Fundamental Studies in Support of GEO-SEQ

LBNL's Consolidated Sequestration Research Program (CSRP)

Project Number FWP ESD09-056

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U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and
Infrastructure for CCS

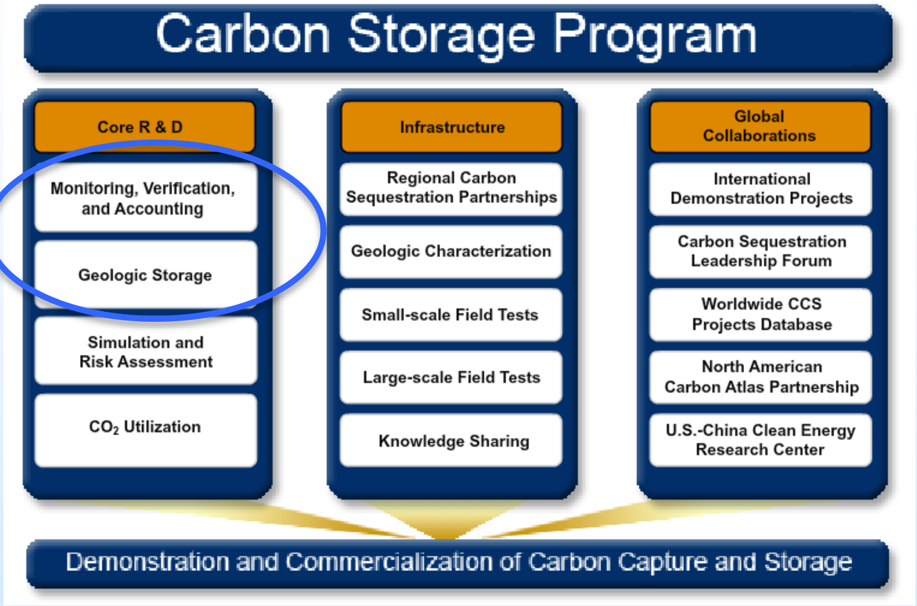
August 12-14, 2014

Presentation Outline

- Benefits and Goals of Fundamental Studies
- Technical Status
  - Monitoring and Instrumentation Development
  - Geochemical Processes
- Accomplishments and Summary

Benefit to the Program

Core R&D:
MVA and Geologic Storage



- This research project is supporting ”real-world” experience in monitoring of sequestration pilots with laboratory and field studies to develop new tools and technologies.

Benefit to the Program

- Support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
- Develop and validate technologies to ensure 99 percent storage permanence.
- Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness.

- DOE and the carbon sequestration community benefit from:
  - a close working relationship with numerous domestic and foreign industrial and academic teams
  - interactions with and assistance given to other regional projects
  - publications and presentations made available to all parties interested in removing barriers to commercial-scale geologic carbon sequestration.

Project Overview: Goals

- Develop and improve field monitoring instrumentation
  - This will lead to improvements in storage capacity estimation, validation and efficiency
- Improve understanding of processes seen in field studies through use of laboratory scale work
  - This will lead to improvements in storage capacity estimation, validation and efficiency

Project Overview: Objectives

- Task 1 Monitoring and Instrument Development
  - Seismic technology – continuous source and fiber-optic monitoring systems
  - Behind Casing Monitoring System Development
- Task 2 Measurement of Fundamental Geochemical Processes at Laboratory Scale
  - Complete “real” brine experiments with controlled $f(O_2)$ for generic reservoir types: clean sand (Frio C), dirty sand (Frio B), altered sand (Cranfield Tuscaloosa) and carbonate (Weyburn Midale Marly).
  - Complete design of simplified geochemical tests specific to reservoir rock type.

Project Overview: Objectives

- Success Criteria (FY14): Contribution of new and/or improved instrumentation for application to GCS and being able to move the technology from the core R&D program into the infrastructure program in support of CO_2 sequestration demonstrations.
  - Milestones
    - Engineer design of behind casing well integrity monitoring and leak detection system
    - Fabrication and testing plan for a high sensitivity fiber-optic acoustic geophone string

Technical Status

- Several monitoring tools have been developed and underlying processes identified and quantified.
  - The work was motivated by GEO-SEQ field projects, and their use as testing facilities to scale up from laboratory to field scale.
  - Fundamental Studies began in FY13 by bringing together existing work to investigate monitoring technologies and fundamental geochemical and petrophysical processes that underpin GCS.
- Current work to be completed in 2015.
  - Monitoring Instrumentation
    - Continuous monitoring: CASSM
    - Fiber optic seismic sensing
    - Behind casing measurement
  - Fundamental Geochemical Processes

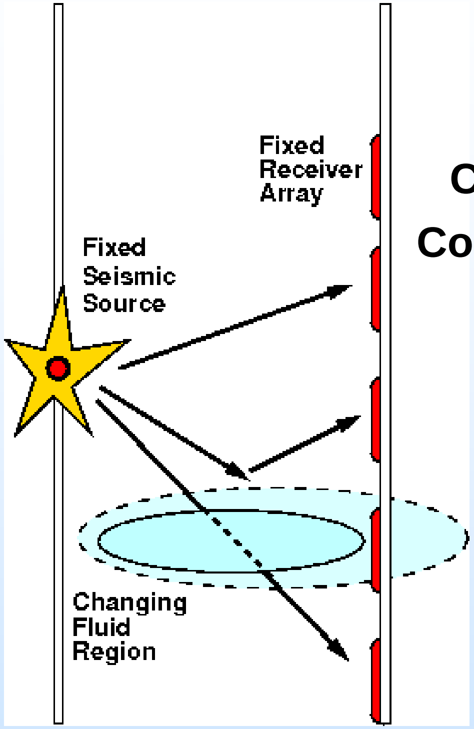
Monitoring Instrumentation

- LBNL's participation in pilot tests via GEO-SEQ led to development and application of novel monitoring tools for GCS
  - U-tube fluid sampling
  - **Continuous Seismic Monitoring (CASSM)**
  - Borehole shear-wave source (orbital vibrator)
  - **Fiber Optic Monitoring**
    - Heat-Pulse Thermal Monitoring with DTS
    - Distributed Acoustic Sensing
  - Behind Casing Measurement

Custom CASSM Controller

CASSM Background

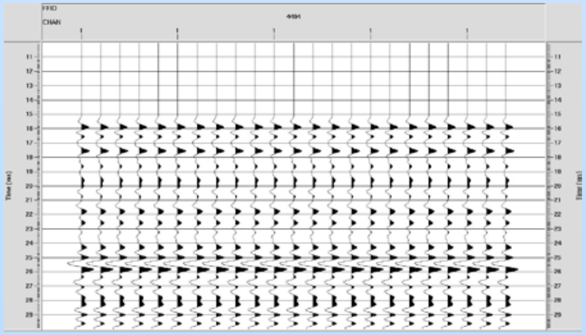
- Goal: Advancing the precision *in situ* monitoring of seismic properties
  - Current: crosswell geometry
  - Planned: surface – borehole

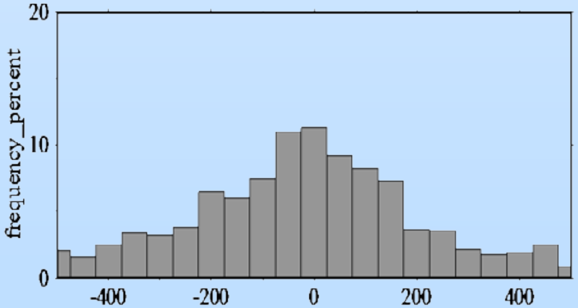


Crosswell Configuration

- Motivation:
  - Monitoring of CO2 sequestration
    - Monitoring for plume dynamics and storage security
    - Reservoir dynamics and petrophysics
      - Velocity/Saturation (fluid effects)

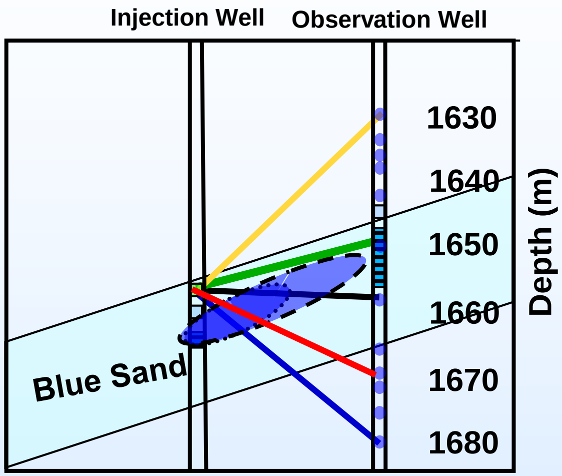
Piezo-tube Source

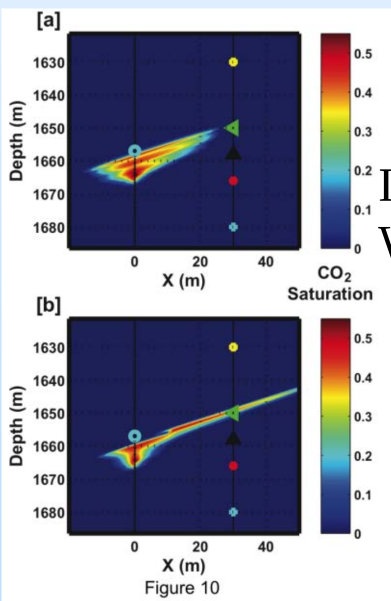




Delay Time (ns)

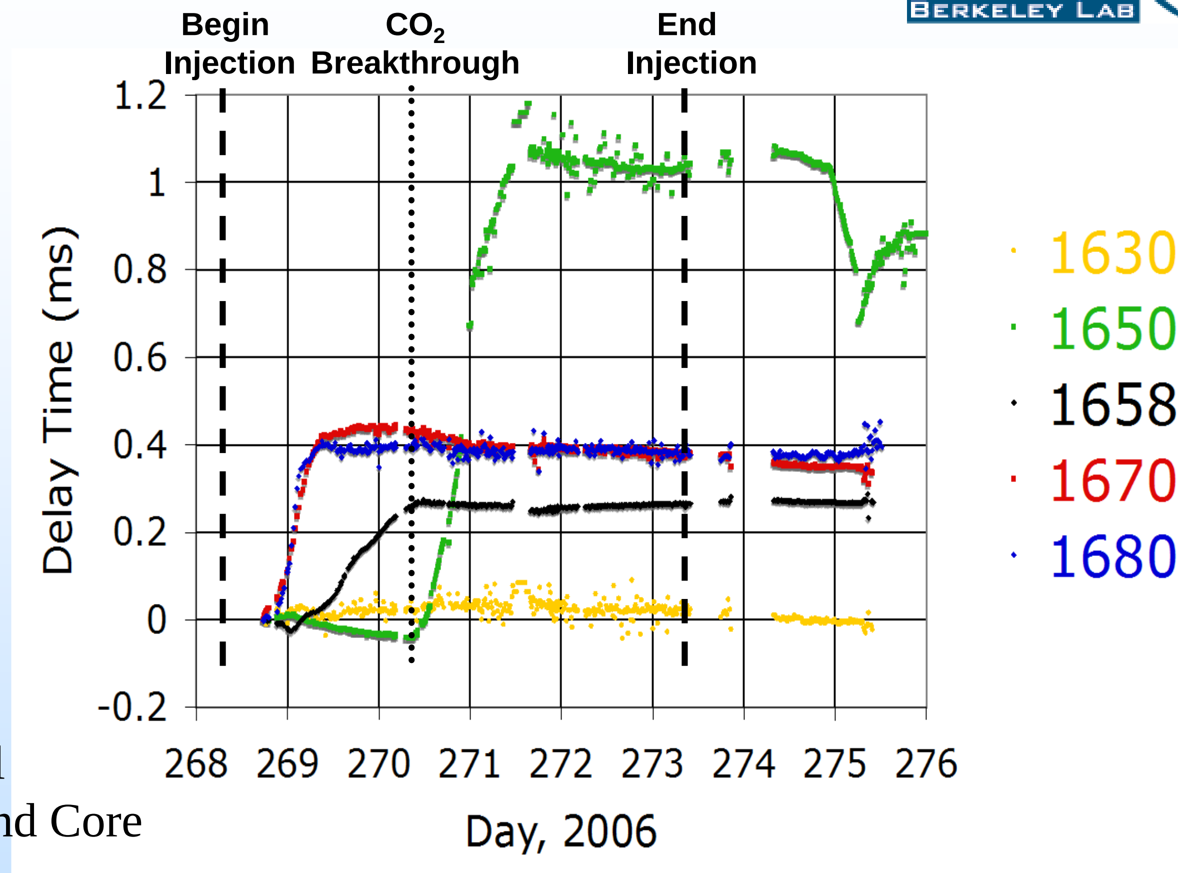
Motivation: Frio-II CASSM Results





Initial model
Well Logs and Core

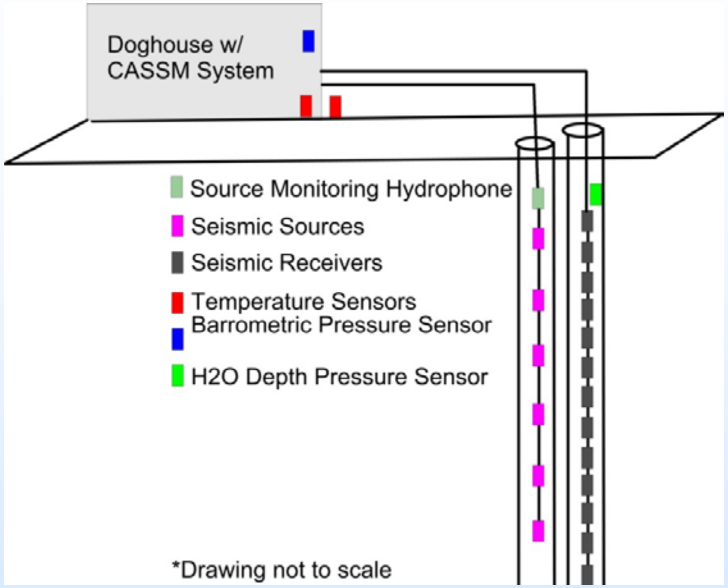
Updated model:
CASSM Constrained

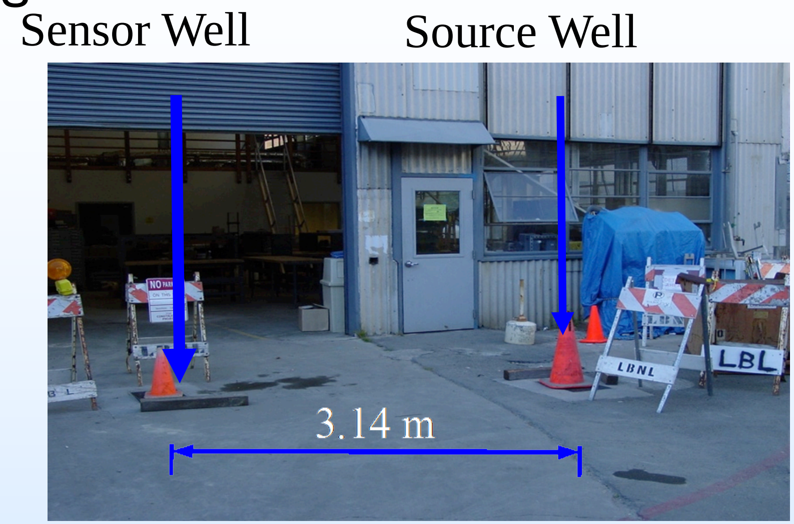


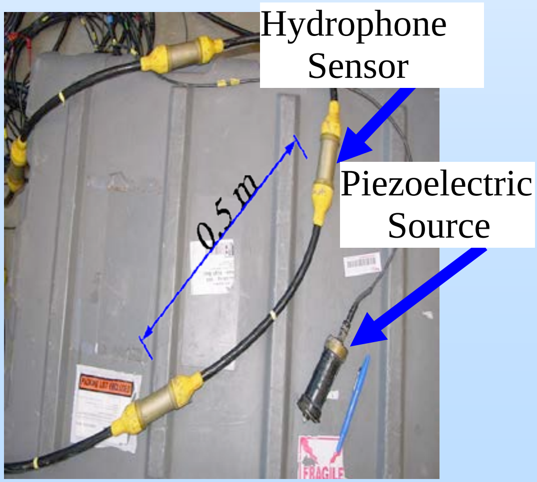
Daley, et al, Geophysics, 2007; IJGCC, 2008.

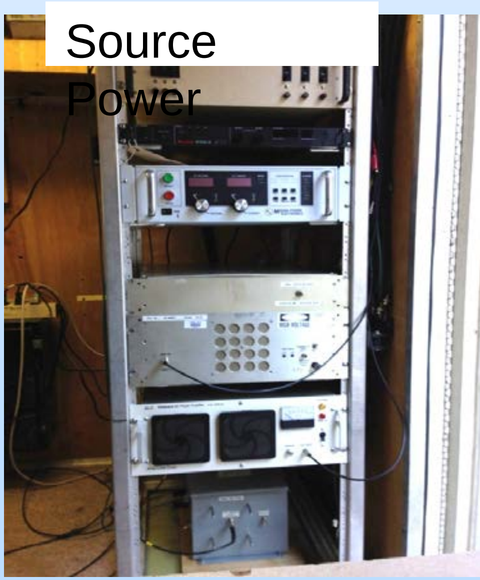
2014 CASSM System Development:

Precision Tests: 3m Well Spacing, 1-10 Source, 24 Hydrophones



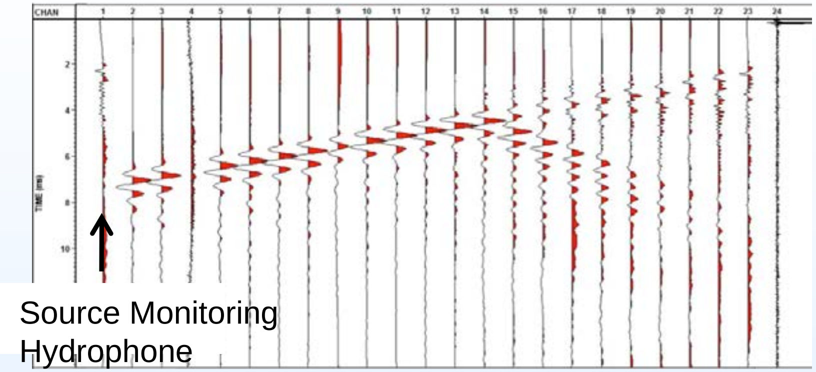


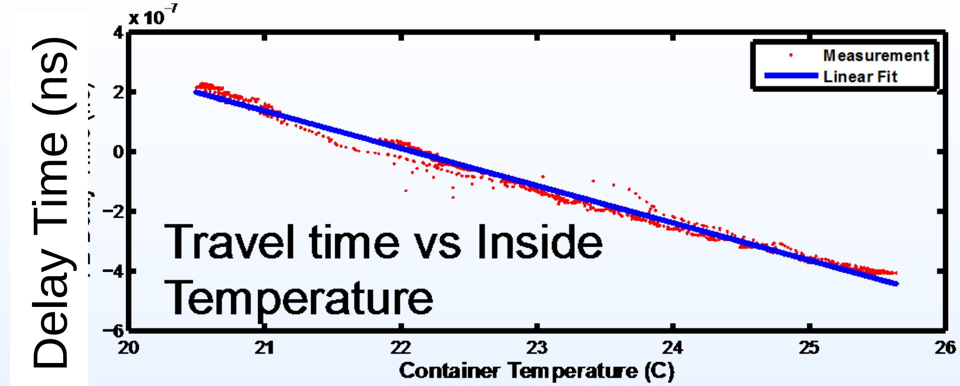




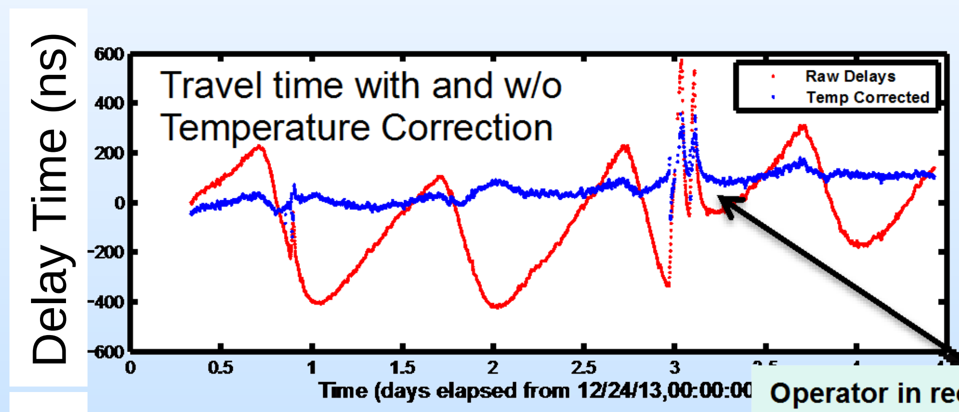
CASSM System Development:

5 days of data investigate levels of precision.

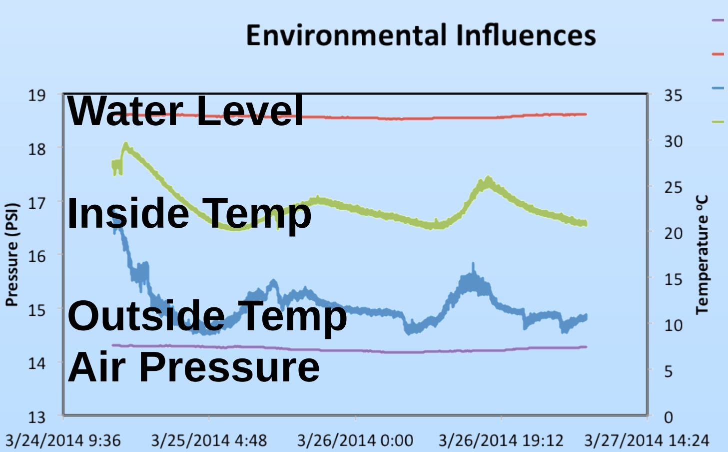


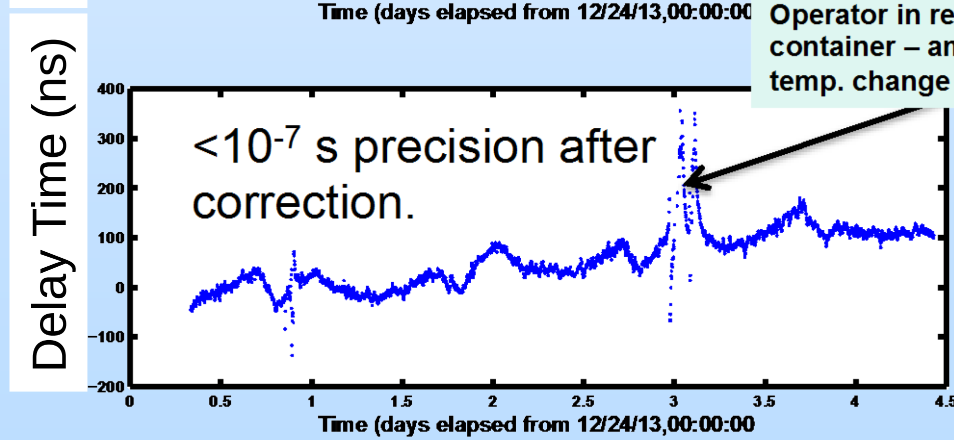


Key test: At high precision, instrument temperature is dominant effect to be removed from travel time measurement
See: Silver, et al, BSSA, 2007



Operator in recording container – ambient temp. change

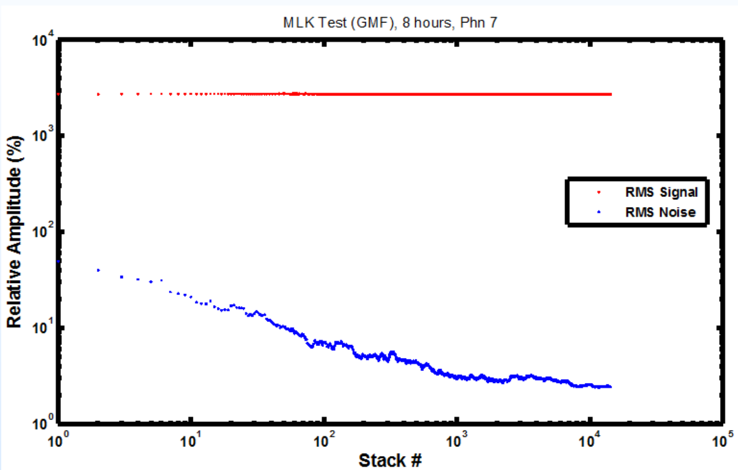




Investigating the Limits of Stacking

What is the nonrandom noise floor?

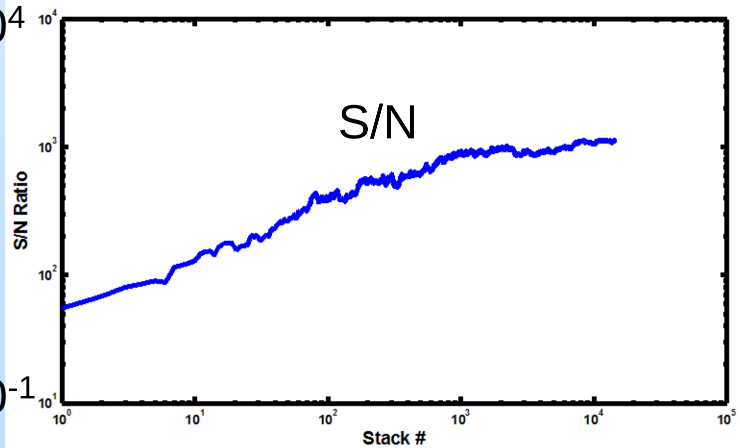
Rel. Amplitude %



10^0 10^2 10^4

10^4

10^{-1}

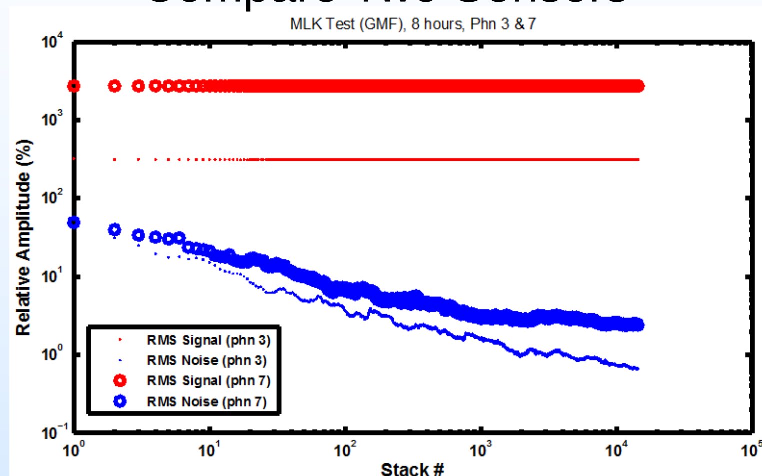


Stacks

Compare Two Sensors

10^4

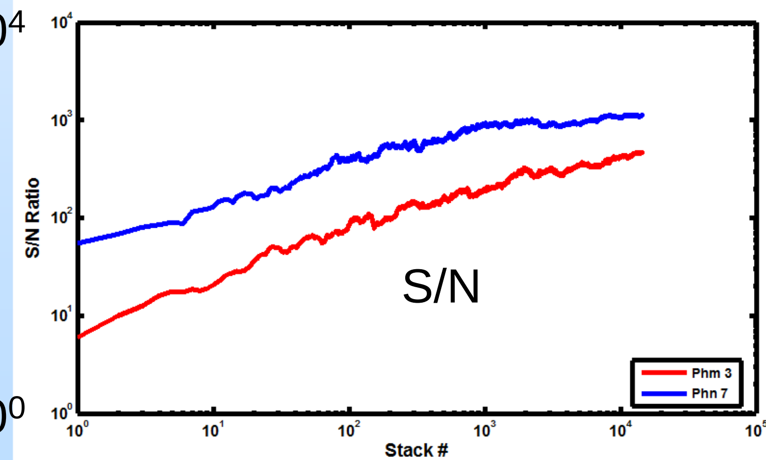
10^0



10^0 10^2 10^4

10^4

10^0



Stacks

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 Acoustic 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

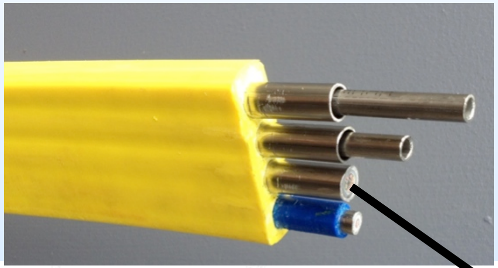
Field Trials of Distributed Acoustic Sensing for Geophysical Monitoring

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®*

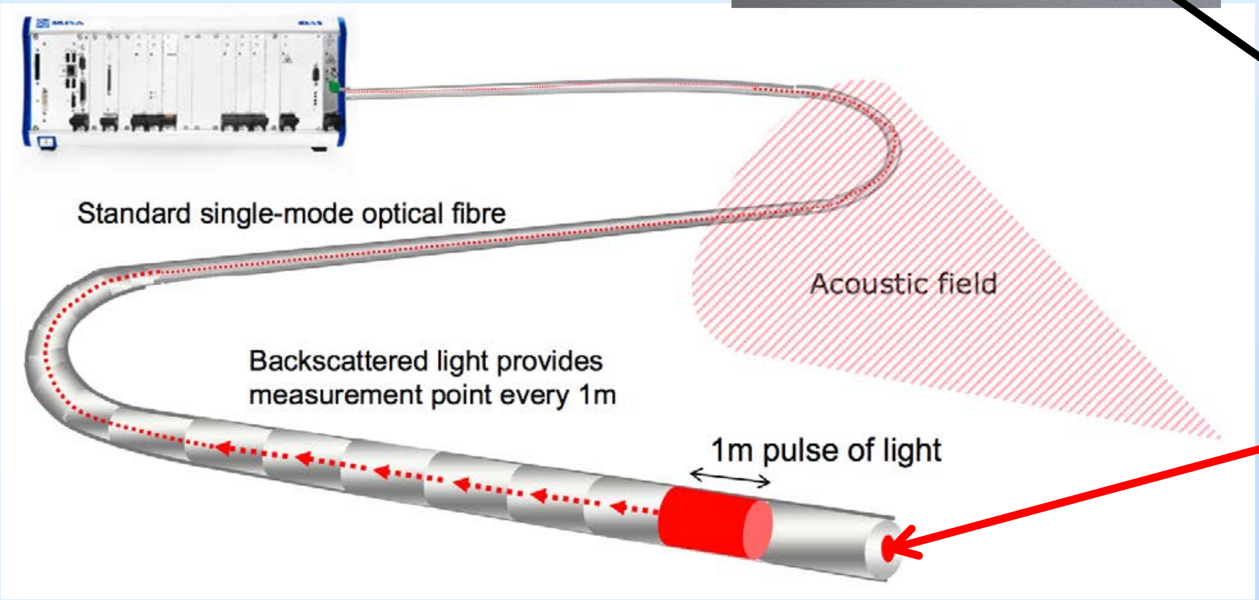
SEG San Antonio 2011 Annual Meeting

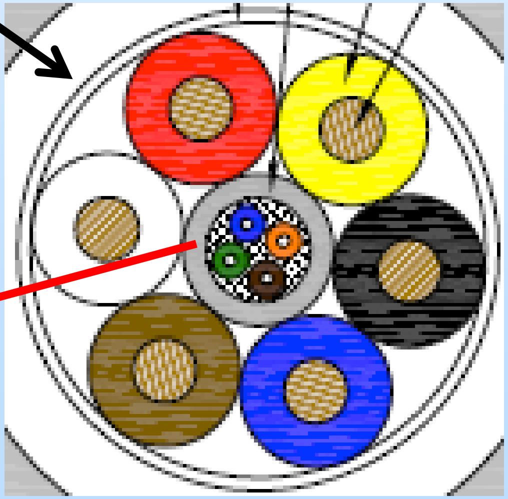
DAS at Citronelle with MBM Cable

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



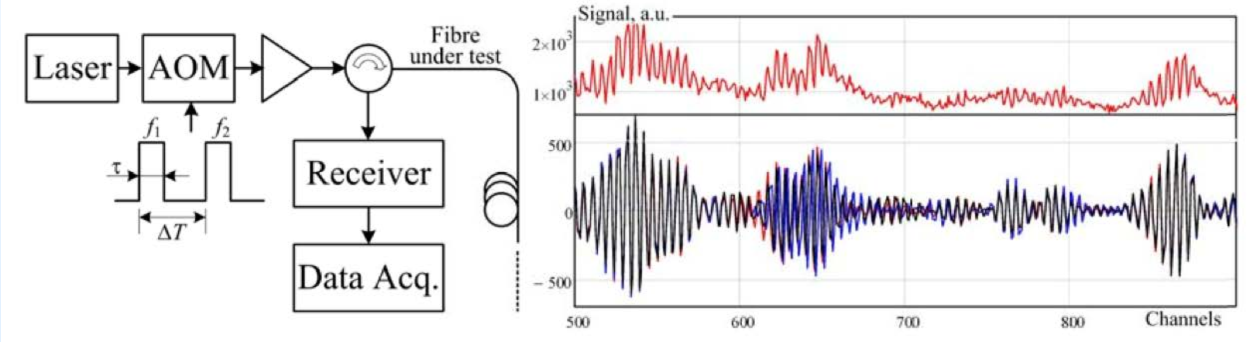
Same cable as
DTS Heat-Pulse





DAS Background

- Light pulse is reflected throughout fiber's length
- DAS system measures changes of the backscattered light - Rayleigh scattering
- 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 (not all simultaneously)



Single Pulse

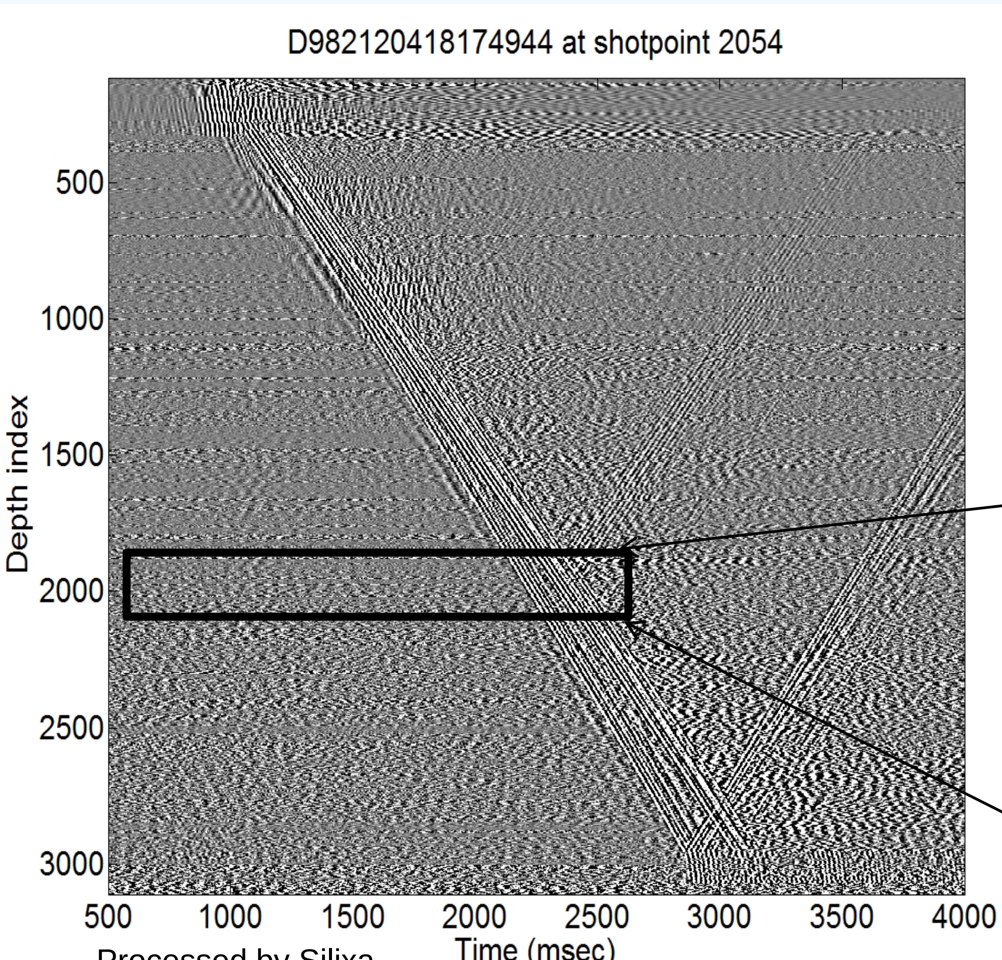
Multiple Filtered Pulses

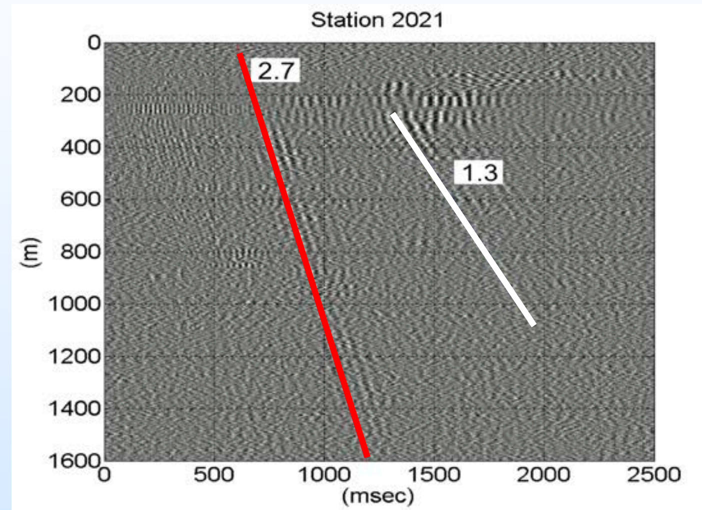
From Hartog, et al, EAGE, 2013

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

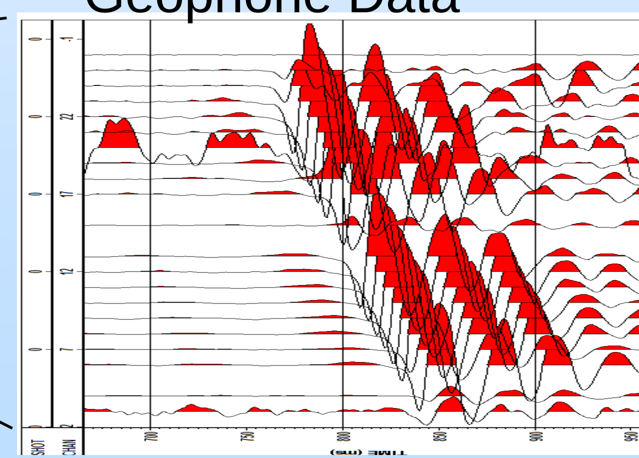
Fiber Optic Monitoring: Initial DAS Testing (SECARB Citronelle Site)

- VSP data ‘piggy-back’ on standard acquisition
- Initial data quality insufficient – greater source effort needed
- Observe tube-waves
- DAS has 1500 sensors (2 m spacing) versus 18



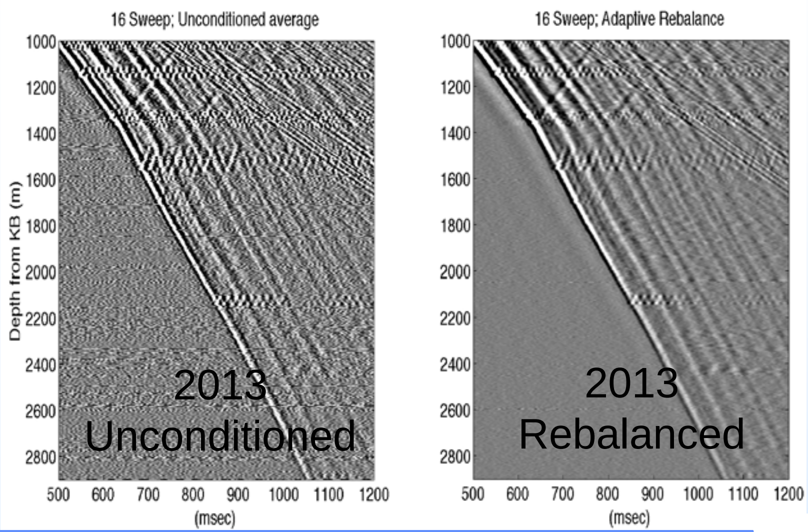


Geophone Data



Daley et al, Leading Edge, 2013

iDAS: Noise Reduction and Rebalancing

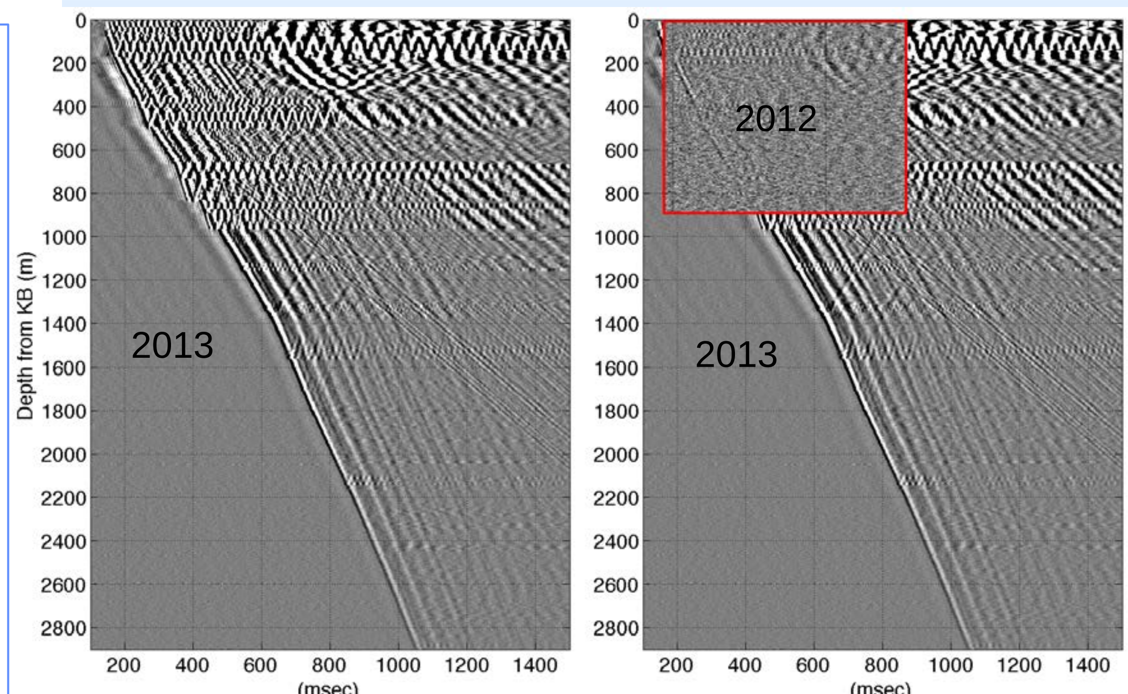


Noise Reduction

- 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, ***giving SNR improvements in excess of one order of magnitude.***

Adaptive Rebalance:

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



iDAS Geophone-equivalent output

- The native iDAS output is strain rate
- The industry standard is the geophone, which measures local velocity.
- *Silixa transforms the native iDAS output into strain and then into a geophone-equivalent output of velocity*.

Fiber displacement: $u(z,t) = u(\varphi)$

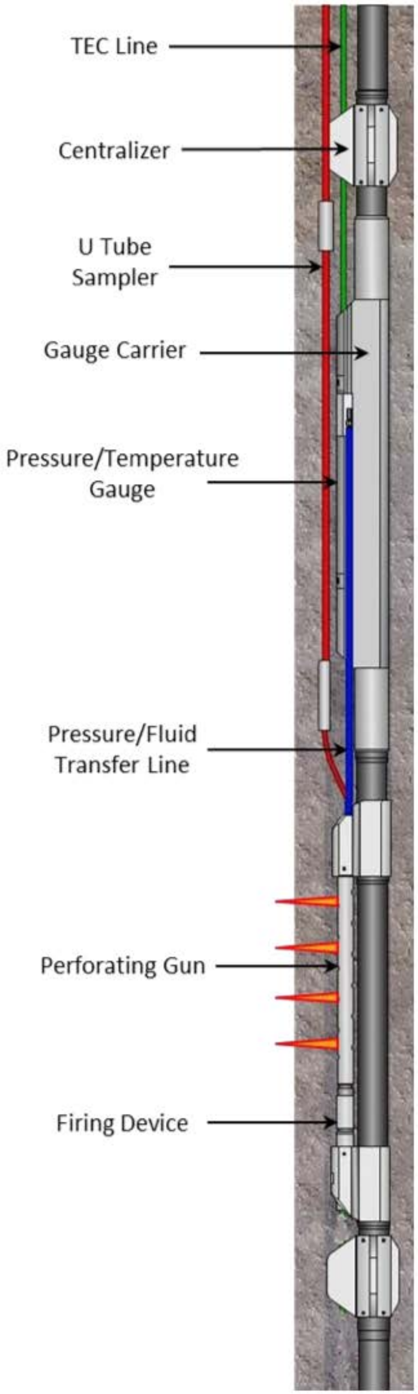
Where $\varphi = (t_0 + t \pm z/c)$ is any event (phase function) with propagation speed *c* *along the fiber axis (apparent velocity)*.

The fiber particle velocity, $v = \partial u/\partial t = \partial u/\partial \varphi$,

And fiber strain
$\varepsilon = \partial u/\partial z = \pm 1/c \; \partial u/\partial \varphi$,

Therefore,

$$\varepsilon = \pm v/c$$



Behind Casing Measurement

PI: Barry Freifeld

- Design components of an integrated system
  - installed behind the casing, cemented into place.
  - Couple the U-tube and pressure/temperature gauge to formation with a perforation gun, creating an open fluid pathway
  - ability to run a fiber-optic cable in parallel with the TEC or as an integral component within a hybrid fiber-optic electrical cable.

US patent application no 14/253,608, “Device Useful as a Borehole Fluid Sampler.”

Geochemical Assessment

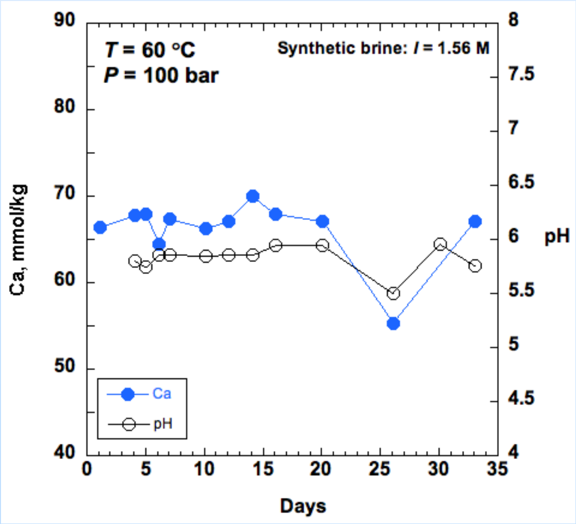
PI: Kevin Knauss, LBNL, kgknauss@lbl.gov

- Tasks for FY14:
  - Complete “real” brine experiments with controlled $f(O_2)$ for generic reservoir types: clean sand (Frio C), dirty sand (Frio B), altered sand (Cranfield Tuscaloosa) and carbonate (Weyburn Midale Marly).
  - Complete design of simplified geochemical tests specific to reservoir rock type.

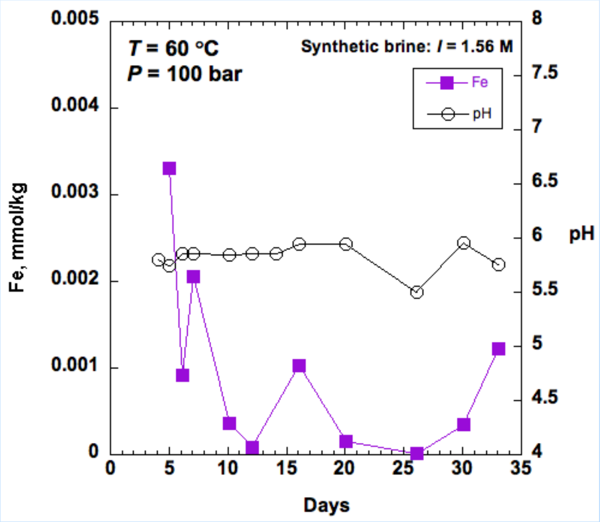
Frio C sand

- 270 ml Au-cell: oxygen fugacity (fO_2) at low levels typical of subsurface conditions.
- *Chemical evolution of the aqueous fluid over the course of the batch experiment 'Frio8b',*
- *synthetic brine and rock core material from the Frio reservoir. The*
- *concentrations of the elements were measured by ICP-OES*

Ca and pH



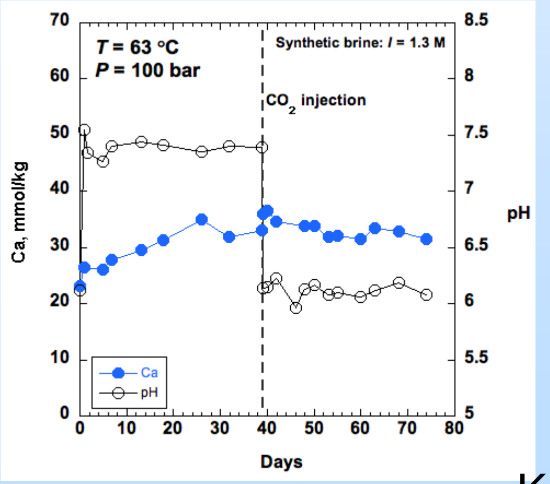
Fe and pH

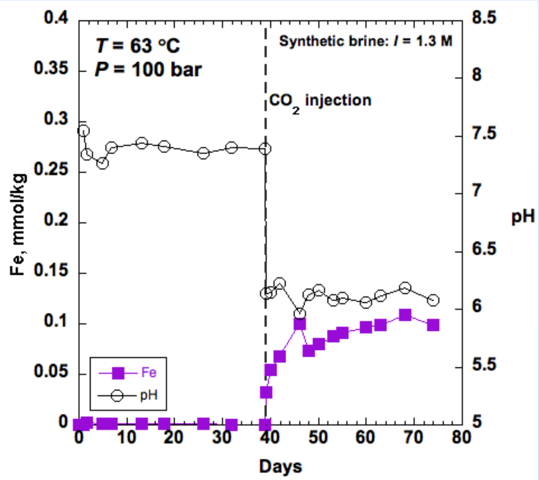


Kevin Knauss

Weyburn Marly Dolomite

- 270 ml Au-cell: oxygen fugacity $f(O_2)$ at low levels typical of subsurface conditions.
- 10 g of ground solid Weyburn material was reacted with 225 g of synthetic brine
- The injection of CO_2 after 40 days leads to a significant pH drop (7.4 to 6.1)
- Ca and Mg are clearly affected and the concentrations increase by ~3-5 mM.
- strong increase for Al, Fe and, to a lesser extent, Si. Fe is most likely released by the dissolution of Pyrite (Fe_2S).





Kevin Knauss

Accomplishments to Date

- Improvement and upgrade of continuous monitoring (CASSM) instrumentation
- Development of fiber optic sensing
  - Significant improvement in DAS from R&D with commercial vendor
  - Application at GCS sites (DOE and International)
- Development of behind casing instrumentation desgin
- Experimental results on geochemical effects of CO2 injection

Summary

- Key Findings
  - CASSM system provides maximum seismic precision (field scale)
  - Fiber optic seismic sensing (DAS) is field ready for monitoring
    - Permanent, repeatable, less expensive
  - Permanent borehole monitoring is improving: behind casing designs available
- Lessons Learned
  - Fiber optic seismic (DAS) improved from dedicated field testing
  - Permanent monitoring dramatically improves geophysical precision
- Future Plans
  - Design/Development of surface CASSM Source
  - Continue assessment of geochemical impacts
  - Wrap up current projects in FY15 (carryover funding)

Appendix

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

Organization Chart

- Fundamental Studies is a subtask of LBNL's Consolidated Sequestration Research Program lead by Barry Freifeld
- Closely linked to GEO-SEQ also lead by Barry Freifeld
- Fundamental Studies has three tasks with principal investigators (PI) and scientific task leads
  - PI: Tom Daley
    - Monitoring Instrumentation PI: Tom Daley
      - Task Leads: Barry Freifeld, Jonathan Ajo-Franklin
    - Geochemical Assessment PI: Kevin Knauss

Fundamental Studies	Title	Role in Task/Subtask
T. Daley	PI and Research Scientist	Lead scientist for fundamental studies
S. Nakagawa	Research Scientist	Scientist working on rock mechanics using resonant bar apparatus
J. Ajo-Franklin	Research Scientist	Geophysicist supporting laboratory studies and field seismic data processing
M. Robertson	Project Scientist	Coordinator of field projects and oversees geophysical measurement facility support
P. Cook	Scientific Engineering Associate	Mechanical engineering and project support
K.G. Knauss	PI and Research Scientist	Geochemist supervising laboratory studies
J.P. Icenhower	Research Scientist	Geochemist working on CO2 laboratory studies
G.D. Saldi	Postdoc	Geochemist working on CO2 laboratory studies
N.J. Pester	Postdoc	Geochemist working on CO2 laboratory studies

Gantt Chart

- The Fundamental Studies Task began in FY13
- Current planning for FY15 is in progress.

MILESTONE GANTT CHART

	Q1 FY14			Q2 FY14			Q3 FY14			Q4 FY14		
Subtask Description	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**
Task 1 Project Management and Planning												
Task 2 GEO-SEQ												
Subtask 2.1 Otway Project									D			
Subtask 2.2 In Salah Industrial-Scale CO_2 Storage			B									C
Subtask 2.3 Ketzin						A*						
Subtask 2.4 Aquistore			E									
Task 3 Monitoring Instrumentation Development						F			G*			
Task 4 Simulation Studies												H, I

* A & G are AOP Tracked milestone

Bibliography (FY14)

- Daley, T.M., Miller, D., Dodds, K., Cook, P., Freifeld, B.M., 2014a (submitted), Field Testing of Modular Borehole Monitoring with Simultaneous Distributed Acoustic Sensing and Geophone Vertical Seismic Profile at Citronelle, Mississippi, submitted to Geophysical Prospecting.

- Vasco, D.W., Thomas M. Daley and Andrey Bakulin, 2014, Utilizing the onset of time-lapse changes: a robust basis for reservoir monitoring and characterization, Geophysical Journal International, doi: 10.1093/gji/ggt526.

- Freifeld, BM., US patent application no 14/253,608, “Device Useful as a Borehole Fluid Sampler.”