Stanford University
Global Climate & Energy Project

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Monitoring Carbon Dioxide Storage in Deep Geological Formations

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Topics

- Purposes for monitoring
- Monitoring techniques
- Examples
- Conclusions

Monitoring is Needed to Ensure Geologic Storage is Safe and Effective

Requirements for Geologic Storage

- Worker and Public Safety
- Performance Confirmation
- Local Environmental Impacts to Groundwater and Ecosystems
- GHG Mitigation Effectiveness

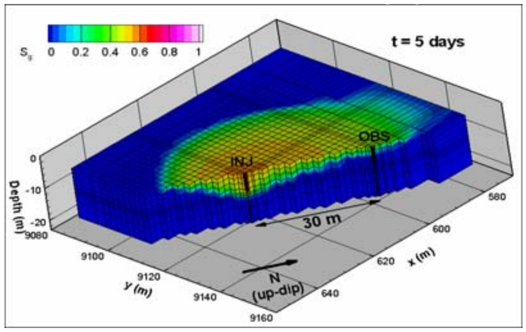
Monitoring Needs

Monitoring for Worker and Public Safety

- Concerns
  - Large-scale releases
  - High concentrations of CO_2 in confined spaces
- Wellheads
- Pipelines
- Surface facilities

Monitoring for Performance Confirmation

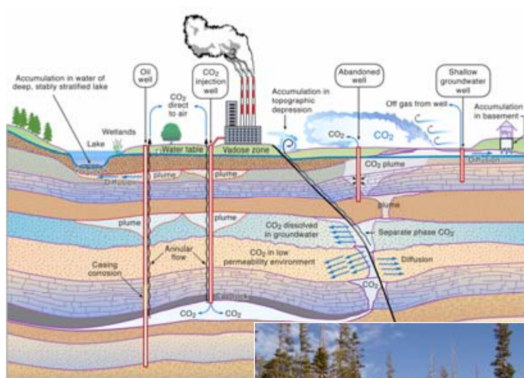
- Model calibration and confirmation
  - Pressure buildup
  - CO_2 migration in the storage formation
  - Effectiveness of trapping mechanisms
    - Solubility trapping
    - Capillary trapping
    - Mineral trapping



Comparison between models and observed plume migration is used to calibrate models and confirm performance

Monitoring for Local Impacts to Groundwater and Ecosystems

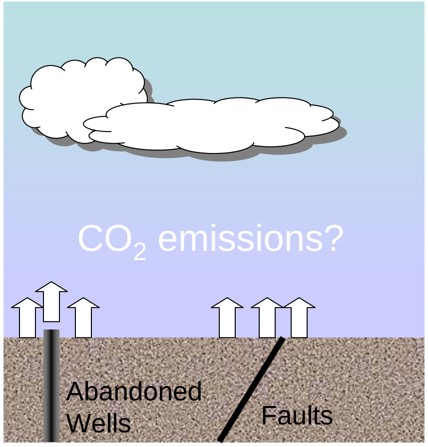
- Leakage from storage reservoir into groundwater systems
  - CO_2 itself
  - Mobilization of metals
  - Mobilized organics
- Displacement of saline or hydrocarbon bearing brines into groundwater systems
- Ecosystems



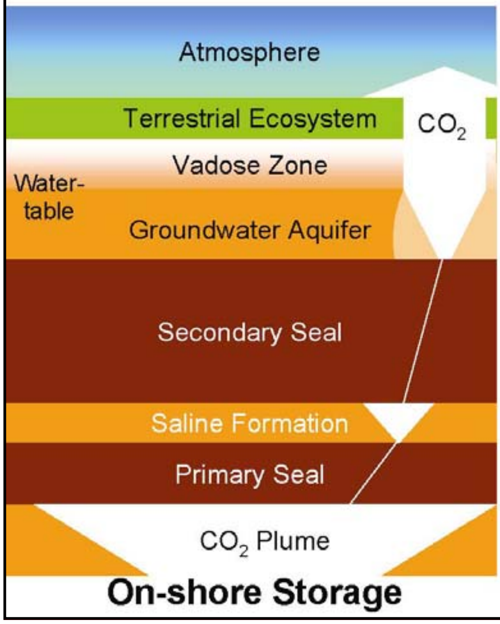
Mammoth Mountain

Monitoring for Effectiveness as a Greenhouse Gas Mitigation Technology

- Seepage back into the atmosphere
  - Wells
  - Faults and fractures
  - Soil
  - Surface water



Monitoring Options



Monitoring Methods

- Well-based methods
- Geophysical methods
- Surface methods

Well-based Monitoring Techniques

- Injection and production rates
- Wellhead and formation pressures
- Wellbore integrity testing and monitoring
- Temperature
- Well logs
- Fluid and gas composition

Geophysical Monitoring Techniques

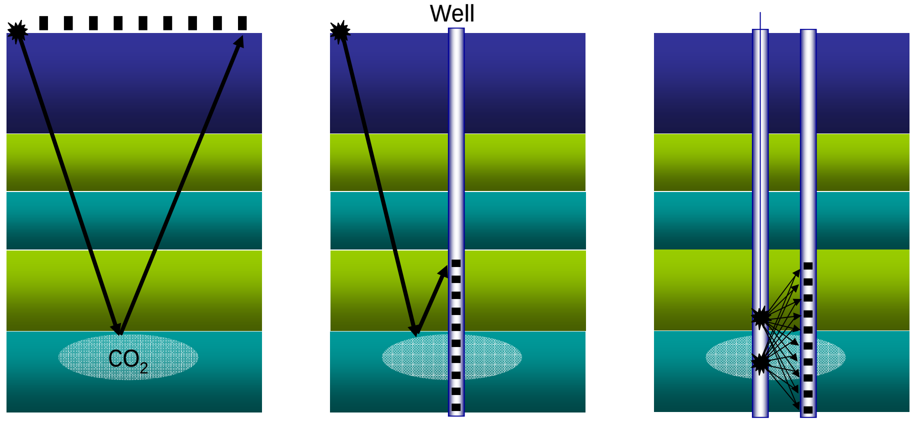
- Seismic geophysics
- Electrical and electromagnetic geophysics
- Gravity
- Tilt measurements
- Airborne or satellite-based land surface deformation
- Microseismicity

Seismic Monitoring

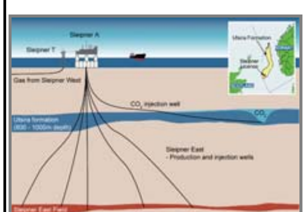
Surface Seismic
2-D, 3-D, and 4D

Vertical Seismic Profile (VSP)

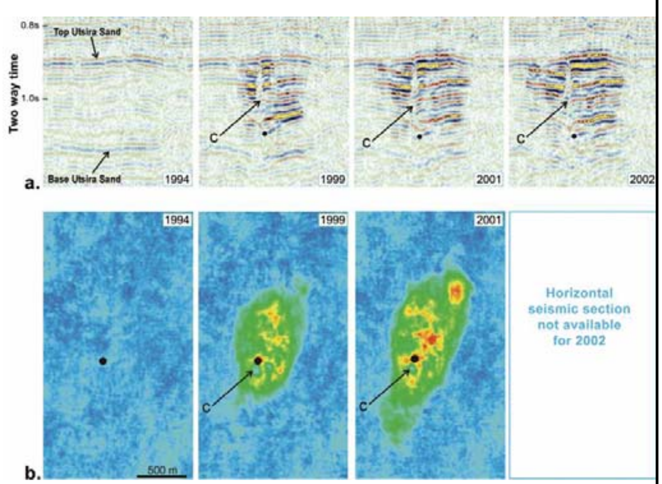
Cross-Well Tomography



Examples: Seismic Data Collected at the Sleipner Project

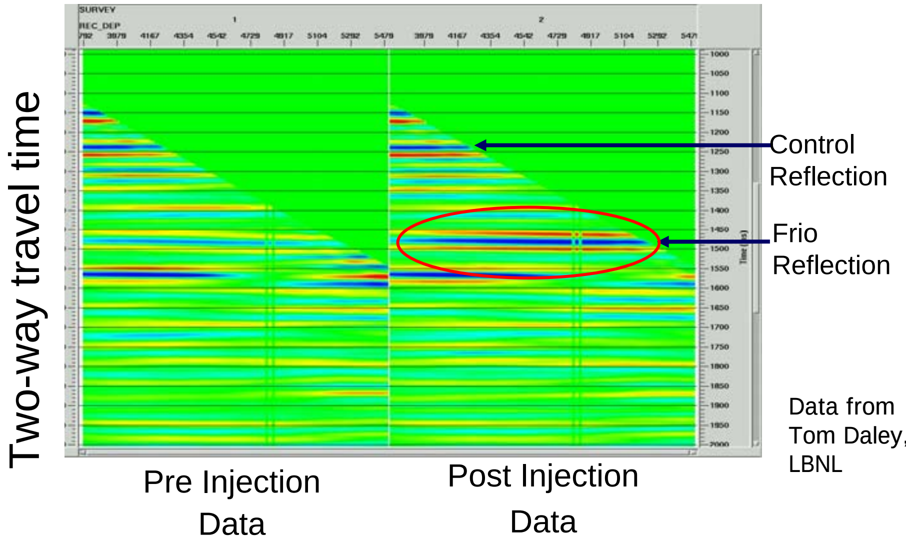


Sleipner Aquifer
Storage Project



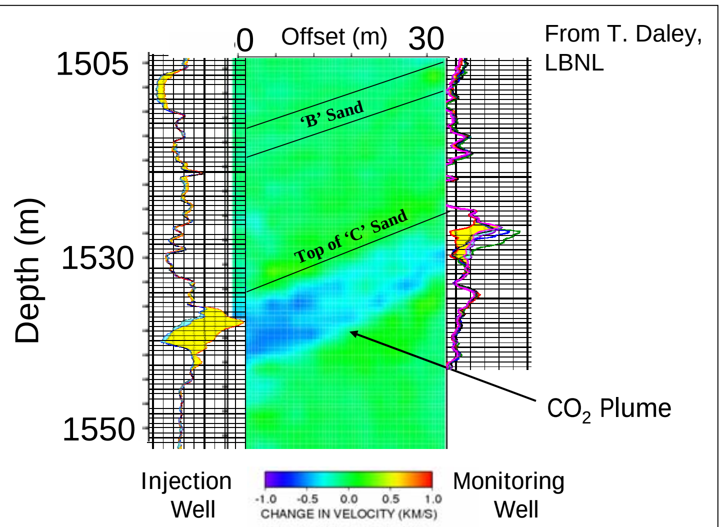
From IPCC, 2005, after Chadwick, 2004

Frio Formation: Vertical Seismic Profile Data



Data from Tom Daley, LBNL

Frio Formation Cross-well Seismic Data



From T. Daley, LBNL

Surface Monitoring for Seepage Detection and Inventory Verification

GCEP

- Soil gas and vadose zone monitoring
- Fluid and gas phase tracers
- Eddy covariance flux monitoring
- Flux chamber monitoring
- Open path optical techniques
  - Surface based
  - Plane
  - Satellite
- Point atmospheric CO_2 concentration

Flux Accumulation Chamber

GCEP

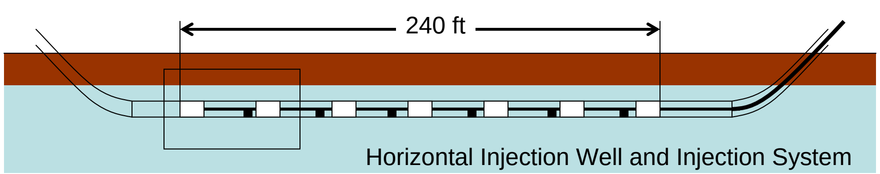
Flux measurements at Matsushiro, Japan

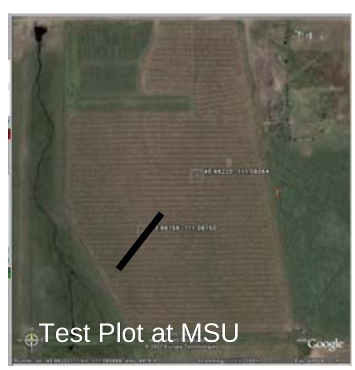
Eddy Covariance for Surface Flux Detection

- Well developed for natural carbon cycle studies
- Large detection footprint
  - Distances of 10 to 100 x tower height
- Sensitive to small fluxes
  - Ecosystem studies
- Detect, locate, quantify
- Best suited for large scale deployment
  - But, early experience for CO_2 storage applications will be useful

Jennifer Lewicki, LBNL

ZERT Detection Verification Facility at MSU (July 2007)





Life Cycle of a Storage Project and Monitoring Requirements

Pre-operation Phase	Operation Phase	Closure Phase	Post-closure Phase
• Site characterization • Risk assessment • Establish monitoring baseline	• Verify injection rates • Track location of plume • Ensure safe operations • Detect 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 may only be needed only if long term storage security not established

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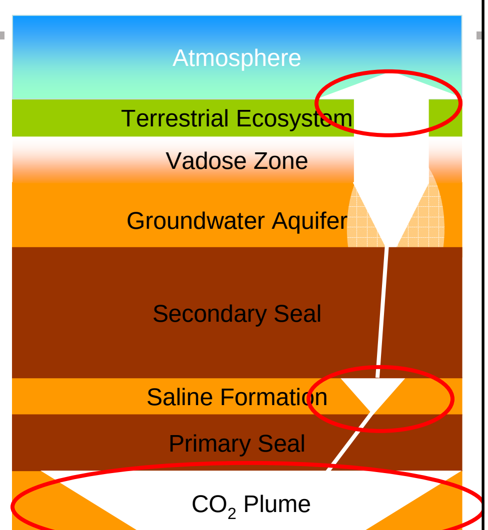
Approximate Time-Line (Years)

From Benson et al., 2006

A Potential Monitoring Program

- Reservoir monitoring to track plume migration
- Secondary accumulations to look for leakage
- Atmospheric flux monitoring



On-shore Storage

GCEP

Conclusions

- Many monitoring options available
- Combinations of techniques will address the range of monitoring needs
- Costs of monitoring are small compared to other CCS costs
- Innovations will improve spatial and temporal resolution
- More demonstrations are needed