Stanford University

GCEP Global Climate & Energy Project

USGS Western Region Colloquium
Menlo Park, California
October 15, 2007

# Carbon Dioxide Capture and Storage in Deep Geological Formations

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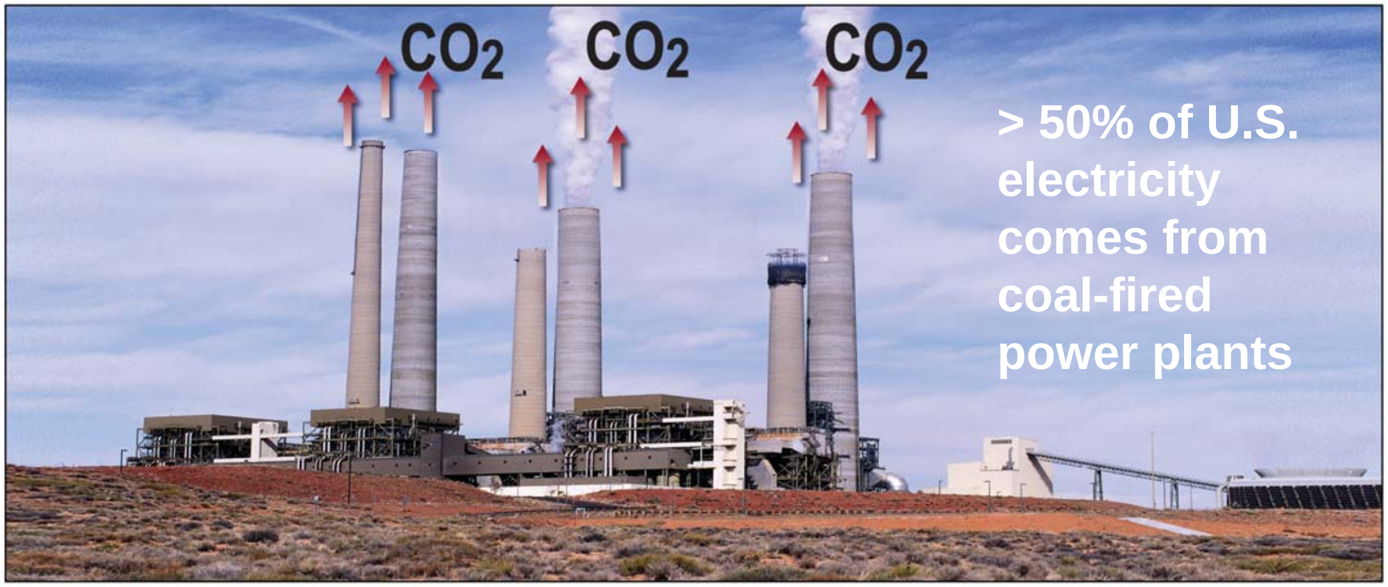
*Science and technology for a low GHG emission world.*

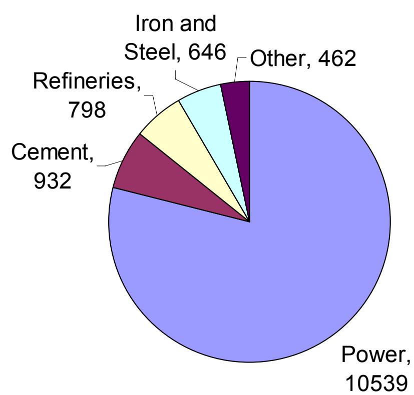
# Topics

- CCS overview
- World-wide potential and status report
- Storage security
- Long term liability
- Conclusions

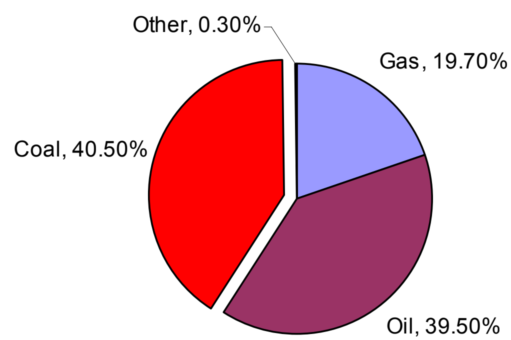
# $CO_2$ Emissions from Fossil Fuels




60% of global fossil fuel emissions come from large stationary sources



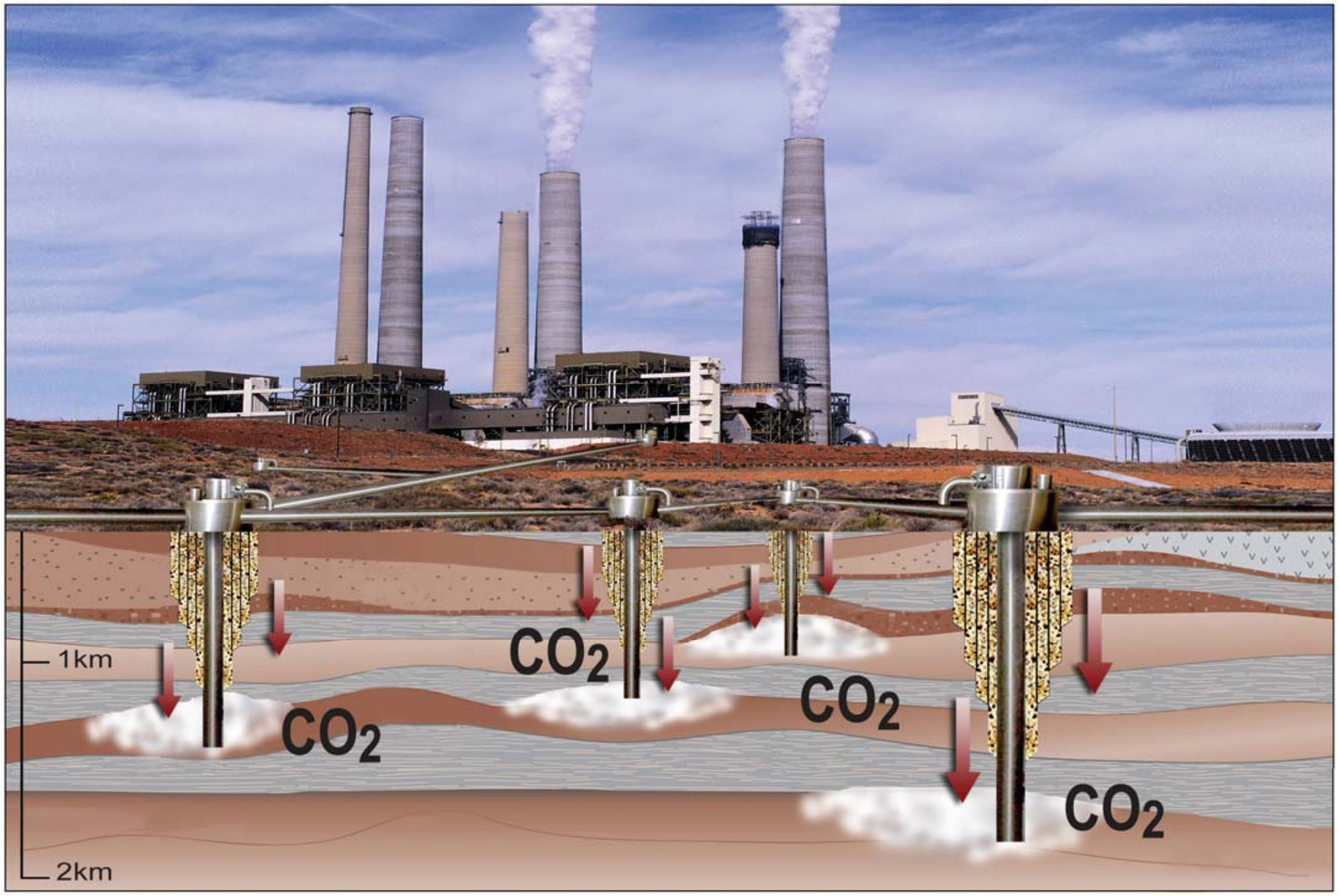

$CO_2$ Emissions (Mt/year)




Global Emissions
27,136 Mt (2005)

40.5% of global emissions come from coal… this is not expected to change any time soon.

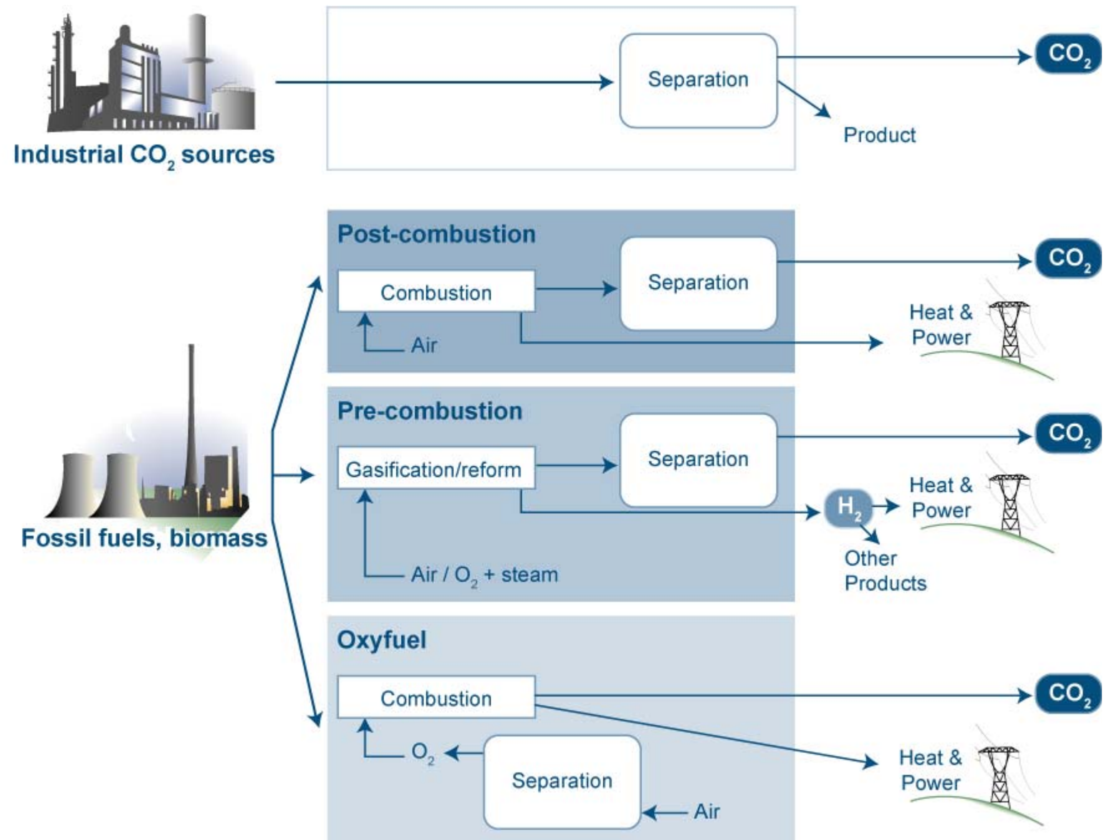
# Carbon Dioxide Capture and Geologic Storage




**Capture** → **Compression** → **Pipeline Transport** → **Underground Injection**

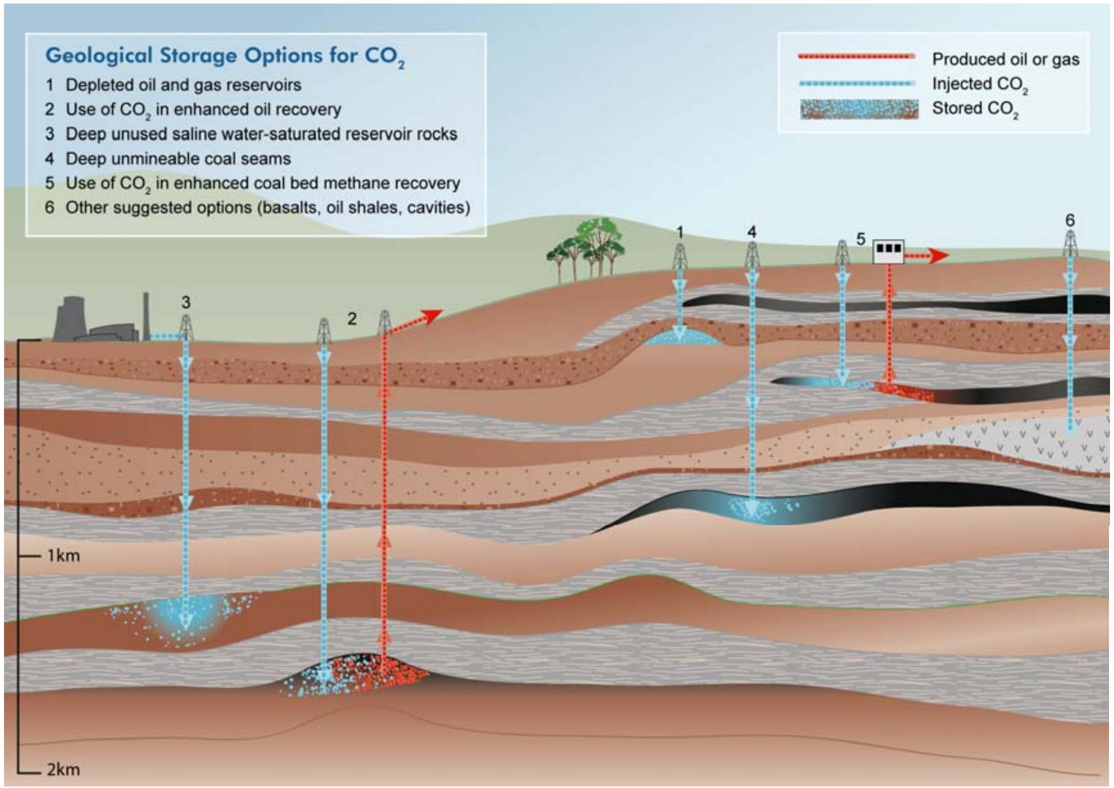
# Options for $CO_2$ Capture

- Post-combustion
  - Established technology
- Pre-combustion
  - Established technology for other applications
  - Not demonstrated for power production
- Oxygen combustion
  - Not demonstrated for power production



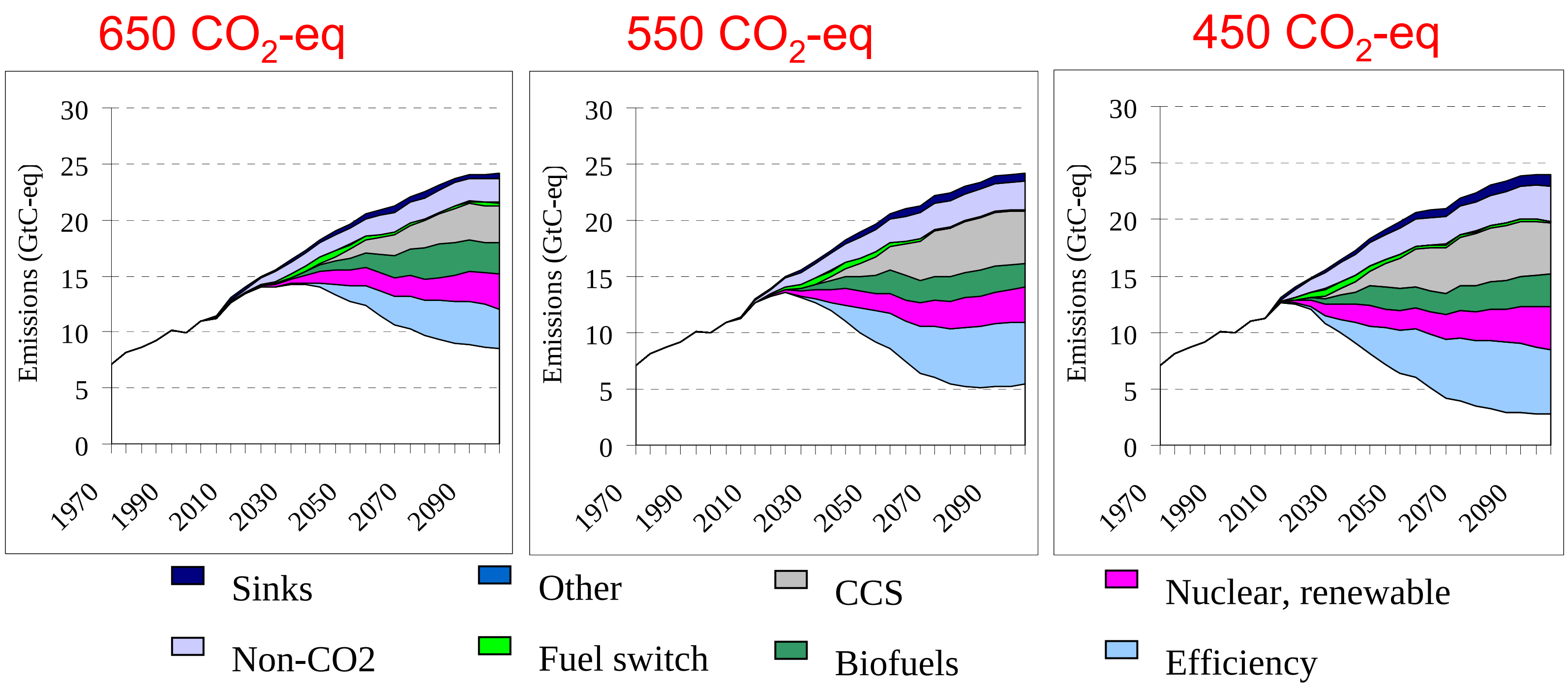
# Options for Geological Storage

- Oil and gas fields
  - Depleted fields
  - EOR, EGR
- Saline formations
- Unminable coal-seams
- Other?
  - Basalt
  - Deep ocean sediments
  - ?




From IPCC Special Report, 2005

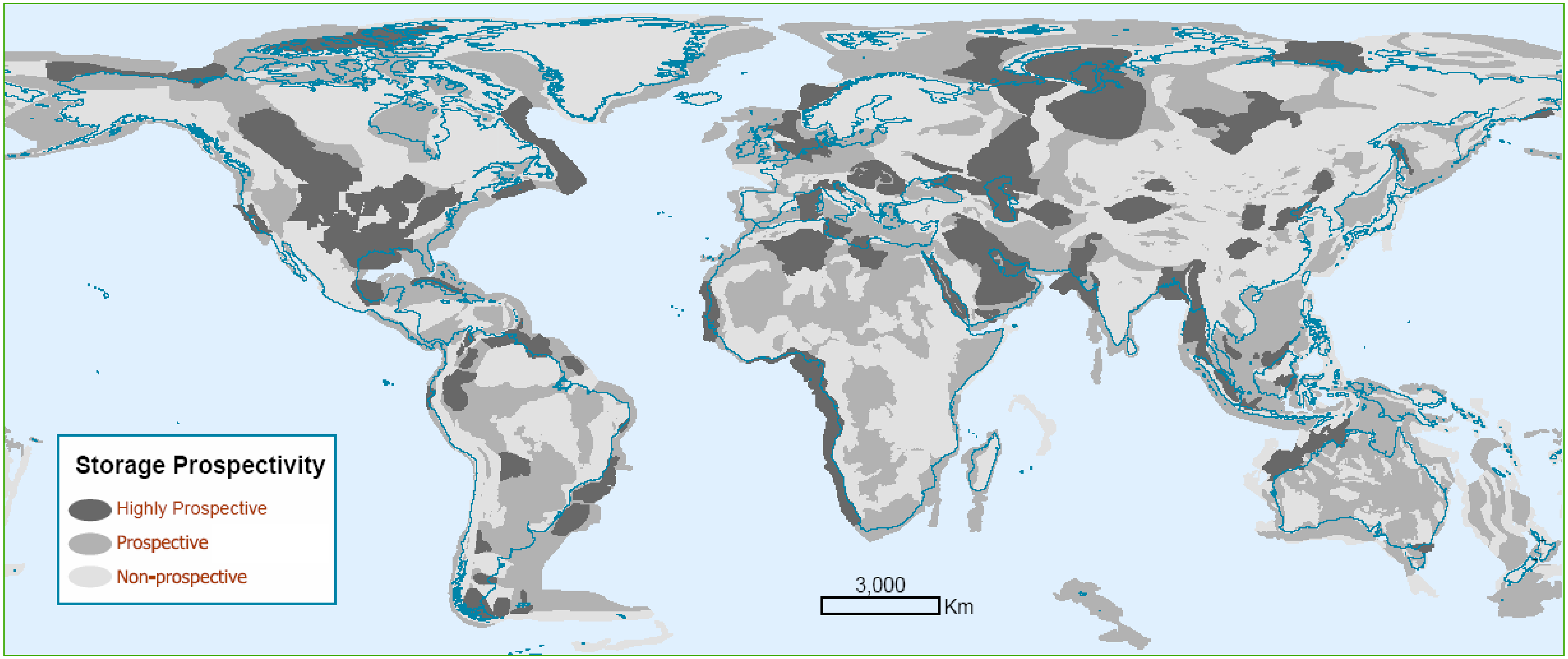
# CCS Could Make a Large Contribution to Reducing $CO_2$ Emissions




*Expected contributions to GHG emissions with carbon prices in the range of \$20 to \$100/t$CO_2$-eq.*

From IPCC, 2007:WG III

# Prospectivity for Storage around the World




**From Bradshaw and Dance 2005**

*"It is likely that the technical potential for geological storage is sufficient to cover the high end of the economic potential range (2200 Gt$CO_2$), but for specific regions, this may not be true."*

# Topics

- CCS Overview
- World-wide status report
- Storage security
- Long term liability
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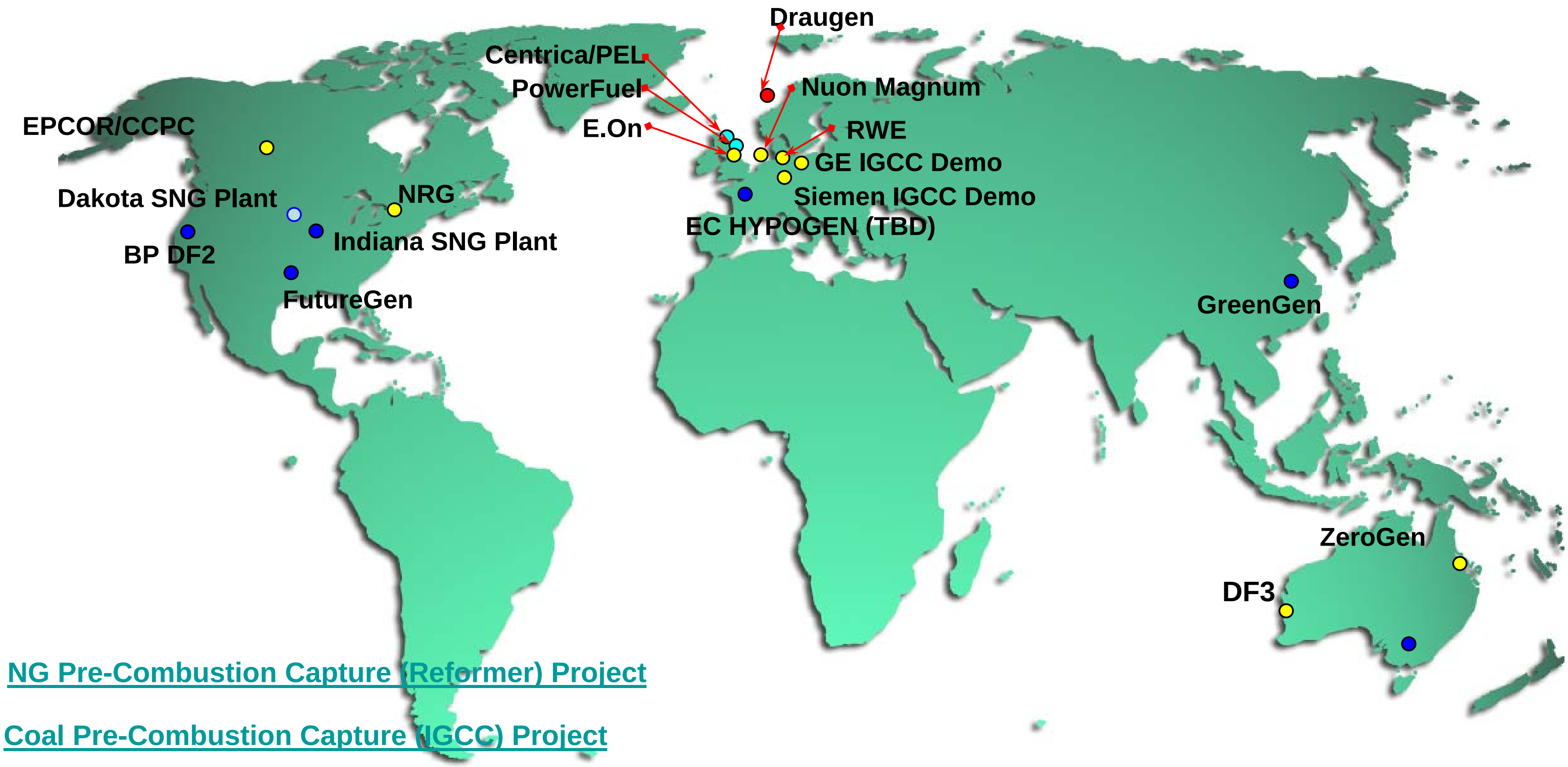
# World-Wide Status Report

- Three industrial-scale projects continuing successfully
  - Sleipner, Off-shore Norway
  - Weyburn, Canada
  - In Salah, Algeria
  - 21 years of collective operating experience
- Snohvit CCS project expected to begin soon
- Many announced planning studies for industrial-scale projects
- High capital costs have been a deterrent to wider application


Snohvit: Next Commercial CCS Operation Expected On-line—Fall 2007

> . . . combating global warming after pledging to undertake the first large scale carbon dioxide geosequestration project in Australia... **will be larger than any other geosequestration scheme** currently contemplated or in production... **The energy giant cleared the final stage of the approvals process for the mammoth liquefied natural gas (LNG) Gorgon project**. The Age, September 7, 2007

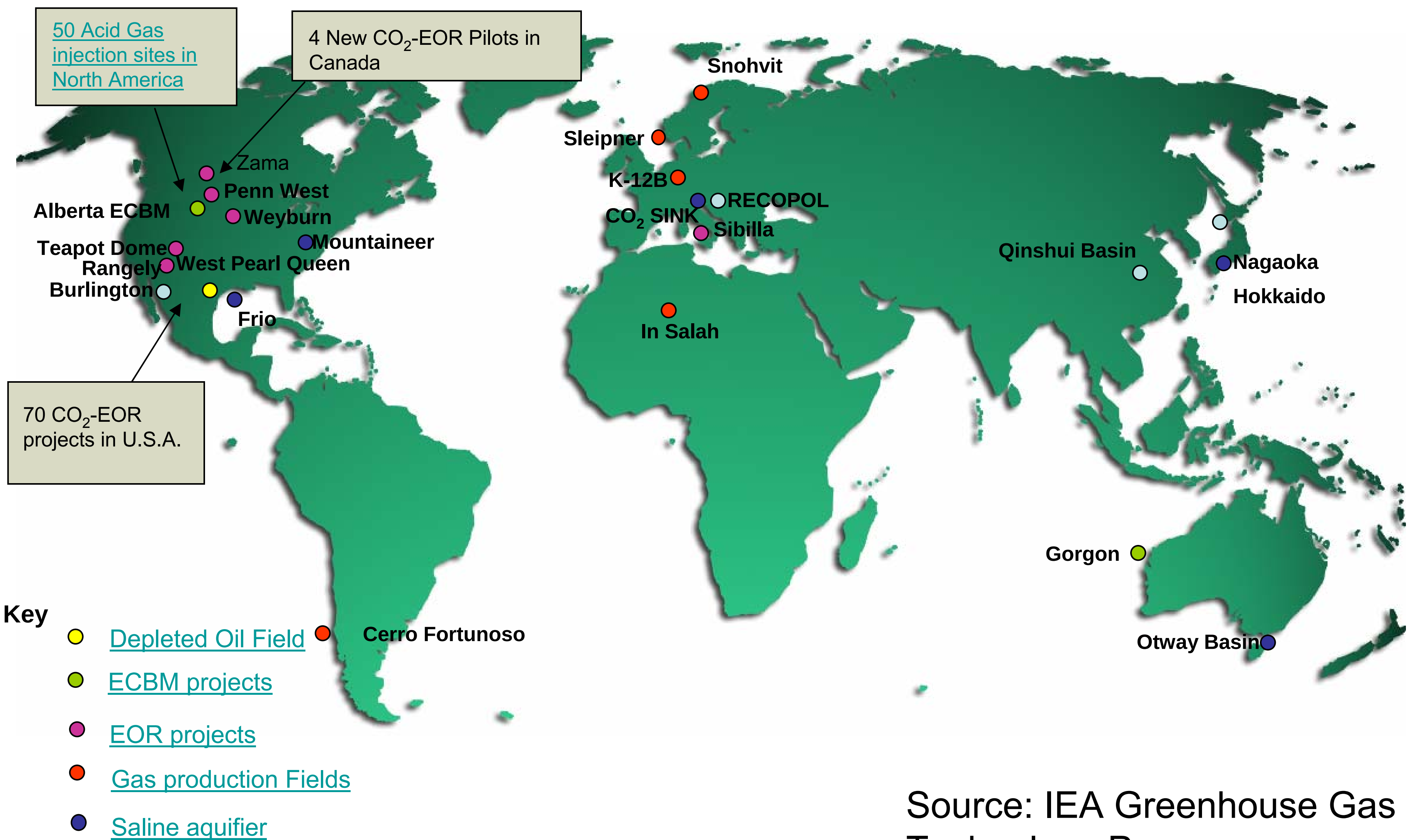
# $CO_2$ Pre-Combustion Capture Projects




- NG Pre-Combustion Capture (Reformer) Project
- Coal Pre-Combustion Capture (IGCC) Project
- Coal Pre-Combustion Capture (IGCC) Project with Poly-Gen option
- Poly-generation Pre-Combustion Capture Project
- Poly-generation Pre-Combustion Capture Project (In Operation)

Source: IEA Greenhouse Gas Technology Programme

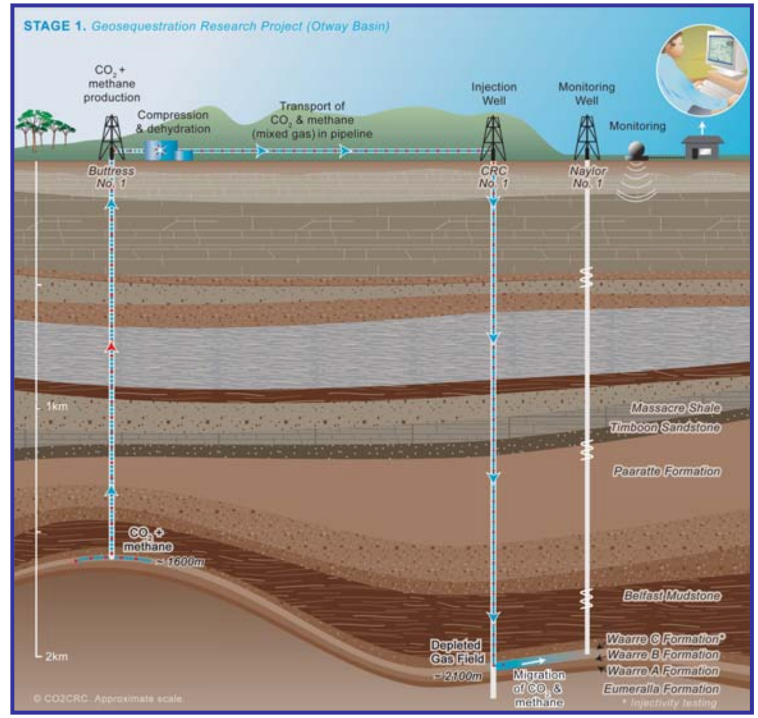
# $CO_2$ Injection and Storage Activities



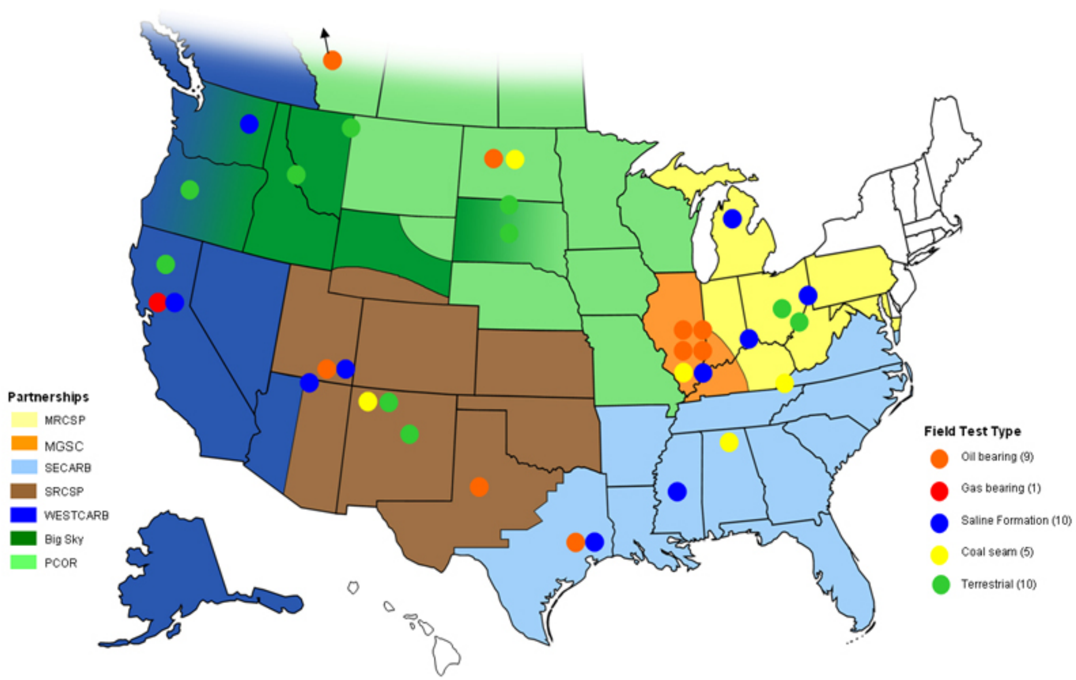

Source: IEA Greenhouse Gas Technology Programme

# World-Wide Status Report

- Increasing government investment in CCS R&D
  - e.g. FutureGen and Regional Sequestration Partnerships
- Cost, regulatory framework and institutional issues at the forefront
- Growing press coverage and public awareness




Otway Basin Pilot Project: Australia
Start: Fall 2007




U.S. DOE Regional Sequestration Partnership Program: Pilot Tests

# Topics

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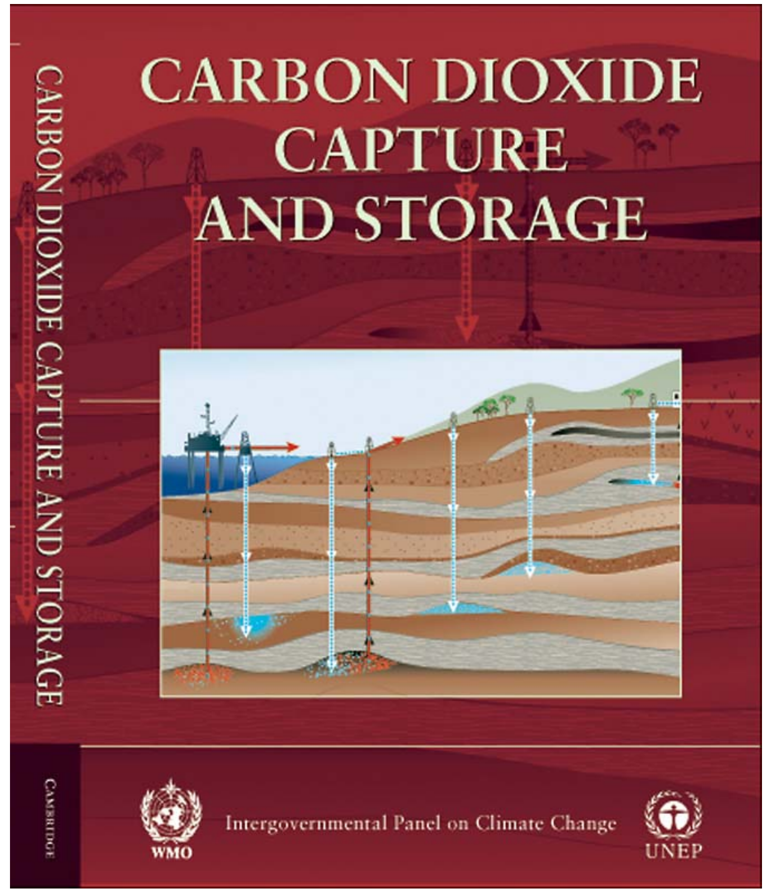
# Expert Opinion about Storage Safety and Security

*“ Observations from engineered and natural analogues as well as models suggest that the fraction retained in appropriately selected and managed geological reservoirs is very likely* to exceed 99% over 100 years and is likely** to exceed 99% over 1,000 years.”*

*“ With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control $CO_2$ releases if they arise, the local health, safety and environment risks of geological storage would be comparable to risks of current activities such as natural gas storage, EOR, and deep underground disposal of acid gas.”*

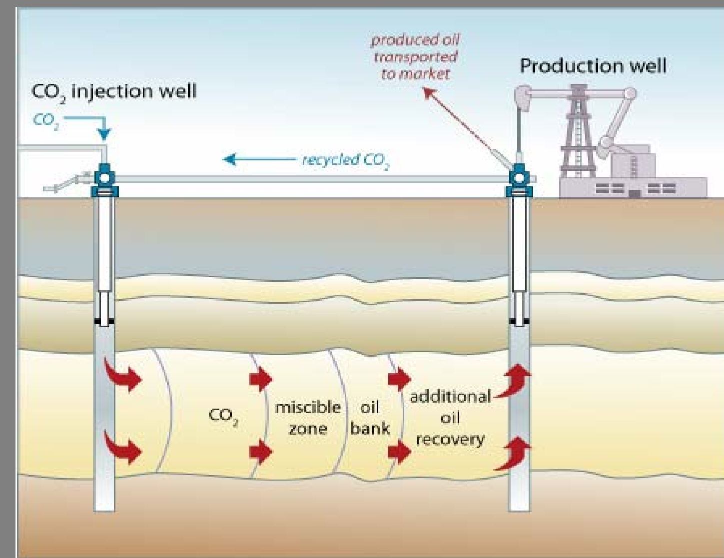



* "Very likely" is a probability between 90 and 99%.

** Likely is a probability between 66 and 90%.

# Evidence to Support these Conclusions

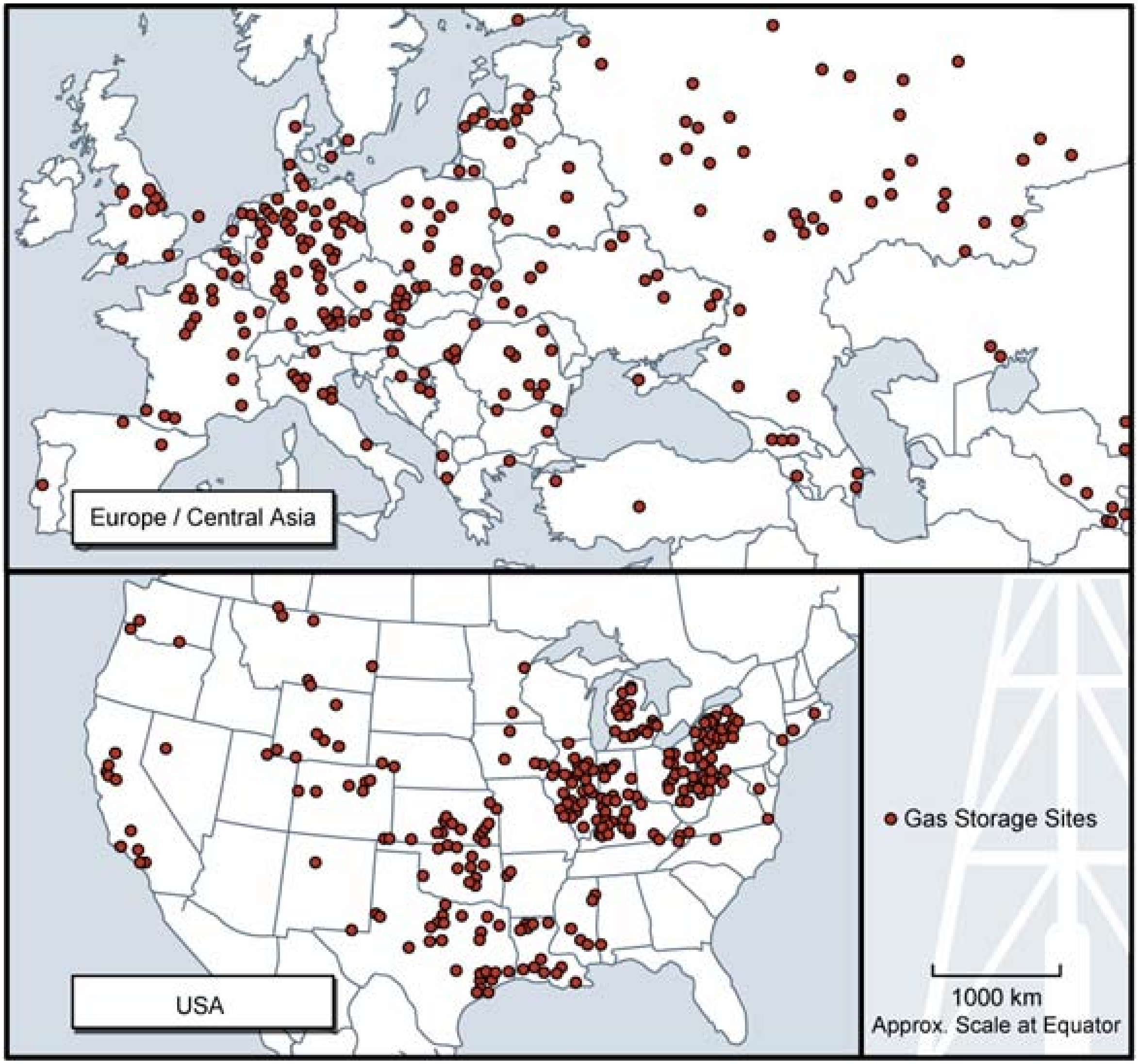
- Natural analogs
  - Oil and gas reservoirs
  - $CO_2$ reservoirs
- Performance of industrial analogs
  - 30+ years experience with $CO_2$ EOR
  - 100 years experience with natural gas storage
  - Acid gas disposal
- 20+ years of cumulative performance of actual $CO_2$ storage projects
  - Sleipner, off-shore Norway, 1996
  - Weyburn, Canada, 2000
  - In Salah, Algeria, 2004





~35 Mt/yr are injected for $CO_2$-EOR

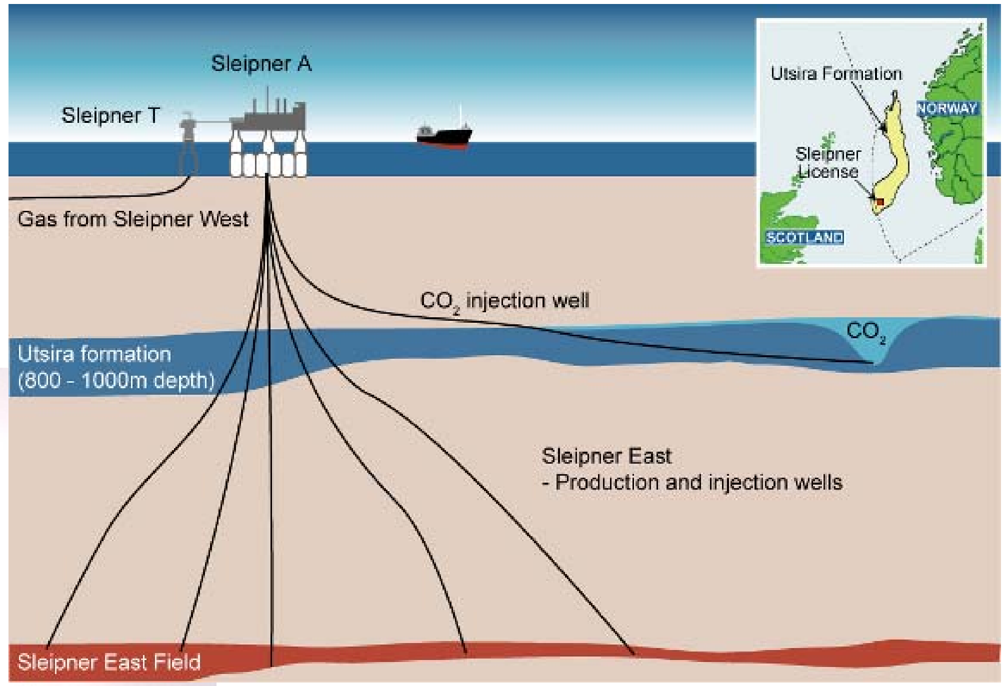
# Natural Gas Storage




- Seasonal storage to meet winter loads
- Storage formations
  - Depleted oil and gas reservoirs
  - Aquifers
  - Caverns

# Sleipner Project, North Sea

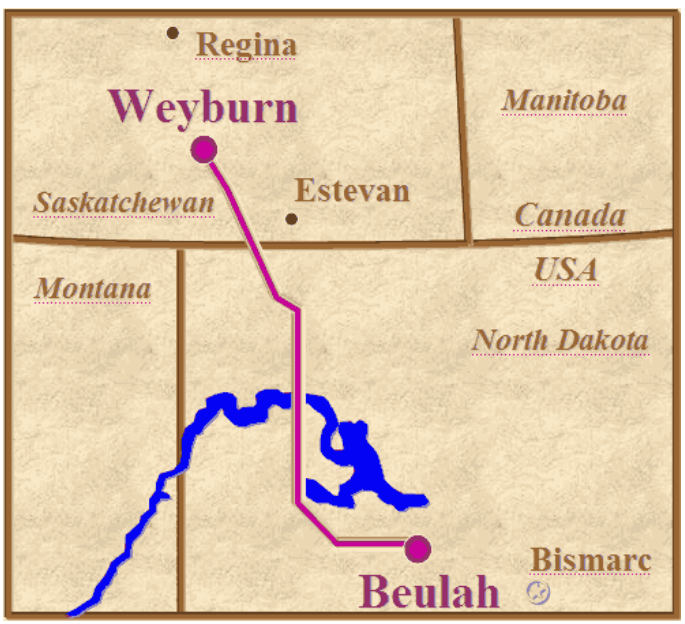
- 1996 to present
- 1 Mt $CO_2$ injection/yr
- Seismic monitoring




Picture compliments of *Statoil*

# Weyburn $CO_2$-EOR and Storage Project

- 2000 to present
- 1-2 Mt/year $CO_2$ injection
- $CO_2$ from the Dakota Gasification Plant in the U.S.



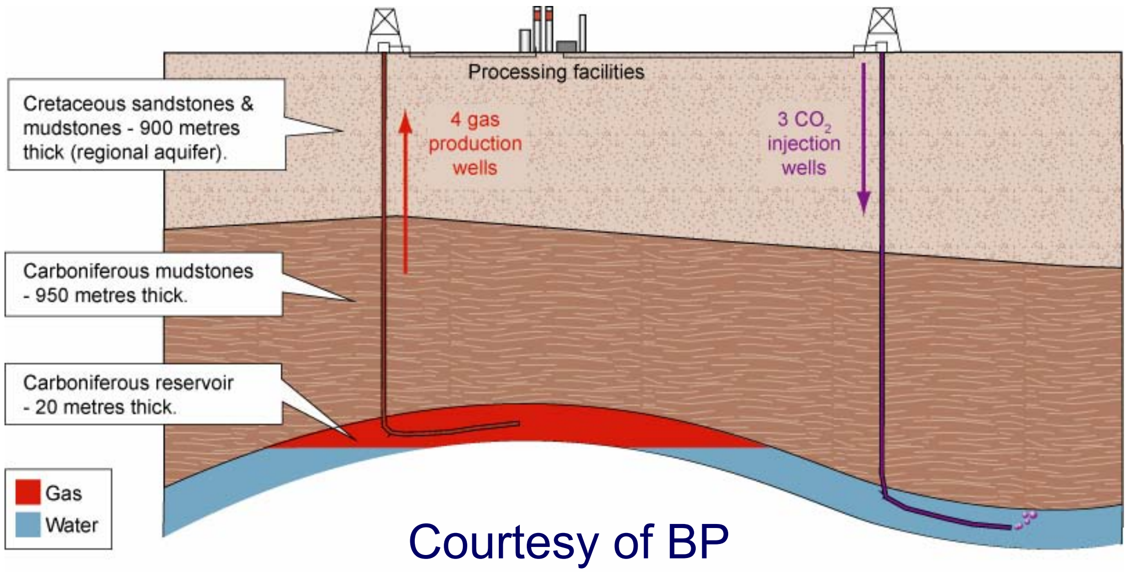

# In Salah Gas Project


In Salah Gas Project
- Krechba, Algeria

Gas Purification
- Amine Extraction

1 Mt/year $CO_2$ Injection

Operations Commence
- June, 2004

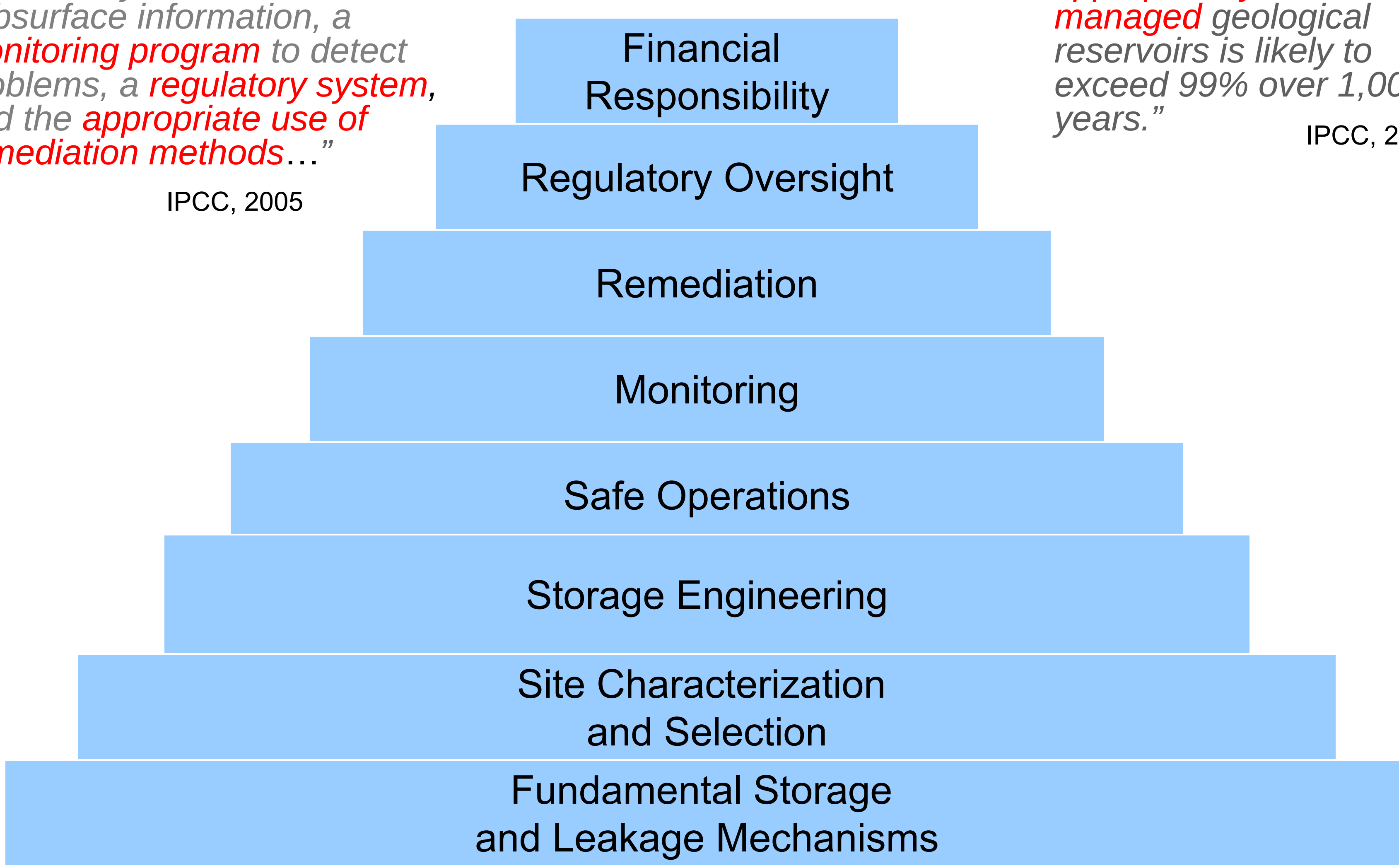



Courtesy of BP

# Geological Storage Safety and Security Pyramid

*" With **appropriate site selection** informed by available subsurface information, a **monitoring program** to detect problems, a **regulatory system**, and the **appropriate use of remediation methods**…"*

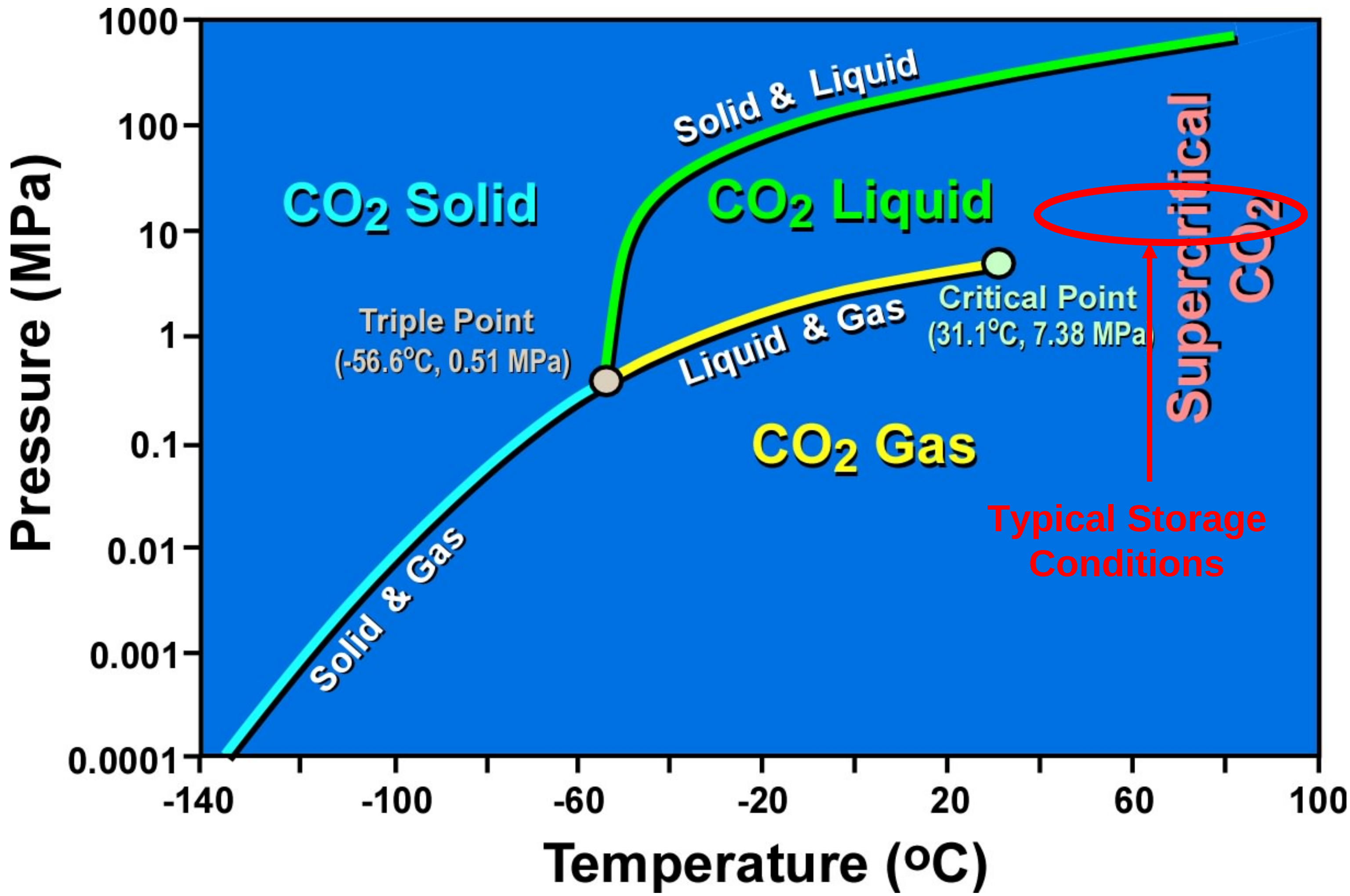
IPCC, 2005



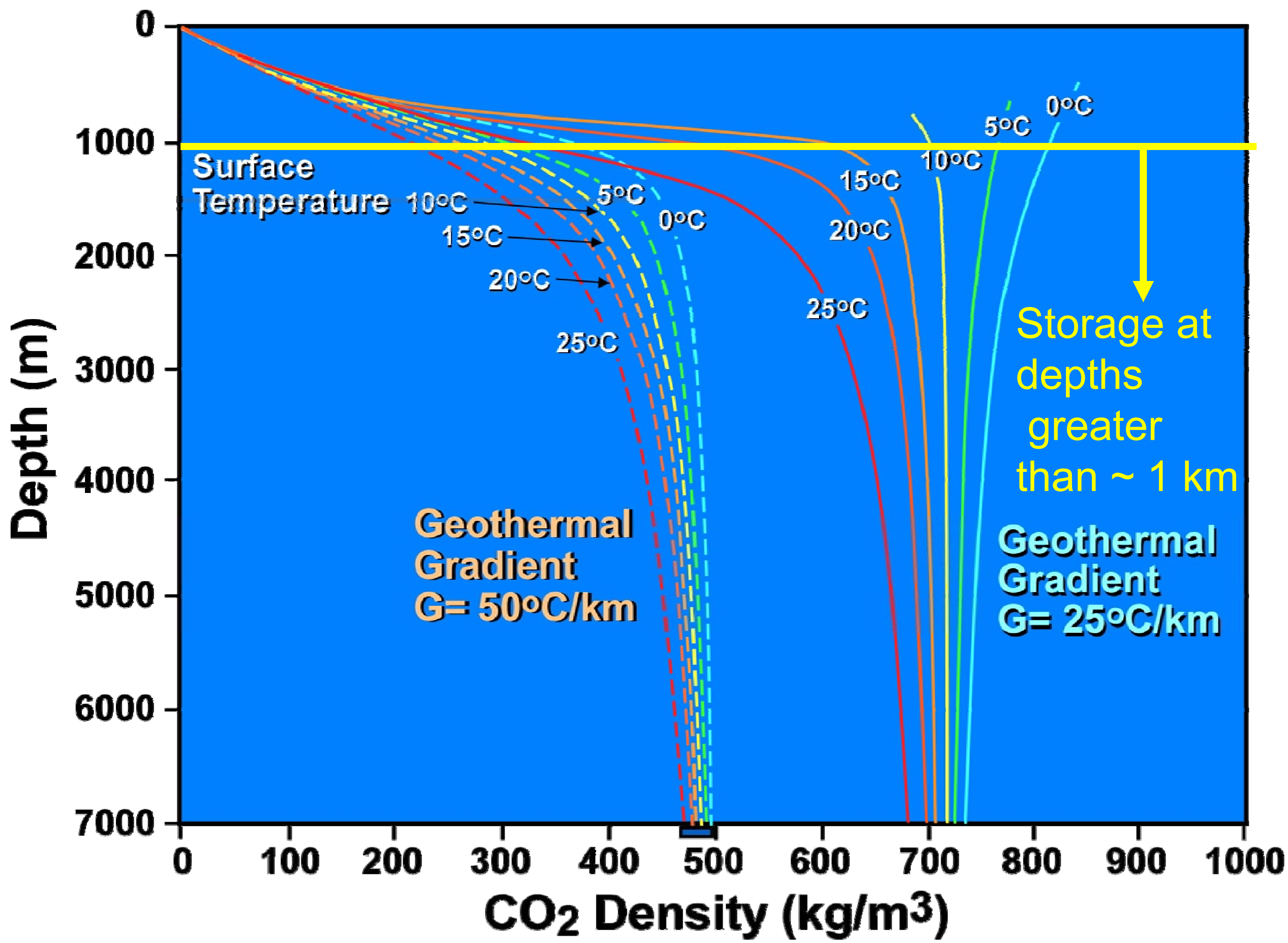

*"… the fraction retained in **appropriately selected and managed** geological reservoirs is likely to exceed 99% over 1,000 years."*

IPCC, 2005

# Phase Diagram for Carbon Dioxide



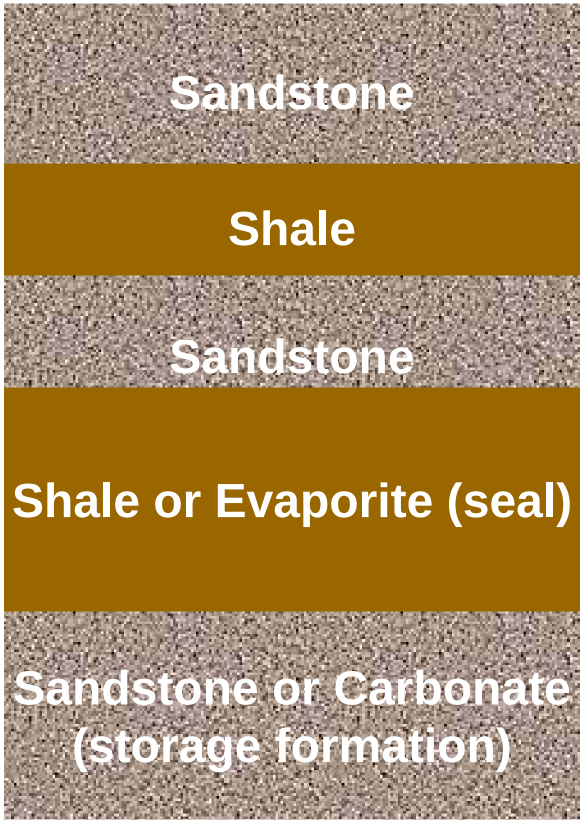
# Variation with Depth and Geothermal Regime of Carbon Dioxide Density




(Bachu, 2003)

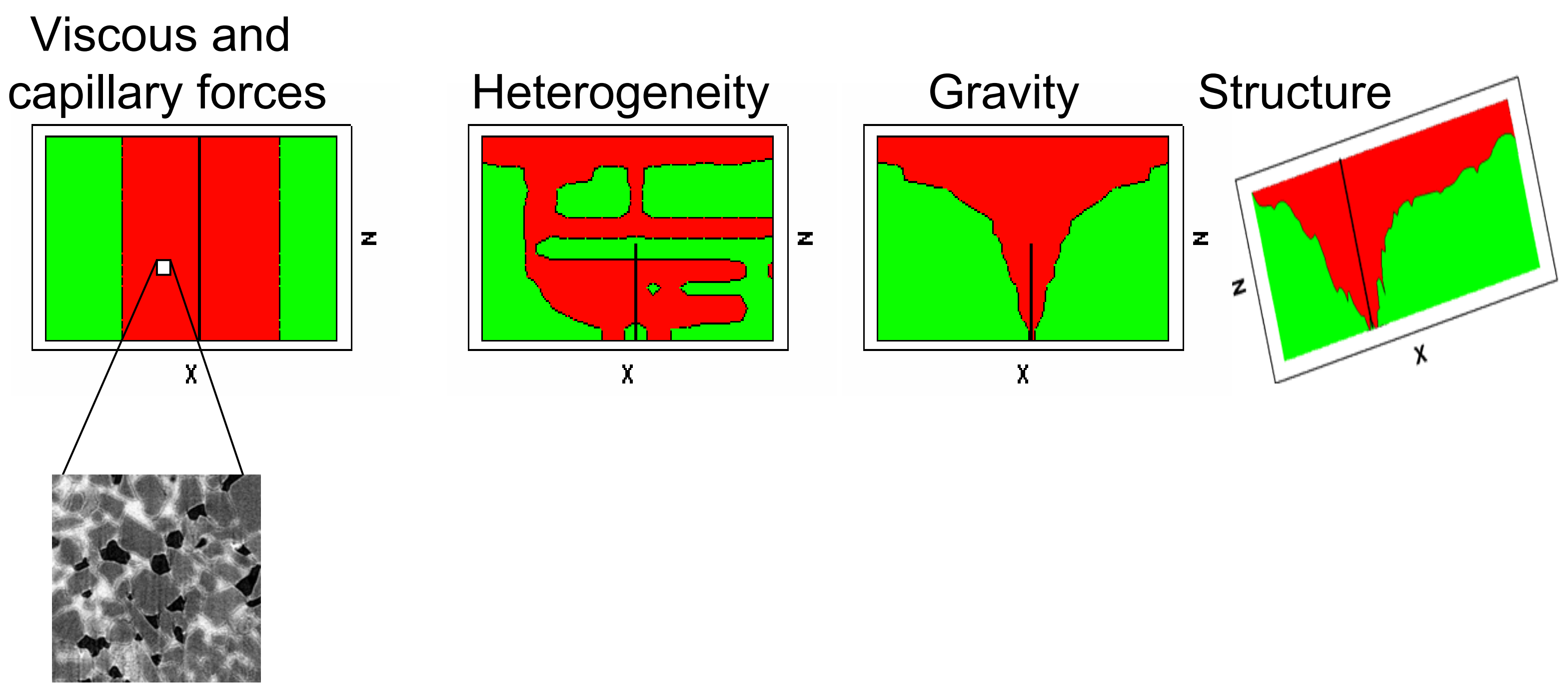
# Storage Mechanisms

- Injected at depths of 1 km or deeper into rocks with tiny pore spaces
- Primary trapping
  - Beneath seals of low permeability rocks
- Secondary trapping
  - $CO_2$ dissolves in water
  - $CO_2$ is trapped by capillary forces
  - $CO_2$ converts to solid minerals
  - $CO_2$ adsorbs to coal




Fundamental Storage
and Leakage Mechanisms

# $CO_2$ Migration Processes and Trapping



# X-ray Micro-tomography at the Advanced Light Source

Micro-tomography Beamline

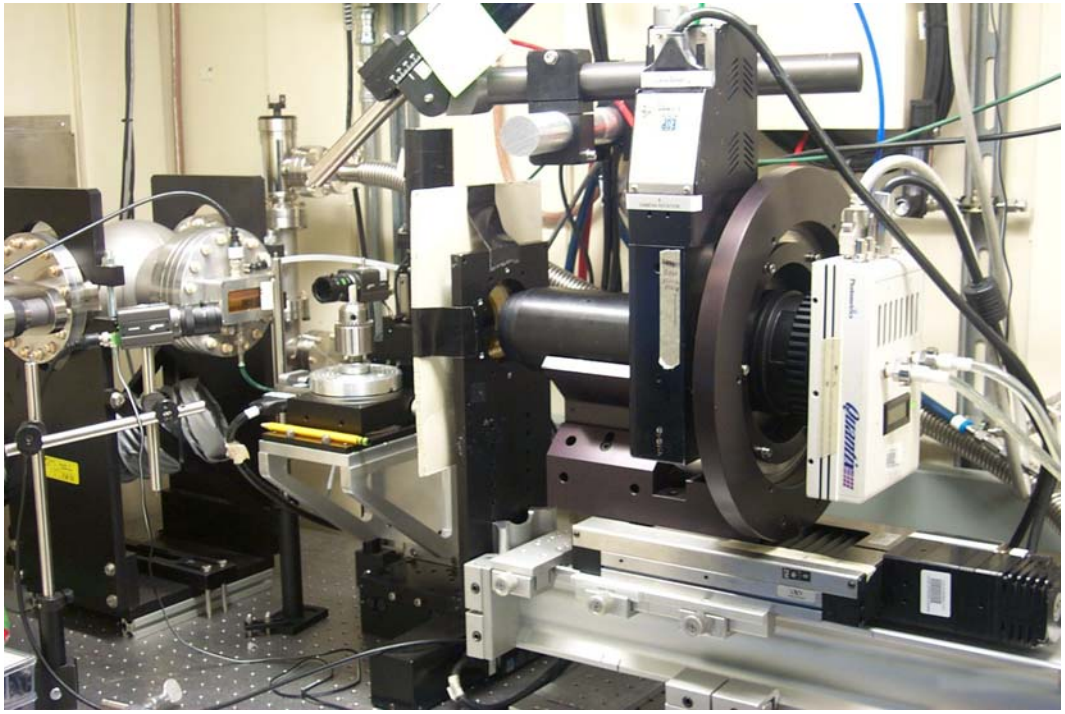
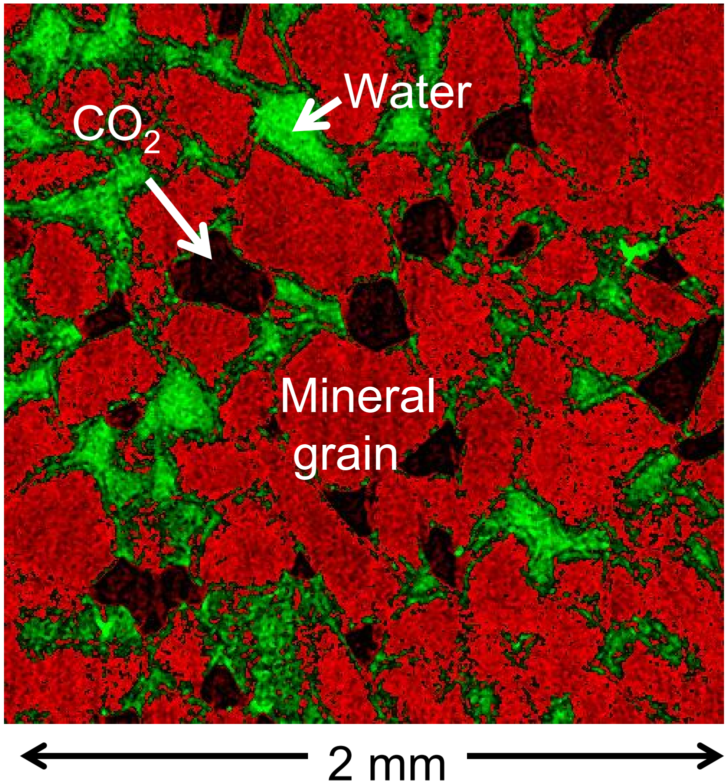
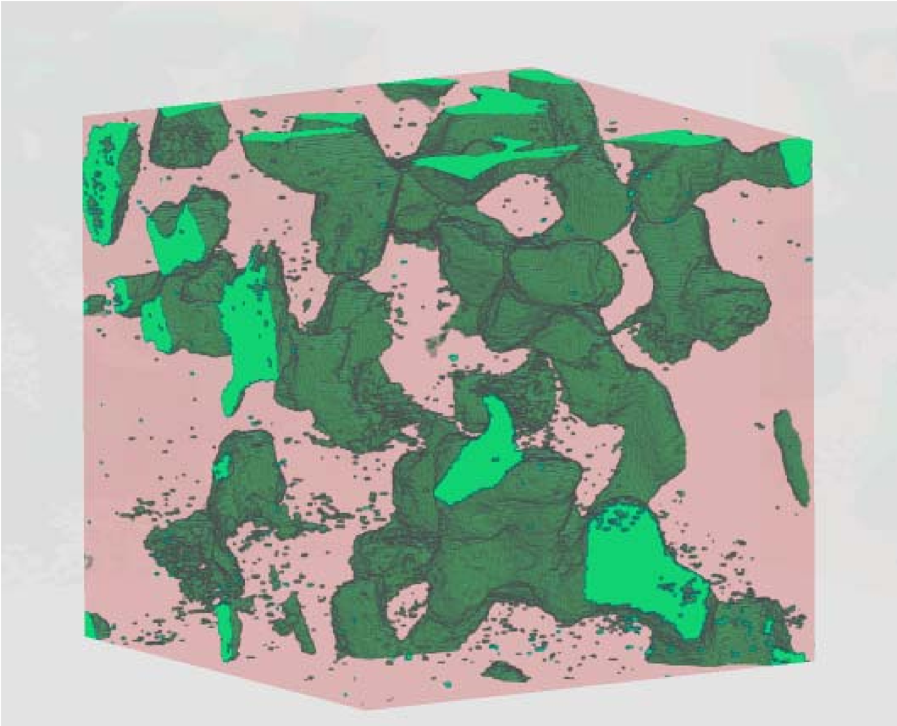


Image of Rock with $CO_2$



# Comparison to Theoretical Distribution



Measured by L. Tomutsa, LBNL

Measured Distribution

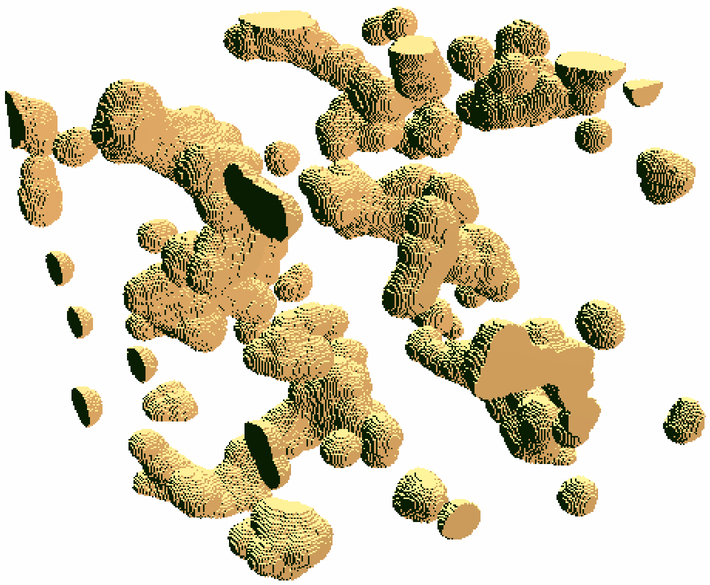


Image calculated by D. Silin, LBNL

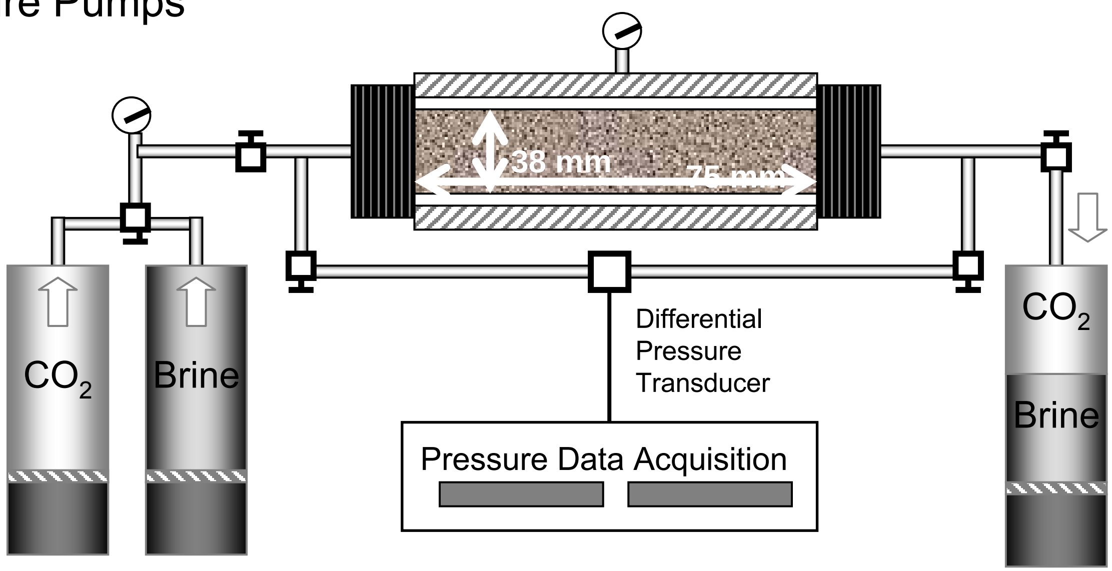
Calculated Distribution at 40% Saturation

From Benson et al., 2006

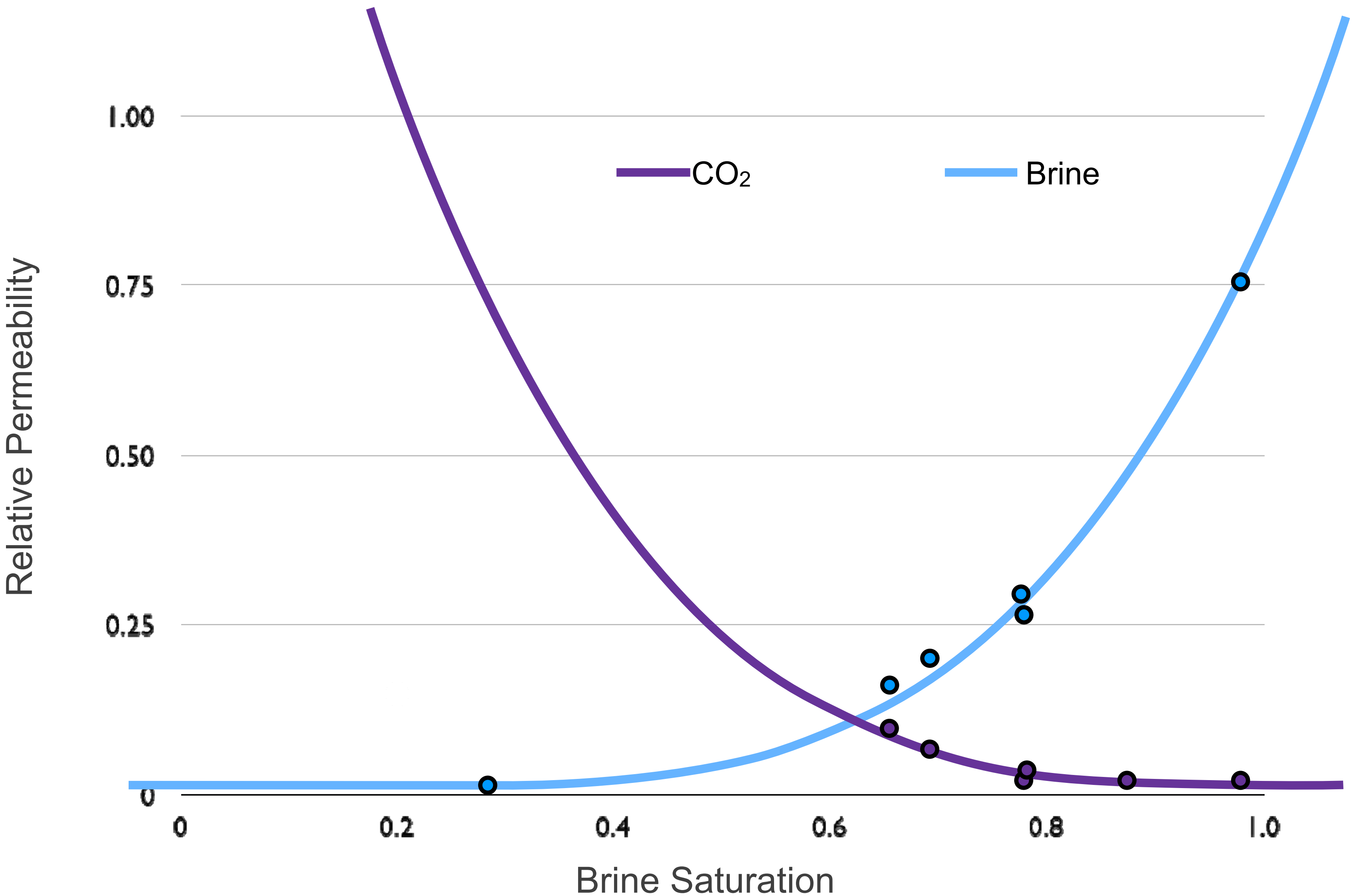
# Multi-phase Flow and Capillary Trapping

High Pressure Pumps

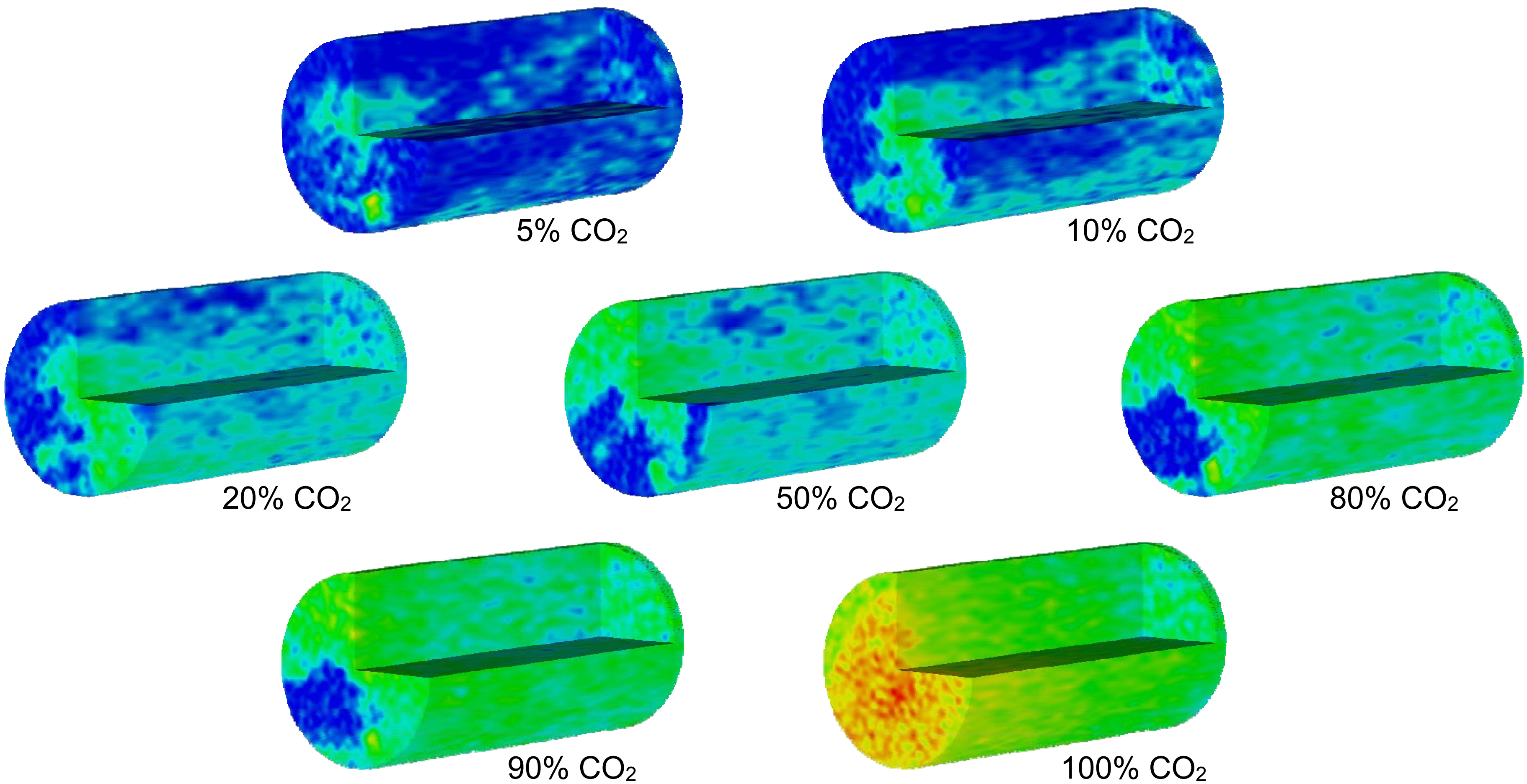
Core Holder In Scanner



# Relative Permeability Curves

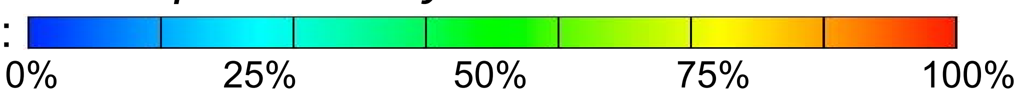


# Small-scale $CO_2$ Saturation Variations



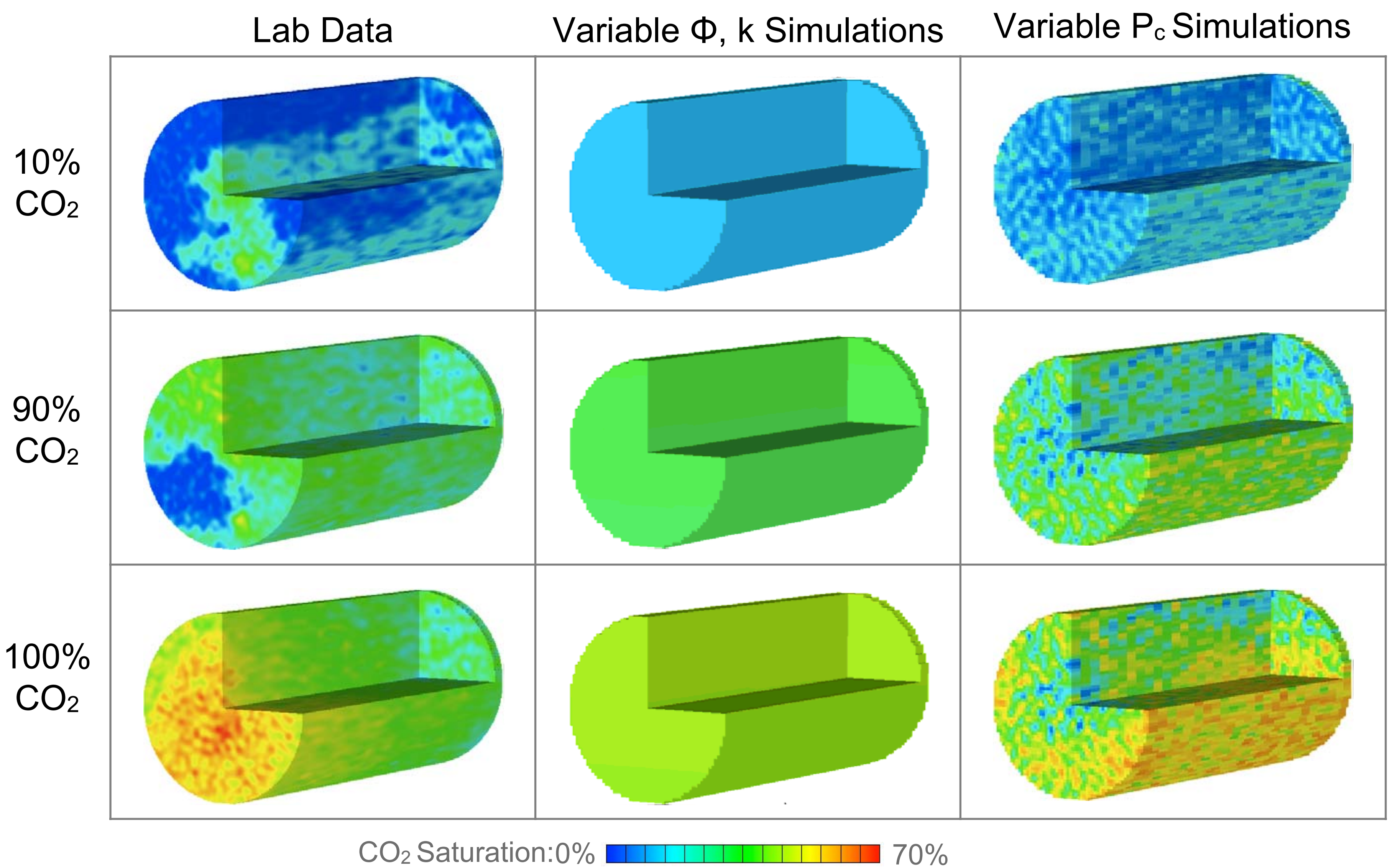

*Sub-corescale saturation variations generally overlooked in relative permeability measurements.*

$CO_2$ Saturation:

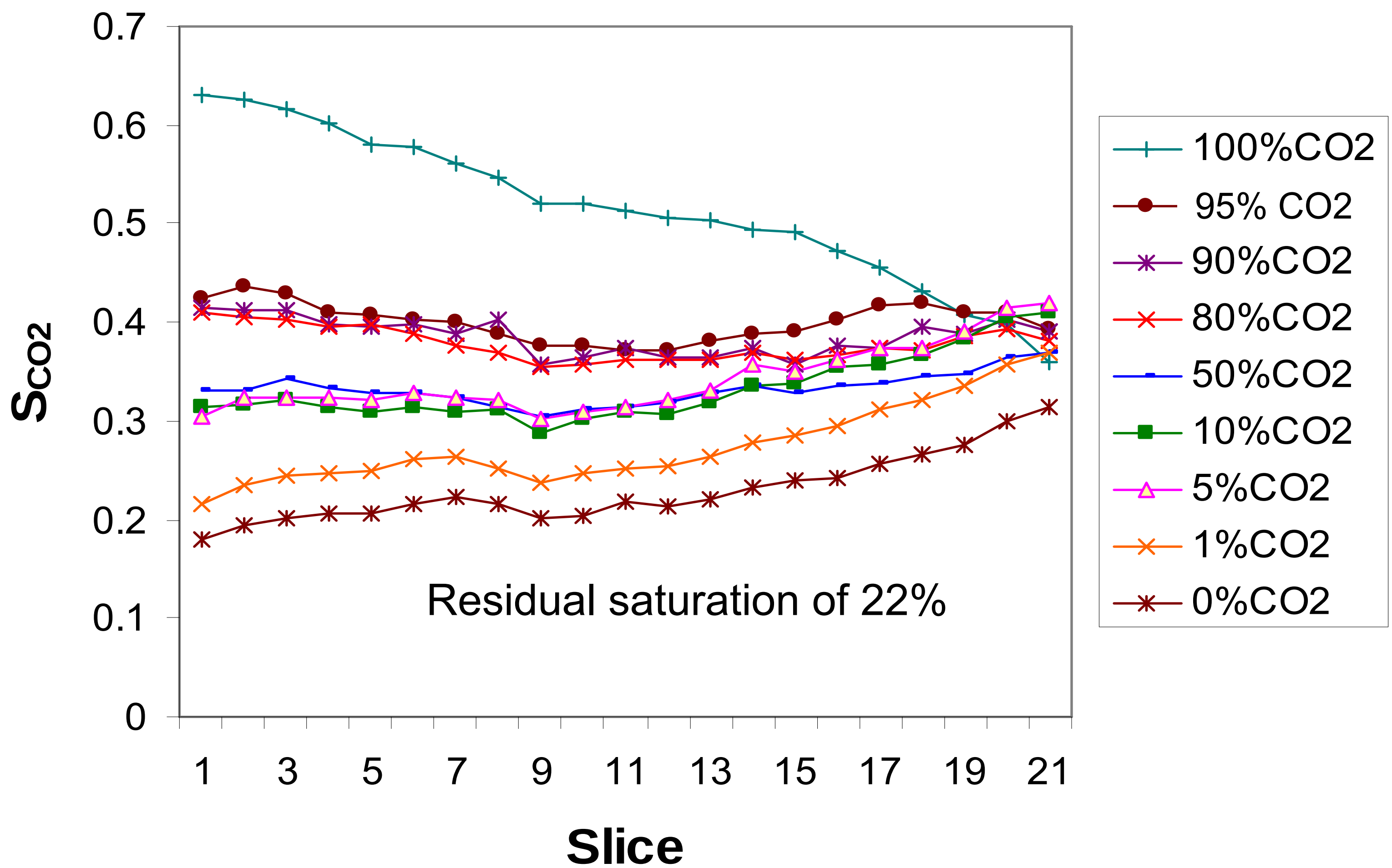


# Simulated $CO_2$ Saturations

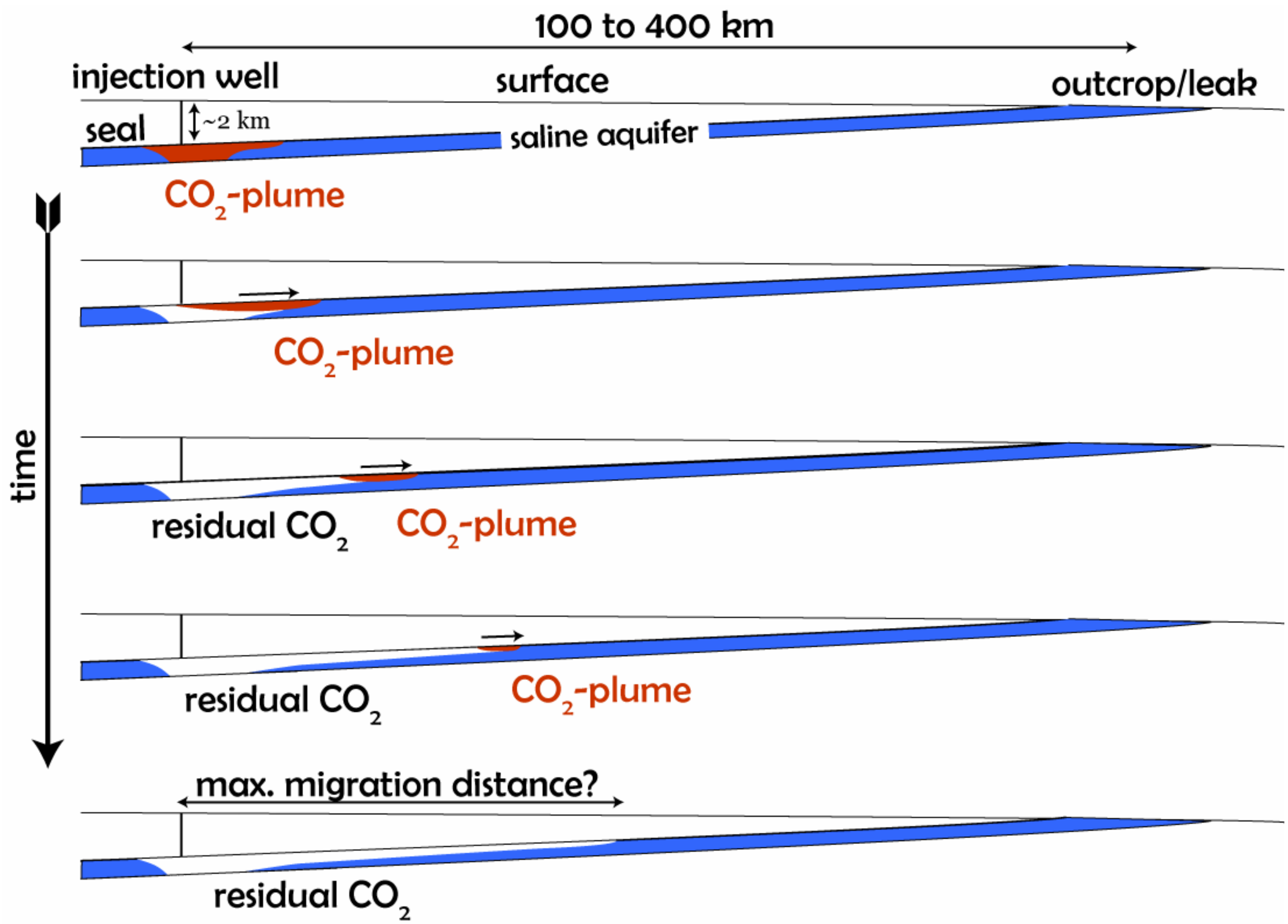
## Variable $P_c$ Produces Small-scale $CO_2$ Saturation Variations



# Capillary Trapping During Water Injection



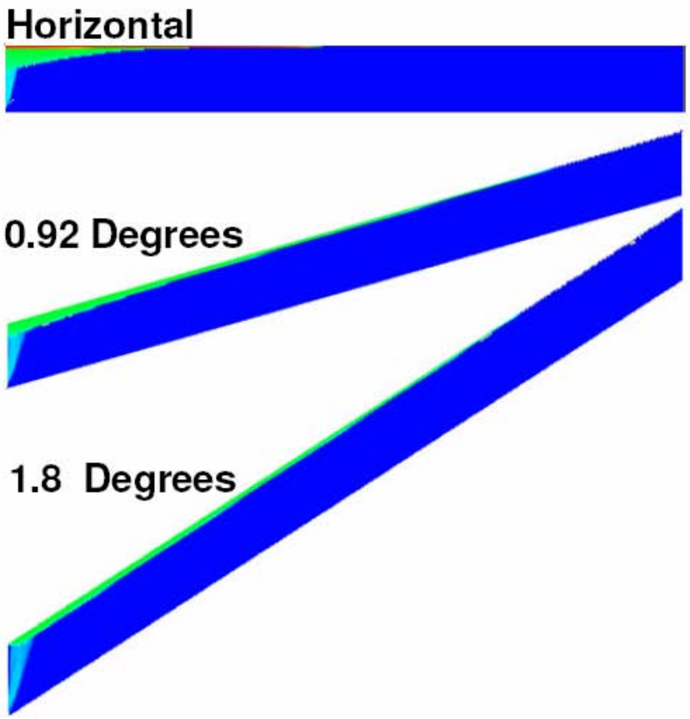
# Effect of Dip Angle on Capillary trapping

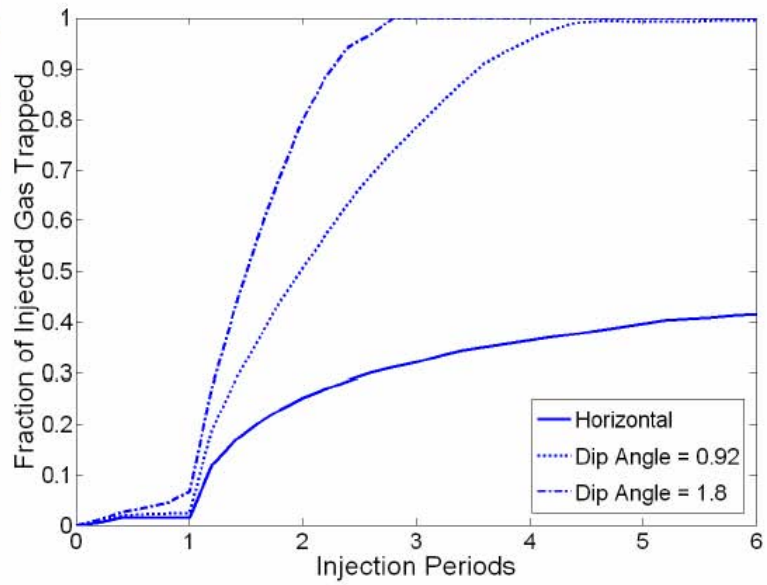



From Hesse at el., 2007

# Small Amounts of Dip Enhance Trapping

Rel Perm Hysteresis, No $P_c$, $N_{gv}$ = 55.6, Homogeneous

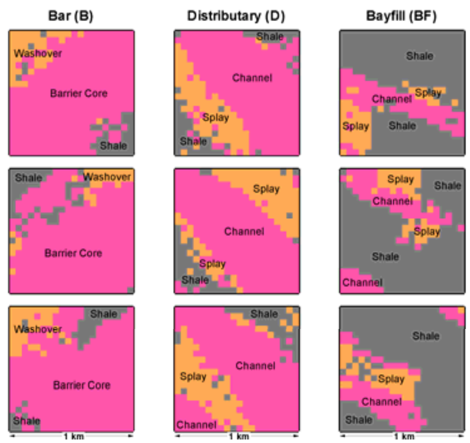


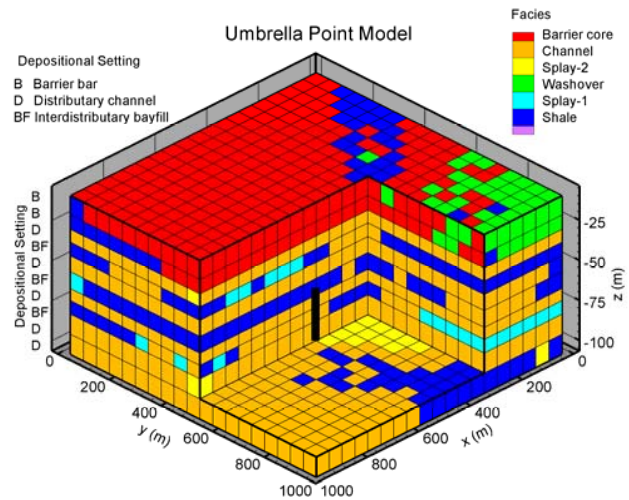

Tilting the reservoir enhances trapping efficiency (amount and rate)

From Hesse at el., 2007

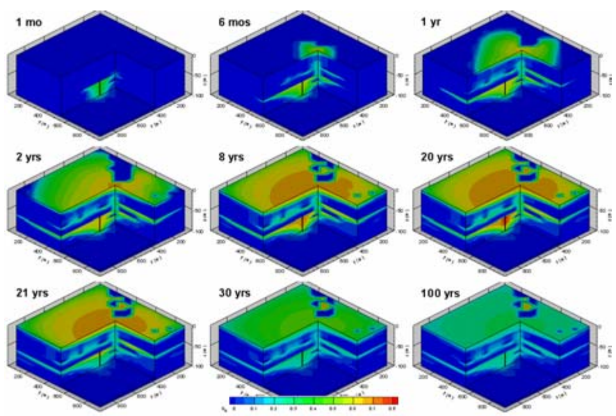
# Storage Capacity and Trapping Mechanisms



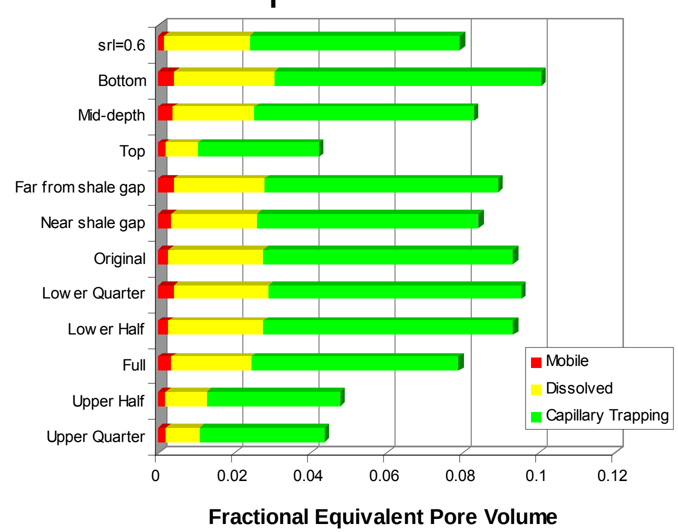

Geological Model




Computational Grid

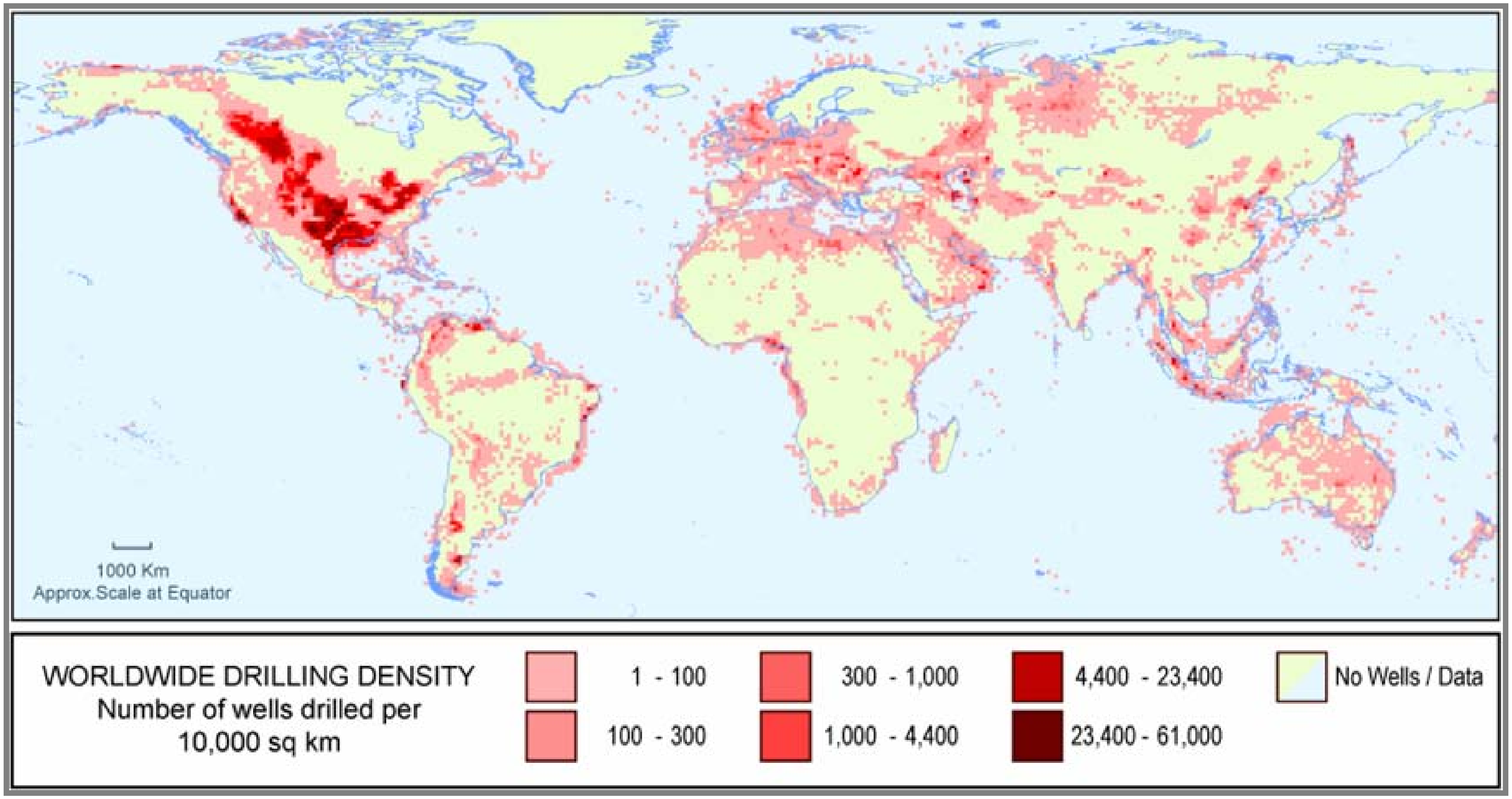



Reservoir Simulation




Storage Capacity and Trapping

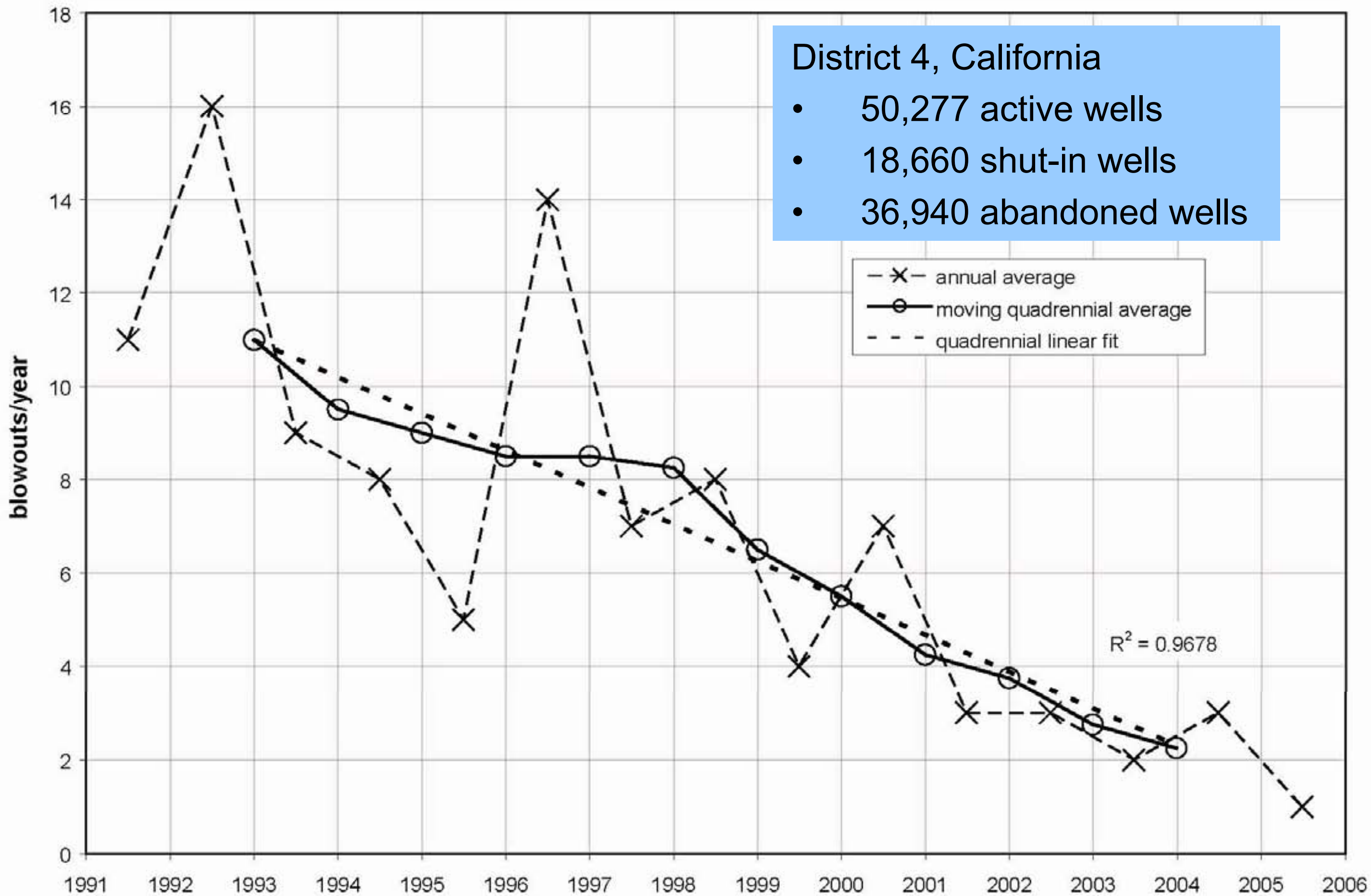
# Sealing Active and Abandoned Wells



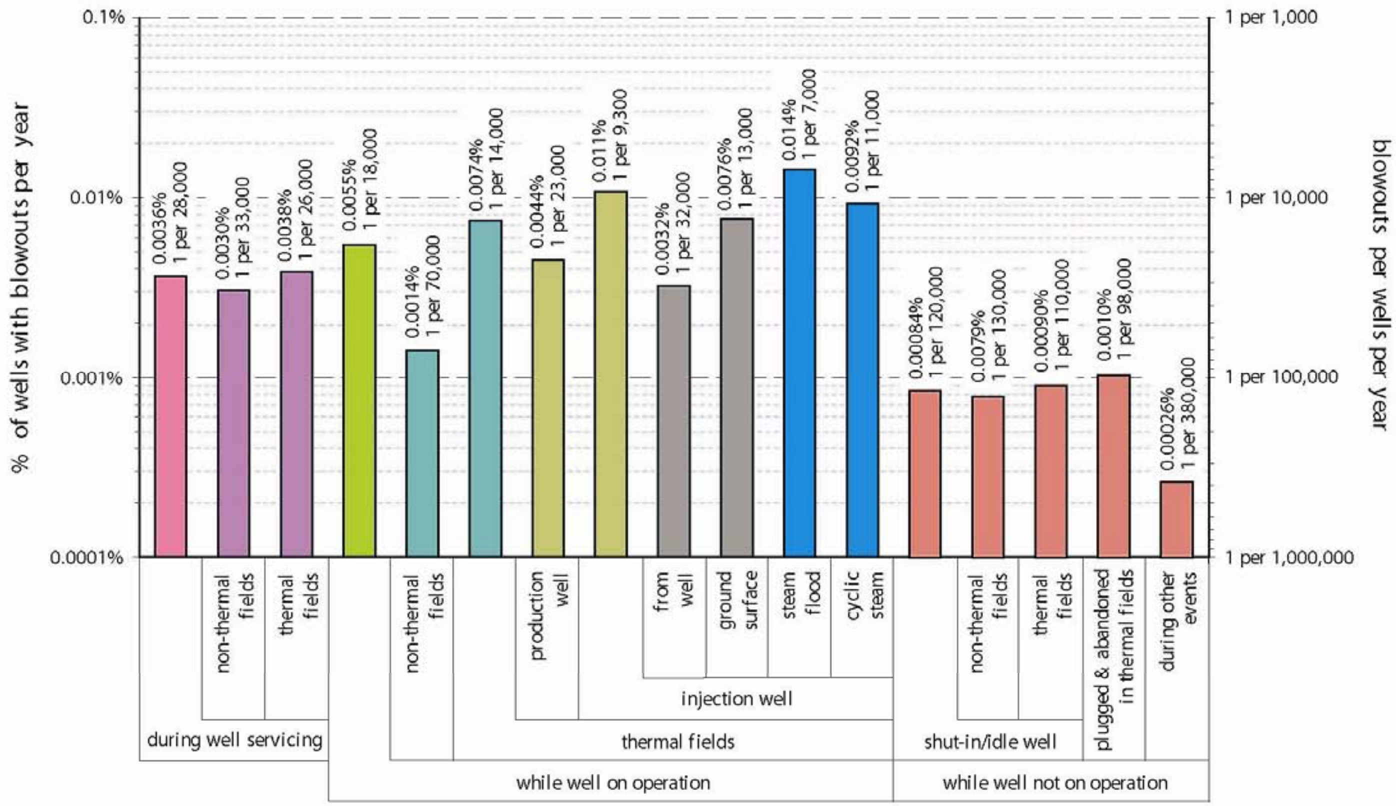

From IPCC, 2005

Safe Operations

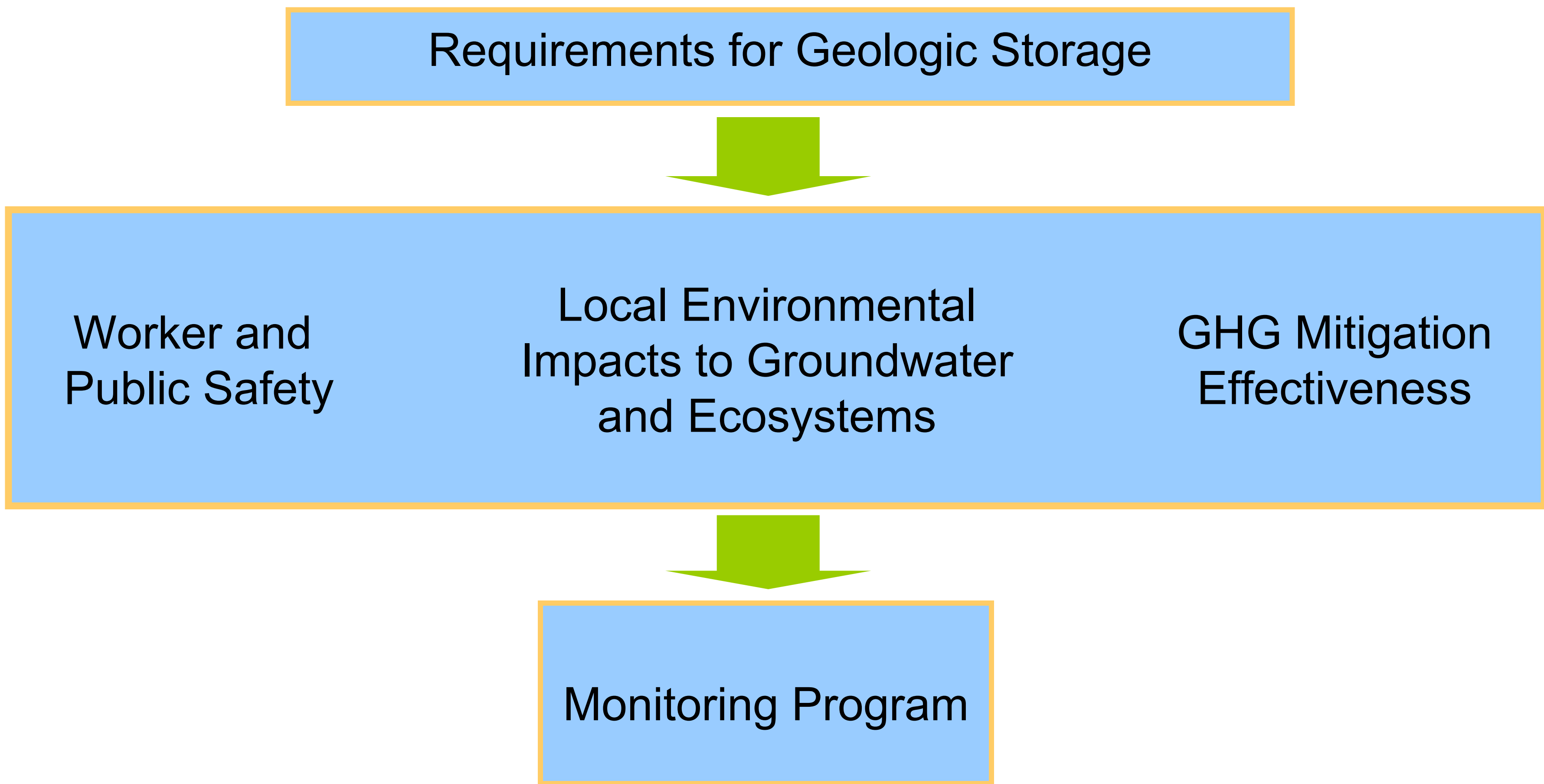
# Well Blowouts in Region IV, California



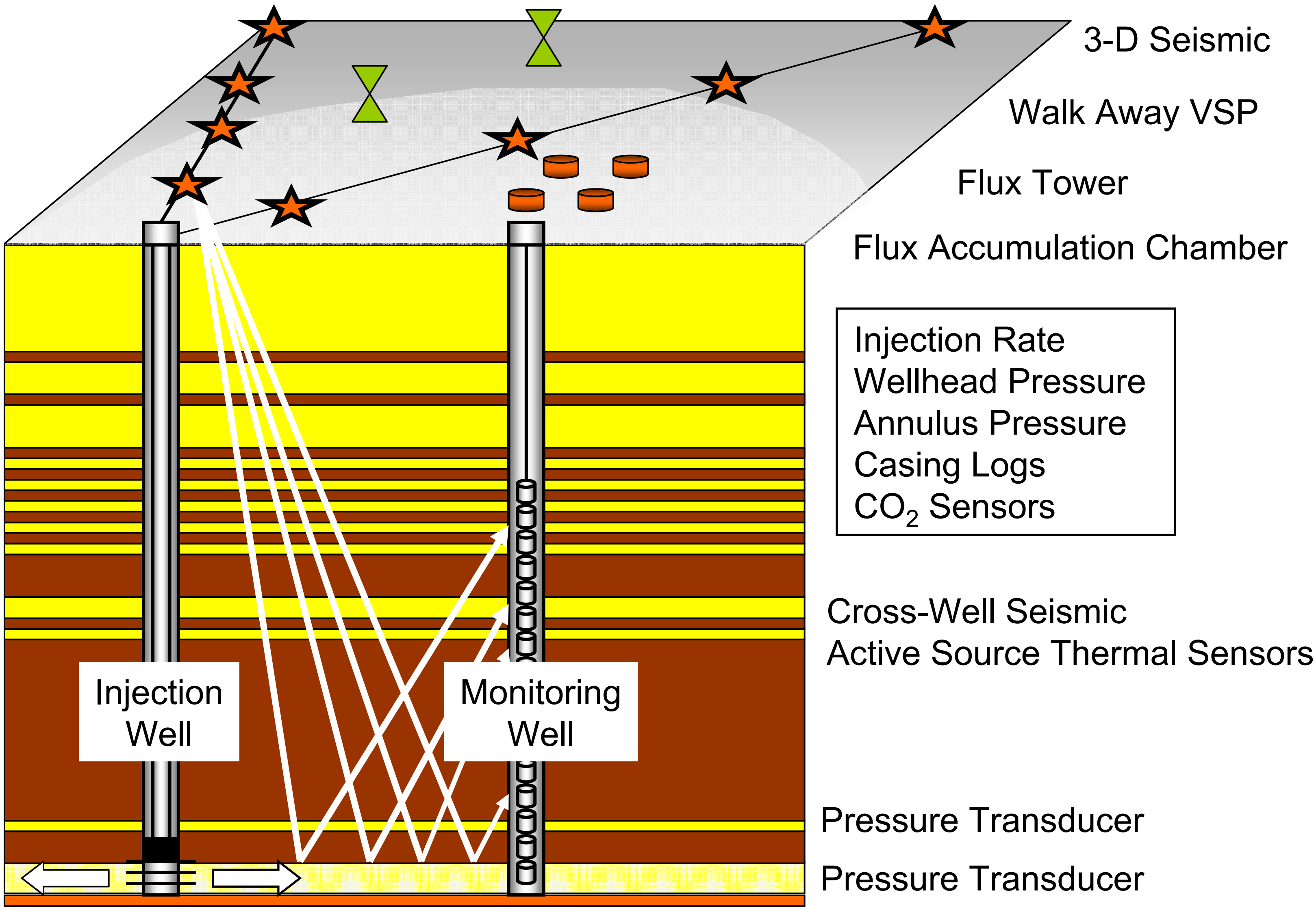
# Blowout Frequency in District 4



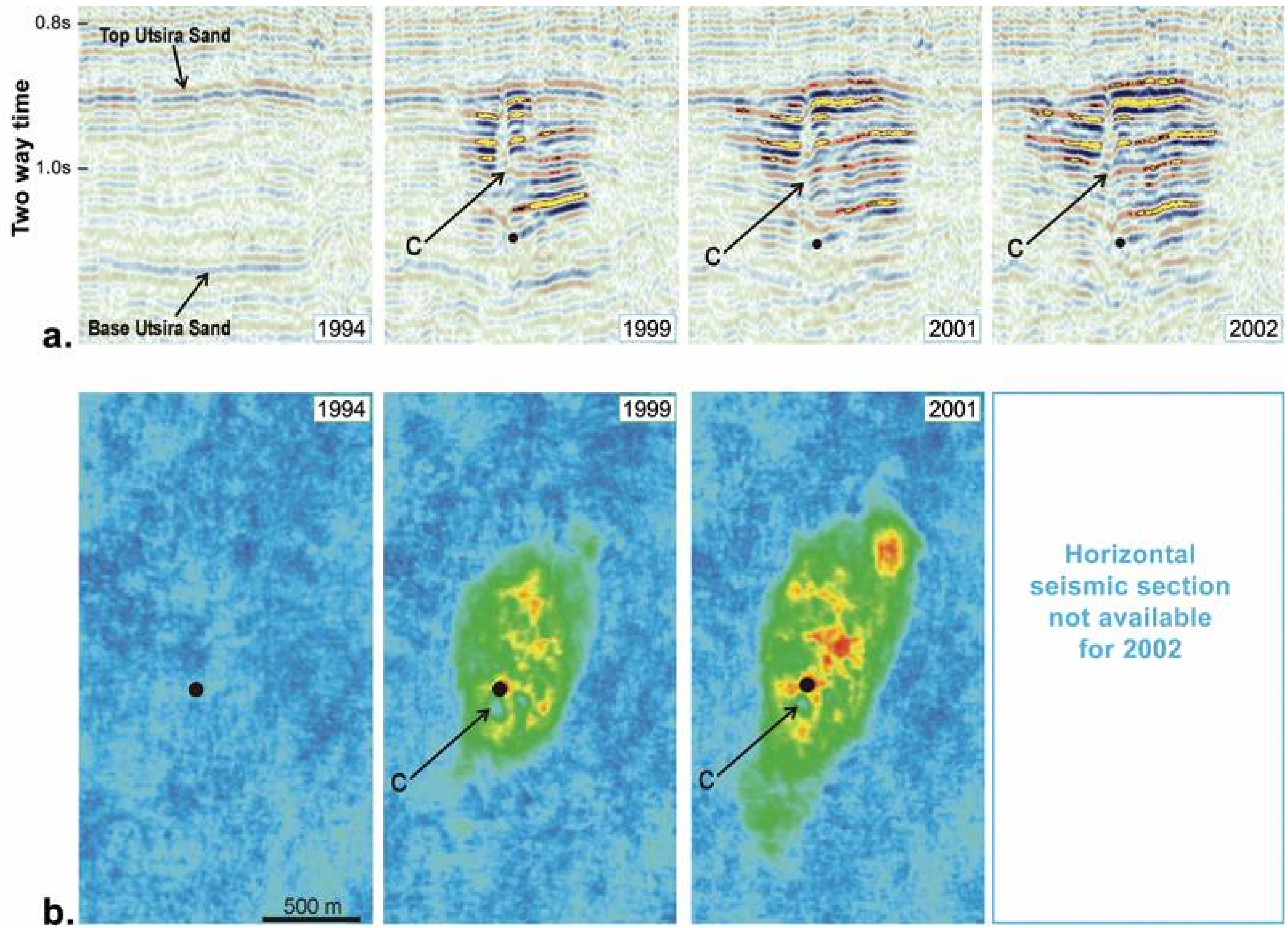
# Monitoring Needs for CCS Projects



# Monitoring Methods

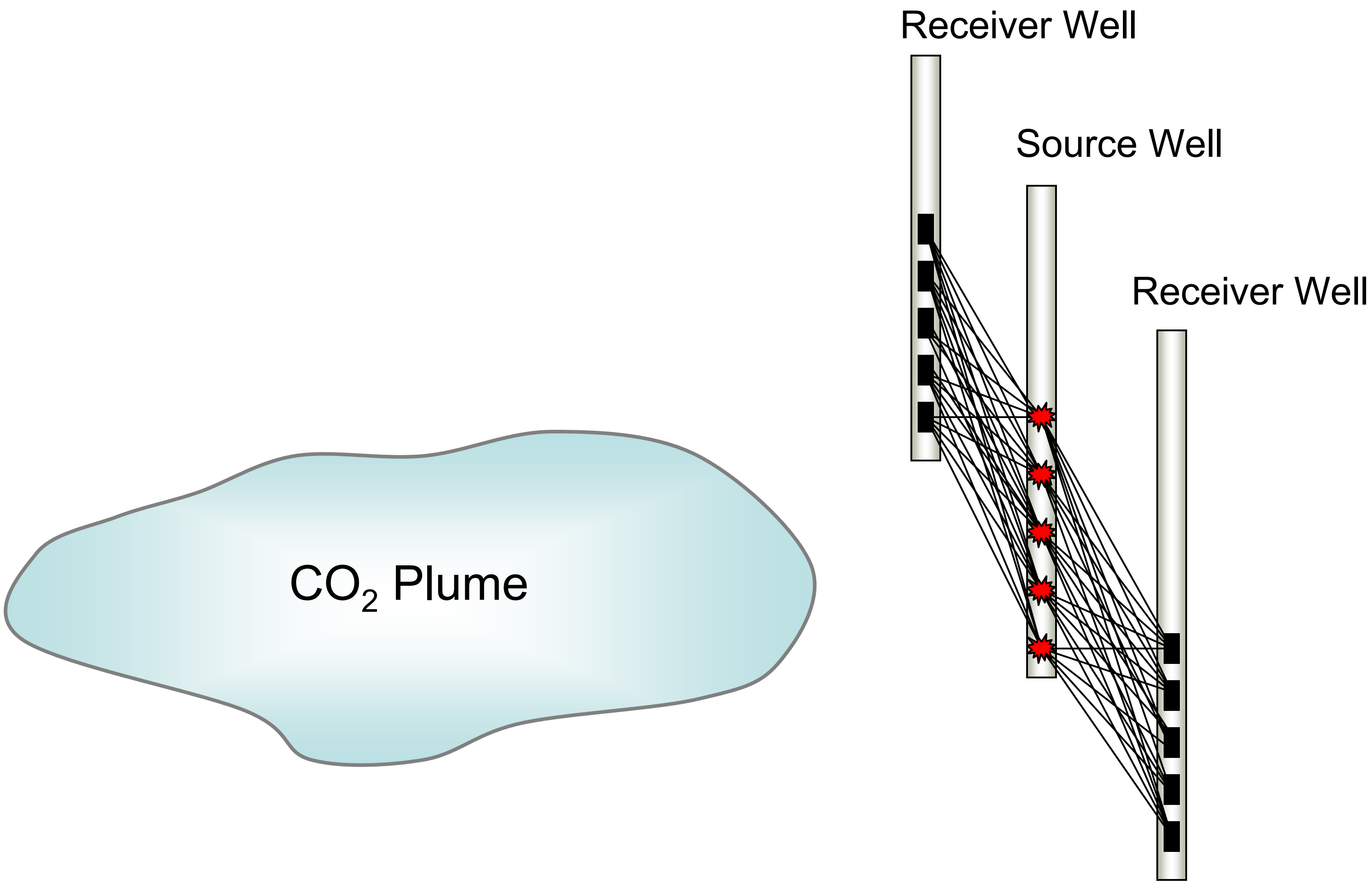


# Seismic Monitoring Data from Sleipner

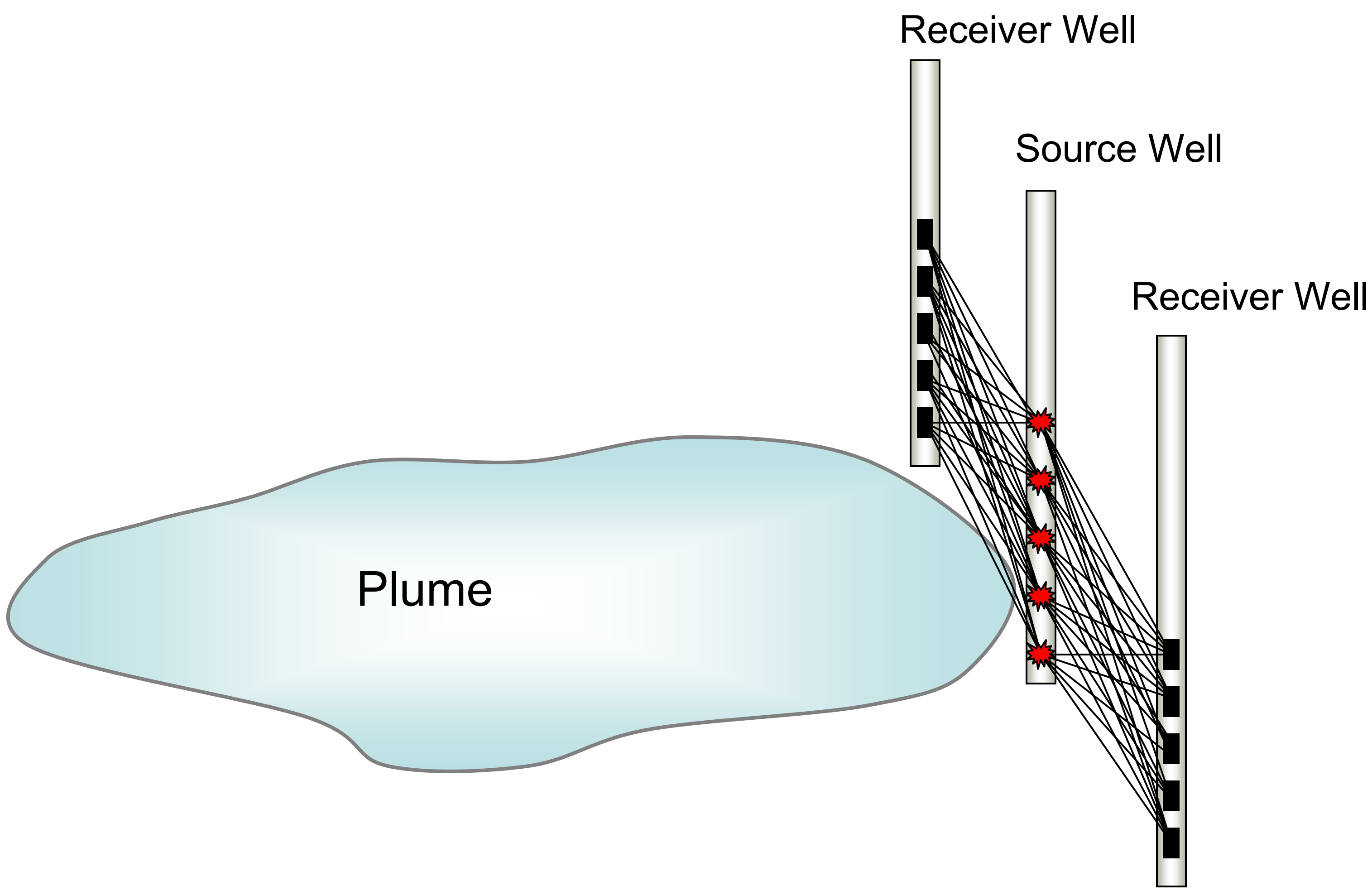



From Andy Chadwick, 2004

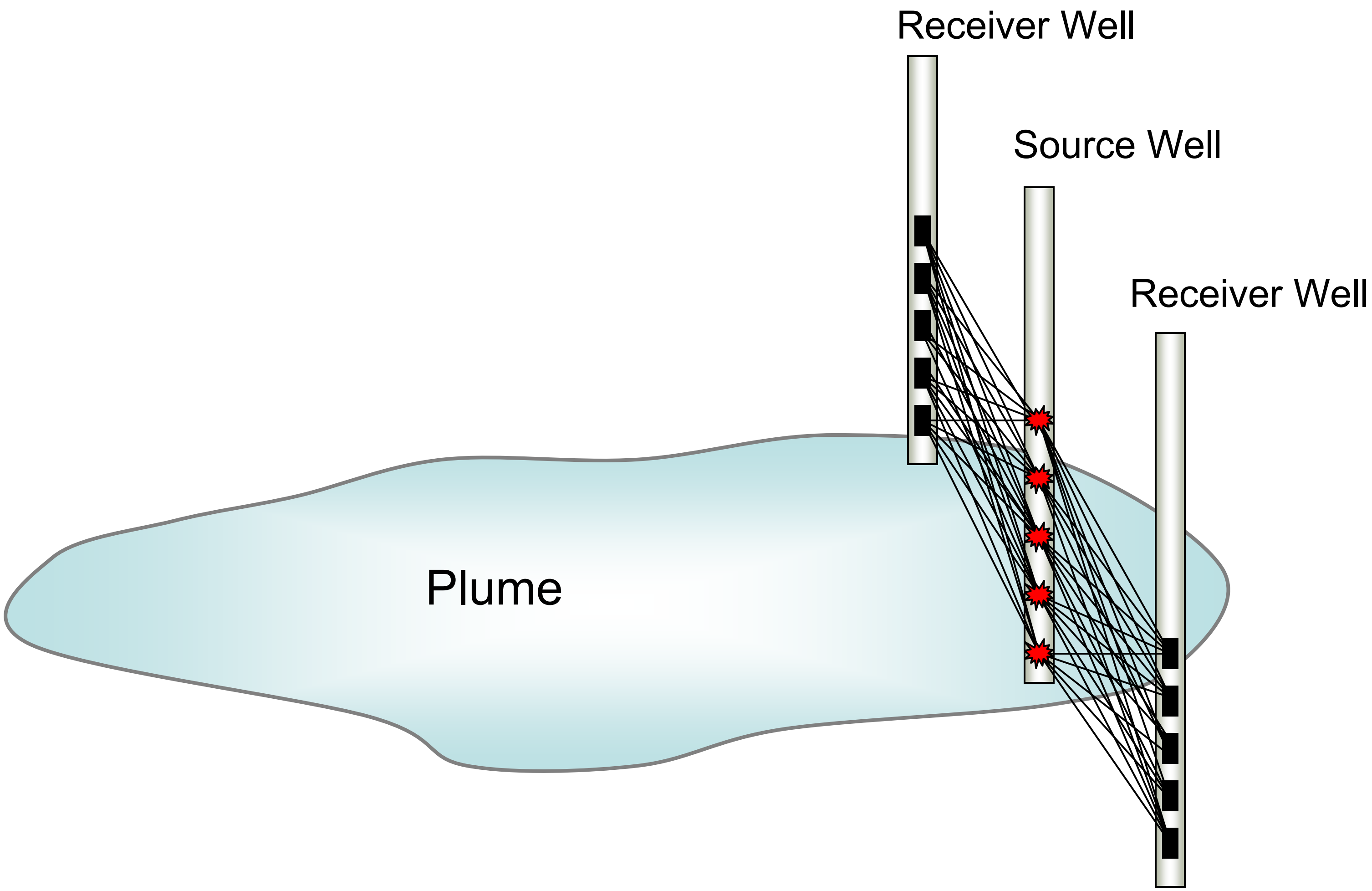
# An Alternative Approach: Real-Time Seismic Monitoring



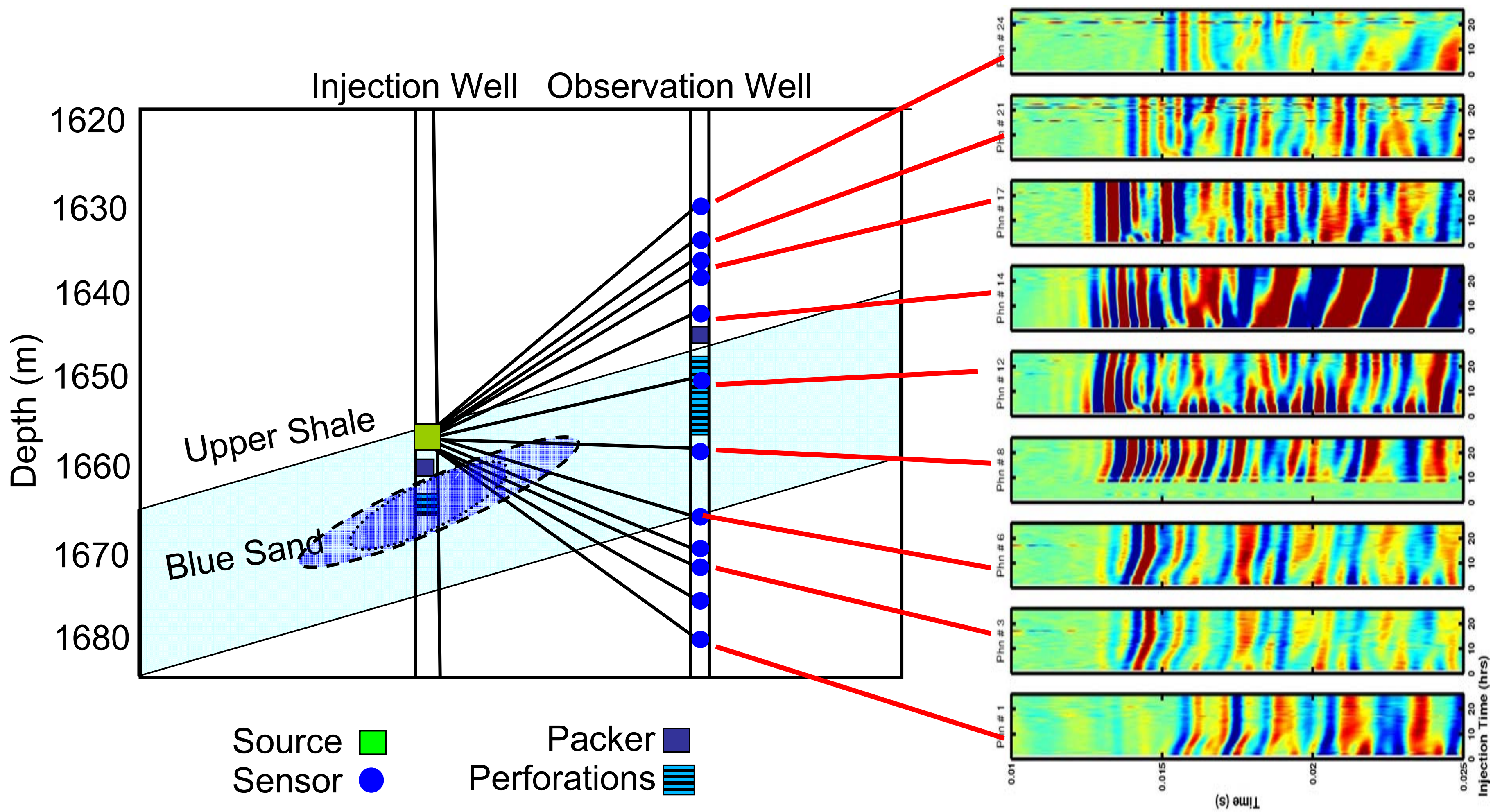
# An Alternative Approach: Real-Time Seismic Monitoring



# An Alternative Approach: Real-Time Seismic Monitoring

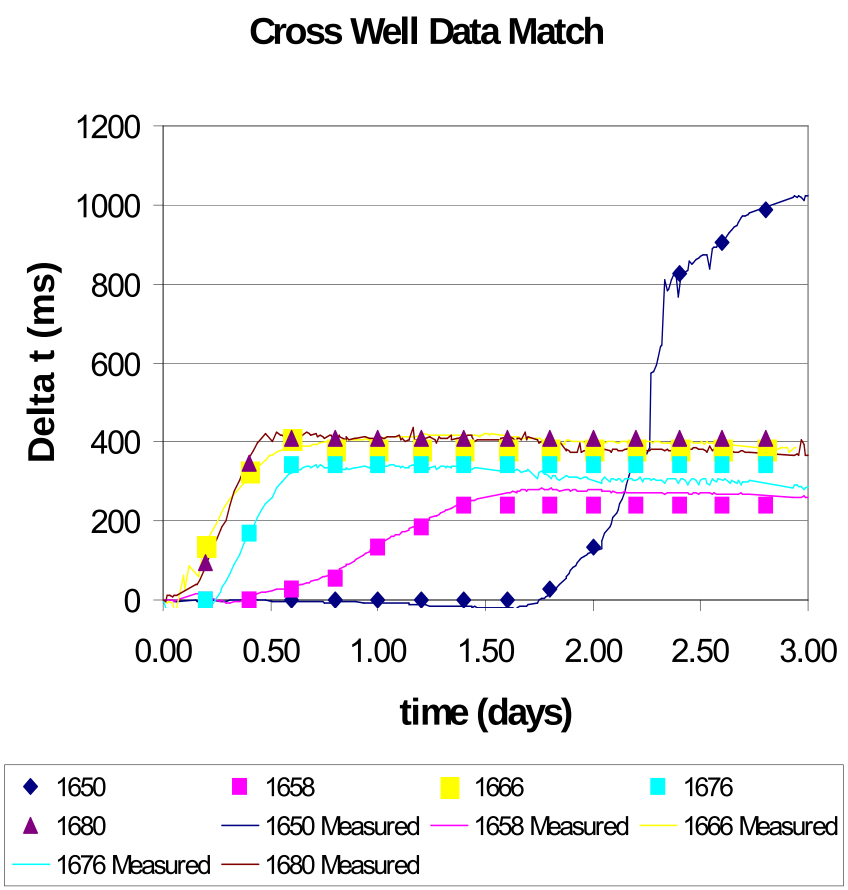


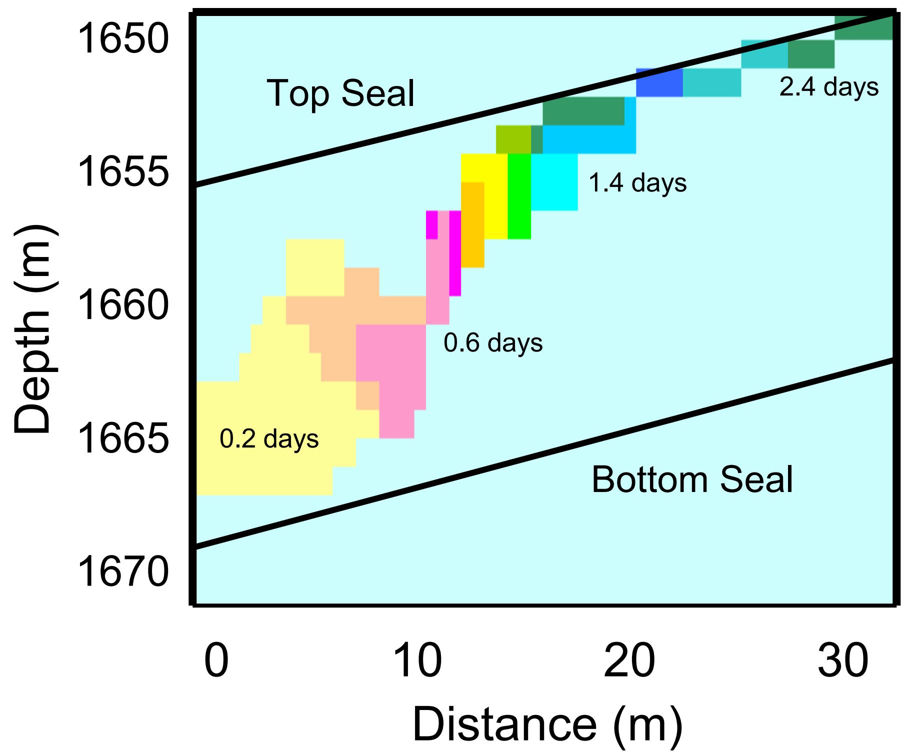
# Proof of Concept: Real-Time Seismic Monitoring




Daley, et al, Geophysics, 2007.

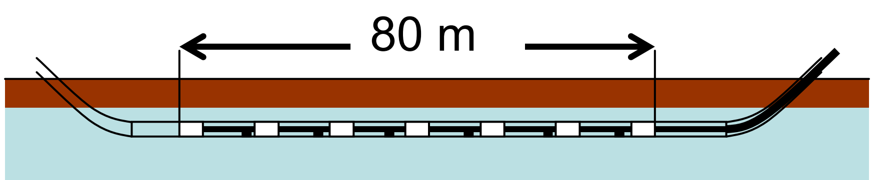
# Real-Time $CO_2$ Tracking

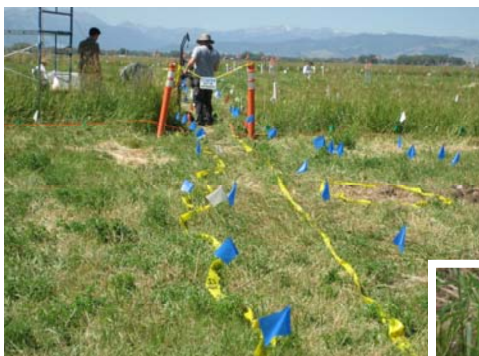


# Surface Monitoring

Detection Verification Facility
(Montana State University)



Field Site

Horizontal
Injection Well

Flow Controllers

Flux
Tower

Hyperspectral
Imaging of
Vegetation

Soil Gas

Flux accumulation chamber

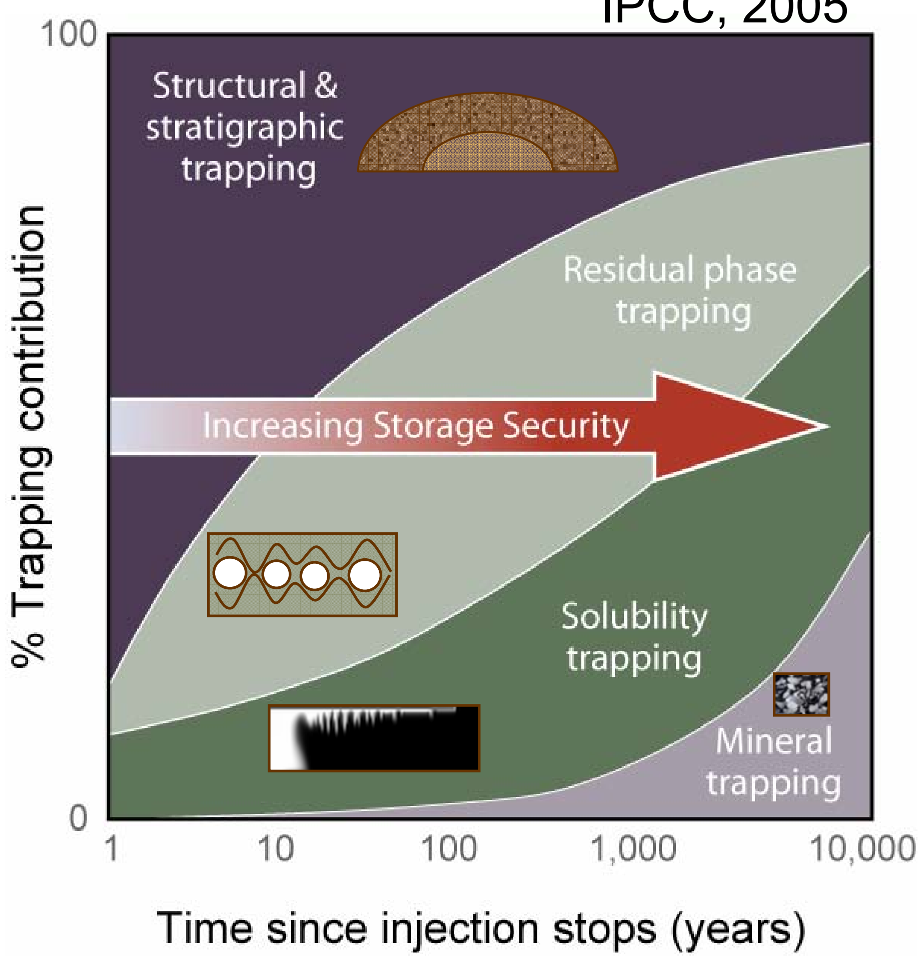
# Topics

- CCS Overview
- World-wide status report
- Storage security
- Long term liability
- Conclusions

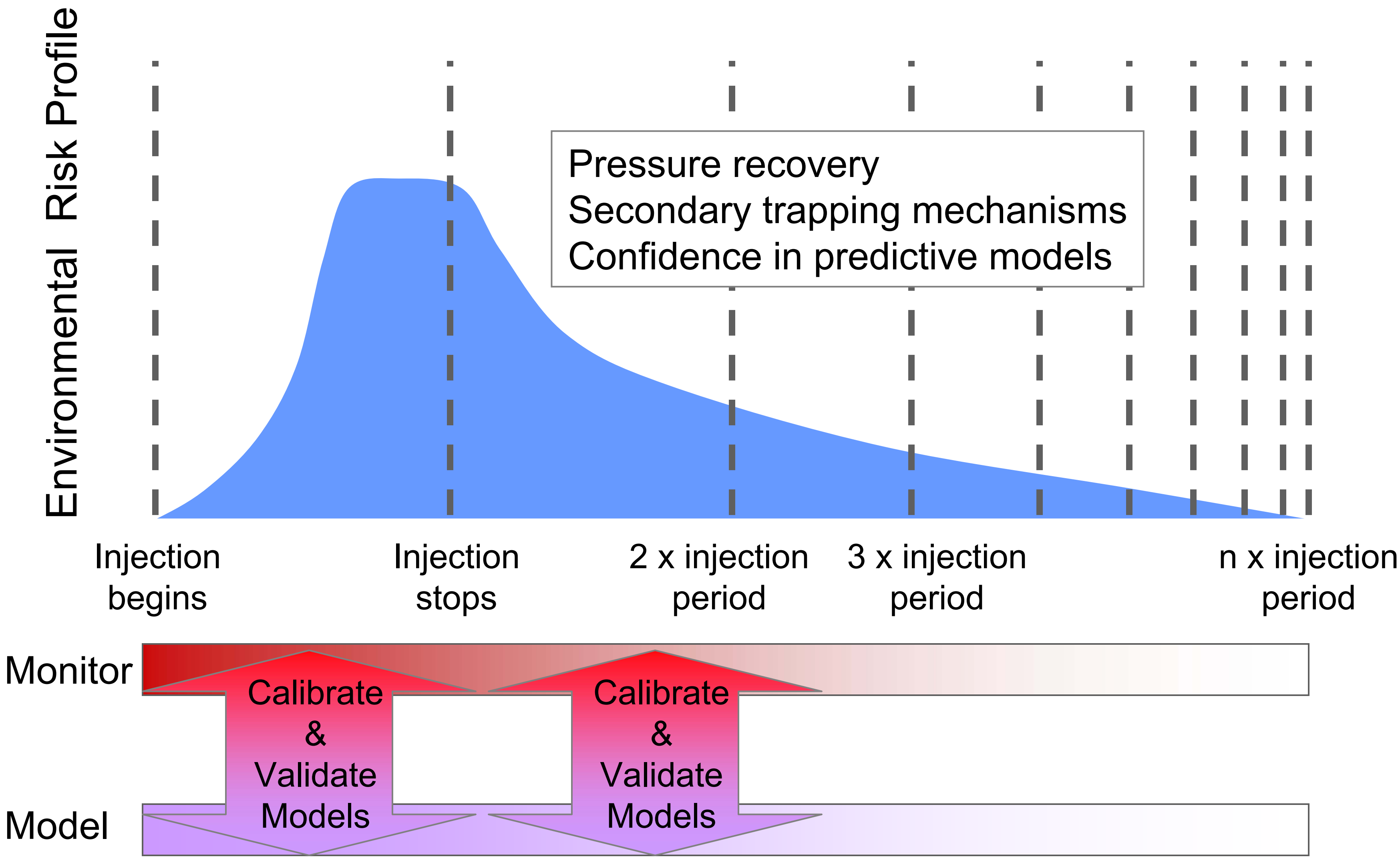
# Widespread Deployment of CCS

- Unresolved institutional issues create investment risk for CCS
- Cost recovery for $CO_2$ capture
- Regulatory framework for $CO_2$ storage
- Pore-space ownership
- Long term financial responsibility
  - Monitoring
  - Remediation

IPCC, 2005



# Risk Profile for $CO_2$ Storage



# Conclusions

- CCS is an important part of the portfolio of technologies for reducing greenhouse gas emissions
- Progress on CCS proceeding on all fronts
  - Industrial-scale projects
  - Demonstration plants
  - R&D
- Technology is sufficiently mature for large scale demonstration projects
- Research is needed to support deployment at scale
  - Capture: Reduce costs and improve reliability
  - Storage: Improve confidence in storage security
- Institutional issues need to be resolved to support widespread deployment