Monitoring Carbon Dioxide Sequestration in Deep Geological Formations for Inventory Verification and Carbon Credits

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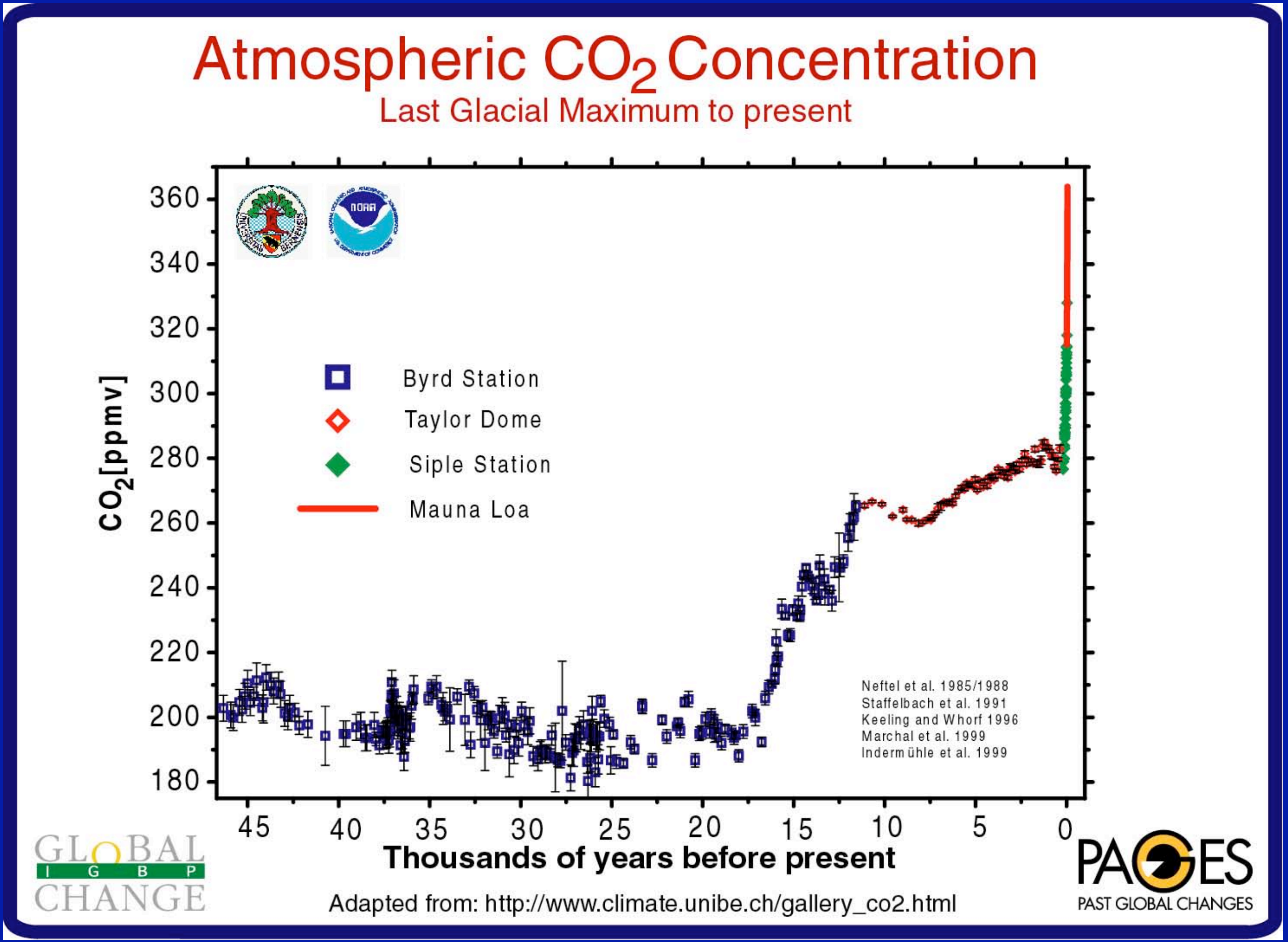
Growing Awareness of the Urgency to Stop Increasing Atmospheric CO_2 Concentrations



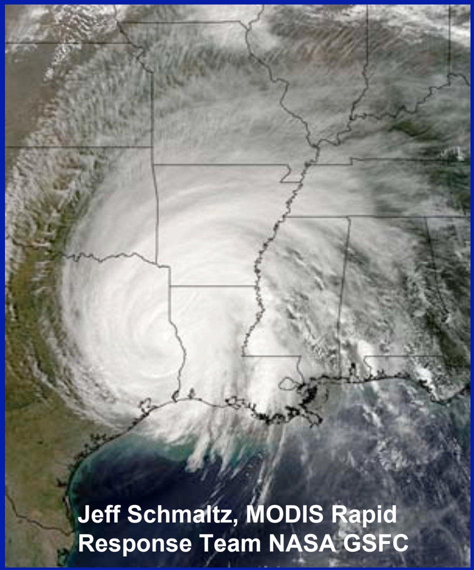
There Are Good Reasons to Begin Doing Something Now

Melting Glaciers

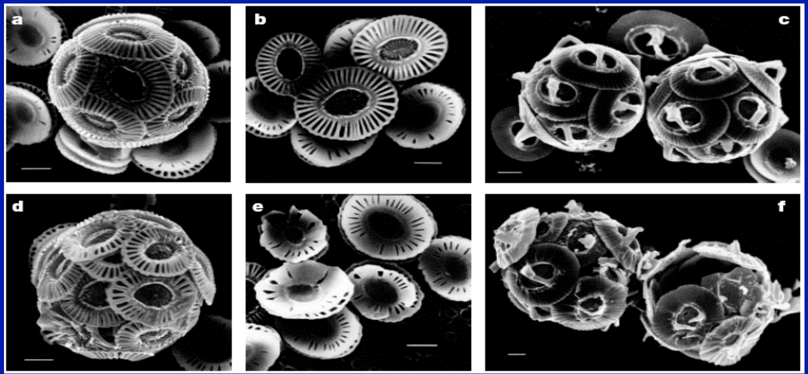
Grinell Glacier
and Grinnell Lake,
Glacier National
Park, 1910-1997

Rising Sea Levels

Stronger Hurricanes



Ocean Acidification



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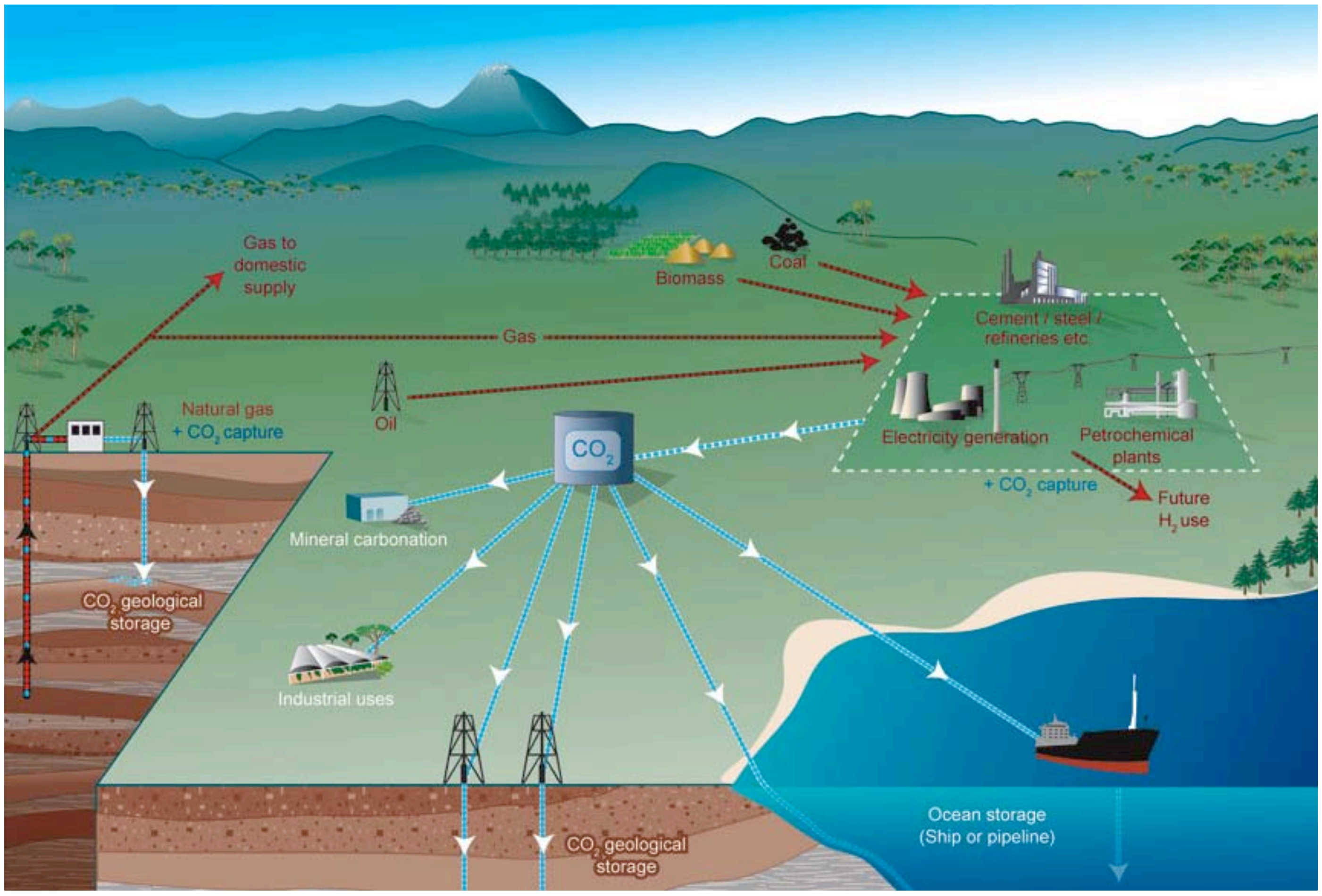
Carbon Dioxide Capture and Storage is an Important Part of the Solution



http://www.ipcc.ch/activity/csspm.pdf

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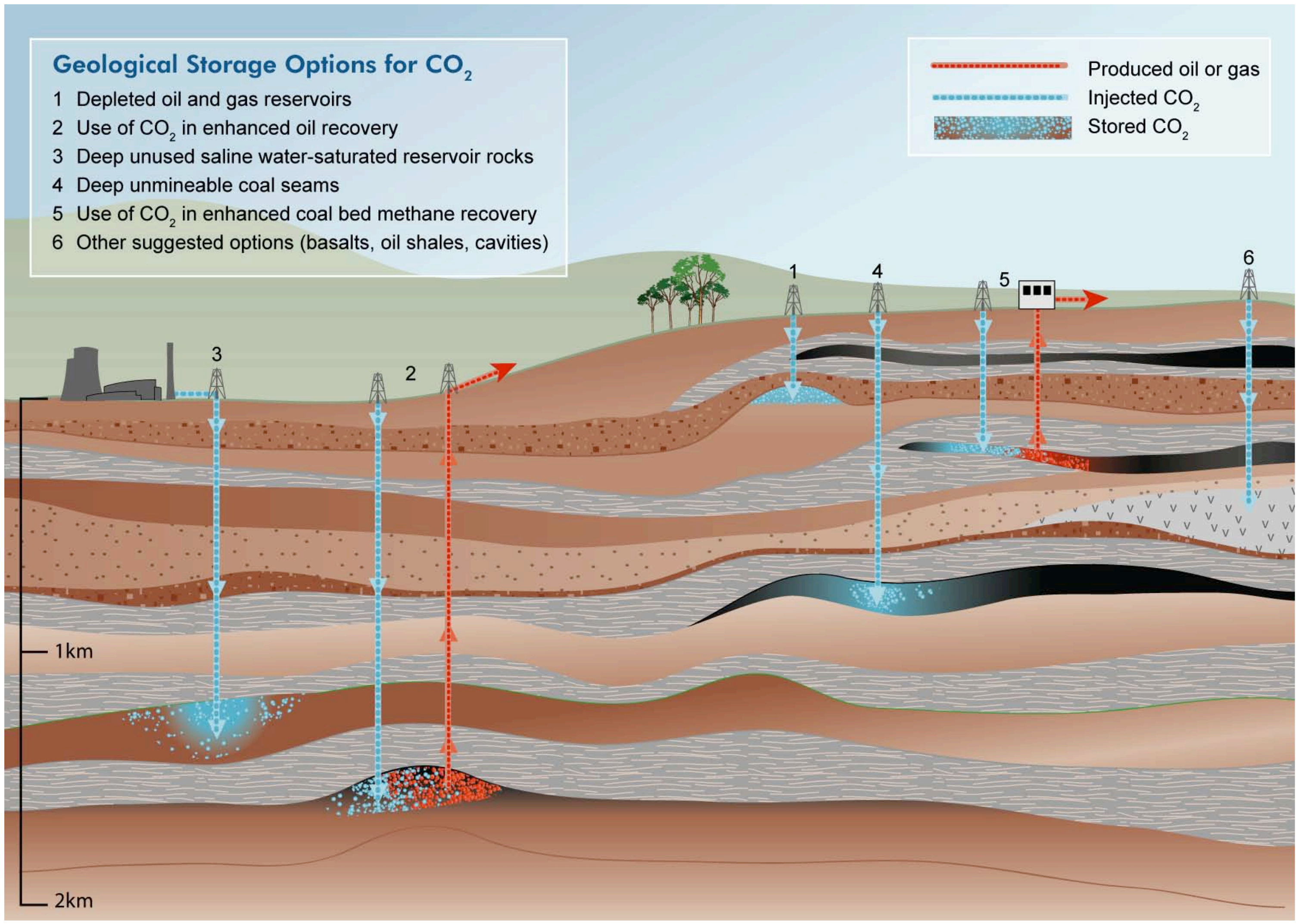
Options for Geological Storage



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Monitoring is a Key Enabling Element of Geological Storage

Purposes for Monitoring

- Health and safety
- Environmental protection
- Natural resource protection
- Model calibration
- Performance assessment
- Verification of national inventories
- Carbon credit trading
- Regulatory compliance
- Establish a pre-injection baseline
- Designing remediation plans
- Etc…

Monitoring Methods

- Pressure
- Fluid sampling and analysis
- Seismic
- Electromagnetic
- Gravity
- Well logs
- Tracers
- Flux towers
- Soil gas
- Accumulation chambers
- Etc…

Motivation for This Study

- More commercial projects are coming on line
- Good news
  - Lots of monitoring techniques
- Bad news
  - Lots of monitoring techniques
- Motivation: Simplify
  - Focus on two specific purposes for monitoring

Purposes for Monitoring

- Health and safety
- Environmental protection
- Natural resource protection
- Model calibration
- Performance assessment
- Verification of national inventories
- Carbon credit trading
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- Establish a pre-injection baseline
- Designing remediation plans
- Etc…

Goals of the Study

1. What information is needed for inventory verification and carbon trading credits?
2. What monitoring strategy and methods are available?
3. With what precision and detection levels should this information be provided?
4. Are satisfactory methods available?
5. What are the opportunities for improvement?

Verification of National Inventories

- Inventory verification is an essential component of national and international strategies to control and reduce CO_2 emissions
- Annual accounting is performed based on sector-specific methodologies
- Newly developed guidelines have been published for CO_2 capture and storage (IPCC, 2006)

> *… methodology for estimating national inventories of greenhouse gas inventories of anthropogenic emissions by sources and removals by sinks.*
>
> *Good practice… neither over- nor under-estimates so far as can be judged and which uncertainties are reduced as far as practicable.*

Revised IPCC Guidelines, 2006

Inventory Guidelines for CO_2 Capture and Storage

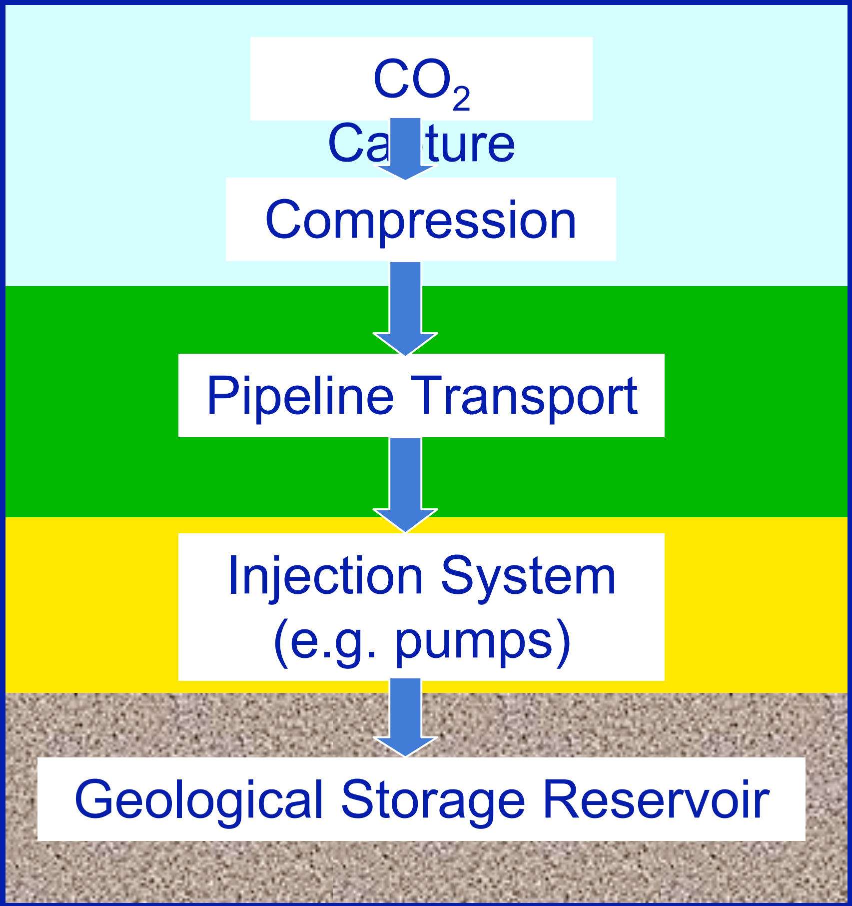
From IPCC, 2006

System 1. Capture and Compression

System 2. Transportation

System 3. Injection

System 4. Geological Storage Reservoir



System Components for On-Shore Storage

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Inventory Guidelines for CO_2 Capture and Storage

From IPCC, 2006

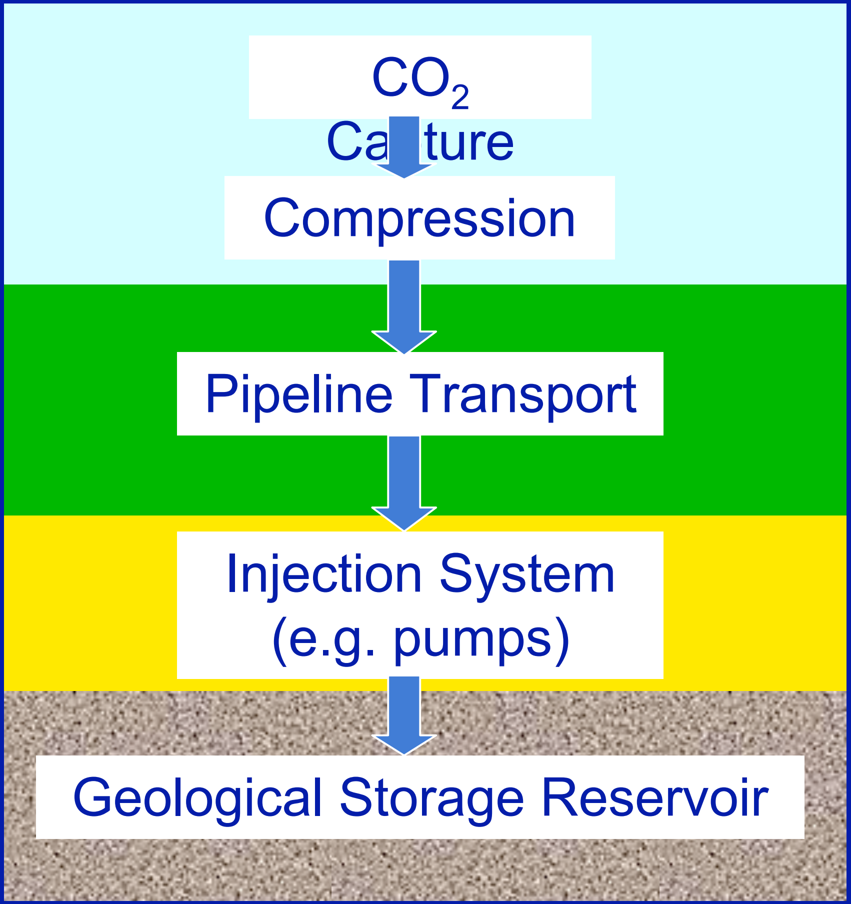
System 1. Capture and Compression

System 2. Transportation

System 3. Injection

System 4. Geological Storage Reservoir

Treat each as an emission source



System Components for On-Shore Storage

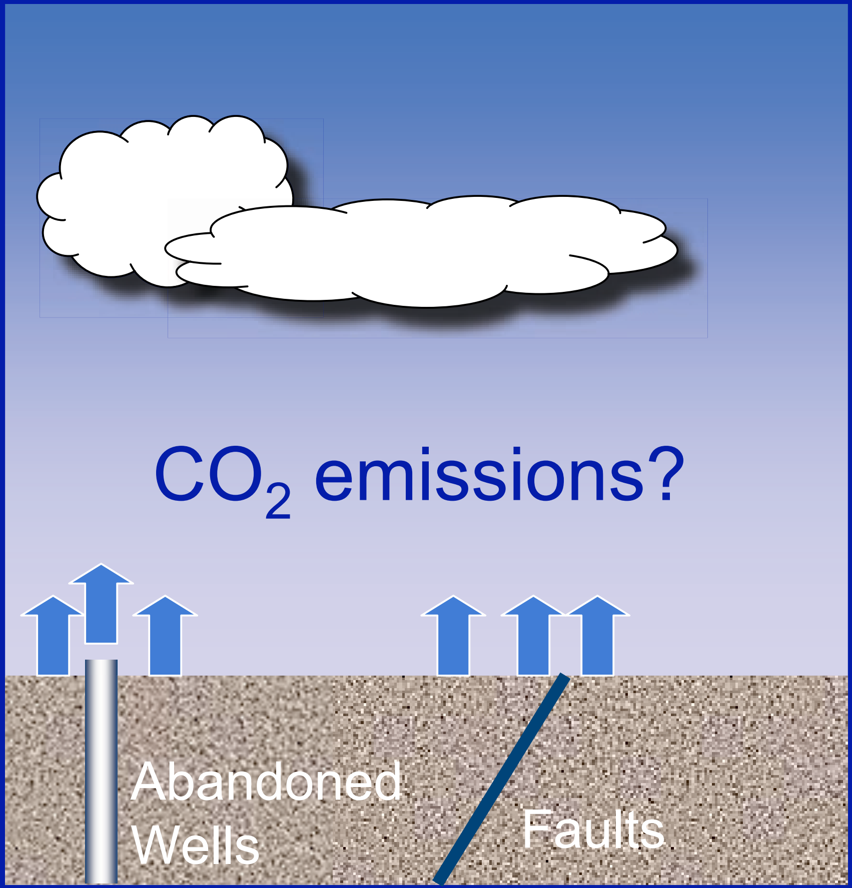
Key Question: Measure Emissions Into the Atmosphere

System 1. Capture and Compression ✓

System 2. Transportation ✓

System 3. Injection ✓

System 4. Geological Storage Reservoir ?



Geological Storage Reservoir

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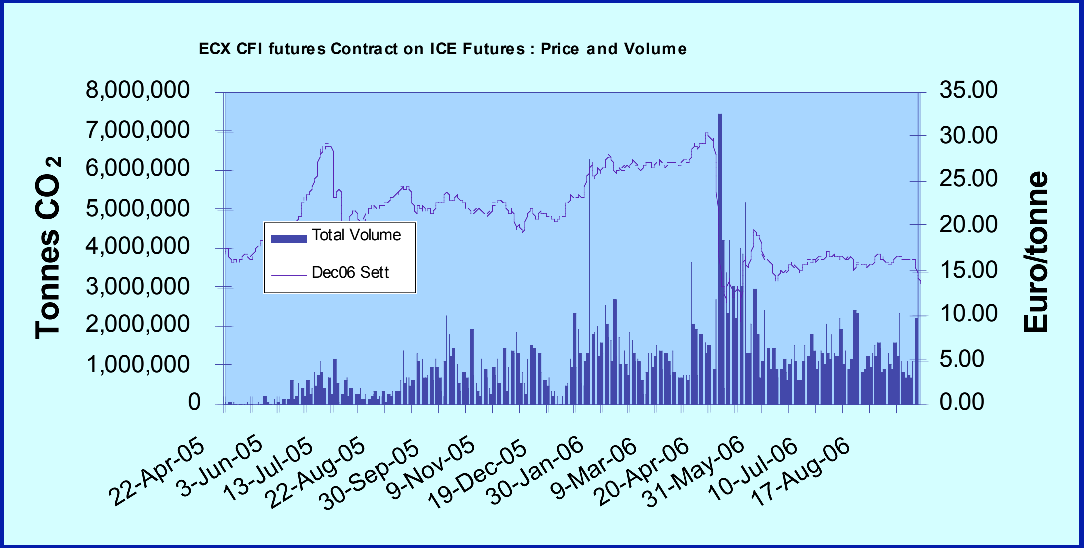
Confidence is Needed to Support Carbon Trading Markets

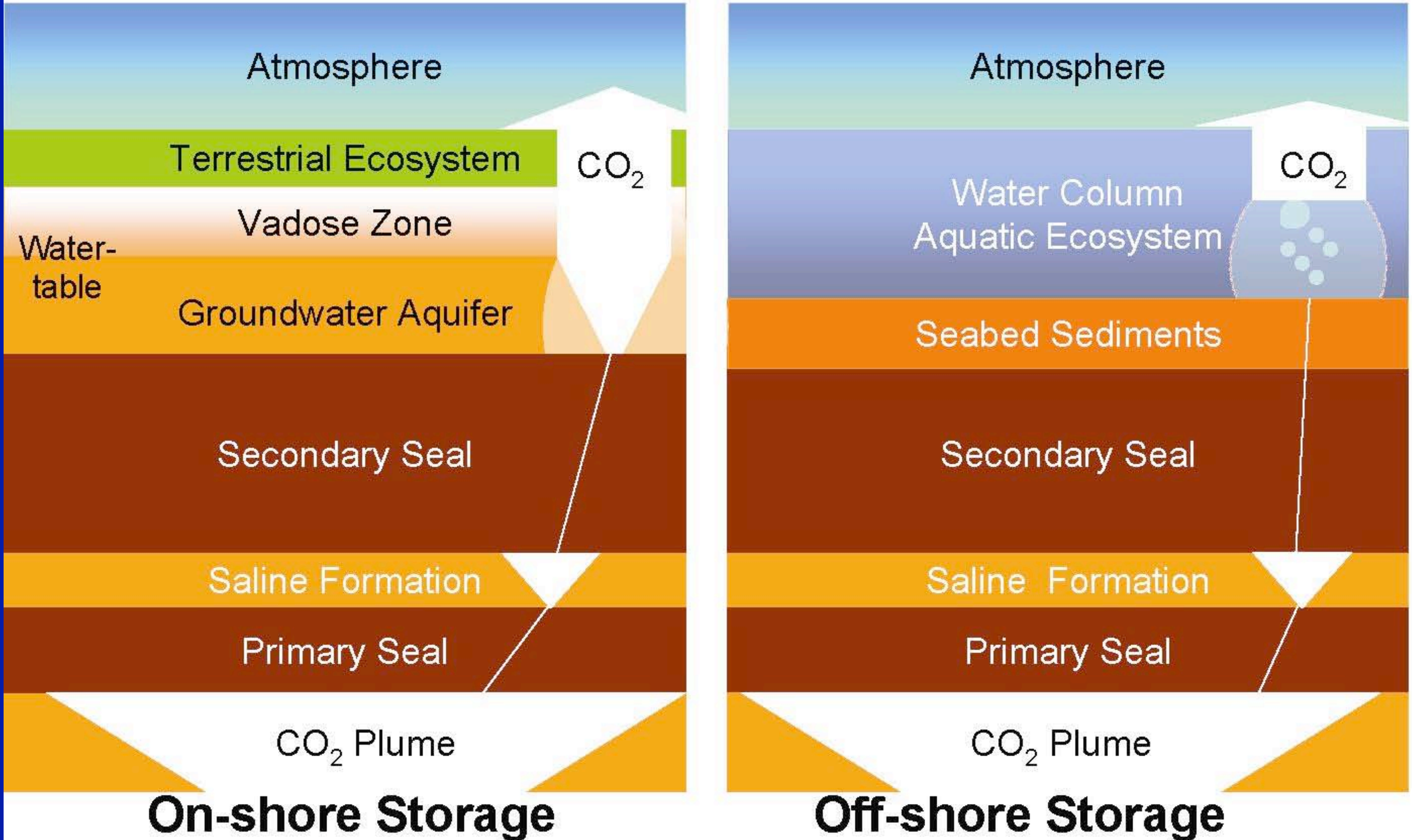
- European Trading System (ETS)
- Clean Development Mechanism (CDM)
- Joint Implementation (JI)



Goals

1. What information is needed for inventory verification and carbon trading credits?
2. What monitoring strategies and methods are available?

Monitoring Options



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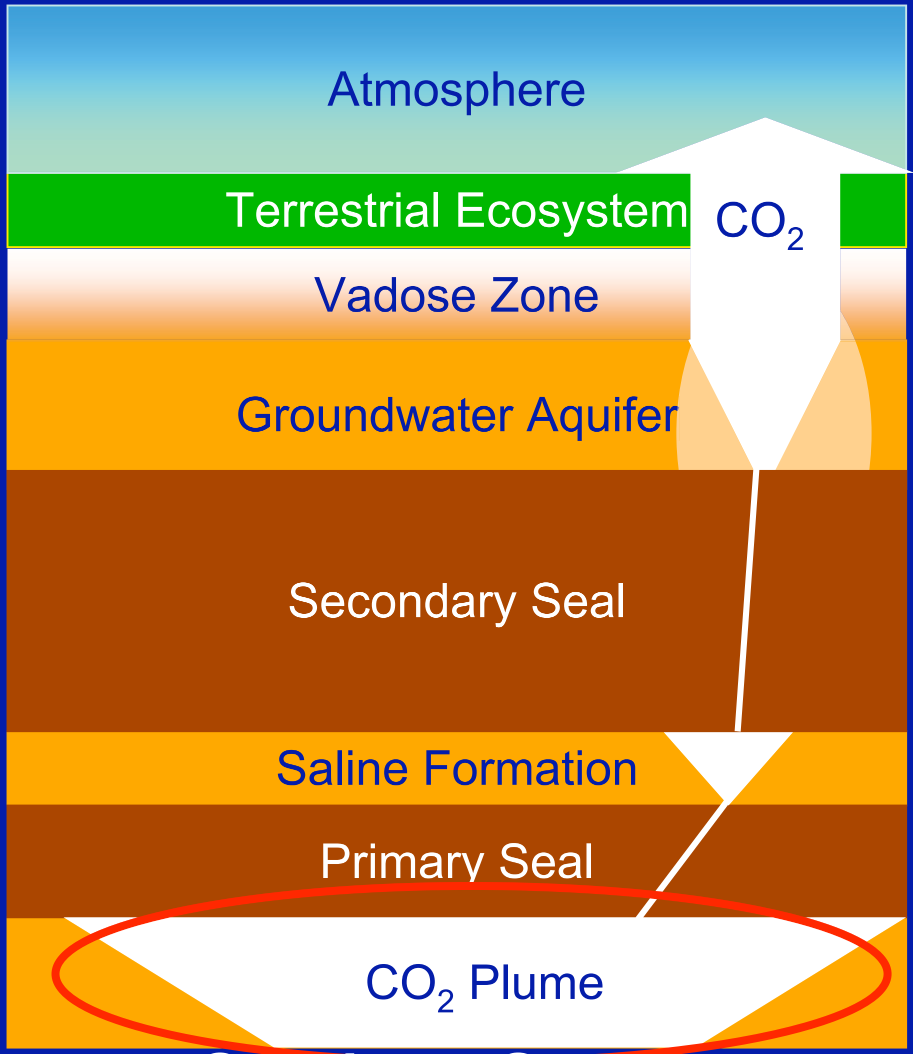
Strategy: Storage Reservoir



On-shore Storage

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Methods

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

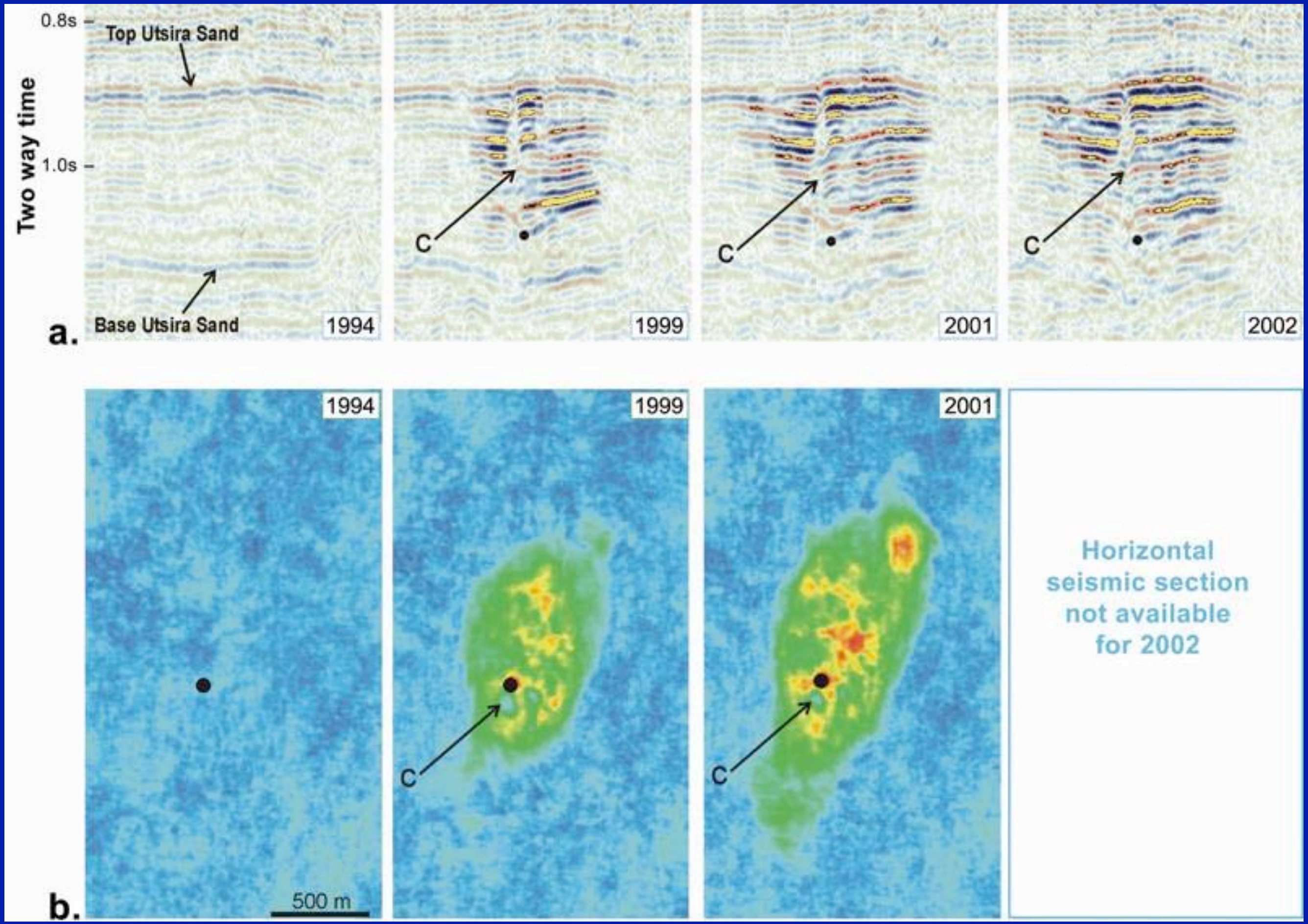
Benefits

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

Drawbacks

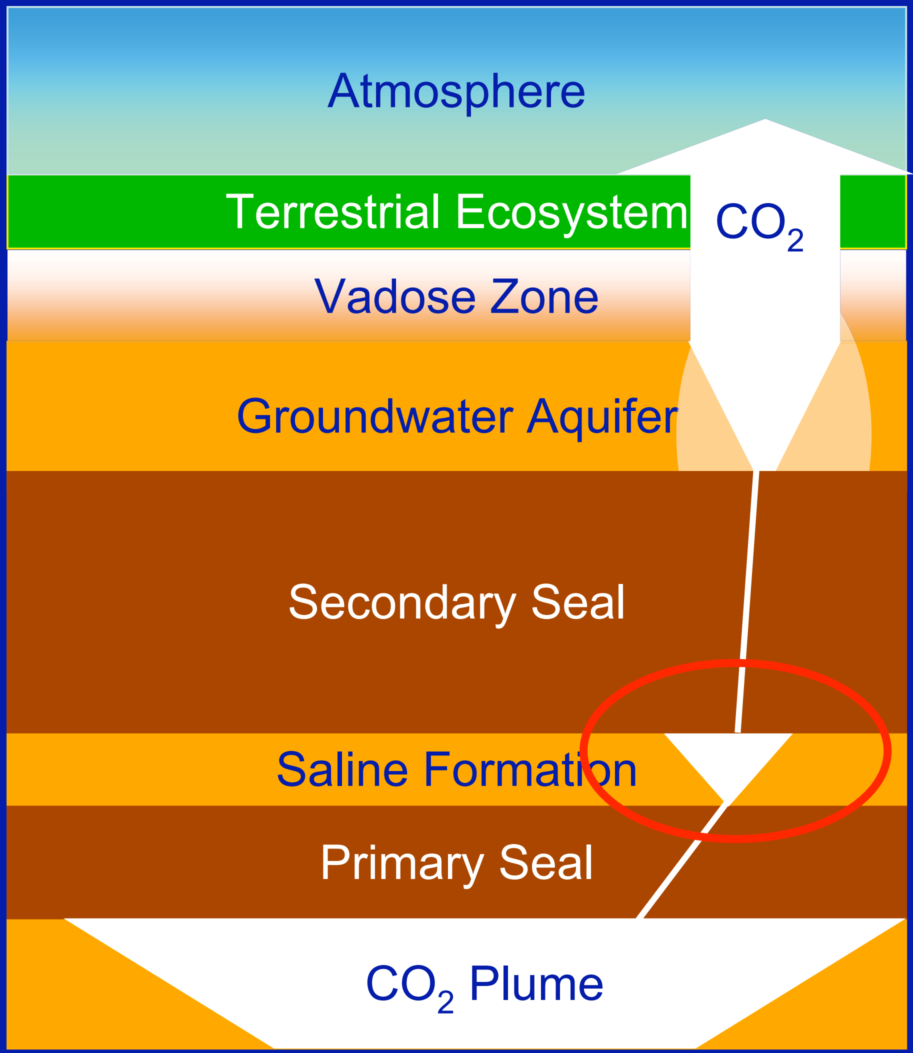
- Mass balance difficult to monitor
- Dissolved and mineralized CO_2 difficult to detect

Examples: Seismic Data Collected at Sleipner



From IPCC, 2005, after Chadwick, 2004

Strategy: Secondary Accumulations



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Methods

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

Benefits

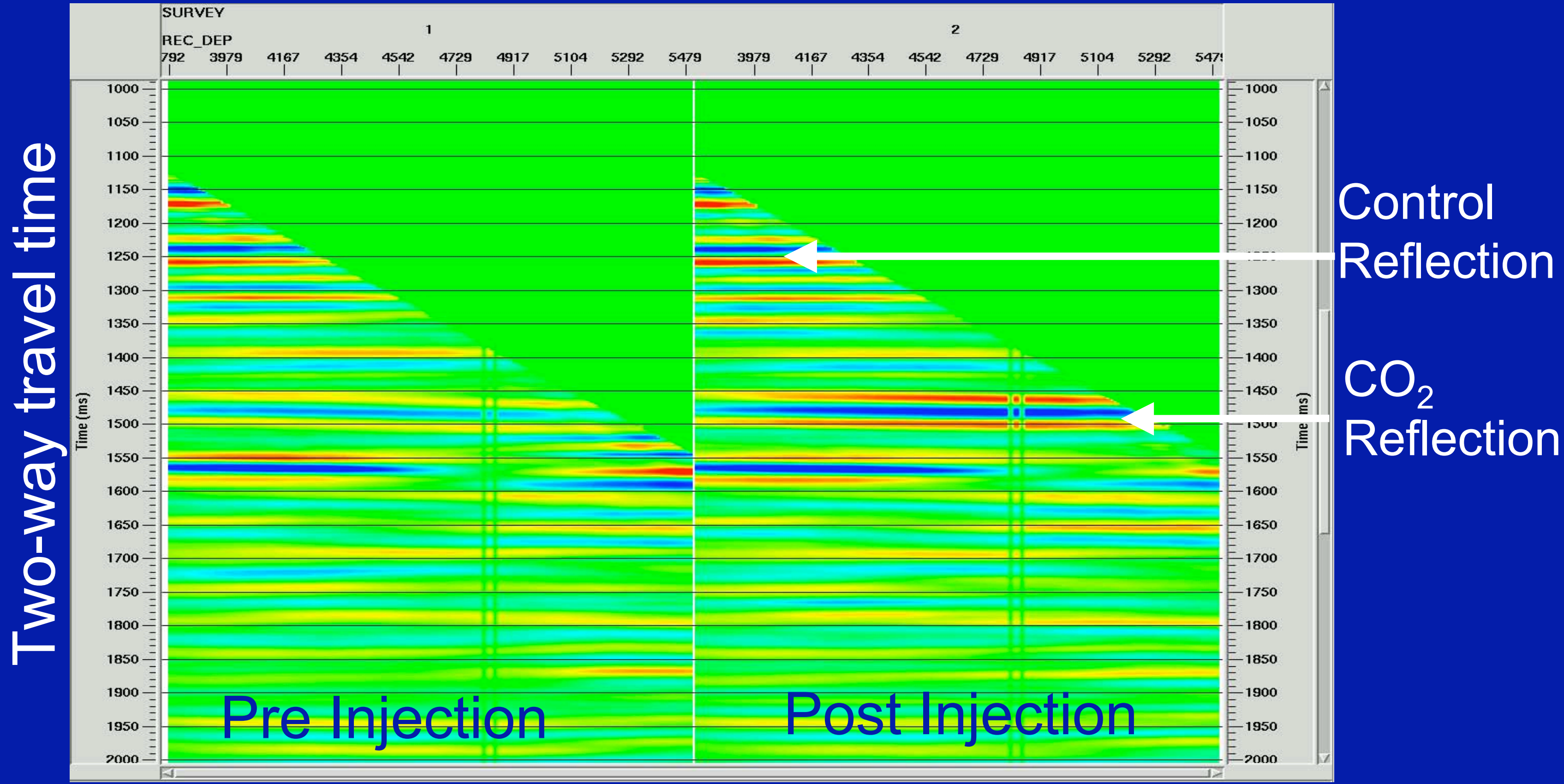
- Sensitivity to small secondary accumulations (~10^3 tonnes) and leakage rates
- Early warning of leakage

Drawbacks

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

Frio Formation: Vertical Seismic Profile Data

1,600 tonnes CO_2



Data from Tom Daley, LBNL

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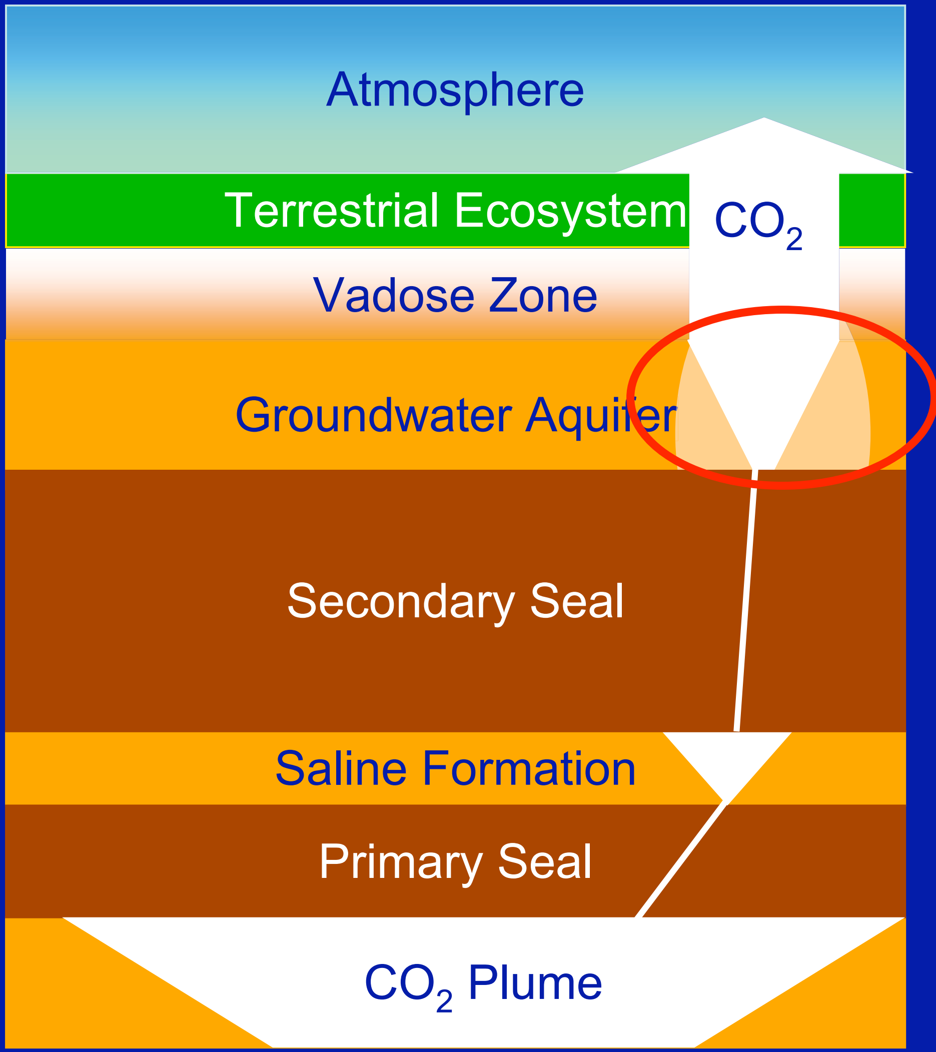
Strategy: Groundwater



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Methods

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

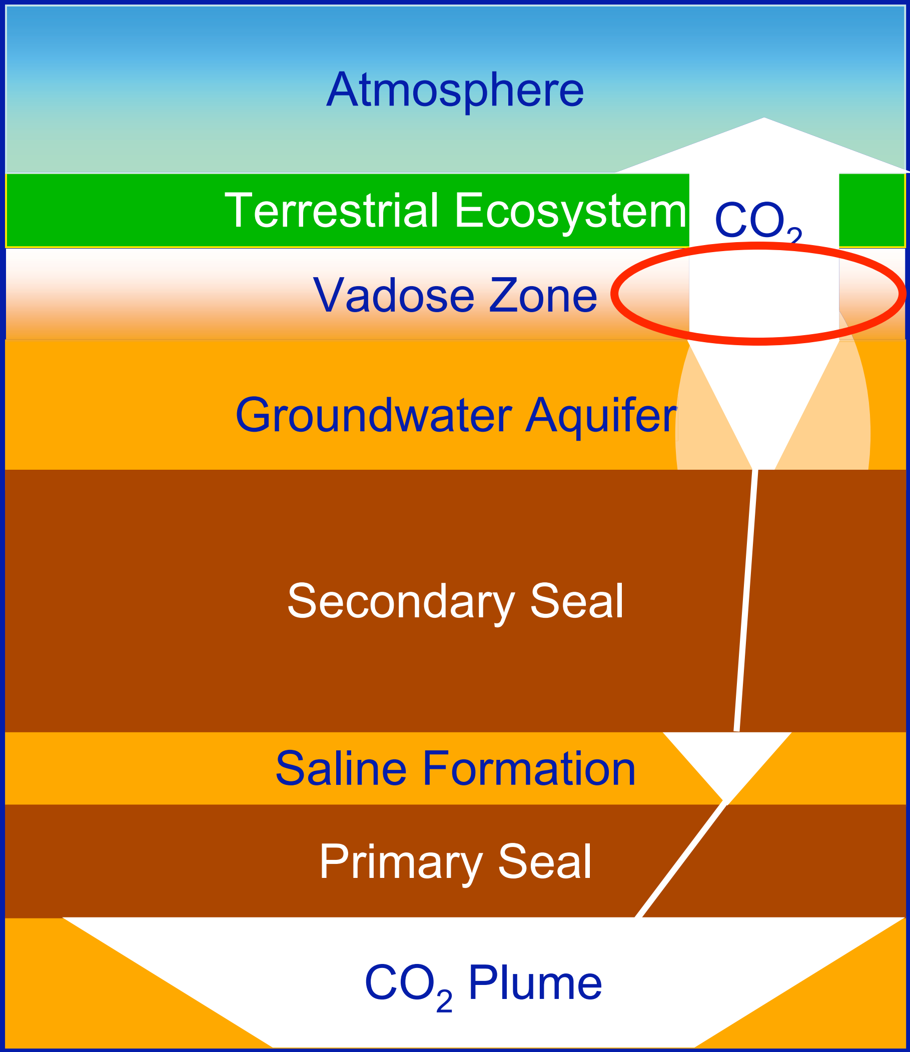
Benefits

- 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



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Methods

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

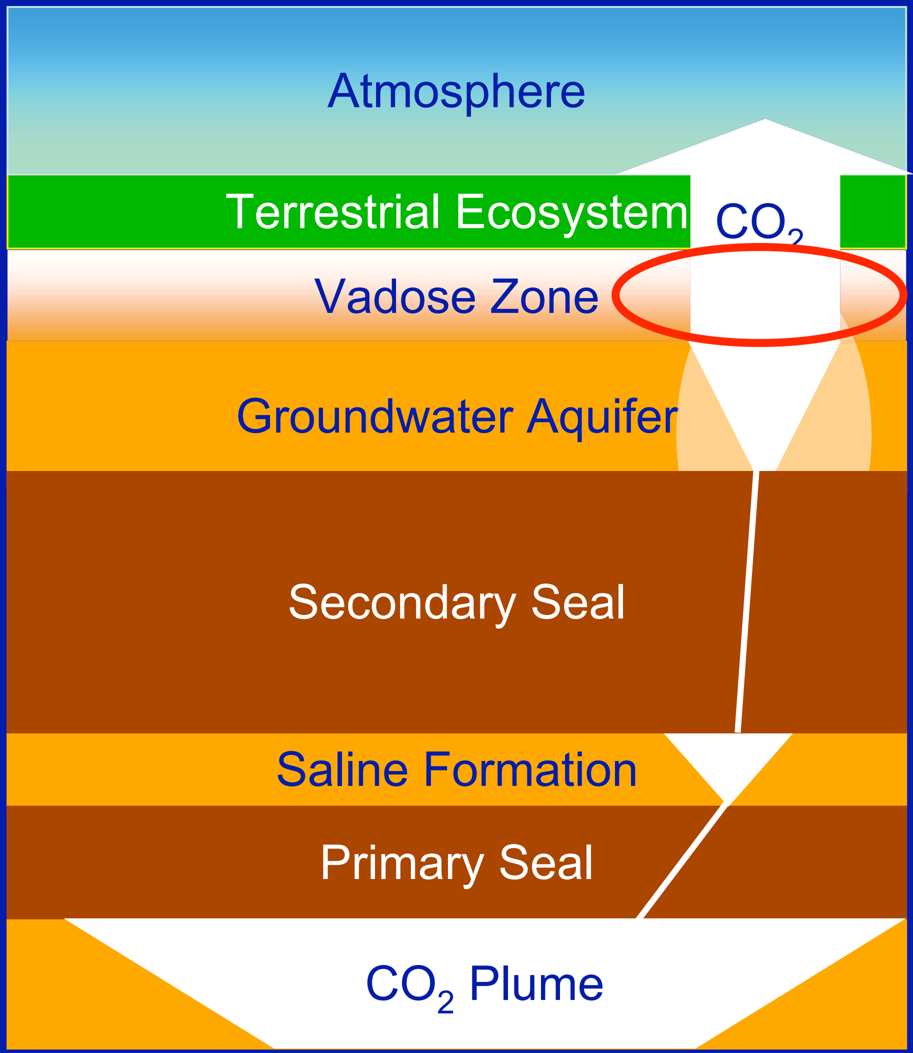
Benefits

- 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: Vadose Zone



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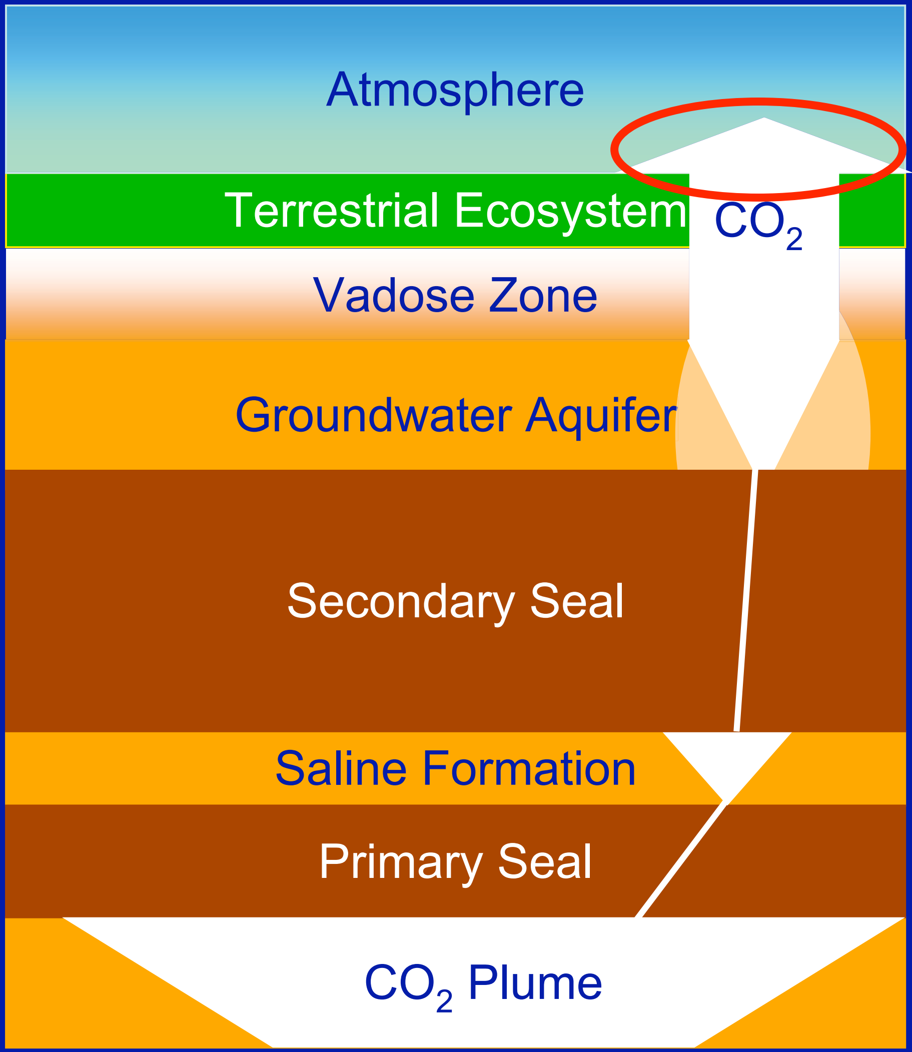
Strategy: Atmosphere



On-shore Storage

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Methods

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

Benefits

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

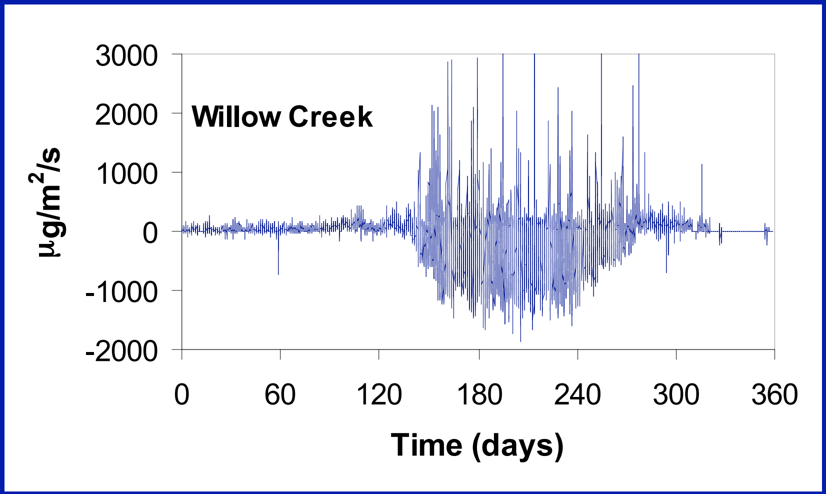
Drawbacks

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

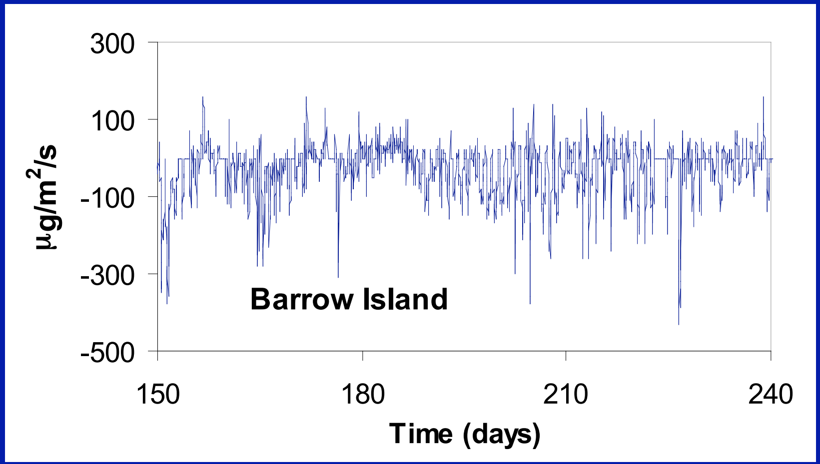
Atmospheric Monitoring Methods

Eddy Covariance Tower

Flux accumulation chamber



Courtesy of Ken Davis and Paul Bolstad



Courtesy of Walter Oechel

Goals

1. What information is needed for inventory verification and carbon trading credits?
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   - What is the best strategy for setting detection levels?
   - What is an appropriate detection level?

Attributes: Practicable Detection Levels

- Simple… both with regard to explaining and implementing the approach
- Defensible… sufficiently stringent to ensure that geological storage will be effective as a GHG mitigation technique
- Verifiable… the value of carbon credits can be assigned with confidence and certainty

Detection Approaches

Method	Example	Simple	Defensible	Verifiable
Fraction of background CO_2 flux	50% of background			✓
% CO_2 stored	0.01%/year		✓	✓
Specified CO_2 emission per year	5,000 tonnes/year	✓	✓	✓
Prescribed CO_2 flux	50 $\mu g/m^2/s$		✓	✓
Instrument- based method	10 using $\mu g/m^2/s$ eddy covariance towers	✓		

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Hypothetical Storage Project

- Annual Injection Rate
  - 5 Mt/year
- Project Duration
  - 50 years
- Reservoir Thickness
  - 100 m
- In Situ CO_2 Density
  - 600 kg/m^3
- Porosity
  - 25%
- Average CO_2 Saturation
  - 10%

600 MW Coal-fired power plant

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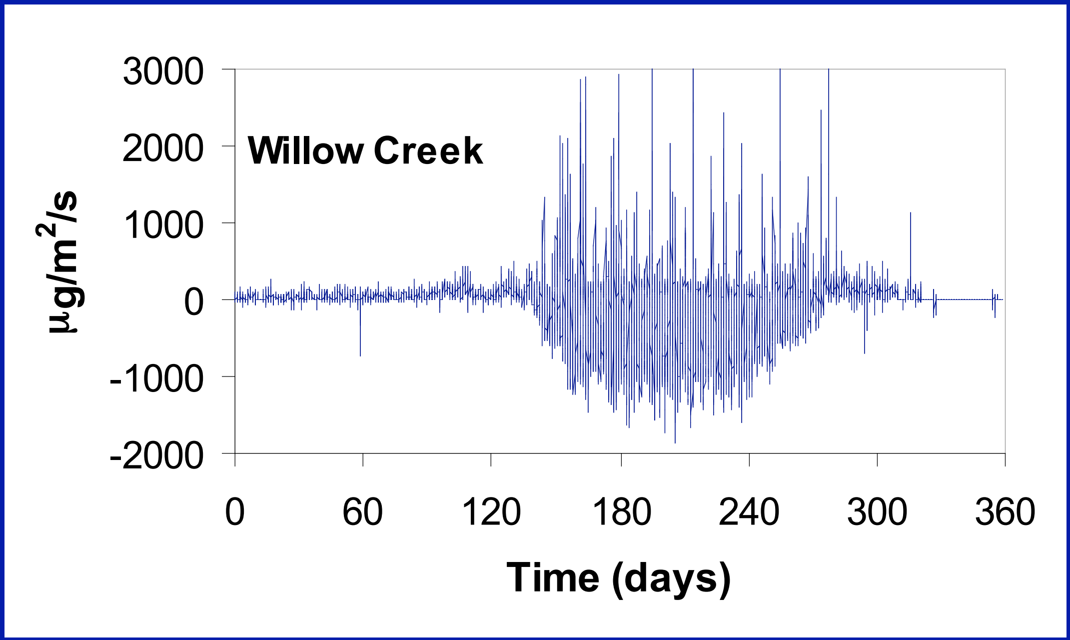
Detection Limit: Specified Mass Flux

- 3 Emission Detection Limits
  - 1,000 t/yr
  - 5,000 t/yr
  - 10,000 t/yr
- Is it simple?
- Is it defensible?
- Is it verifiable?



Courtesy of Ken Davis and Paul Bolstad

Is This Approach Defensible?

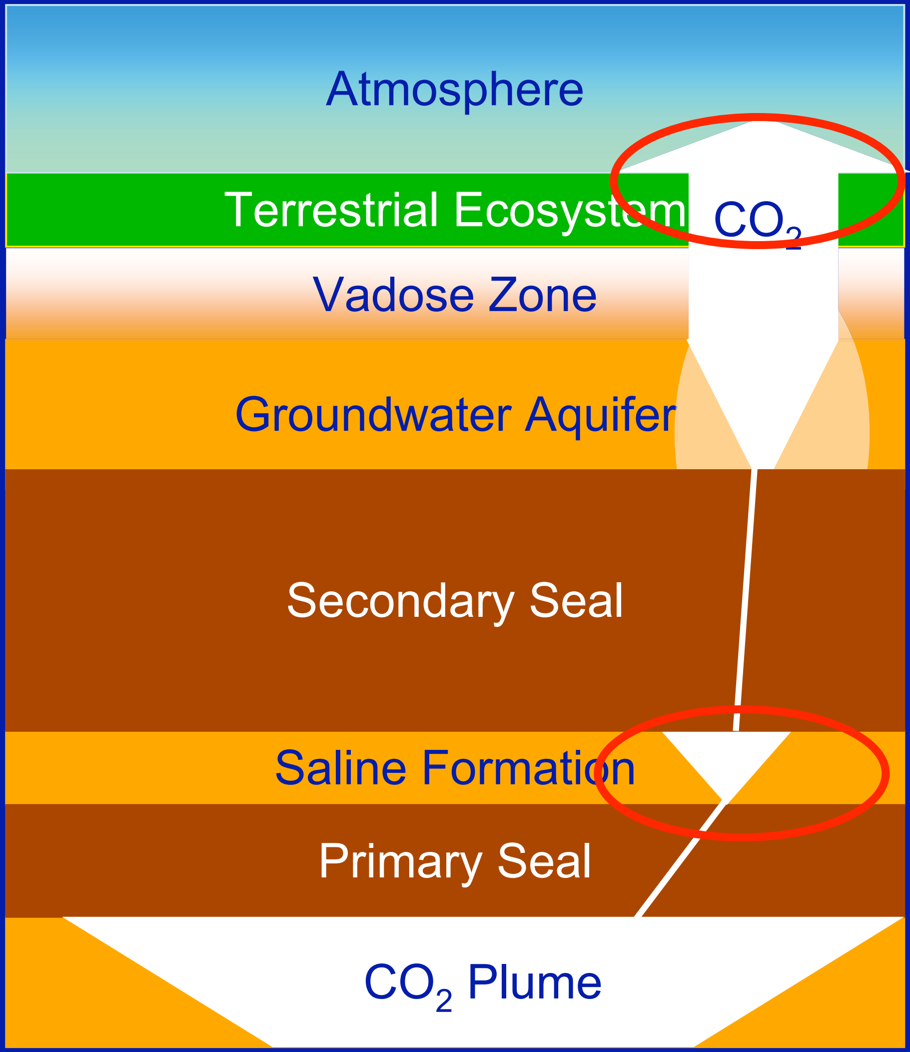
50 years x 5 Mt/year = 250 Mt

Detection Level	Retention Rate Over 1,000 Years
1,000 t/yr	99%
5,000 t/yr	98%
10,000 t/yr	96%

✓

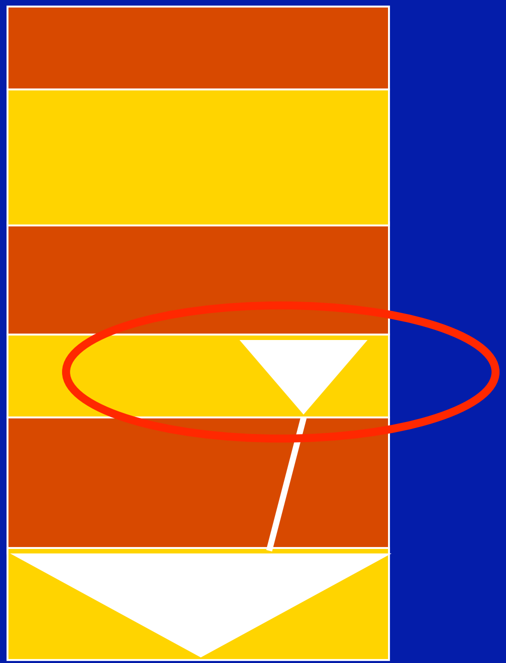
Is the approach verifiable?

- Secondary accumulations
  - Seismic
  - Pressure monitoring
- Atmospheric monitoring



On-shore Storage

Sensitivity of Seismic Methods



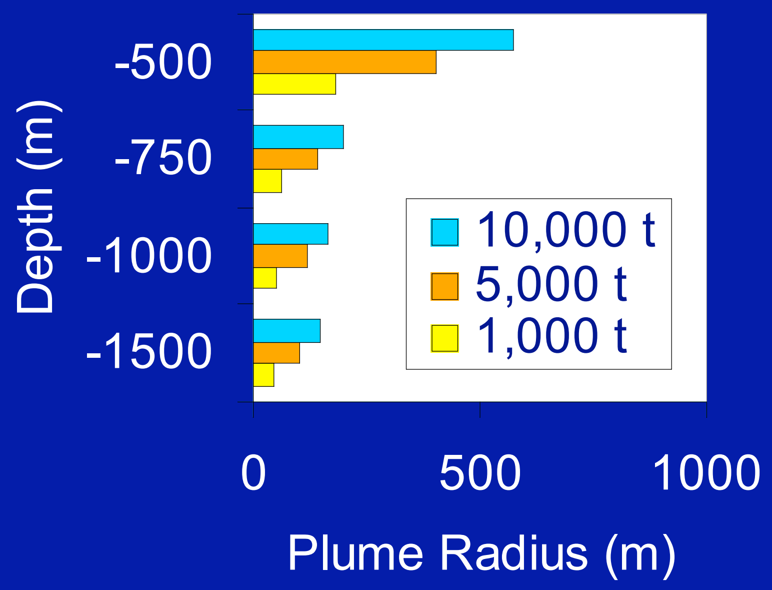
Detection Limits at Reservoir Depth

Myer et al, 2002: 10,000 tonnes

Chadwich et al.: Sleipner, 1,600 tonnes

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

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



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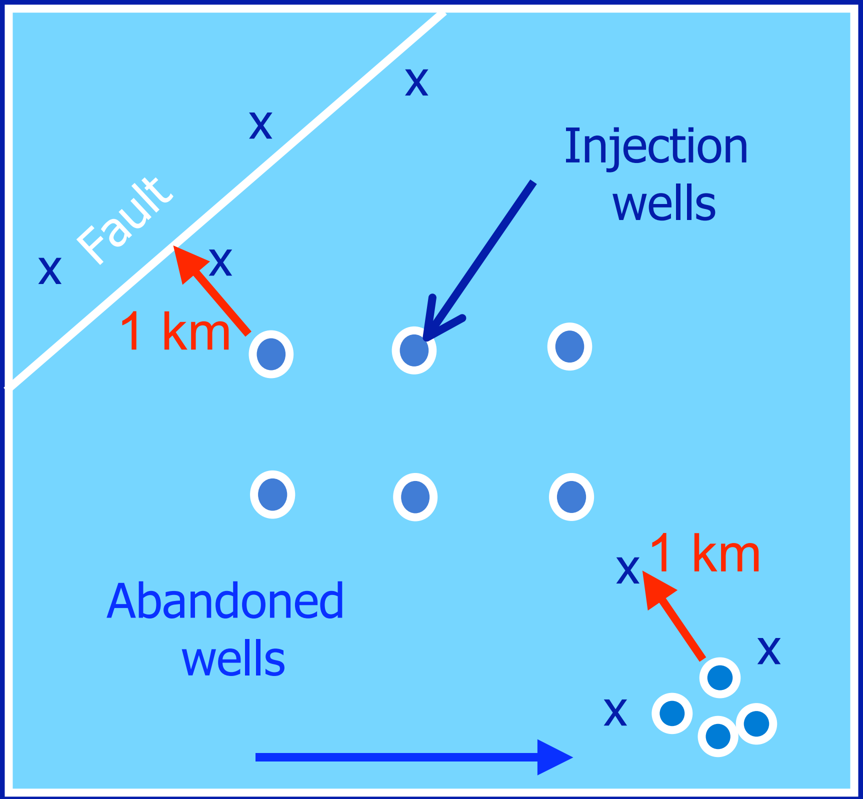
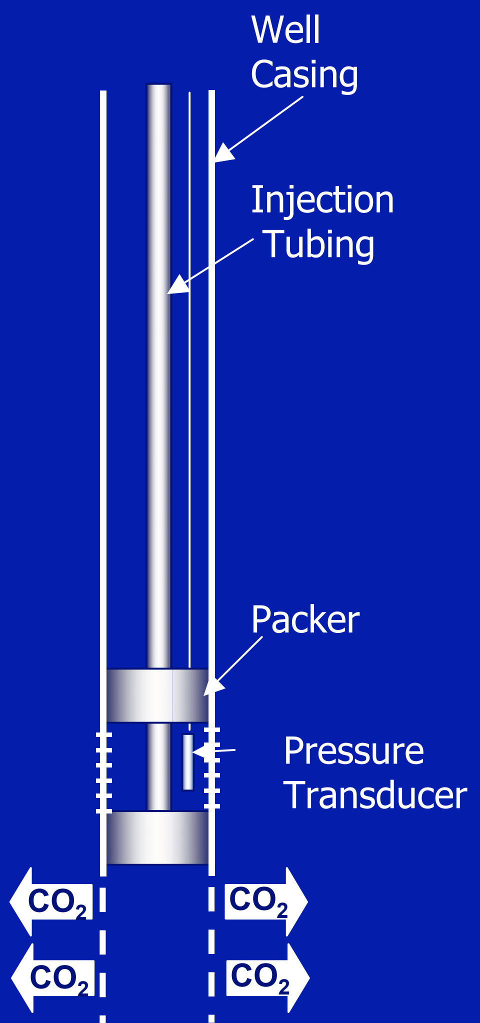
Sensitivity of Pressure Monitoring





Injection/Monitoring Well

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

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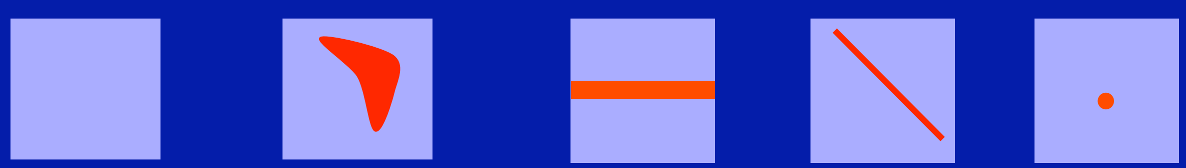
Sensitivity of Atmospheric Monitoring

The average annual baseline flux is -25.2 µg/m^2/s for Willow Creek

	Average Annual CO_2 Fluxes (µg/m^2/s)				
	Footprint of CO_2 Emissions Sources as a Fraction of the Plume Footprint				
Emission Rate (tonnes/year)	**100%**	**25%**	**10%**	**5%**	**1%**
1,000	**-25.0**	**-24.2**	**-22.8**	**-20.3**	**-0.8**
5,000	**-24.0**	**-20.3**	**-13.0**	**-0.80**	**96.8**
10,000	**-22.8**	**-15.4**	**-0.80**	**23.6**	**219**



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Opportunities for Improvement

- Direct emission measurements from existing CO_2-EOR projects
- Controlled release experiments for demonstrating the ability to detect, locate and quantify emissions
- Optical techniques with path lengths of ~1 km
- Approaches to distinguish natural ecosystem fluxes and other anthropogenic emissions from geological storage reservoir emissions
- Improve detection of small secondary accumulations of CO_2

Conclusions

- Geological storage reservoirs will be treated as an emission source
- Monitoring methods are available today
- Detection limits need to be determined
  - Simple, defensible and verifiable
  - Specified mass flux per year appears robust (range of 1,000 to 10,000 tonnes per year)
- Detect, locate, then quantify
- Maintain flexibility
  - Different strategies for different locations
- Opportunities for improvement
  - Experience, verification and innovation