# Continuous Crosswell Seismic Measurement: Applications to Monitoring of Stress and $CO_2$

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**CO2 Monitoring Collaborators:**

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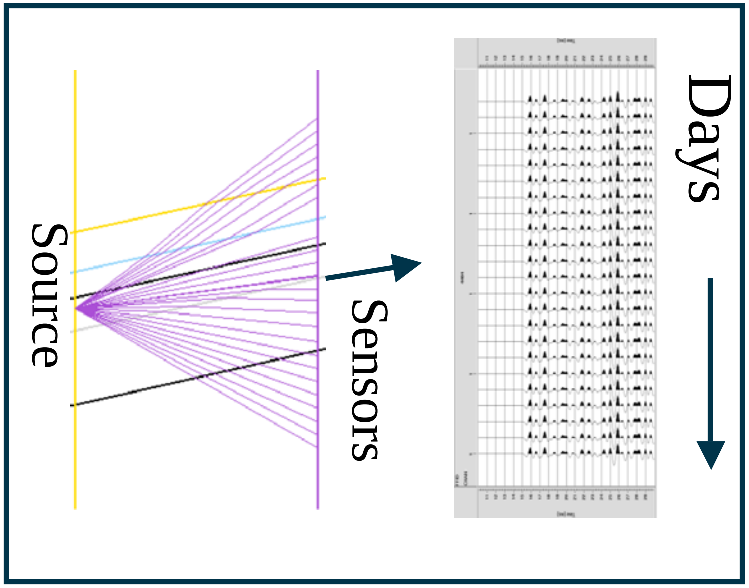
# Outline

- **Background**
  - **Active source monitoring**
  - **Delay time precision and optimal frequency**
- **Field Experiment Results**
  - **Crosswell equipment - Initial shallow experiments**
  - **Stress monitoring tests at San Andreas Fault Observatory at Depth (SAFOD)**
  - **$CO_2$ Geologic Sequestration Monitoring**

# Background

- **Goal: Precision In-situ monitoring of seismic velocity via crosswell geometery**

- **Motivation:**
  - **Earthquake 'forecasting'**
    - **Measure tectonic stress change**
    - **Need calibration signal:**
      - **Barometric pressure**
  - **Monitoring of CO2 sequestration**
    - **Constrain in-situ processes, petrophysics**
    - **Monitoring for 'leakage'**




**Schematic Example**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# Delay Time Precision

- For crosswell acquisition parameters we can simplify the Cramer-Rao bound (Silver, et al, BSSA, 2007 )
  - T=window length, B=fractional bandwidth, SNR=Signal-to-Noise Ratio,
  - $\sigma_\tau = \sigma_\varepsilon$ = delay time precision (std. dev.)

$$\sigma_\varepsilon = \sigma_\tau f_0 \geq \frac{1}{2\pi \cdot SNR}\sqrt{\frac{1}{f_0 TB}} \sim \boxed{\frac{1}{2\pi \cdot SNR}}$$

- **Result:**
  - The precision of crosswell travel time monitoring is mainly dependent on signal-to-noise ratio
  - Massive stacking can maximize SNR ($10^4$-$10^5$), minimize $\sigma_e < 10^{-7}$ s

# Optimal Acquisition Frequency

- **Want to maximize number of wavelengths = N, for a crosswell distance L, allowing for attenuation Q**

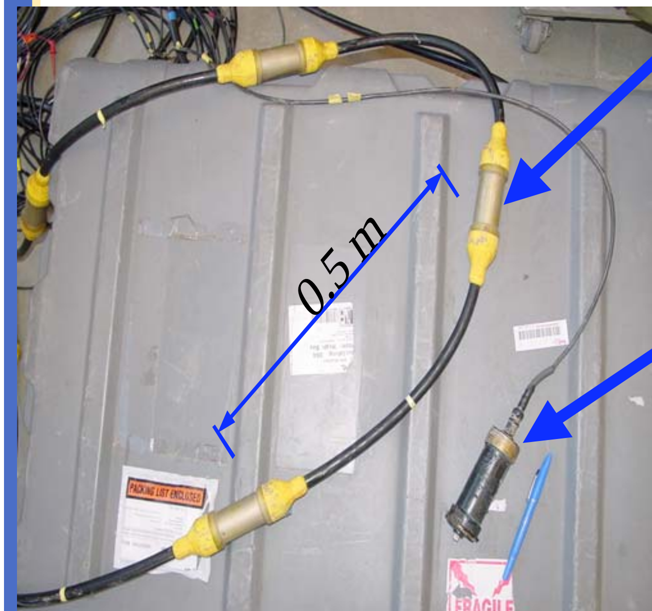
**For $\pi /Q << 1$   $N \sim Q/\pi$   (Silver, et al, BSSA, 2007)**

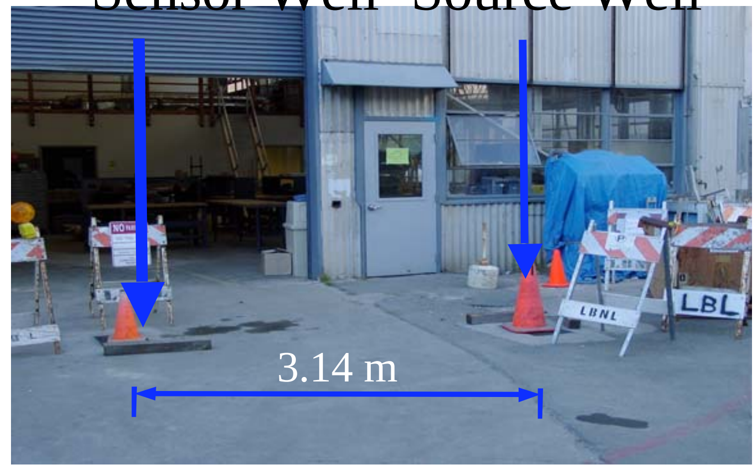
**Example: Q=60, N=20; if Vp=1.5 km/s, L=30 m,**

**Then optimal frequency f=1000 Hz**

- **Shorter distances need higher frequencies.**

# Initial Tests: 3m Spacing, 2003; 30 m Spacing 2004

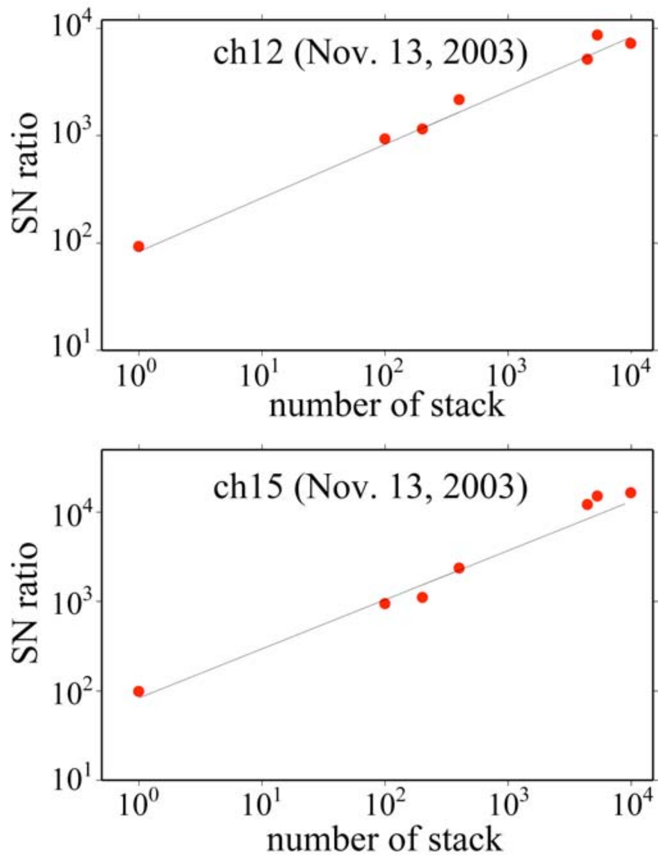


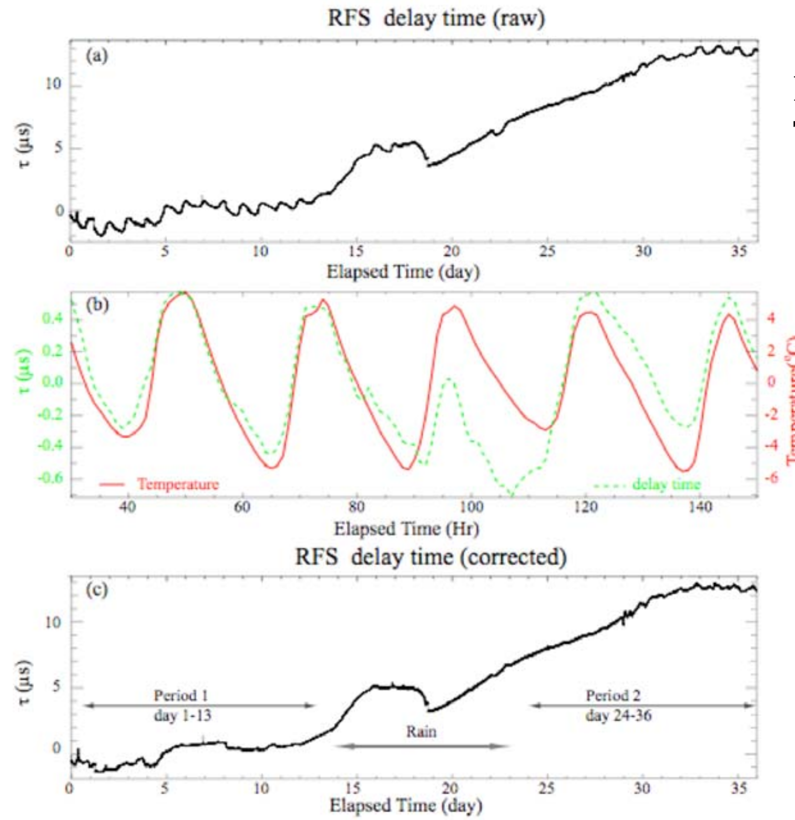

**Rec. System**

# Massive Stacking and Temperature Correction

- **Get $N^{1/2}$ improvement out to at least 10,000 traces!**




**Temperature Correction ~ 0.1μs/ºC**




Raw Delay Time

Temp. vs Delay Time

Temp. Corrected Delay Time

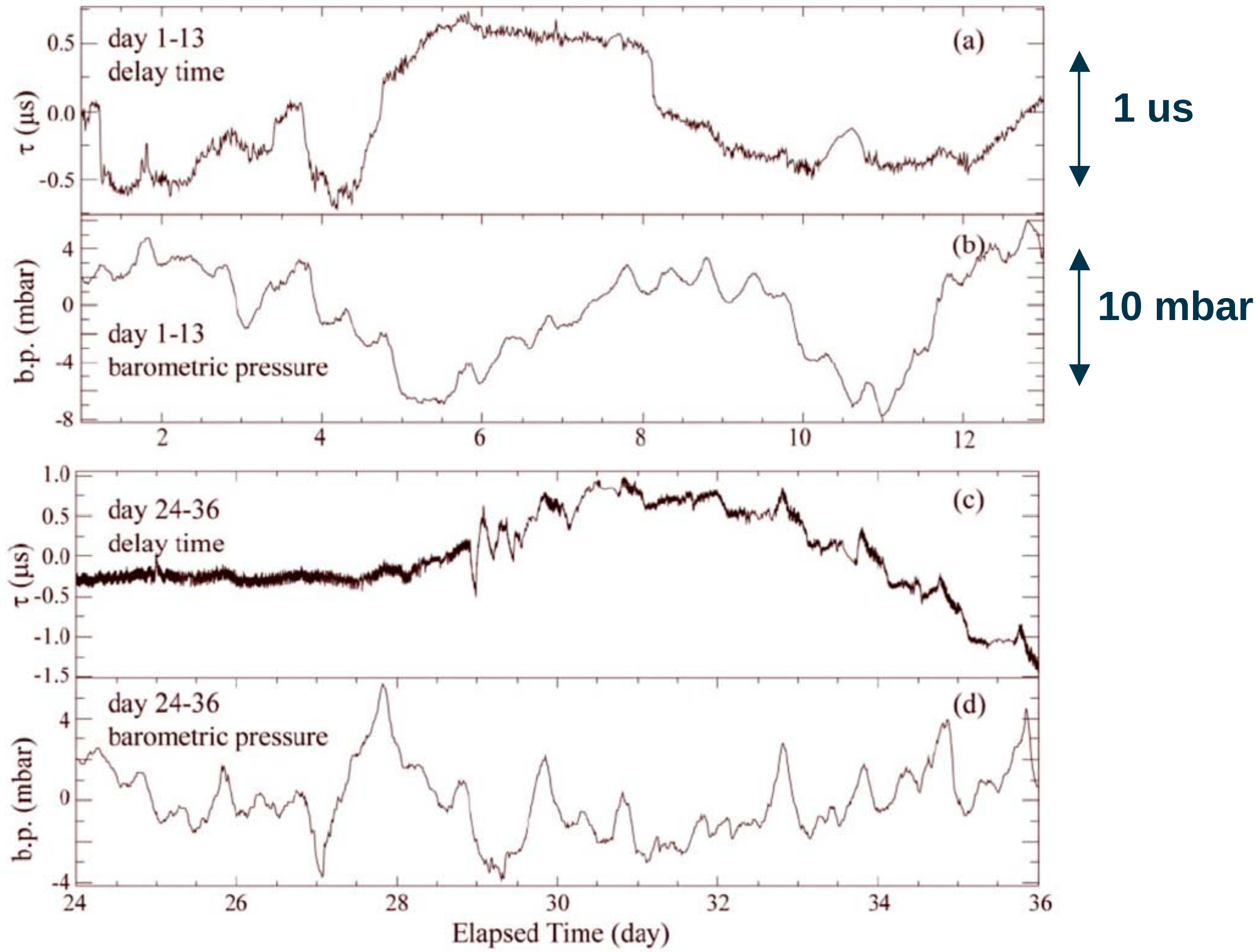
**Silver et al, 2007, BSSA**

# Shallow Stress Monitoring Results: 30 m Scale

**2 Measurement Periods of ~ 12 days**

**Barometric pressure used for calibration**

**Measured Stress Sensitivity = ~ $10^{-7}$ /Pa**




**Silver et al., 2007, BSSA**

# Stress Monitoring: SAFOD Boreholes - 2006

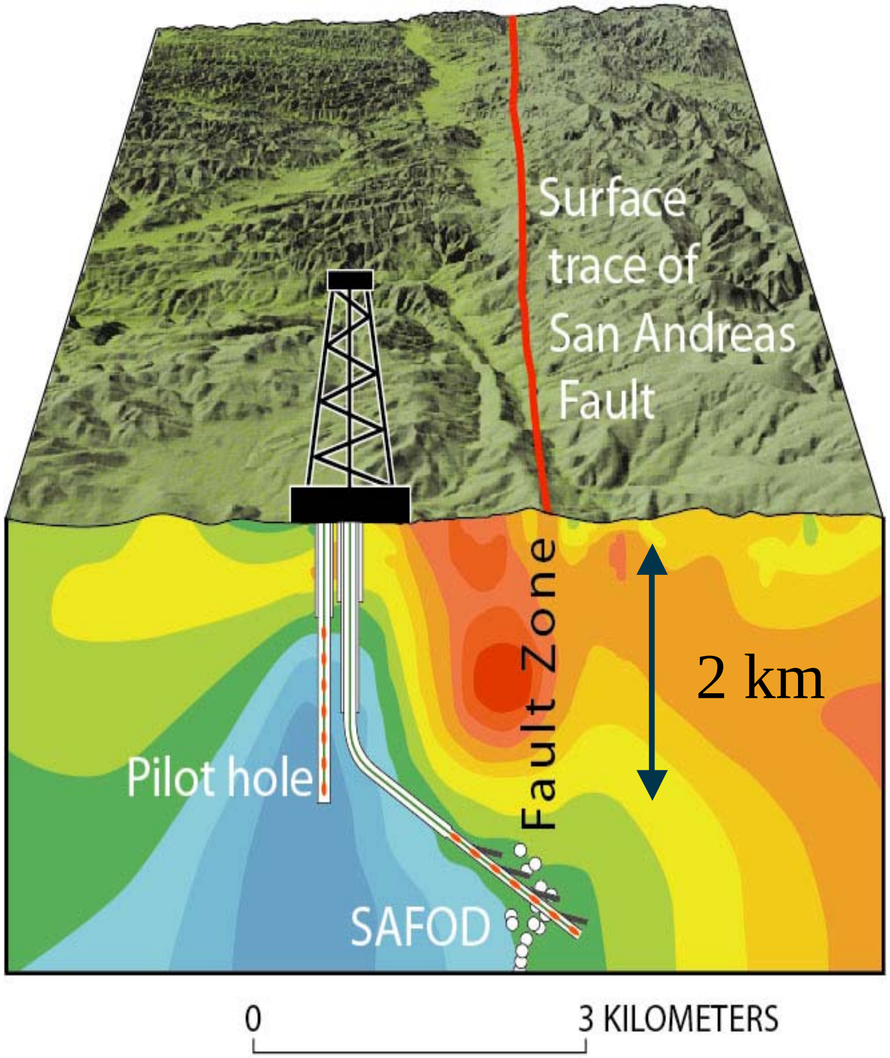
Crosswell:

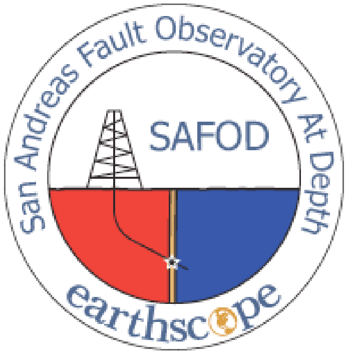
- 1.1 km deep

~12 m apart

- Piezoelectric Source
- 3-C Accelerometer Sensor

- Details shown in talk T53C-06 Niu, et al.



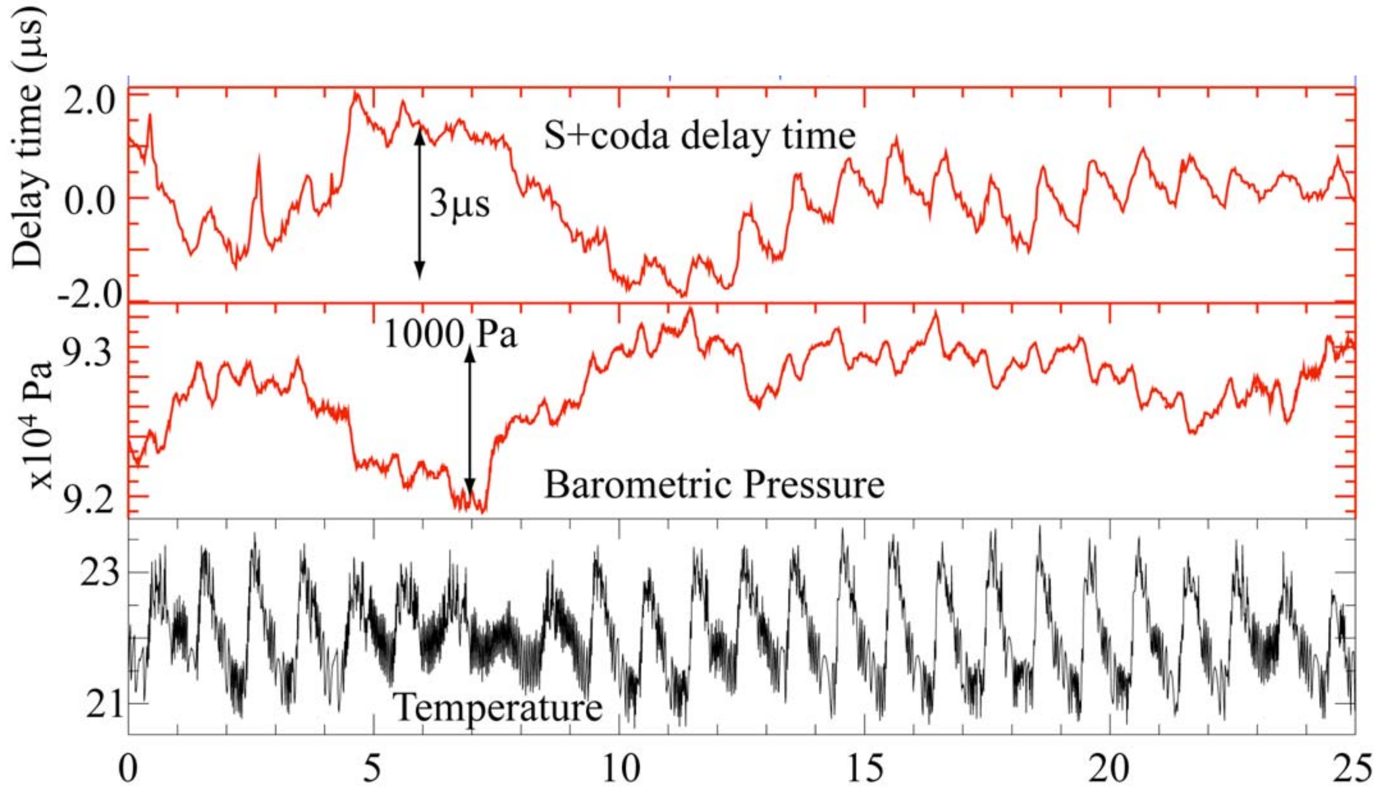

Resistivity from Unsworth and Bedrosian, 2004 GRL

# SAFOD Boreholes and Equipment

Piezoelectric Source

3C Clamping Sensor

# Result from First Month: S-wave

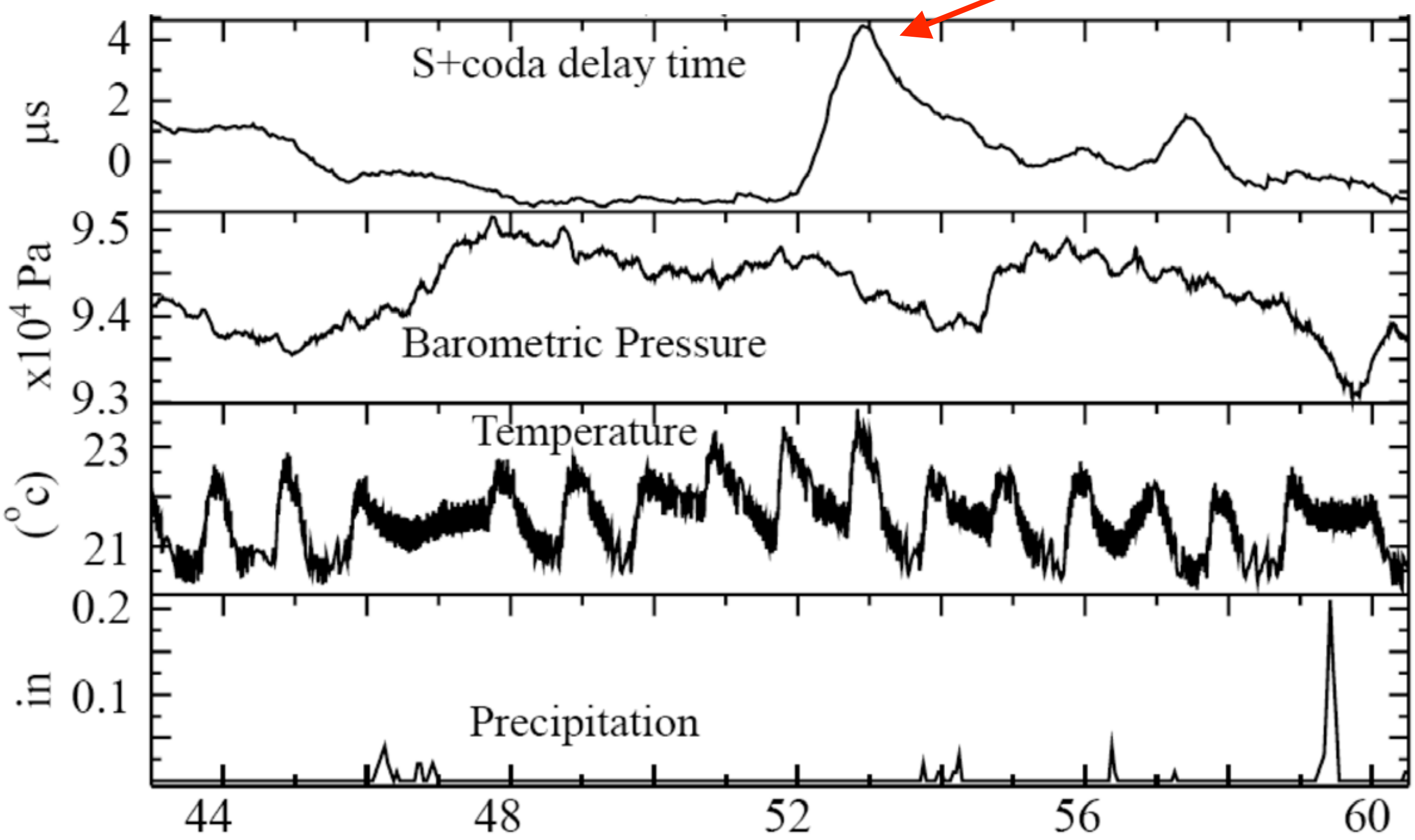



Velocity change: 3.0 $10^{-4}$; Stress sensitivity 3.0 $10^{-7}$/Pa

**Niu, et al, Submitted to Nature**

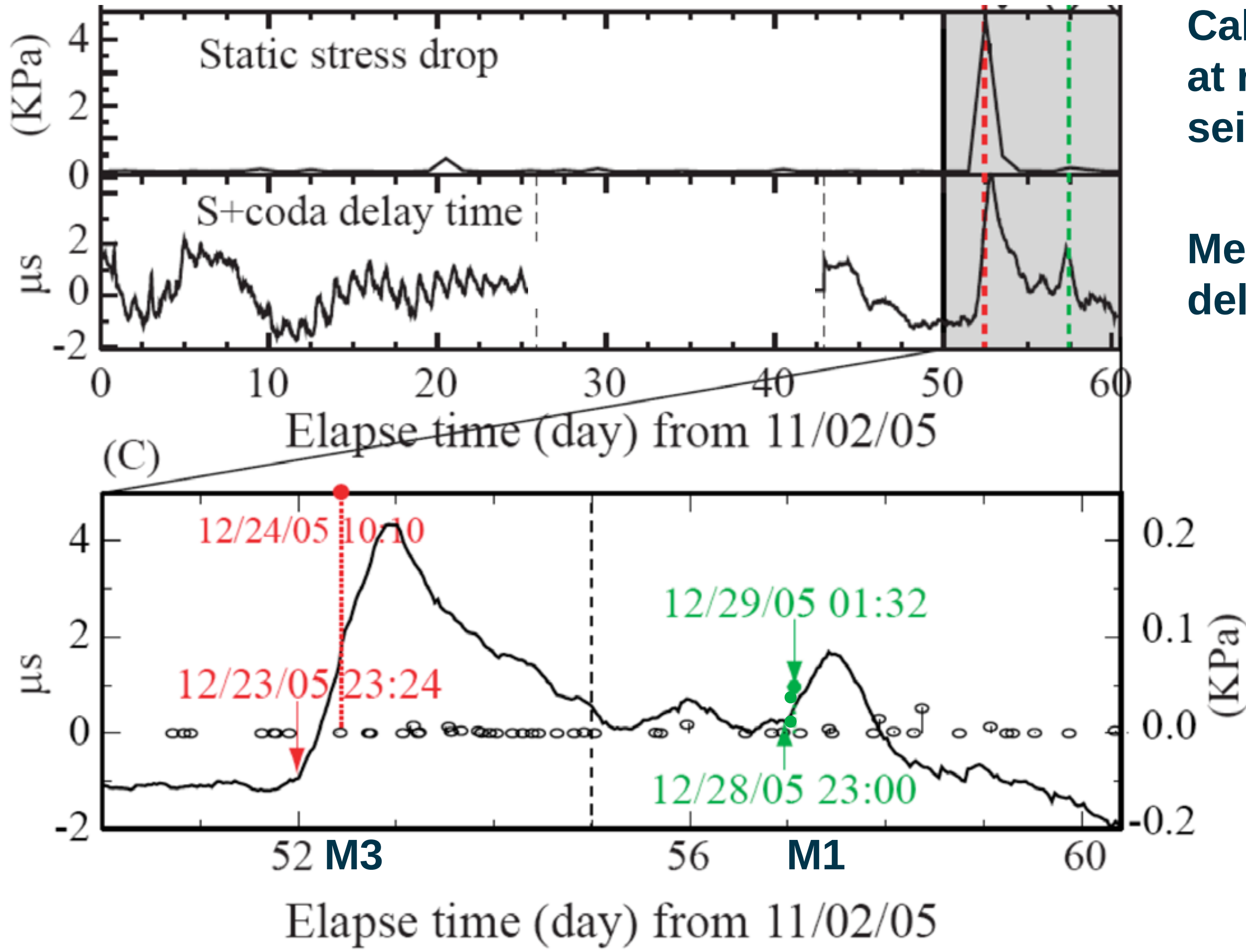
# SAFOD: Second Data Set

Large Change in delay time




Niu, et al, Submitted to Nature

# Coseismic stress change from M3 and M1 events!




**Calculated Stress drop at recording site from seismic events**

**Measured crosswell delay time**

**For M3 and M1 events, delay time change begins before event**

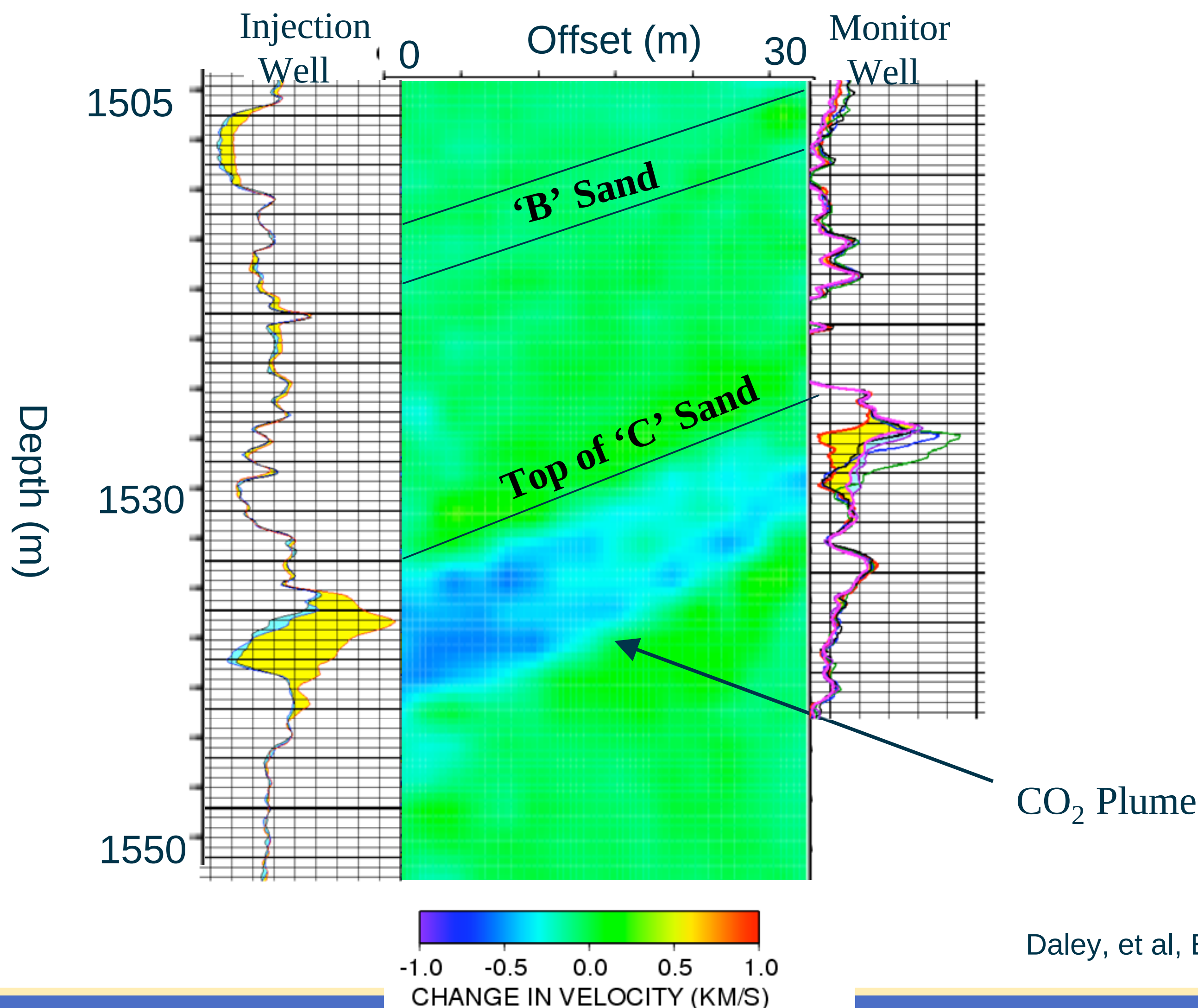
**Niu, et al, Submitted to Nature**

# CO2 Monitoring
## CASSM: Continuous Active Source Seismic Monitoring

- **Motivation**
  - **Apply techniques developed for stress monitoring to reservoir monitoring of $CO_2$ injection**

- **Frio-II Pilot $CO_2$ Injection**
  - **How to monitor spatiotemporal evolution of $CO_2$ plume during injection (emphasis on buoyant rise of $CO_2$ in reservoir).**

# Frio Pilot: Supercritical CO2 injected at ~1600 m
# P-wave Tomography showed large velocity change




Daley, et al, Env. Geol., 2007.

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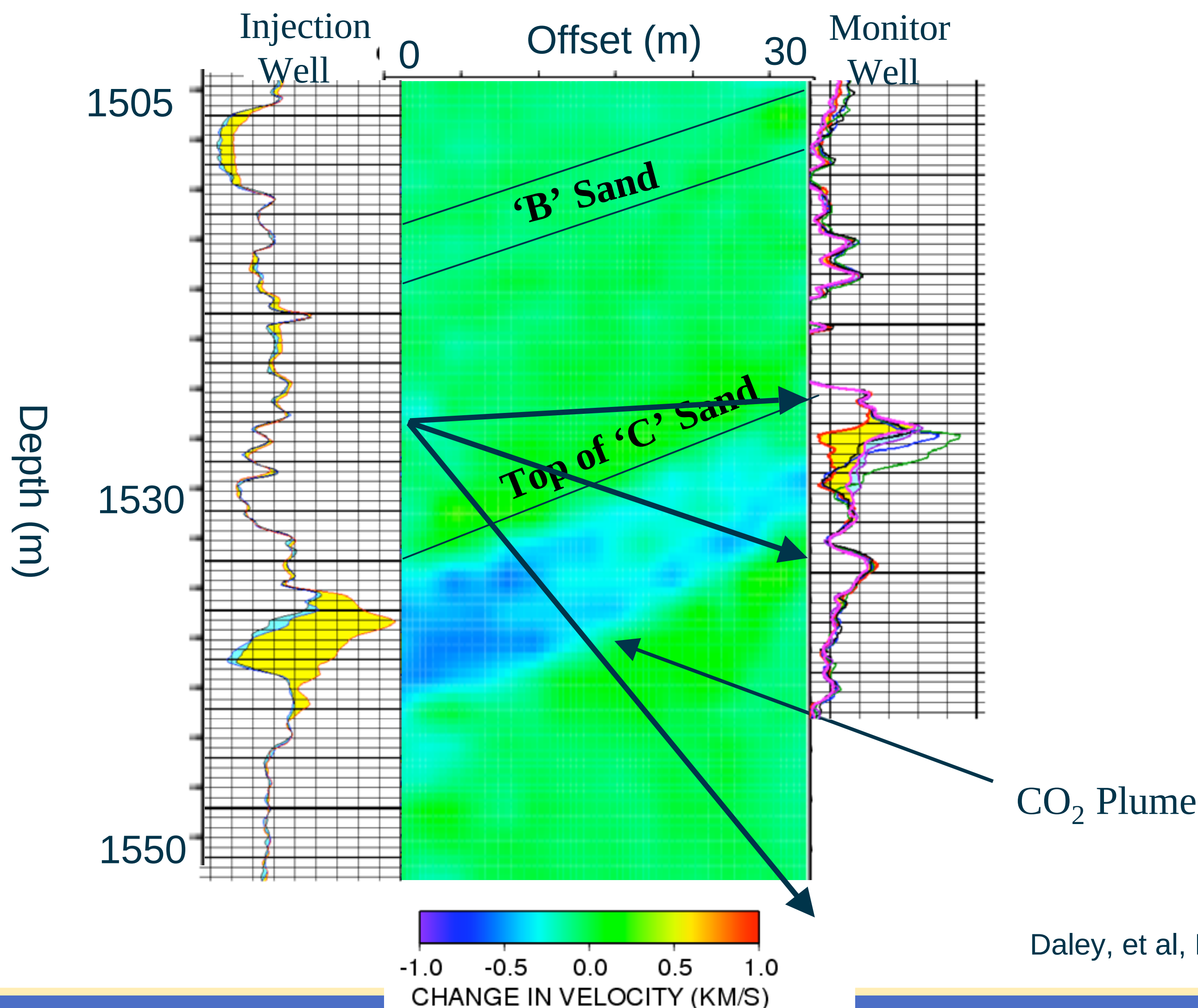
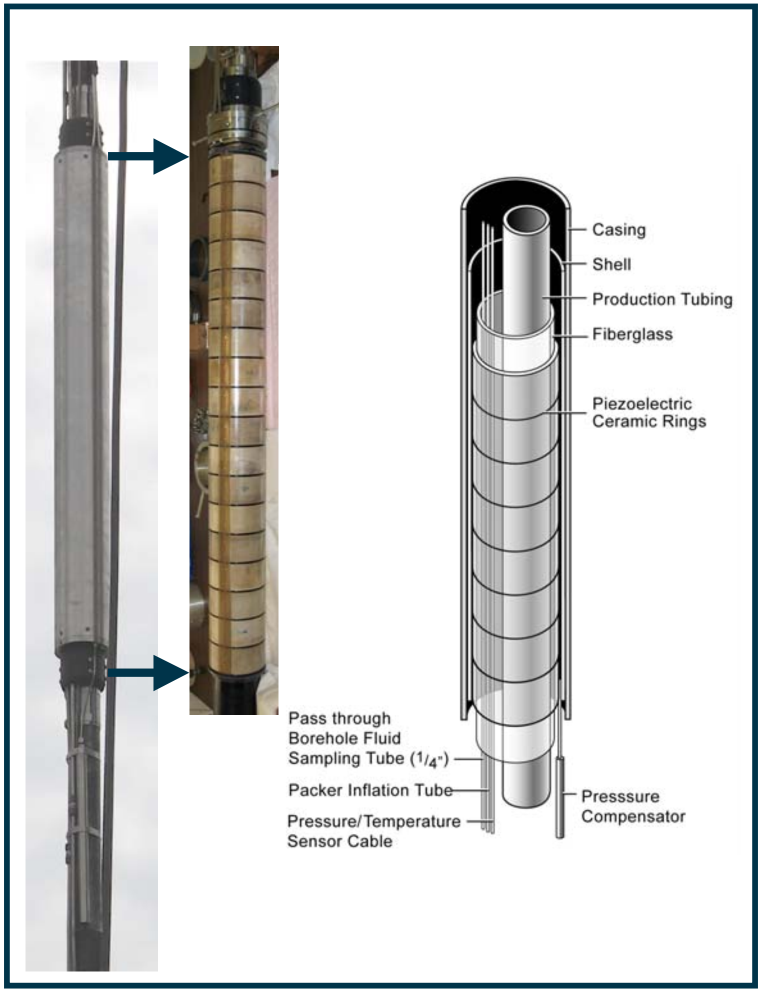



Daley, et al, Env. Geol., 2007

# “Piezotube” Source;  Hydrophone Sensor

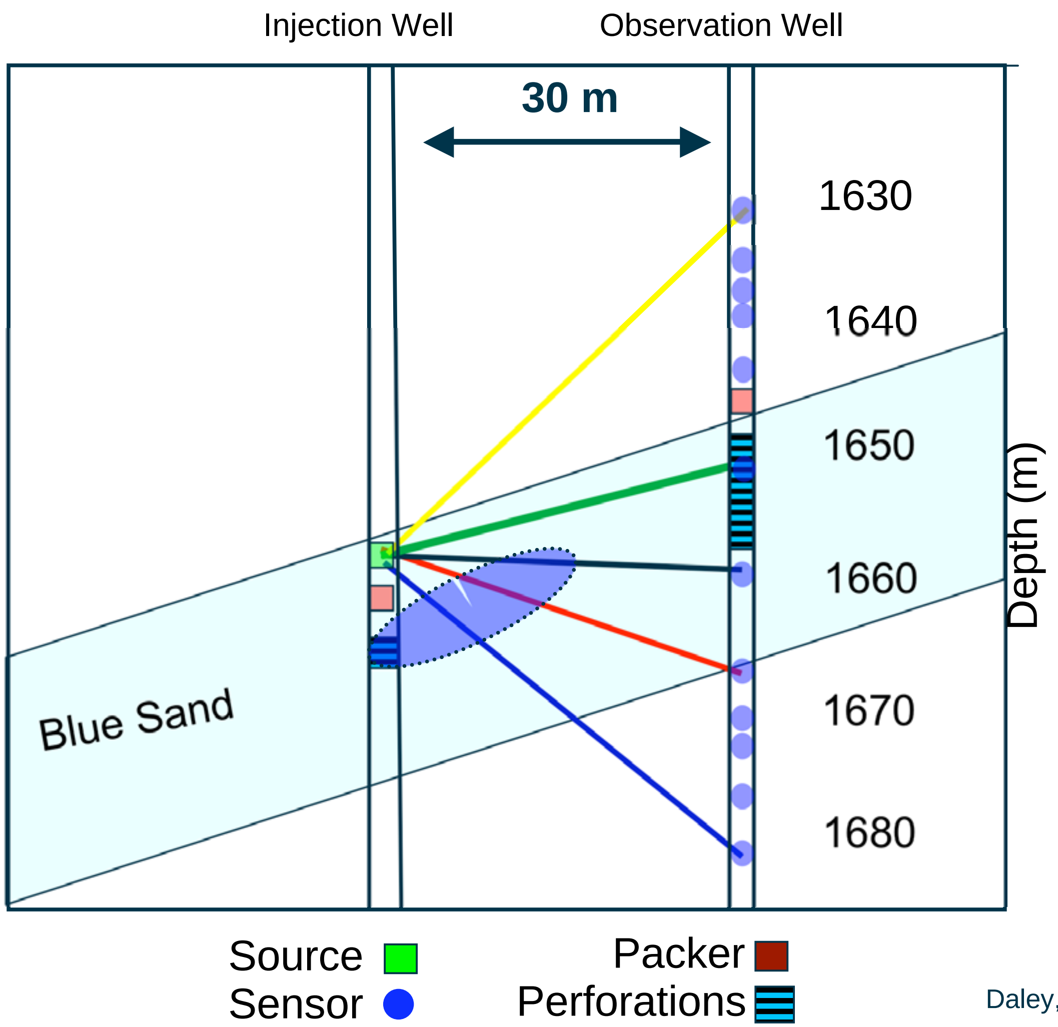



**Patent Pending**

**Hydrophone mounted on tubing**

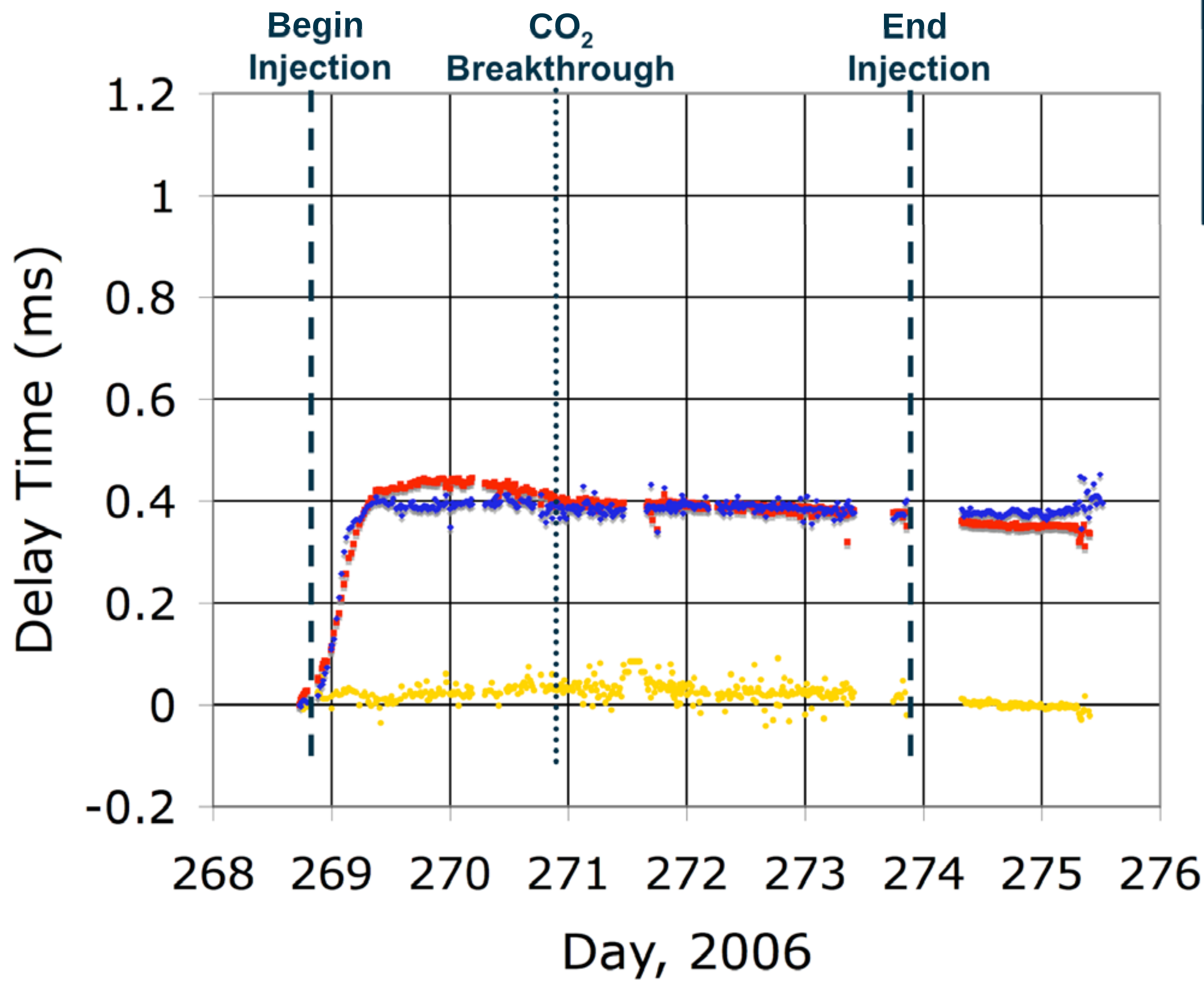
Daley, et al, Geophysics, 2007.

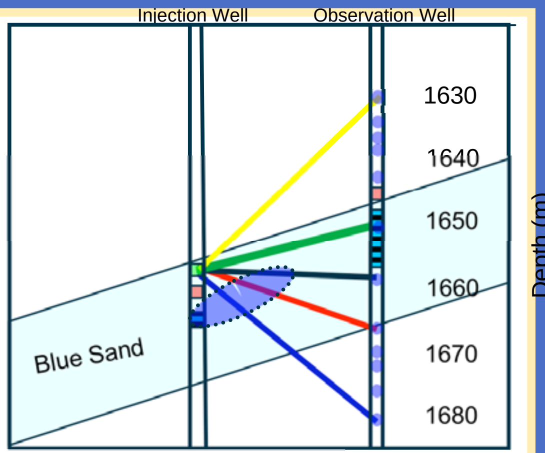
# Frio-II Continuous Active-Source Seismic Monitoring (CASSM): 5 Raypaths




Daley, et al, Geophysics, 2007.

# CASSM

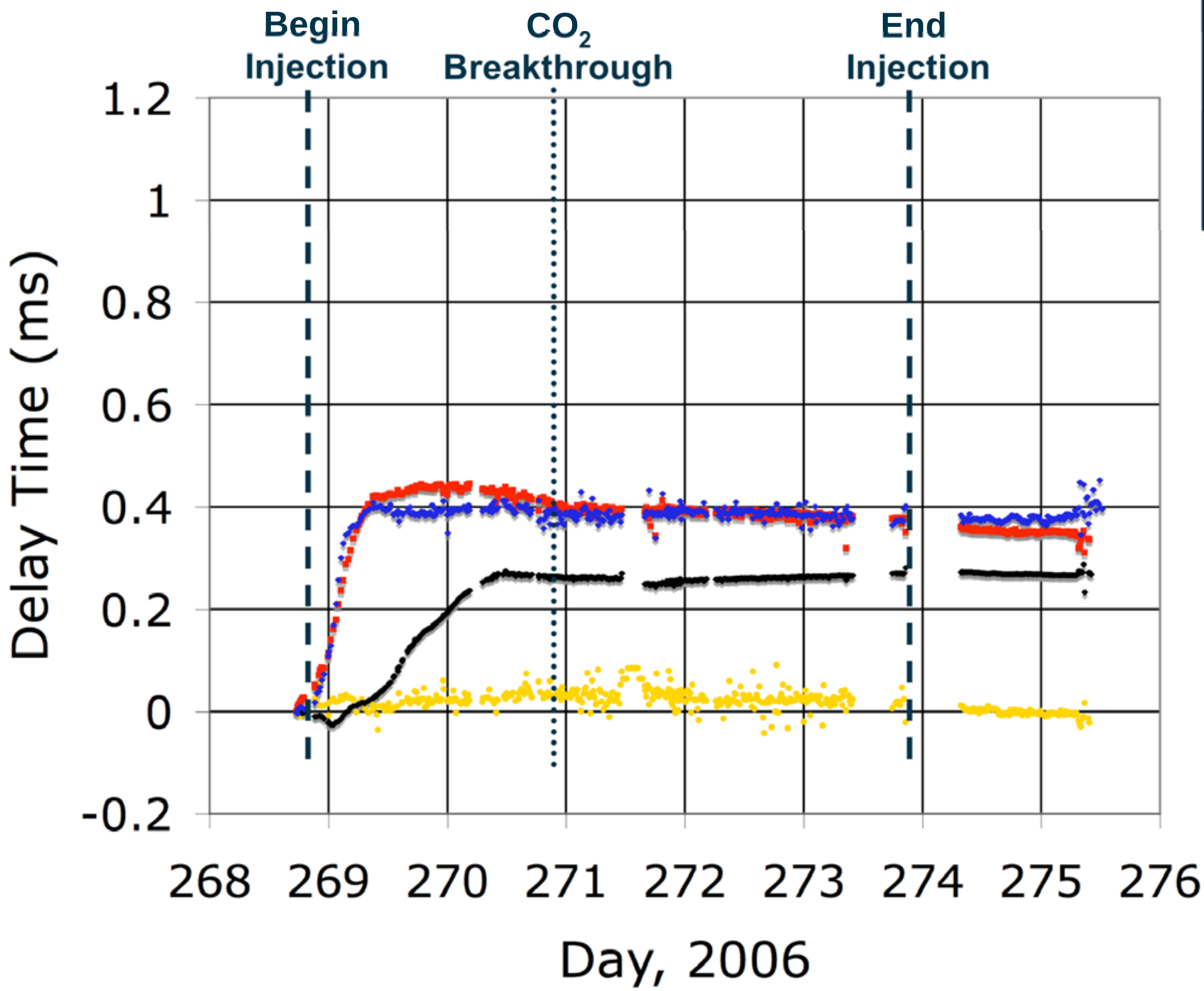


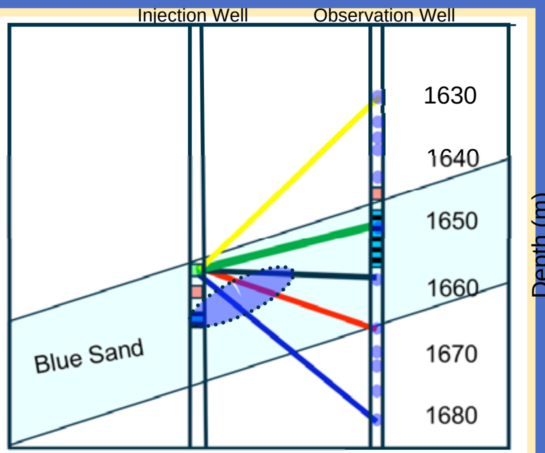



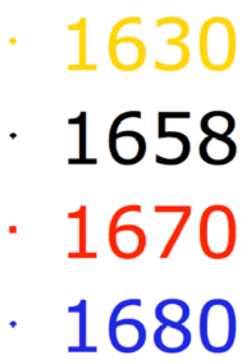

1630
1670
1680

Daley, et al, Geophysics, 2007.
Modified

# CASSM

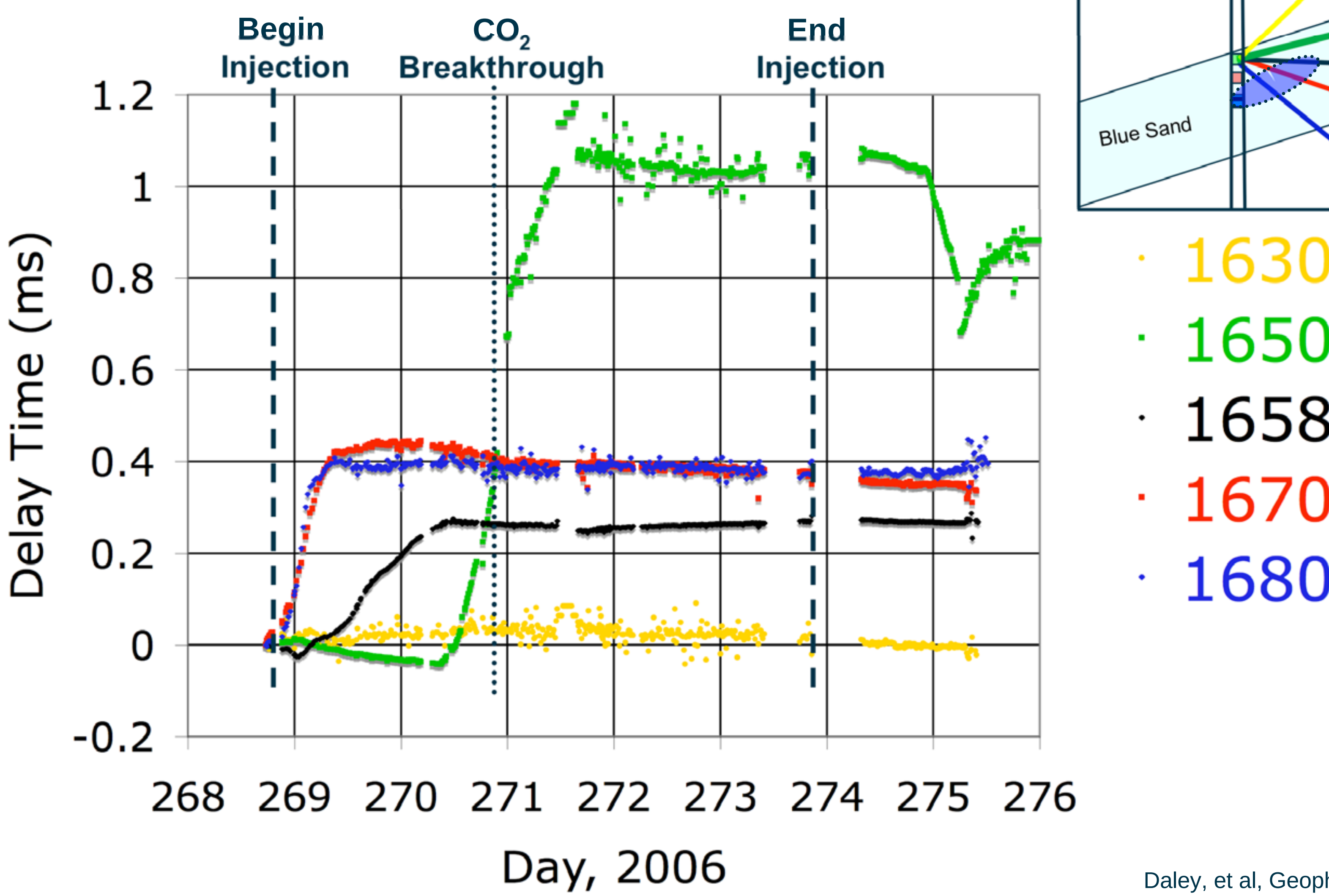


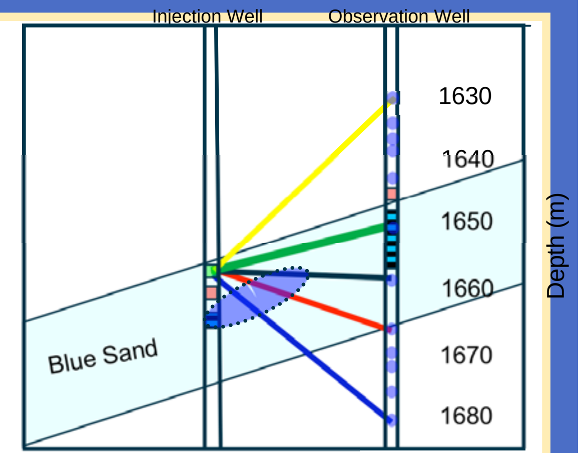




Daley, et al, Geophysics, 2007. Modified

# CASSM




Daley, et al, Geophysics, 2007.
Modified

# Summary and Conclusions

- Continuous crosswell travel time measurements can monitor stress induced velocity changes with non-permanent equipment installation.
- At SAFOD we see indications of coseismic and prerupture stress induced velocity change.
- Reservoir processes such as $CO_2$ injection can be monitored for spatial and temporal changes using CASSM technique.

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