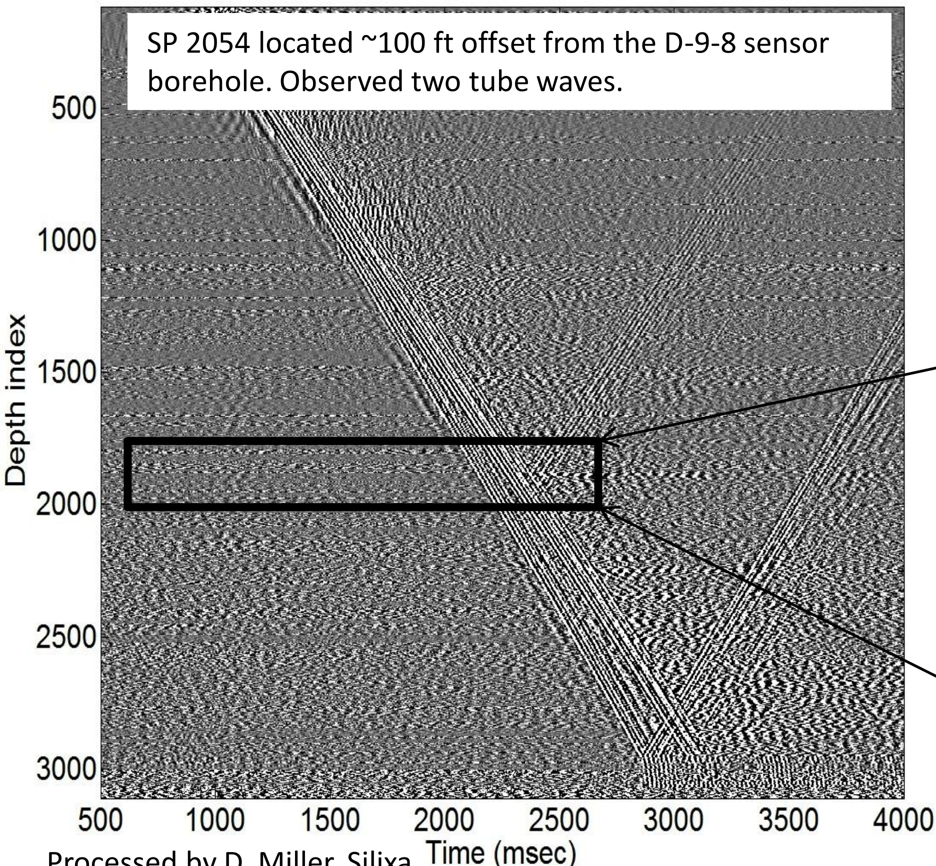
2012 DAS Testing
3 km, Tubing Deployed

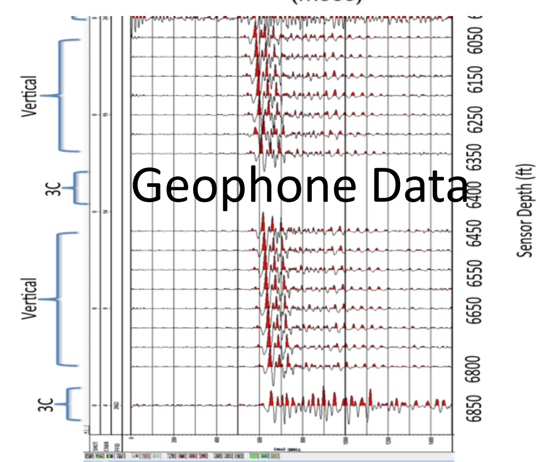
- DAS VSP ‘piggy-back’ on standard acquisition
- Initial data quality insufficient to observe P-wave below ~1600 m, triggering needed improvement
- Benefit: 3000 sensors versus 18

SP 2021 located ~700 ft offset from the D-9-8 sensor borehole. Estimated wave speeds for two events (red and blue lines) are labeled in km/s.



SP 2054 located ~100 ft offset from the D-9-8 sensor borehole. Observed two tube waves.



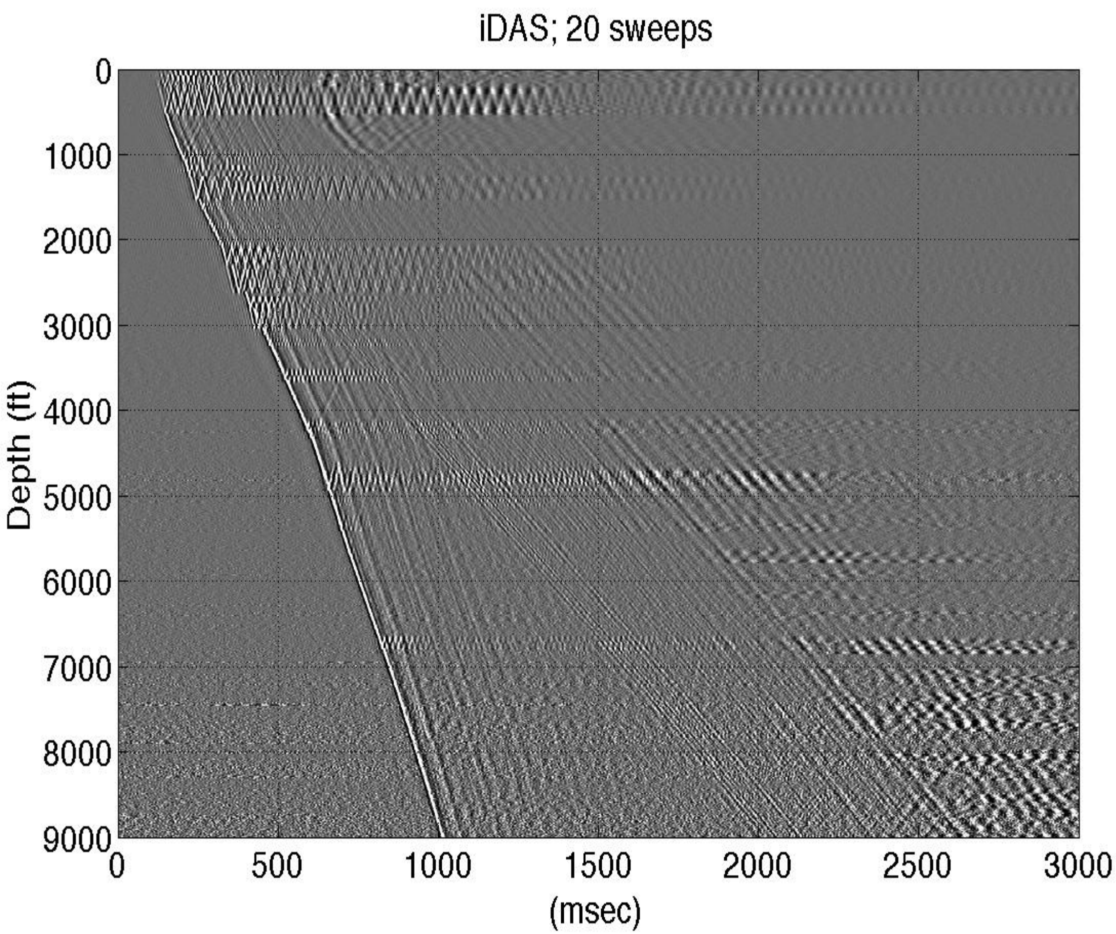


From Daley, et al, Leading Edge, 2013

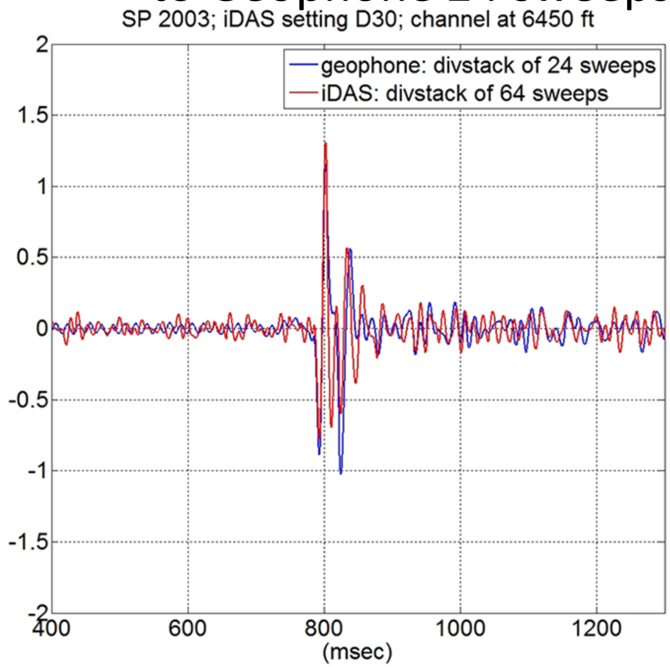
Processed by D. Miller, Silixa

2013 DAS Testingvs MBM Geophone Comparison

Improvement: Acquisition of more source sweeps and improved triggering increased DAS data signal to noise ratio, producing data comparable to more sensitive geophones
Approximately 9 dB difference in sensitivity – can be overcome with extra source effort.



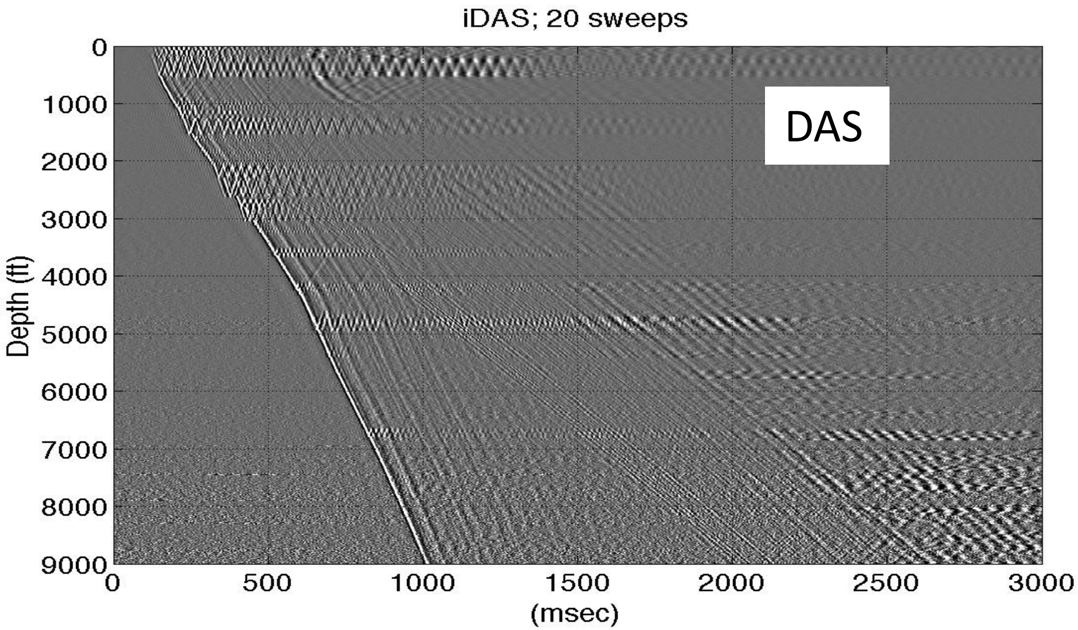
Single Channel Comparison:
DAS 64 sweeps
comparable
to Geophone 24 sweeps

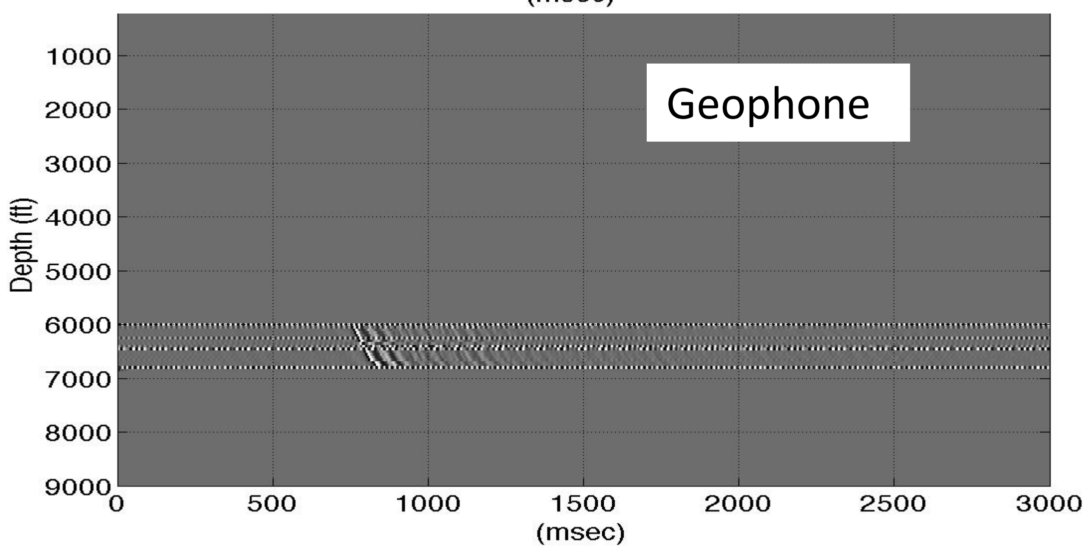


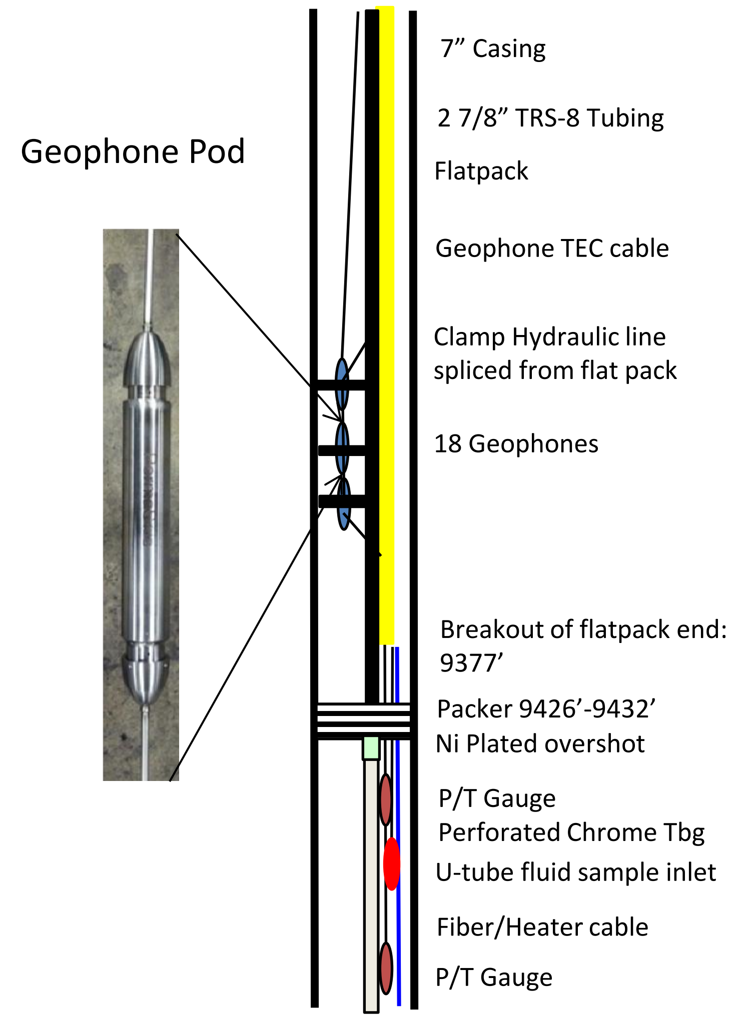
Courtesty D. Miller, Silixa

DAS Advantage in Number of Sensors

- Comparison of data acquired from one source point
  eophones vs 3000 DAS channels







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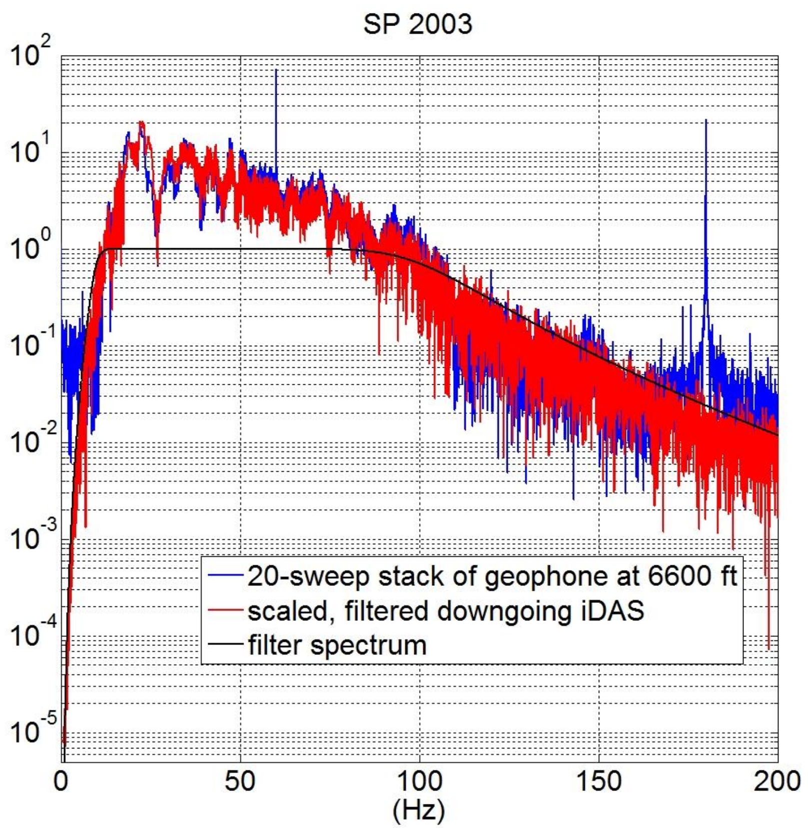
2013 Citronelle DAS vs MBM Geophone Comparison

- Comparison of Spectral Response
  - DAS matches geophone



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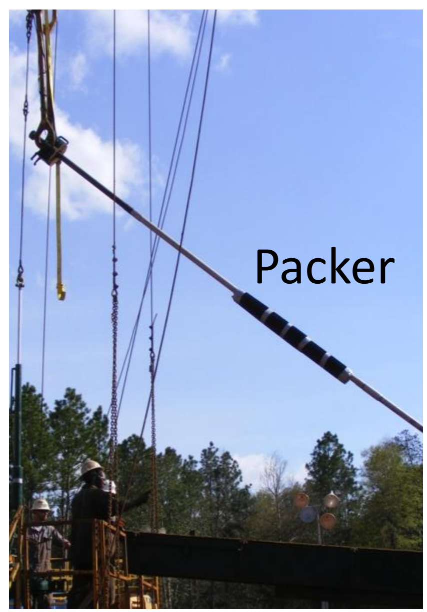
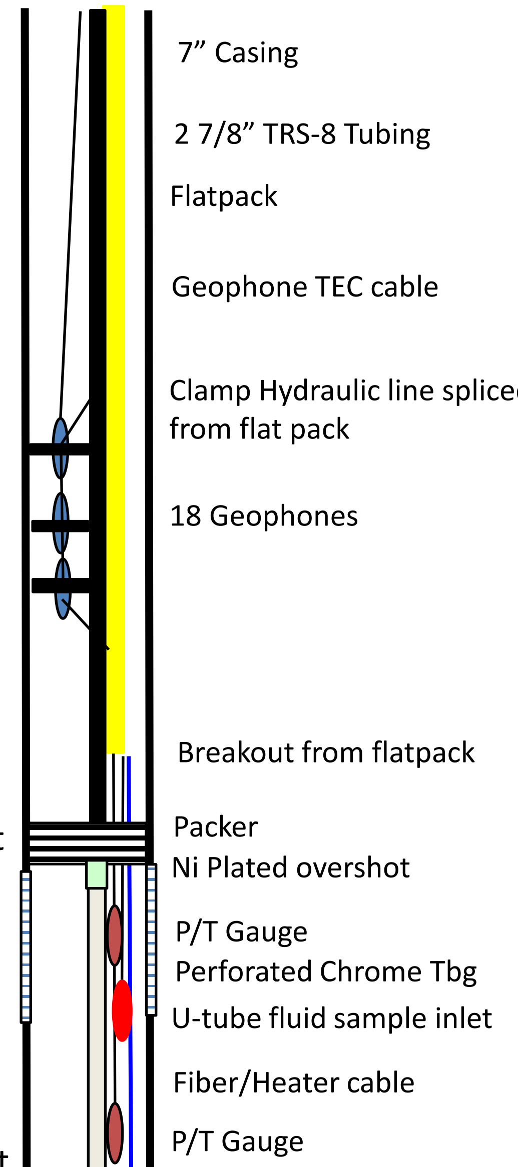
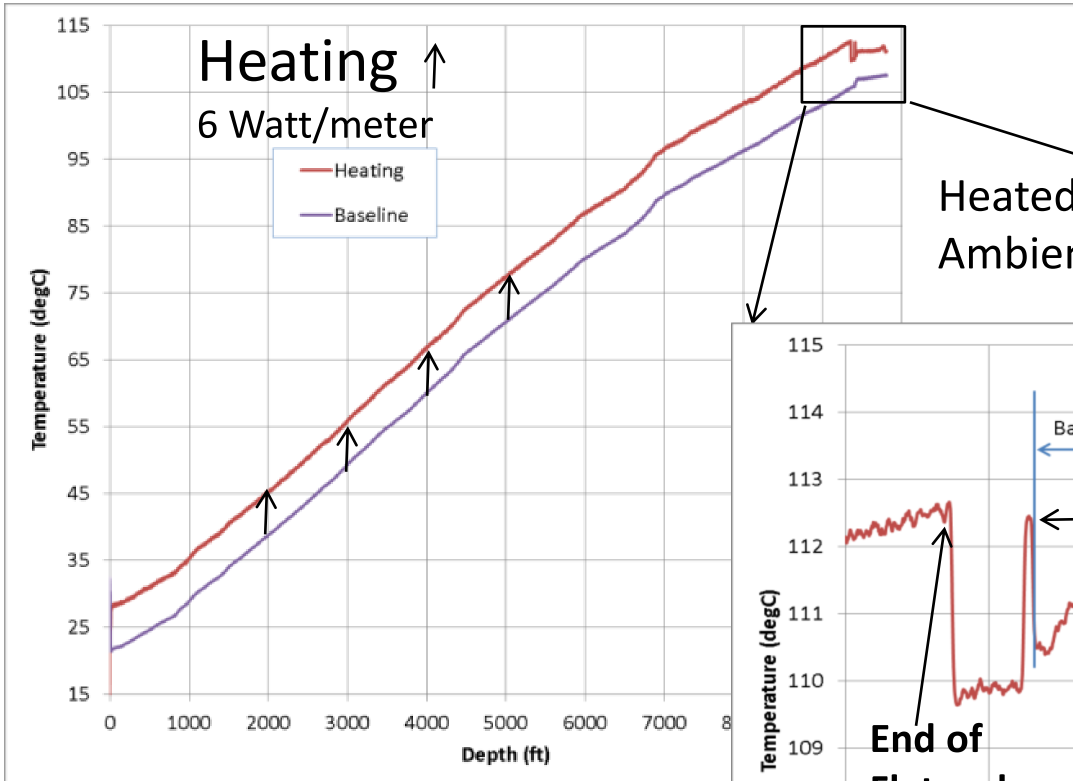
Fiber Optic Temperature at Citronelle

- Heat Pulse with Distributed Temperature Sensing (DTS)



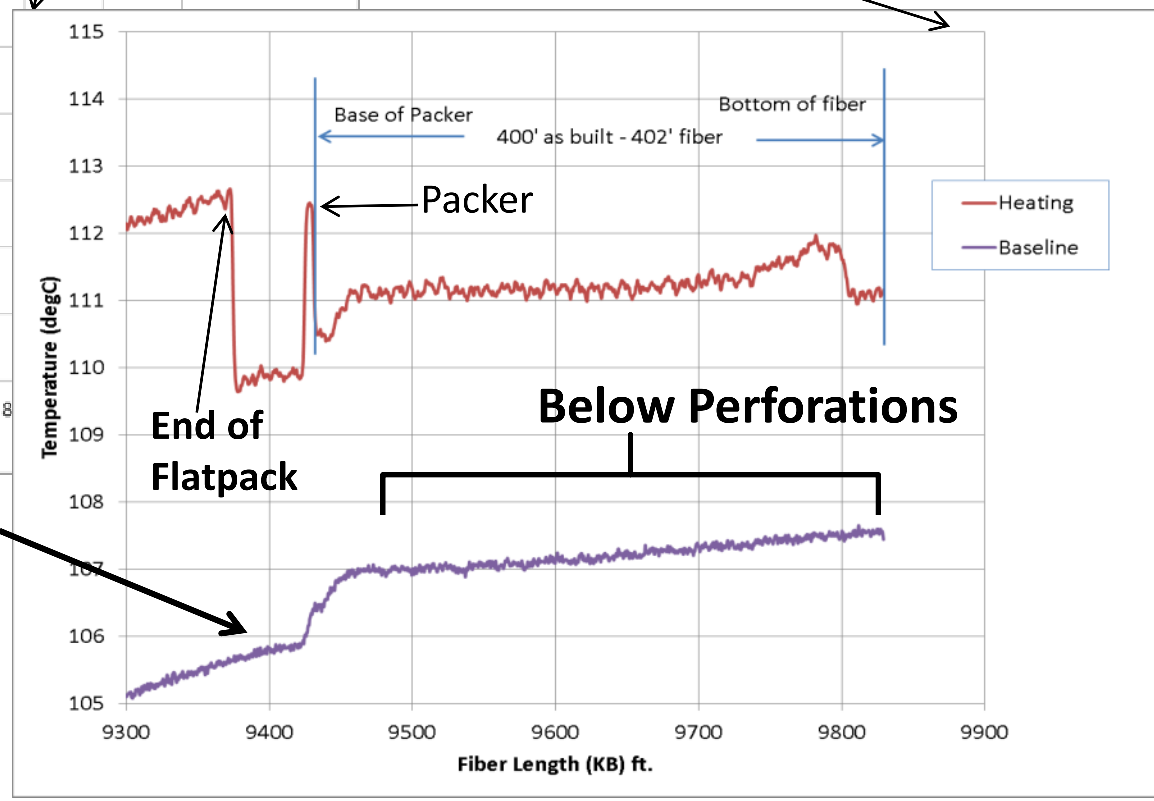


Monitoring with DTS Using Heat Pulse (Static Wellbore Conditions)



- Initial completion of well included use of MBM for diagnostic testing

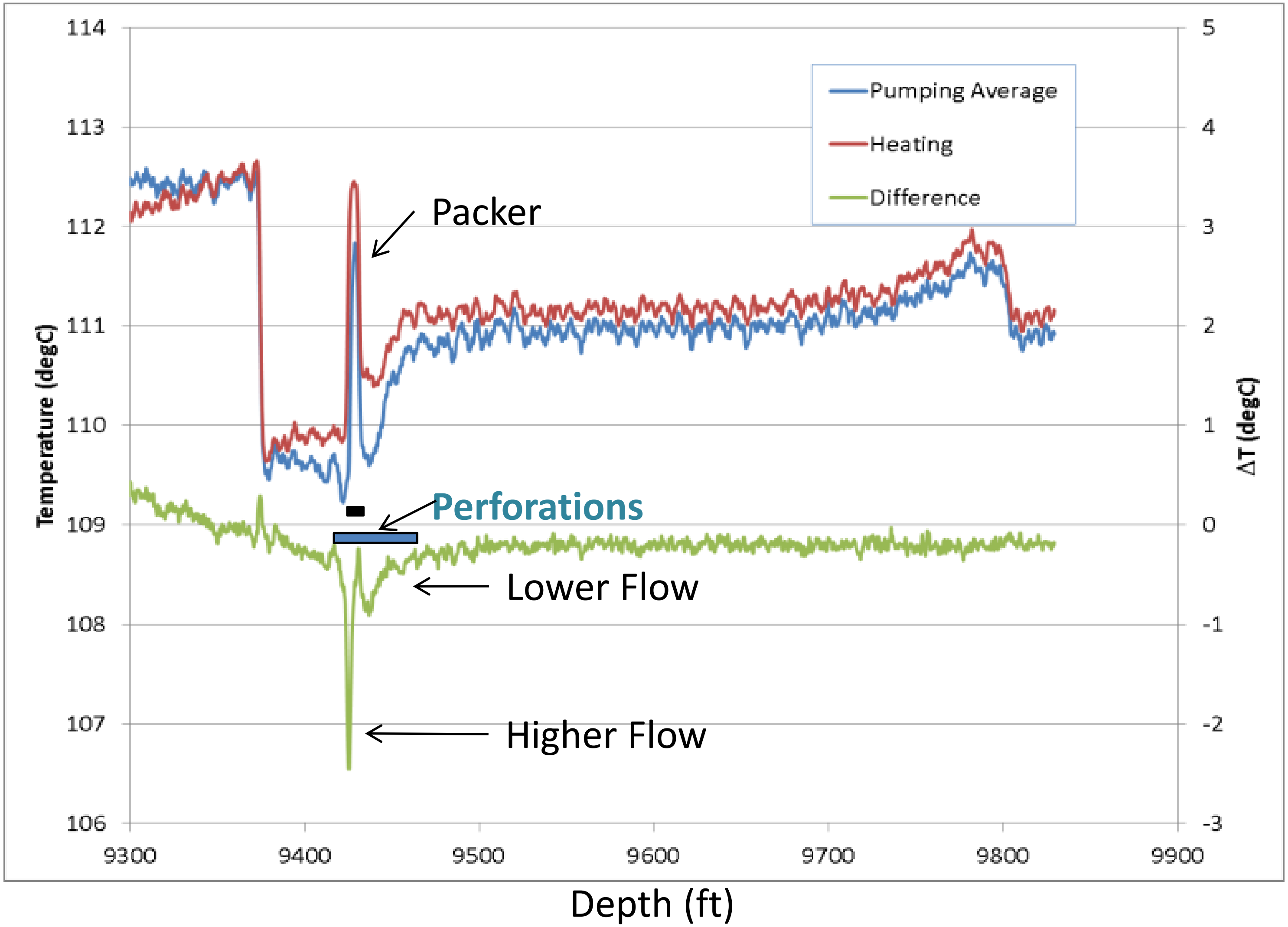
Heated Temperature (Red)
Ambient Temperature (Blue)



Colder Kill Fluid

- **Heat Pulse located perforation w.r.t packer**
- **Information used in regulatory assessment of completion**

Well Diagnostics Using Heat Pulse Monitoring
Flowing Annulus – Thermal Change (Green)



Citronelle Heat-Pulse Diagnostic Test

- Location of the packer is determined ±1 ft.*
- Perforation flow zone interpreted from distinct cooling noted from a 10±1.5 m zone.*
- The thermal profiles indicate flow both above and below the packer
  - strong likelihood that the packer has been set within the perforated interval

* Depth measured from bottom of fiber

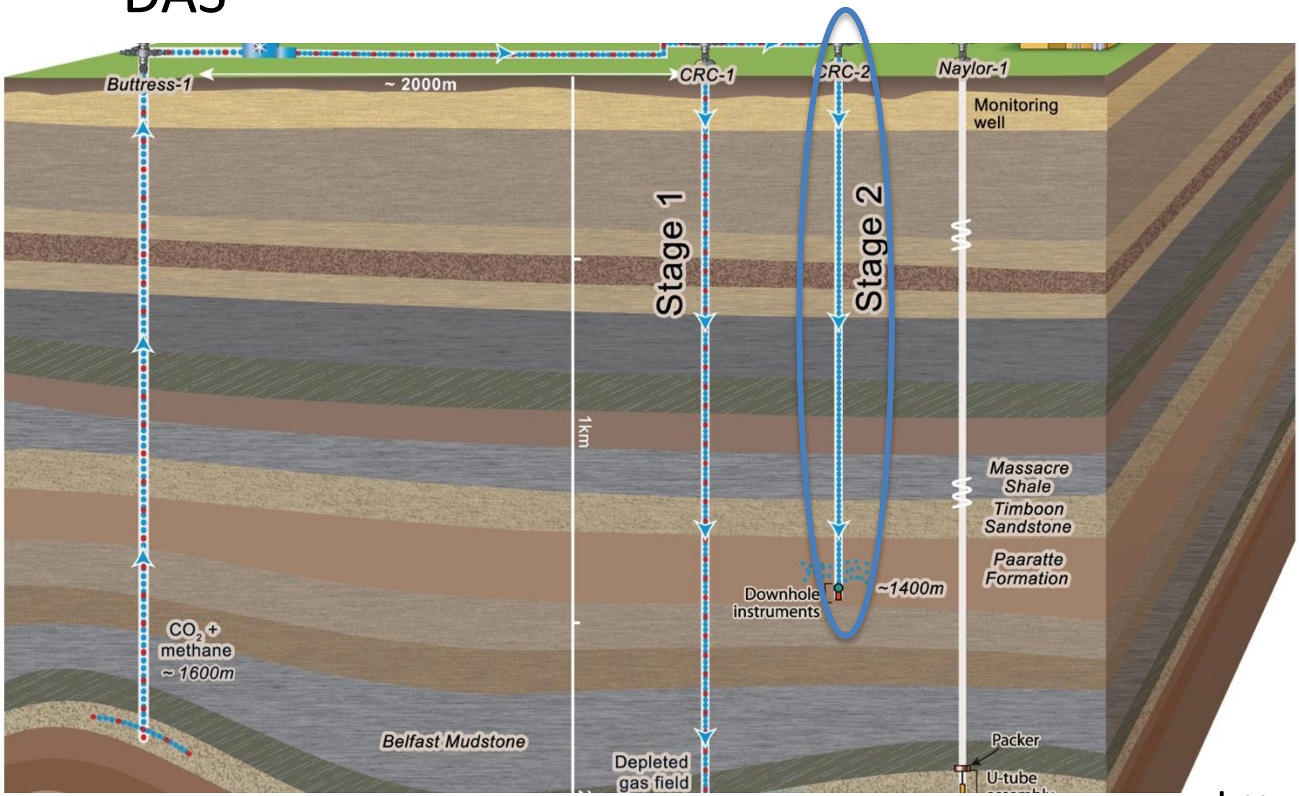
Citronelle/MBM Summary

- SECARB's Anthropogenic Pilot is an operational integrated CCS project
- A modular borehole monitoring (MBM) system was designed, built and deployed for Citronelle
- The MBM system includes:
  - P/T gauges, U-tube fluid sampling, hydraulic clamping geophones,
  - **Fiber optic temperature (with heat pulse) and seismic (DAS)**
- MBM system is operational and was useful in understanding well completion
- Following initial proof-of-concept testing MBM DAS VSP acquisition was improved and is very promising
  - **Sensitivity within ~9 dB of clamped geophones**

DAS Testing at Otway: 2012

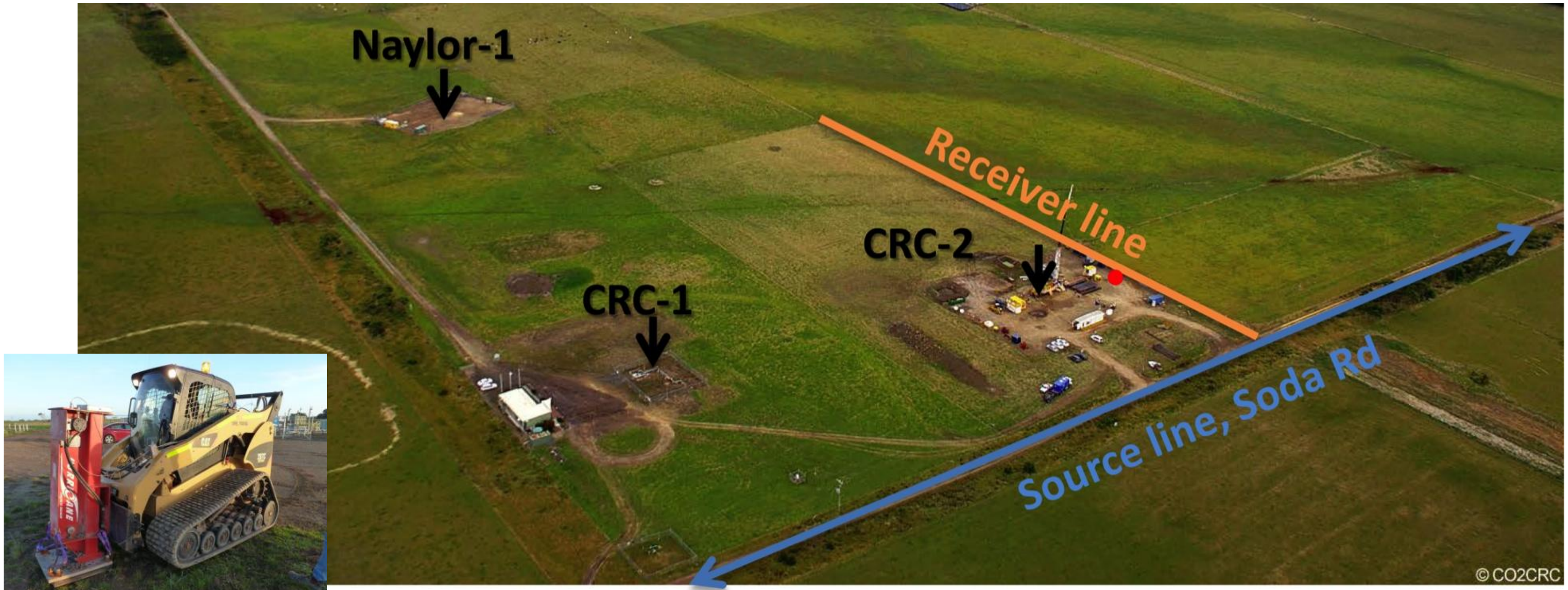
Stage 2: Well CRC-2

- ~1400 m, Tubing Deployed Fiber plus Surface cable
- DTS (with heat pulse)
- DAS

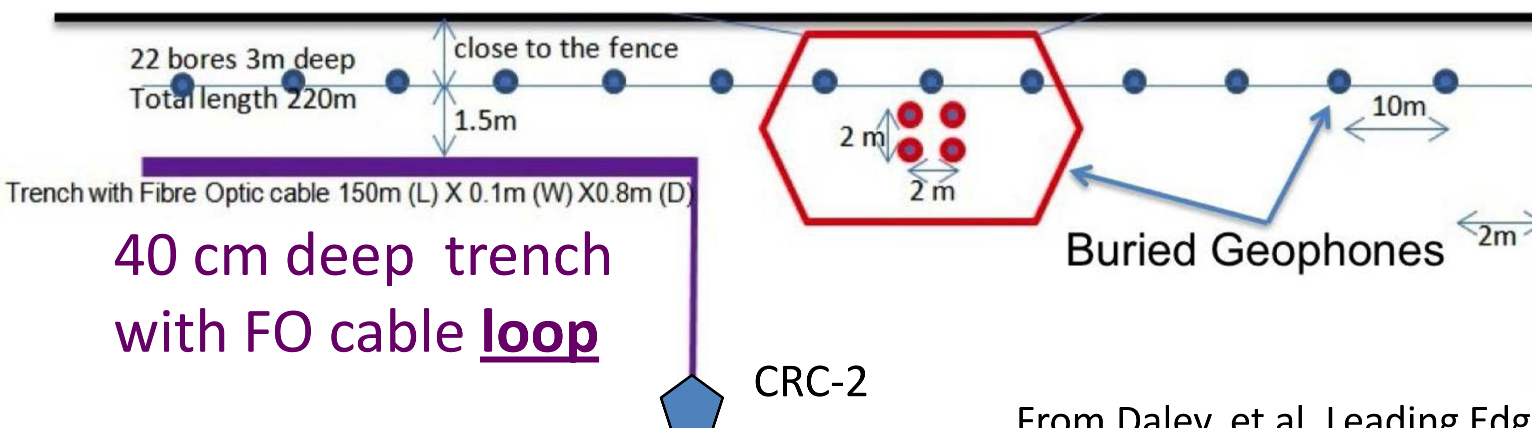


http://www.co2crc.com.au/

Otway DAS included borehole (VSP) and surface cable



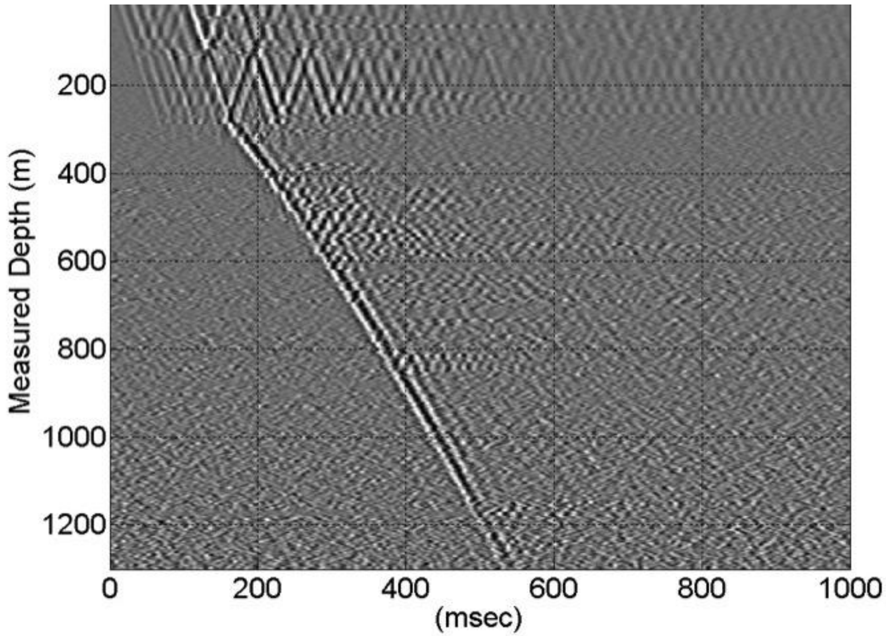
Weight Drop Source



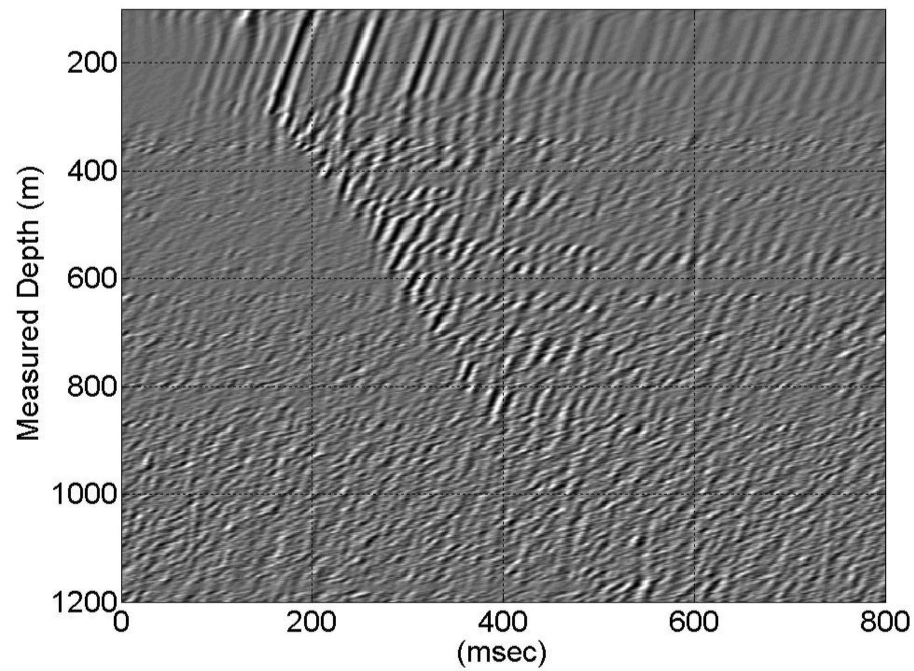
From Daley, et al, Leading Edge, 2013

Otway DAS VSP

Raw Stacked Data



Reflections (upgoing)

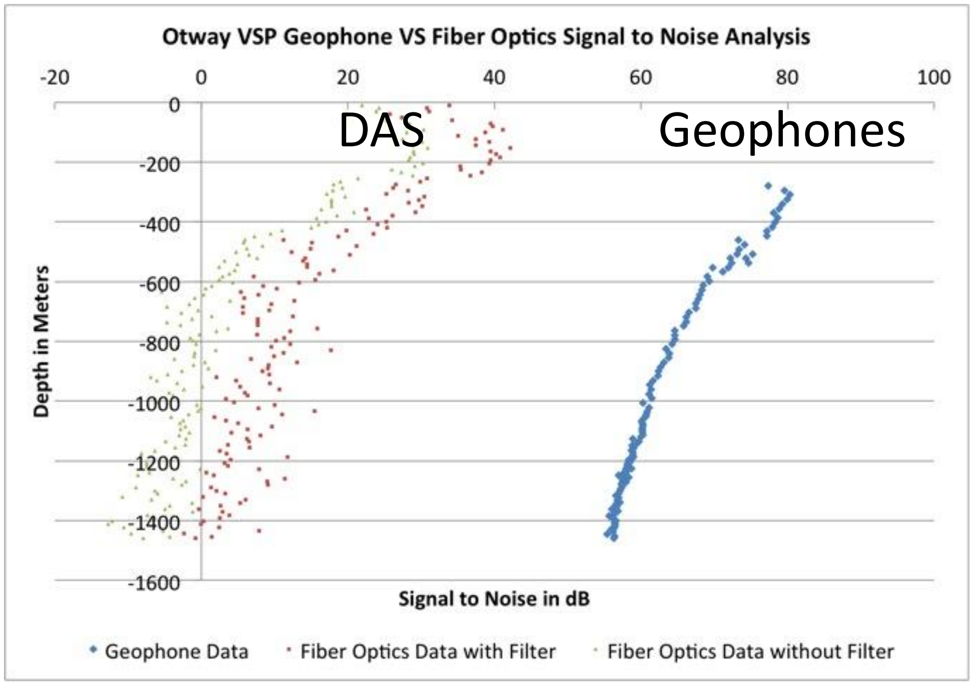


Data Compared to previous wireline geophone VSP

Increase Source Effort (stack 41 vs 5-10)

From Daley, et al, Leading Edge, 2013

Otway Tubing DAS VSP vs Clamped Wireline Geophone Signal/Noise



From Daley, et al, Leading Edge, 2013

How Much Extra Source Effort?

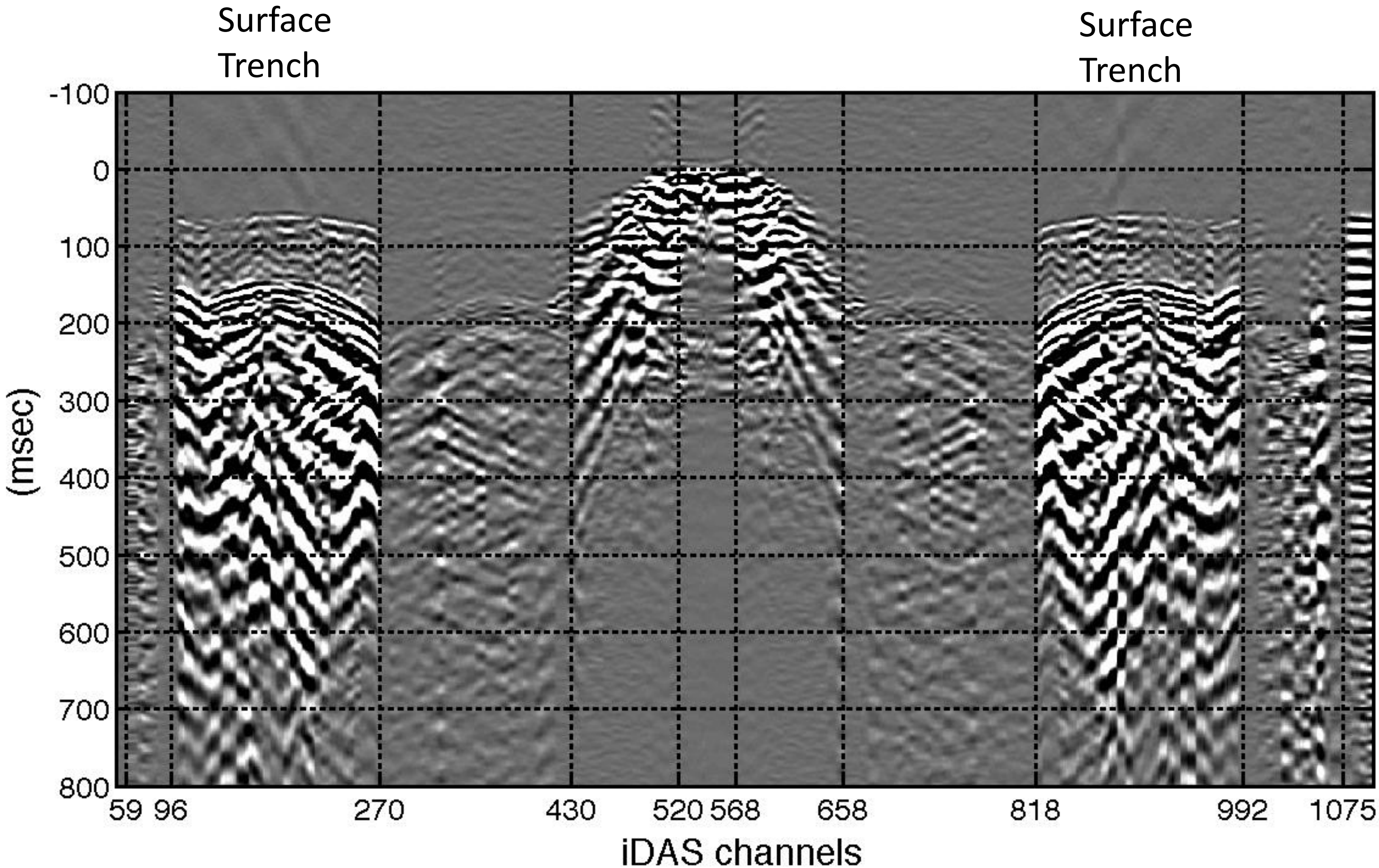
2012 Otway test says 40 dB

2013 testing at Citronelle indicates ~9 dB

Otway is not simultaneous acquisition -> Citronelle better comparison

Note: Stack of 100 = 20 dB

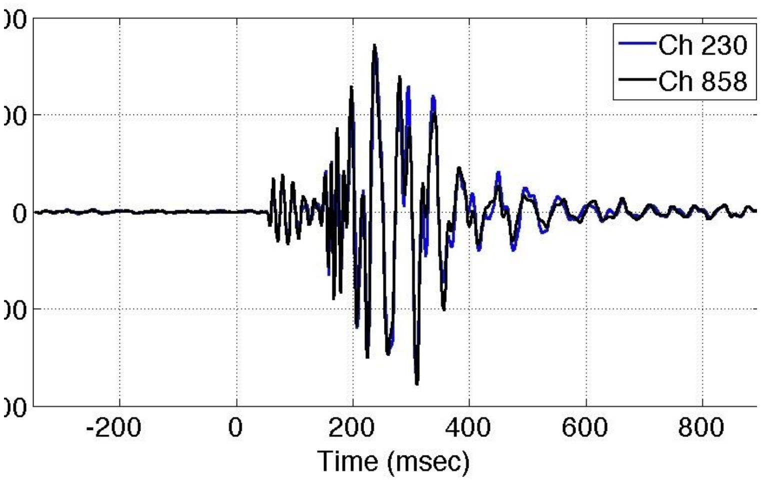
Otway DAS Surface Data
Single Cable: Borehole and Surface



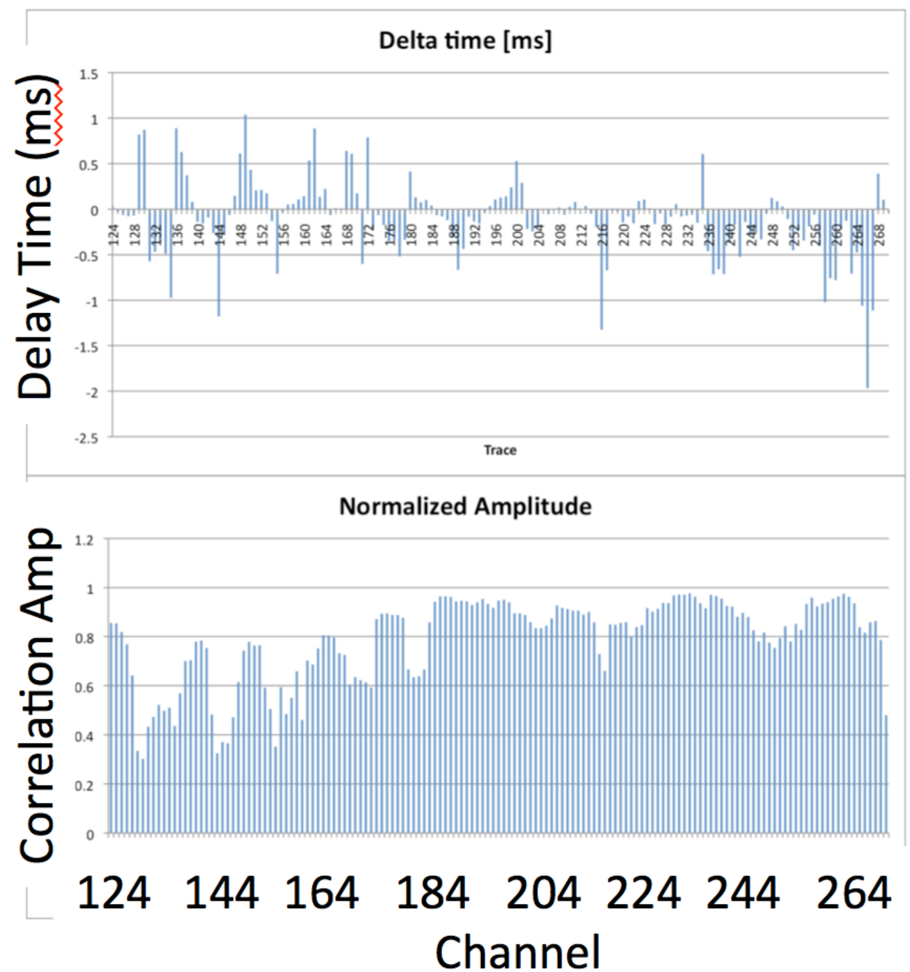
From Daley, et al, Leading Edge, 2013

Parallel Surface Cables (Loop)
Very Similar Response

Two individual channels (1 m segments



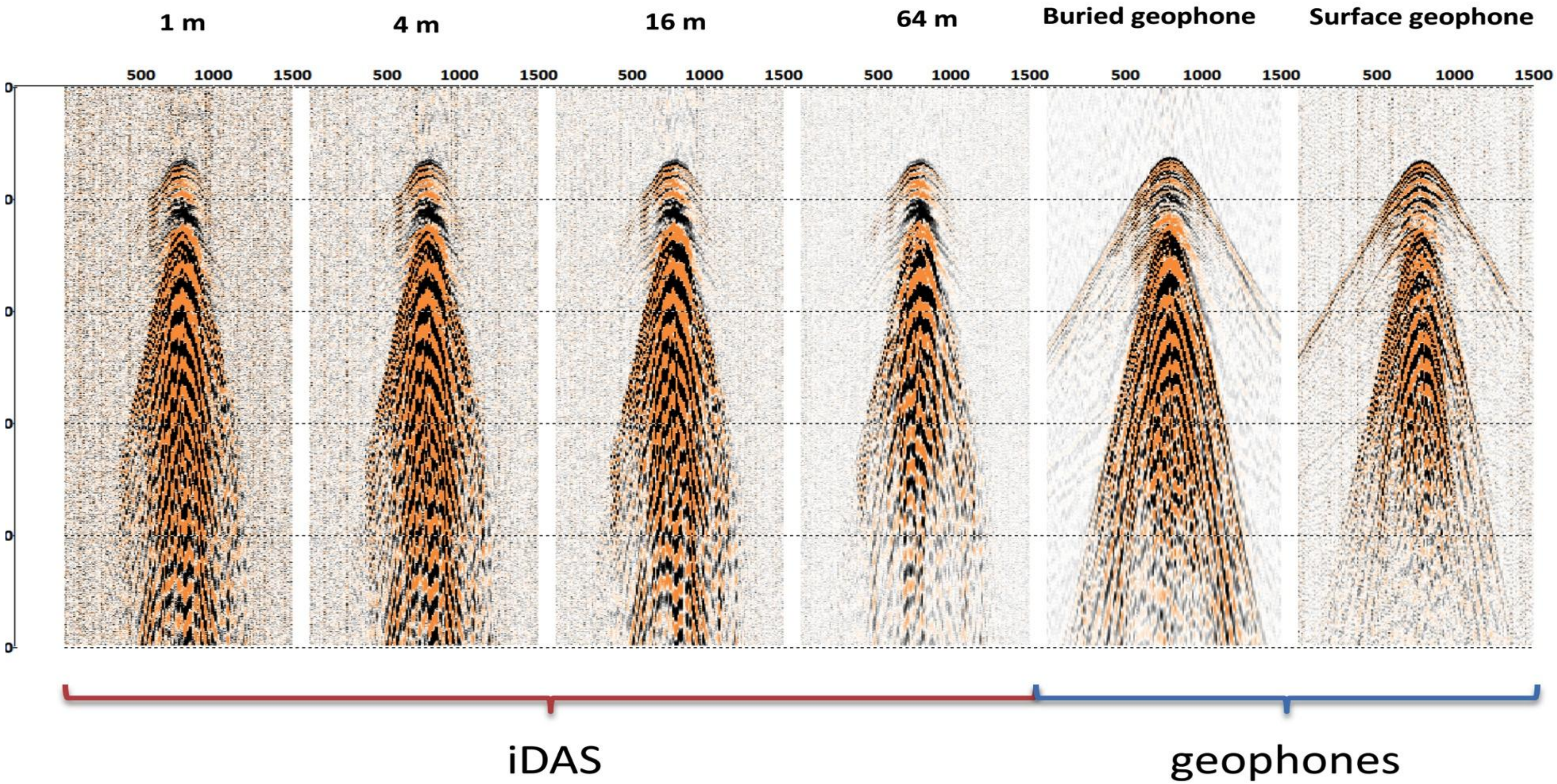
Cross correlation of all channels:
Time shifts < +/- 1 ms
Correlation Coefficent:~0.8-0.95



From Daley, et al, Leading Edge, 2013

DAS as Surface Seismic Cable: Stacking Different Fiber Lengths

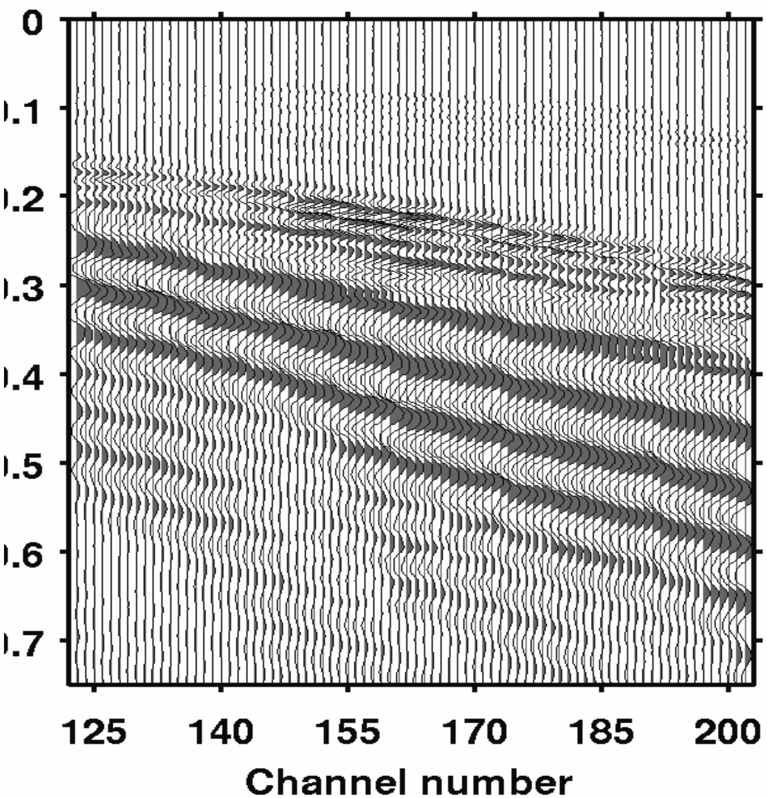
Directionality of DAS limits reflection signal: can improve by stacking, but Surface waves dominate signal compared to vertical geophones

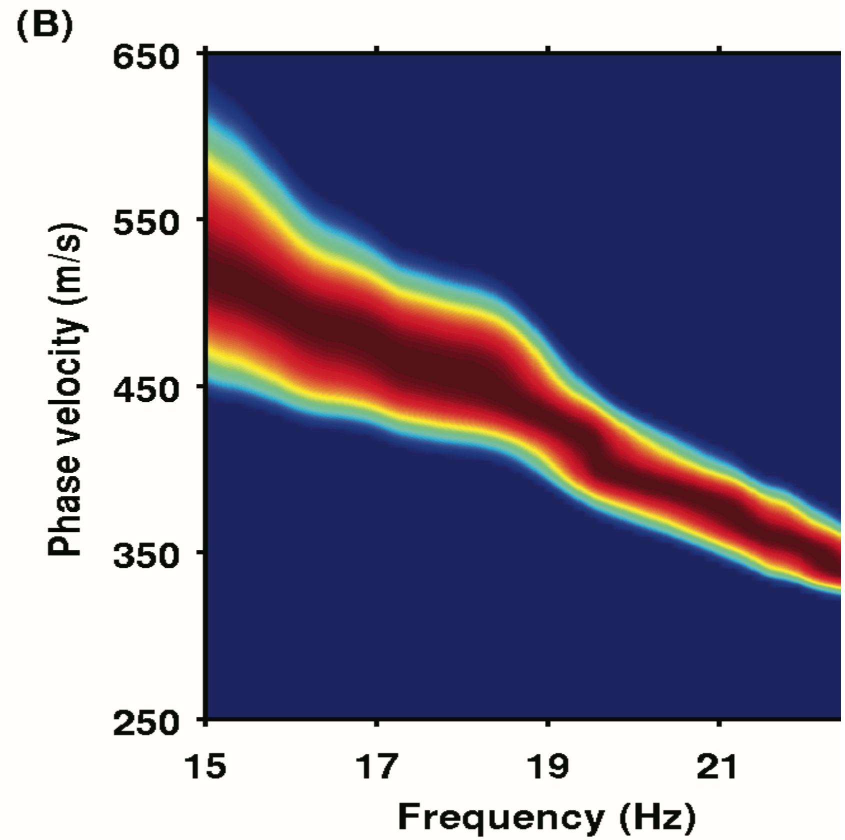


From Daley, et al, Leading Edge, 2013

Otway DAS: Surface Wave Analysis

Result: Useful data for near surface properties
(spectral analysis of surface waves – SASW)





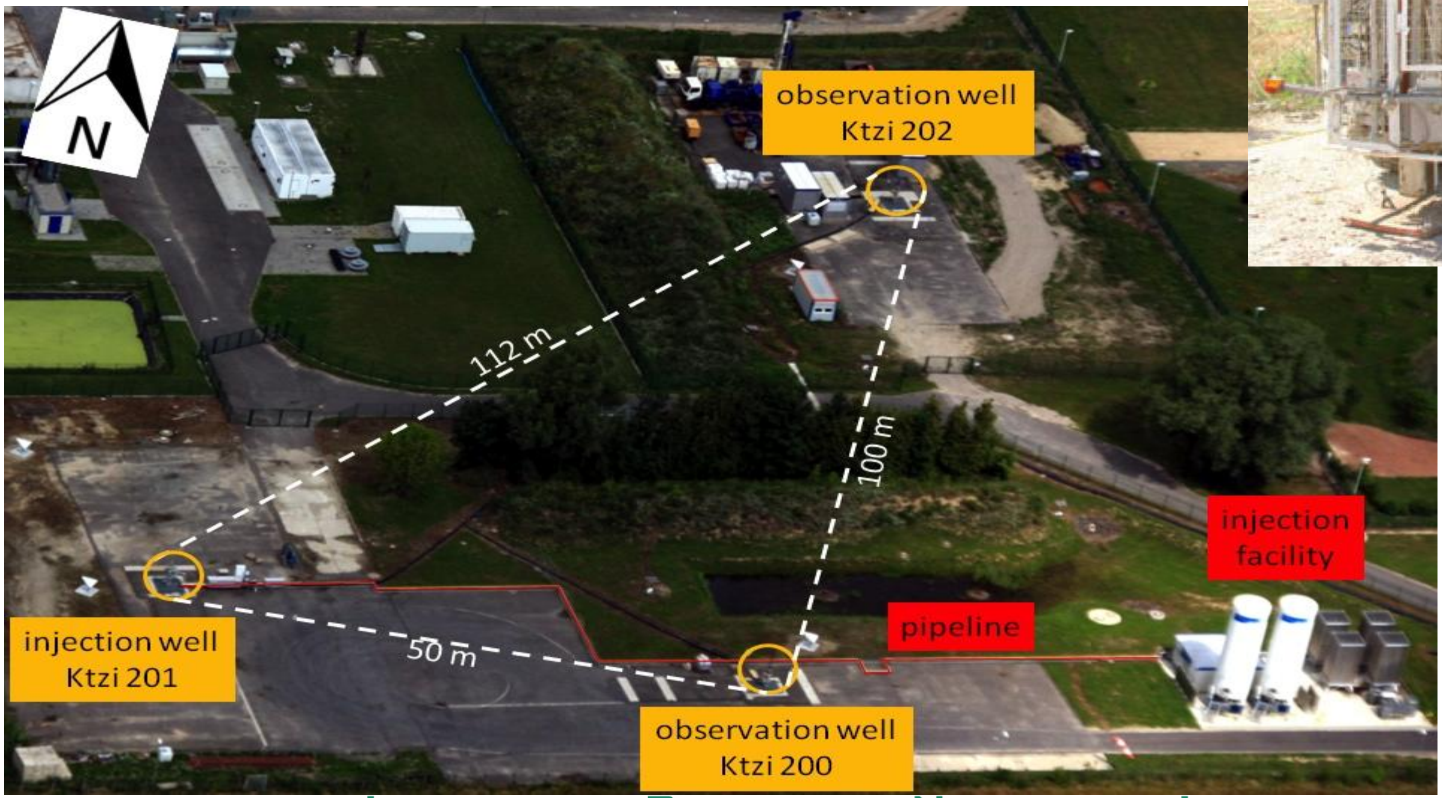
From Daley, et al, Leading Edge, 2013

Otway Test Summary

- DAS VSP data ~40dB below high quality geophones
  - Note: great improvement seen at second Citronelle test
- Simultaneous borehole and surface data on one cable
- DAS Surface wave data analysis is good quality

Ketzin Project

- CO_2 Storage Pilot operated by the German Research Centre for Geosciences (GFZ); Injection at ~700 m
- Injection well and 3 observation wells
- DAS acquisition in 2012 (2 wells) and 2013 (4 wells)
- Weight Drop Source (240 kg)

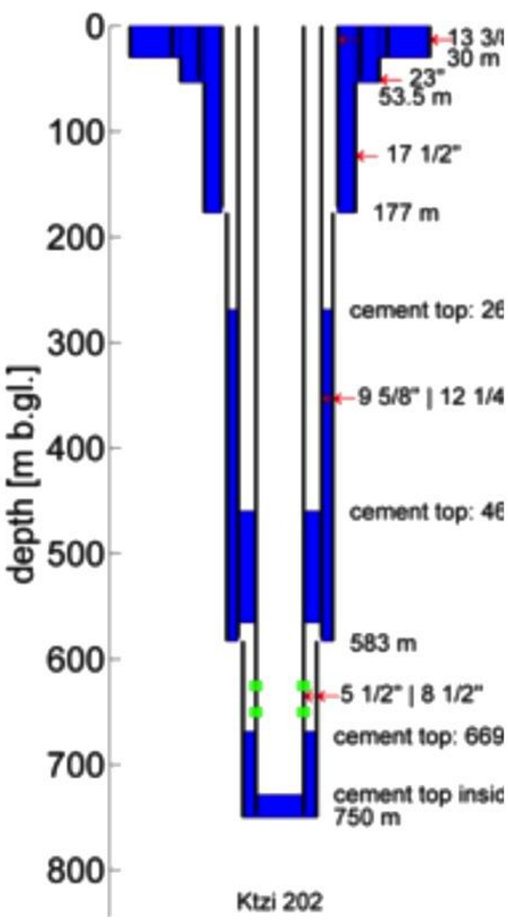


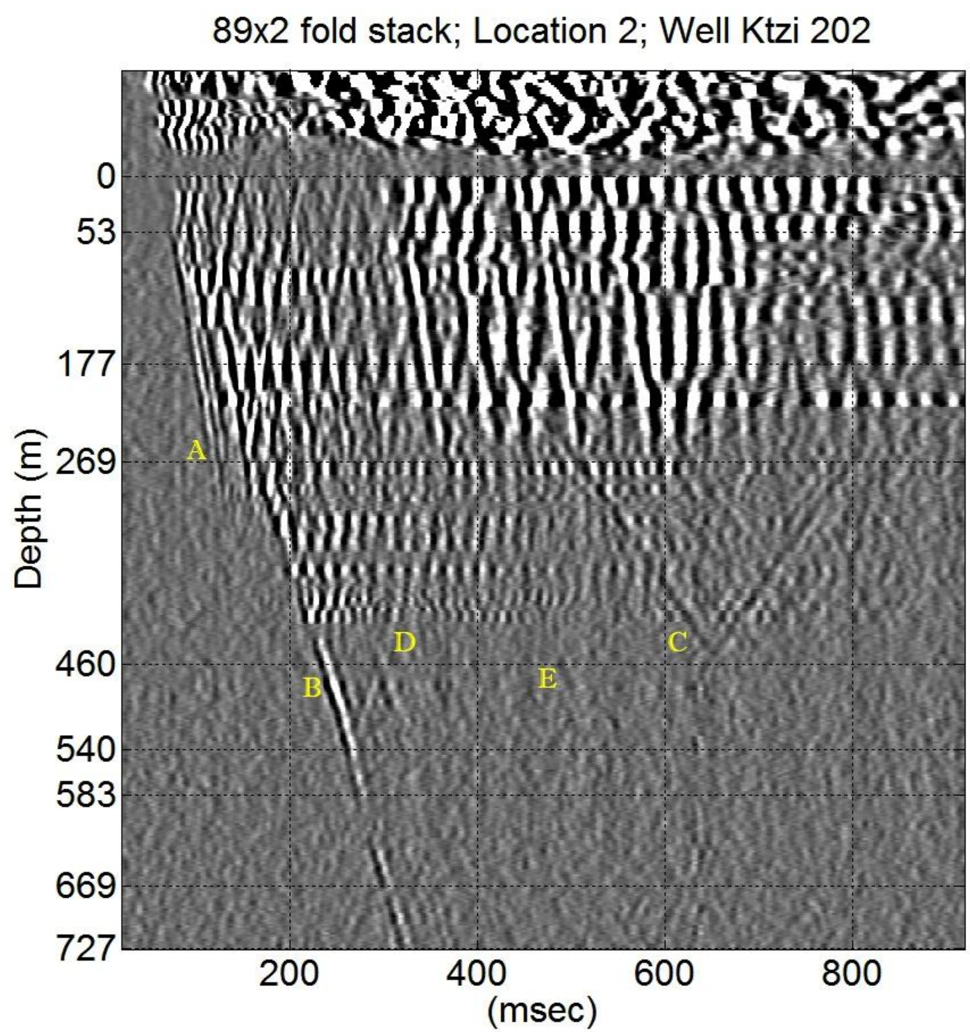
Distributed acoustic VSP source:
Geophysik GGD, Leipzig, Germany

Ketzin: 2012 DAS survey – 2 Wells

- Two Wells Simultaneous
- Fiber Behind Casing
- Surface connecting fiber added for VSP

Good Quality Data: Various Waves Observed

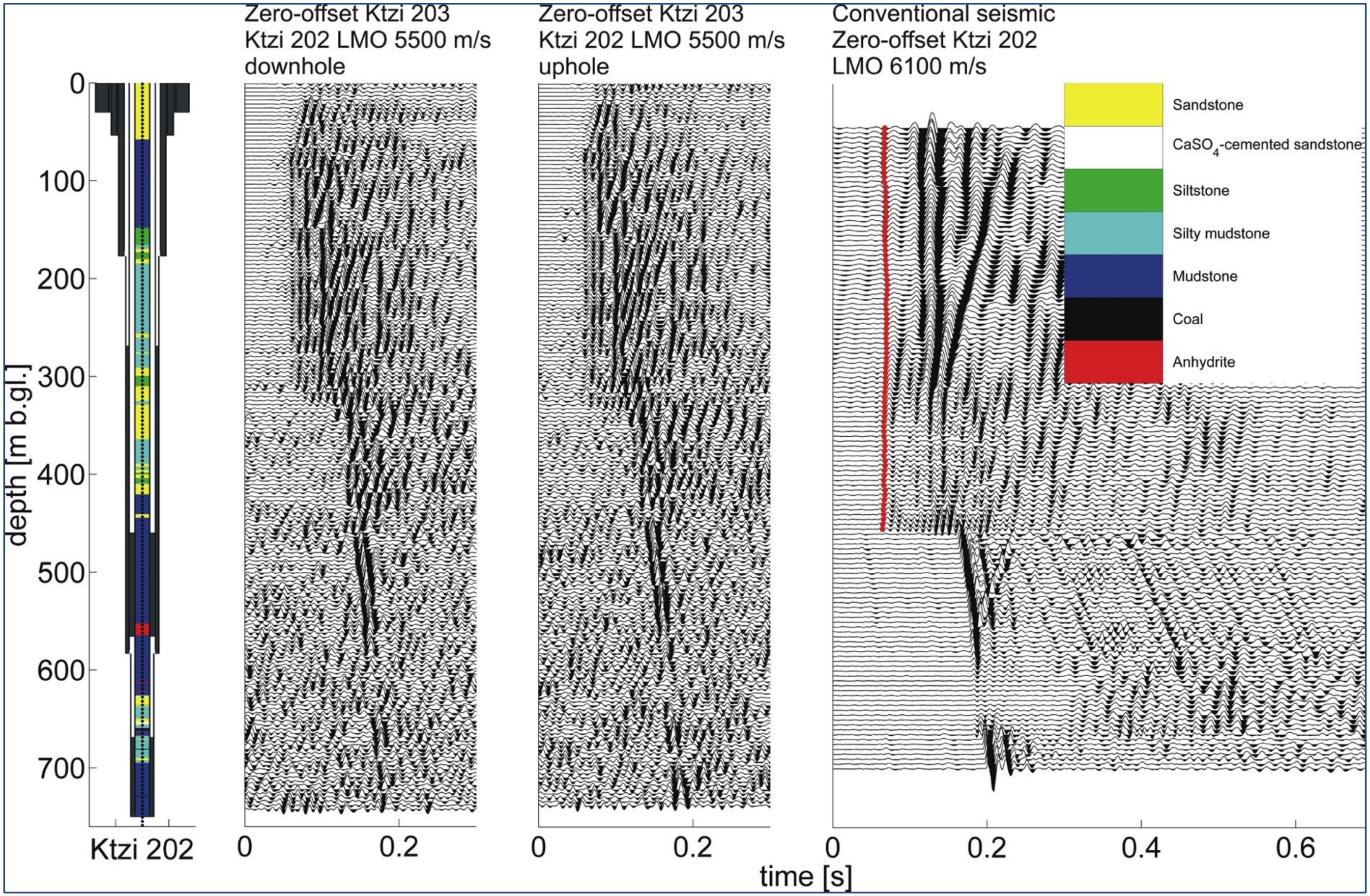




(A) Extensional signal propagating in undamped casing above 269m (5.5 km/sec)
(B) Direct compressional formation arrival (3 km/sec)
(C) Tubewave propagating in fluid annulus above 460m (1.35 km/sec)
(D) Reflected formation arrival from reflector at 540m
(E) Downgoing formation shear (1.67 km/sec)

Courtesty D. Miller, Silixa

Fiber deployed behind casing, but not cemented at all depths
DAS records waves related to well casing completion

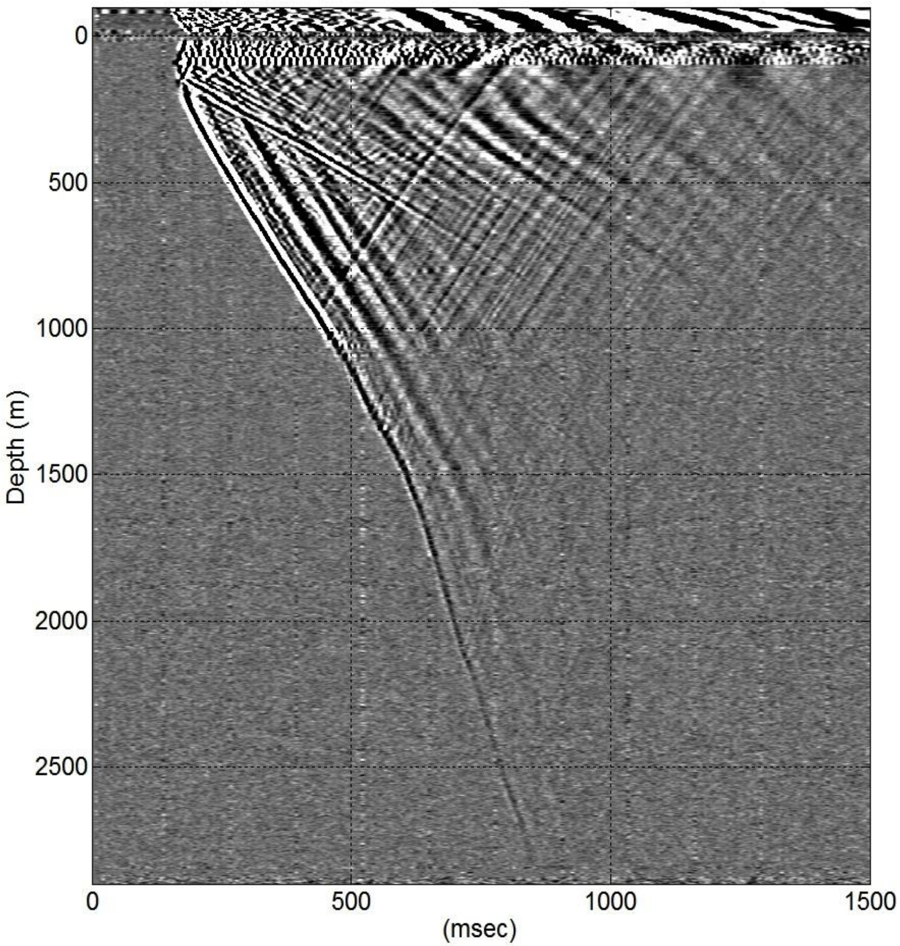


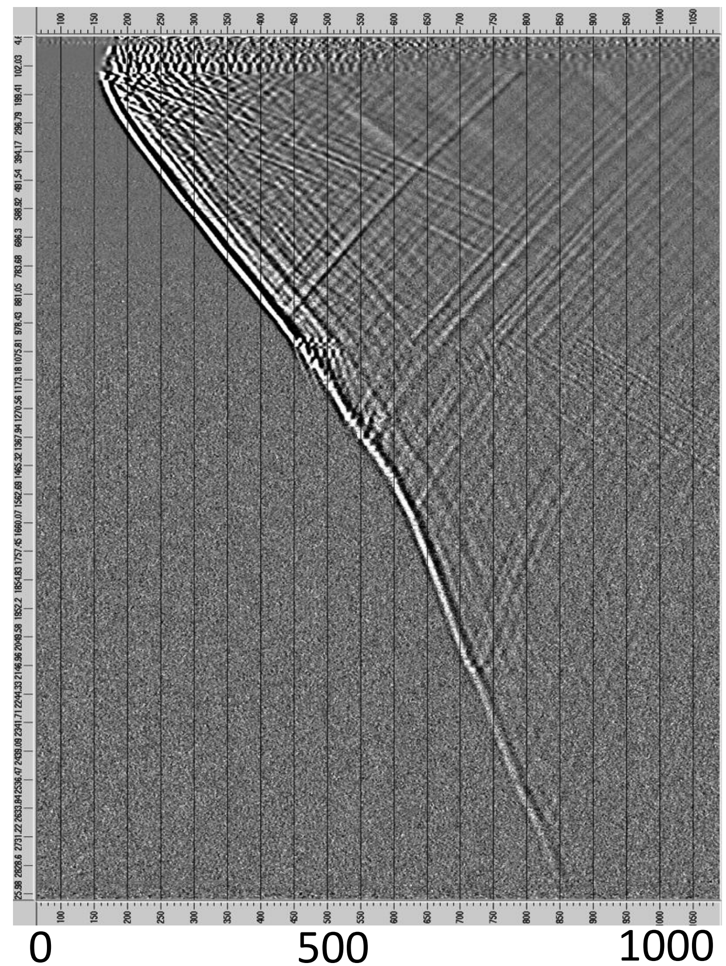
Weak signal at ~650m in both geophone and DAS data – no cement

From Daley, et al, Leading Edge, 2013
Courtesy J. Gotz, GFZ

Aquistore DAS 3D-VSP
2 Example Shots

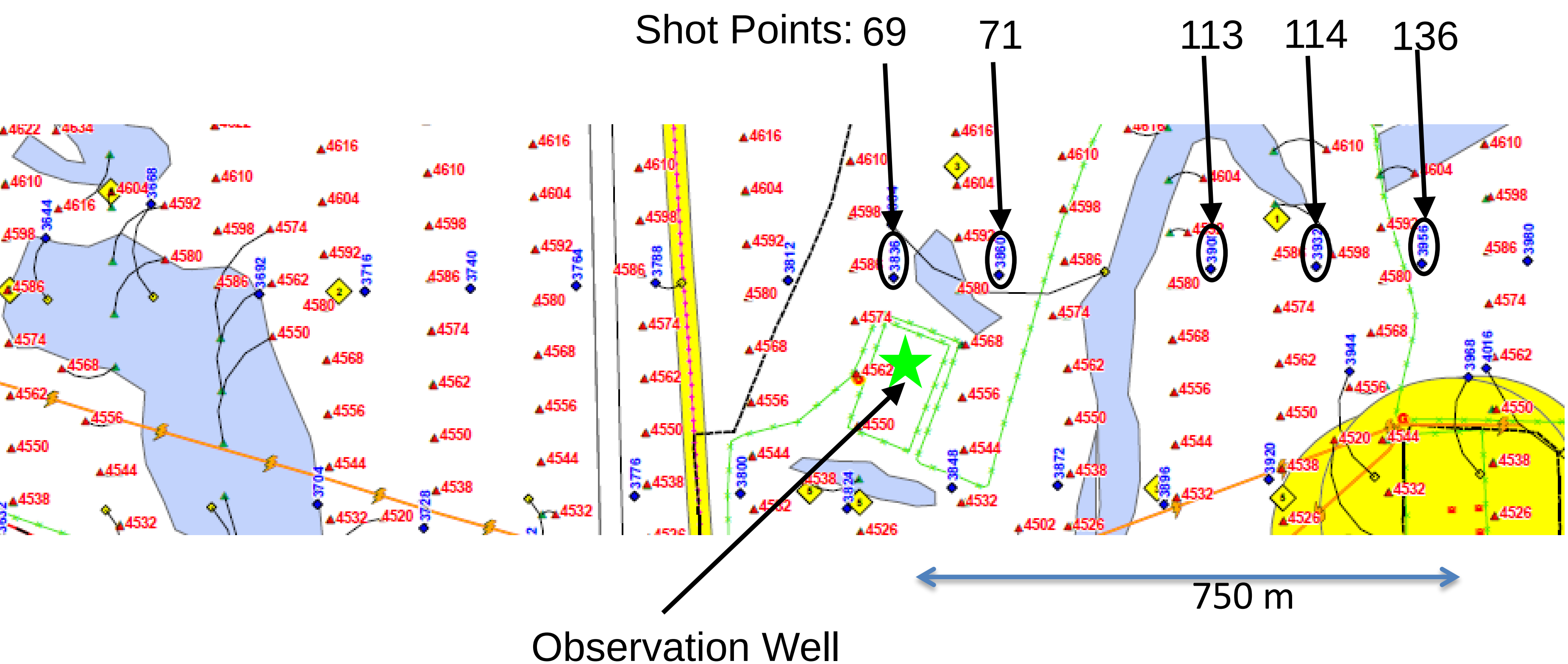
- ~3 km Fiber Behind Casing, cemented, explosive shot
- Initial recording May 2013 of >200 shots
- Second recording Nov 2013 > 600 shots; being processed analyzed



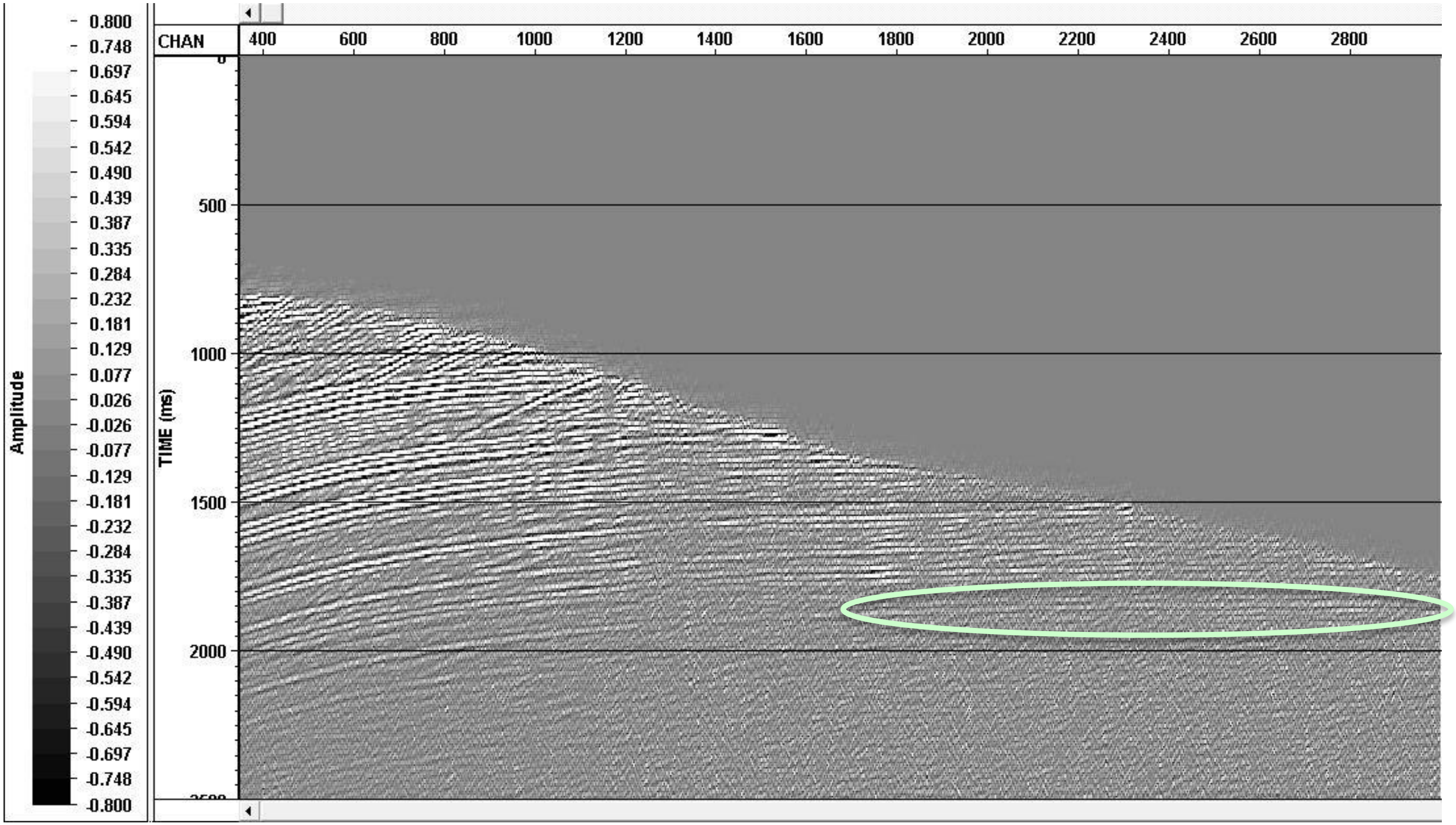


May 2013 DAS VSP

- Currently: Processing of individual shots



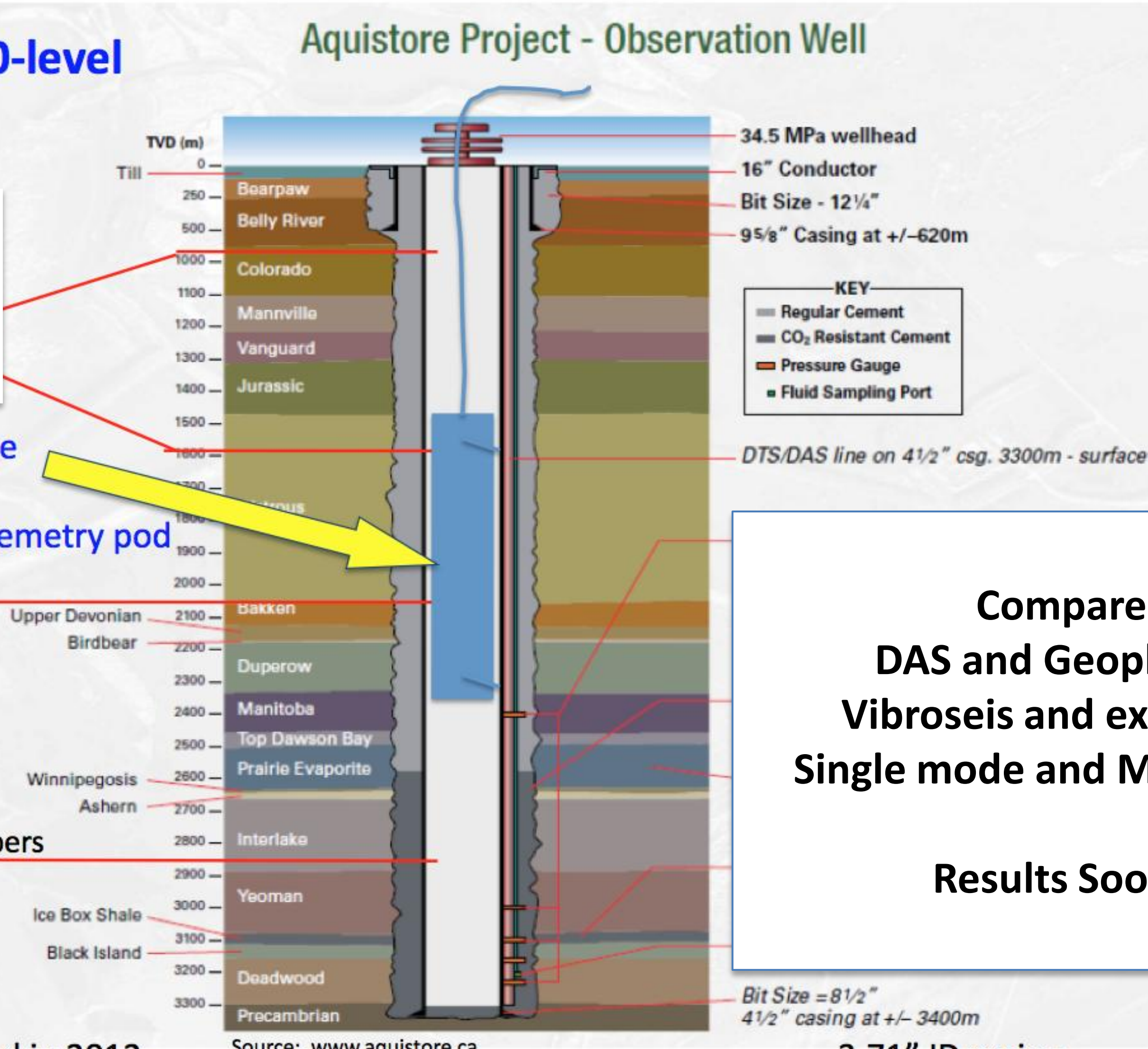
May 2013 Aquistore: Shot #136 (730m offset) VSP Reflection Image



Possible Reservoir Reflection At ~3.2 km

New Data: Aquistore Nov 2013 DAS and Geophone 3D-VSP

MaxiWave 60-level



60-level MaxiWave
1470 to 2355 m
15m spacing + telemetry pod

Staging collar 2068 m

1x SM and 2x MM fibers
broken at ~2867m

OBS well completed in 2012

Source: www.aquistore.ca

Compare:
DAS and Geophones;
Vibroseis and explosive;
Single mode and Multi-mode

Results Soon!!

3.71" ID casing

Summary 1

- CO_2 monitoring needs improved borehole methods
- DAS and Heat-Pulse DTS are new, useful fiber-optic applications
- Modular borehole deployments make sense for CCS monitoring
- DAS testing conducted within CO_2 monitoring R&D
- Citronelle site
  - Tubing deployed, 2.9 km, with short 260 m geophone string
  - Initial test had relatively low sensitivity
  - Repeat test greatly improved, about 9 dB below geophones, good potential for monitoring
- Otway site,
  - Tubing-deployed, 1.5 km, poor in comparison with previous geophone survey
  - Larger source effort needed, but promising result
  - Surface cable gives useful data

Summary 2

- Ketzin site,
  - casing deployed, ~750 m
  - Multiple wells recorded simultaneously on single cable loop
  - good overall data quality but adverse effects from uncemented zones.
  - DAS data has upgoing VSP reflections over the ~700-m depth of the well.
- Aquistore Site
  - Casing deployed, 3 km
  - Good quality data
  - Repeat with wireline 3-C geophones

- DAS is very promising technology, which is still improving
- Fiber optic sensing, in general, has application for CCS:
  - Improved monitoring while reducing risk from monitoring wells

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  - *the U.S. Department of Energy,*
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Questions?

Photo: Citronelle
Southeast Regional Carbon Sequestration Partnership (SECARB):
Anthropogenic CO_2 Injection Field Test

Monitoring Well:
Citronelle D-9-8 #2