Monitoring Performance of Geological Storage Projects

RITE/METI CCS Workshop: Ensuring Safety Towards Public Acceptance| Tokyo, Japan

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Outline

- Purposes for monitoring
- Monitoring options and examples
- Project lifecycle and monitoring packages

Purposes for Monitoring

Parameters

Health, Safety, and Environmental Protection
- Protect worker and public health and safety
- Groundwater protection
- Ecosystem protection
- Seismic hazards

CO_2 concentrations
Groundwater quality
Microseismic activity

Emission Reduction Compliance and Credits
- Verification of national inventories
- Carbon credit trading

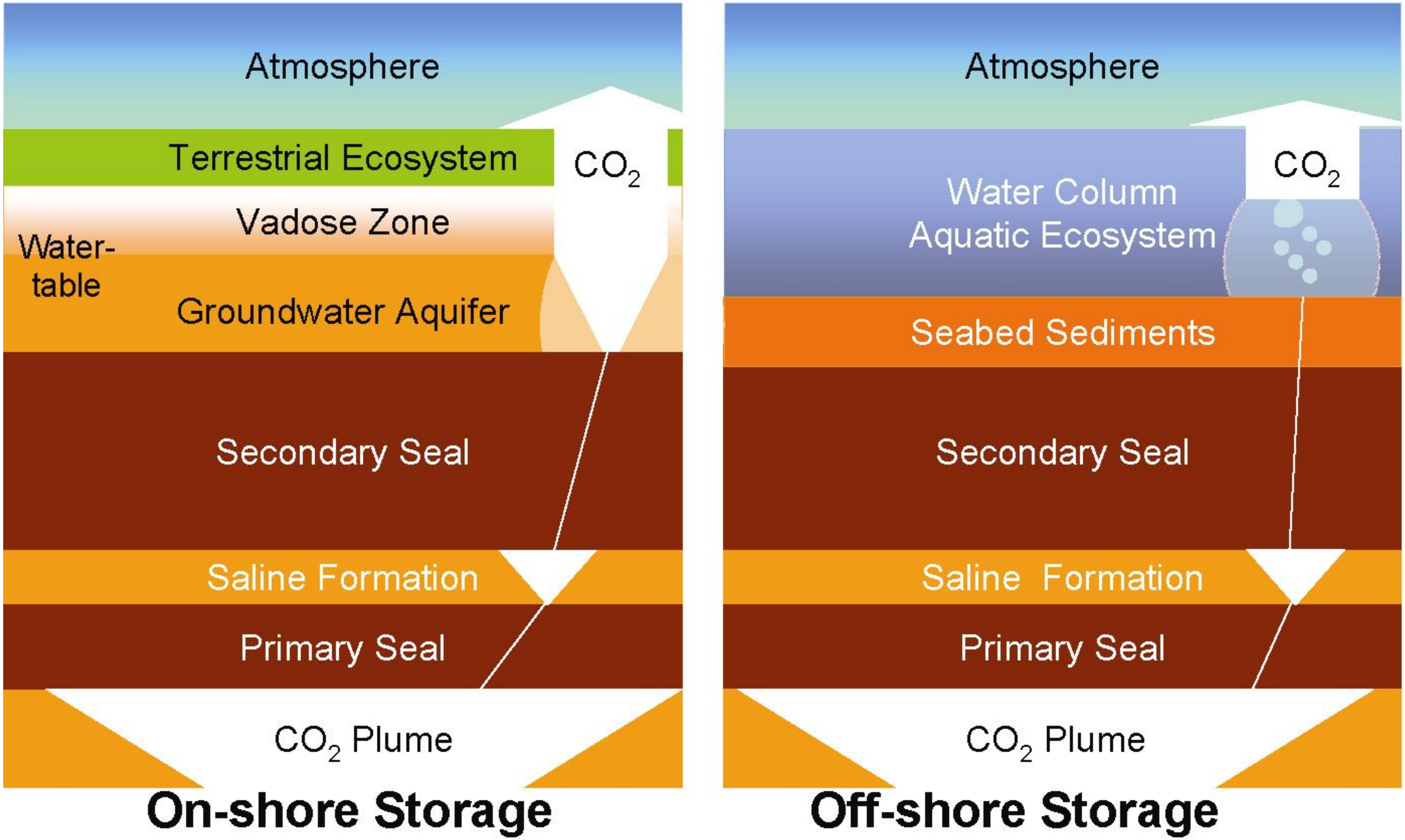
CO_2 releases (fluxes)

Project Conformance and Optimization
- Model calibration and history matching
- Performance assessment
- Storage engineering and optimization
- Remediation planning and assessment

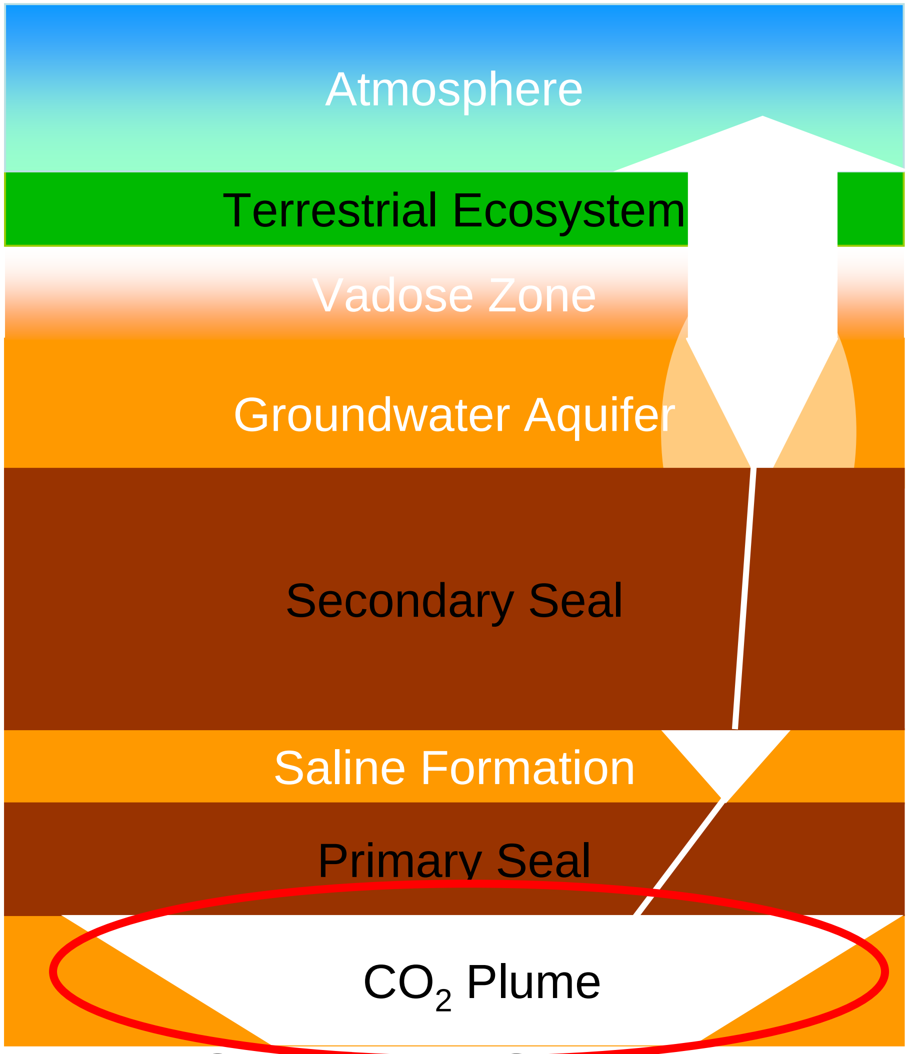
Location of the CO_2 plume

Pressure buildup

Monitoring Options



Strategy: Sequestration Reservoir



On-shore Storage

Methods

- Geophysical methods
  - **Seismic**
  - Electrical
  - Gravity
  - Tilt
- **Reservoir pressure**
- **Well logs**
- **Fluid sampling**

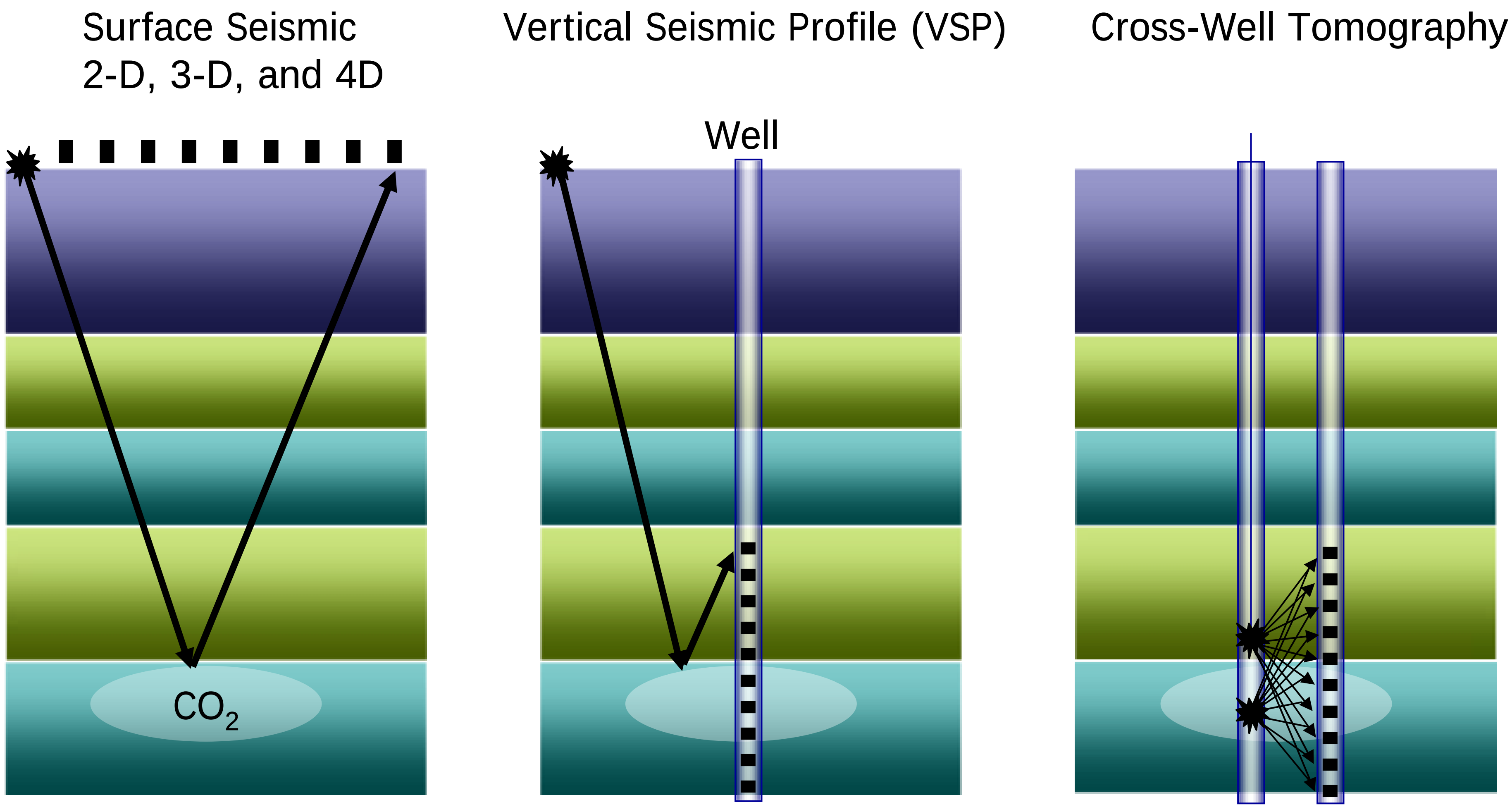
Benefits

- History match to calibrate and validate models
- Document project conformance
- Early warning of leakage

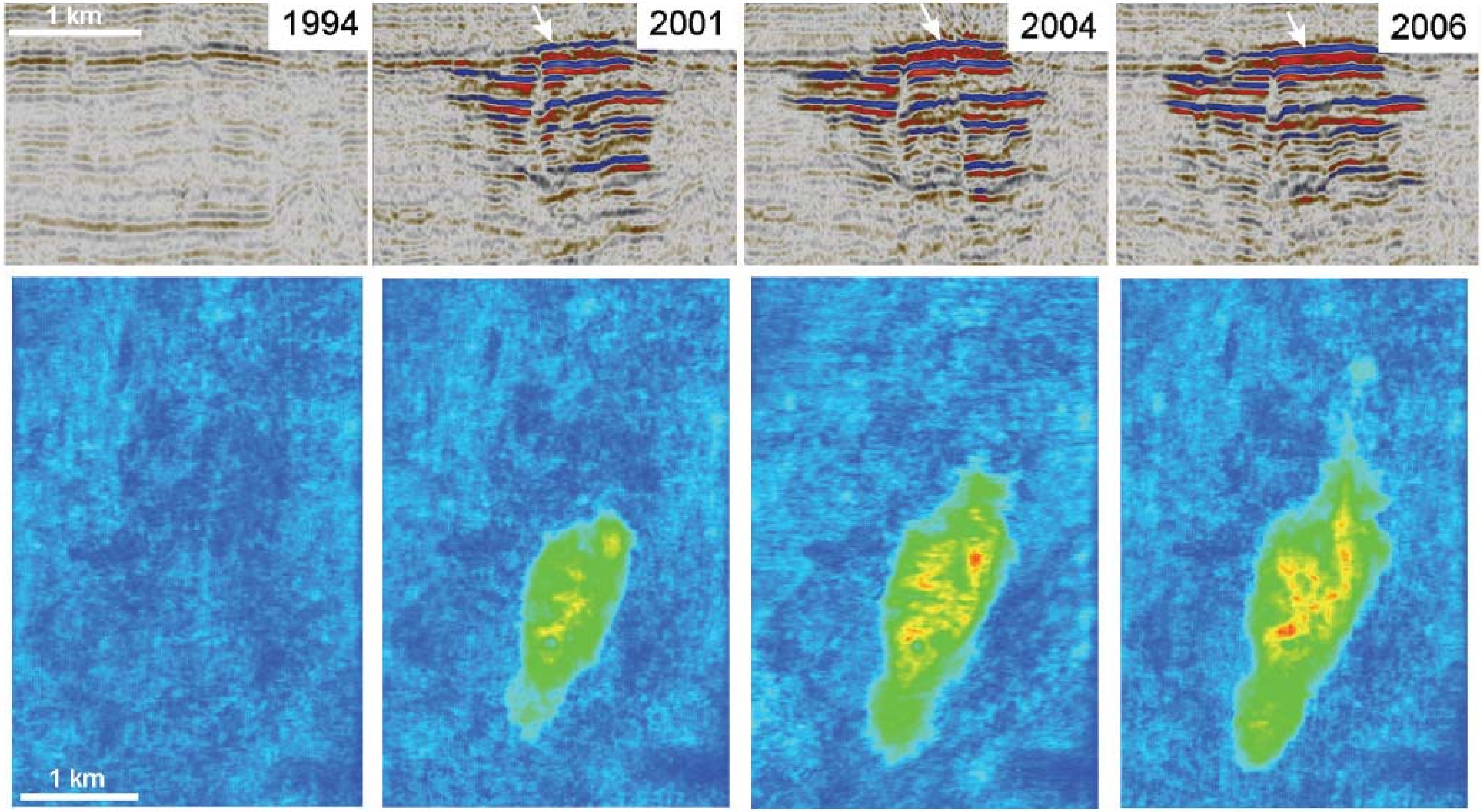
Drawbacks

- Mass balance difficult to monitor
- Dissolved and mineralized CO_2 difficult to detect

Seismic Monitoring Options



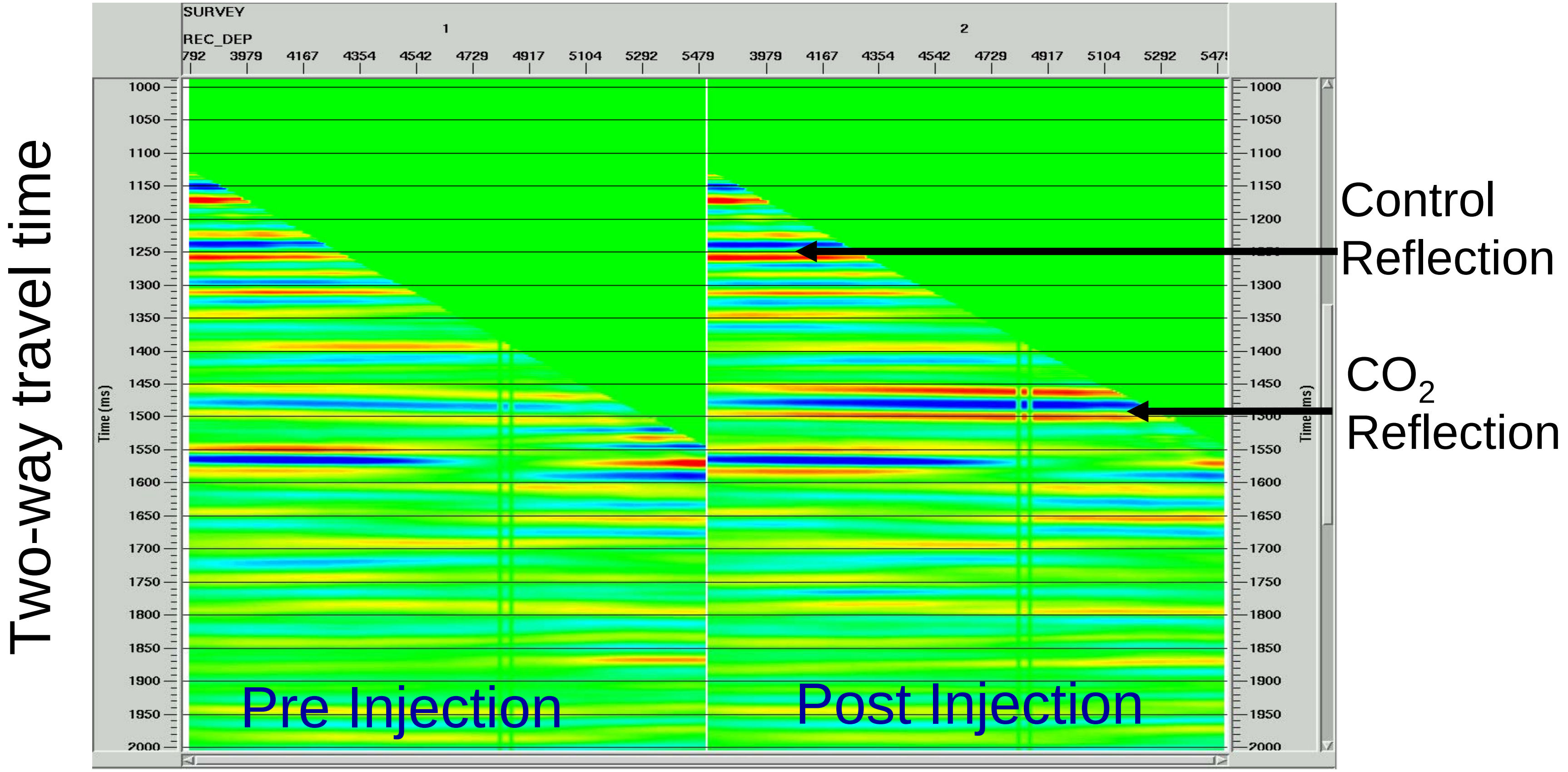
Seismic Monitoring Data from Sleipner



From Chadwick et al., GHGT-9, 2008.

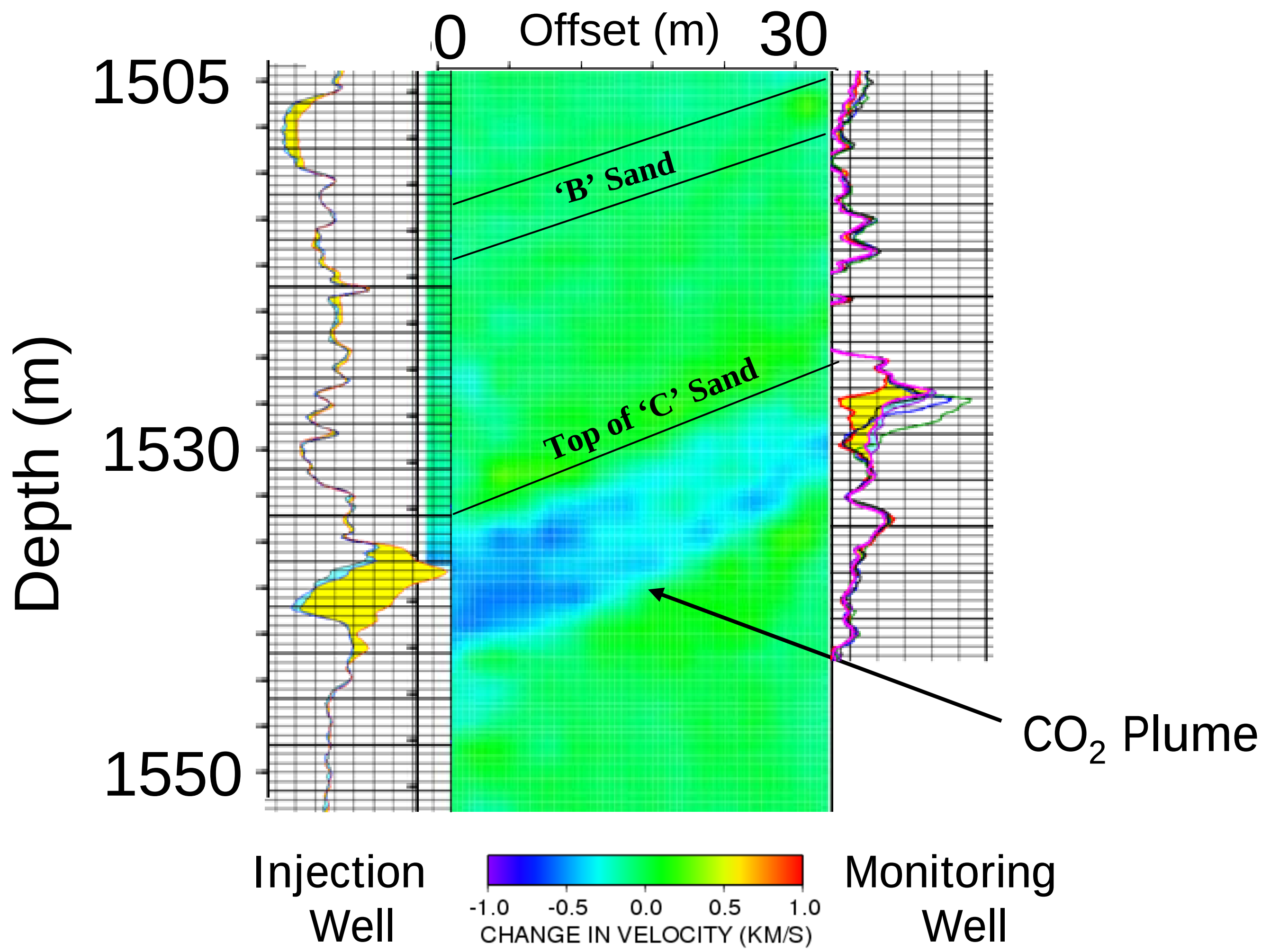
Frio Formation: Vertical Seismic Profile Data

1,600 tonnes CO_2

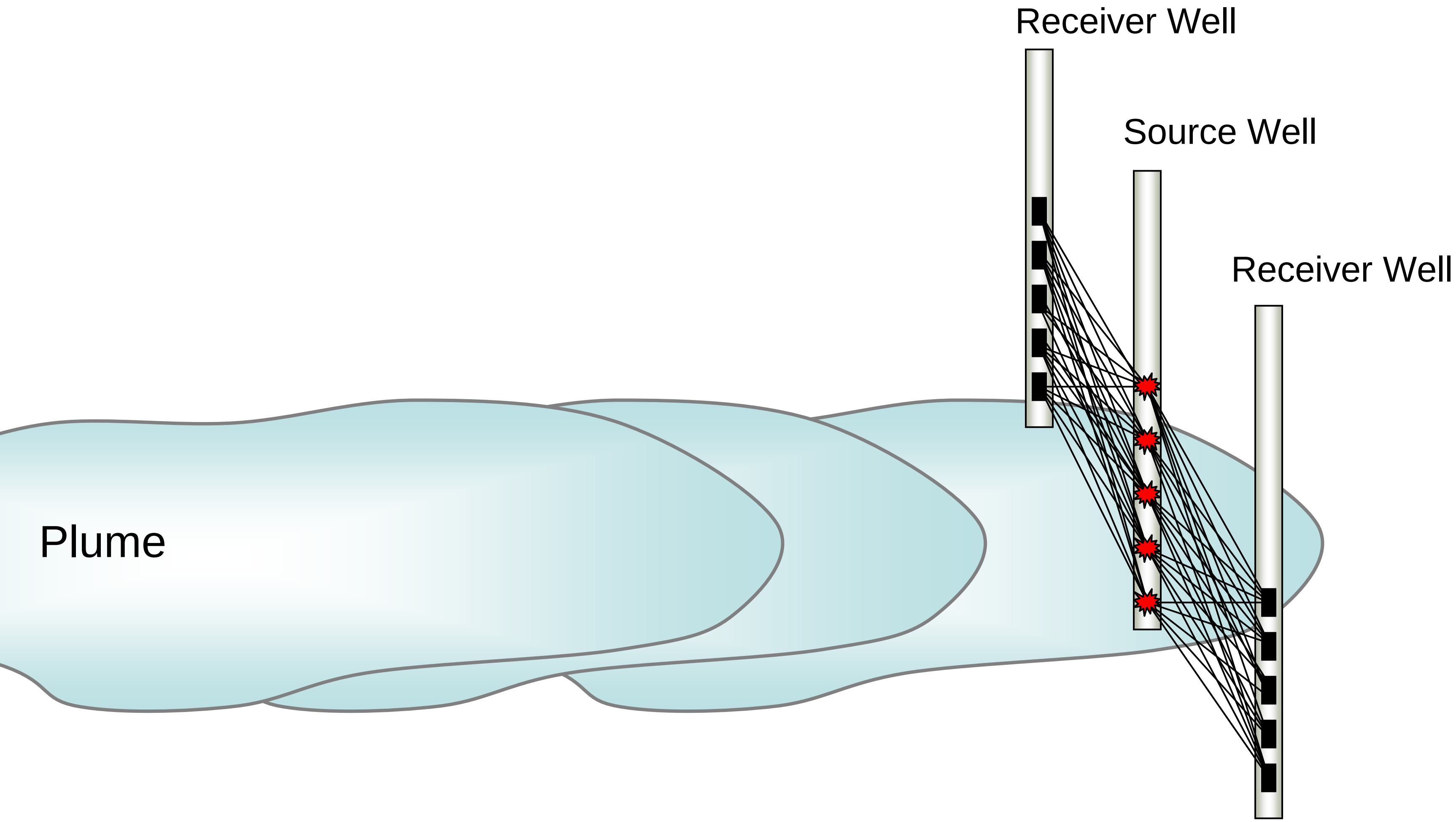


Data from Tom Daley, LBNL

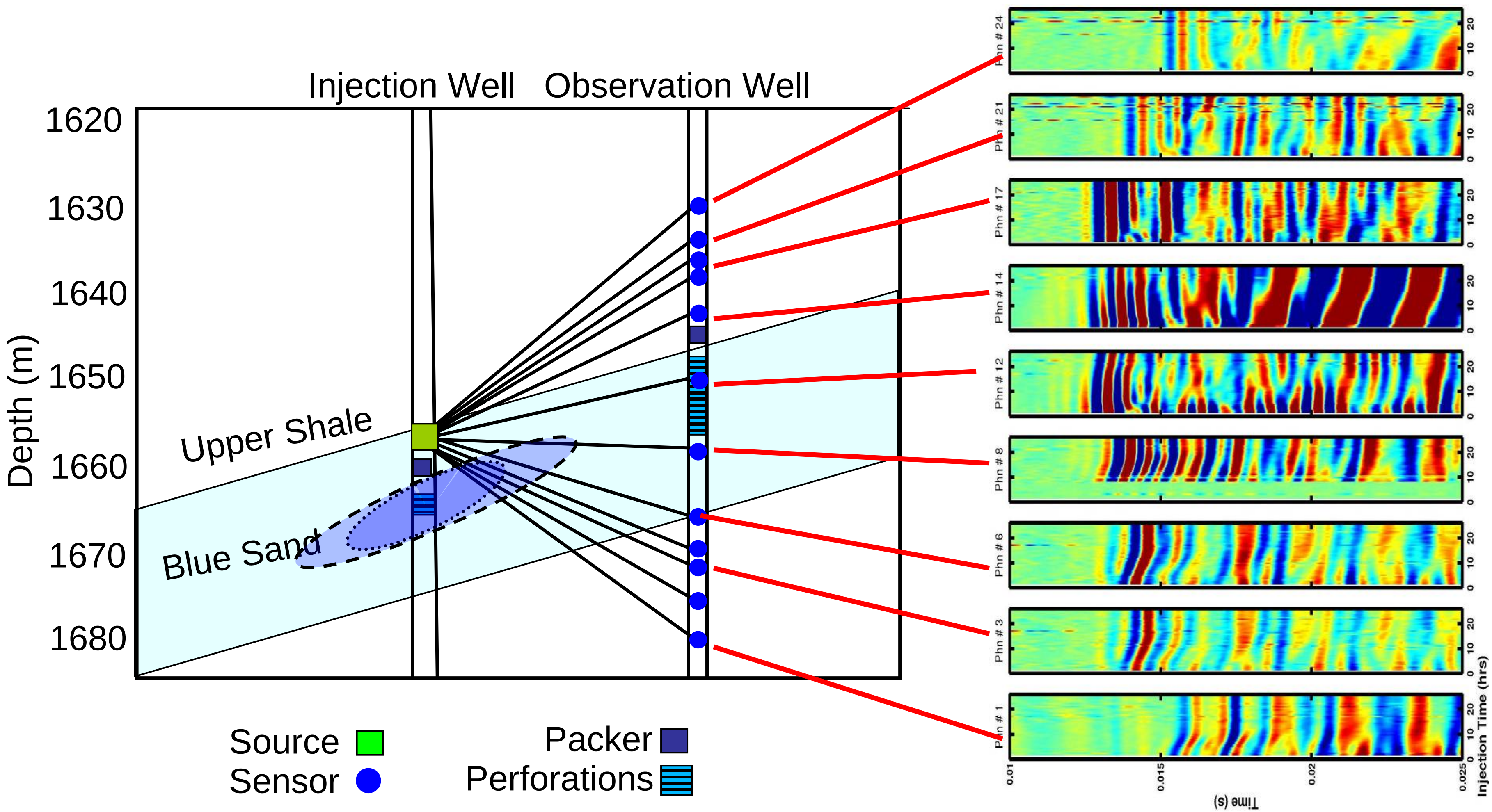
Frio Formation: Cross-well Seismic Data



An Alternative Approach: Real-Time Seismic Monitoring

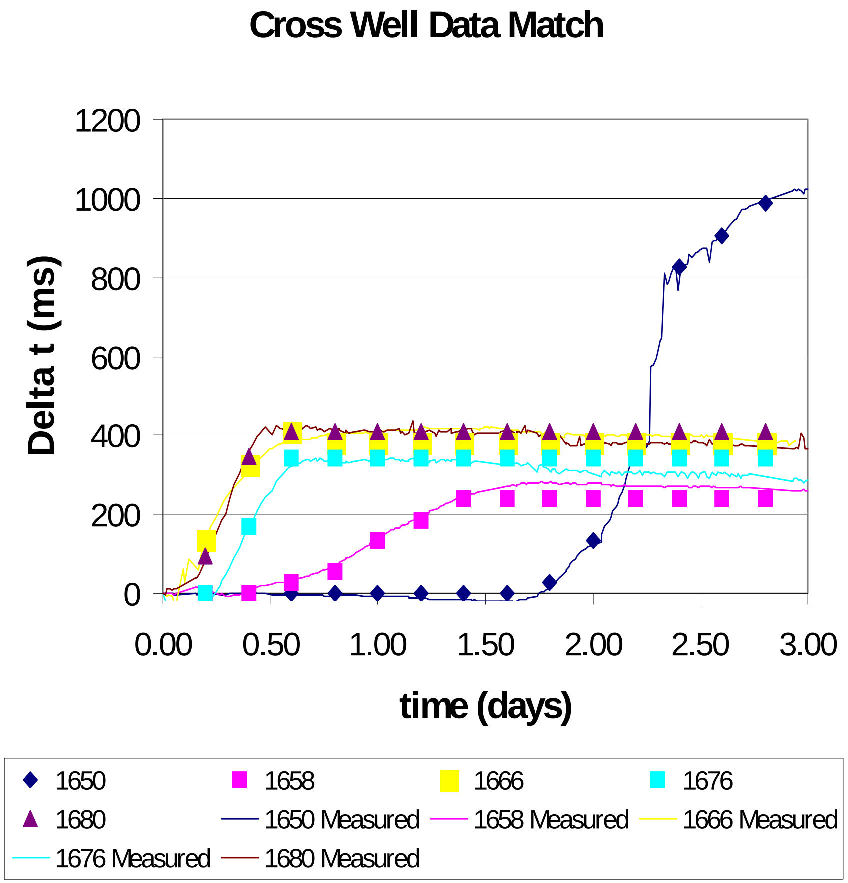


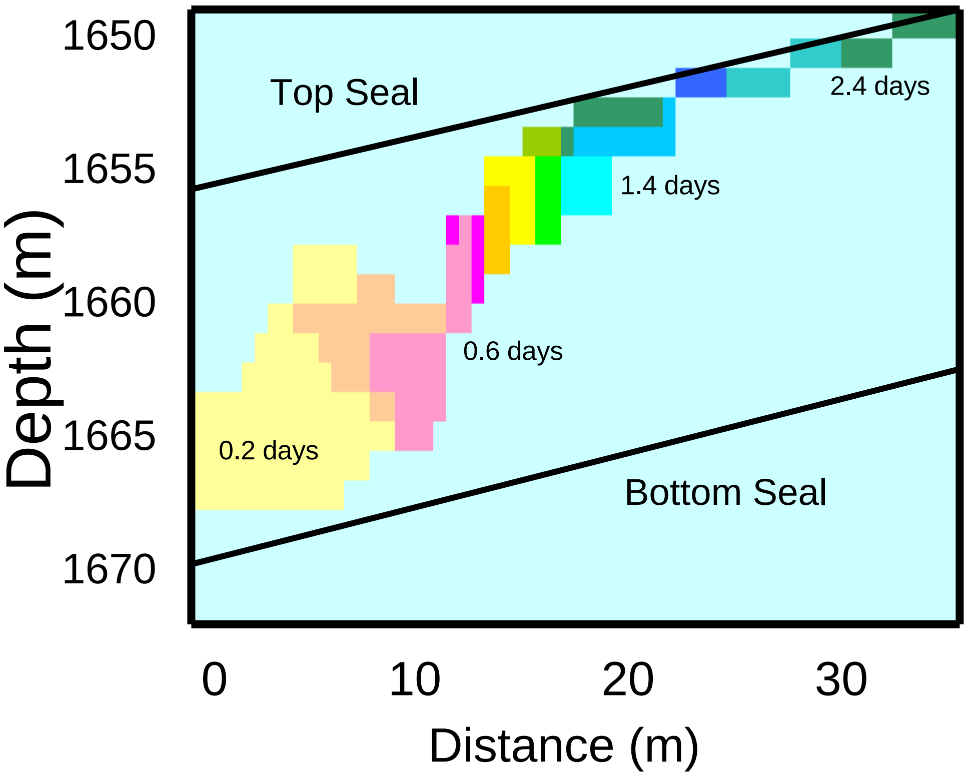
Proof of Concept:
Real-Time Seismic Monitoring



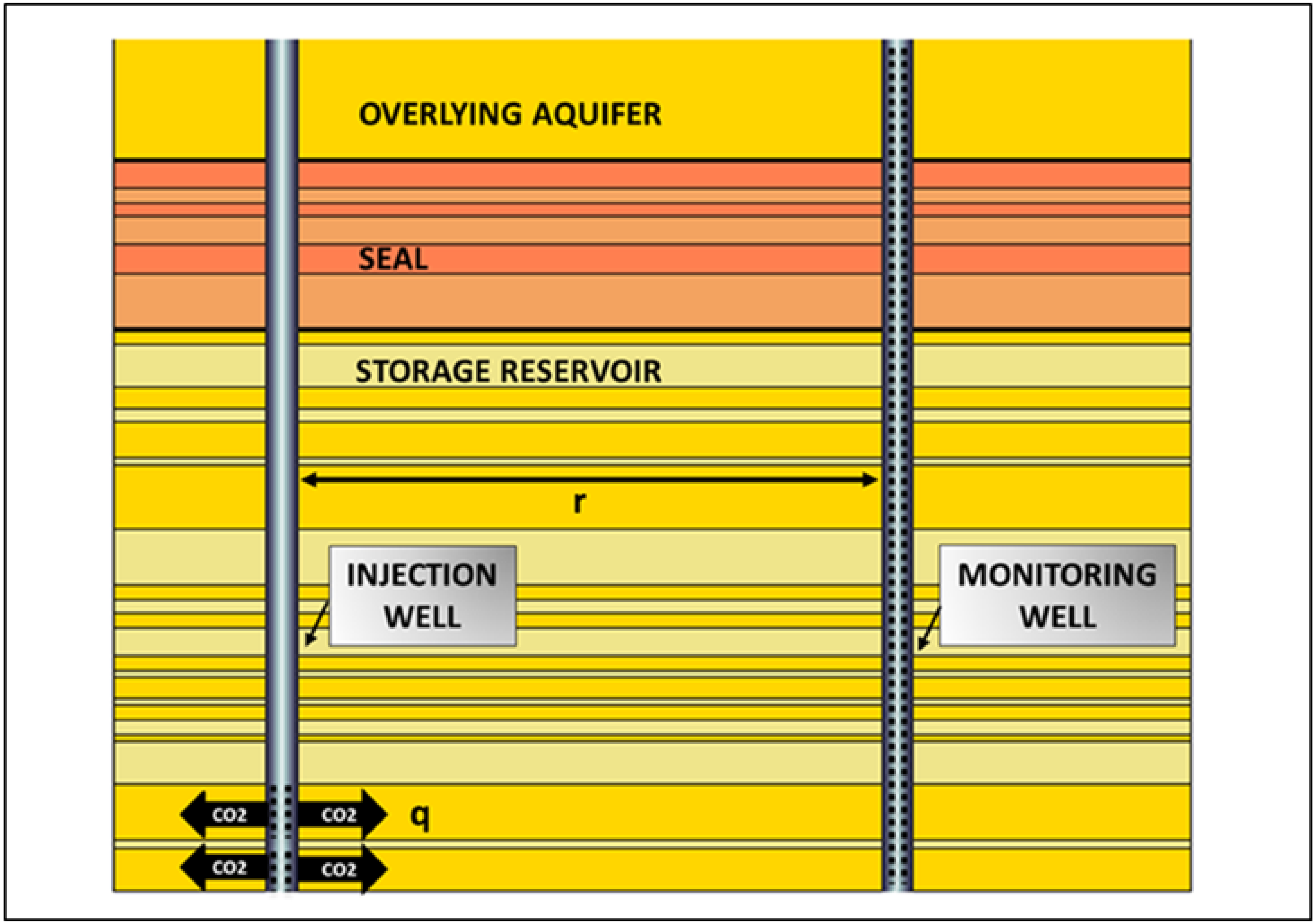
Daley, et al, Geophysics, in press.

Real-Time CO_2 Tracking

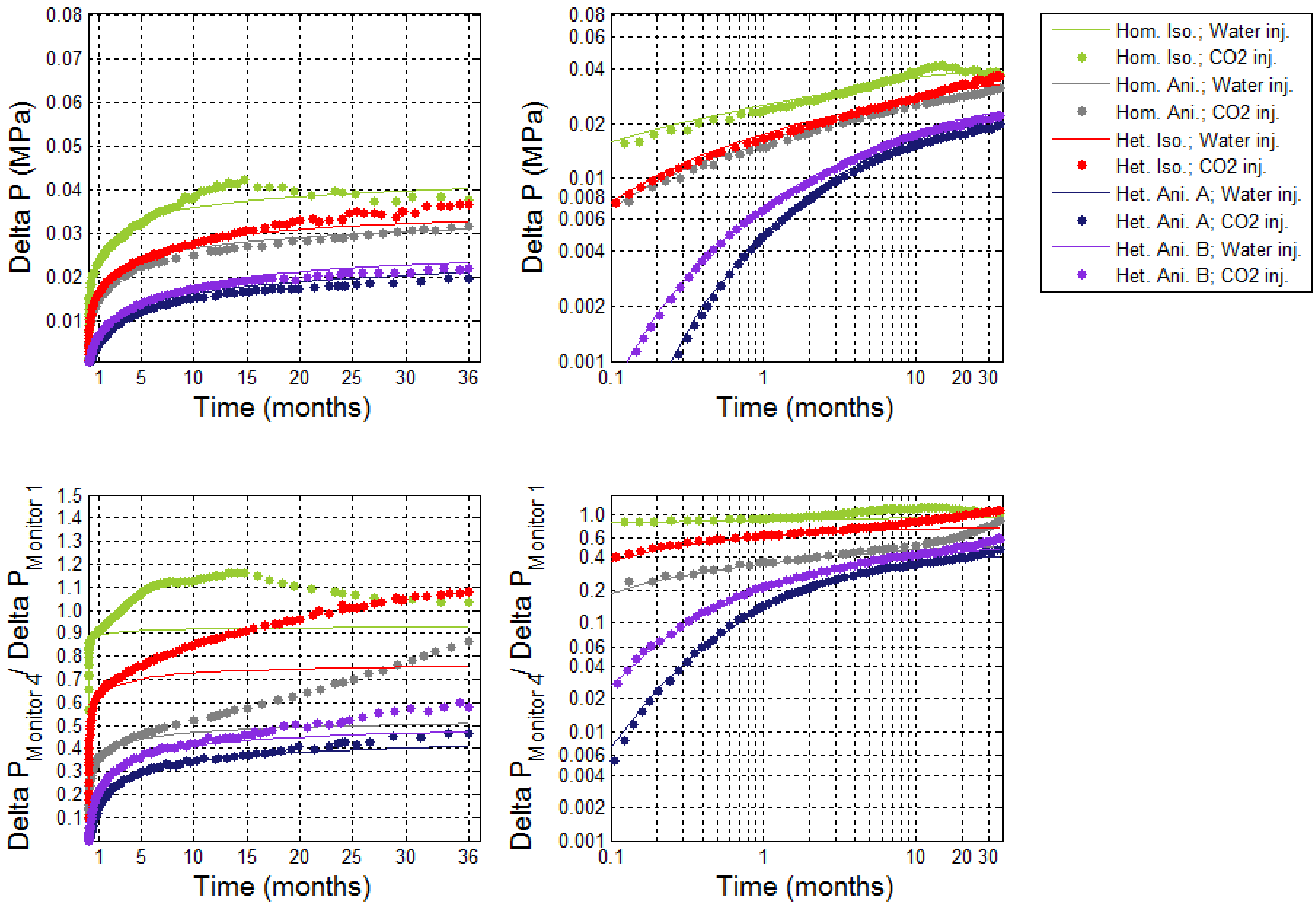




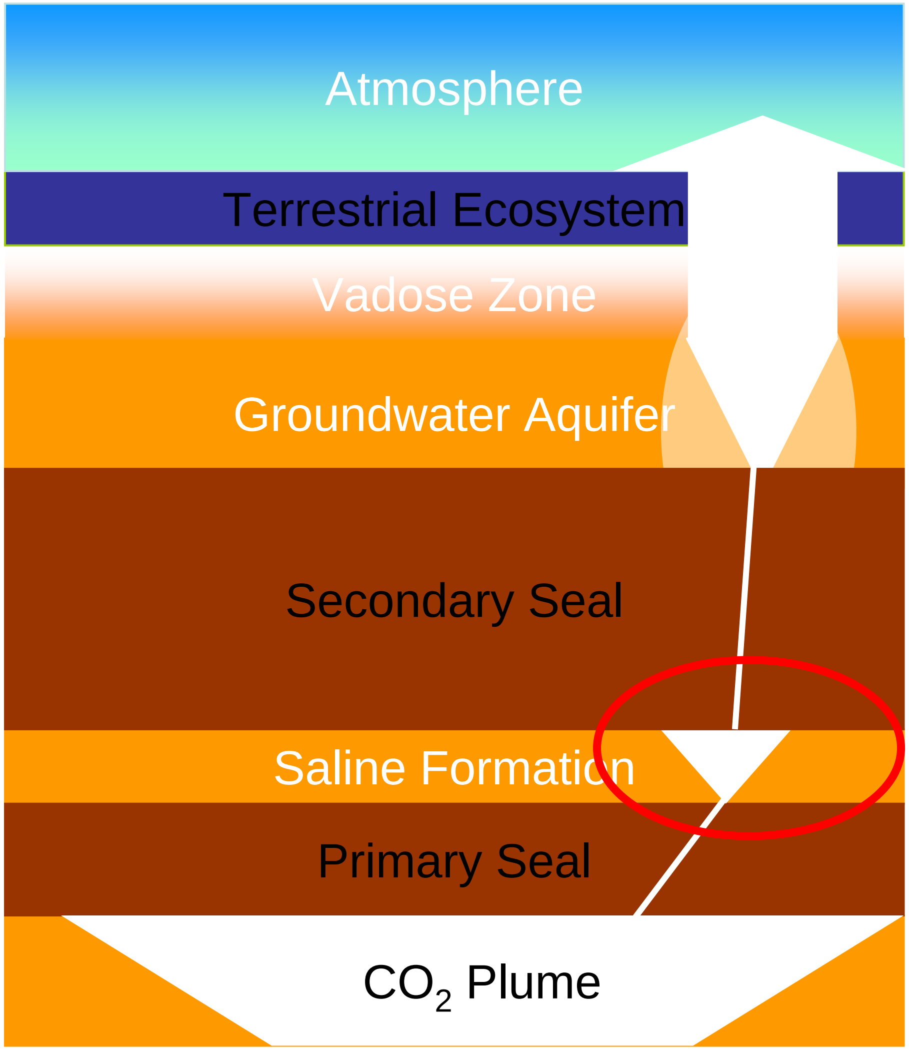
Multi-Level Pressure Monitoring



Reservoir Architecture and CO_2 Buoyancy Yield Unique Pressure Signatures



Strategy: Secondary Accumulations



On-shore Storage

Methods

- Geophysical methods
  - **Seismic**
  - Electrical
  - SP
  - Gravity
  - Tilt
- **Formation pressure**
- Well logs (e.g. RST)
- Fluid sampling

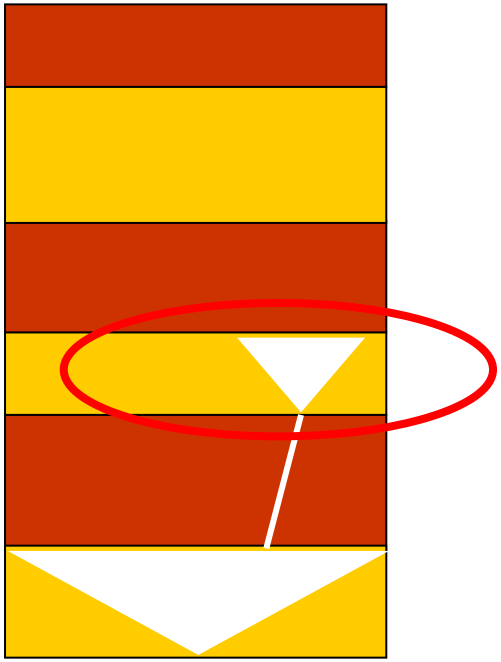
Benefits

- Sensitivity to small secondary accumulations (~10^3 tonnes) and leakage rates
- Early warning of leakage

Drawbacks

- Detection difficult if secondary accumulations do not occur
- Dissolved and mineralized CO_2 difficult to detect

Sensitivity of Seismic Methods



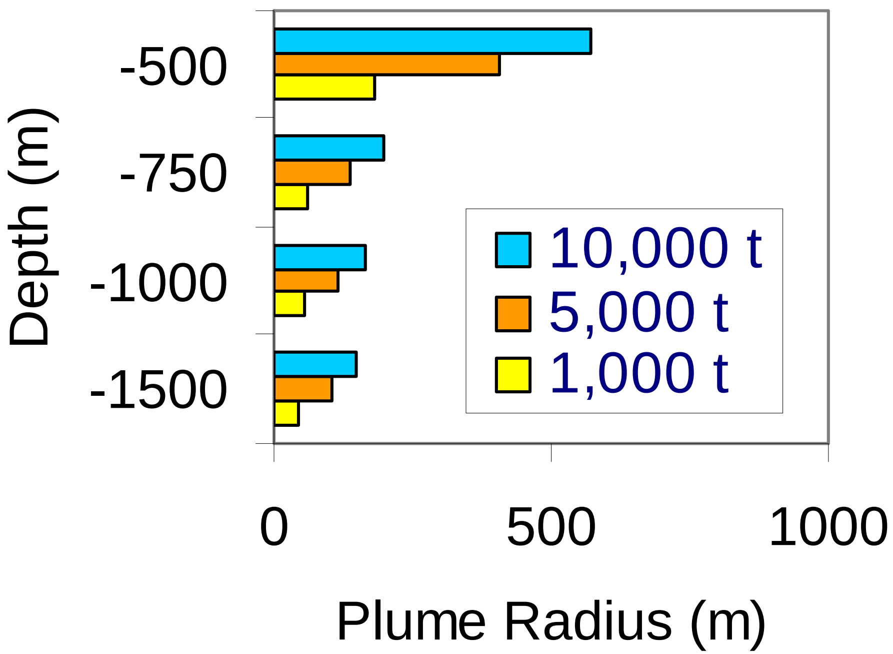
Detection Limits at Reservoir Depth

Myer et al, 2002: 10,000 tonnes

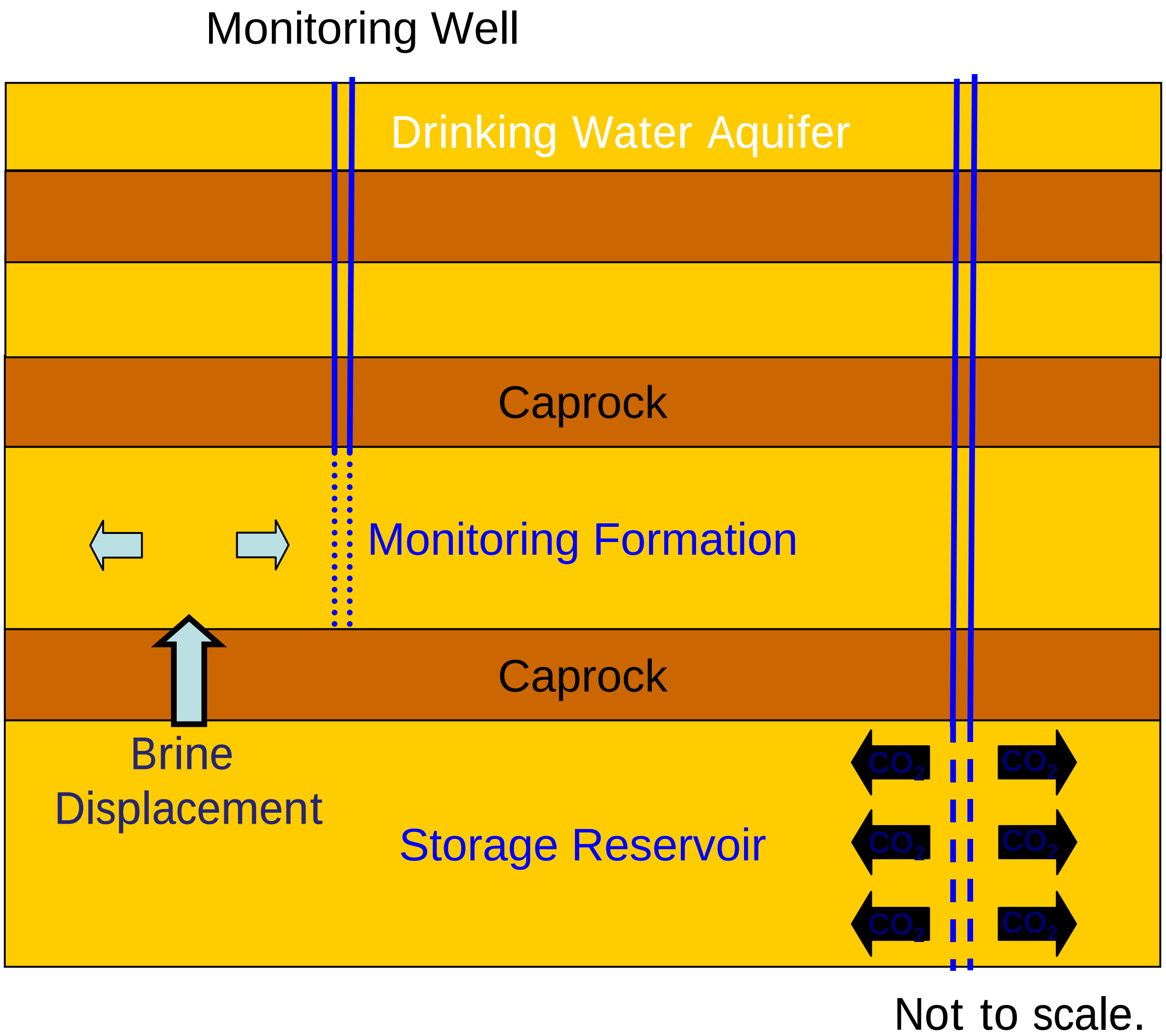
Chadwich et al.: Sleipner, 2,500 tonnes

White el al., 2004: Weyburn, 2,500 tonnes

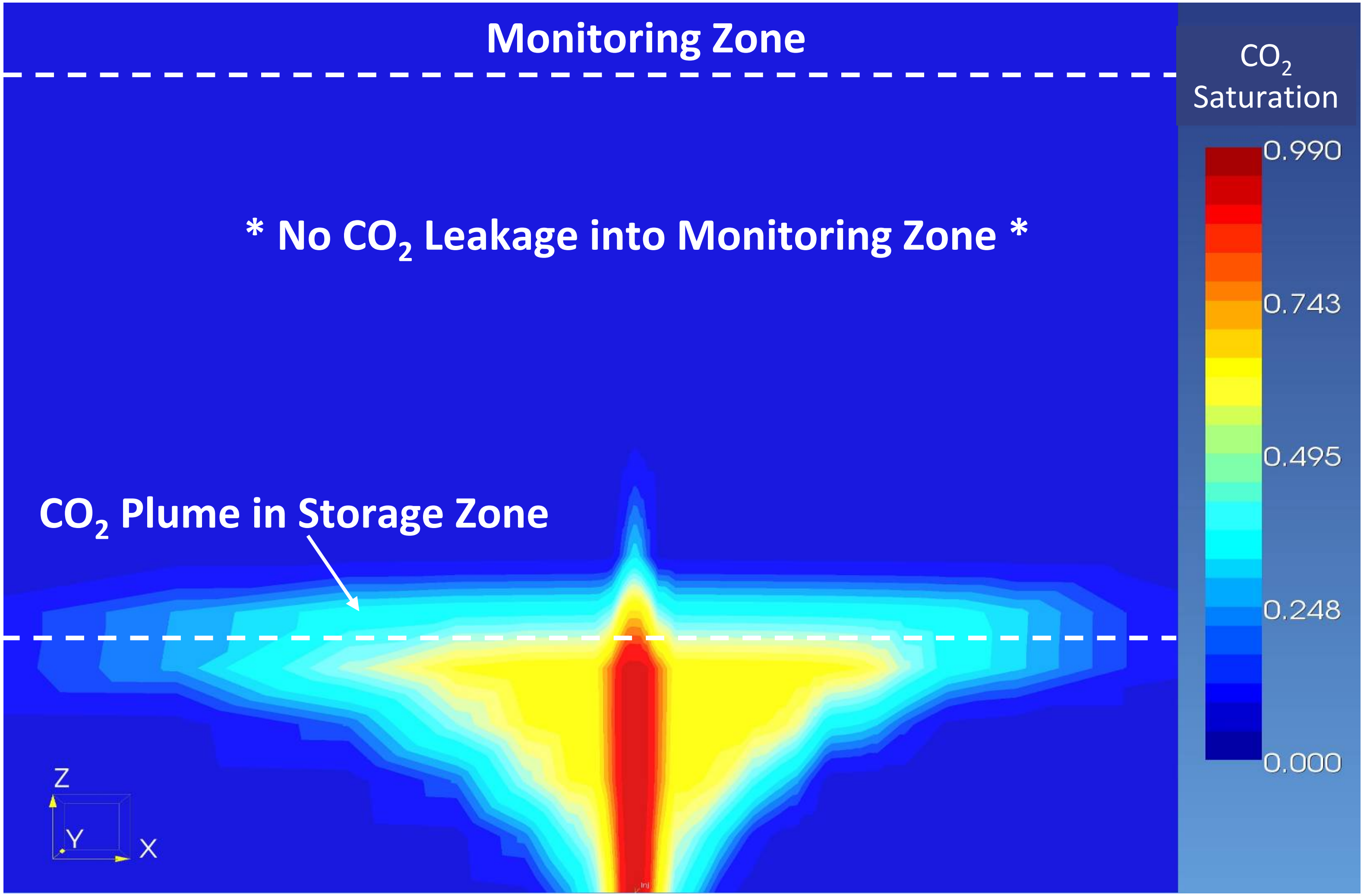
Daley et al., 2005: Frio Formation, 1,600 tonnes



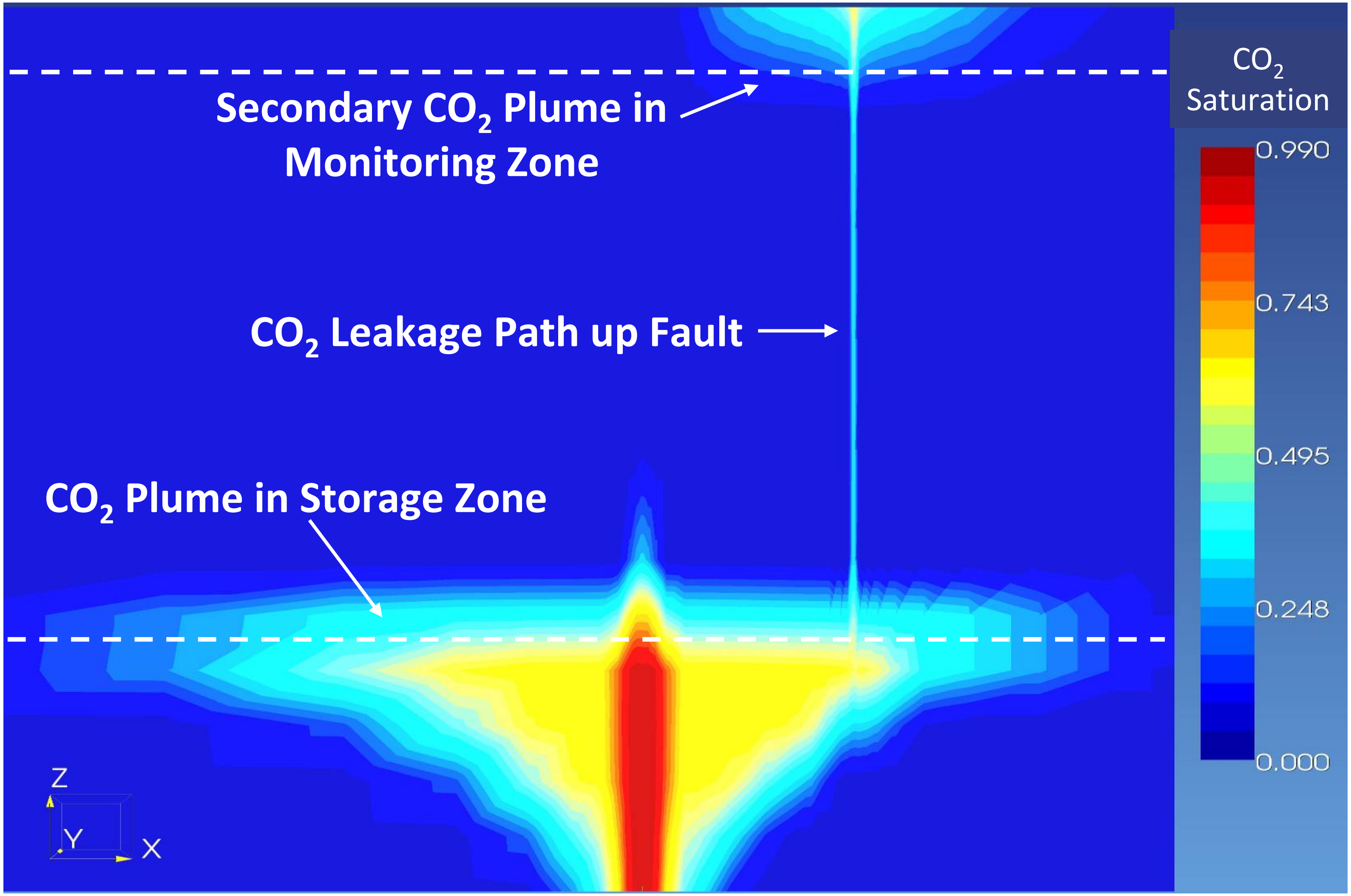
Pressure Monitoring



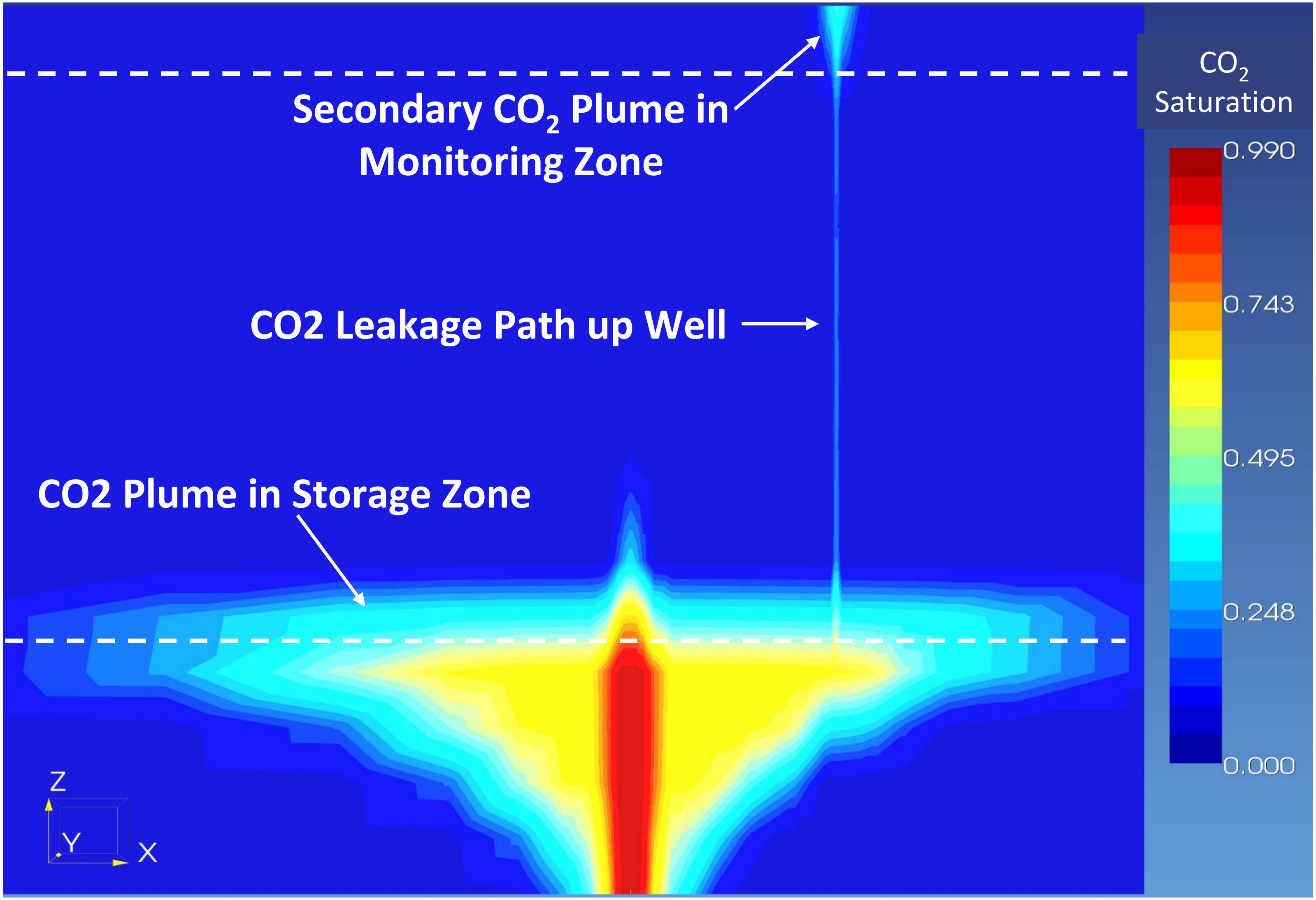
Base Study: No Leakage Path



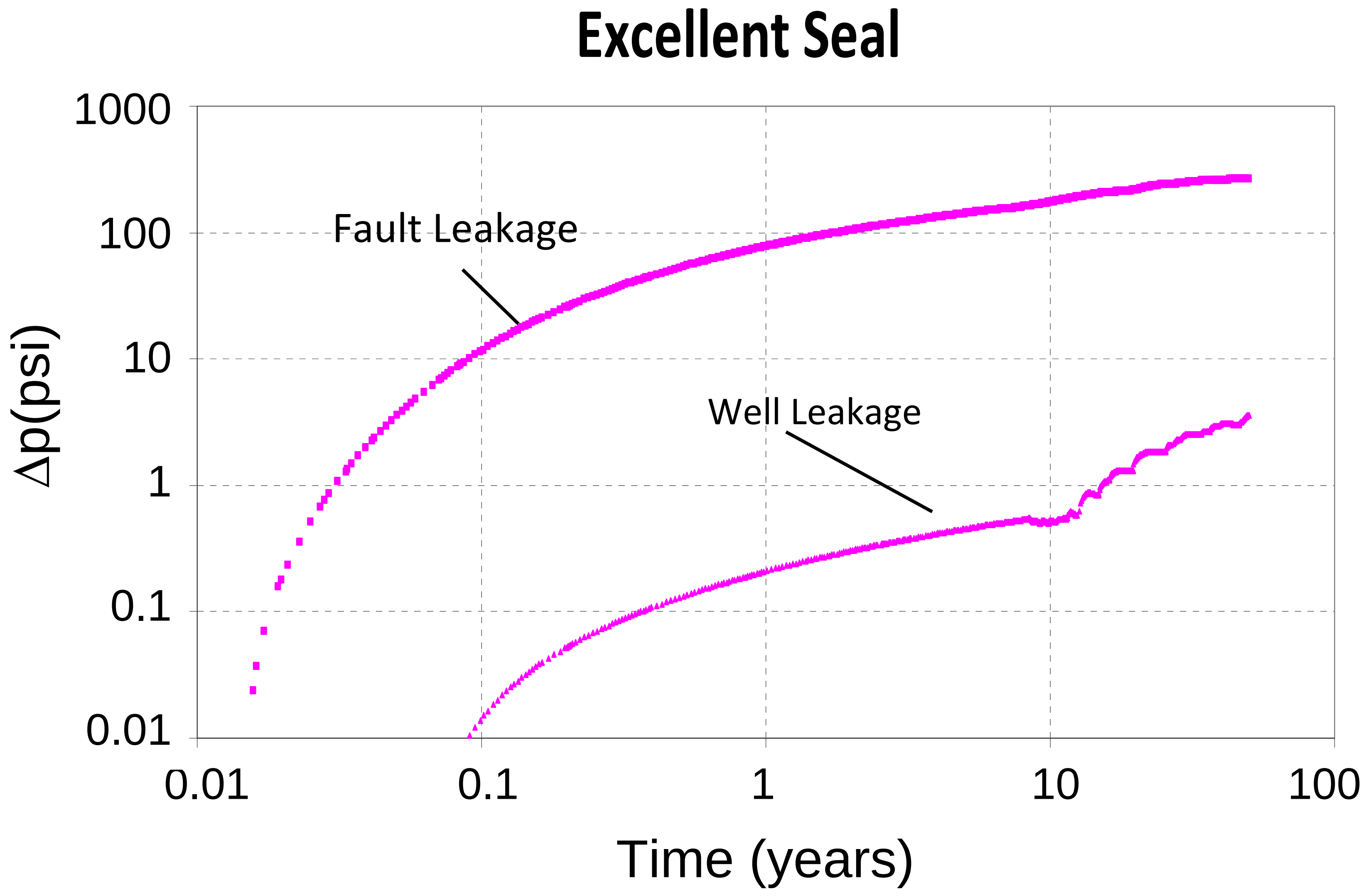
Leakage Up a Fault



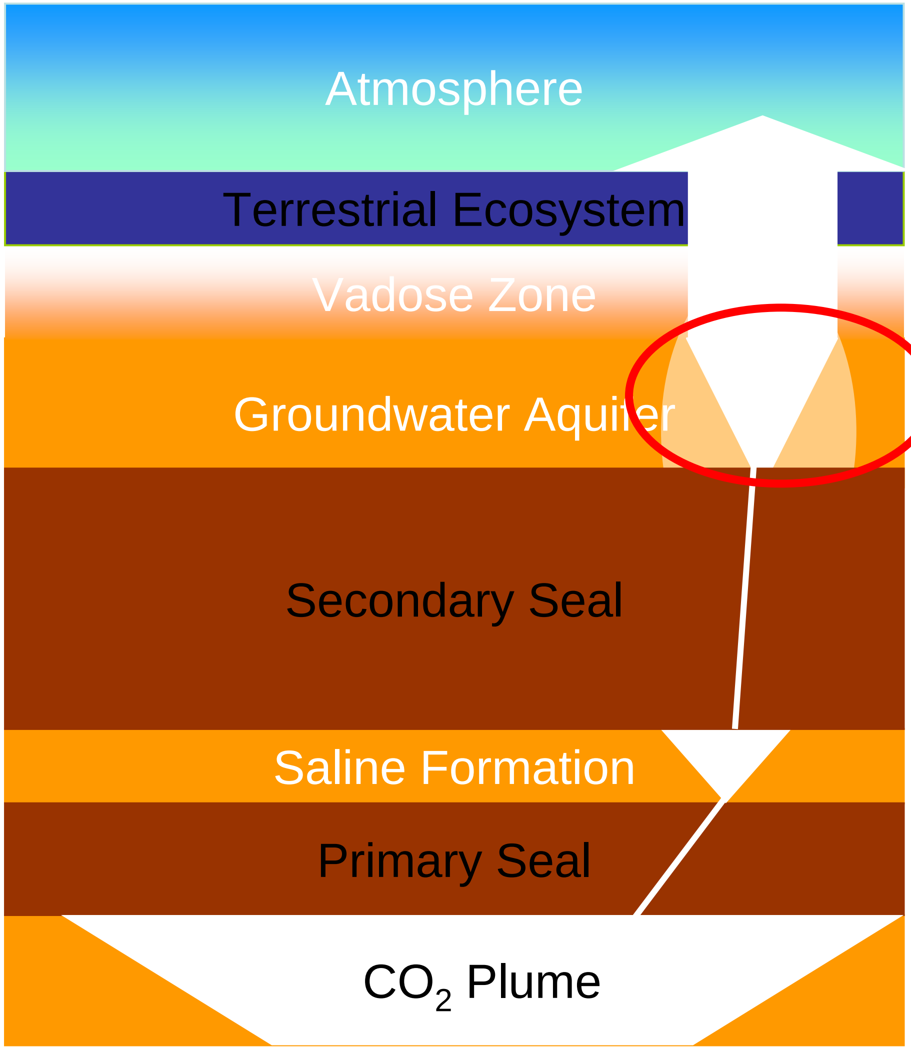
Leakage Up a Well



Leakage Detectable Within a Year Based on Pressure Changes



Strategy: Groundwater



On-shore Storage

Methods

- Geophysical methods
  - **Seismic**
  - **Electrical**
  - SP
  - **Gravity**
  - **Tilt**
- **Formation pressure**
- Well logs
- **Fluid sampling**

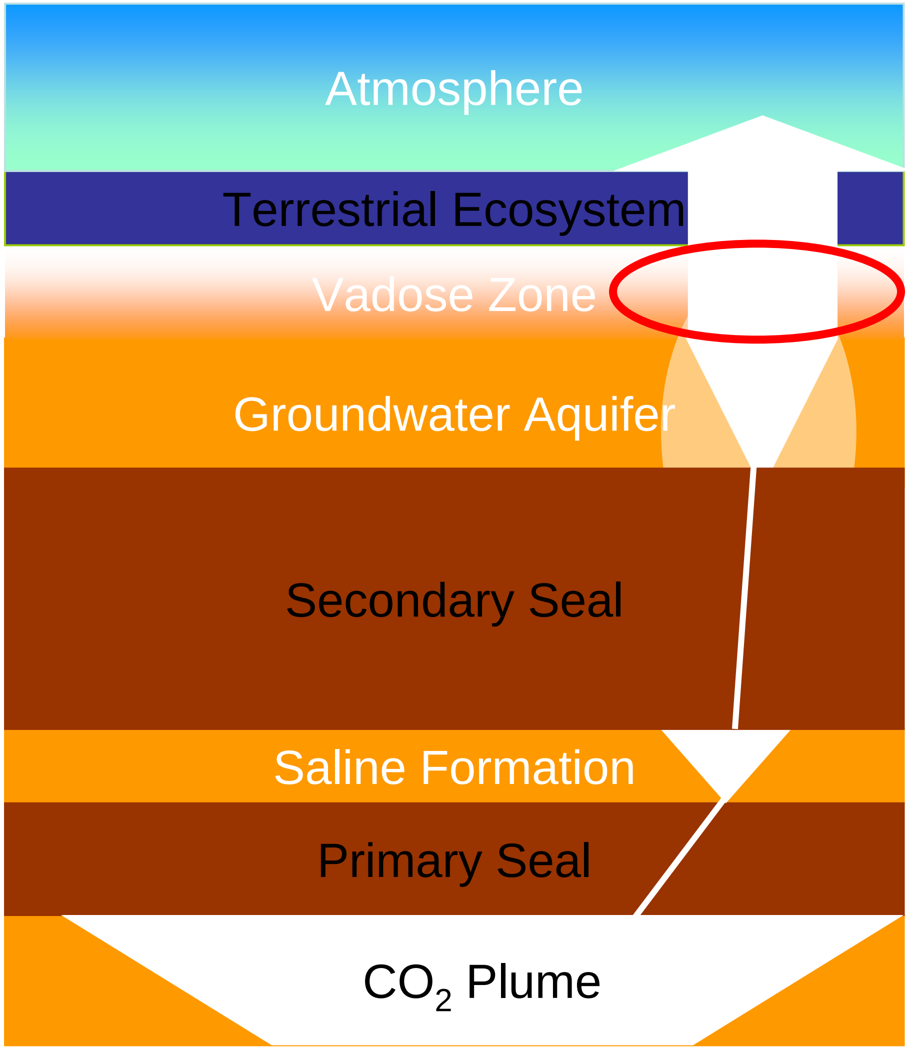
Benefits

- Sensitivity to small secondary accumulations (~10^2-10^3 tonnes) and leakage rates
- More monitoring methods available
- Detection of dissolved CO_2 less costly with shallow wells

Drawbacks

- Detection after significant leakage has occurred
- Detection after potential groundwater impacts have occurred

Strategy: Vadose Zone



On-shore Storage

Methods

- Geophysical methods
  - Electrical
- **Soil gas and vadose zone sampling**
- **Vegetative stress**

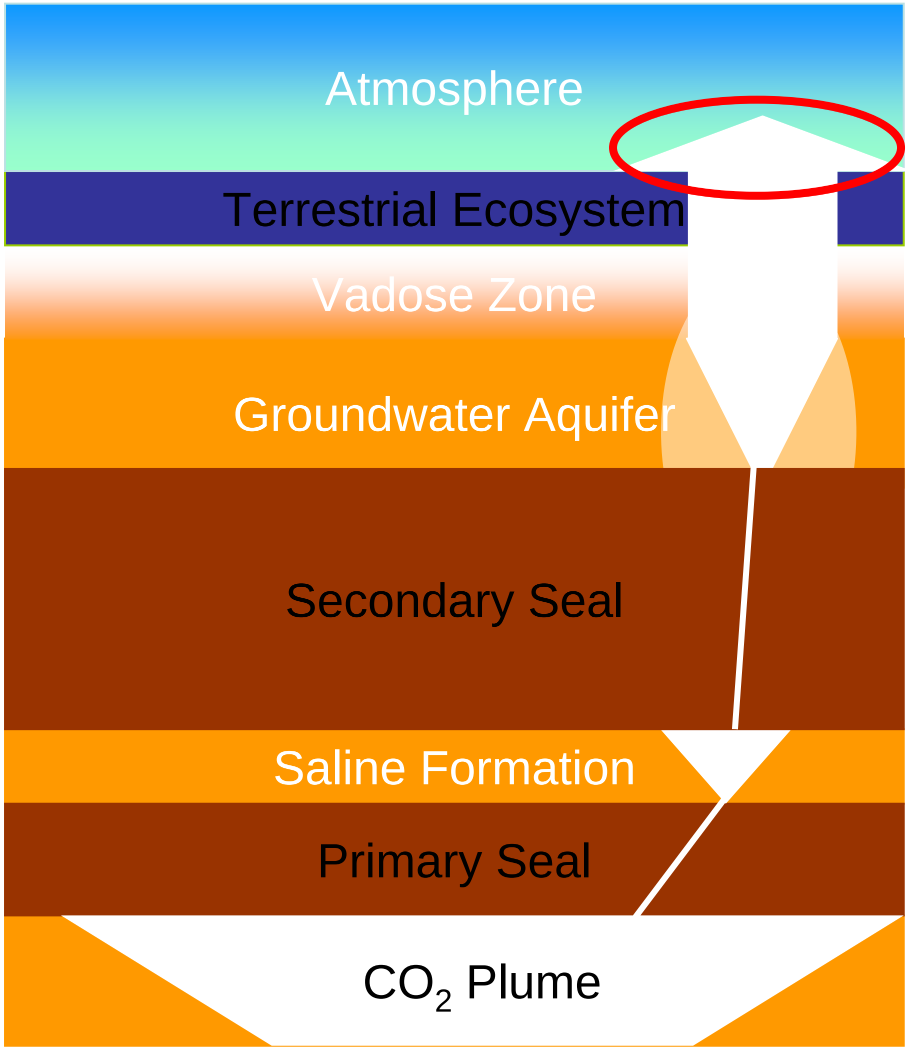
Benefits

- High concentrations of CO_2 occur with small leaks
- Early detection could trigger remediation to avoid atmospheric emissions

Drawbacks

- Significant effort for null result
- Detection only after some seepage is imminent
- Detection after potential ecosystem impacts have occurred

Strategy: Atmosphere



On-shore Storage

Methods

- **Eddy covariance**
- **Flux accumulation chamber**
- **Mobile CO_2 measurements**
- Soil gas and vadose zone flux monitoring
- Optical methods (lidar)

Benefits

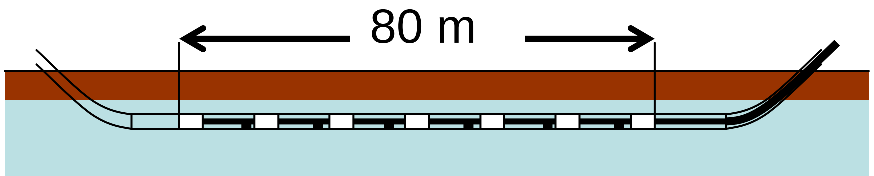
- Direct measurement of seepage
- Detection, location and quantification of seepage flux

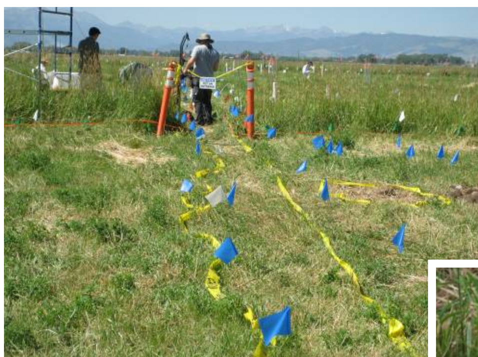
Drawbacks

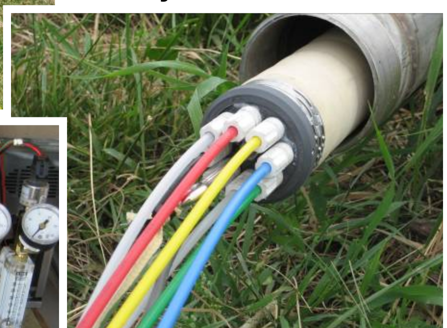
- Distinguishing storage related fluxes from natural ecosystem and industrial sources necessitates comprehensive monitoring
- Significant effort for null result

Surface Monitoring

Detection Verification Facility
(ZERT Experimental Facility)




Field Site


Horizontal Injection Well


Flow Controllers

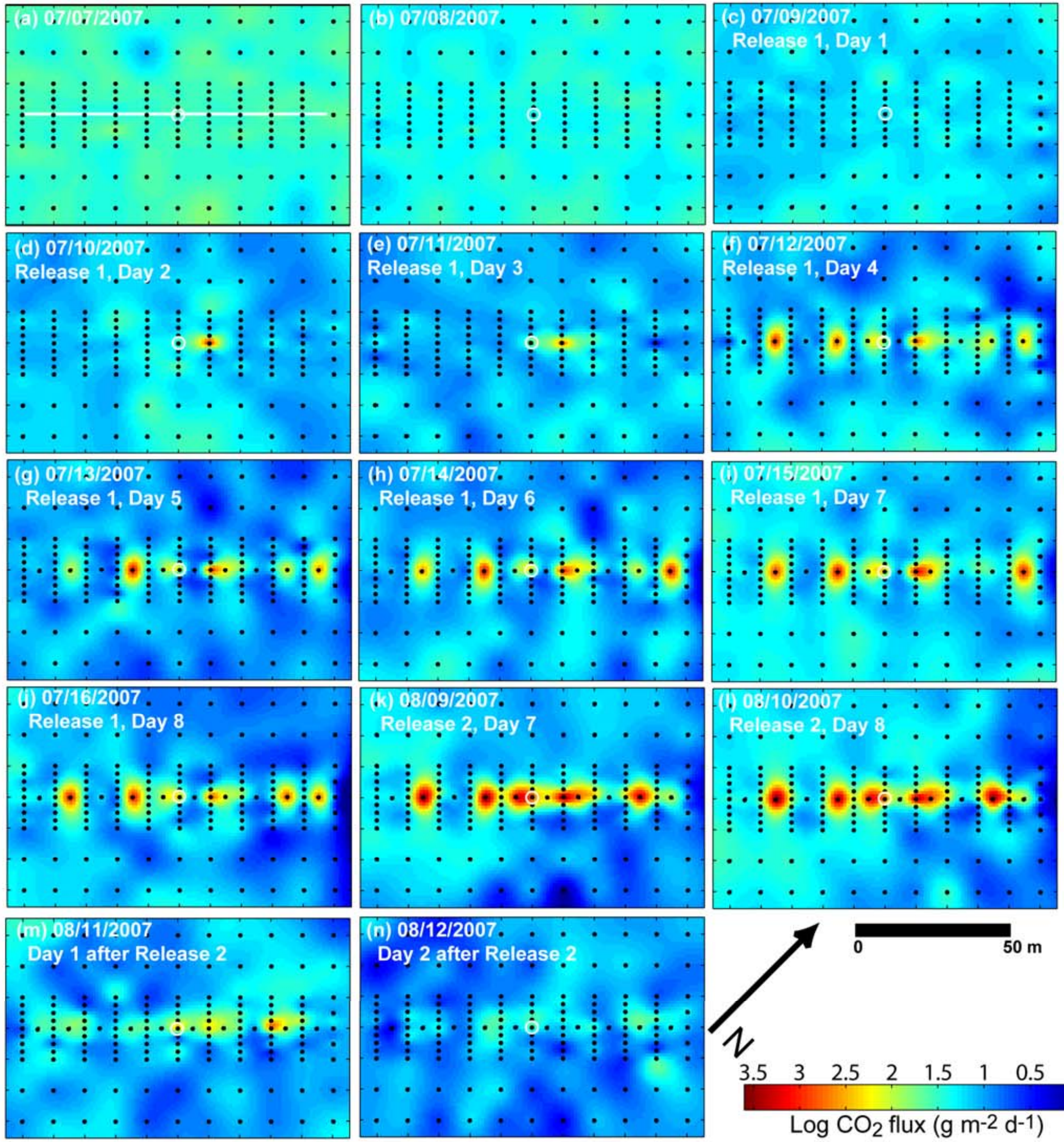

Flux Tower


Hyperspectral Imaging of Vegetation

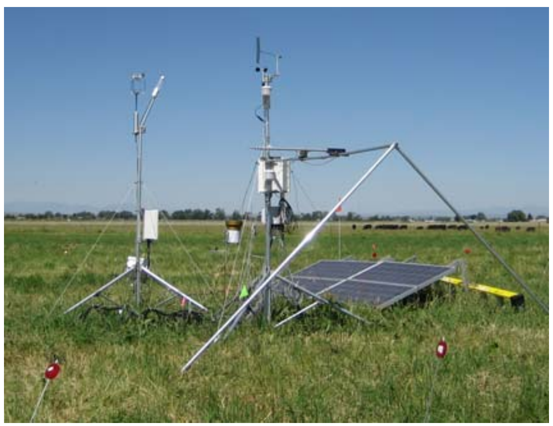

Soil Gas

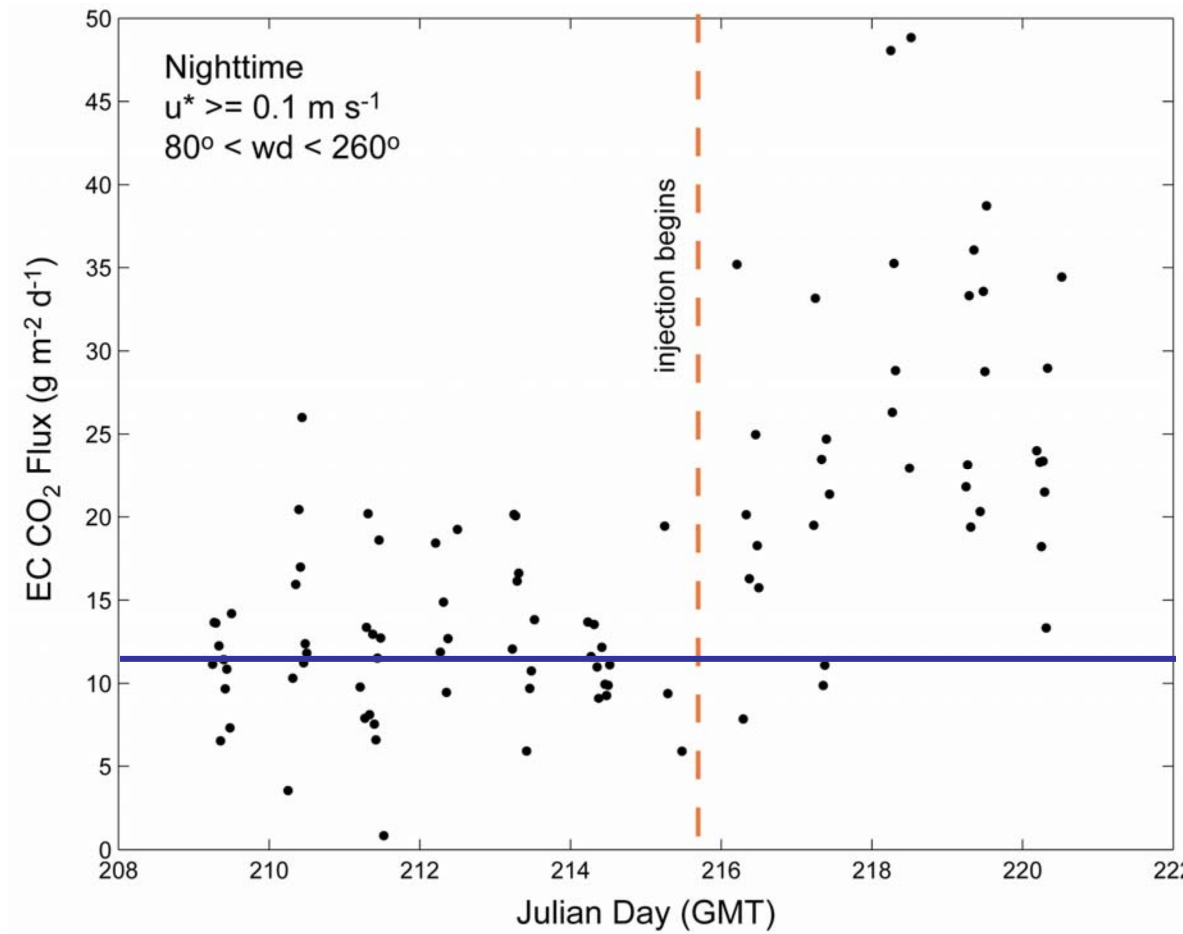

Flux accumulation chamber

Flux accumulation chamber data from Jennifer Lewicki, LBNL, 2007



Eddy flux tower data, Jennifer Lewicki, LBNL, 2007



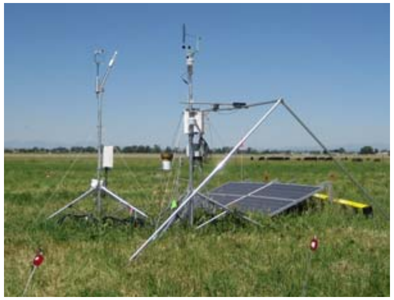


ZERT Detection Verification Facility

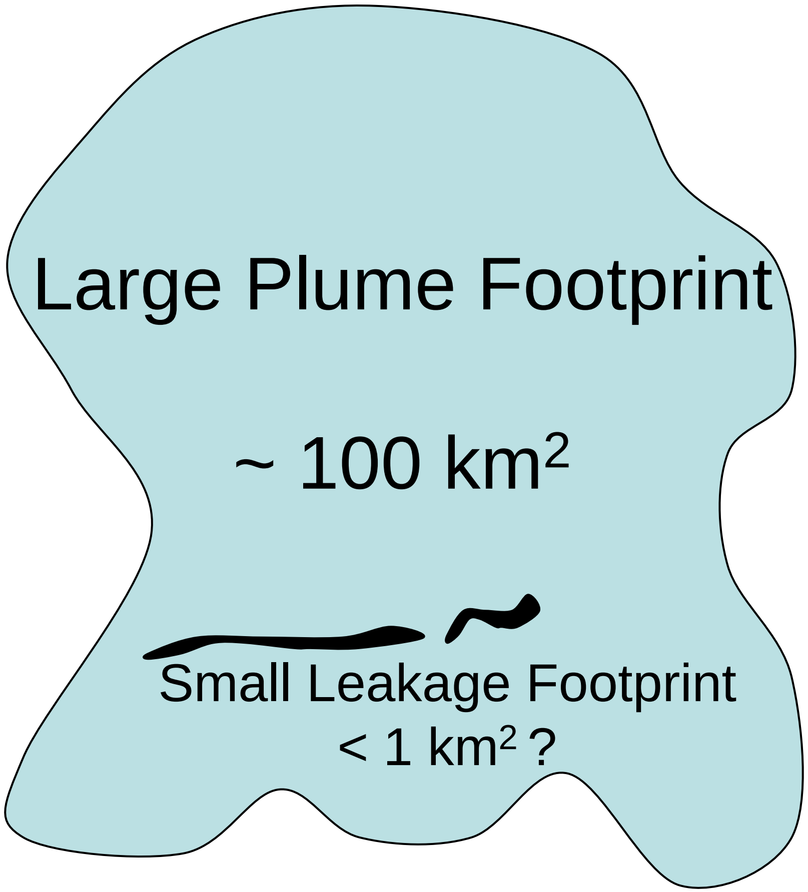
100 kg/day release → 36 tonnes/year

300 kg/day release → 110 tonnes/year

Both releases were detectable and quantifiable using one or more methods

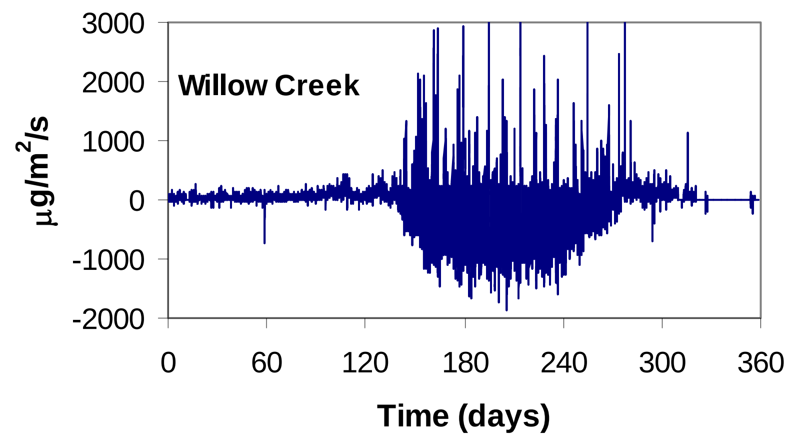


Detection Challenge

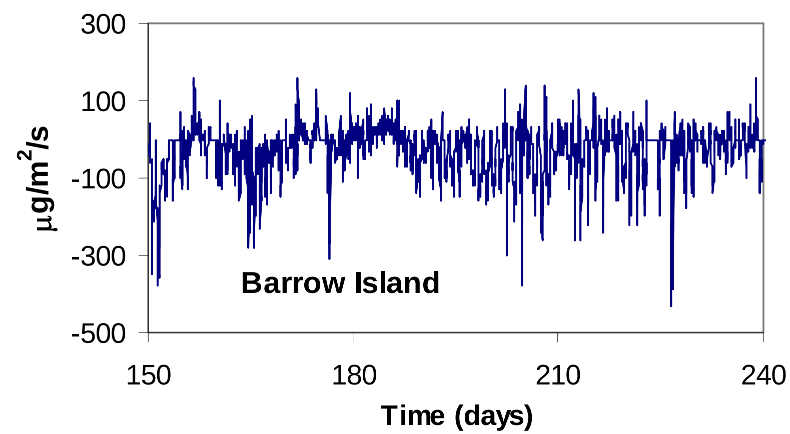


What if you don't know where the leak is?

Large Fluctuations in Background CO_2 Fluxes



Courtesy of Ken Davis and Paul Bolstad



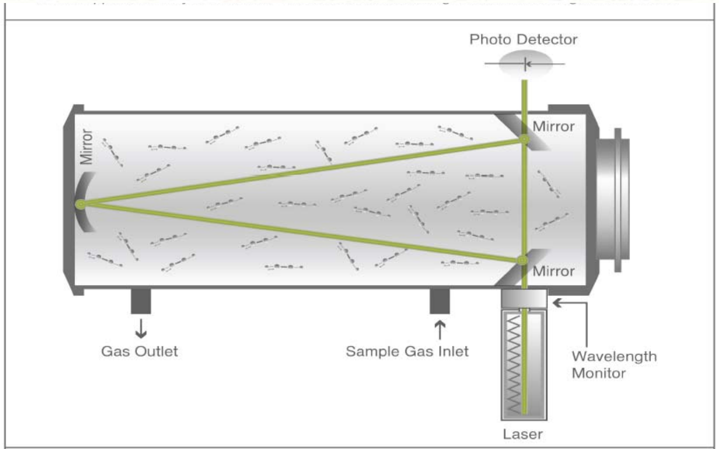
Courtesy of Walter Oechel

C Isotopic Signatures

- Natural gas ~ -45 $^{o}/_{oo}$ (parts per thousand)
- Coal ~ -30 $^{o}/_{oo}$ (parts per thousand)
- Ecosystem fluxes (-25 $^{o}/_{oo}$ (parts per thousand)
- Air ~ -8 $^{o}/_{oo}$ (parts per thousand)

Isotopes provide built-in natural tracers for leakage.

CO_2 and ^{13}C Isotopic Anomalies for Monitoring Leakage

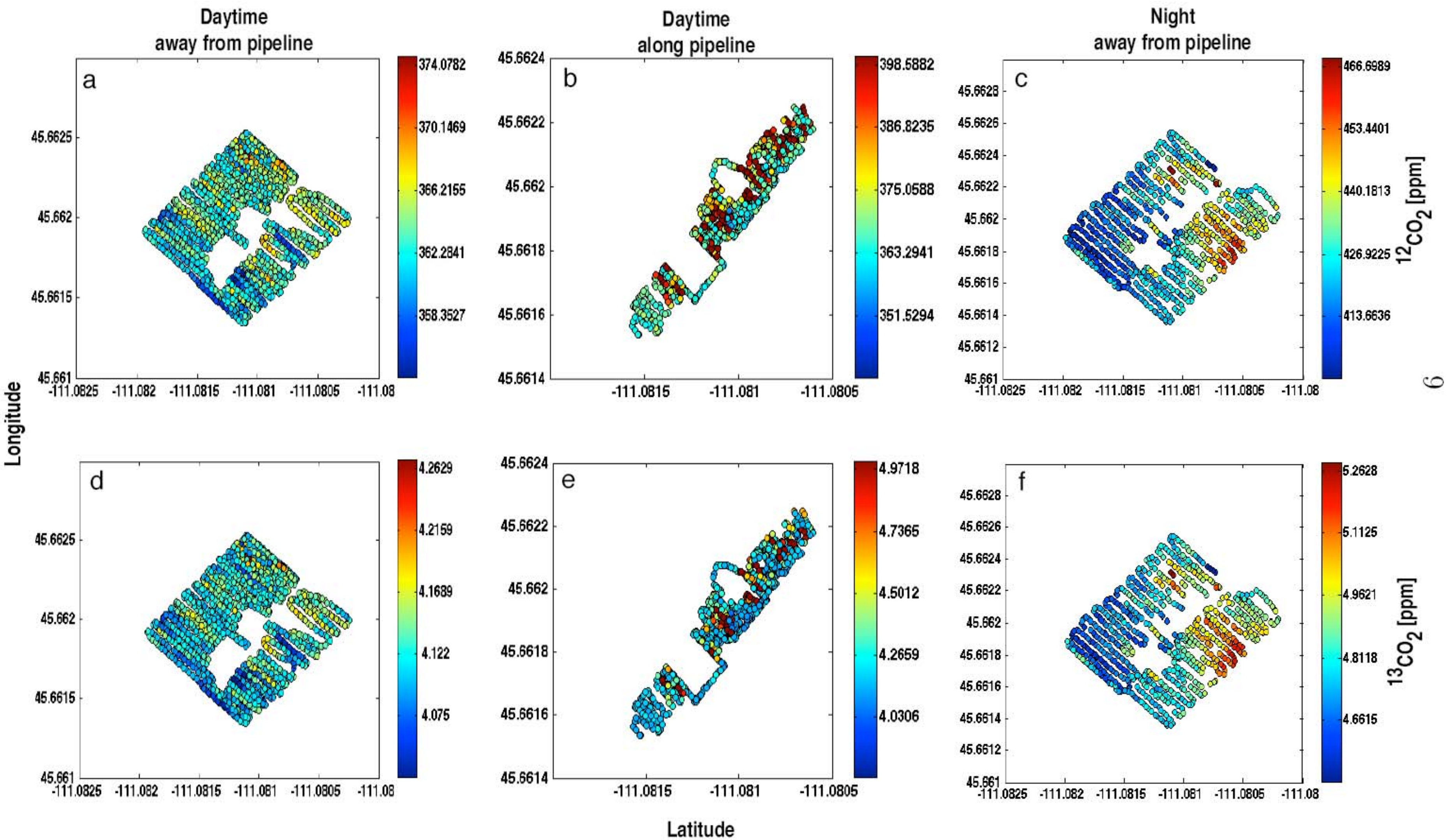


CRDS: Measures the time it takes for light to be lost in the cavity

High precision isotopic $^{12}CO_2$ and $^{13}CO_2$ analyzer:
Picarro Instruments cavity ring down spectrometer

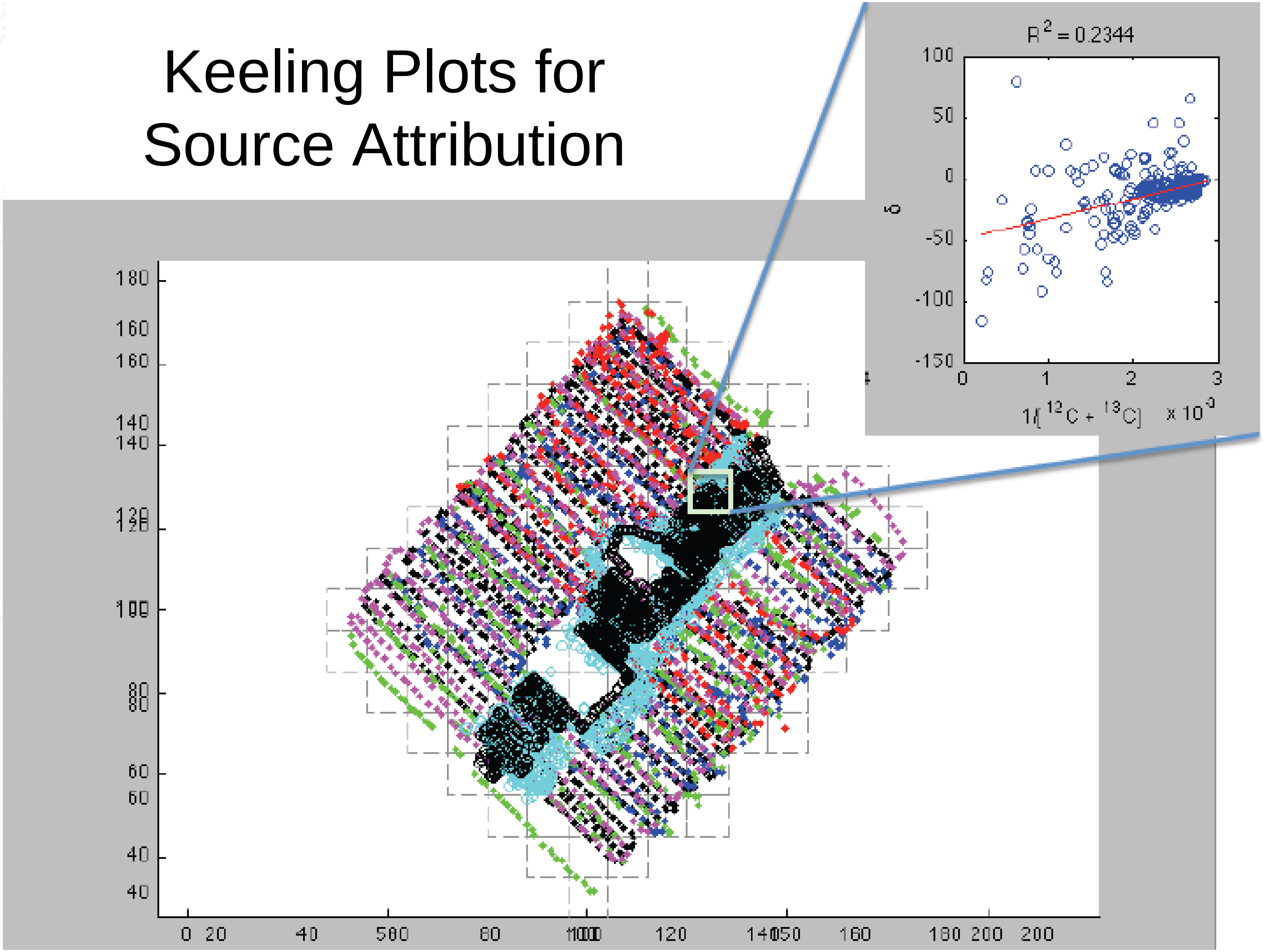
Krevor et al., 2011 , International Journal of Greenhouse Gas Control Technology

Raw 12CO_2 and 13CO_2 Data



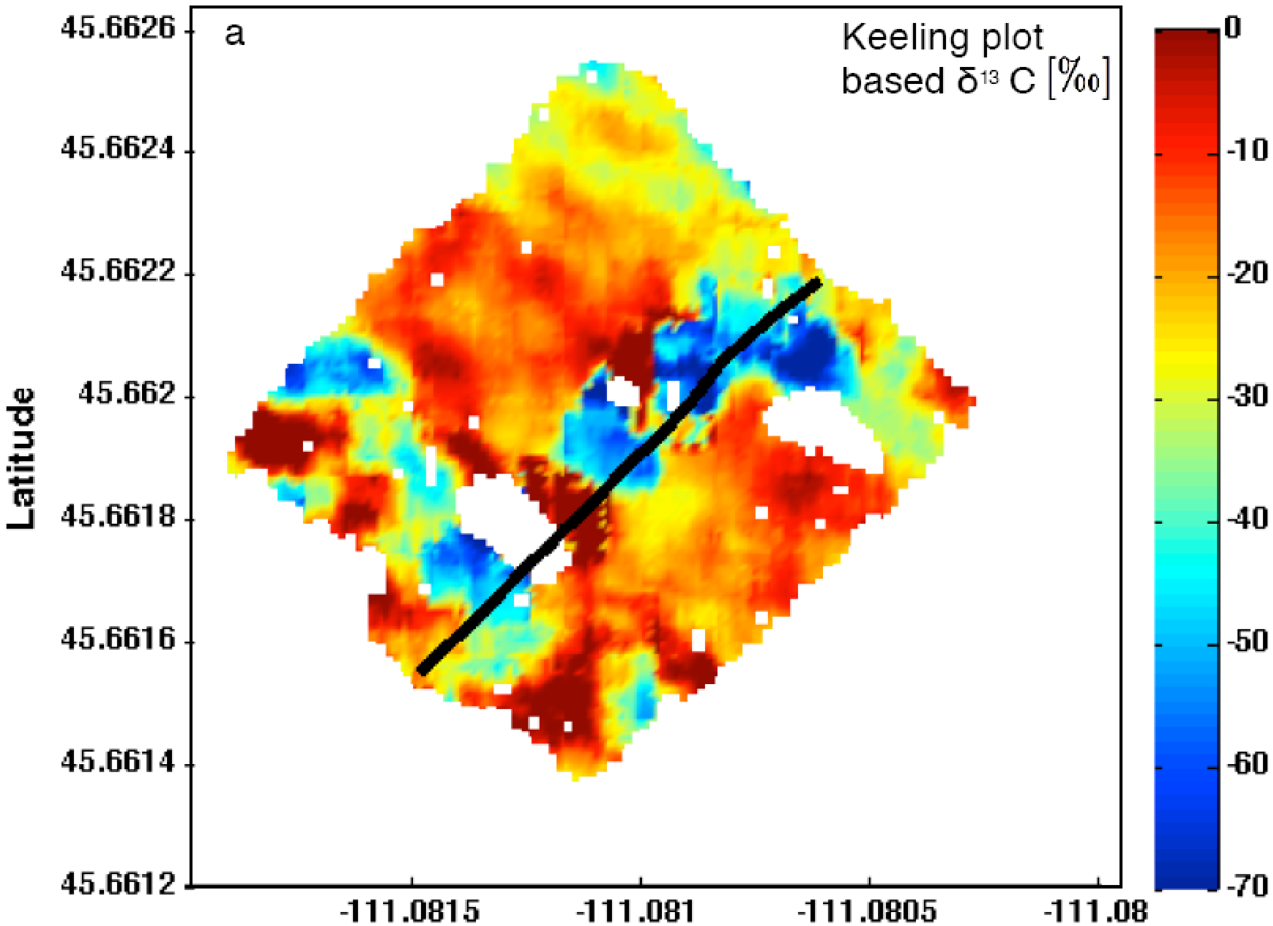
Krevor et al., 2010, International Journal of Greenhouse Gas Control Technology

Keeling Plots for Source Attribution



Leakage Detection and Source Term Characterization

Leak Rate = 200 kg/day (73 tonnes/year!)



From Krevor et al., 2010, International Journal of Greenhouse Gas Control Technology

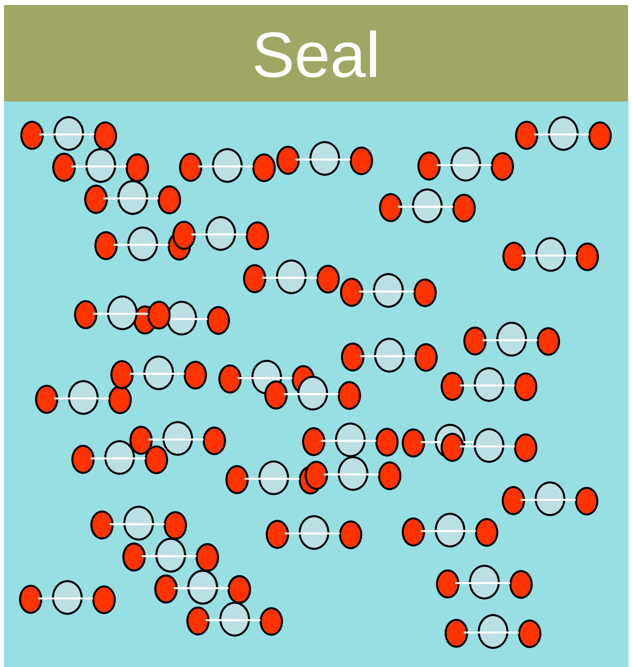
Life Cycle of a Storage Project and Monitoring Packages

Pre-operation Phase	Operation Phase	Closure Phase	Post-closure Phase
• Site character-ization • Risk assessment • Establish monitoring baseline	• Surface facilities and injection rates monitored • Ensure safe operations • Assure project compliance • Monitor project conformance • Detect leakage and prevent environmental impacts	• CO_2 injection stops • Surface facilities removed; wells abandoned • Confirm long-term security of storage project	• Completed records given to regulatory authorities • Monitoring needed only if long term storage security not established

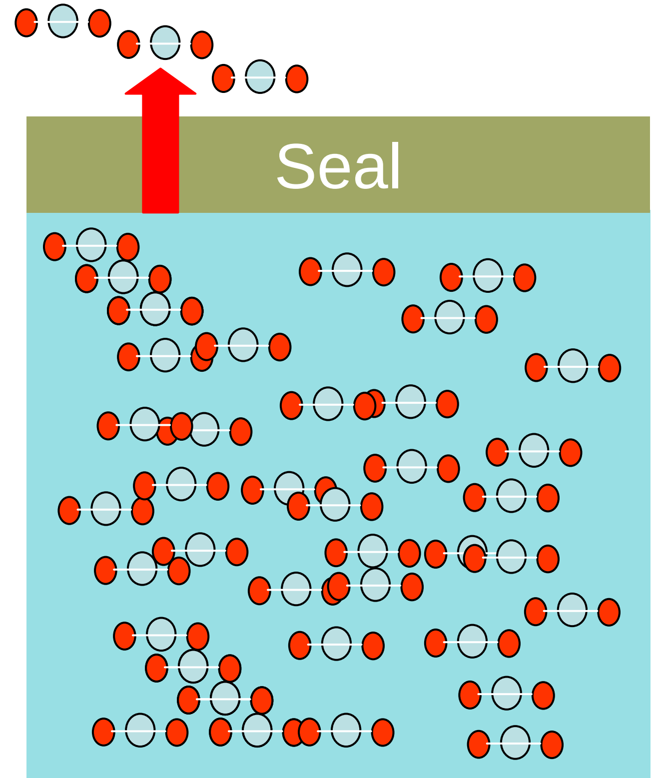
0 5 35 45 - ?

Approximate Time-Line (Years)

Two Critical and Complementary Components of a Monitoring Program



Track Location of Separate Phase CO_2 in the Storage System



Detect and Quantify Releases

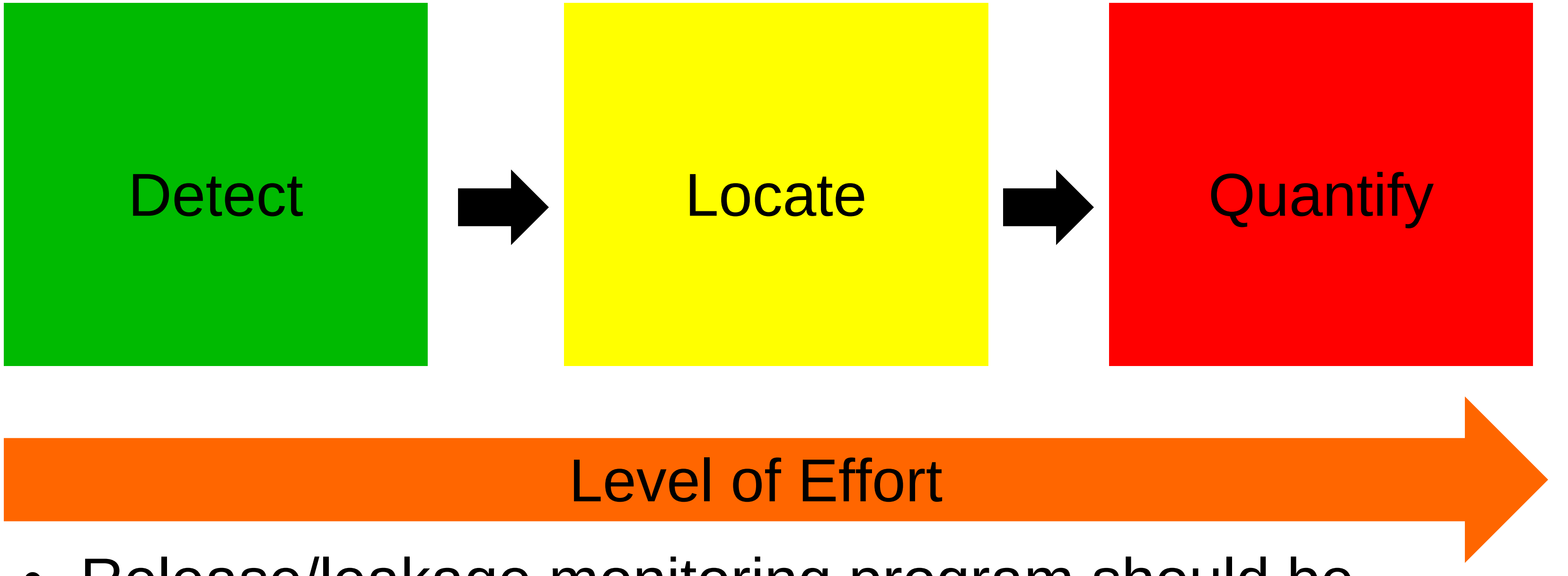
- Secondary Accumulations
- Pressure increases
- Surface Fluxes

CO_2 Detection Levels Needed for Emission Reduction Compliance and Credits

Typical Project: 50 years x 5 Mt/year = 250 Mt

Leakage Detection Threshold	Corresponding Retention Rate Over 1,000 Years
2,500 t/yr	99%
5,000 t/yr	98%
10,000 t/yr	96%
25,000 t/yr	90%

Release/Leak Monitoring Strategy



- Release/leakage monitoring program should be optimized to detect leakage
- Monitoring focused on precisely locating and quantifying leaks should only be initiated if releases are detected.

Components of the Basic and Enhanced Monitoring Programs

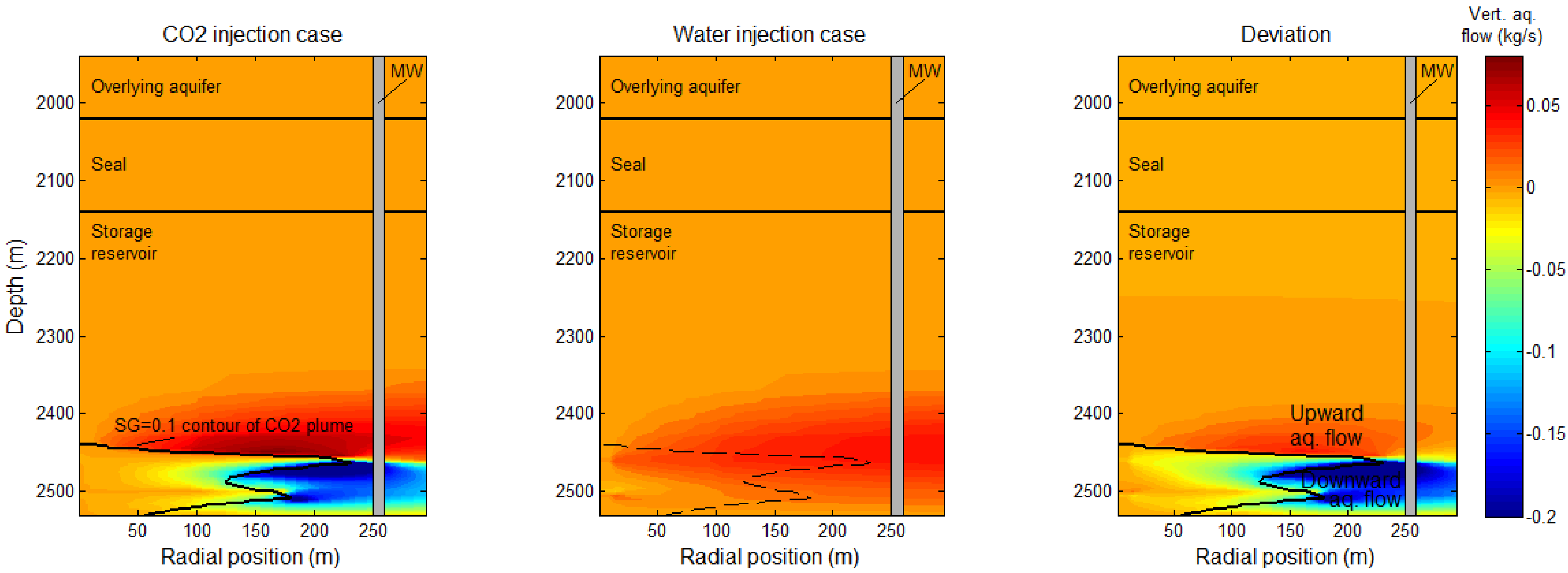
	Basic Monitoring Program	Additional Measurements for Enhanced Monitoring Program
Pre-operational Monitoring	• Well logs • Wellhead pressure • Formation pressure • Injection and production rate testing • Seismic survey • Microseismic background survey • Atmospheric CO_2 monitoring • Baseline groundwater quality sampling	• Pressure and water quality above the storage formation • Gravity survey • Electromagnetic survey • CO_2 flux monitoring
Operational Monitoring	• Wellhead pressure • Injection and production rates • Wellhead atmospheric CO_2 monitoring • Microseismicity • Seismic surveys	• Well logs • Pressure and water quality above the storage formation • Gravity and electromagnetic surveys • CO_2 flux monitoring • Satellite land-surface deformation or tilt
Closure Monitoring	• Seismic surveys • Pressure monitoring until equilibration is reached	• Pressure and water quality above the storage formation • Gravity and electromagnetic surveys • CO_2 flux monitoring

Towards Implementation: Monitoring Performance

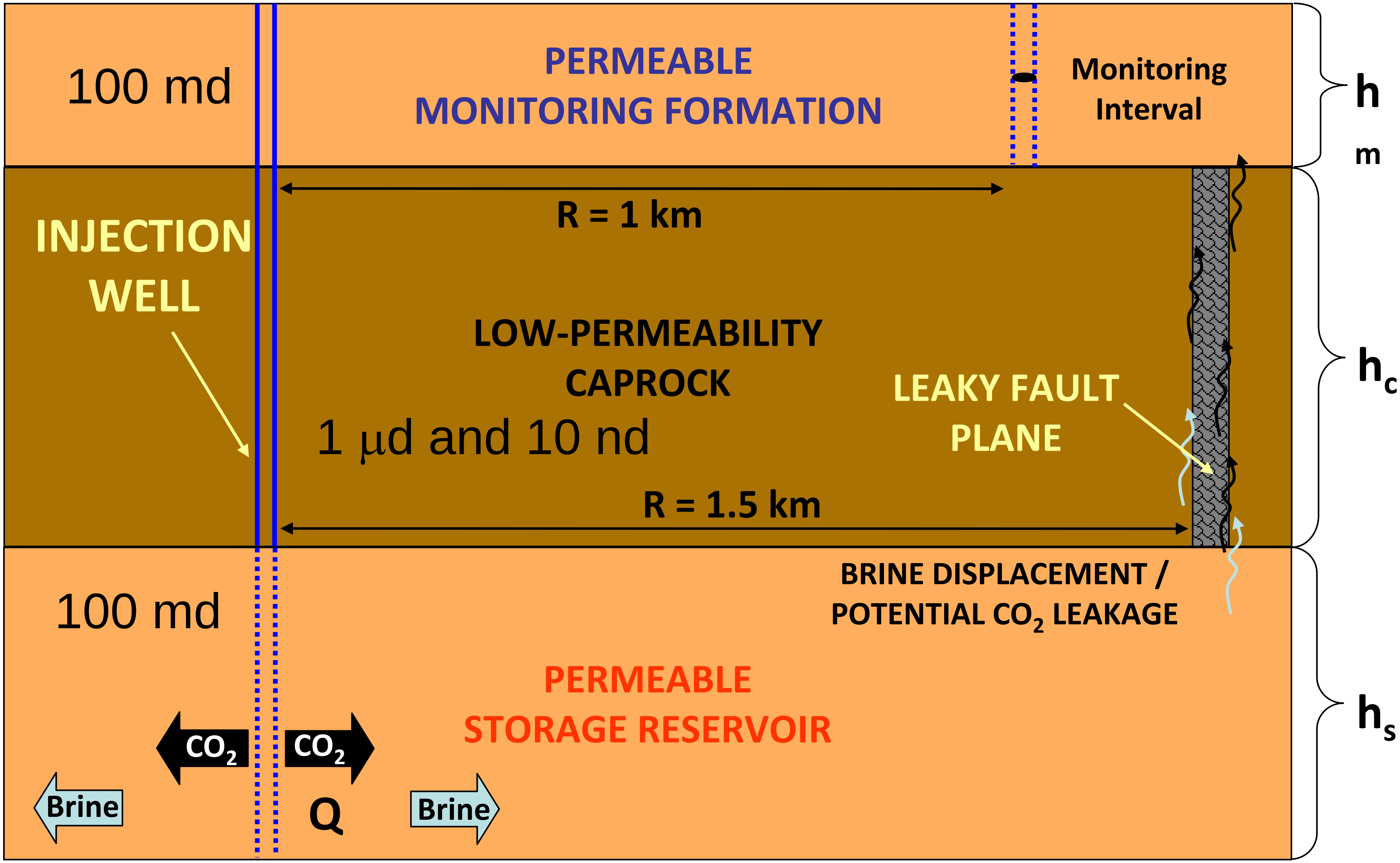
- Monitoring serves several important purposes
  - Health, Safety, and Environmental Protection
  - Emission Reduction Compliance and Credits
  - Project Conformance and Optimization
- Each has unique requirements and goals
  - Detection thresholds should be established
  - Monitoring selections should be fit for purpose
- Combination of plume tracking and release/leak detection is most efficient meeting compliance and conformance assurance
  - Plume tracking: Monitor location of the separate phase CO_2 plume
  - Release/leaks: Detect > Locate > Quantify
- Many technology options are available today
  - Plume tracking: seismic imaging
  - Release/leak detection: seismic imaging and pressure monitoring

Backup Slides

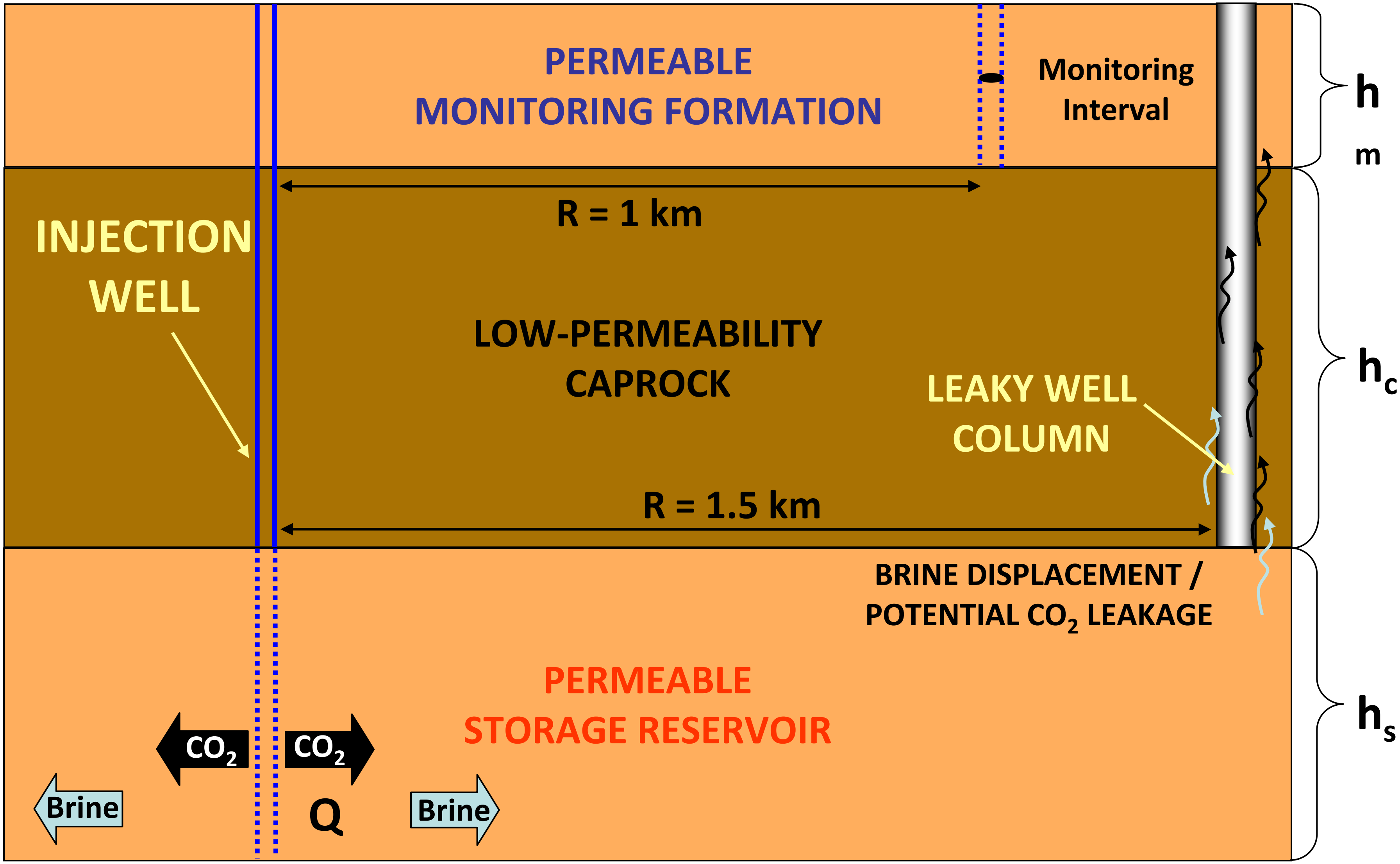
Anomalous Vertical Flows Due to Buoyancy Cause Pressure Deviations



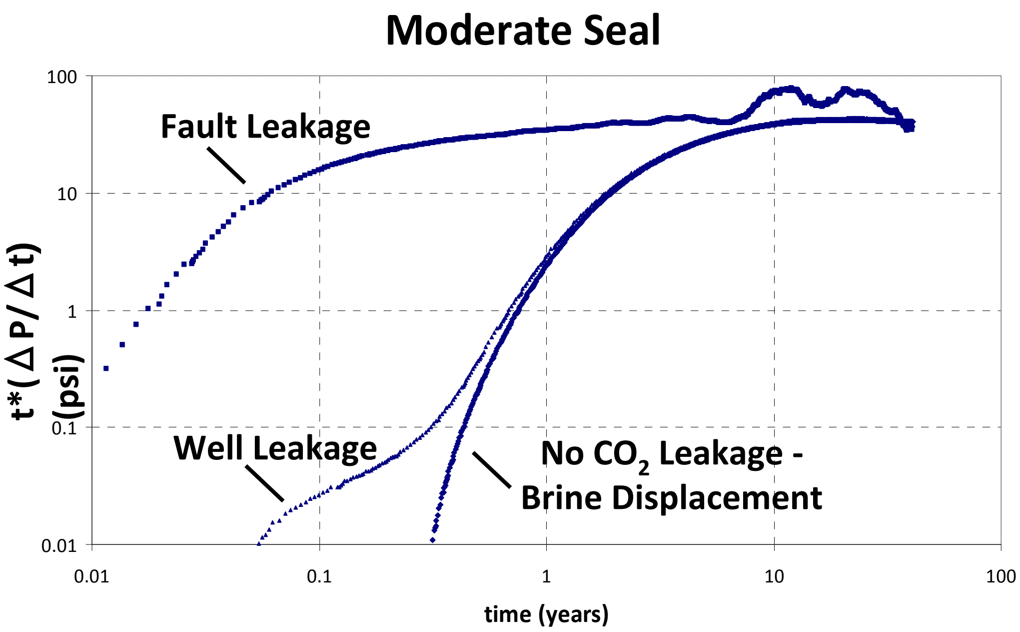
Leakage Up a Fault



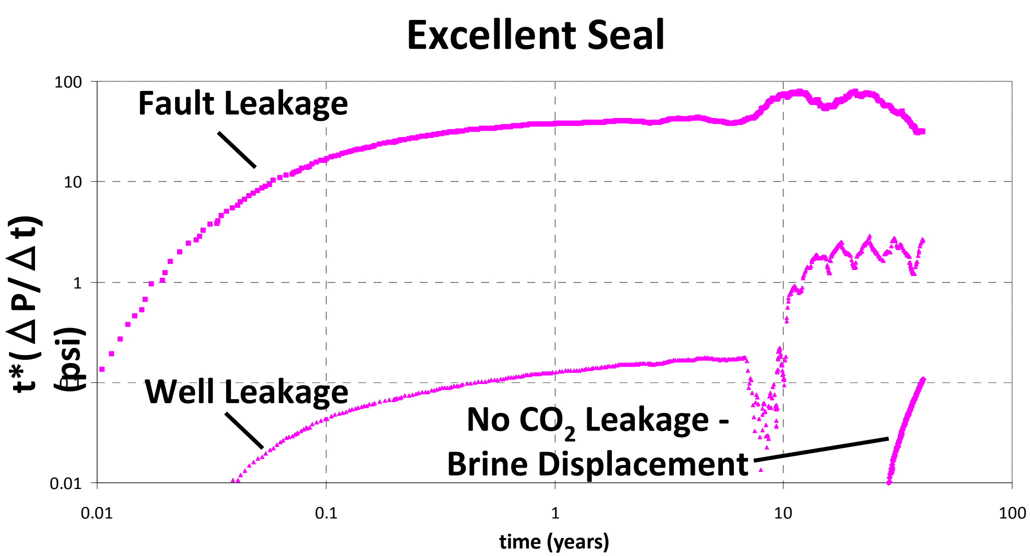
Leakage Up a Well



Pressure Derivative Comparison



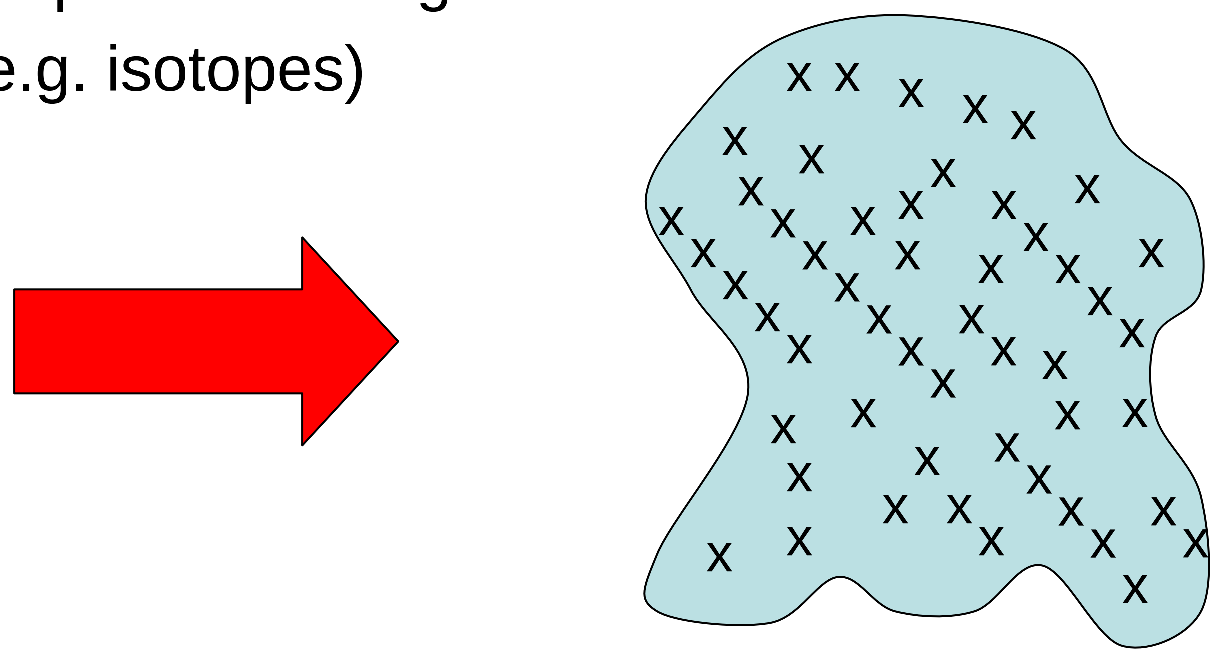
- Early-time response through well/fault
- Late-time dominance by brine displacement through cap rock
- CO_2 presence is notable in derivative curve (fault only)



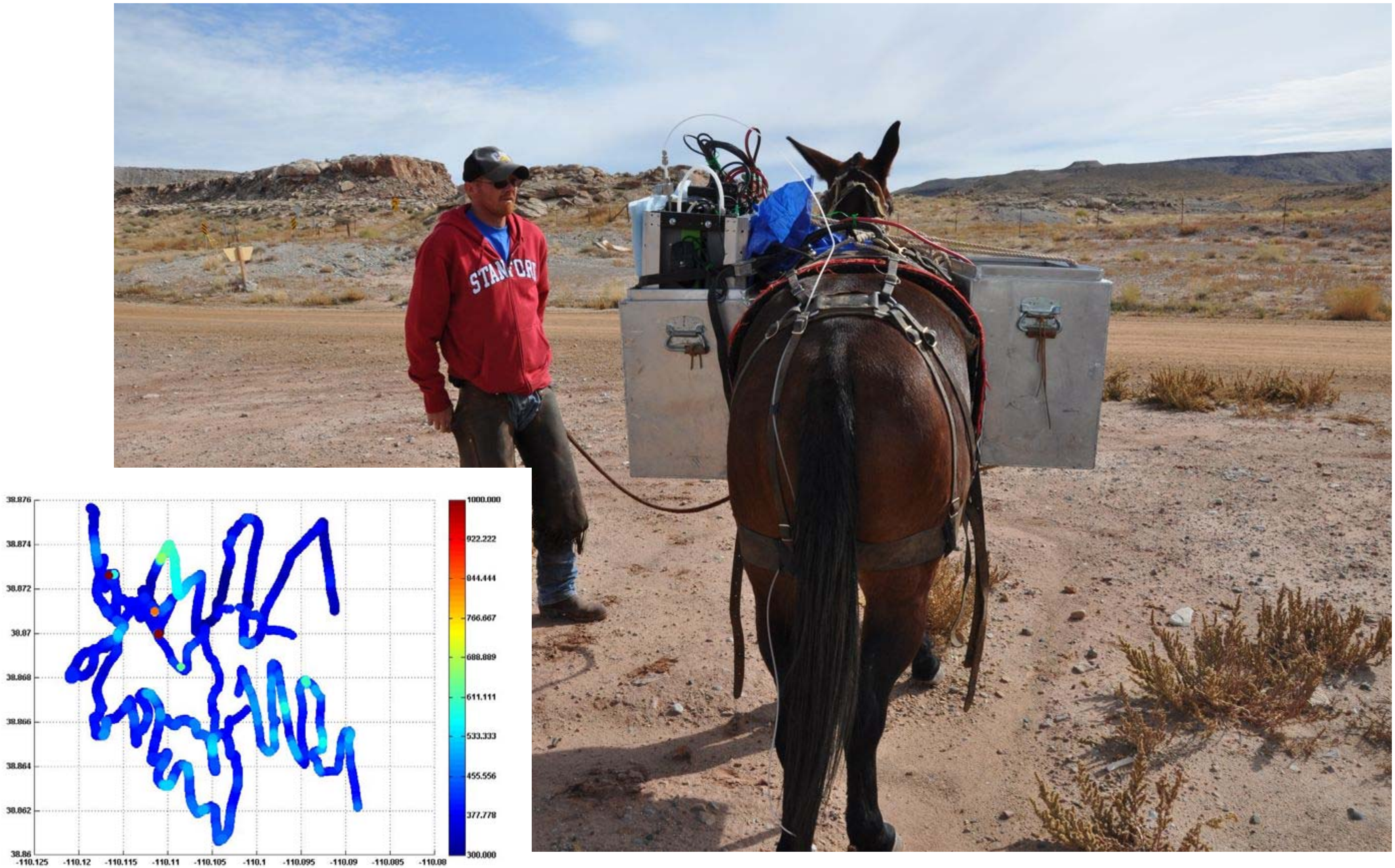
- Early-time response through well/fault
- Nominal brine displacement effect
- CO_2 presence is notable in derivative curve (fault & well)

Detection Ability

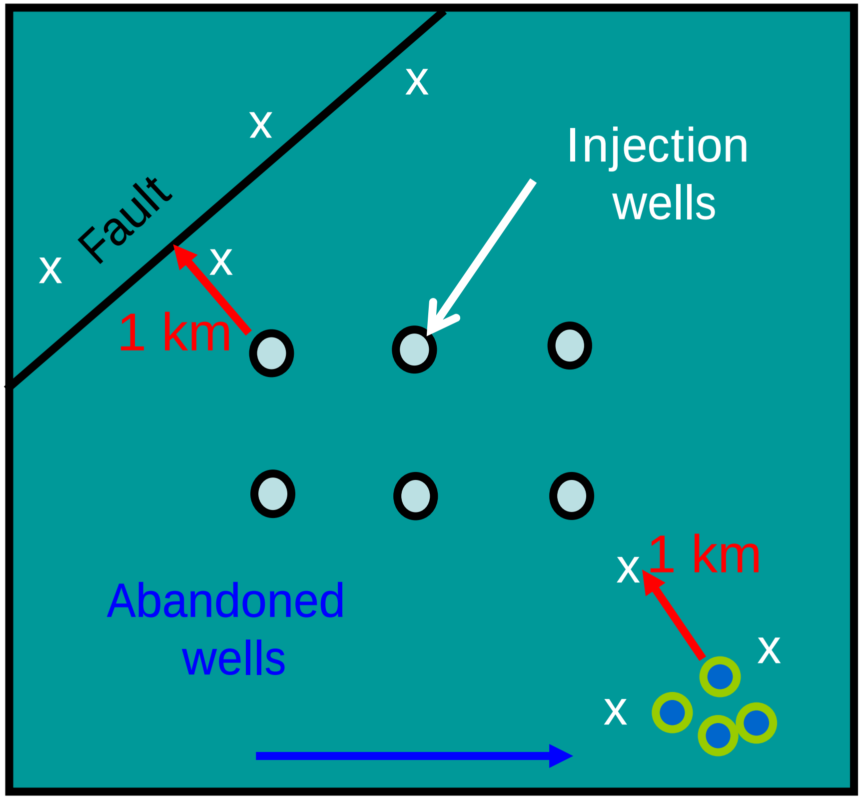
- Increases with:
  - Small footprint of the leak (<10% of the footprint of the plume)
  - Long time series and evaluation of cumulative fluxes
  - Monitoring devices with a footprint ~ size of the leak
  - Extensive spatial coverage
  - Tracers (e.g. isotopes)

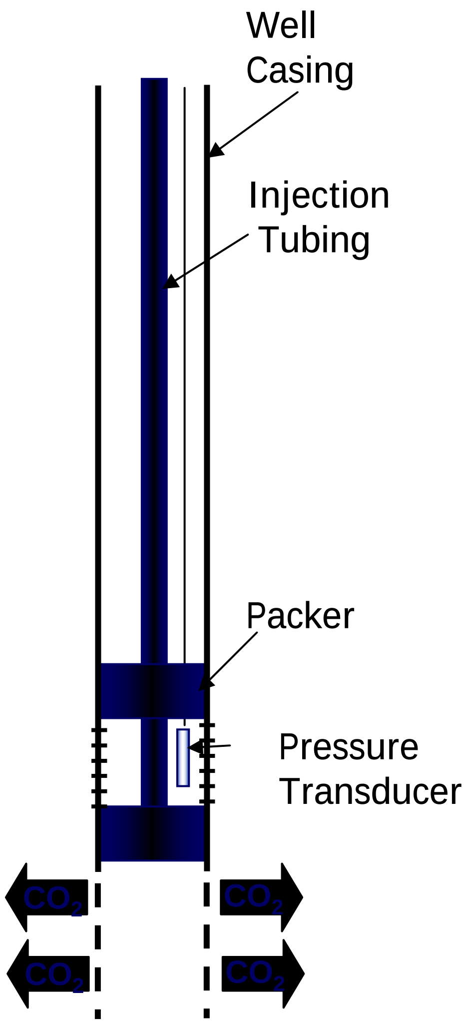


Scaling Up Isotopic Monitoring



Sensitivity of Pressure Monitoring





Injection/Monitoring Well

For favorable permeability-thickness product: measurable pressure increases within a year.