Time-lapse attenuation variations during CO_2 injection using DAS VSP data from the CaMI.FRS

Yichuan Wang and Don Lawton

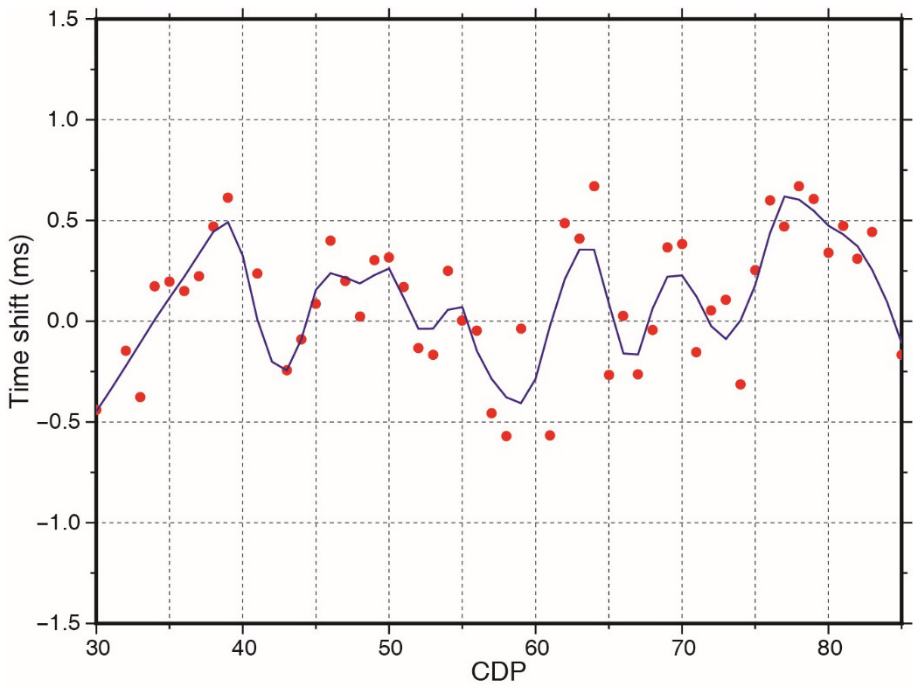
CREWES Annual Meeting

Dec 1st, 2022

Outline

- DAS VSP survey and data processing
- Time-lapse attenuation measurements
- Accuracy and resolution of estimated attenuation
- Discussion
- Conclusions

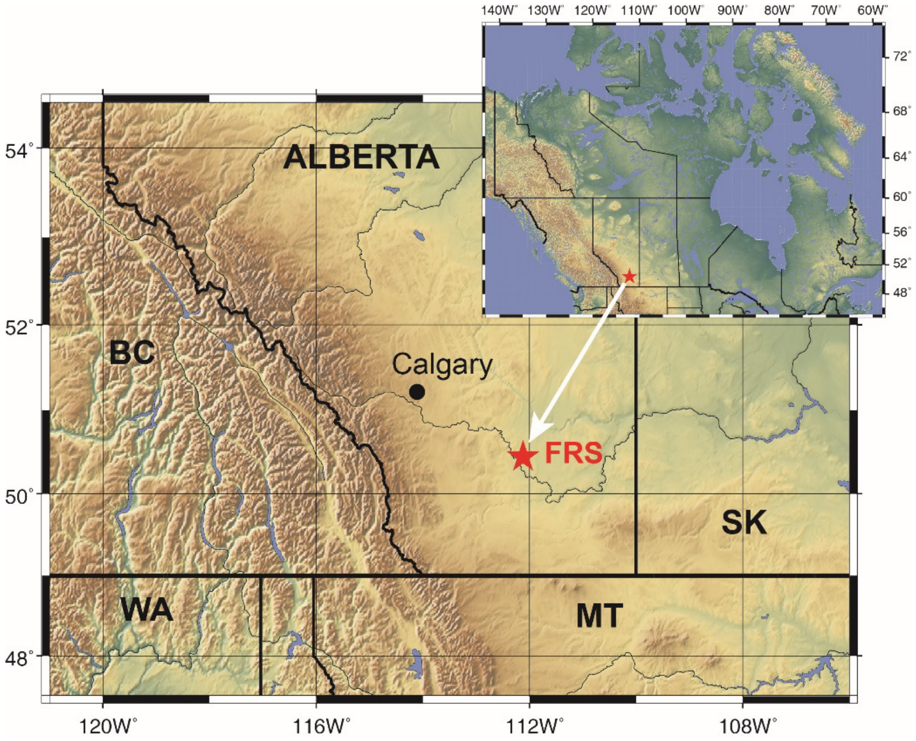
Motivation



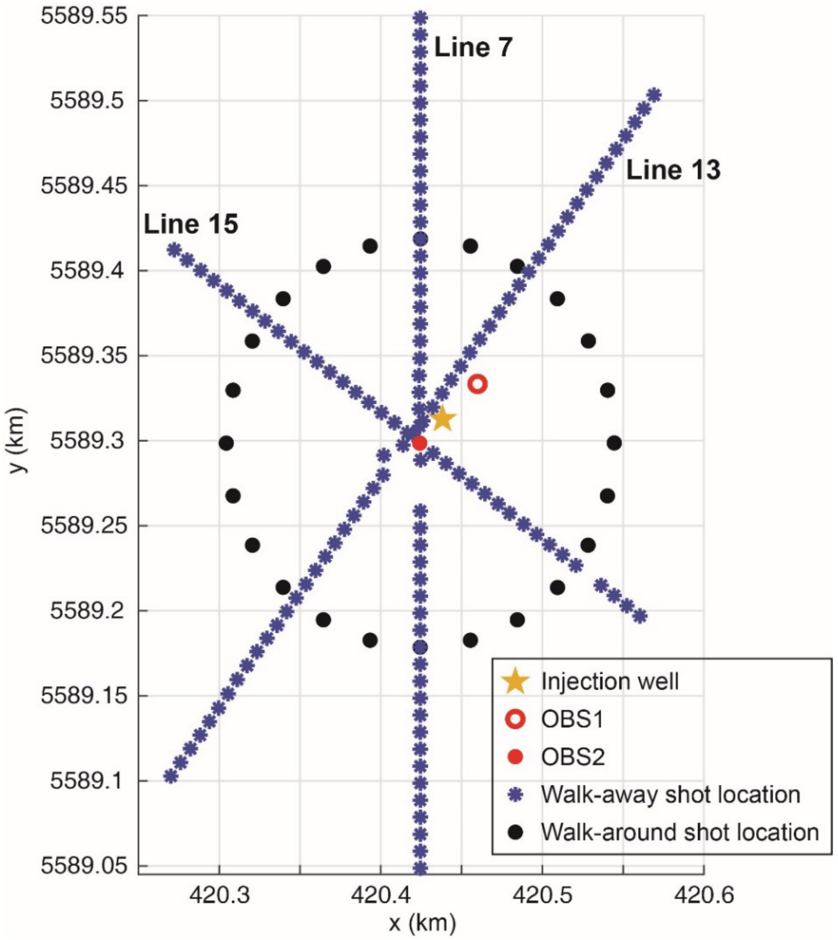
Time shifts along the first reflection horizon below CO_2 injection zone

- Injection zone at the FRS is thin (~7 m)
- Injected CO_2 may cause a decrease in P-wave velocity of only a few percent
- Such a decrease is near the seismic noise level for detection
- S/N of VSP data obtained through DAS fiber cable is generally lower than that from geophone
- Compared with velocity or density variations, attenuation is more sensitive to changes in saturation, permeability, and pore fluid

DAS VSP layout

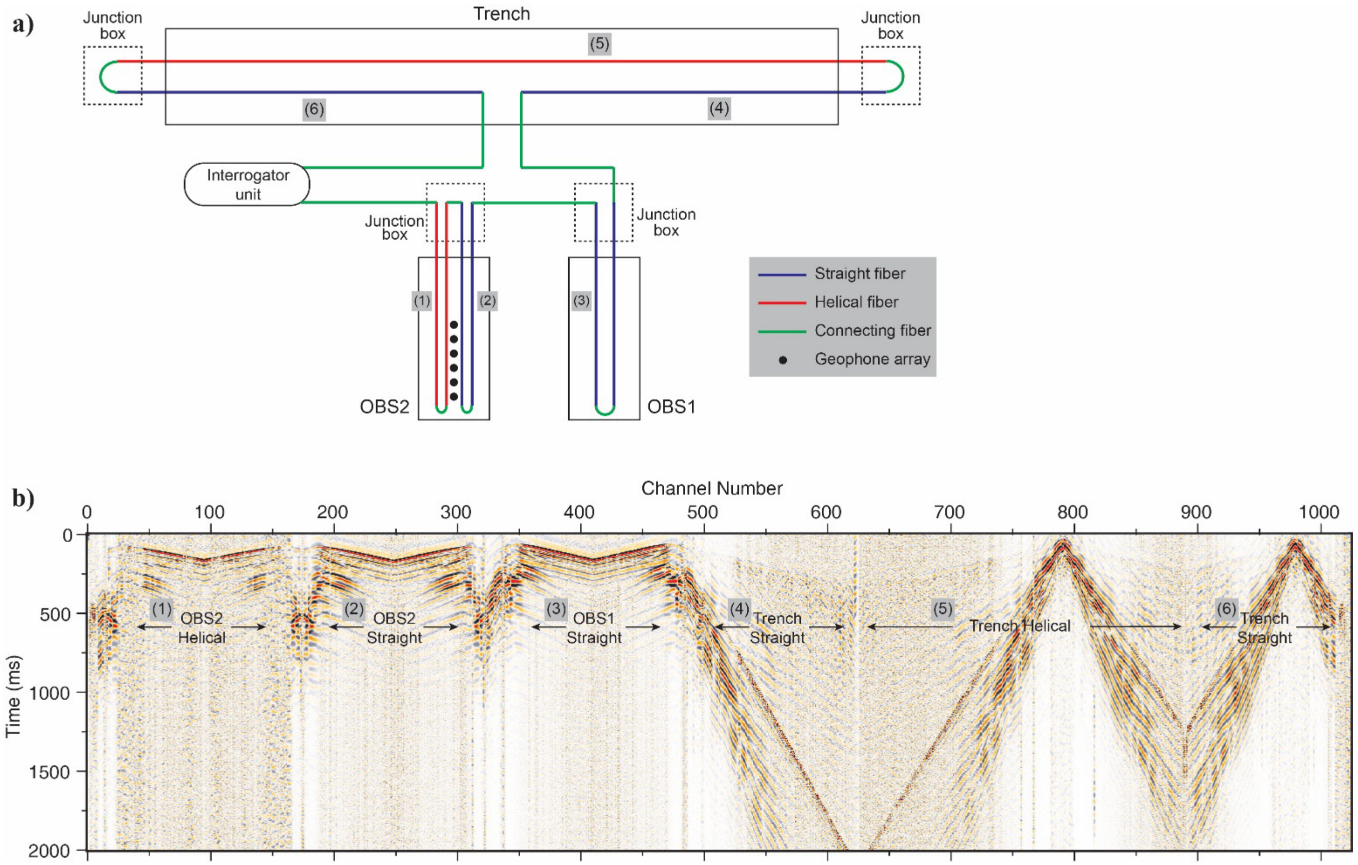


Location map of CaMI FRS in southern Alberta, Canada



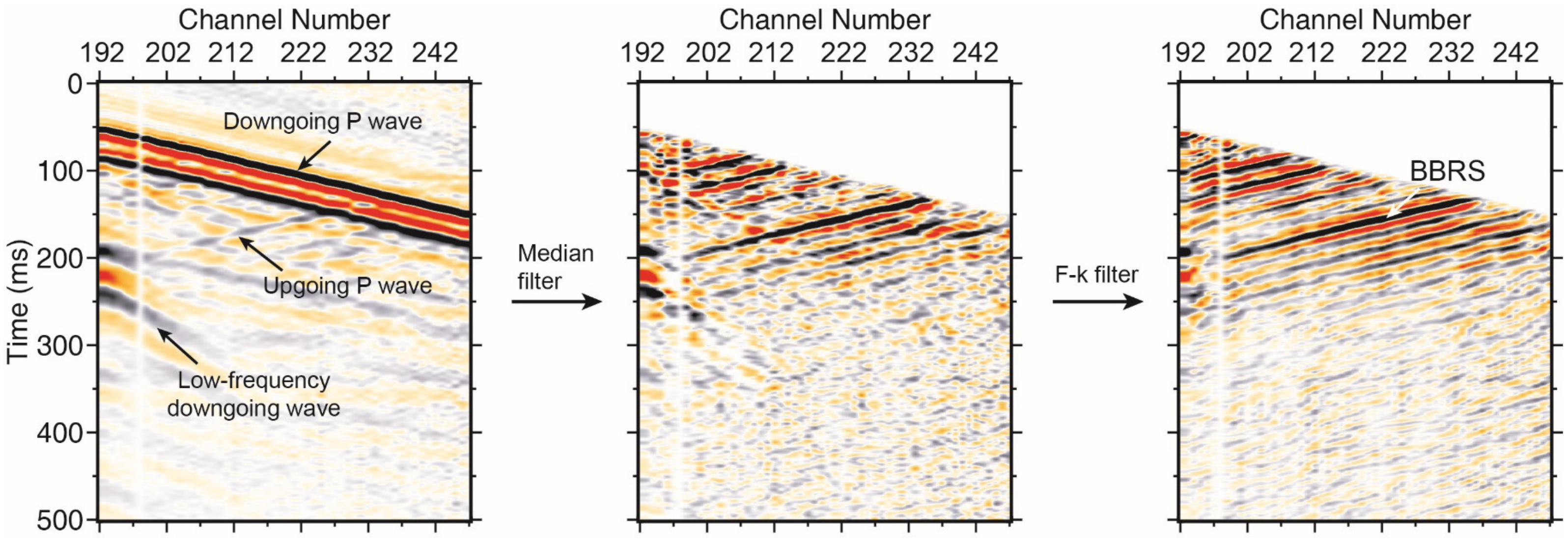
- Monitor survey acquired in March 2021
- ~34 tonnes of CO_2 injected prior to this date

Fiber layout and data



- Continuous fiber loop (5km) and raw DAS shot gather
- Tag numbers indicate the corresponding data from different portions of fiber loop
- DAS data from the straight fiber in OBS2
- Identical data processing for different vintages of DAS data

Wavefield separation



- Construct attenuation-attribute images from reflection signal for monitoring injected CO_2
- Separate downgoing and upgoing wavefields through a median filter followed by a f-k filter
- Upgoing P-wave reflections are clearly isolated and evident over the entire depth coverage

Seismic attenuation model

1) Non-stationary convolutional model for reflection signal:

$$A(t,f)=S(f)R(t,f)F(t,f)G(t)$$

- A: time-frequency variant amplitude of reflection signal
- S: spectrum of seismic source
- R: time-frequency response of reflectivity
- F: seismic attenuation $F(t,f)=\exp\left[-\pi f\int_0^t d\tau/Q(\tau)\right]$ (anelastic)
- G: focusing or defocusing $G(t)=\exp\left[-\int_0^t \gamma(\tau)\,d\tau\right]$ (elastic)

2) Take logarithm and time derivative:

$$\gamma+\pi fQ^{-1}=\frac{\partial}{\partial t}\left[\ln R(t,f)-\ln A(t,f)\right]$$

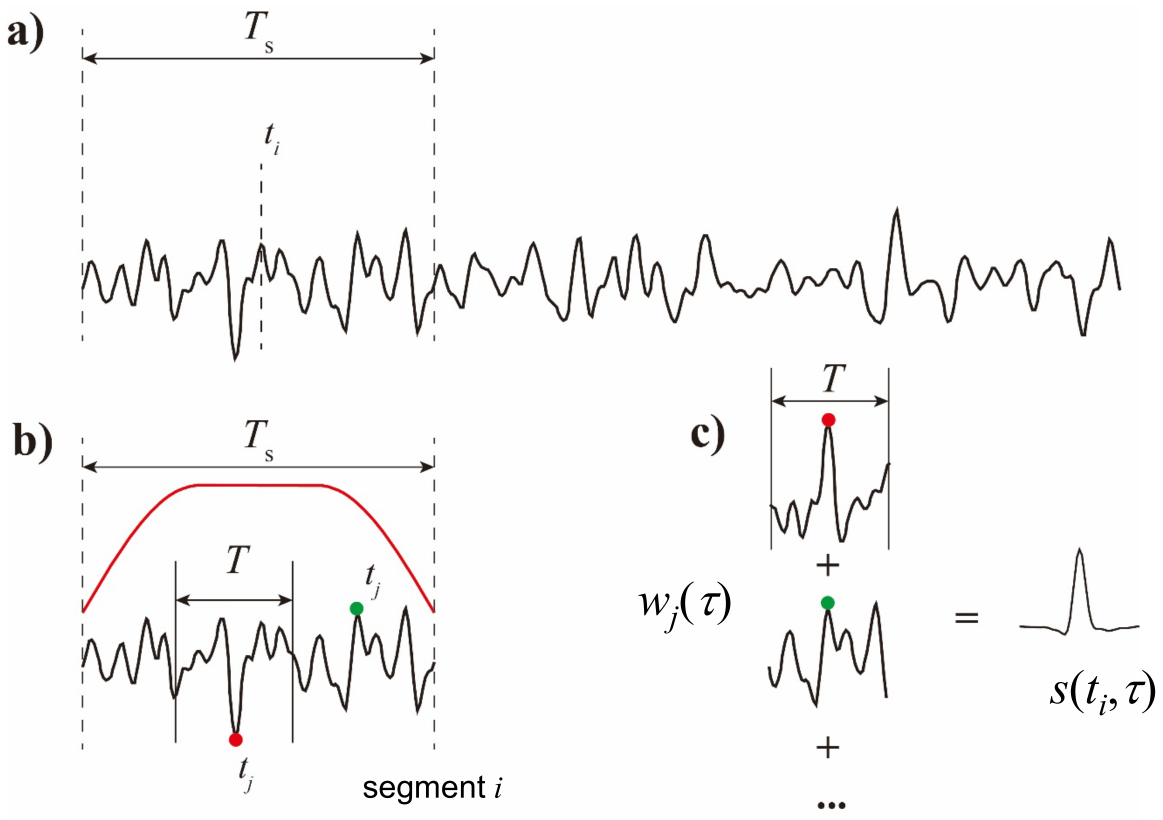
- γ is a “geometric” counterpart for Q^{-1}

3) Under the assumption $R(t,f)=const$:

$$\gamma_A+\pi fQ_A^{-1}=-\frac{\partial \ln A(t,f)}{\partial t}$$

- γ_A and Q_A are the “apparent” attenuation
- Require smooth estimates of $A(t,f)$

Time-variant spectra



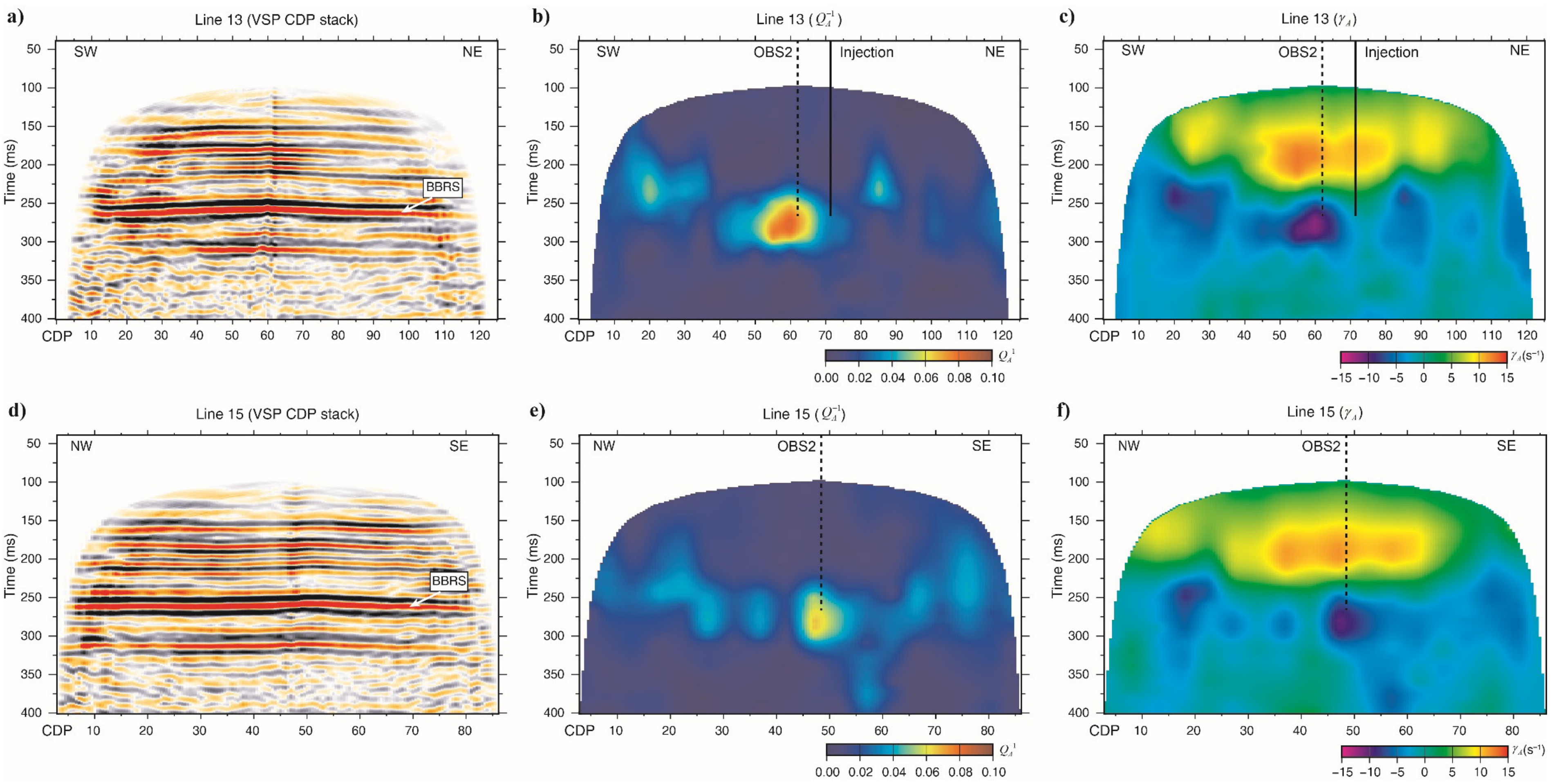
$$s(t_i,\tau) = c_0 \sum_{j \in \text{segment } i} h\left(\frac{t_j - t_i}{T_s}\right) w_j(\tau)$$

- c_0 scales peak amplitude equal to $s(t_i,\tau) = 1$
- Hann window h of the same length T_s with segment i
  - Apply weights to $w_j(\tau)$ located within different parts centered on t_j of each peak
  - Located at the middle of segment has the maximum weight and at the edge has a zero weight
- Temporal resolution of the resulting spectra can be estimated as the half segment length $T_s/2$

Attenuation measurements from monitor data

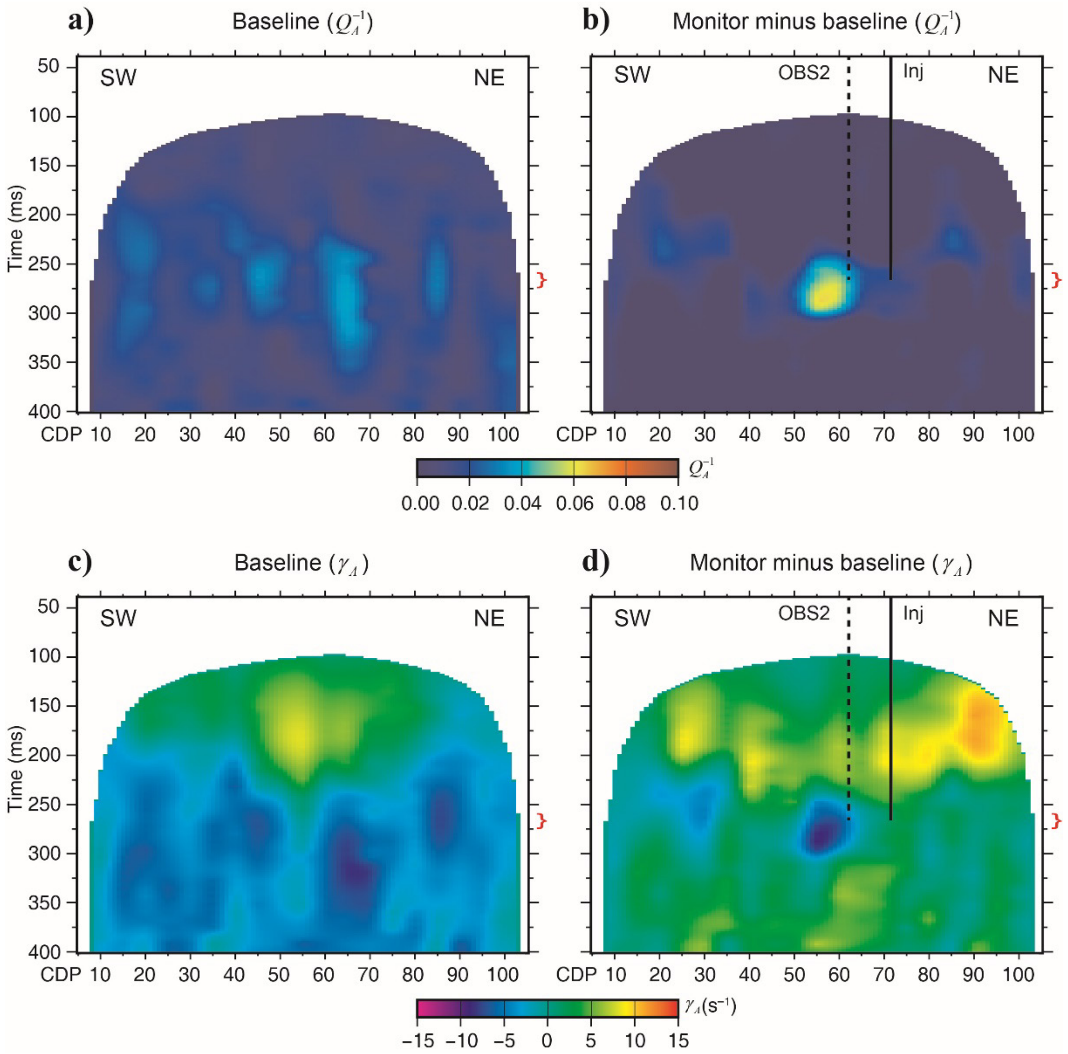
Line 13

Line 15



- Large γ_A and Q_A^{-1} around OBS2 at the BBRS injection zone
- Increased CO_2 saturation and/or pore pressure
- Consistent γ_A and Q_A^{-1} around OBS2 from two different lines

Time-lapse attenuation variations



- Measurements from baseline data show there is no anomaly prior to CO_2 injection
- Time-lapse responses show a clear increase to the SW of OBS2
- Attenuation increase not around the injection well indicates the migration of injected CO_2
- From liquid phase around the injection well to gas phase at the leading edge of the plume

Outline

- DAS VSP survey and data processing
- Time-lapse attenuation measurements
- Accuracy and resolution of estimated attenuation
- Discussion
- Conclusions

Accuracy and temporal resolution

$$a_k = \gamma + \pi\left(f_k - \bar{f}\right)Q^{-1}$$

Empirical error

Errors for regression coefficients (Q^{-1} and γ) are

$$s_{\hat{\gamma}} = \frac{\sigma_{\hat{a}}}{\sqrt{n}}$$ (intercept)

$$s_{\hat{Q}^{-1}} = \frac{\sigma_{\hat{a}}}{\pi\sqrt{\sum\left(f_k - \bar{f}\right)^2}} = \frac{s_{\hat{\gamma}}}{\pi\left\langle f_k - \bar{f}\right\rangle_{RMS}}$$ (slope)

- $\langle\cdots\rangle_{RMS}$: RMS average
- $\sigma_{\hat{a}}^2$: variance of the estimated spectral quantity

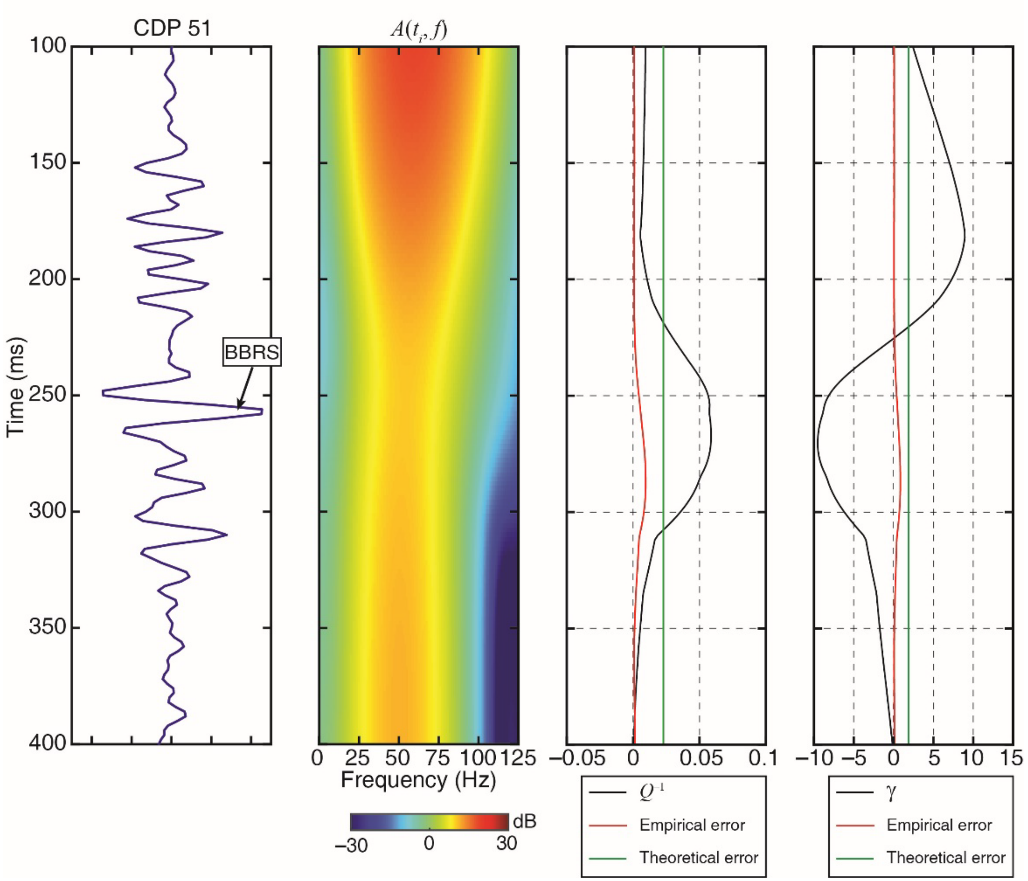
Theoretical error

$$s_{\hat{\gamma}} = \frac{1}{\sqrt{2\Delta t}}\frac{1}{\sqrt{BT}}$$

$$s_{\hat{Q}^{-1}} = \frac{s_{\hat{\gamma}}}{\pi c B} = \frac{1}{\pi\sqrt{2c}}\frac{1}{\sqrt{BT}}\frac{1}{B\Delta t}$$

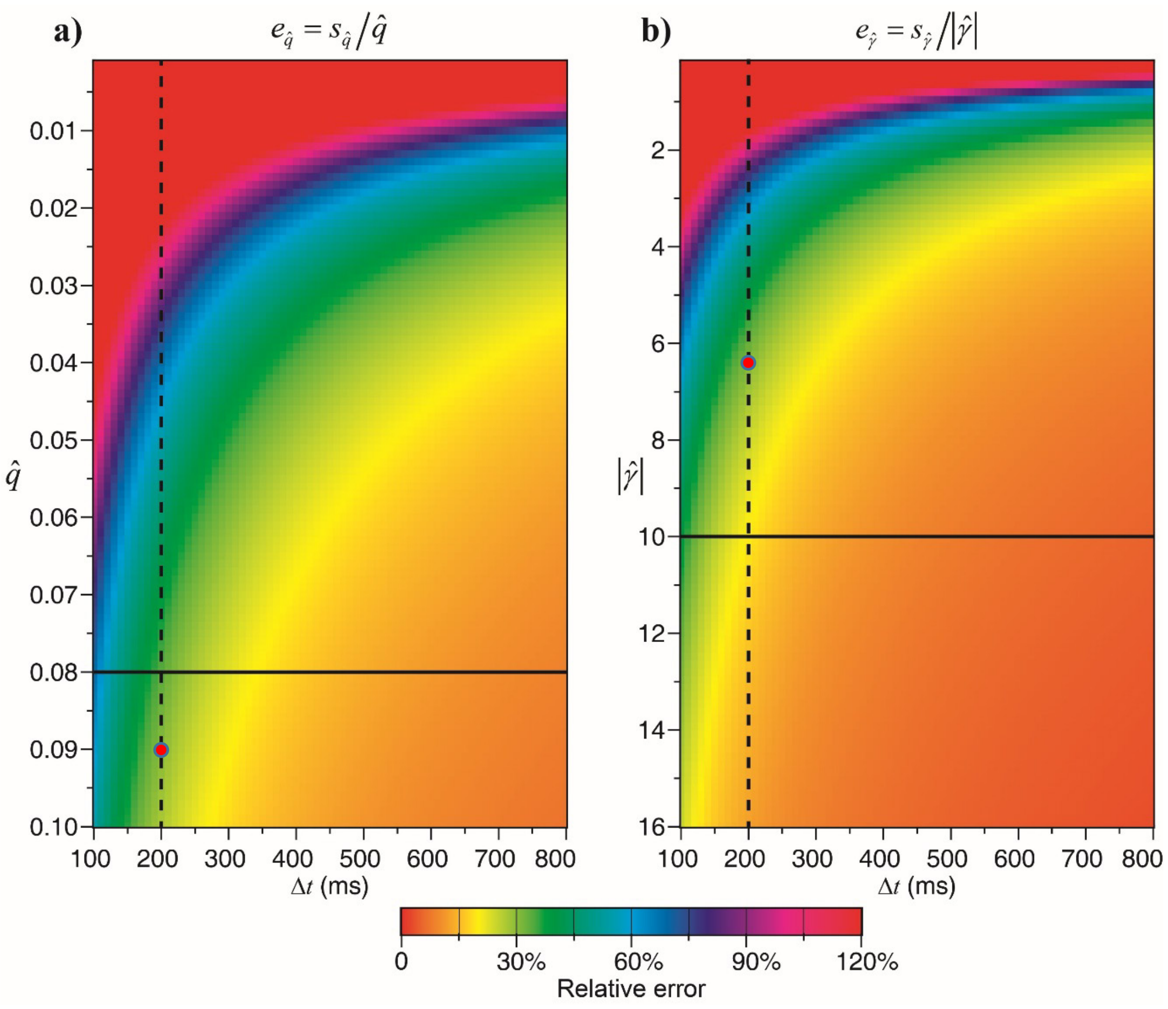
- B: signal frequency bandwidth
- T: waveform length in spectral measurement
- Δt: temporal resolution
- Independent of γ or Q^{-1} value
- Key parameter is the desired temporal resolution Δt

Measurement errors



- Resolution of $\Delta t = 200$ ms
- Q^{-1} is below theoretical error (green line) for most depths above and below the BBRS
- Limited accuracy of Q^{-1} for areas outside of injection zone
- Around the BBRS that is with high attenuation, Q^{-1} is much larger than error
- Accuracy of γ is higher with the theoretical error smaller than γ for all the depths

Relative errors

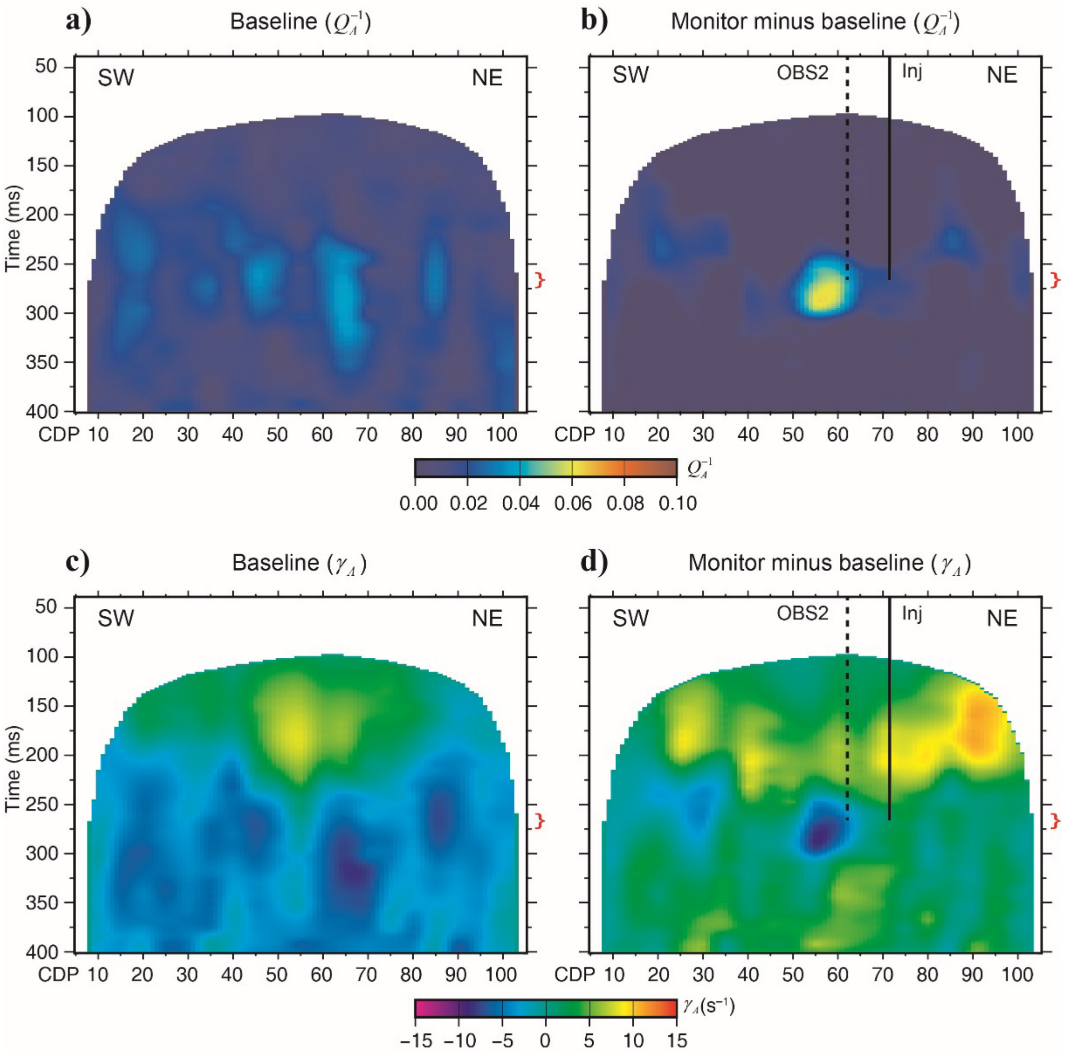


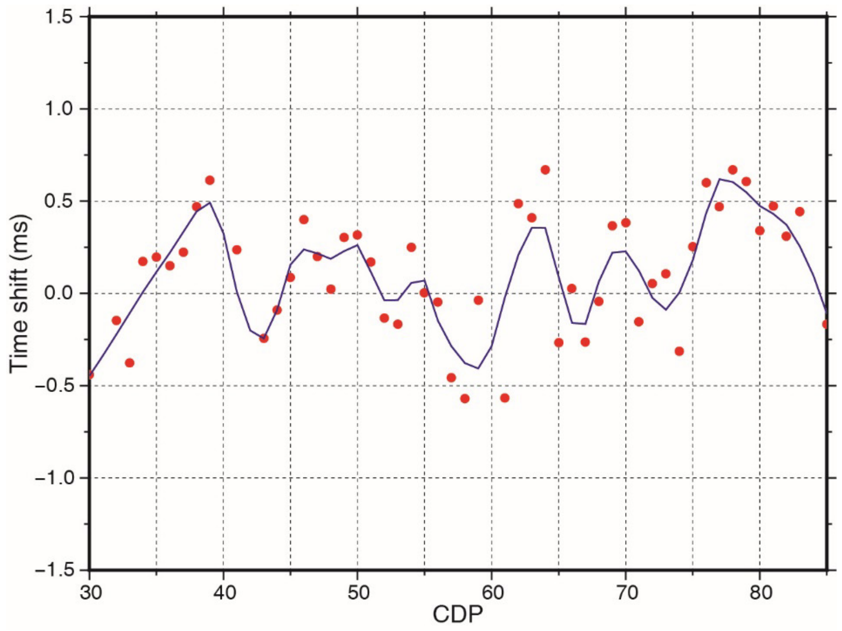
- Black dashed line: resolution of $\Delta t = 200$ ms
- Black solid line: a) estimated Q^{-1} of 0.08; b) estimated γ of 10 s^{-1}
- Significant trade-off between accuracy of estimated Q^{-1} or γ and temporal resolution
- $Q^{-1} > 0.09$ and $|\gamma| > 6.5 s^{-1}$ for achieving an error lower than 30%
- Around the BBRS injection zone, relative errors are modest $e_{\hat{Q}^{-1}} \approx 34\%$ and $e_{\hat{\gamma}} \approx 20\%$

Outline

- DAS VSP survey and data processing
- Time-lapse attenuation measurements
- Accuracy and resolution of estimated attenuation
- Discussion
- Conclusions

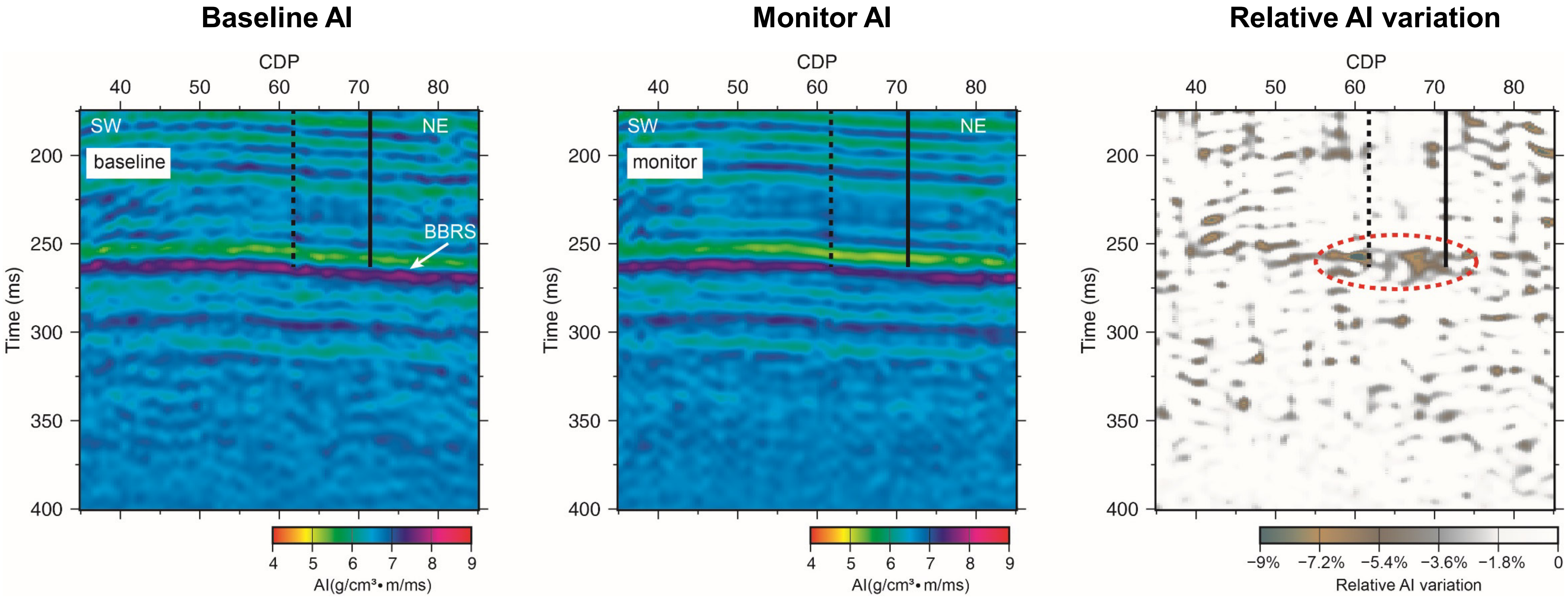
Comparison with time shifts





Time shifts along the first reflection horizon below injection zone

Comparison with impedance variations



Conclusions

- Both Q^{-1} and its geometric counterpart γ are measured from the DAS VSP data for monitoring the CO_2 injection.
- The variations of Q^{-1} or γ are correlated with injection zone and interpretated as being caused by an increase in CO_2 saturation.
- Evaluations of measurement accuracy show the measured Q^{-1} or γ of large values around the injection zone are reliable.
- Attenuation is a sensitive property that can complement velocity change for monitoring injected CO_2 during geologic CO_2 storage.

Acknowledgements

- CREWES sponsors, staff, students
- CMC JIP subscribers
- Global Research Initiative at the University of Calgary
- Natural Science and Engineering Research Council of Canada