Subsurface Monitoring of Carbon Sequestration – Recent Advances and Research Frontiers

Barry Freifeld

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Briefing on Subsurface Technology Engineering Challenges and R&D Opportunities: New Subsurface Signals

U.S. Energy Association

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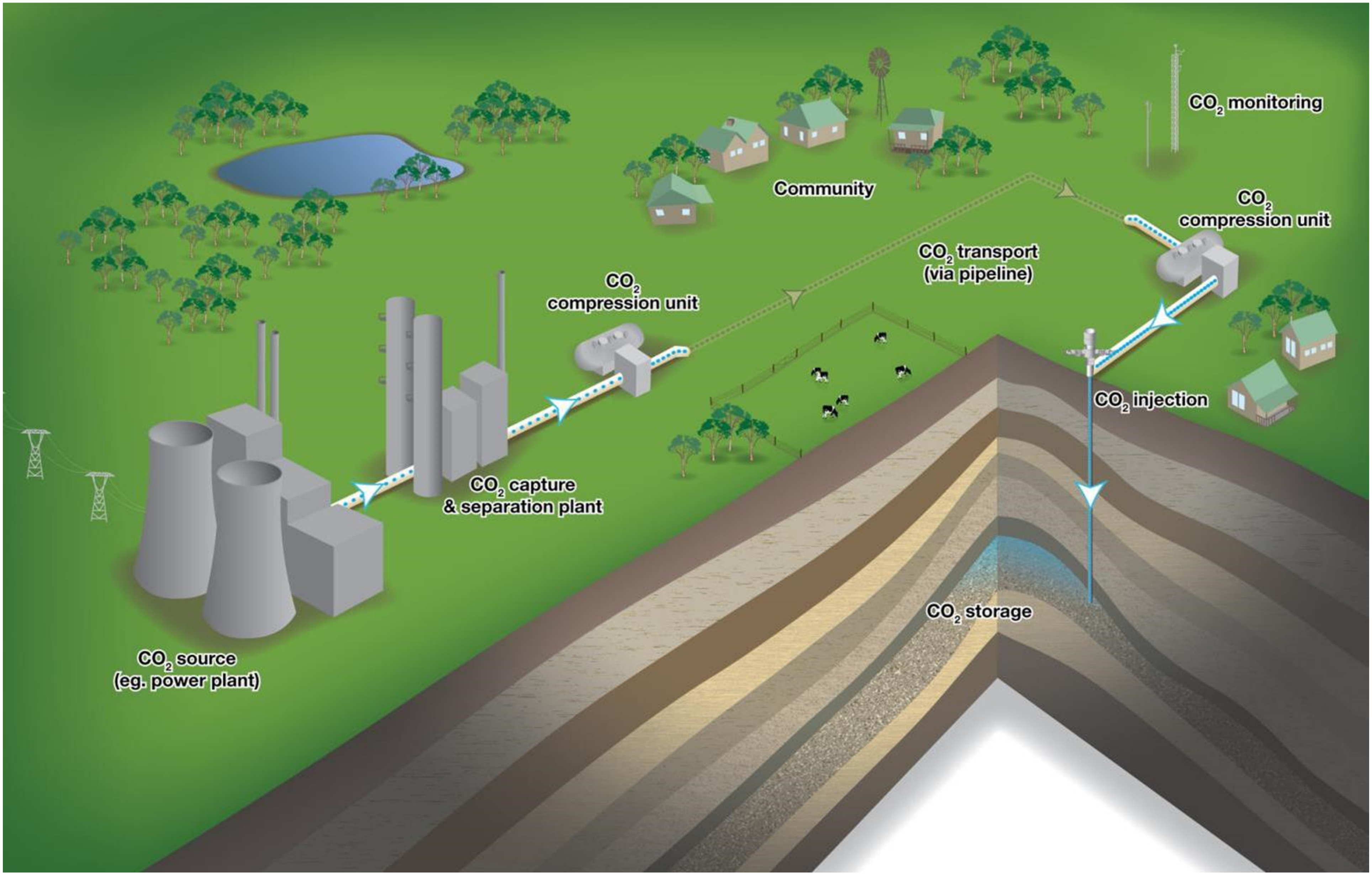
Outline

- CO_2 in the subsurface – Meeting the challenges of GCS in a Class VI regulatory environment
- New Monitoring Strategies
  - U-tube fluid sampling
  - Continuous Active Source Seismic Monitoring (CASSM)
  - Heat-pulse fiber-optic monitoring
  - Integrated Deployment (MBM)
- Future Research Frontiers

The Challenge of CO_2 Sequestration – a new problem with new requirements

Class VI well requirements prescribe detailed information needs.

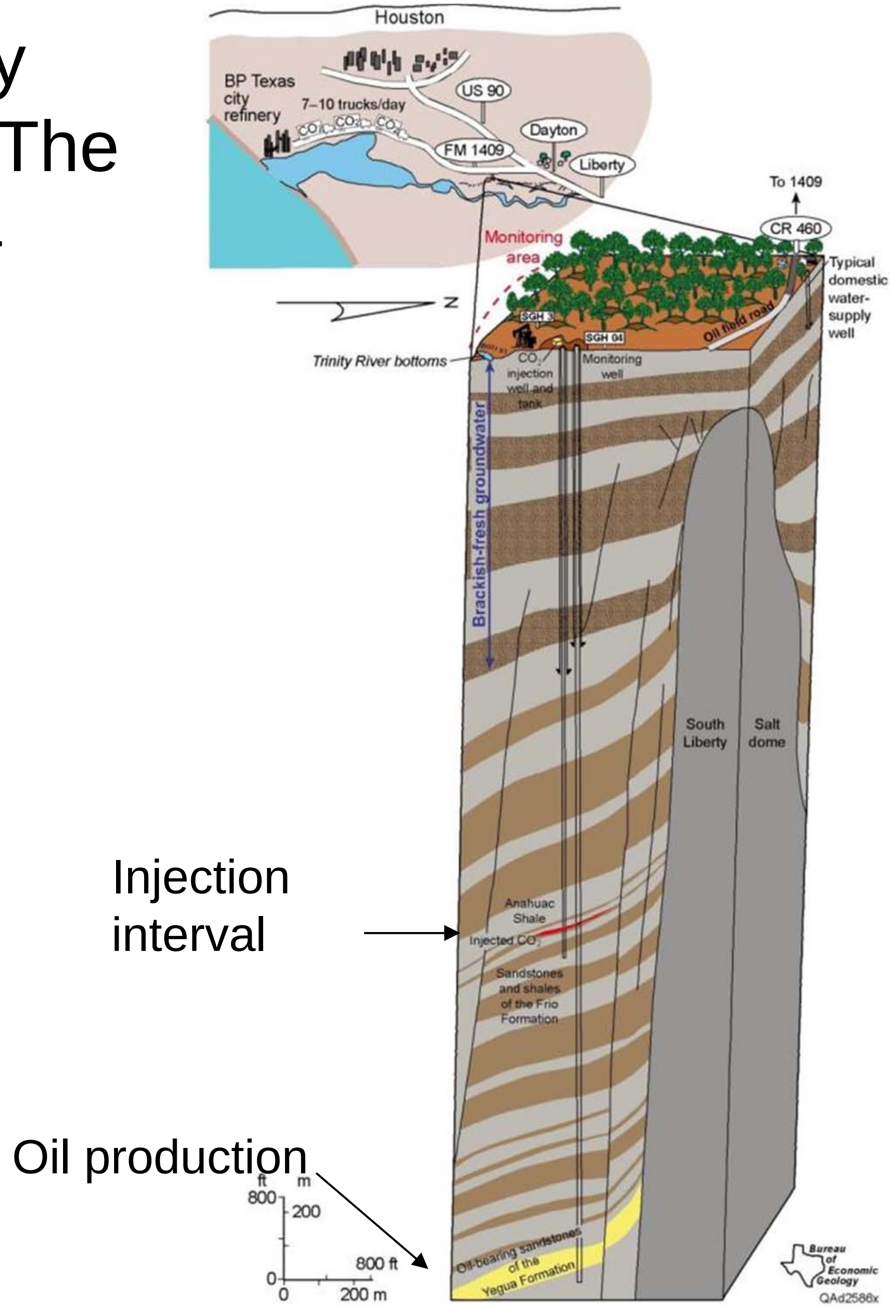


Regulatory Drivers for Subsurface Monitoring

- CO_2 storage projects governed by rule 40 CFR § 144- § 146
- Guiding principle – prevent the movement of contaminants into USDW
- (Some) requirements for Class VI wells
  - AOR delineation including existing wells and pertinent surficial features (model and assumptions)
  - Geologic structure and hydrogeological properties including reservoir and overlying formations, location of USDWs
  - Seismic history and determination that seismicity would not interfere with containment
  - Baseline geochemical data including from USDWs in area
- Operator must demonstrate sufficient capacity for planned storage volume and confining zone free of flaws that would compromise storage

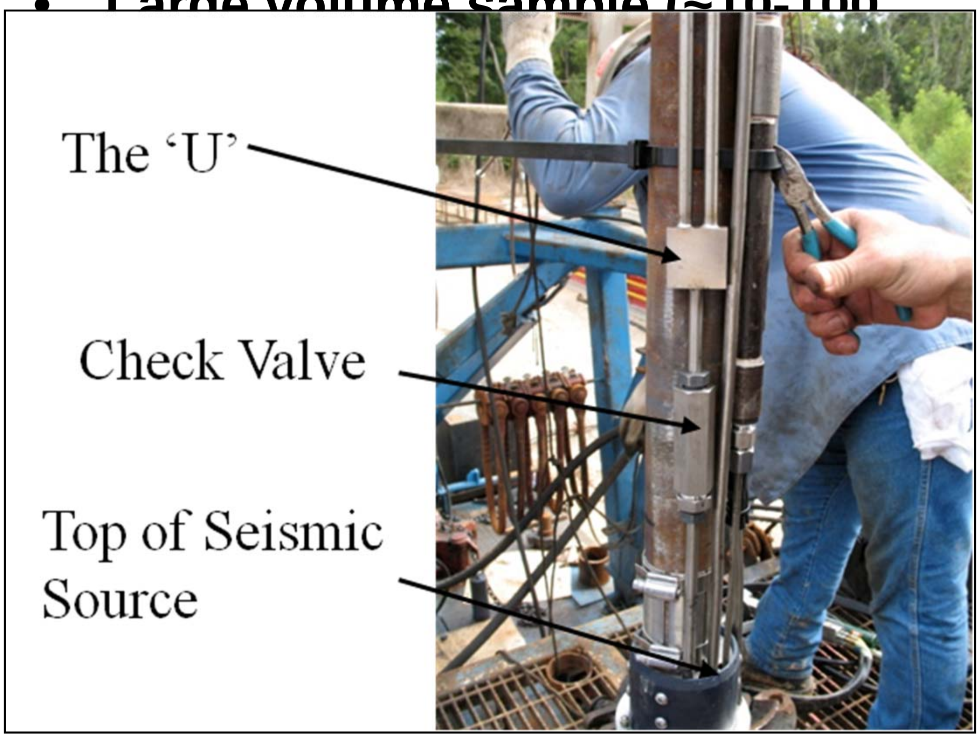
First Comprehensively Monitored Field Study – The Frio Brine Pilot, 2004

- Injection interval: 24-m-thick, mineralogically complex Oligocene reworked fluvial sandstone, porosity 30%, Permeability 2.3 Darcys
- 6m perforated zone
- Seals – numerous thick shales, small fault block
- Depth 4,900 ft (1,500 m)
- Brine-rock system, no hydrocarbons
- 150 bar, 53 ^oC, supercritical CO_2

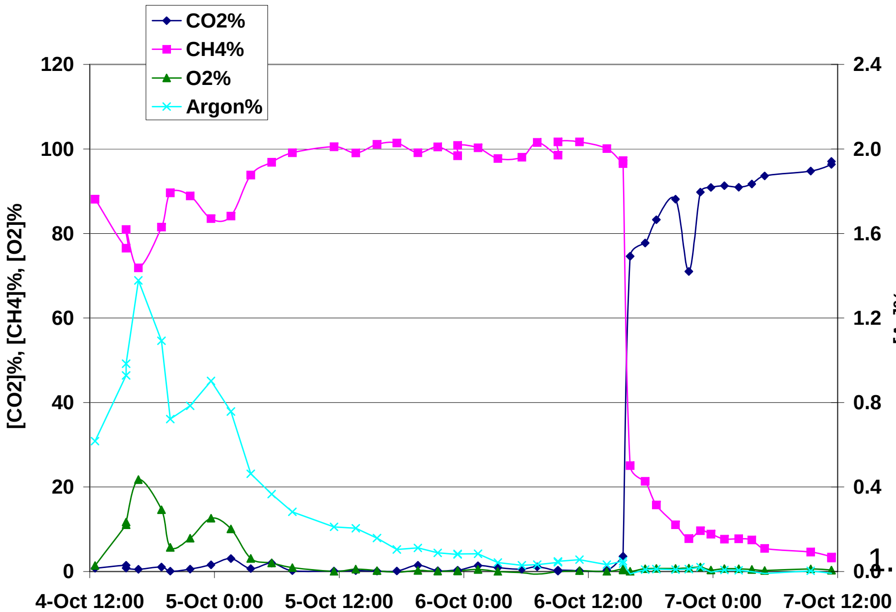


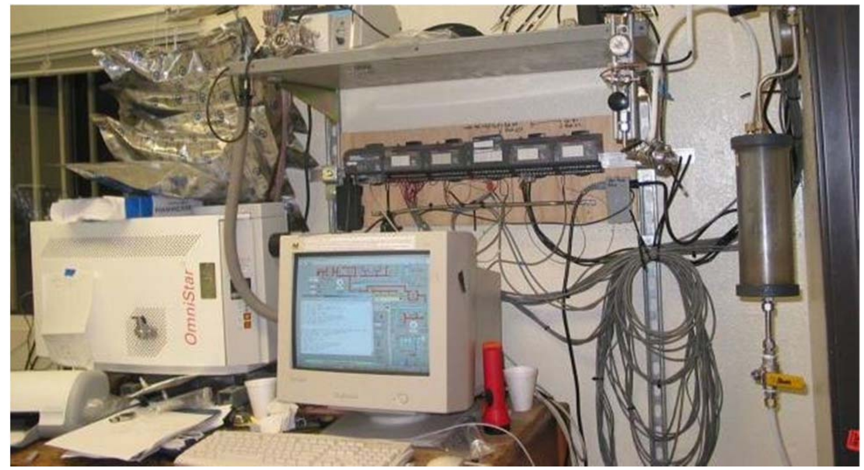
New Technology: U-Tube Fluid Sampling

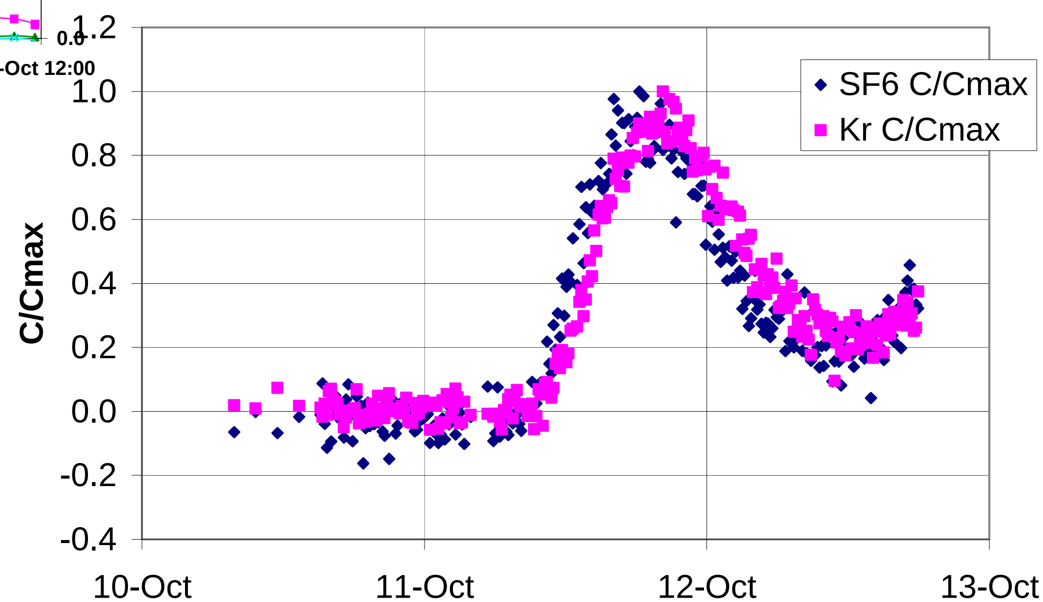
- **Down-hole check valve permits fluid entry into a loop of stainless steel tube**
- **Fluid driven to surface with compressed ultra-pure N_2**
- **Large volume sample (~10-100**



Frio U-tube: real-time analysis







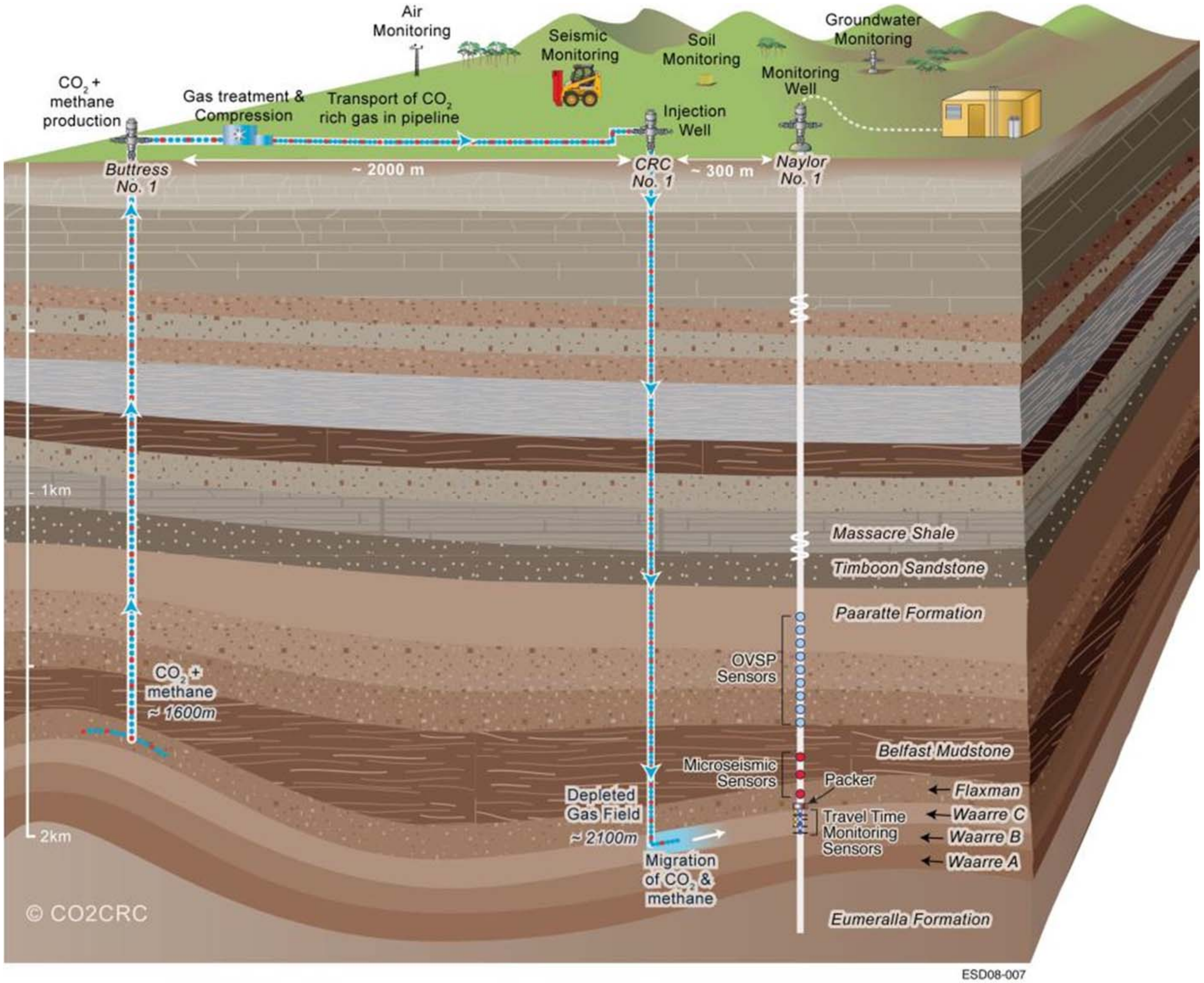
Ref: Freifeld, B. M., et al., (2005), The U-tube: A novel system for acquiring borehole fluid samples from a deep geologic CO2 sequestration experiment, *J. Geophys. Res.*, 110, B10203, doi:10.1029/2005JB003735**.**

U-tube Deployment History

Location	Installation Date	Number of U-tubes	Depth (m)	Temp (°C)	Comments/Formation
Frio Brine Pilot, Dayton TX, USA	September, 2004	1	1500	61	C-sand Test
Yucca Mountain, Amargosa Valley, NV, USA	March, 2006	4	262, 350	30	Volcanic tuff
Frio Brine Pilot, Dayton TX, USA	September, 2006	2	1550	62	Blue-sand test
High Lake Project, Nunuvut Territory, Canada	July, 2007	1	400	2	Sub-permafrost sampling
Otway Project - Stage I, Victoria, Australia	October, 2007	3	2040	96	Waarre-C Depleted Gas Test
Greenland Analogue Project, Kangerluusuaq, Greenland	July, 2009	1	240	1	Sub-permafrost sampling
SECARB Cranfield, Cranfield, MS, USA	November, 2009	2	3100	127	Tuscaloosa D Sandstone
Otway Project - Stage 2b, Victoria, Australia	February, 2011	2	1440	56	Paarratte Formation - Residual Gas Test
Citronelle Dome, Citronelle, AL, USA	March, 2012	1	3000	106	Paluxy Formation
Hontomin Project, Hontomin, Spain	December 2013	1	1500	60	Sinemuriense Dolomites
MUSTANG Project, Heletz, Israel	February 2014	2	1600	62	Heletz Sandstone
Planned projects using U-tubes (well drilling in 2014):					
Big Sky Regional Carbon Sequestration Partnership/ Kevin Dome, Montana, USA					
Kansas Wellington Field - Arbuckle Small Scale Injection Test, Kansas, USA					

Otway Basin—Depleted Gas Field

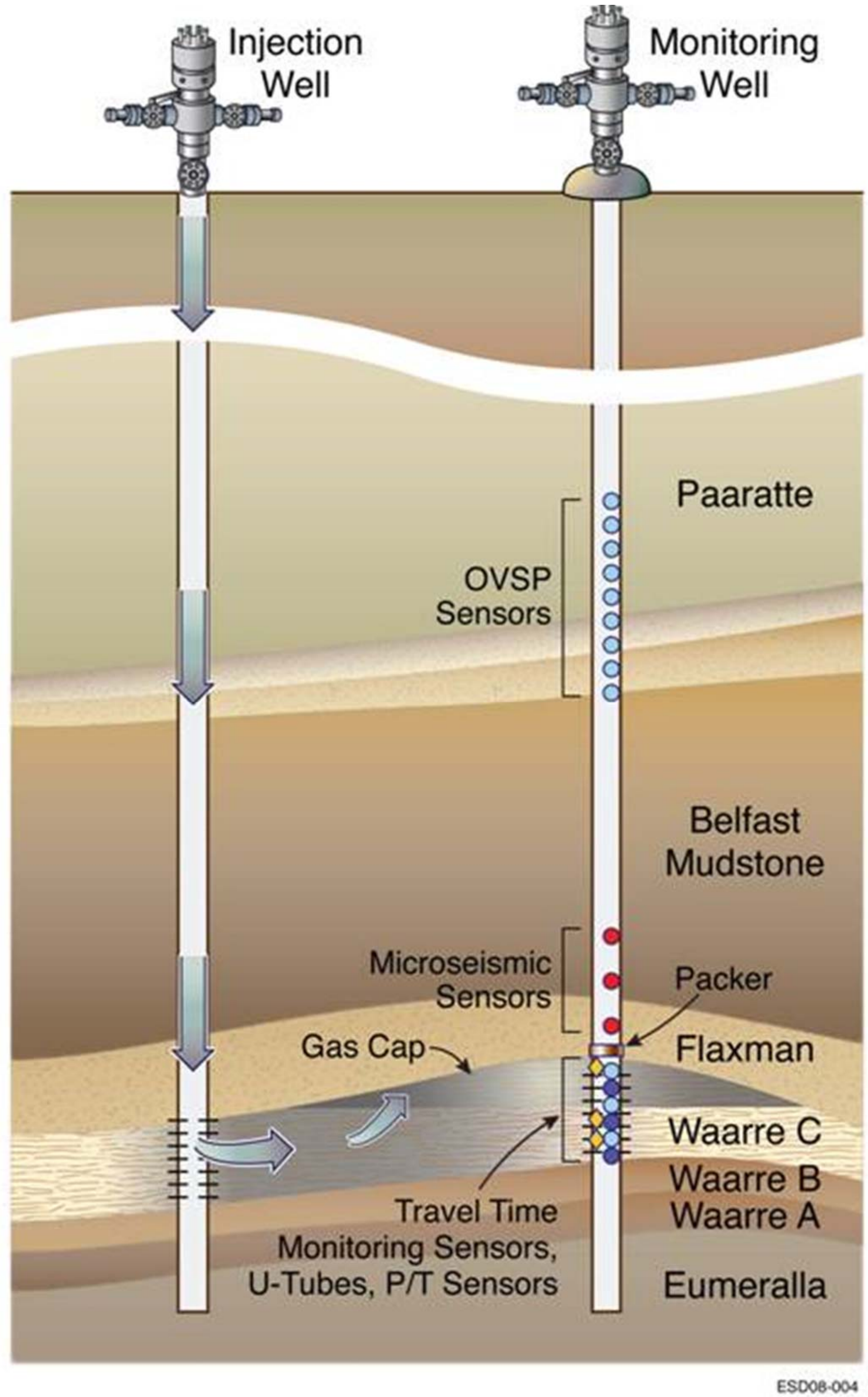
- **Produce Buttress-1 80% CO_2 20% CH_4**
- **Compress and transport 2 km**
- **Inject CRC-1**
  - **~1.6kg/s (Injection started April 1, 2008)**
- **Monitoring: surface seismic, 3D VSP CRC-1, Naylor-1, soil gas, shallow groundwater and atmosphere**



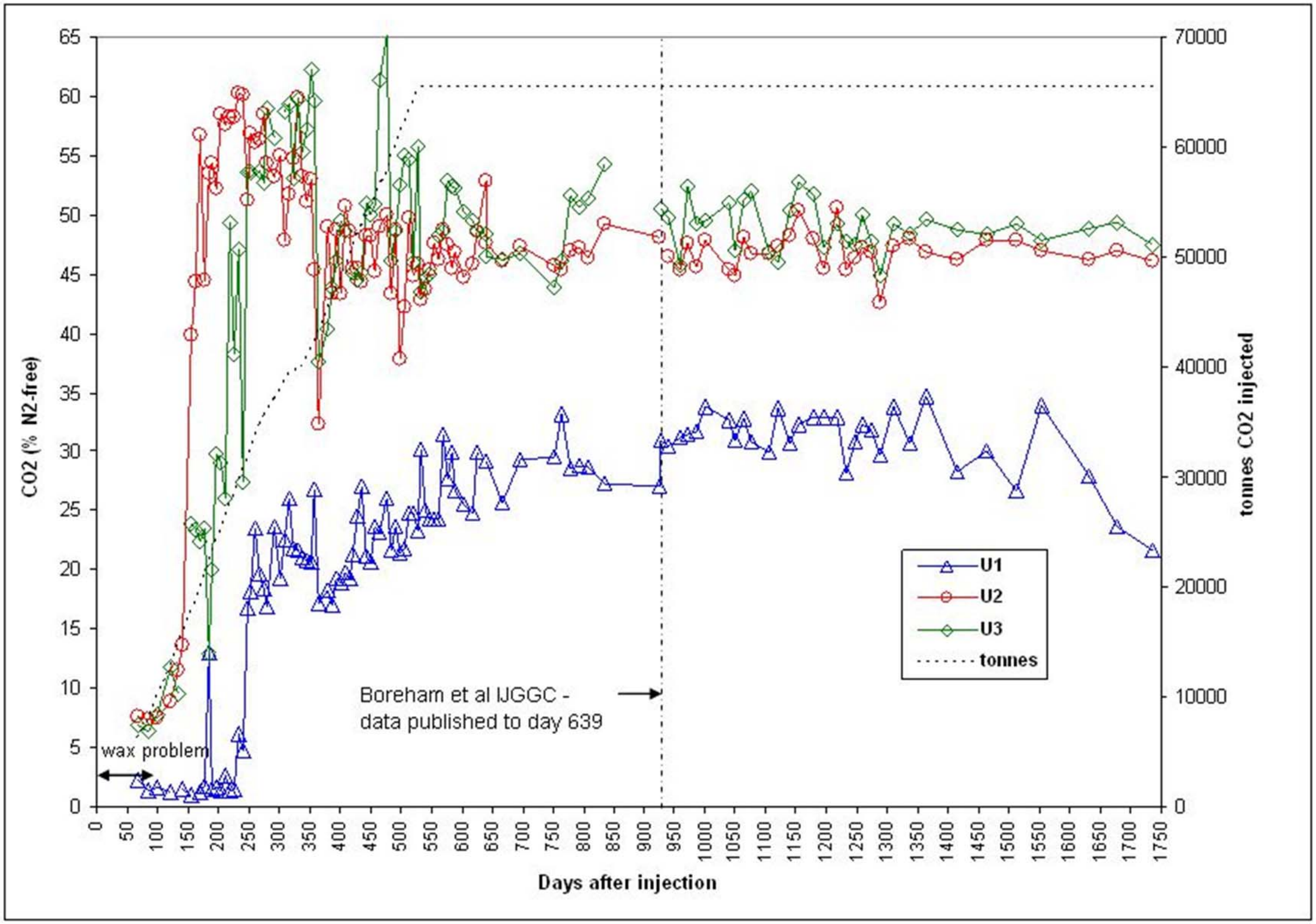
Key Monitoring Objectives

- **Identify arrival of CO_2**
- **Location of CO_2**
- **Monitor GWC movement**
- **Arrival of tracers**

Light blue circle	Geophone with clamp
Red circle	3c Geophone with clamp
Dark blue circle	Hydrophone
Yellow diamond	Pressure/Temp and U-tube Inlet



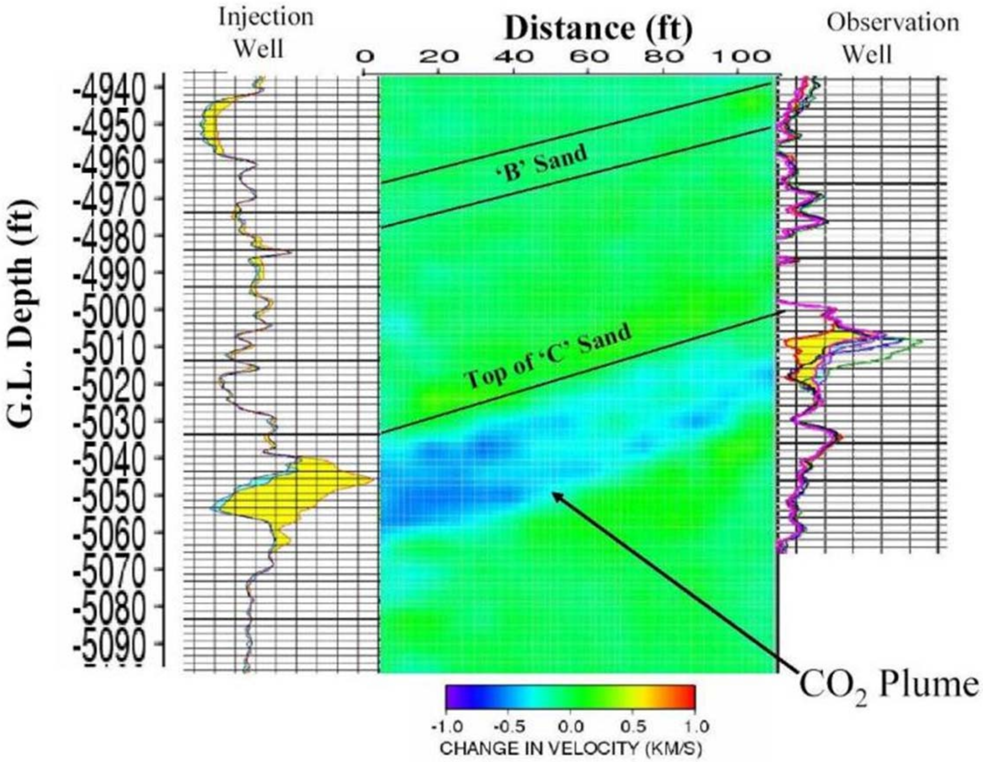
Otway U-tube CO_2 Data

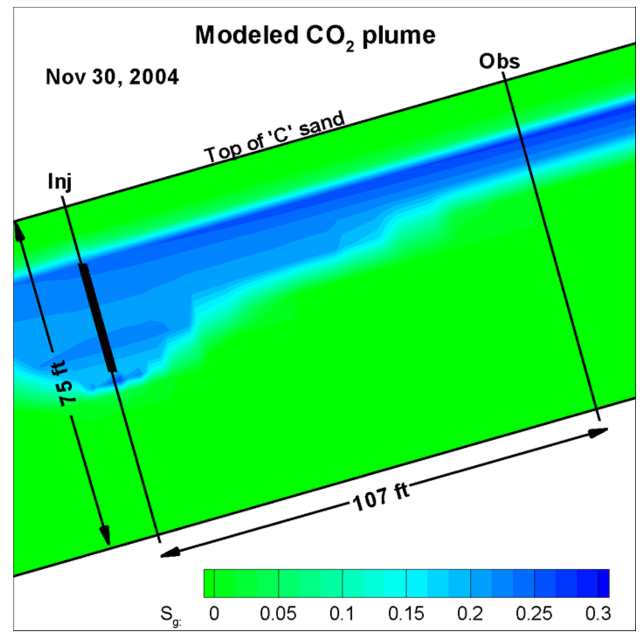


Further innovations: tube-in-tube U-tube – simplify RIH

CASSM monitoring – continuous active source seismic monitoring

Motivation: large decrease in seismic velocity for CO_2



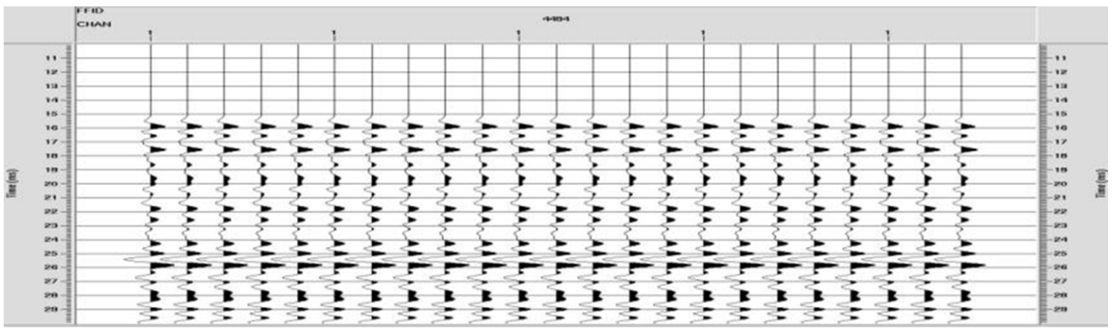


Crosshole seismic tomography at Frio Brine Pilot

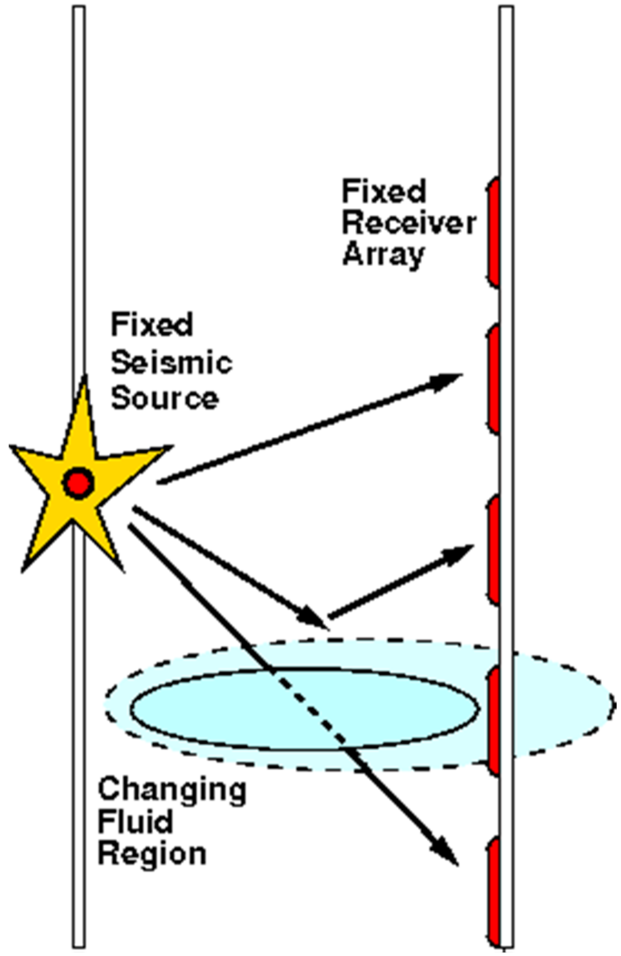
Continuous Active Source Seismic Monitoring (CASSM)

- Goal: Precision *In Situ* monitoring of seismic properties via crosswell geometry

- CASSM Applications:
  - Earthquake 'forecasting'
    - Measure tectonic stress change
    - Need calibration signal:
      - Barometric pressure
  - Monitoring of *In Situ* Processes
    - CO_2 sequestration - plume dynamics and petrophysics
    - Monitoring for groundwater remediation



Crosswell Configuration



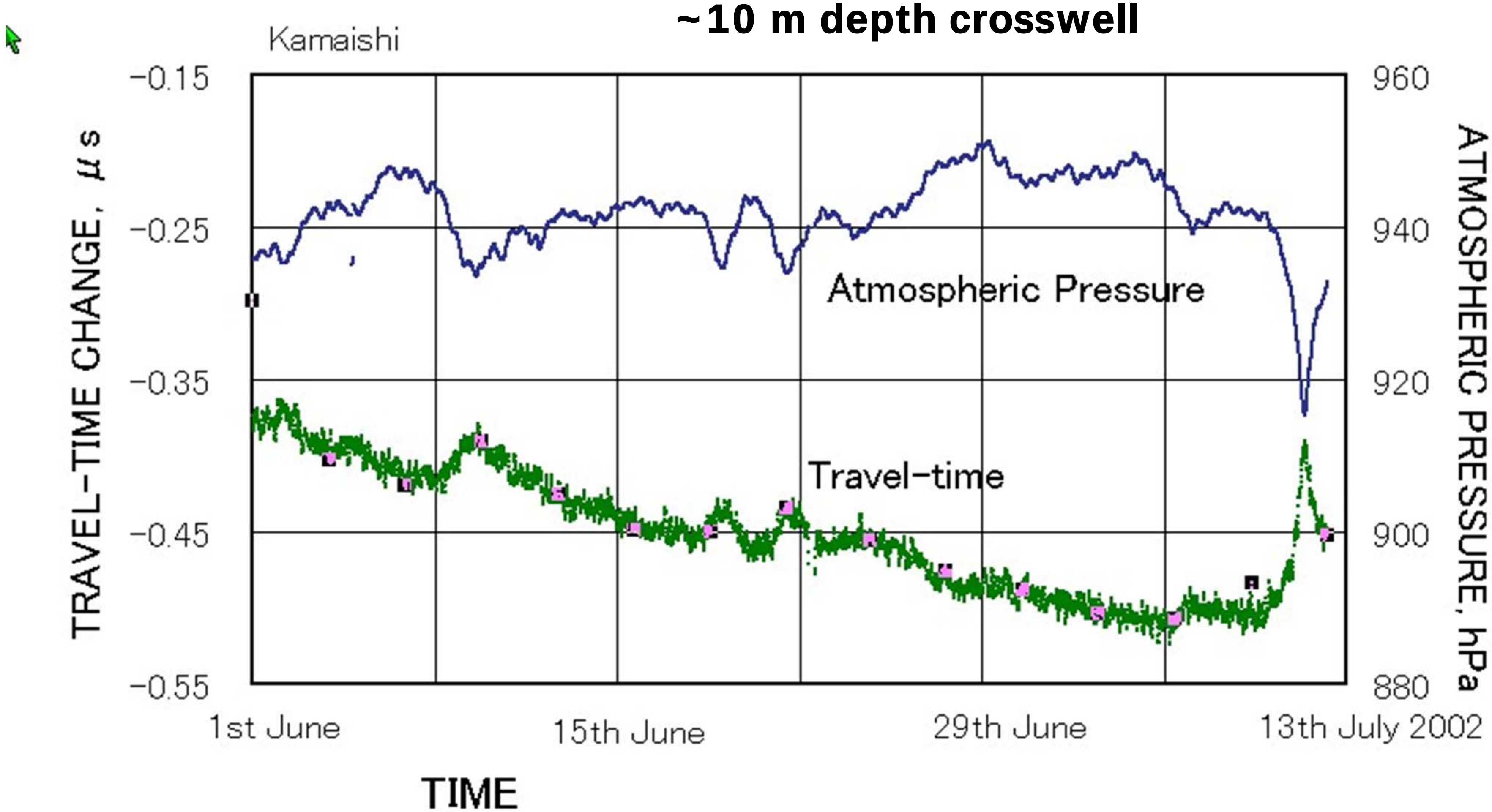
Background

- Lab studies demonstrate stress sensitivity
  - Stress sensitivity of velocity ~10^{-9} to 10^{-6} /Pa
- Attempts at field scale measurement date back decades (e.g. Reasenberg and Aki, JGR 1974), with recent work using 4D surface seismic
- Crosswell geometry improves repeatability and frequency content (no near surface variations) and gives *in situ* result
- Continuous monitoring significantly reduces error due to positioning and allows better understanding of time-varying processes (as opposed to time-lapse 'snapshots')

2002: Observation of Barometric Pressure (Earthquake Res. Inst., Univ. Tokyo)

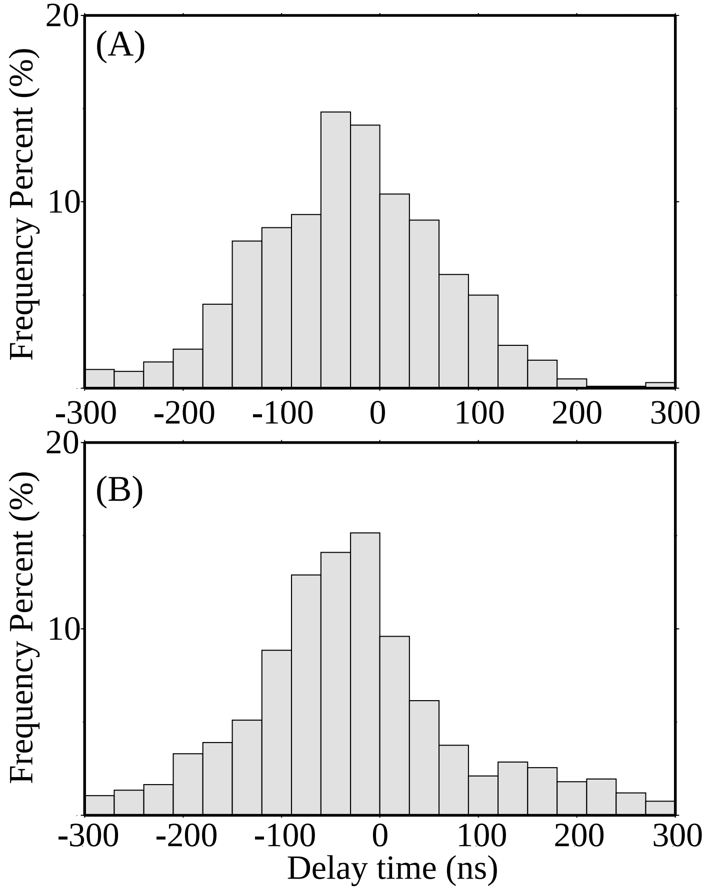
Piezo source, offset=12 m, every 30 min for 1 year. Velocity precision 10^{-4} ,
Velocity-stress sensitivity 5 x 10^{-7}
(Yamamura et al., JGR, 2003; Sano, et al, 1997)

~10 m depth crosswell

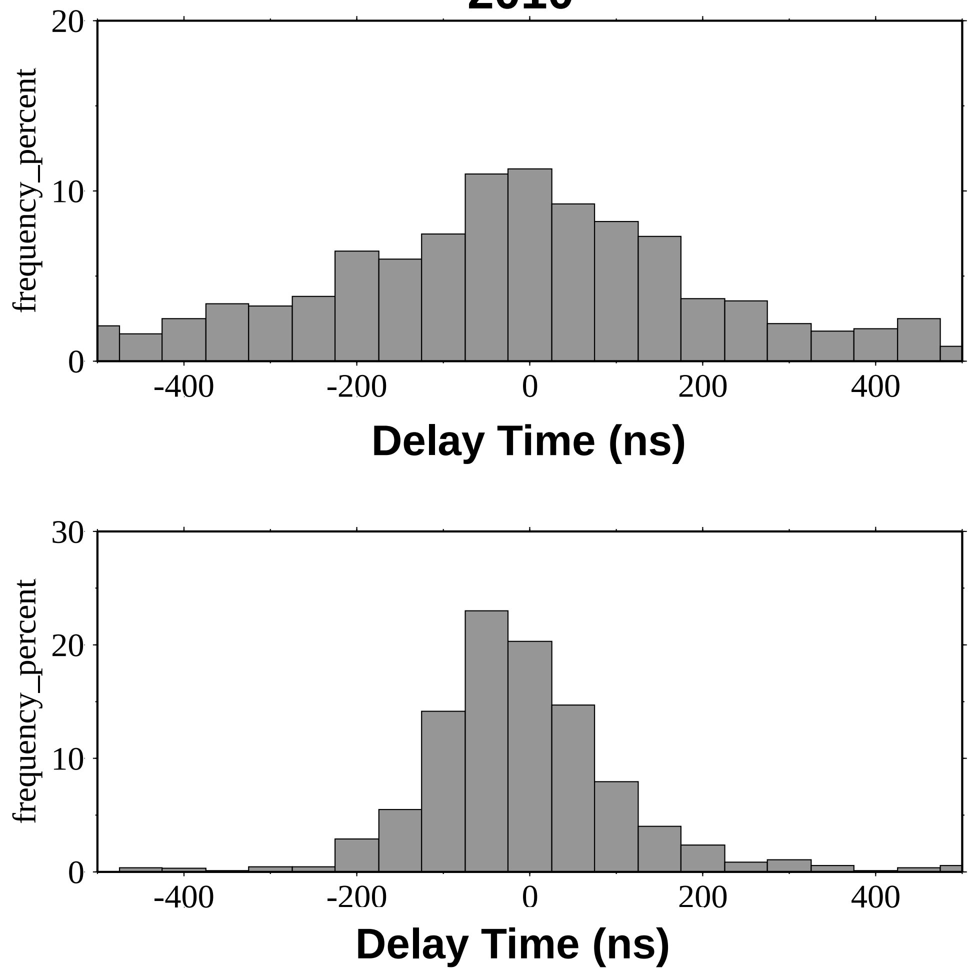


Measured Delay Time Repeatability: < 10^{-6} s

2006



2010

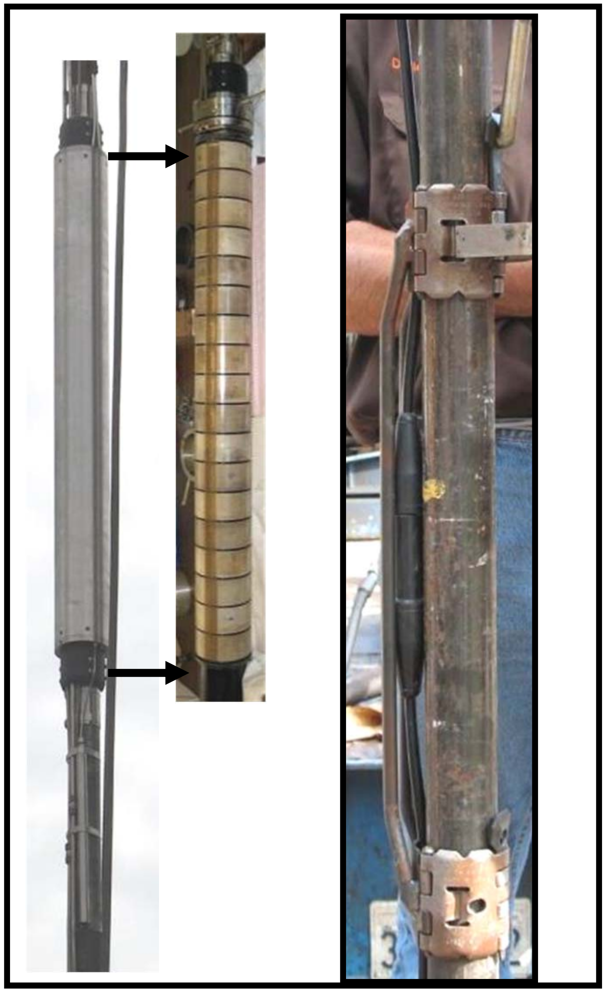


SAFOD: Histogram of the measured delay time between two consecutive 45-minute records for two channels. 2006 data from *Niu, et al, 2008, Nature (supplemental material)*

CASSM for CO_2 Monitoring

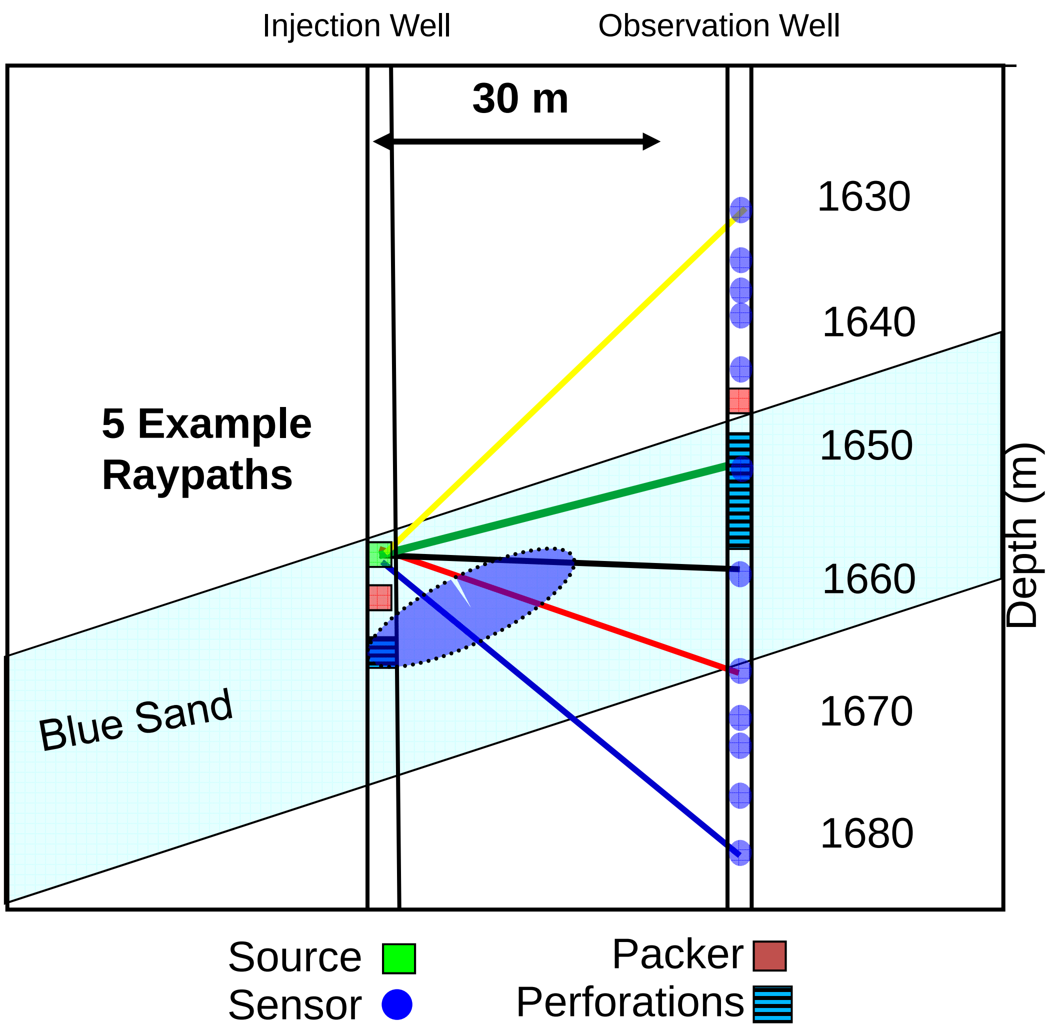
- Motivation
  - Apply techniques developed for stress monitoring to reservoir monitoring of CO_2 injection and storage
- US DOE CO_2 InjectionTests: Frio-II (Texas) and SECARB (Mississippi)
  - Frio-II: Monitor evolution of CO_2 plume (Daley, et al, 2008 Geophysics)
  - SECARB: Extend technique to 3 km, 120 ^{o}C, multiple sources and sensors

2006 Frio-II CASSM: Design for 1500 m depth
Multiple Sensors Give Spatial Variation:



'Piezotube' Source and Hydrophone sensor mounted on tubing

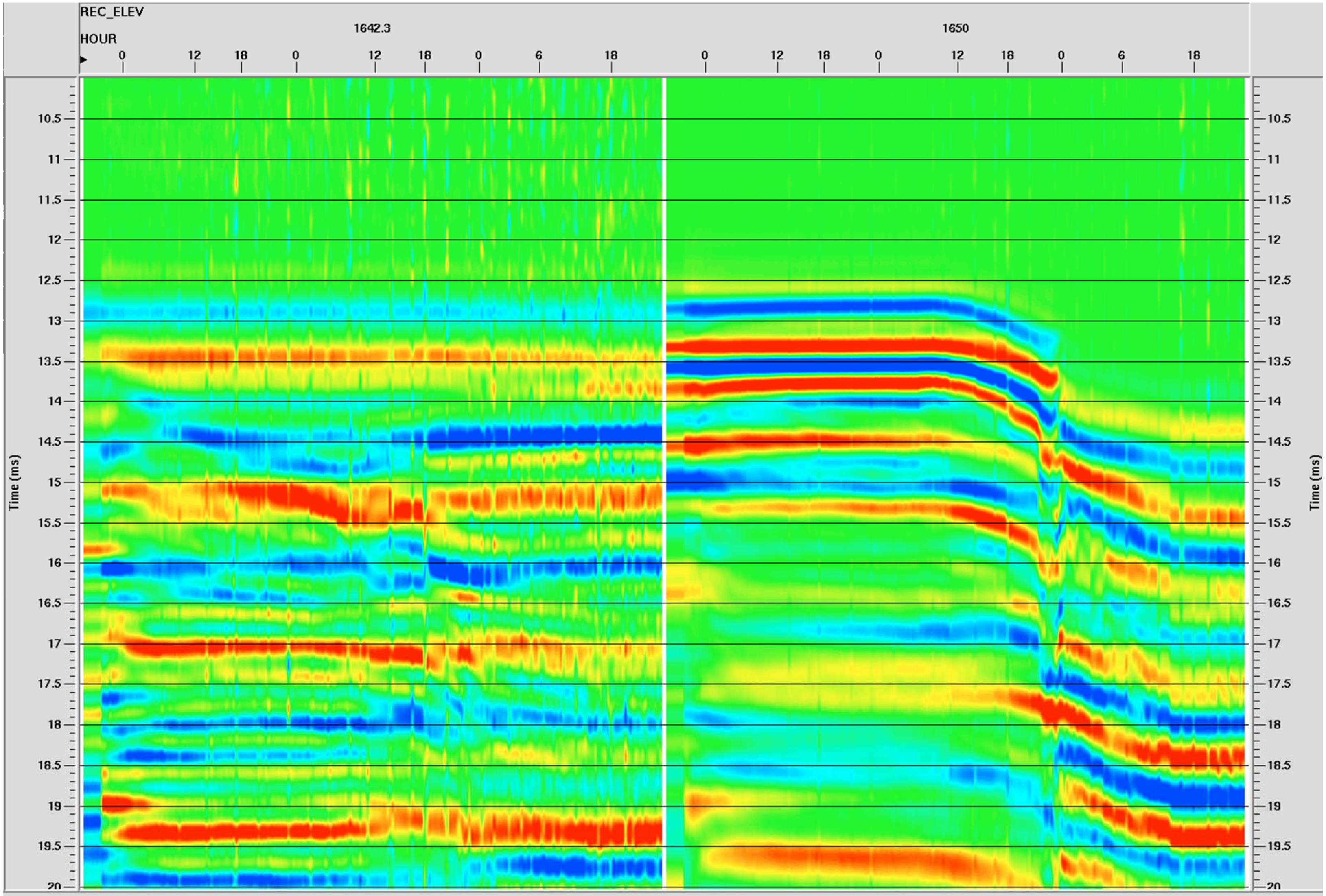
Piezotube: Patent Applied



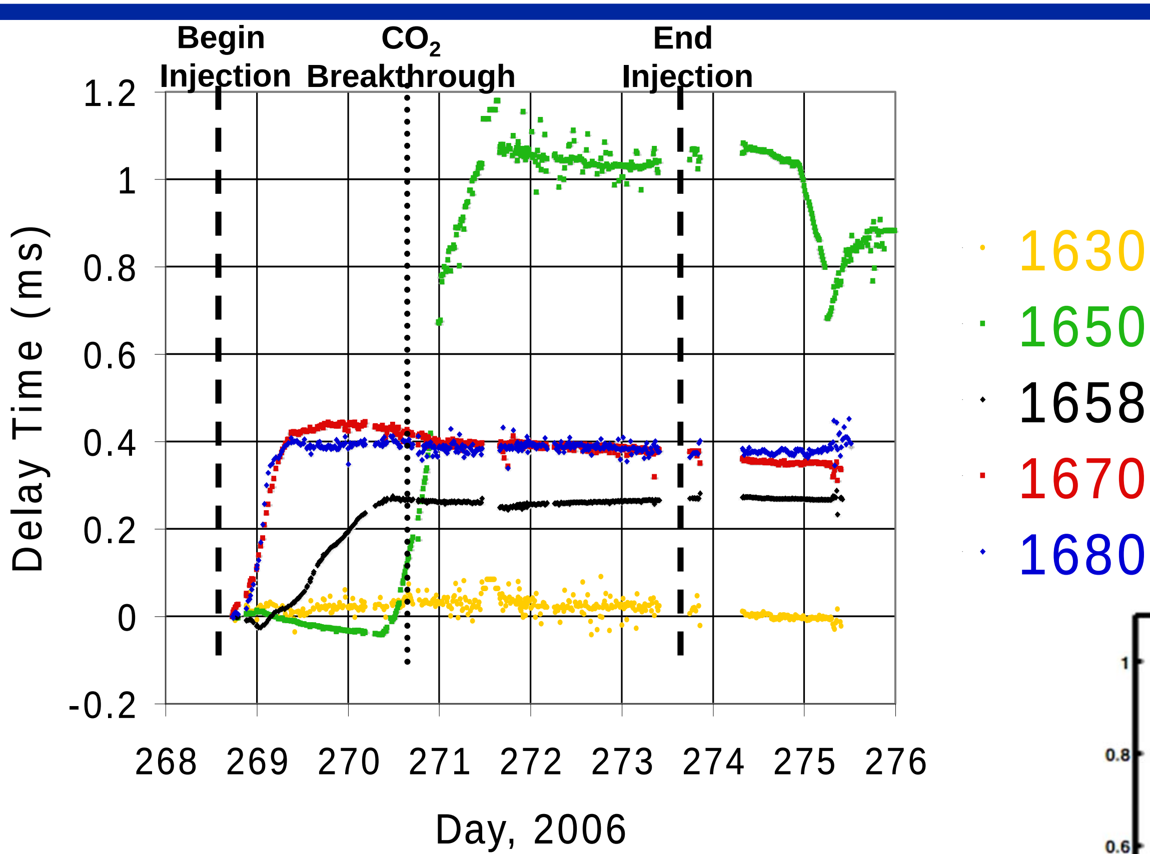
Daley, et al, Geophysics, 2007.

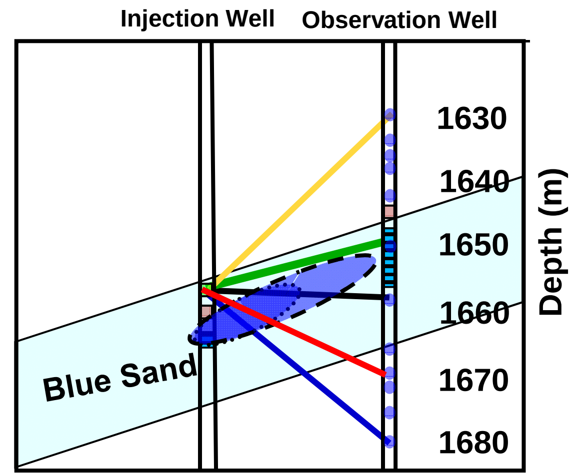
Frio-II CASSM Data (~3 Days)

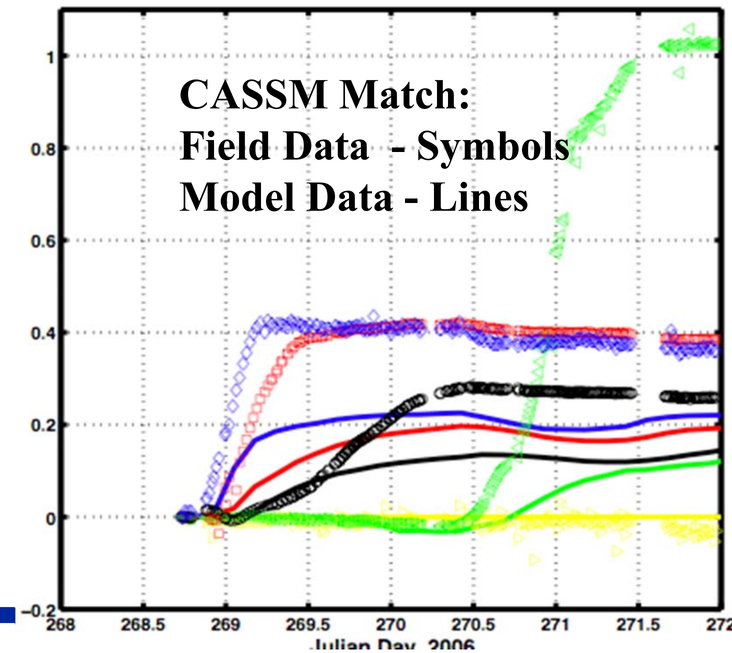
'Control' Raypath in Seal **Top Reservoir Raypath**



Frio-II CASSM Results

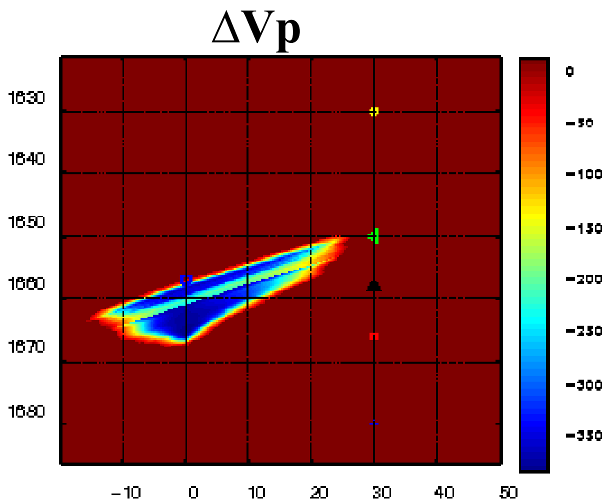




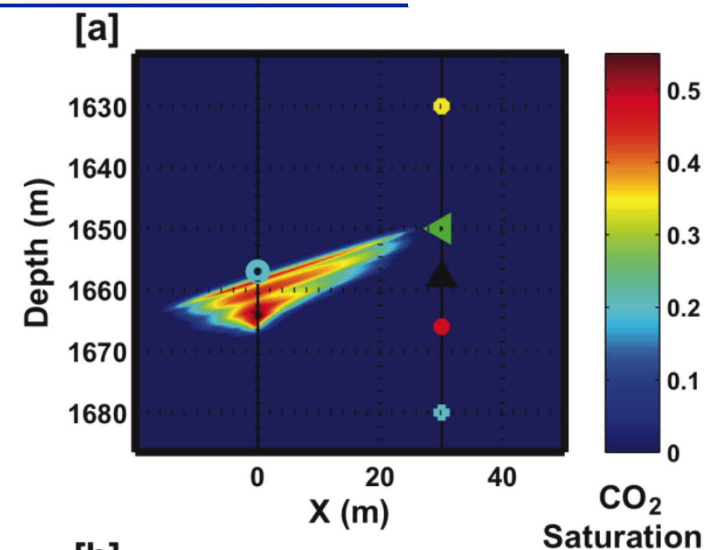


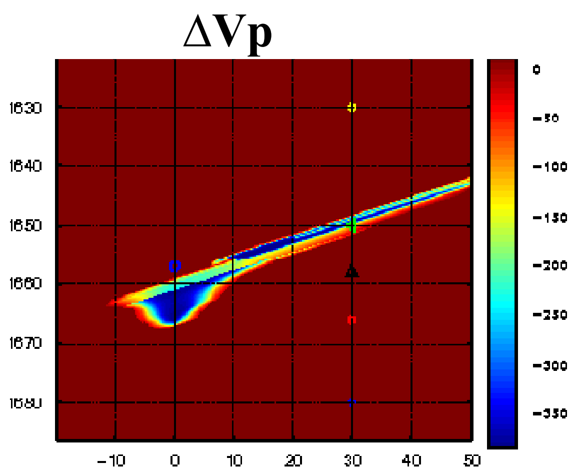
Daley, et al, 2011, IJGGC

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

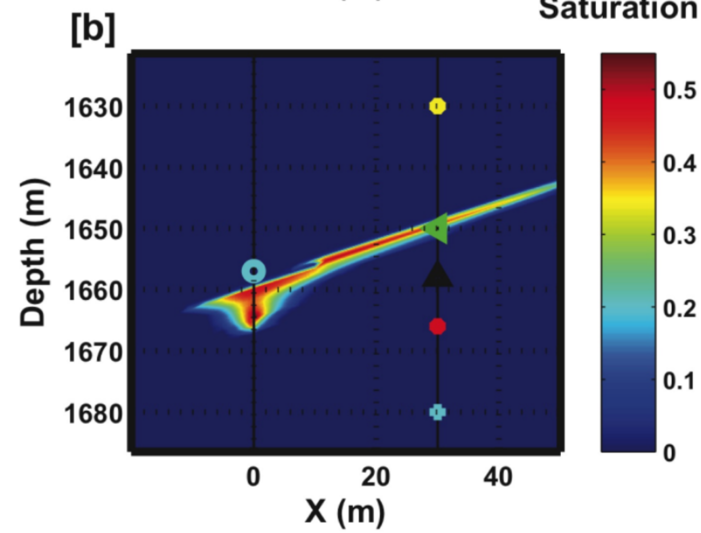


Initial model
Well Logs and Core





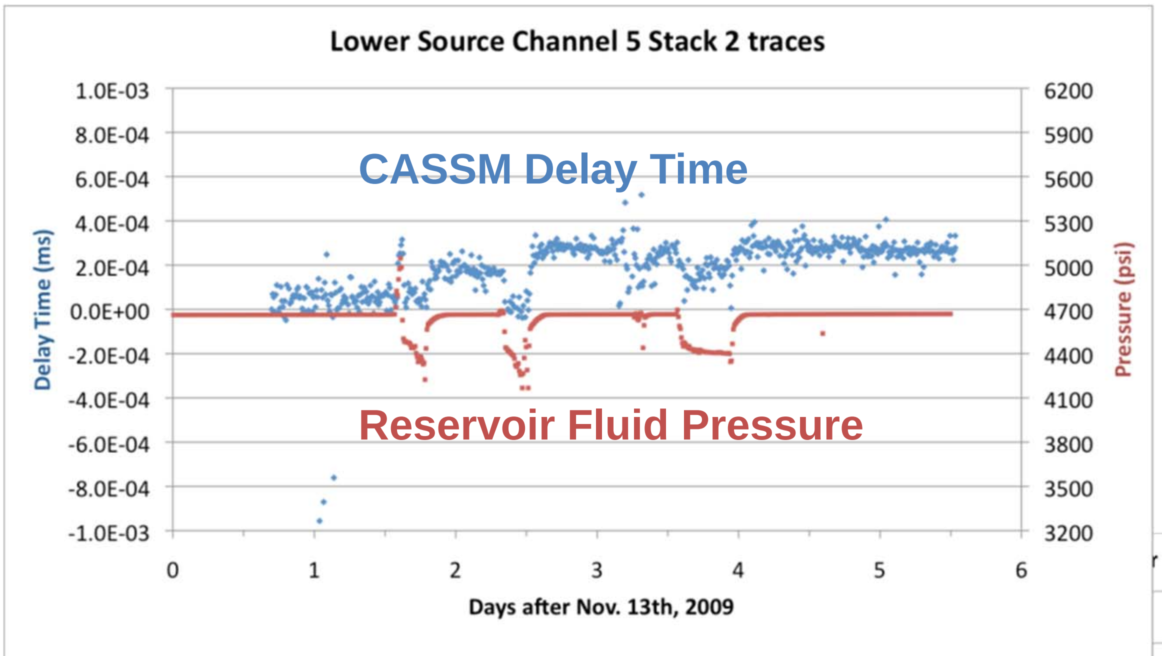
Updated model:
CASSM Constrained



CO_2 plume is affected by buoyancy more than predicted, and is thinner and longer, than original estimate, with 'step' between wells.

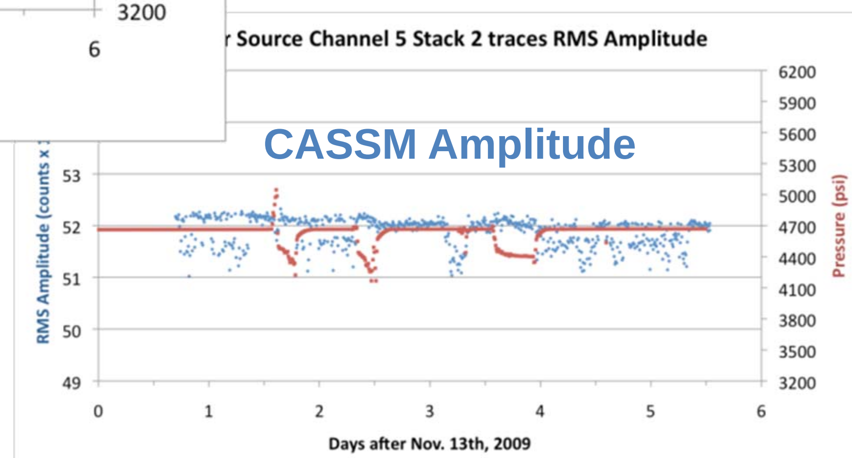
Daley, et al, 2011, IJGGC

Cranfield CASSM: Calibrating Seismic Pressure Response with Well Pump Test



Change in seismic velocity per unit change in reservoir pressure

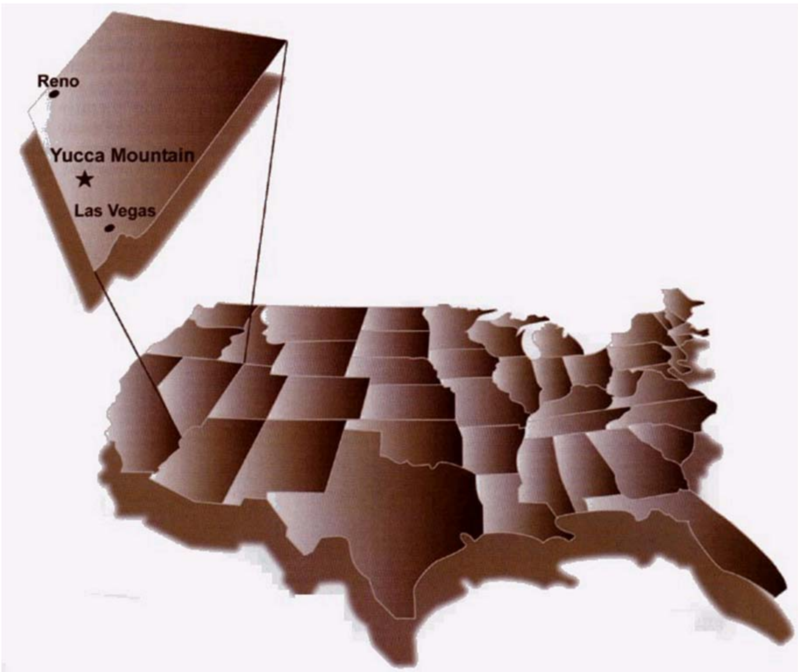
Calibration Factor:
10^{-5} m/s per 300 psi
$=3\times10^{-8}$/psi
$=5\times10^{-6}$/Mpa



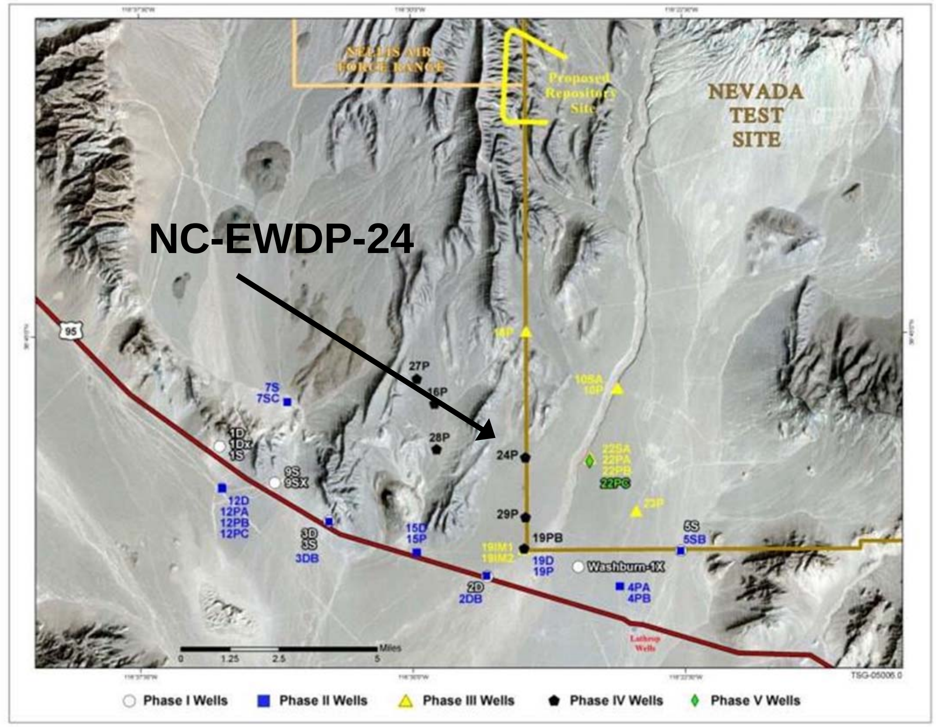
Provides important calibration for monitoring subsurface pressure with surface seismic.

T. Daley, J. Ajo-Franklin, V. Leung, LBNL

Fiber-Optic heat-pulse monitoring

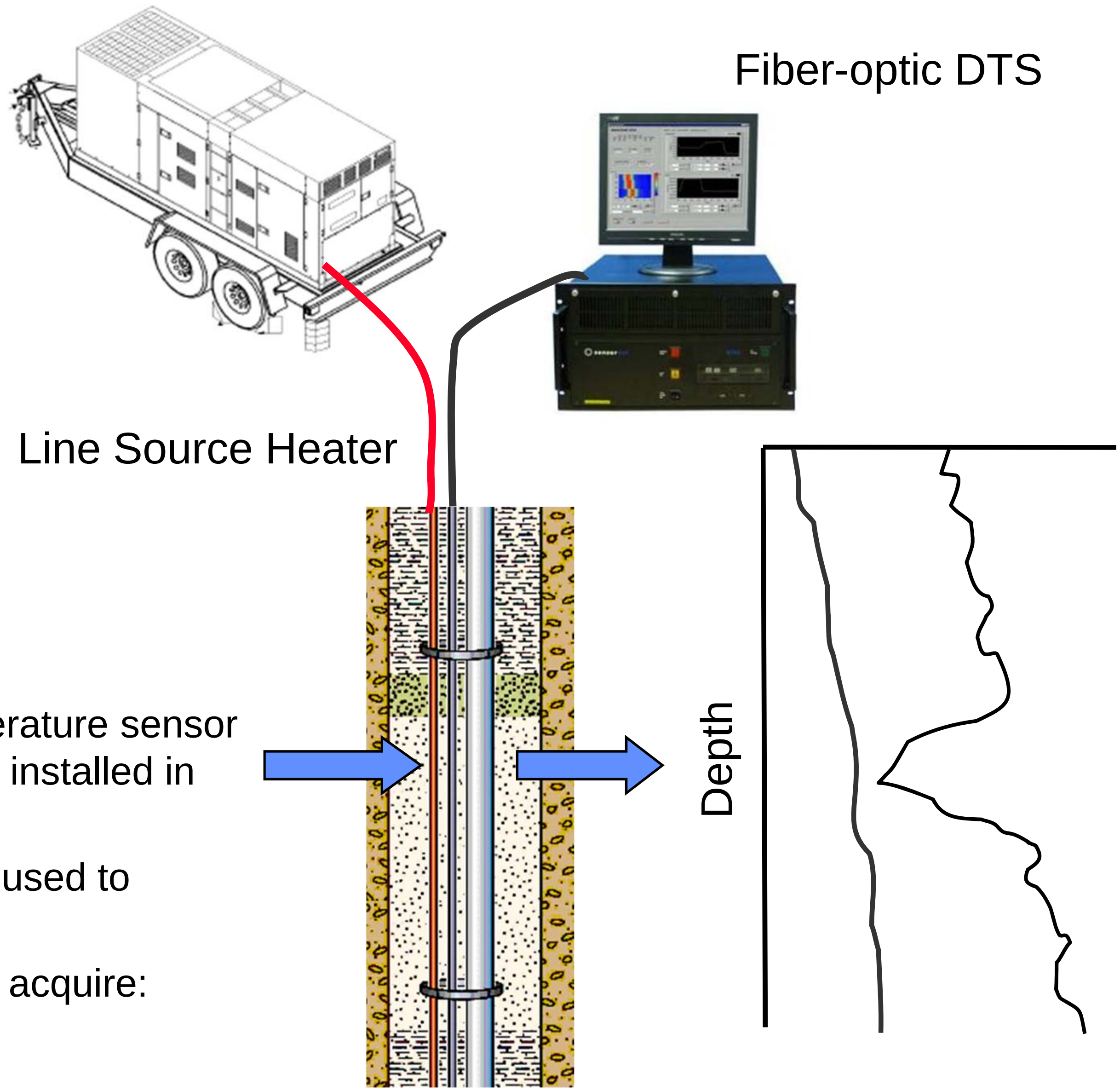


Location of the proposed monitored geologic repository at Yucca Mountain, Nevada



In 2006 unexpected observations of rapid groundwater flow using FEC logging south of Yucca Mountain required an alternate path of investigation to confirm or refute initial results

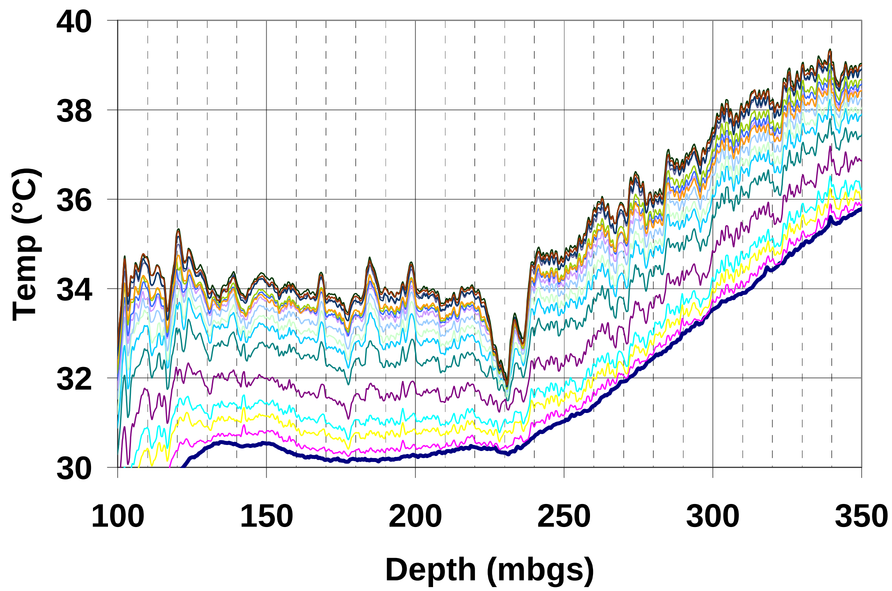
Fiber-Optic Heat-Pulse Monitoring

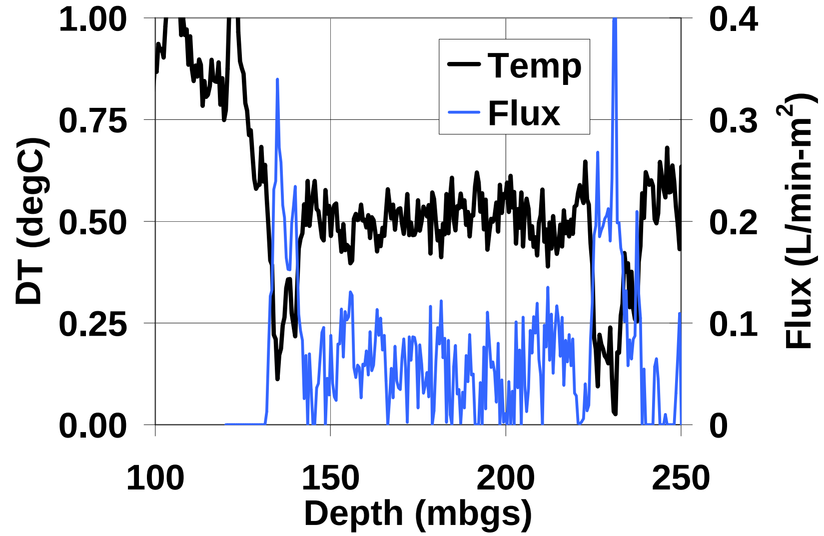


Heat-pulse measurement:

- A distributed fiber-optic temperature sensor and a continuous heater were installed in 24PB
- A sand/bentonite backfill was used to eliminate intraborehole flow
- Temperatures were logged to acquire:
  - –Baseline conditions
  - –Heating/cooling profiles

Estimation of Fluid Flux using Heat-Pulse Observations





•Distributed Thermal Perturbation Sensor data acquired while heating at 20 W/m

•The coolest temperature profile is the baseline thermal condition. Note the absence of a geothermal profile between 125 mbgs–230 mbgs

•The large thermal perturbation (230 mbgs) corresponds with the same high flux interval determined during FEC logging

The fluid flux distribution along the length of 24PB is shown. The heat-pulse high flux zones corroborate the FEC logging results

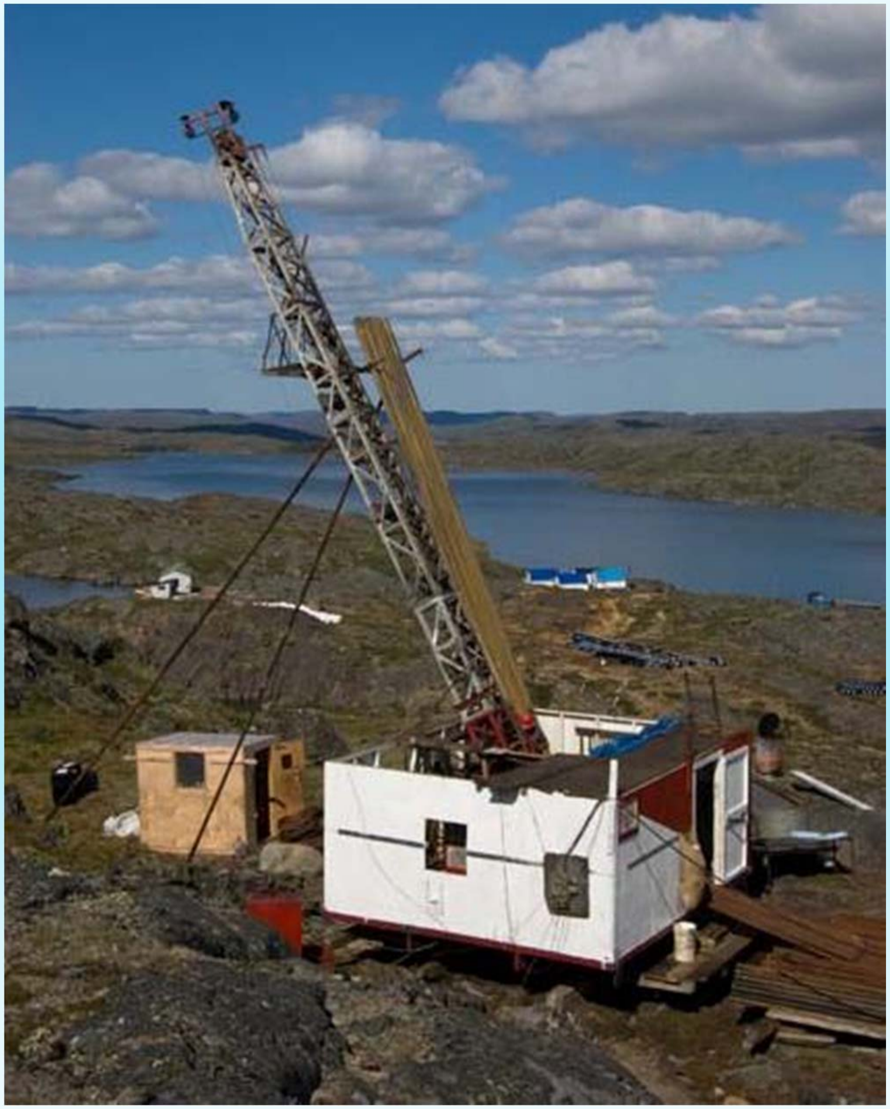
2nd Heat-pulse example: High Lake Mineral Exploration Site, Nunavut Terr., Canada

- Use the DTS to obtain a baseline temperature profile

- Given the heterogeneous thermal conductivity profile, use heat-pulse to estimate thermal conductivity

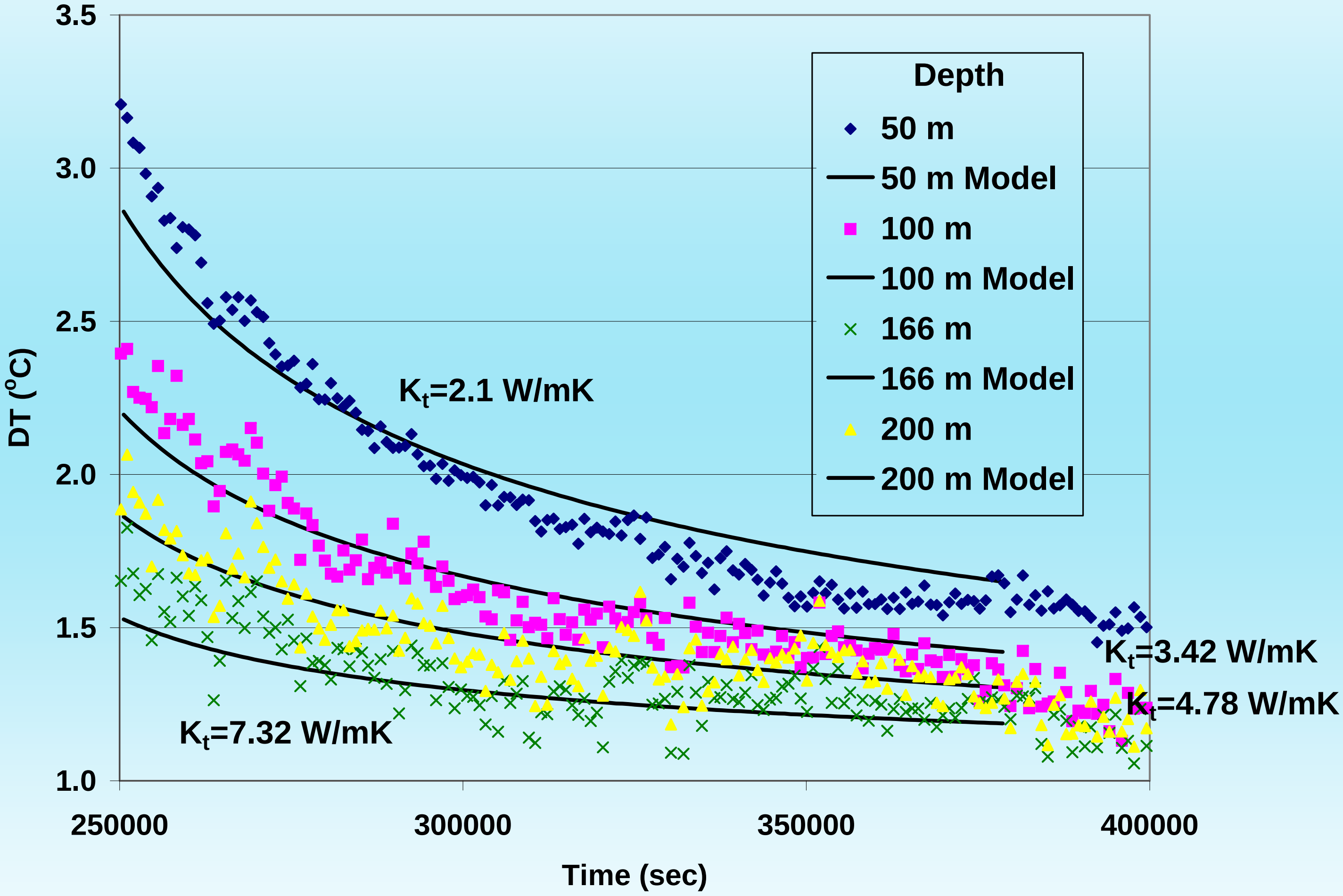
- Determine paleoclimate through ground surface temperature history reconstruction

High Lake heat-pulse installation

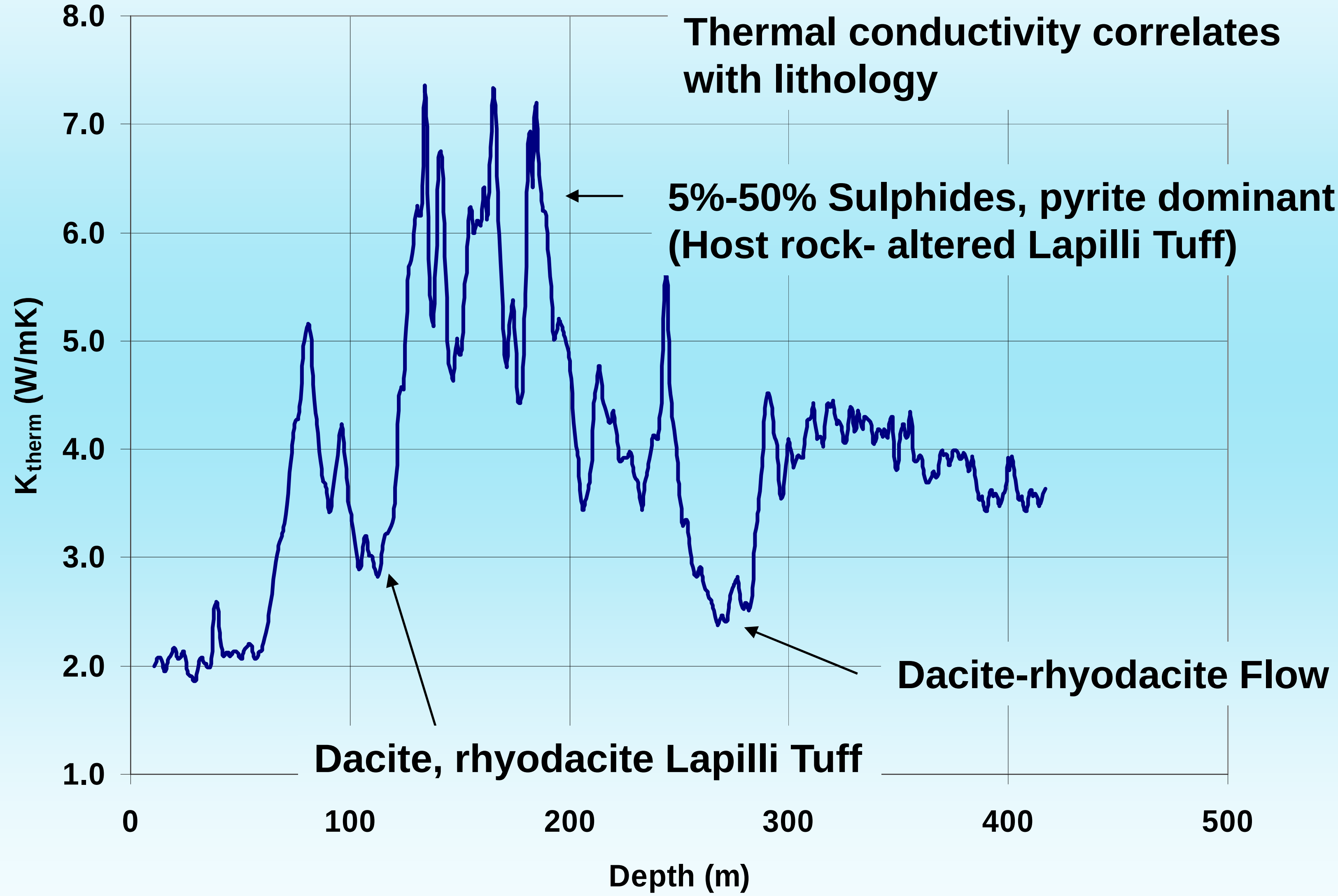


- Multifunctional completion for geochemical sampling and physical property measurement in 75 mm borehole
- Polyethylene sheathed multimode fiber-optic cable and heating cable lowered to near the base of the permafrost
- Downhole pressure/temperature sensor to provide a calibration reference
- U-tube below packer

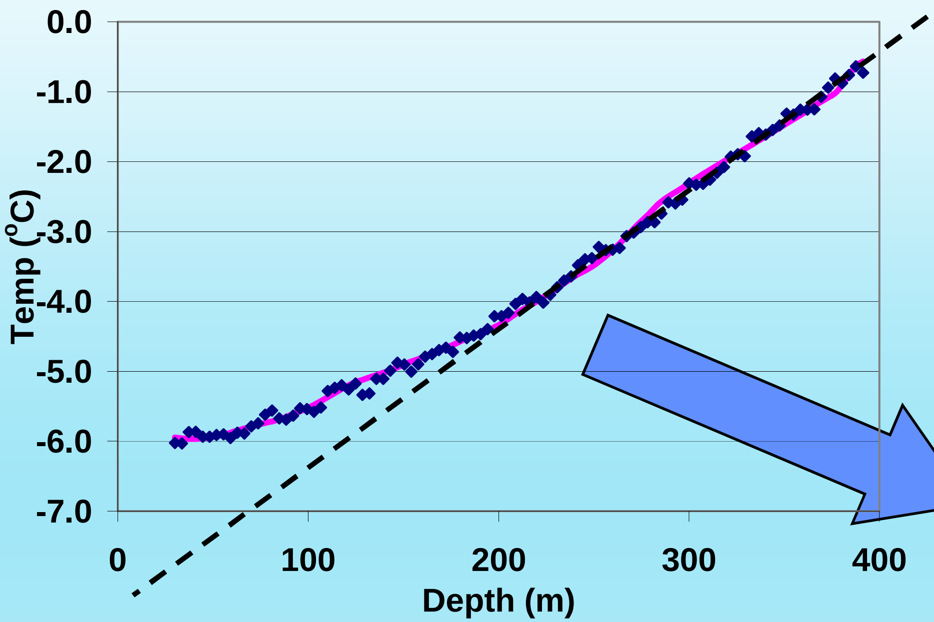
Estimate K_{therm} using *in situ* data – assume radial conduction



Estimate K_{therm} using *in situ* data – assume radial conduction

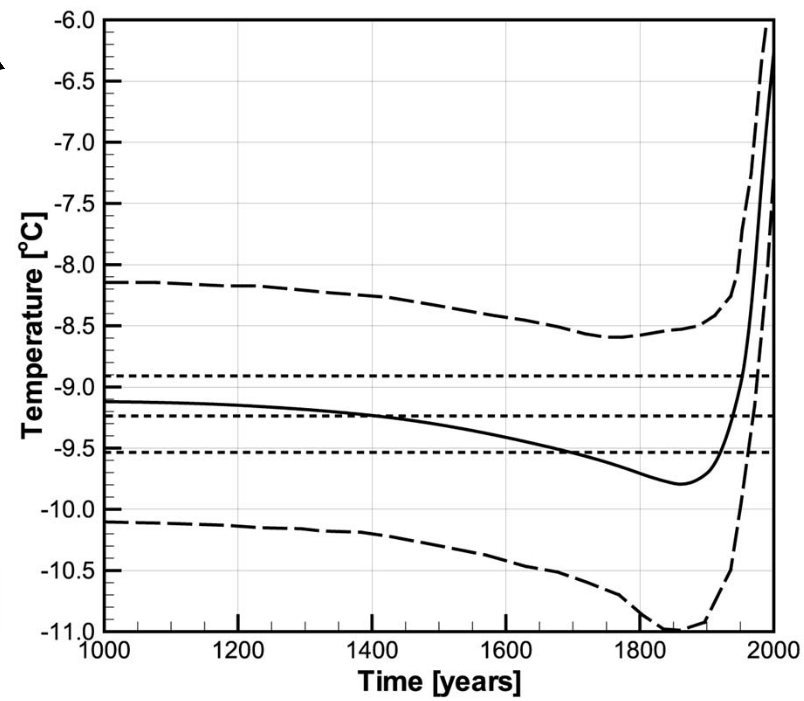


Ground Surface Temperature History



Using iTOUGH2 code invert baseline temperature profile.

- **Use vertical 1-D model with heat conduction and estimated Kt values**
- **Model parameters**
  - **-Geothermal Heat Flux**
  - **-Ground surface temperatures**



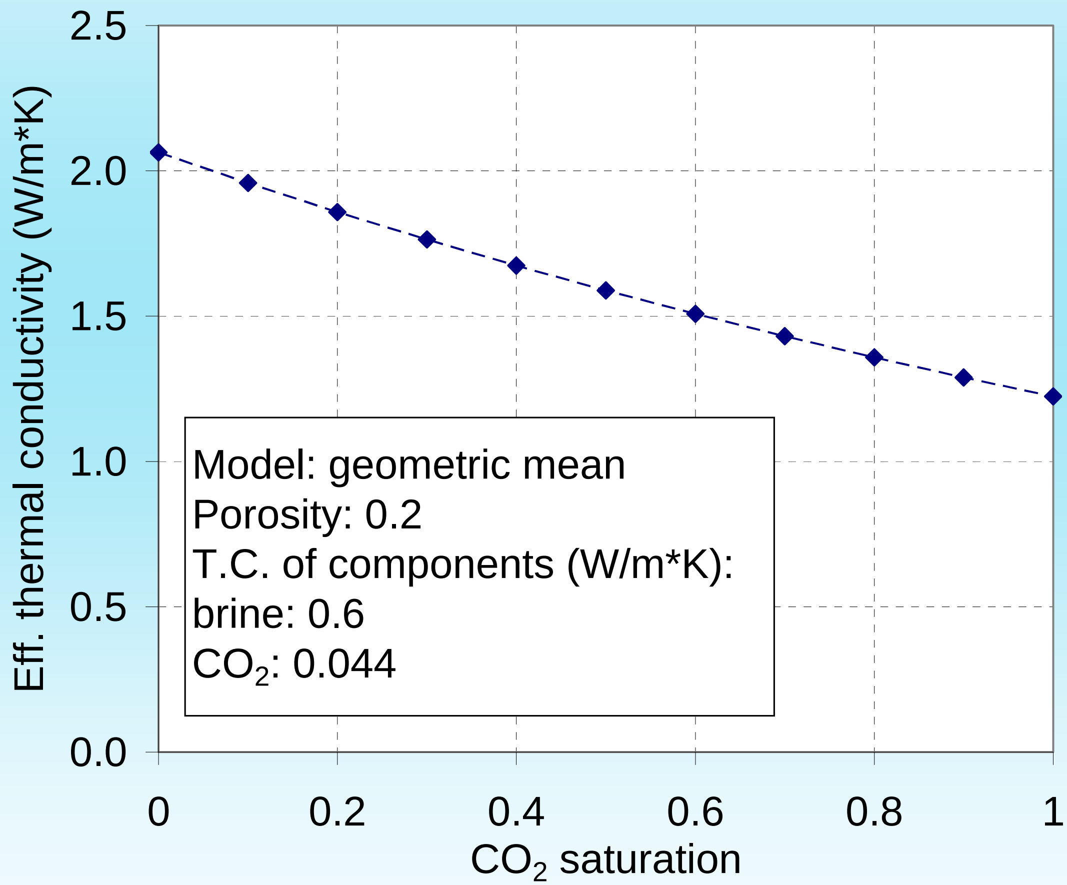
Freifeld, B. M. et al., *Geophys. Res. Lett.* 35, L14309, (2008)

GSTH Predictions:

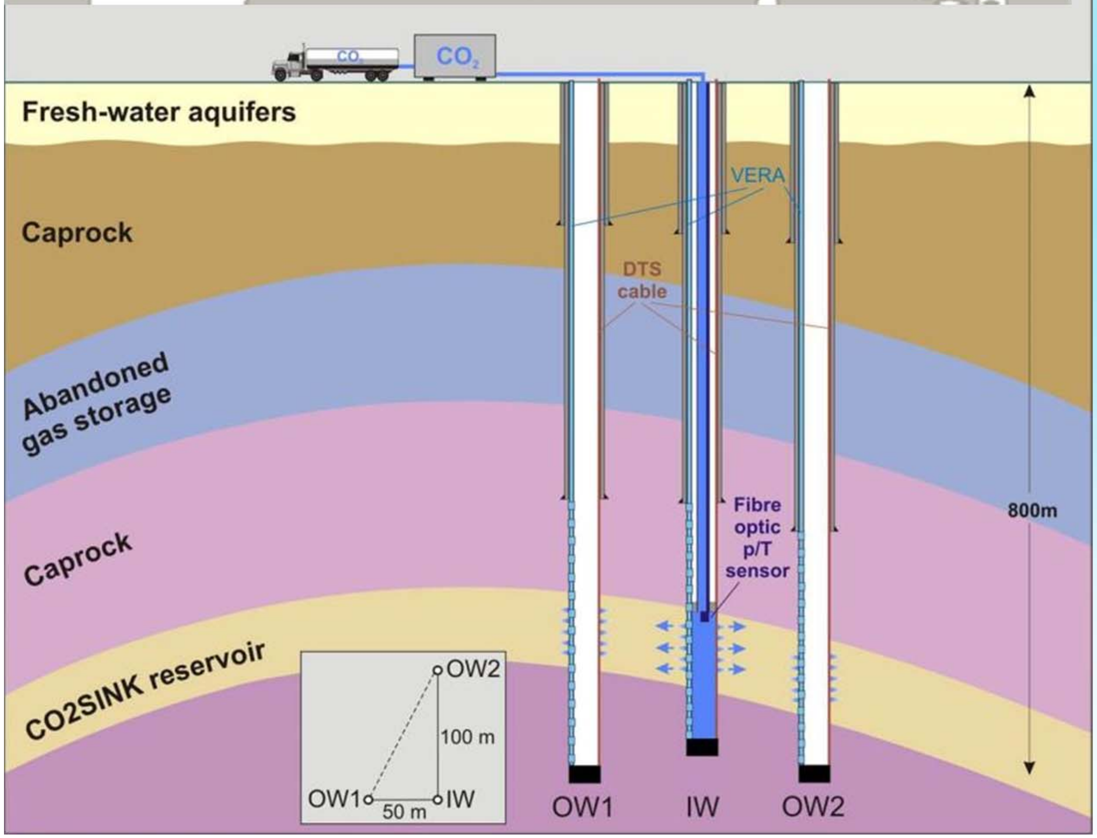
- **Geothermal heat flux estimate 67±1 mW/mK**
- **GST has increased 3.0 ± 0.8°C over the long term average**

Heat-Pulse for CO_2 sequestration

$K_{therm} = f(CO_2sat)$

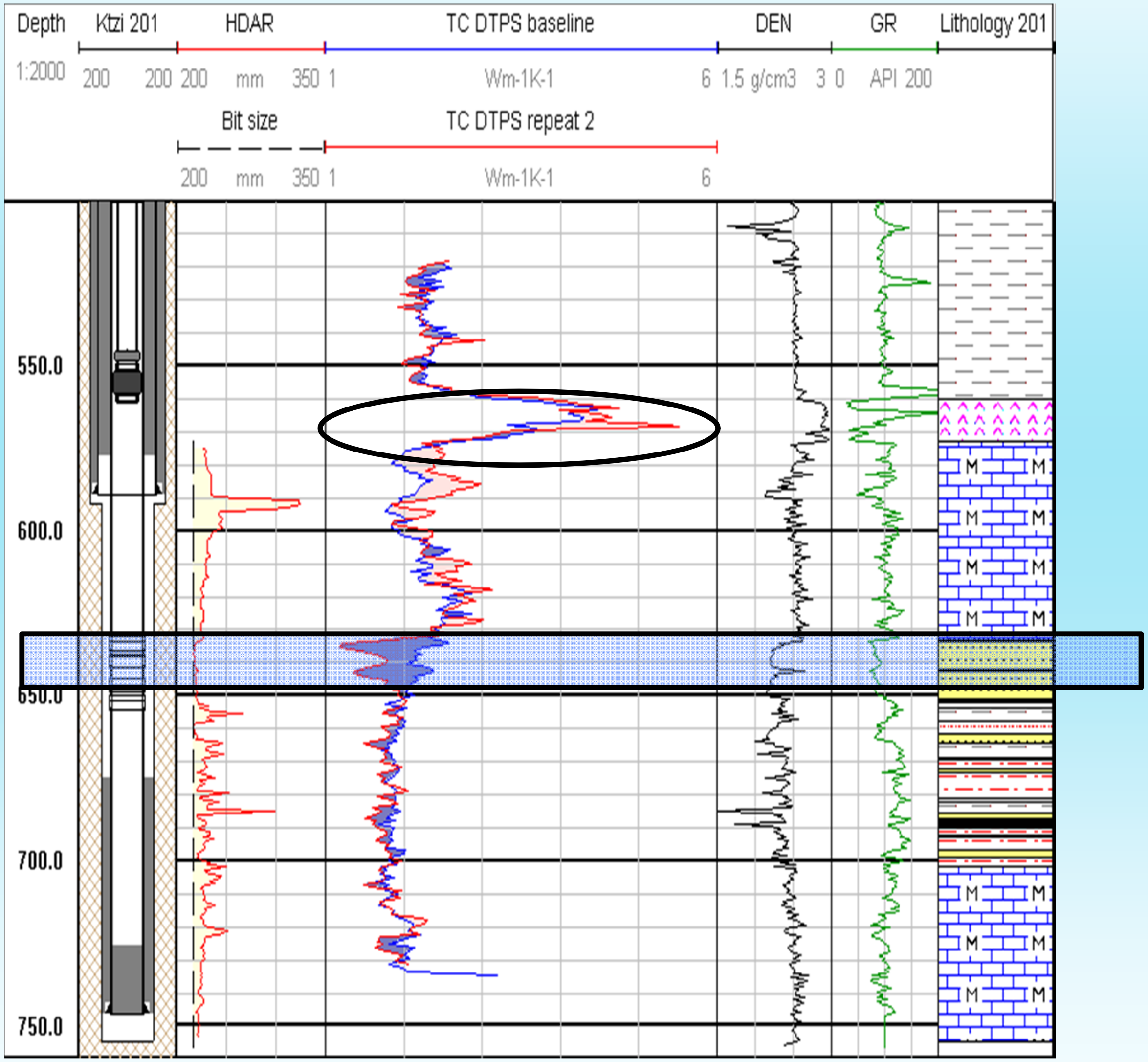


About 40% reduction of effective t.c. by replacing brine by CO_2



In collaboration with Dr. Jan Henninges, GFZ, Potsdam

Thermal conductivity repeat DTPS Ktzi201 (after start of CO_2 injection)



Good overall fit to baseline results (e.g. K2 marker horizon).

Distinct zone with decrease in thermal conductivity: main zone of CO2 injection.

No clear indications for CO2 below „main“ injection interval.

Collaboration with J. Henninges, GFZ, Potsdam

Can we integrate our monitoring tools into a single robust deployment package?

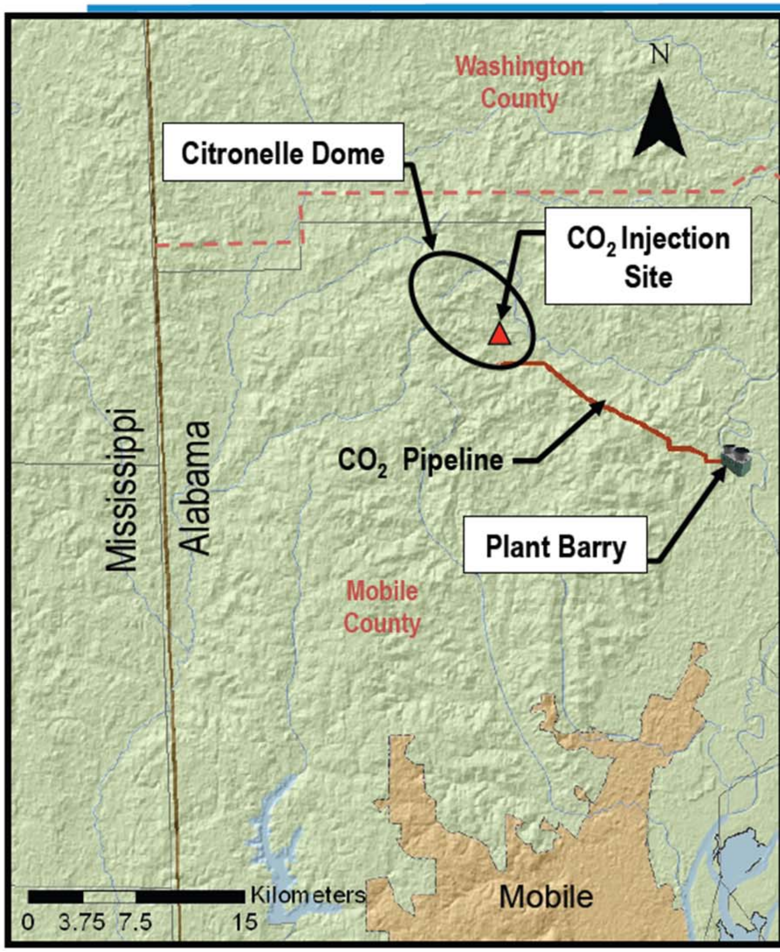
Modular Borehole Monitoring System

CO_2 Capture Project

Funding provided by CO_2 Capture Project to implement a Modular Borehole Monitoring (MBM) System, building on the lessons learned from prior deployments.

CCP/Modular Borehole Monitoring System

SECARB's Phase III Anthropogenic Test



Project Schedule and Milestones

The CO_2 capture unit at Alabama Power's (Southern Co.) Plant Barry became operational in 3Q 2011.

A newly built 12 mile CO_2 pipeline from Plant Barry to the Citronelle Dome completed in 4Q 2011.

A characterization well was drilled in 1Q 2011 to confirmed geology.

Two injection wells were drilled in 4Q 2011.

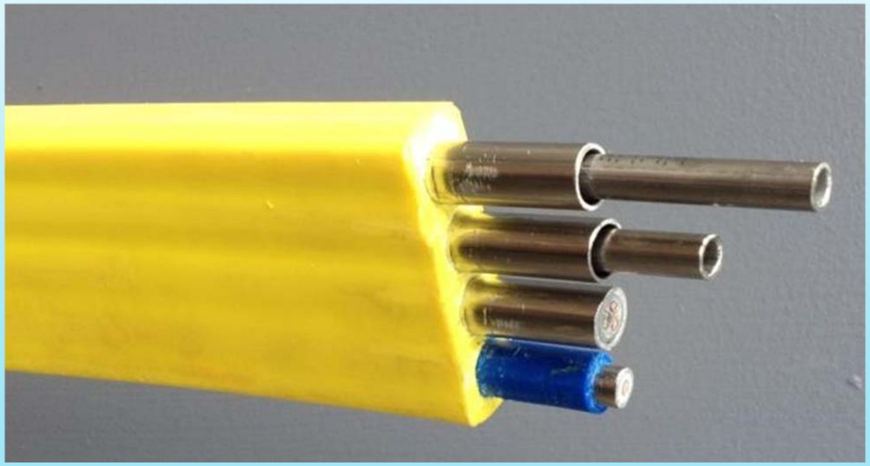
100 to 300 thousand metric tons of CO_2 will be injected into a saline formation over 2 to 3 year period beginning in summer of 2012.

3 years of post-injection monitoring.

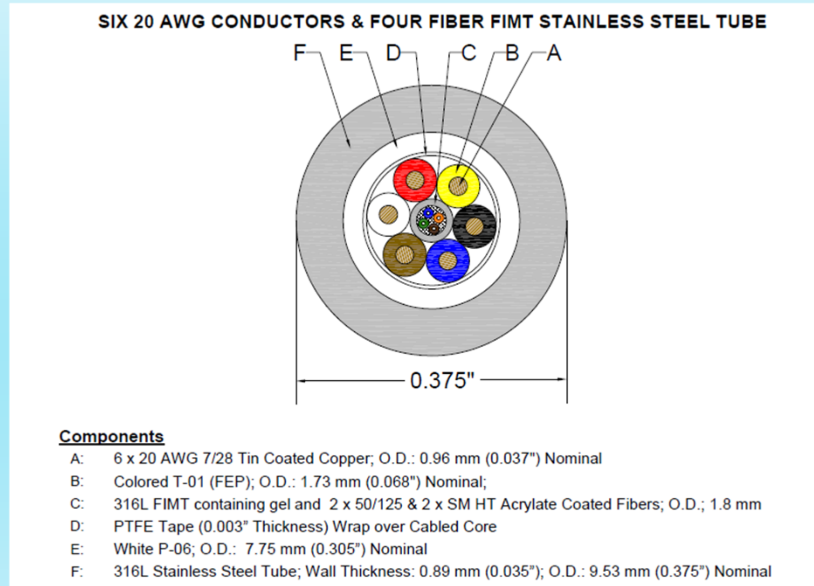
Ref: Riestenberg, ARI 2012

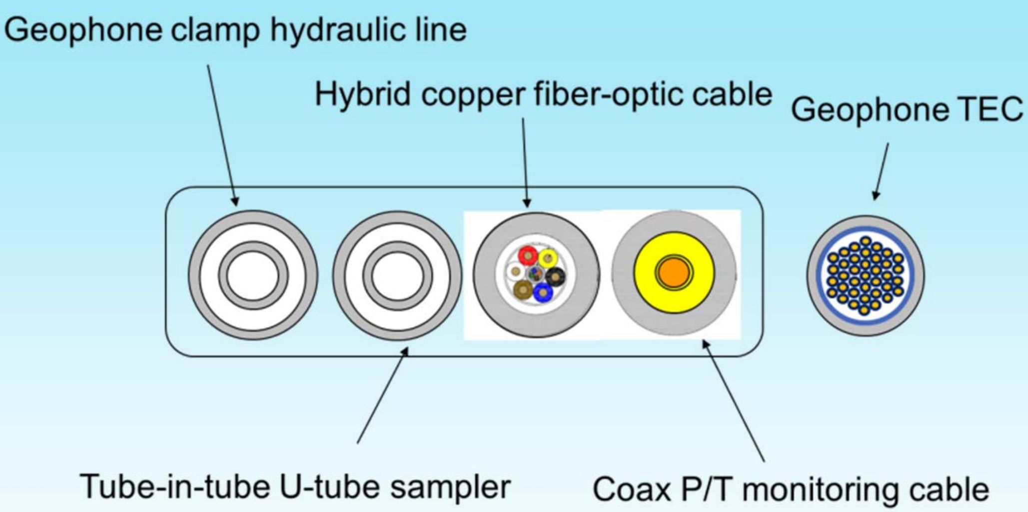
2012 SECARB Citronelle Pilot: MBM Multifunction Flat-Pack for Tubing Deployment

Flatpack replaces 7 lines



Combined DTS, Heater, DAS hybrid copper/fiber-optic cable





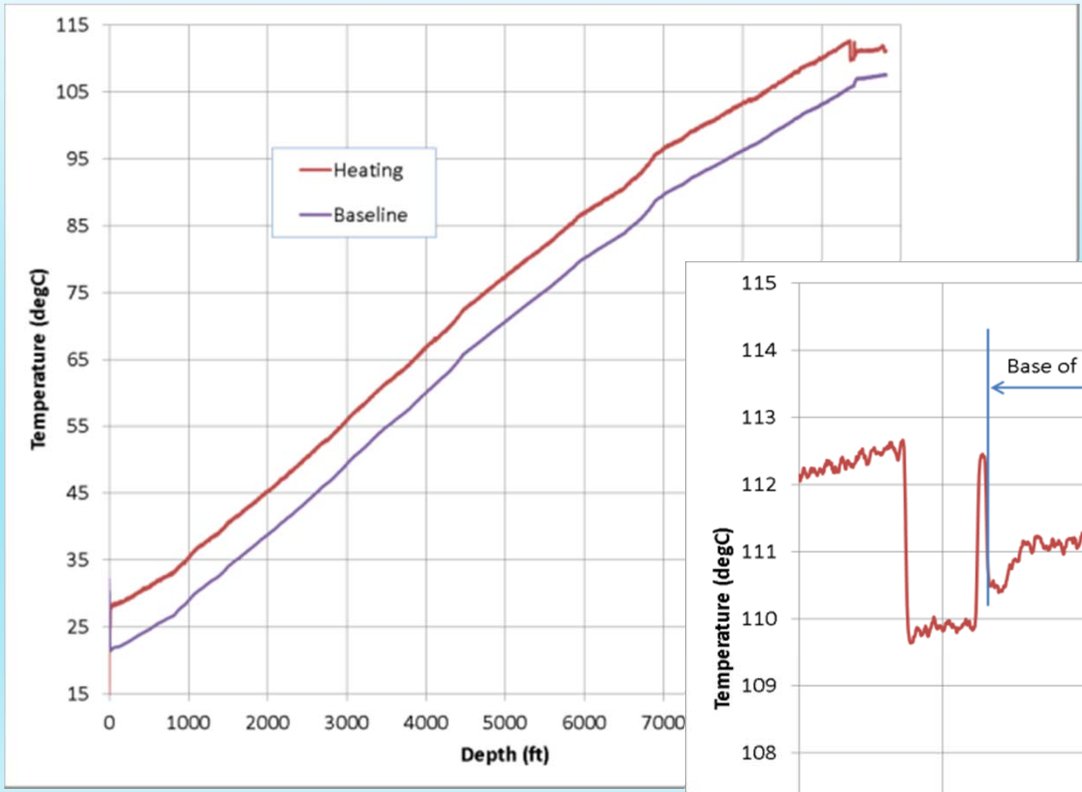
Welded Geophone Line
Paulsson Inc.

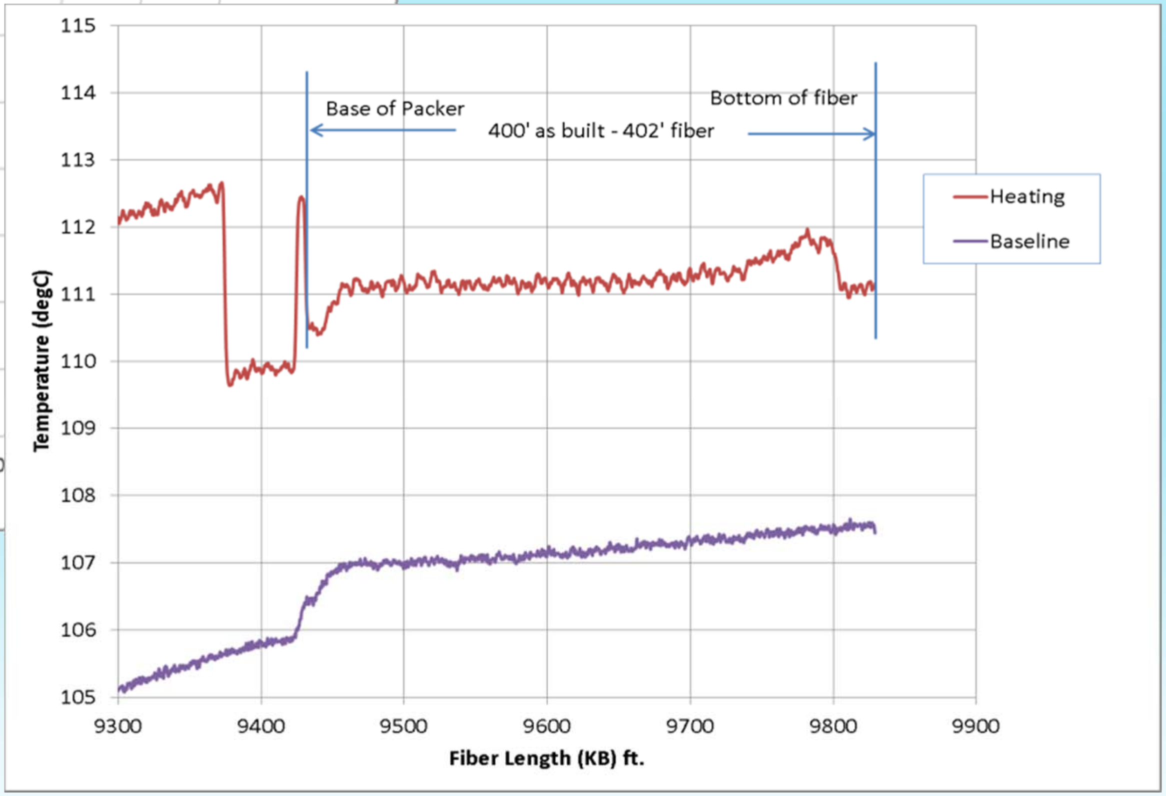
Freifeld, Cook and Daley, LBNL & SECARB

Much more manageable operation with only three spools…

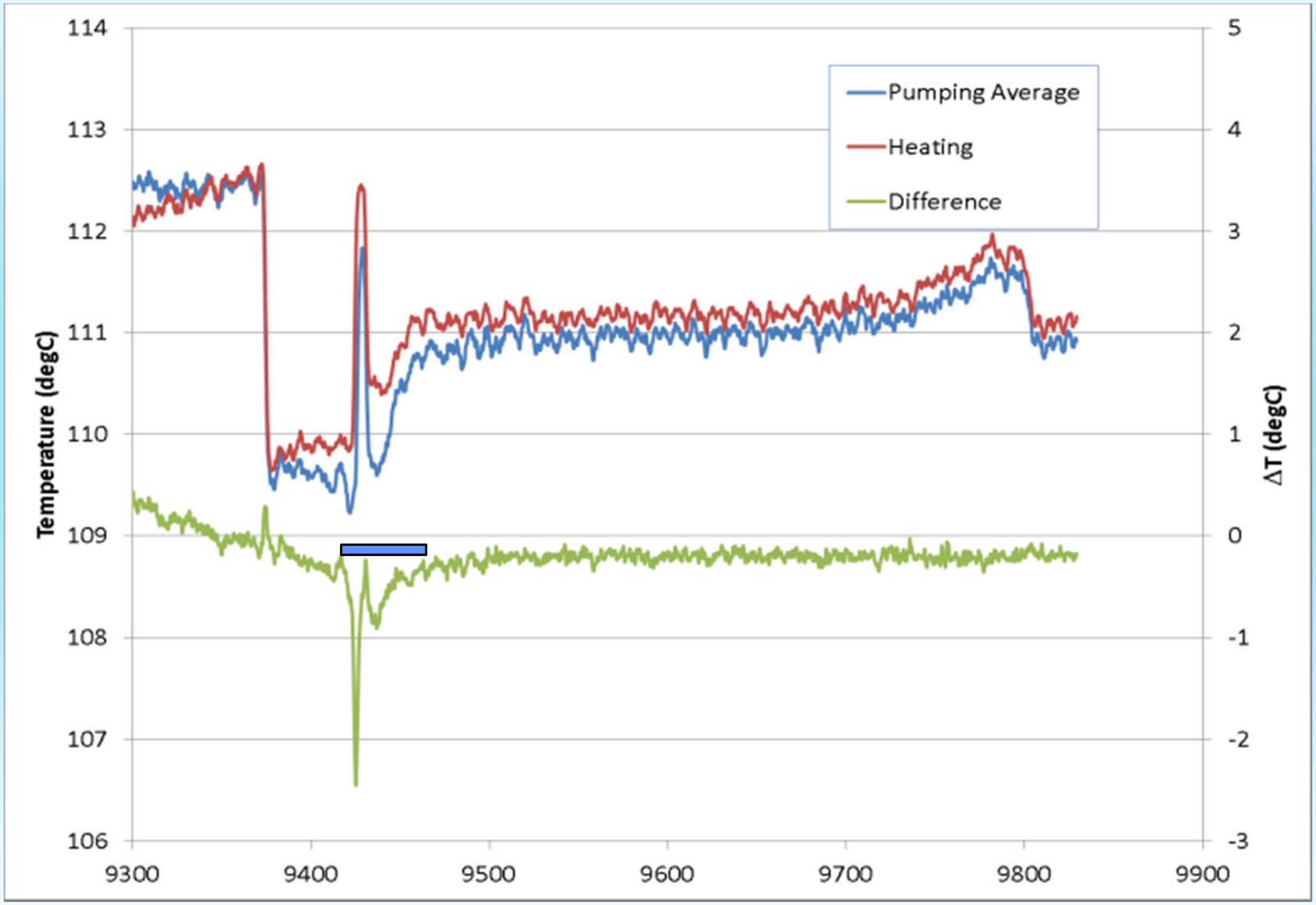
Tubing Deployed Clamping Geophone

DTS Heat-Pulse Helps Image Well Completion



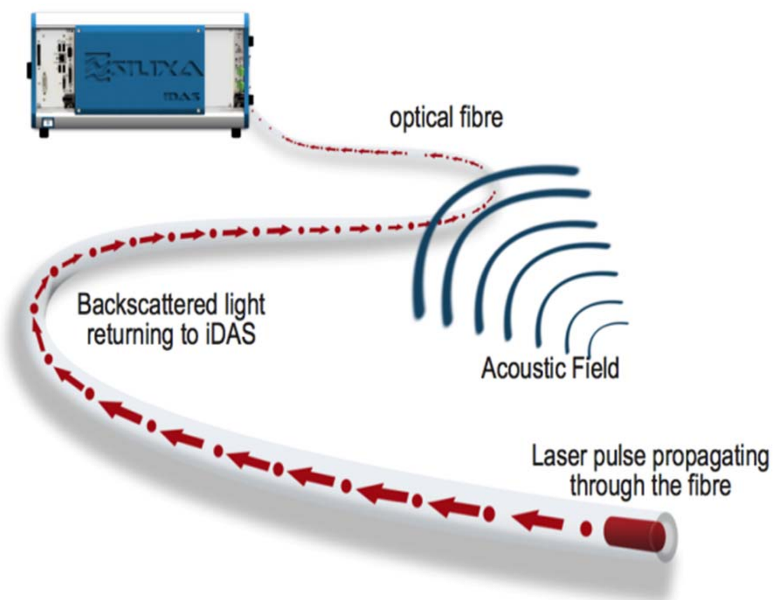


Flow profiling – Identify location of 30 ft perforated interval



Research Frontiers:
Fiber-optic Distributed Seismic

What is DAS? How does it work?



- Light pulses are sent into a standard optical fibre
- Backscattered optical signal is analysed to continuously monitor local changes in optical reflectivity resulting from local dynamic strain of the fibre
- Output stream is converted to seismic records that are effectively continuous in both distance and time
  - Typically 1 or 2 m and 1-10 kHz

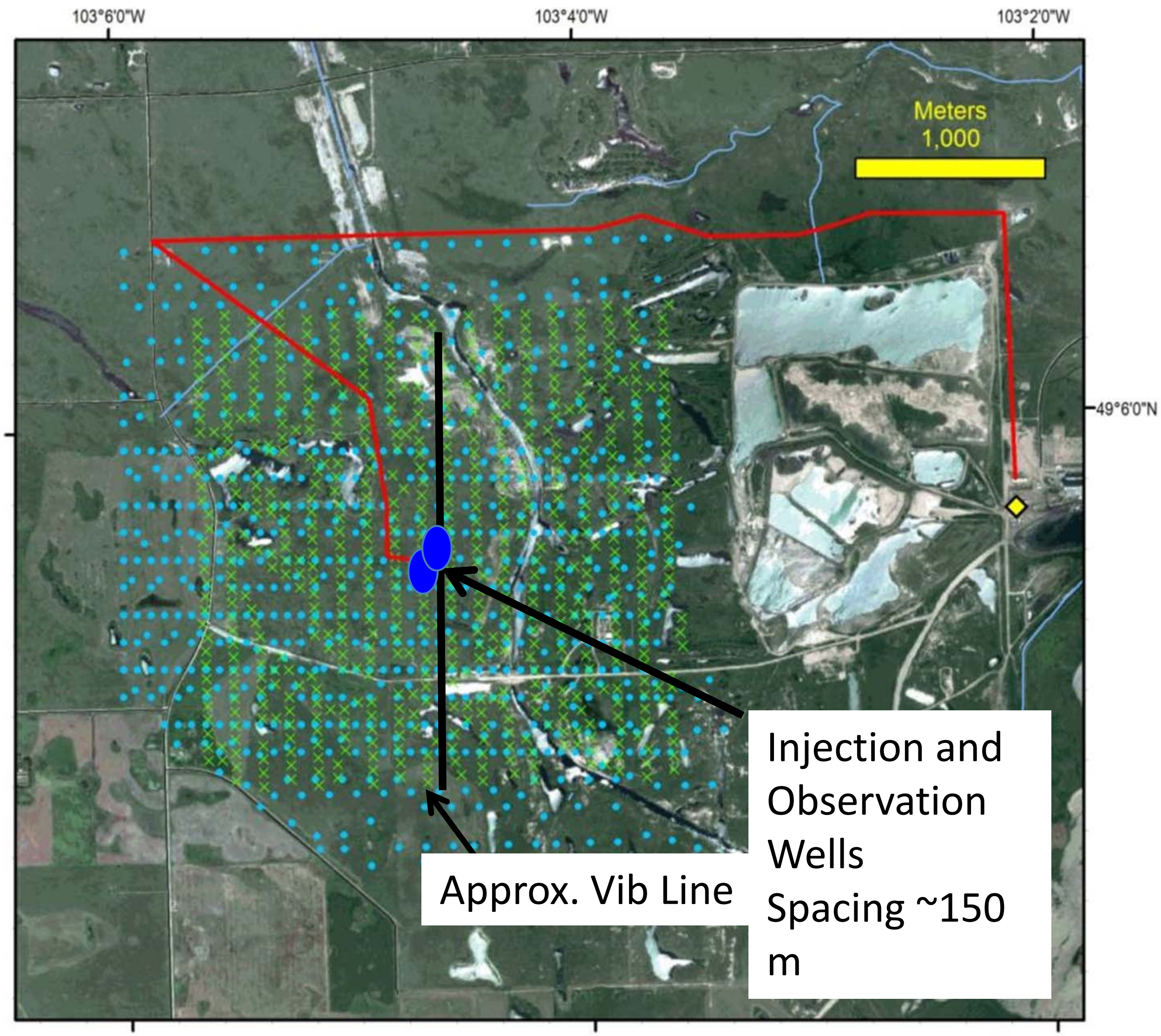
Comparison of DAS and Conventional Technology

- **Sources**:
- 682 dynamite shots,
  - 1 kg at 15 m depth
- 2 vibroseis
  - 44,000 lbs Vibroseis force run at 70%
- 54 VP's

- **<u>Recorders</u>**:
- GSR-1 surface recorders,
  - continuous mode, not triggered
- Sercel WaveLab recorder
- SM and MM DAS recorders

- **<u>Sensors:</u>**
- 630 surface 3C geophones
  - 20m depth in 3 x 3 km array
- 54 live 3C geophones
  - 1470 – 2355 m depth
- 1x Single mode (SM) fiber
  - outside OBS well casing to 2867 m
- 2x Multi-mode (MM) fiber
  - outside OBS well casing to 2867

Permanent Surface Seismic Sensors (Green); Explosive Shot Holes (Blue); Vibroseis Test Line



DAS Data Processing: Noise Reduction and Spectral Rebalance

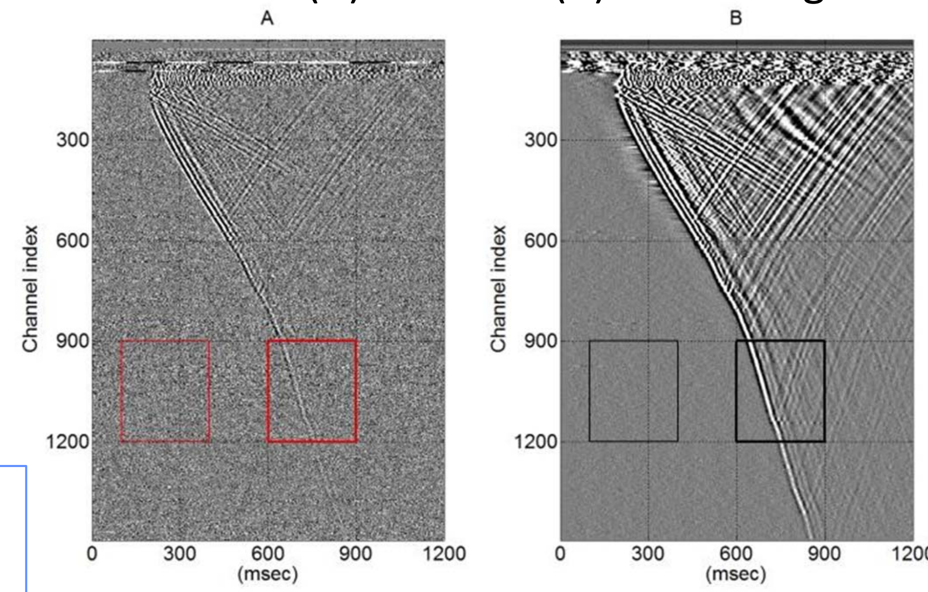
Noise Reduction

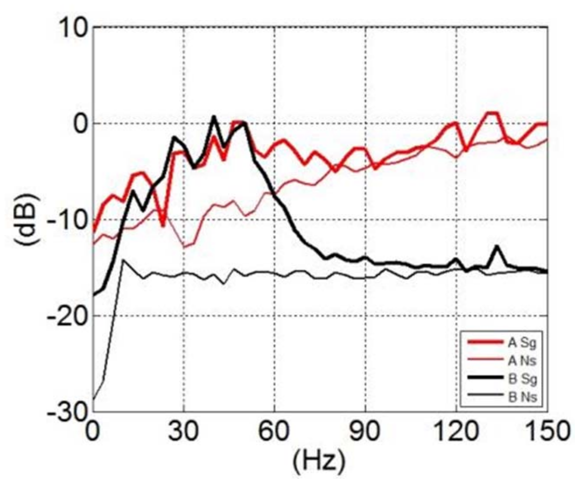
- The statistics of the scattering processes influence the noise on the resultant acoustic signal.
- Advanced adaptive stacking algorithms allow the stacking to become far more efficient, *<u>giving SNR improvements in excess of one order of magnitude.</u>*

Adaptive Rebalance:

- The native output is <u>strain rate</u> along the sensing fibre.
- Noise-adaptive rebalancing combines optimally weighted averaging with rebalancing of the temporal spectrum which, to good approximation, gives strain
- Result: ***<u>axial strain</u>***
    - not the native strain-rate

Pre (A) and Post (B) Processing

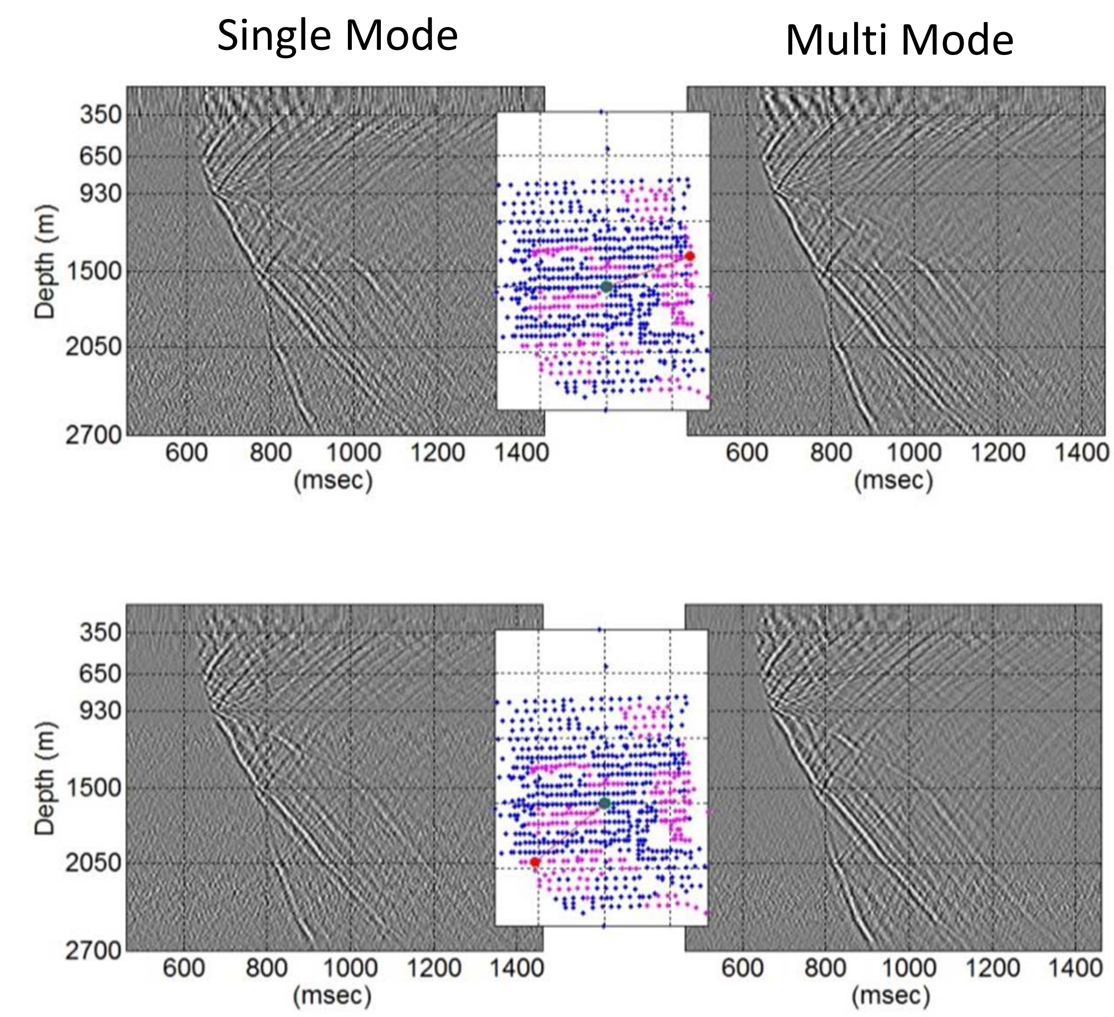




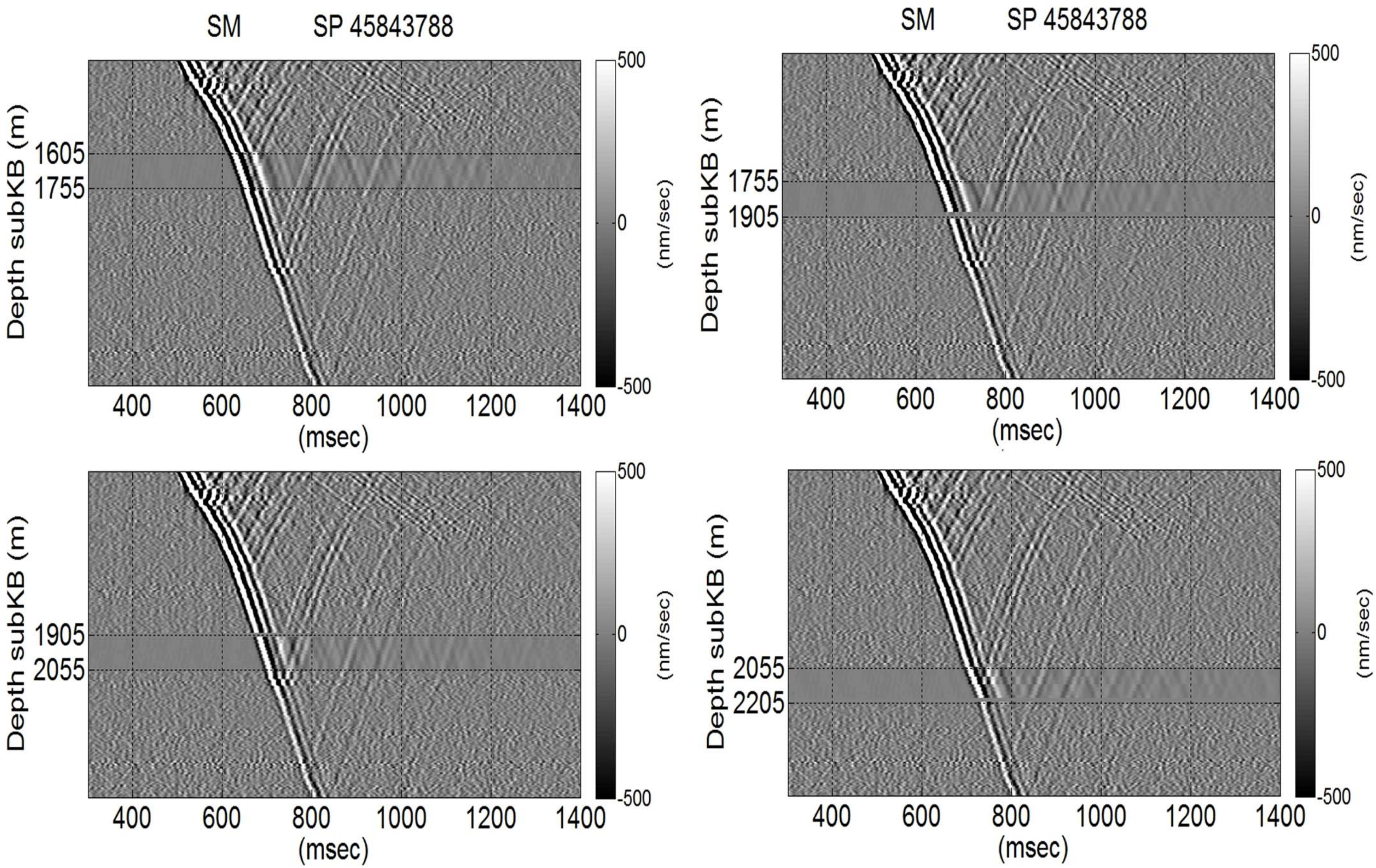
Signal and Noise Spectra:
Pre – Red
Post - Grey

Aquistore DAS Data: Multi-Mode and Single-Mode

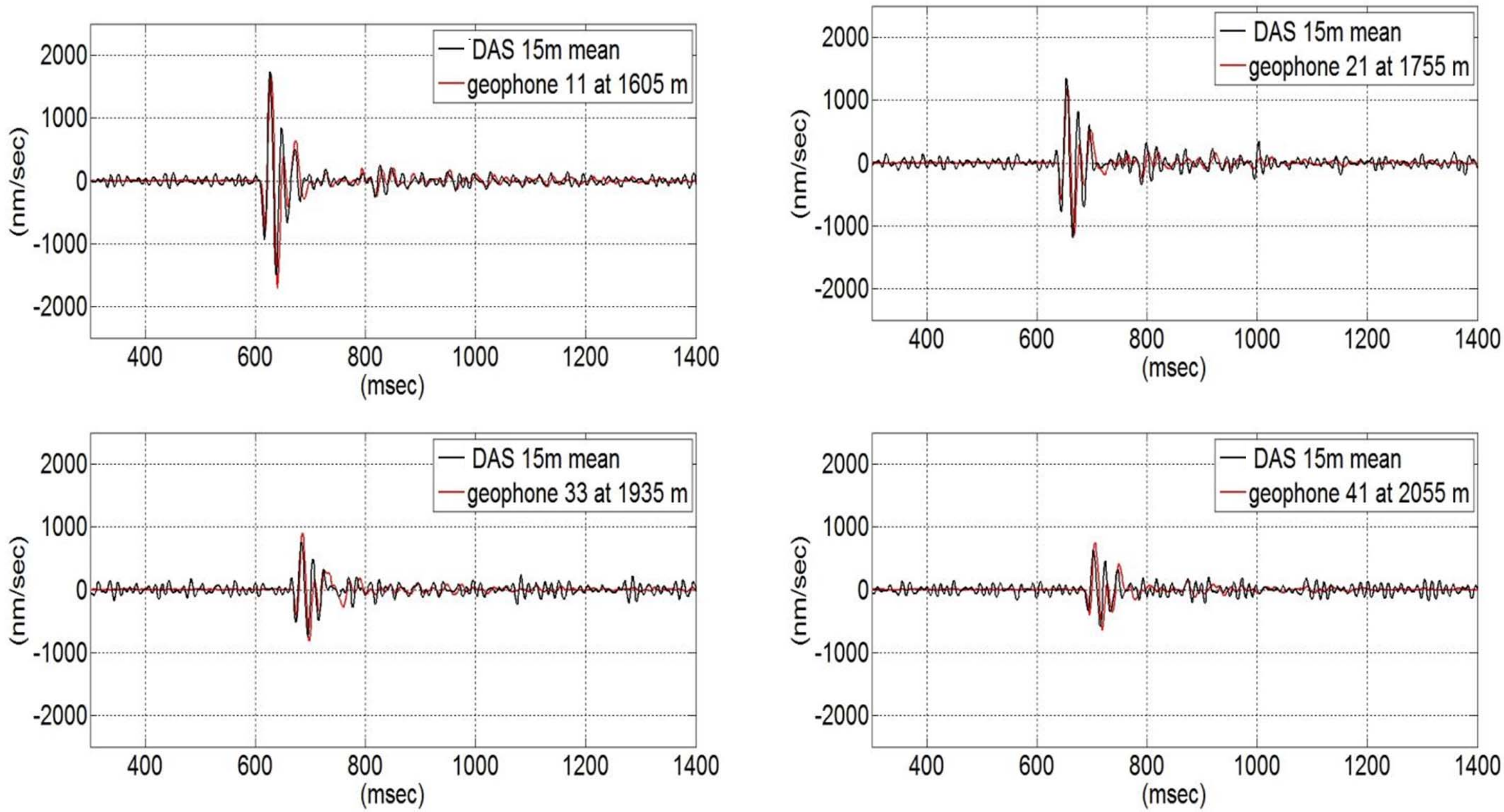
- The Aquistore Observation well has both single-mode and multi-mode in the same cable cemented behind casing
- Previously, DAS required single-mode fibers
- Most existing fibres used for Distributed Temperature sensing (DTS) are multi-mode (MM)
- This field trial showed that DAS performs well with either type of fibre



Comparison: DAS and Geophone
Subset of Depths in Each Plot



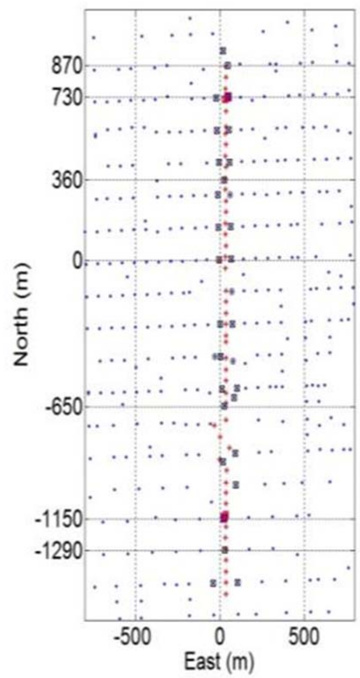
Geophone and DAS: Noise Constant as Signal Decreases



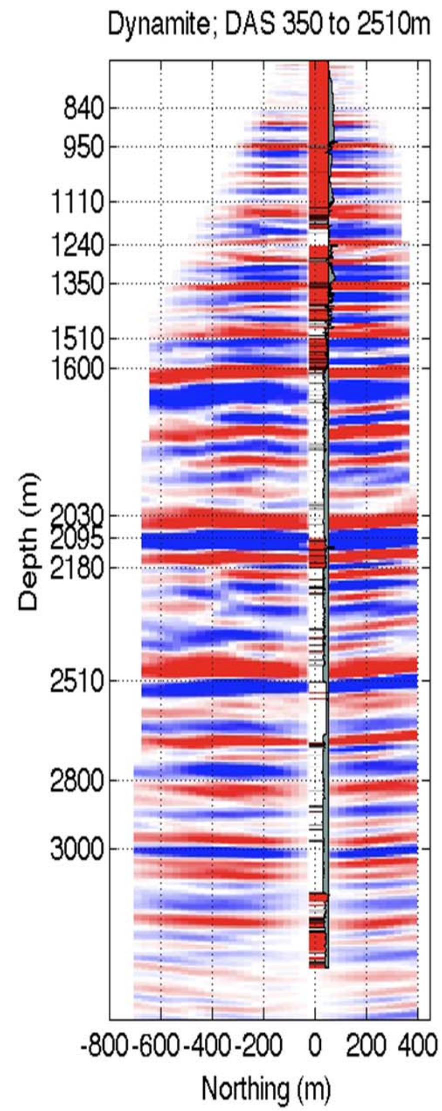
DAS 2D Walkaway: Dynamite vs Vibroseis Comparison

- Started with denoised data as recently delivered
- Processed Walkaway & comparable dynamite lines using chain specified
- Sensors 350 - 2510 m
- Generally good quality
  - some differences due to geometry differences

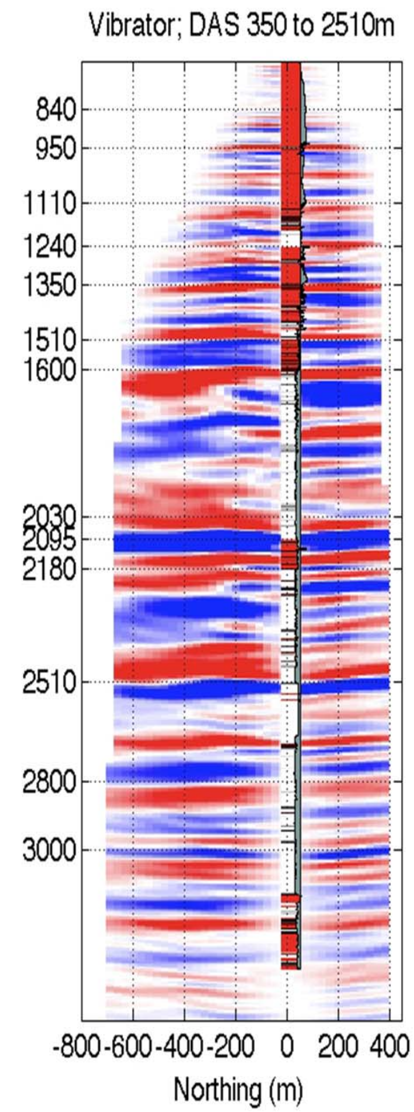
Vib and Exp Shot Points



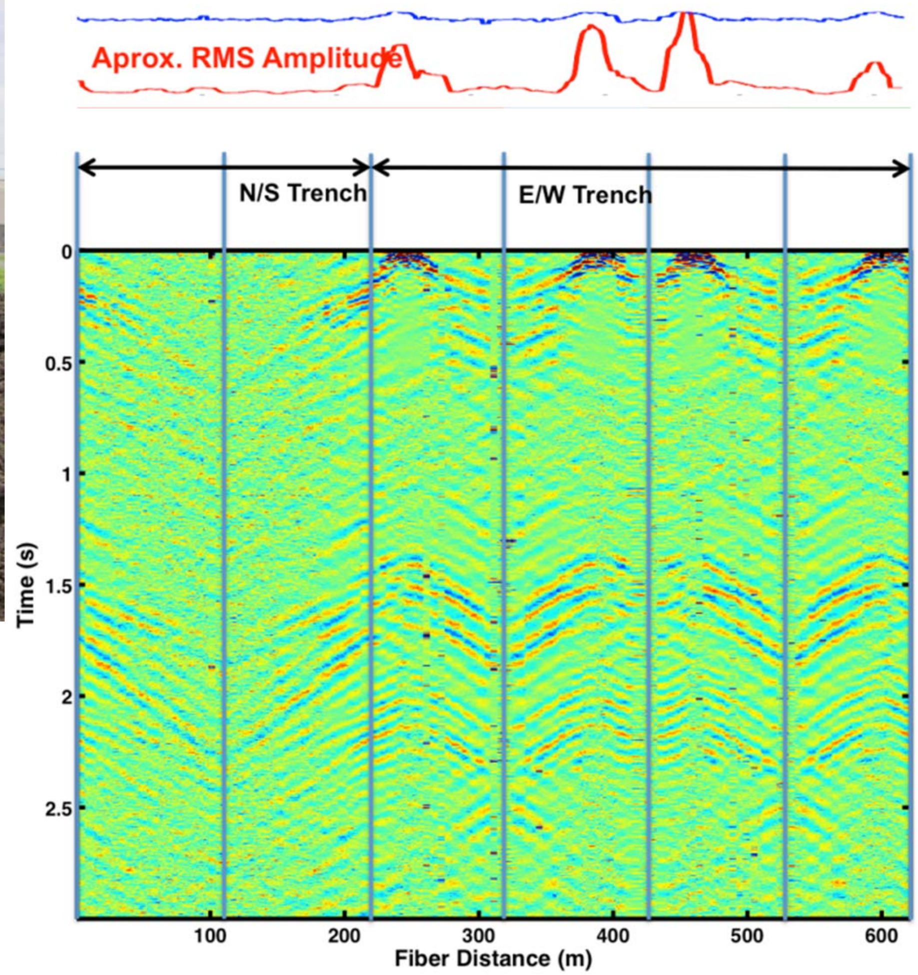
Explosive



Vibroseis



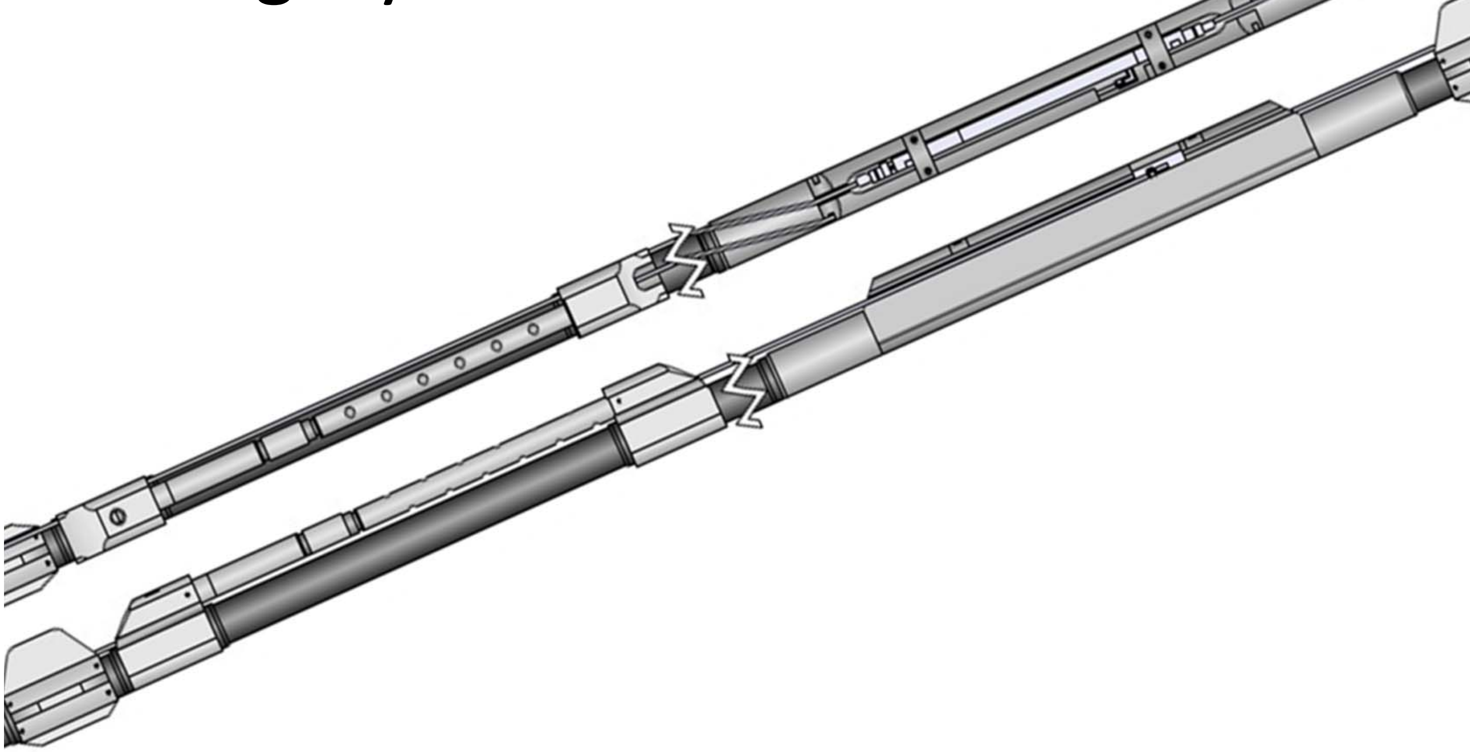
Surface Seismic Using DAS

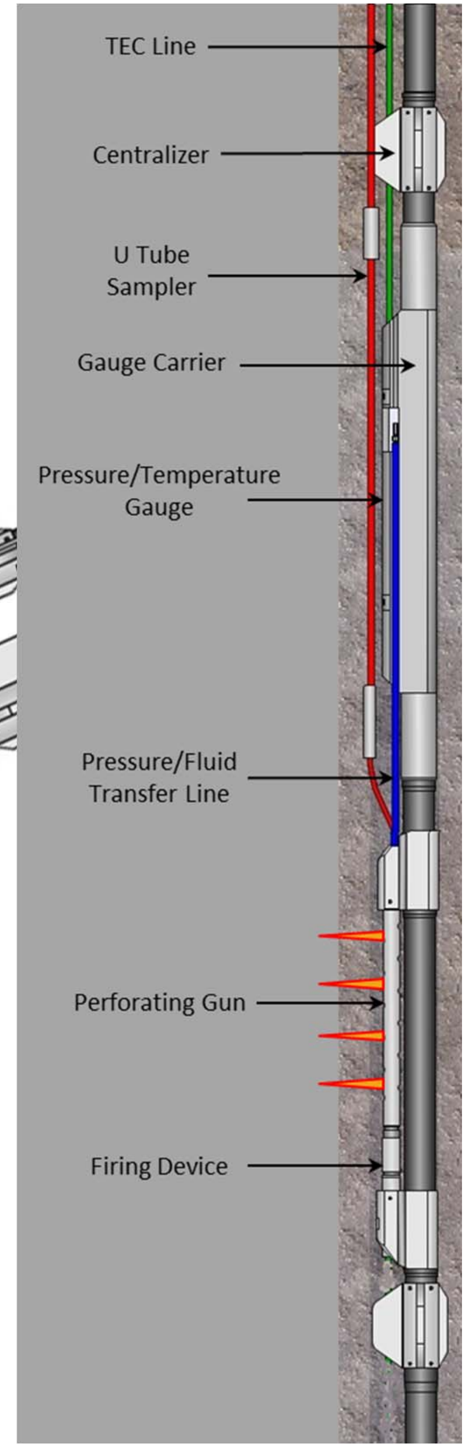


Testing cables for surface reflection surveys – optimizing cable sensitivity for P-wave reflectivity

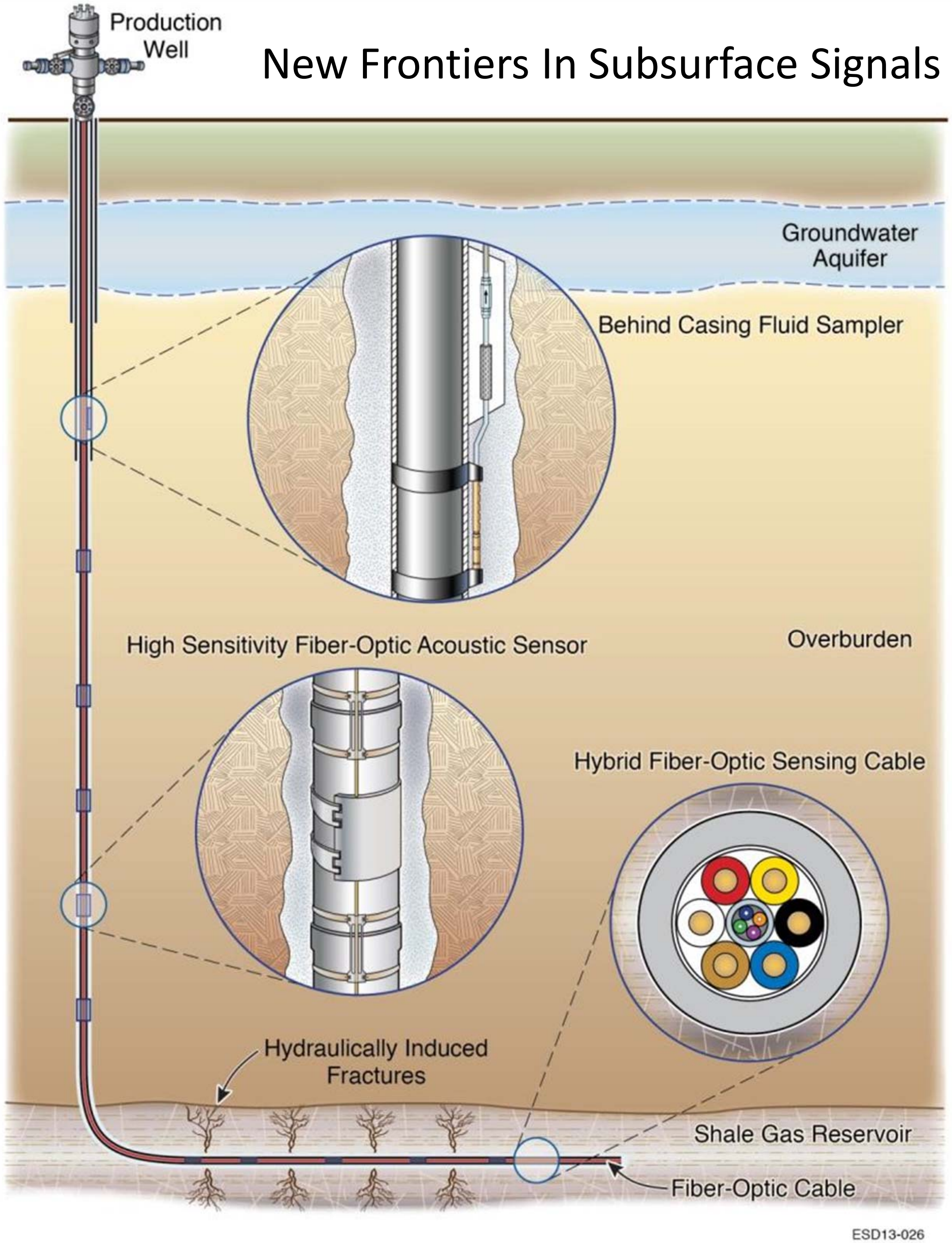
New Frontiers in Well Integrity and Reservoir Protection:

Behind Casing Monitoring for Protection of USDW and Cement Integrity Assessment





New Frontiers In Subsurface Signals



Thank you!
Questions?