Stanford University

GCEP Global Climate & Energy Project

Woods Institute for the Environment
Energy Seminar
Stanford, May 16, 2007

Security of Geological Storage of CO_2: What Do We and Don't We Know?

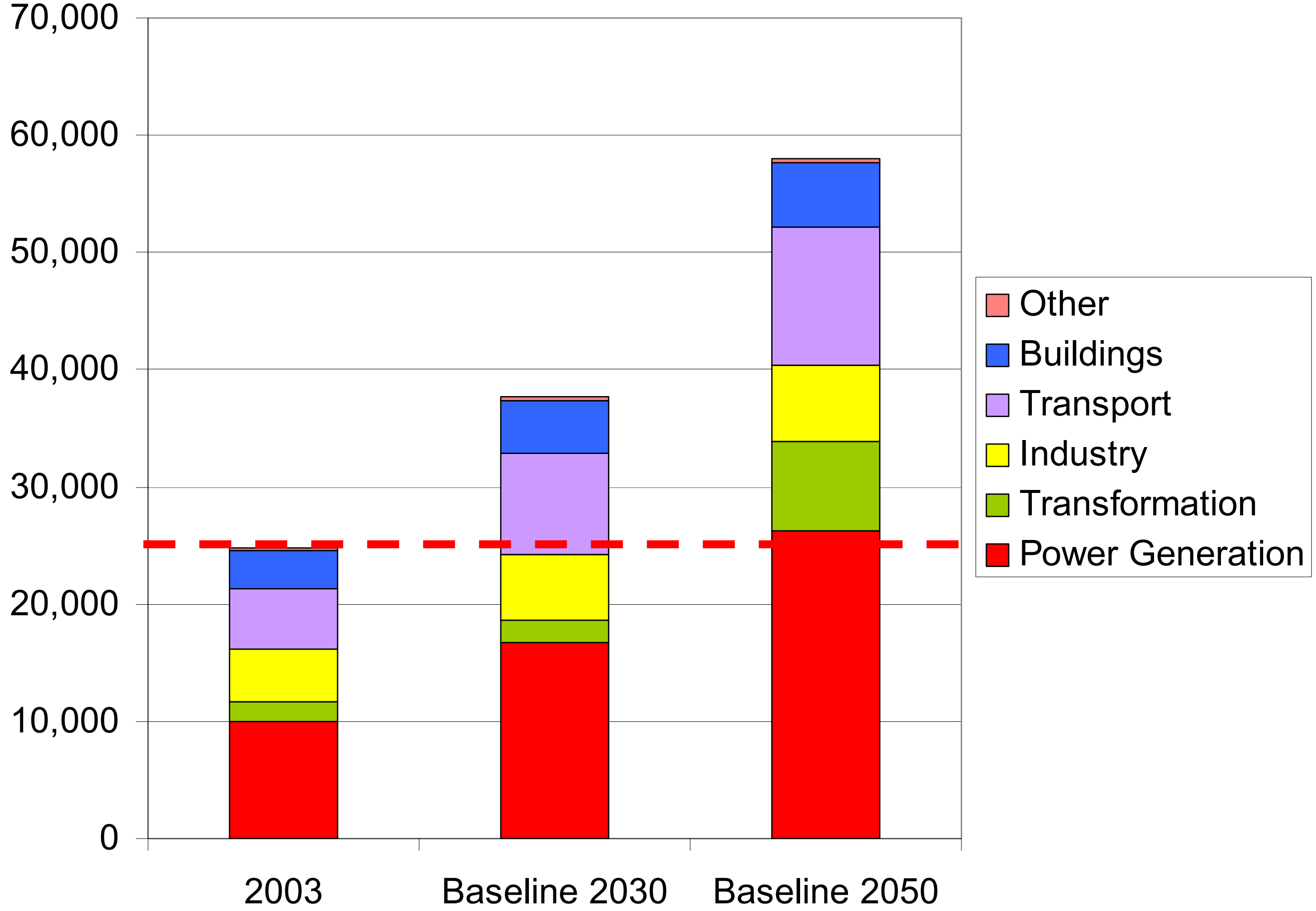
Sally M. Benson
Energy Resources Engineering Dept., Stanford University
Executive Director, Global Climate and Energy Project

Outline

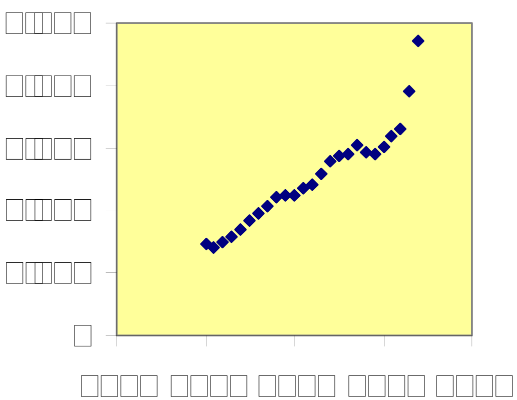
- What is CO_2 capture and storage—and why it is important
- Expert opinion about the security of geological storage and the evidence to support it
- Storage security pyramid—a concept to frame the issue
  - Highlight some active areas of my research team
- Fundamental research needs and opportunities

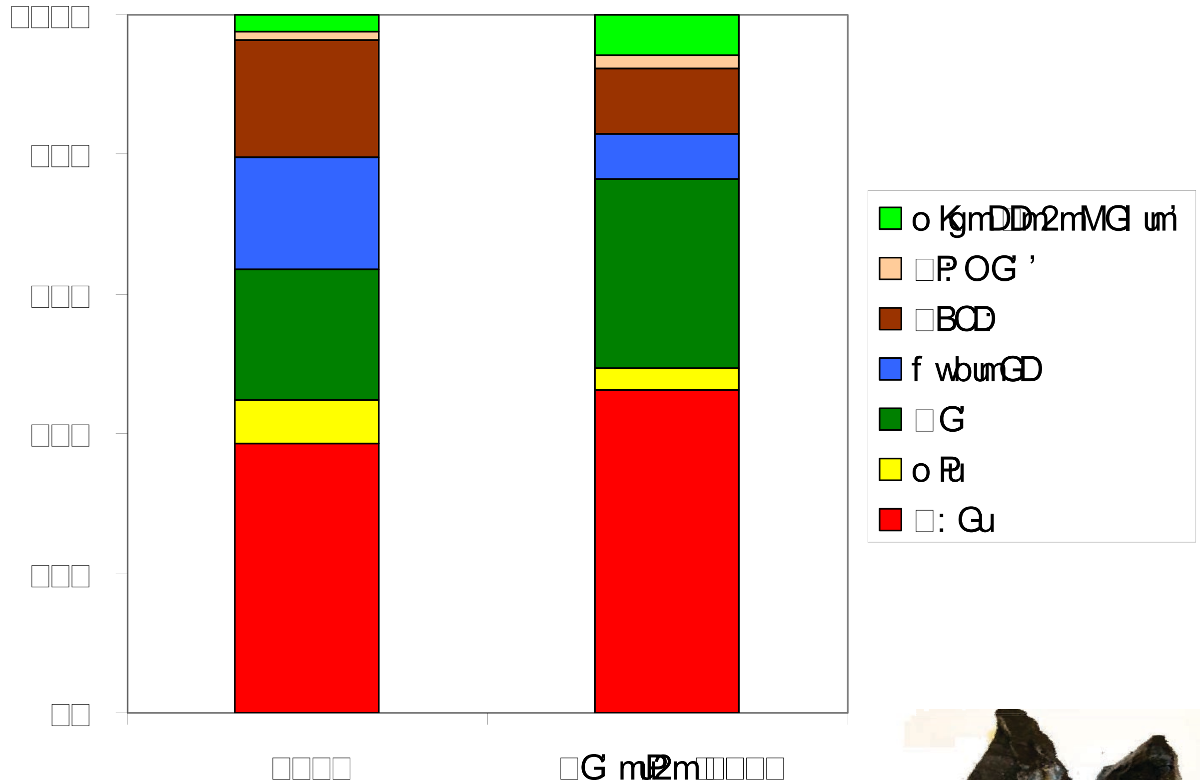
Where Do the CO_2 Emissions Come From?

Power Plant

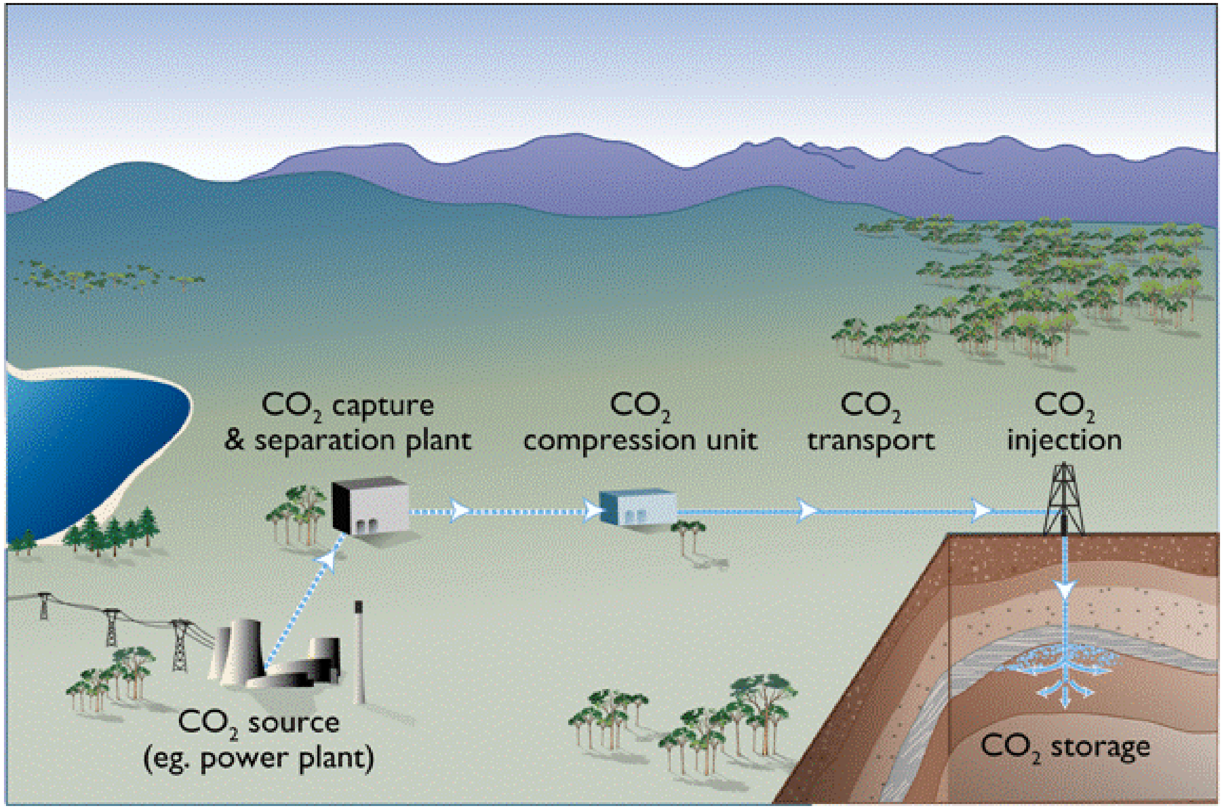


Source: IEA, 2006





Capture and Geologic Storage of CO_2 Avoids Emissions

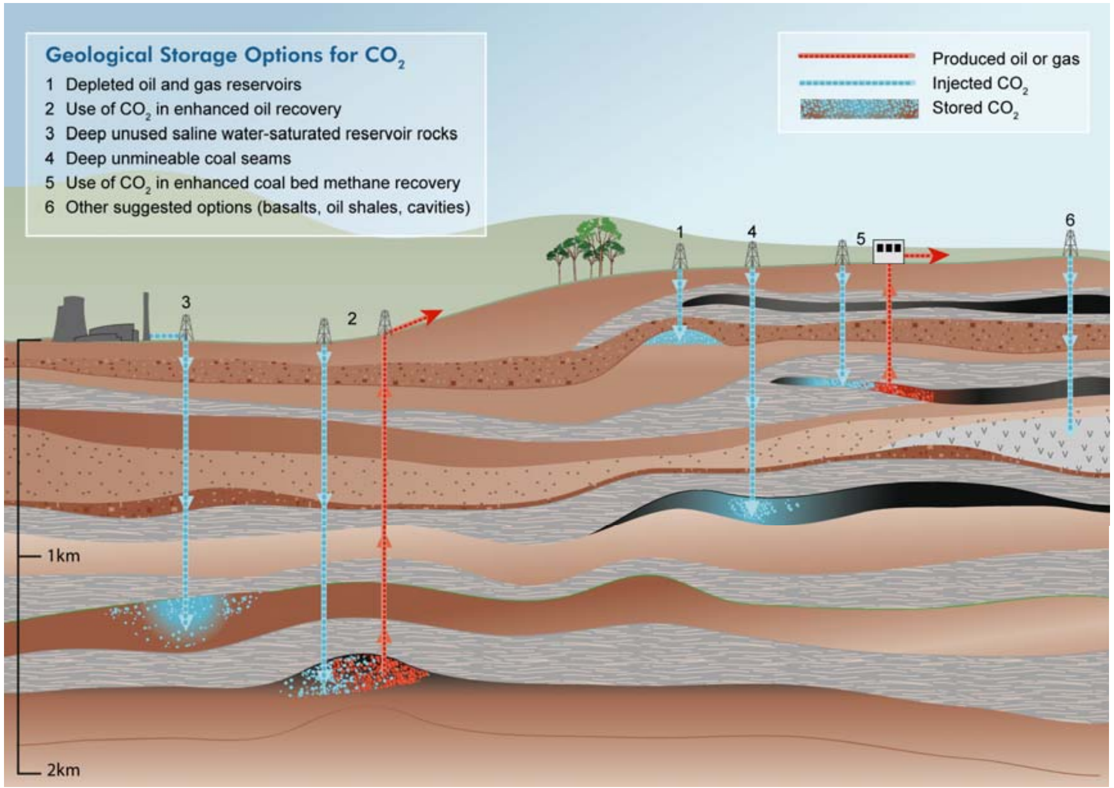


CO_2 Capture and Storage: A Four Step Process

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

Options for Geological Storage

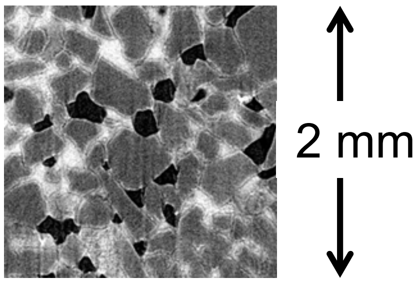
- Oil and gas fields
  - Depleted fields
  - EOR, EGR
- Saline formations
- Unminable coal-seams
- Other
  - Basalt
  - Deep ocean sediments
  - ?



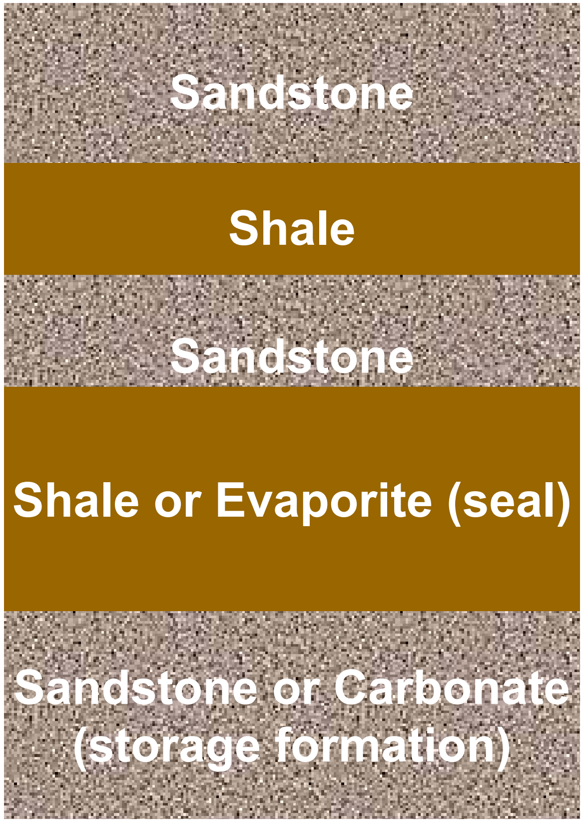
From IPCC Special Report, 2005

What Keeps the CO_2 Underground?

- Injected at depths of 1 km or deeper into rocks with tiny pore spaces



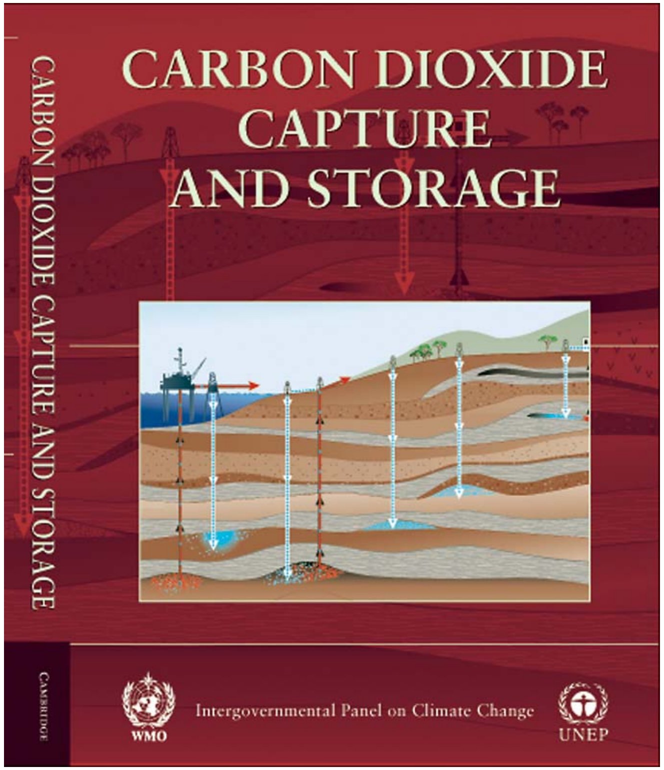
- Primary trapping
  - Beneath seals made of fine textured rocks that provide a membrane and permeability barrier
- Secondary trapping
  - CO_2 dissolves in water
  - CO_2 is trapped by capillary forces
  - CO_2 converts to solid minerals



Expert Opinion about Storage Security from the IPCC Special Report on CO_2 Capture and Storage

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

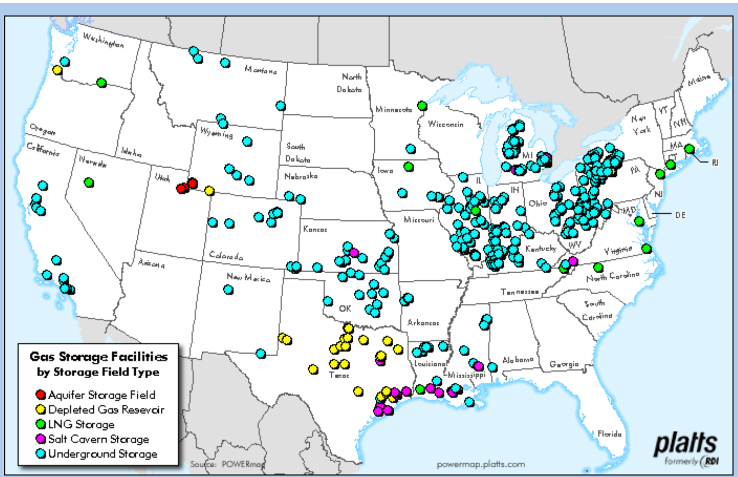
" With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO_2 releases if they arise, the local health, safety and environment risks of geological storage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



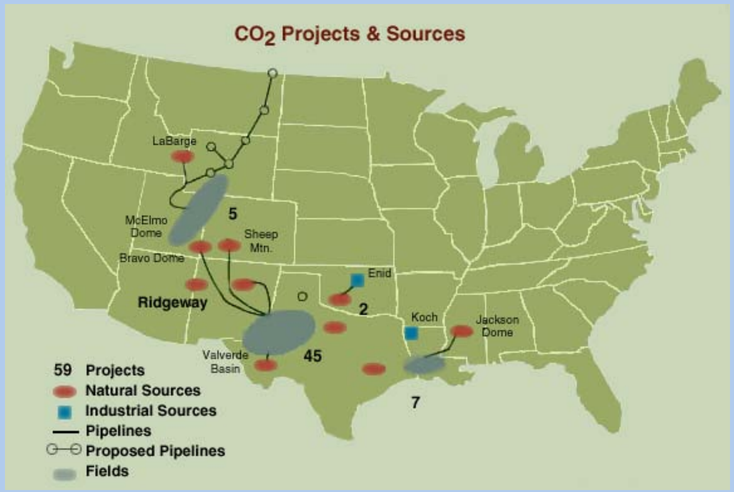
IPCC Special Report on CO_2 Capture and Storage, 2005

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



Underground Natural Gas Storage



~35 Mt/yr are injected for CO_2-EOR

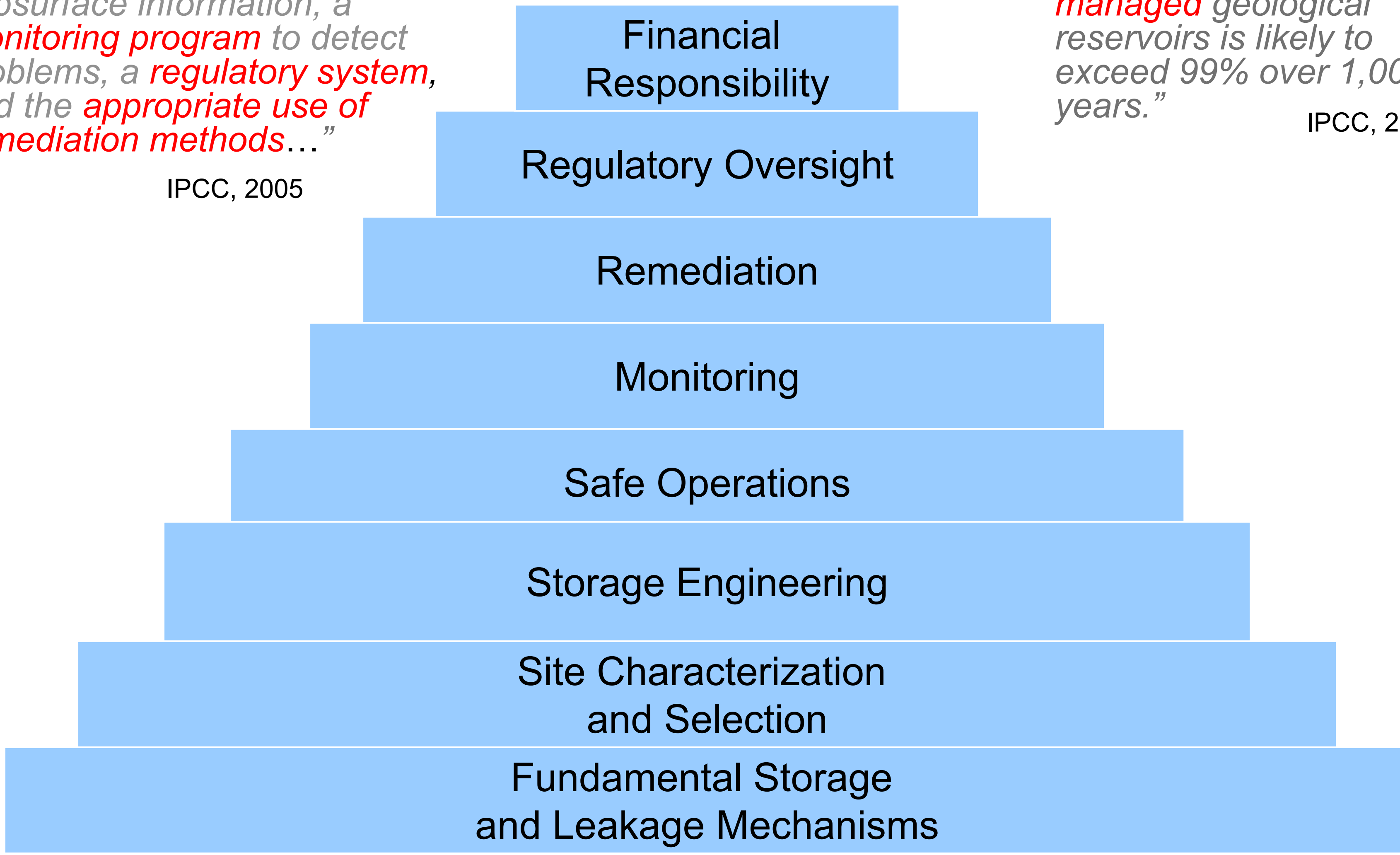
Geological Storage Safety and Security Pyramid

" 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."

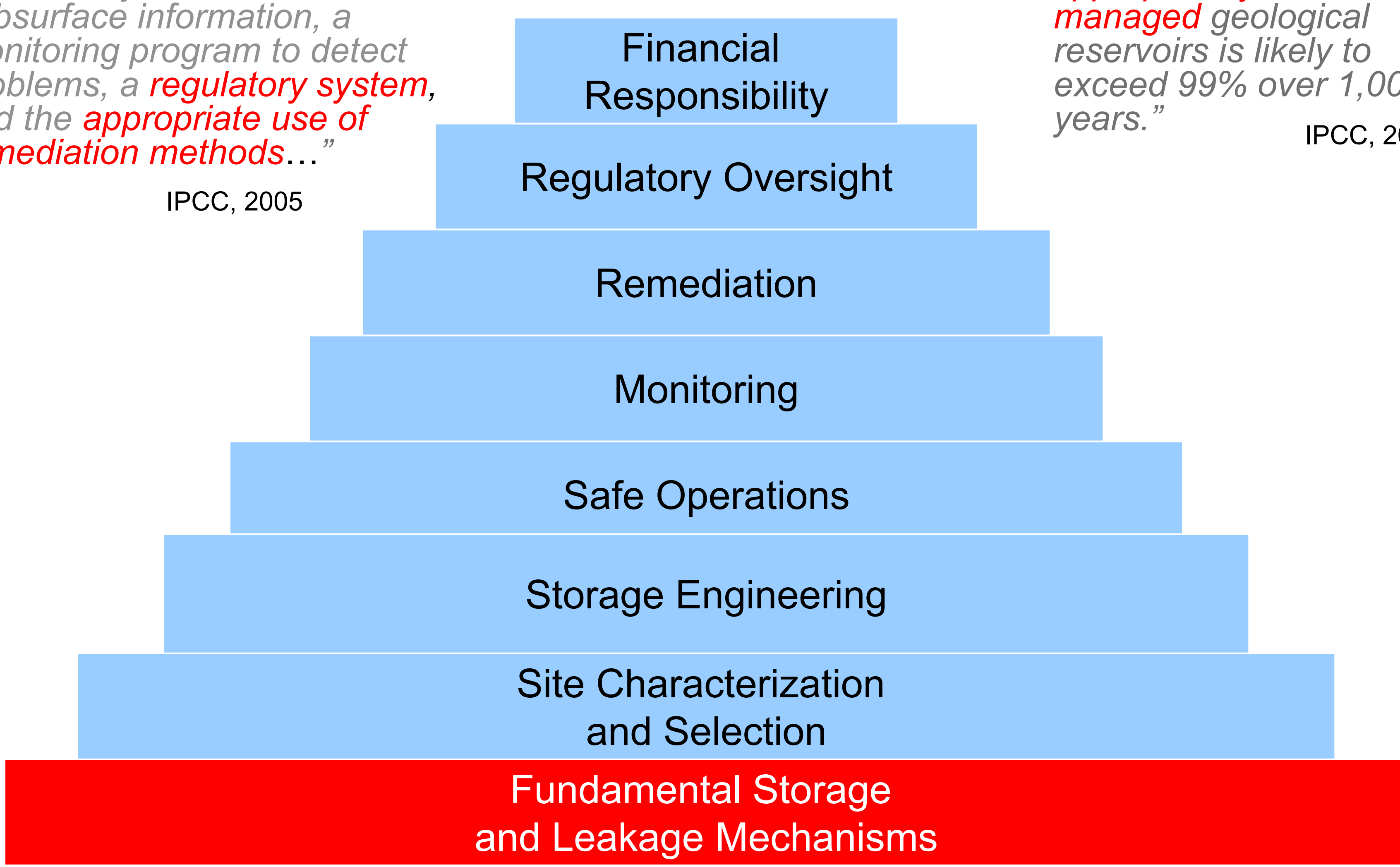
IPCC, 2005



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

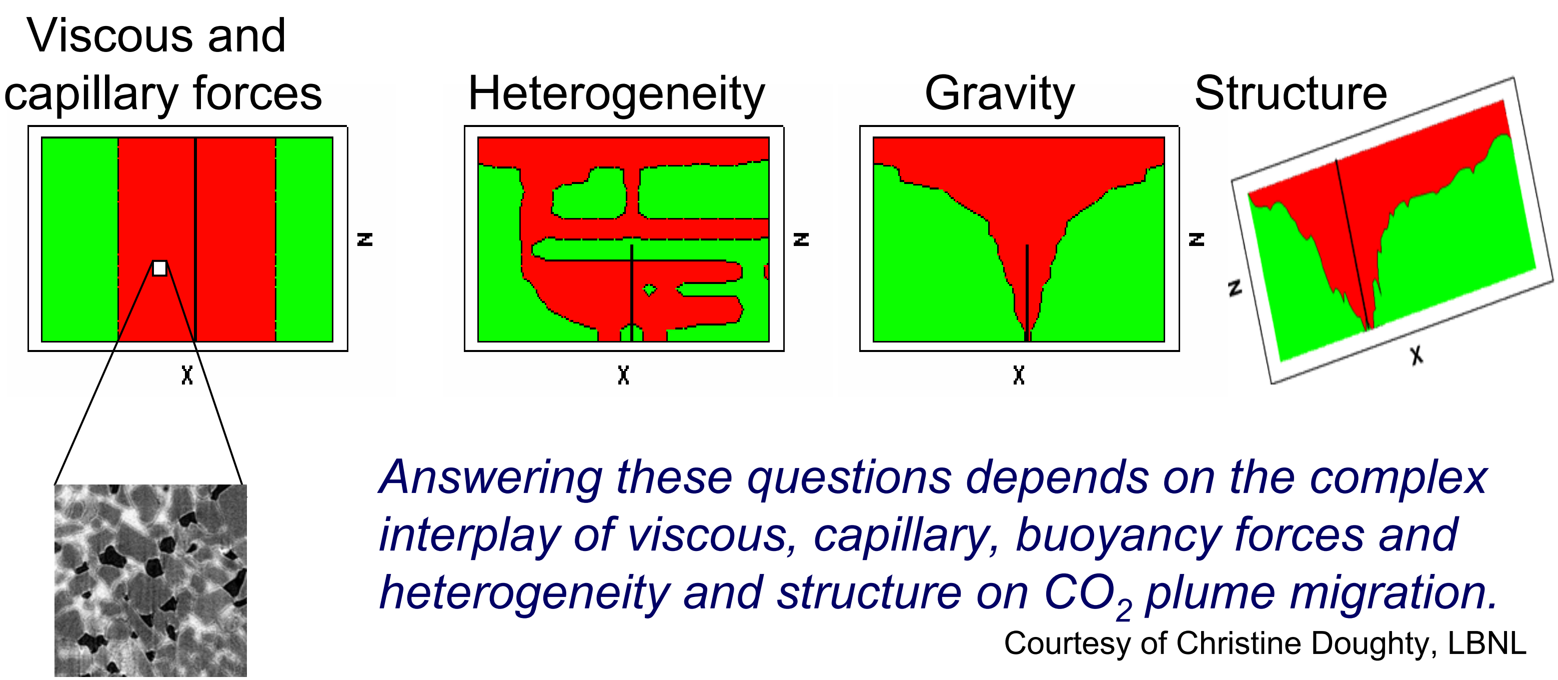


"… the fraction retained in ***appropriately selected and managed*** *geological reservoirs is likely to exceed 99% over 1,000 years."*

IPCC, 2005

Some Key Issues for CO_2 Storage in Deep Saline Aquifers

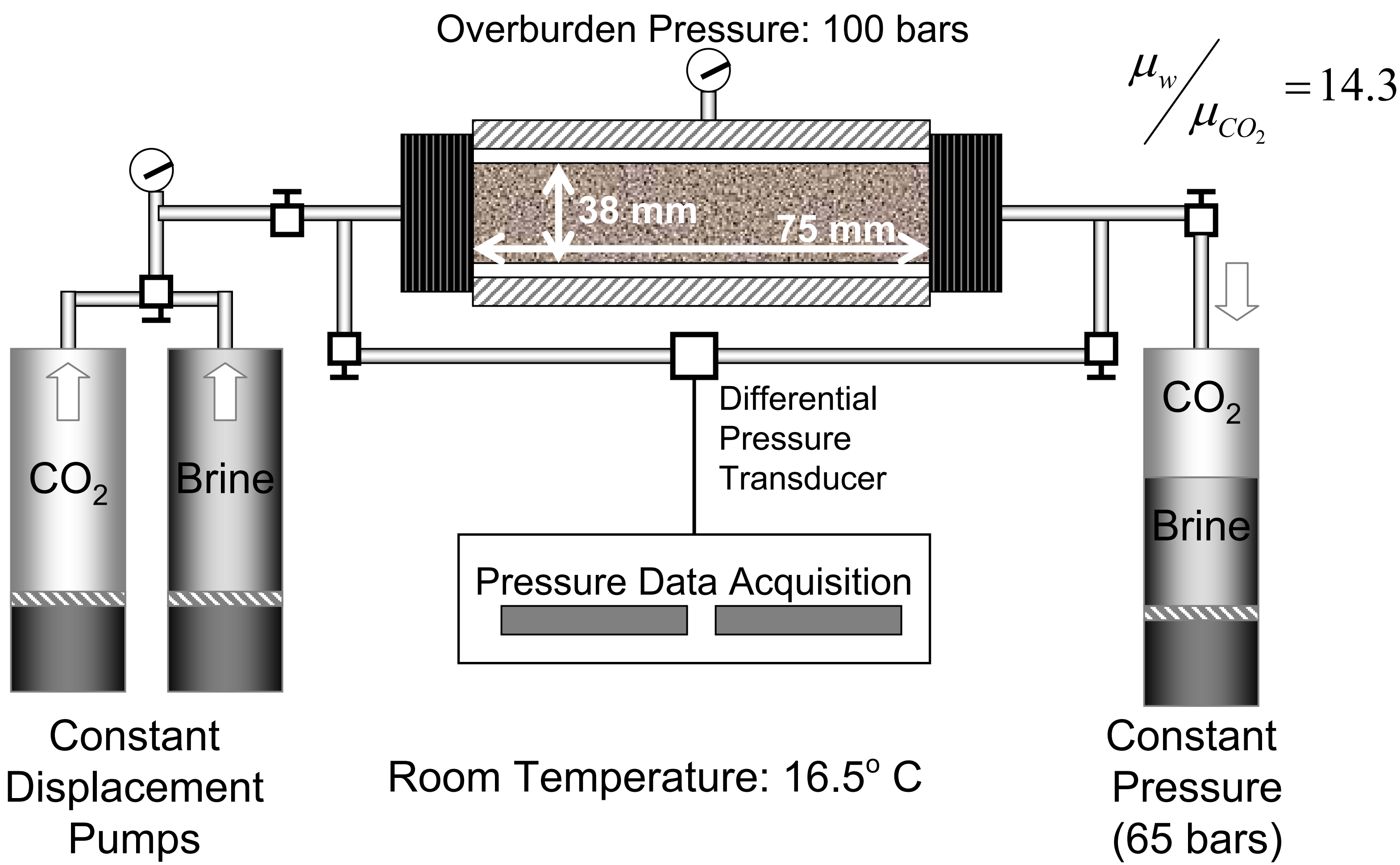
- What fraction of the pore space can be filled with CO_2?
- How big will the CO_2 plume be?
- How much CO_2 will be dissolved?
- How much will capillary trapping immobilize CO_2?
- Can accurate models be developed to predict CO_2 fate and transport?



Answering these questions depends on the complex interplay of viscous, capillary, buoyancy forces and heterogeneity and structure on CO_2 plume migration.

Courtesy of Christine Doughty, LBNL

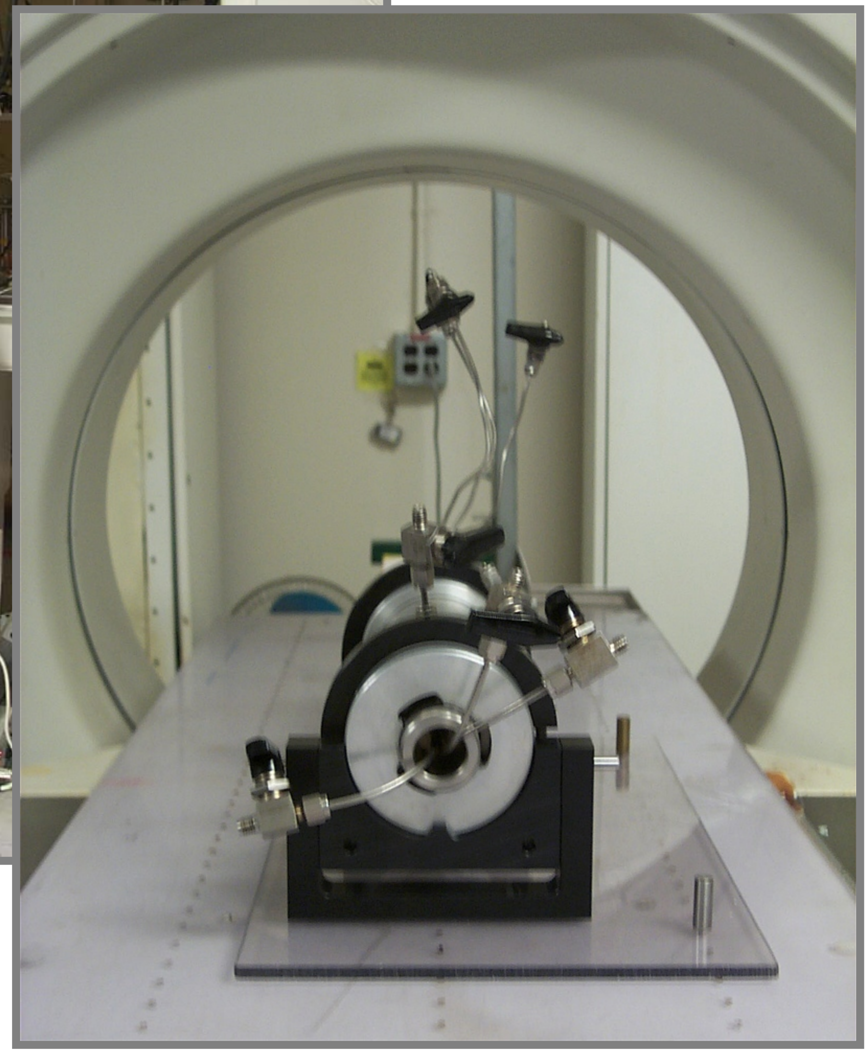
Core-flood Set-Up for Relative Permeability Measurements



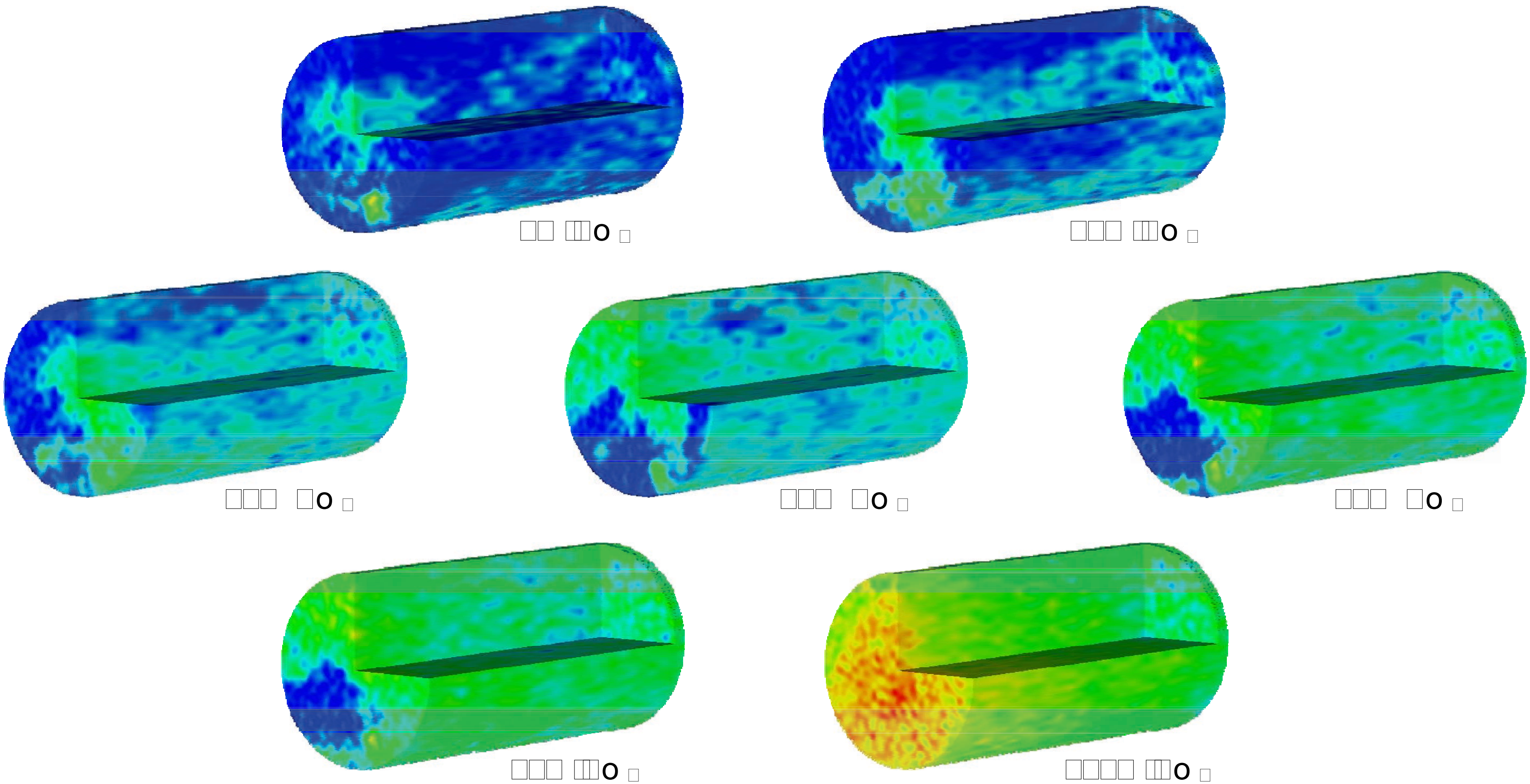
*Brine composition: CO_2 saturated brine with 0.5 molar potassium iodide

Core-Scale Imaging of CO_2 Distributions

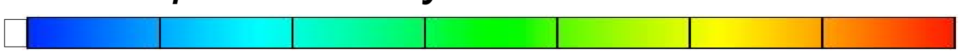
High Pressure Pumps



Core Holder
In Scanner

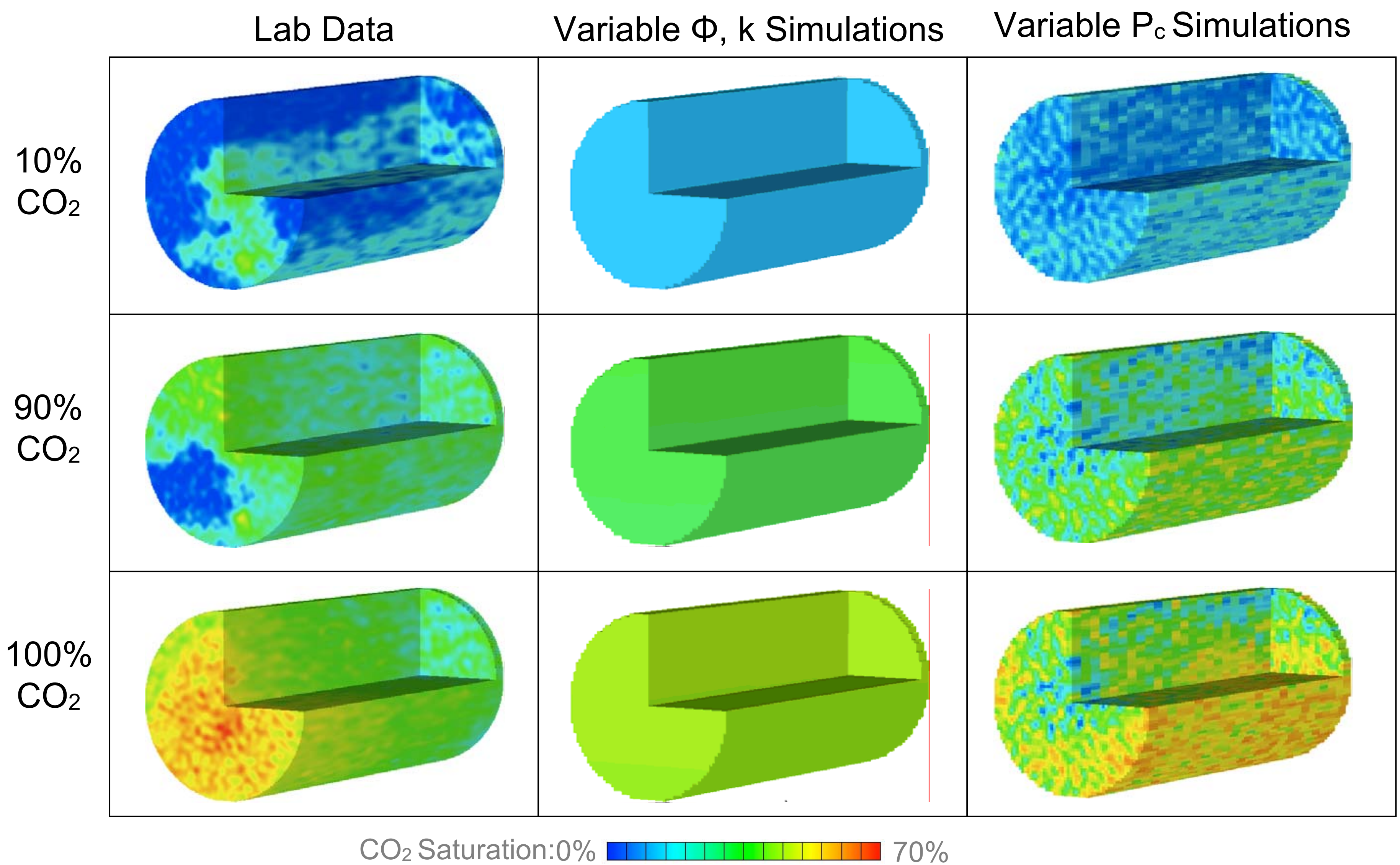


Sub-corescale saturation variations generally overlooked in relative permeability measurements.



Simulated CO_2 Saturations

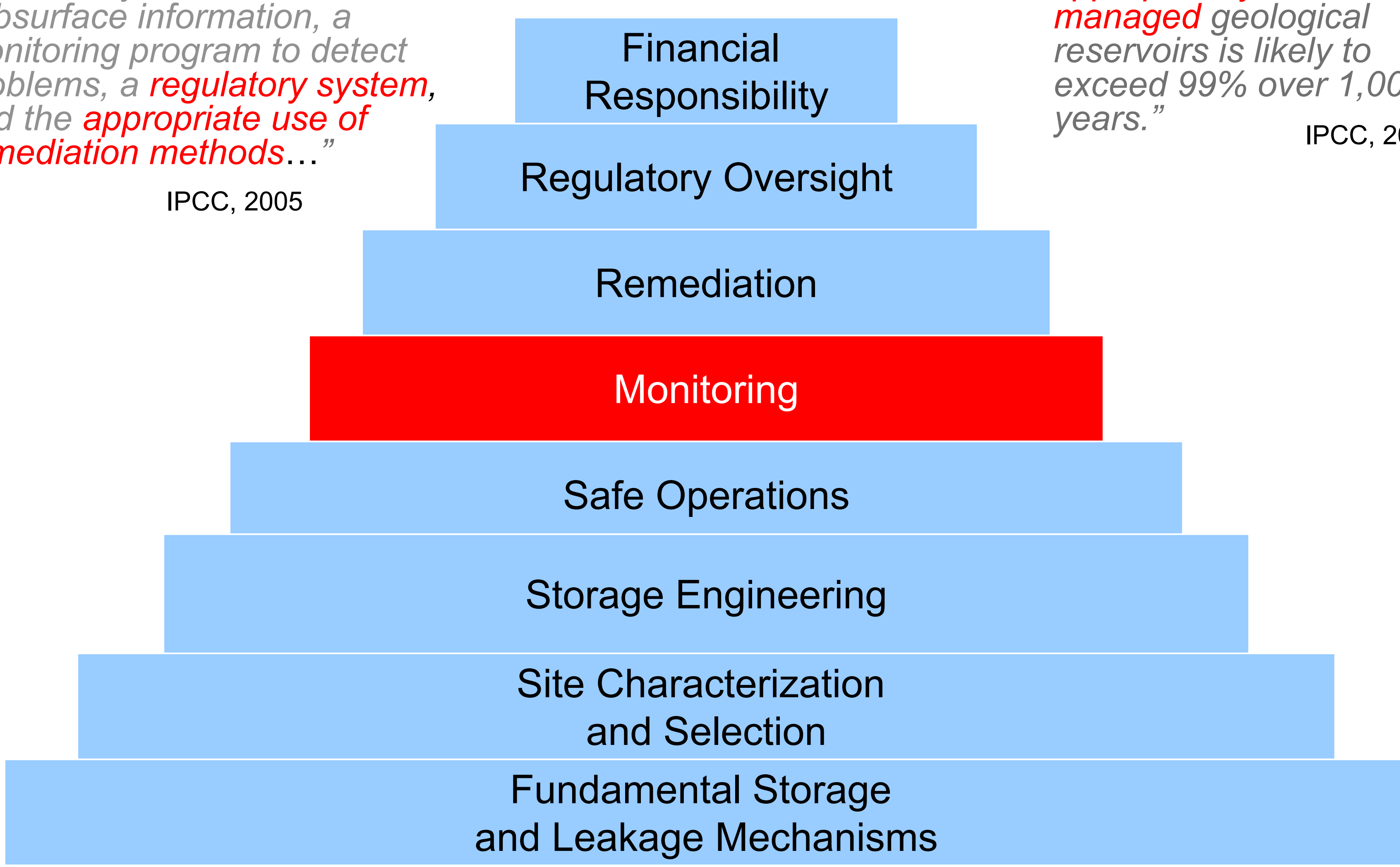
Variable P_c Produces Small-scale CO_2 Saturation Variations



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…"

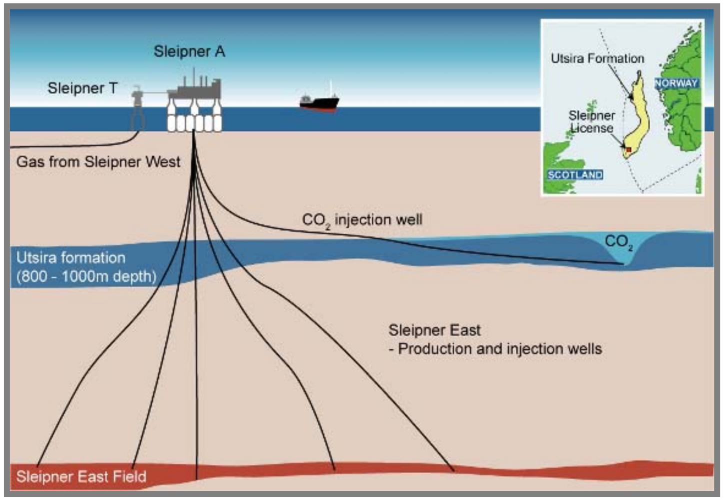
IPCC, 2005



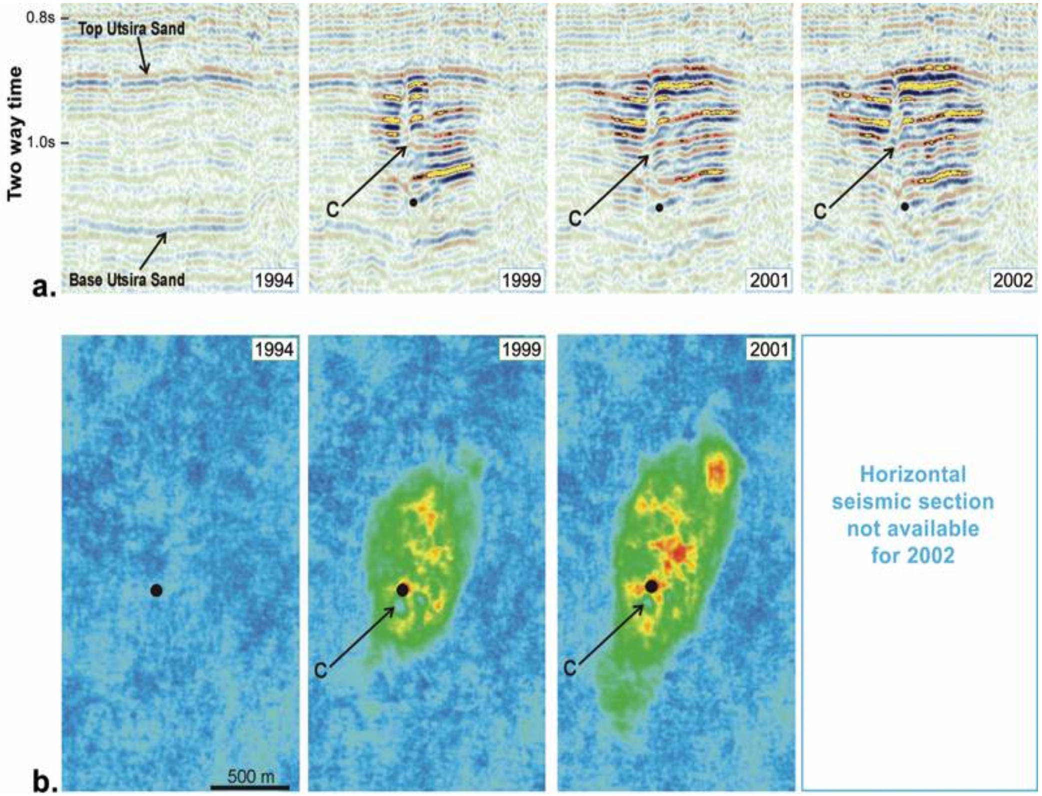
"… the fraction retained in appropriately selected and managed geological reservoirs is likely to exceed 99% over 1,000 years."

IPCC, 2005

Seismic Monitoring Data from Sleipner



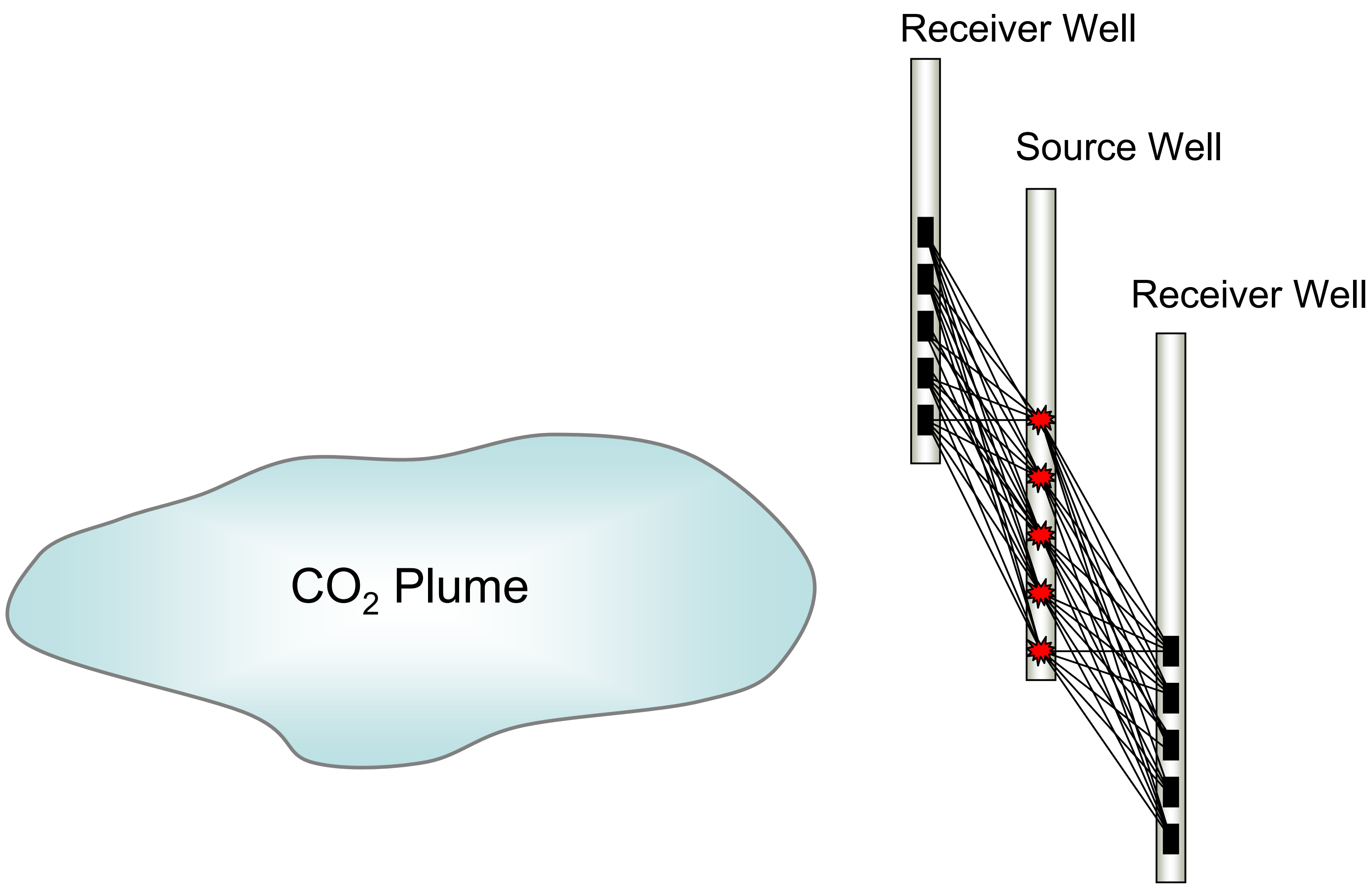
Sleipner Aquifer Storage Project



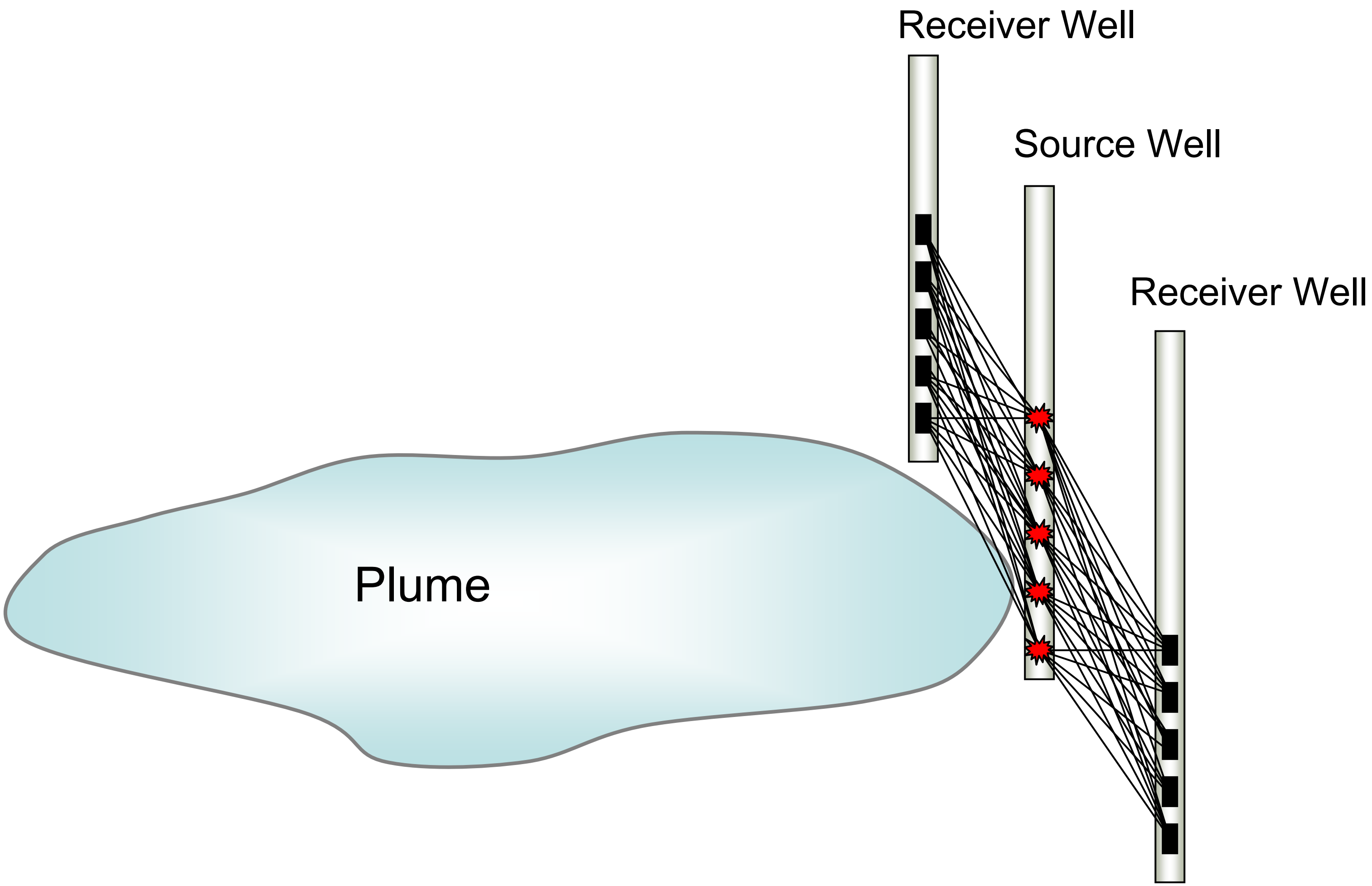
From Andy Chadwick, 2004

Photo and image, courtesy of Statoil

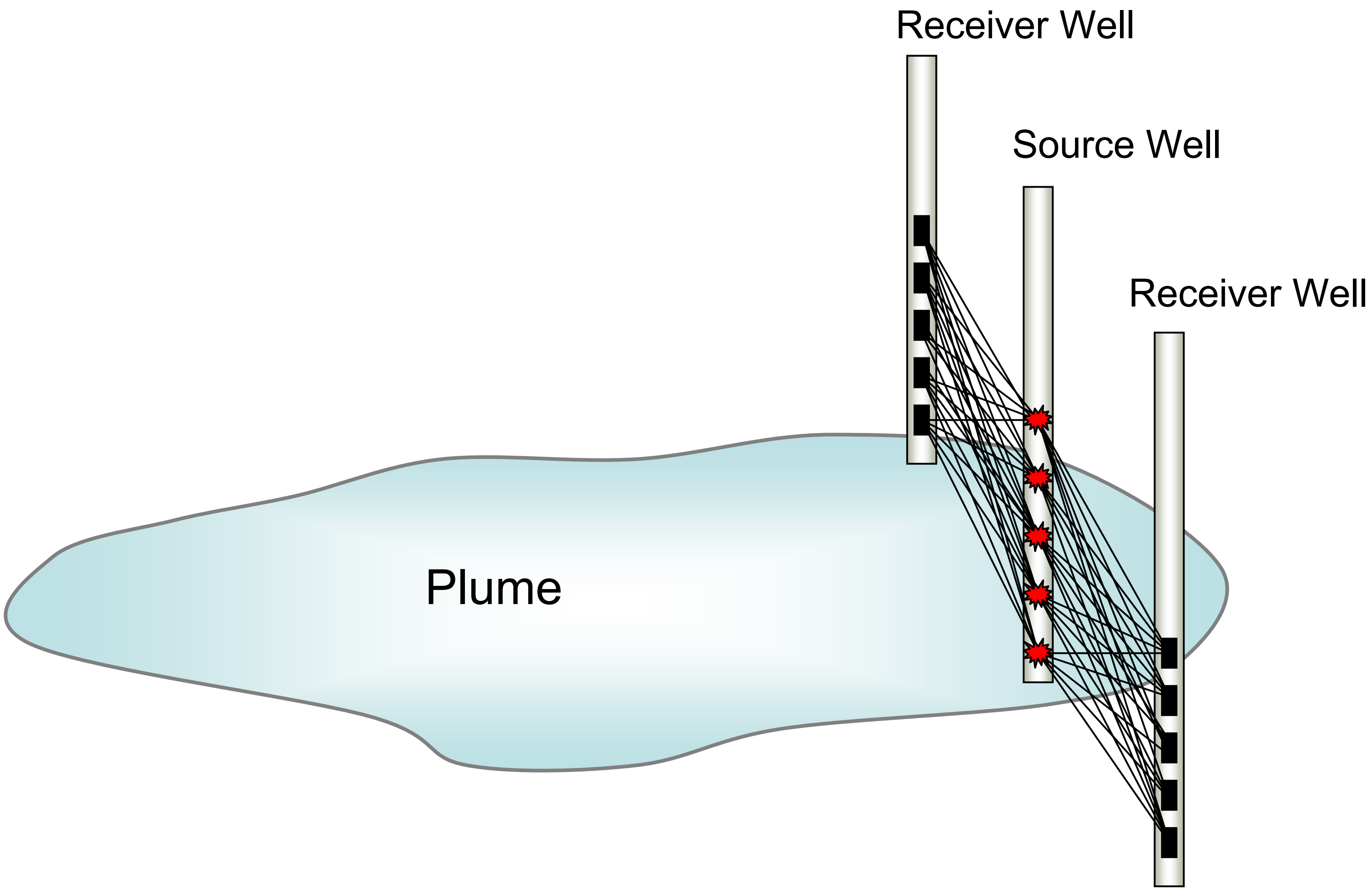
An Alternative Approach: Real-Time Seismic Monitoring



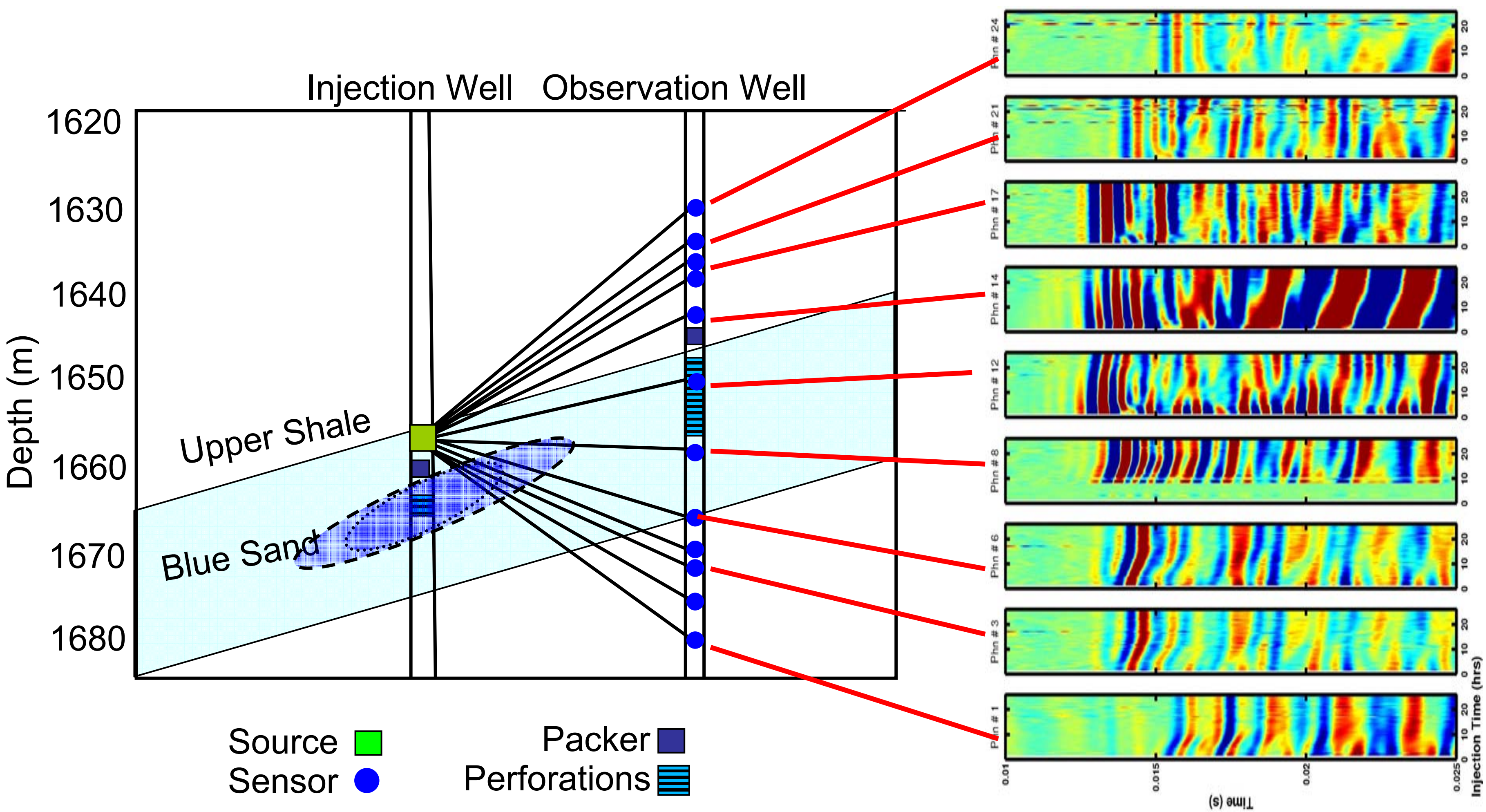
An Alternative Approach: Real-Time Seismic Monitoring



An Alternative Approach: Real-Time Seismic Monitoring

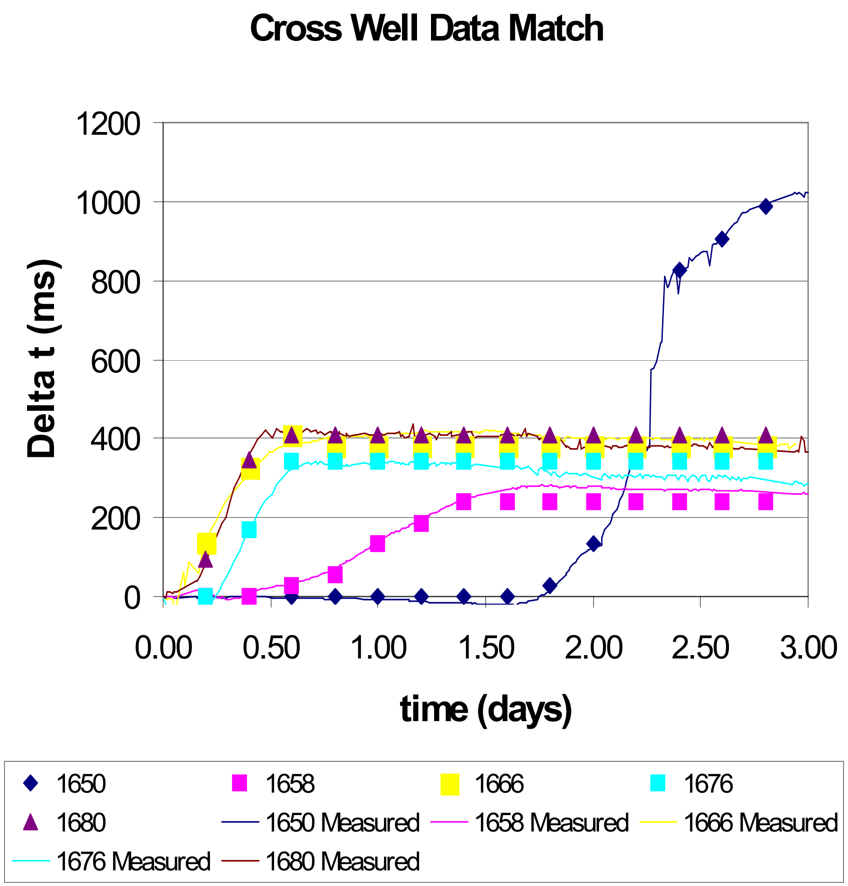


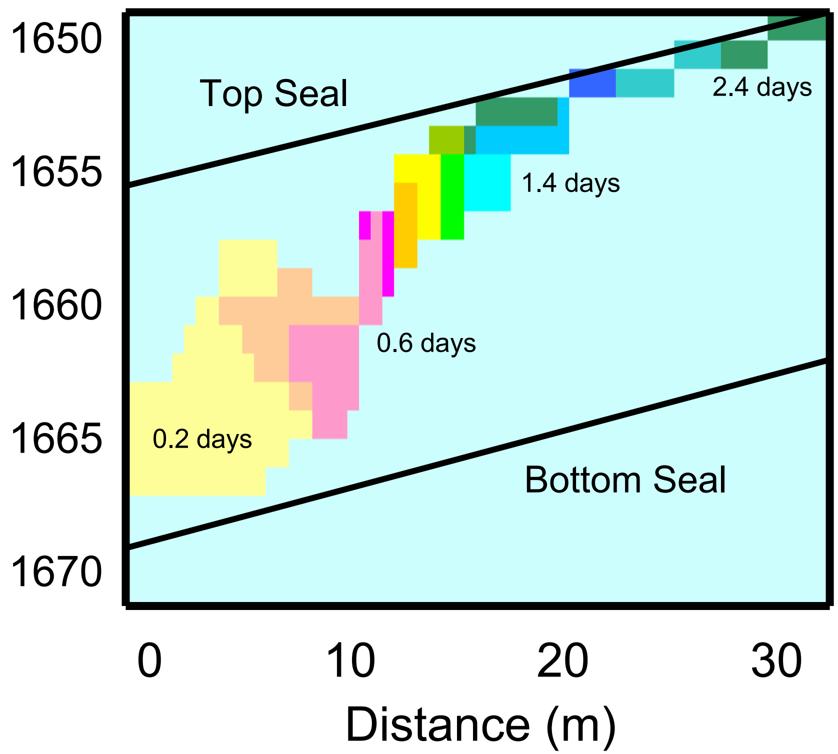
Proof of Concept: Real-Time Seismic Monitoring



Daley, et al, Geophysics, in press.

Real-Time CO_2 Tracking





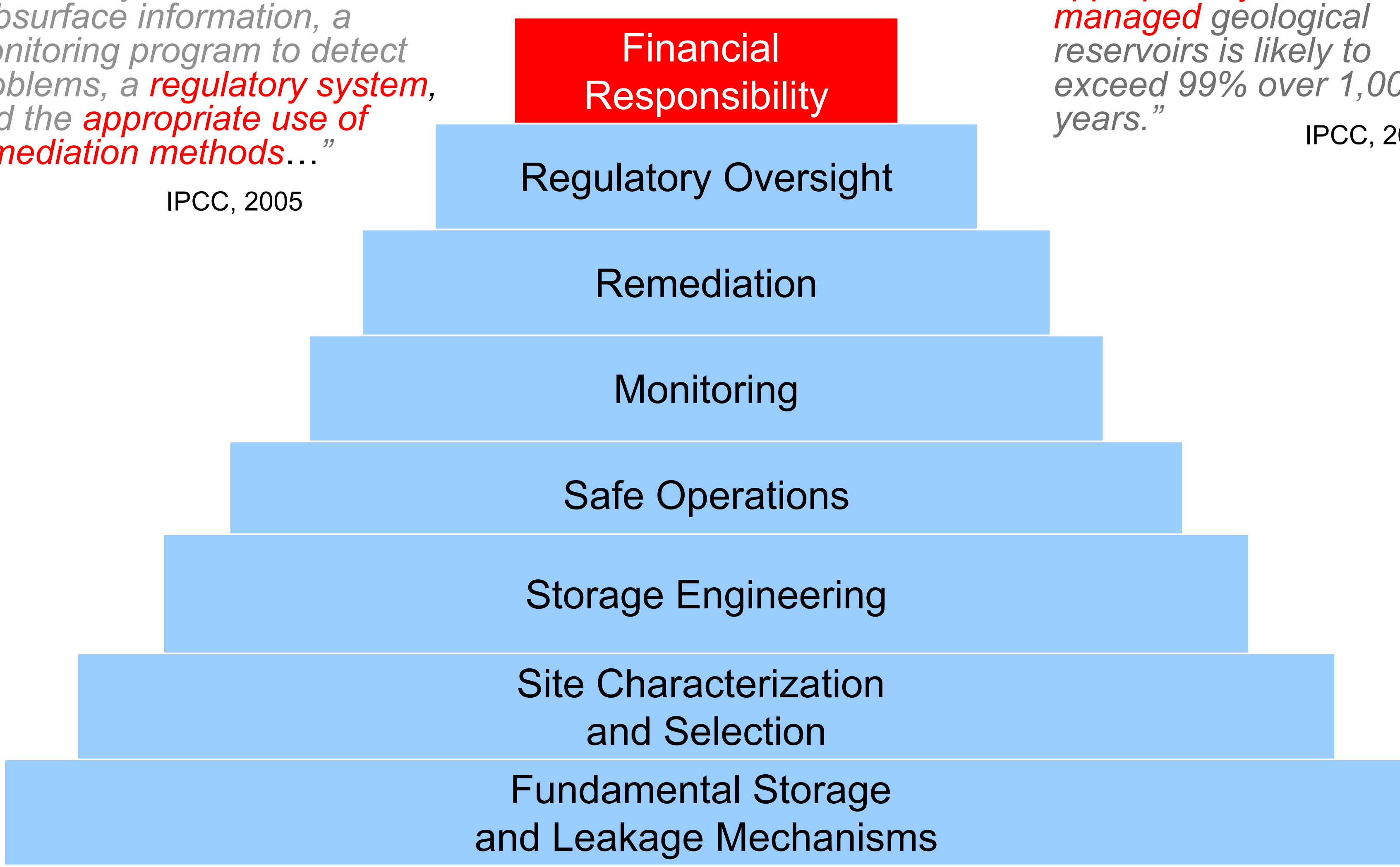
Geological Storage Safety and Security Pyramid

*" 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**…"*

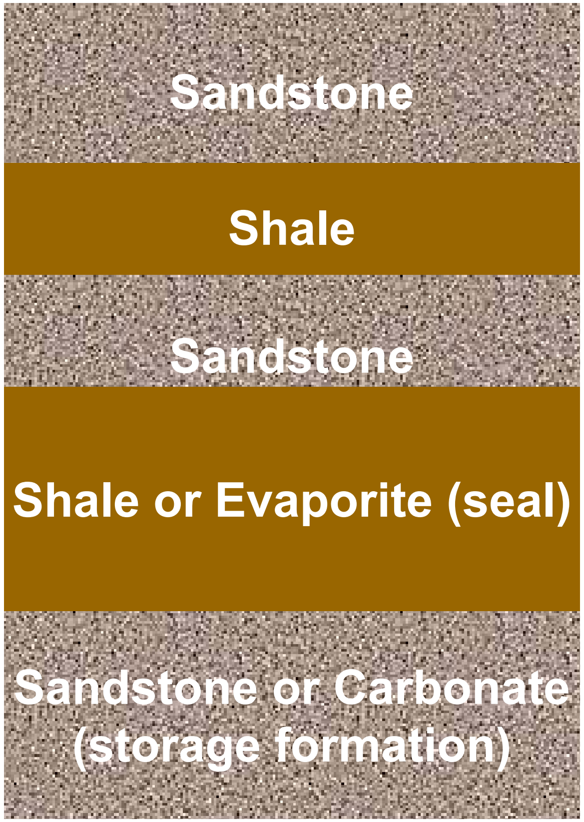
IPCC, 2005

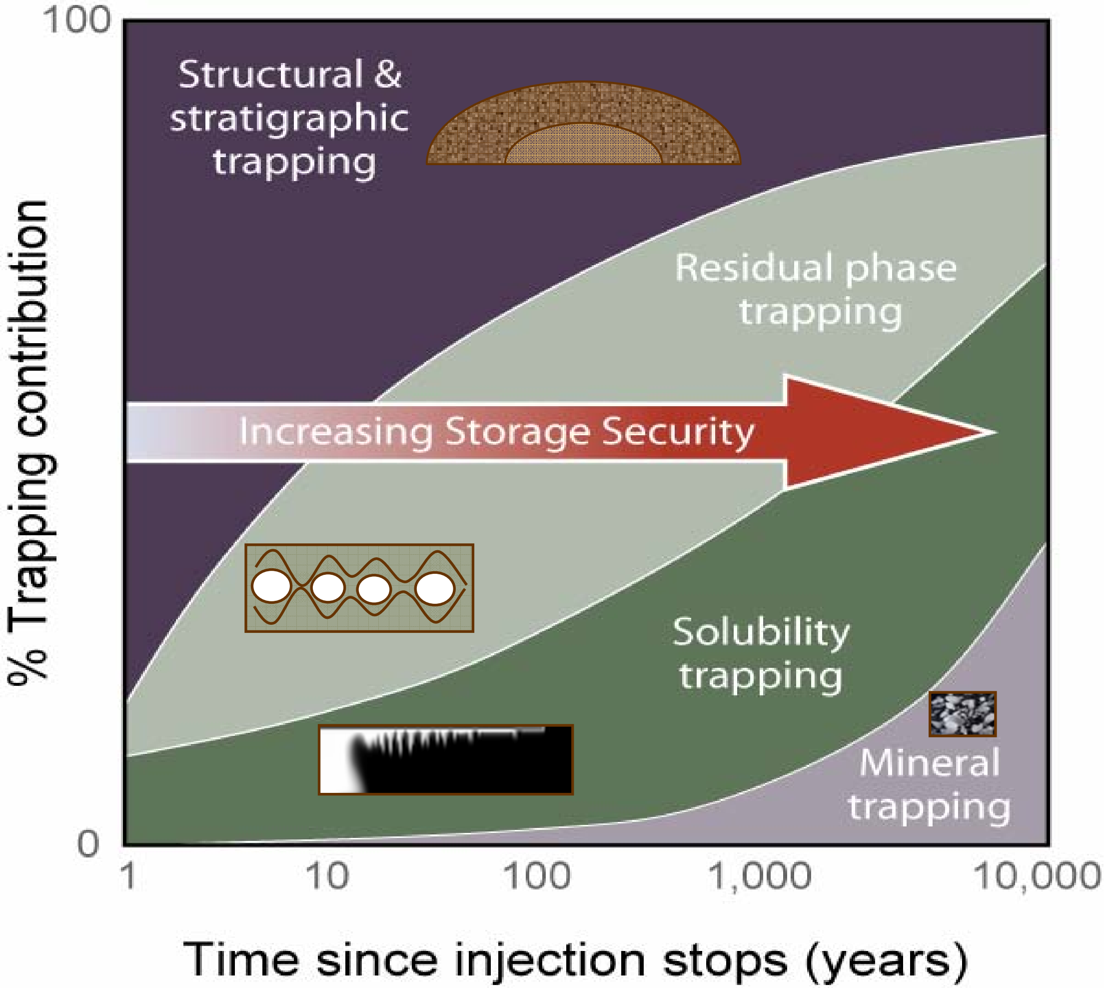
*"… the fraction retained in **appropriately selected and managed** geological reservoirs is likely to exceed 99% over 1,000 years."*

IPCC, 2005

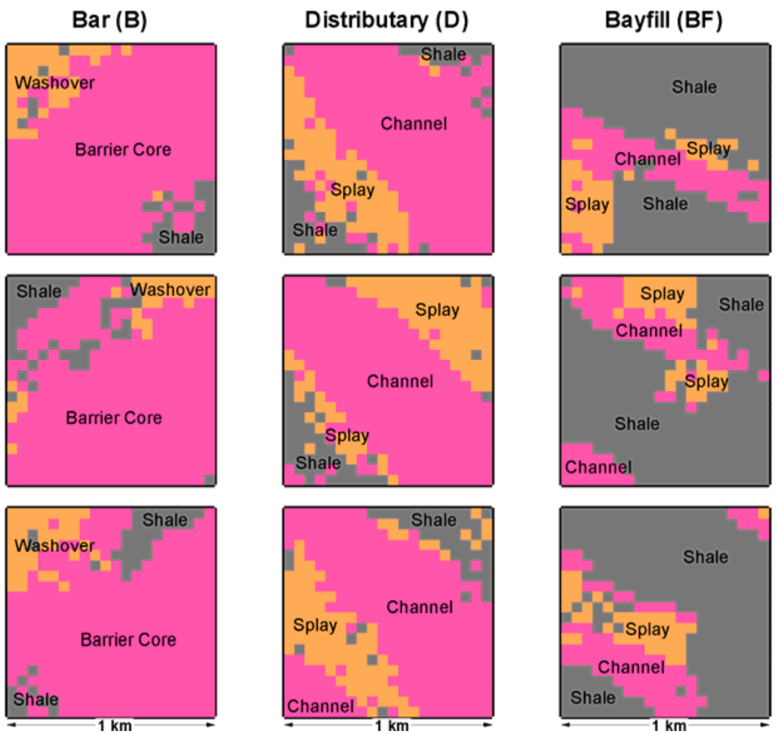


Primary and Secondary Trapping Mechanisms

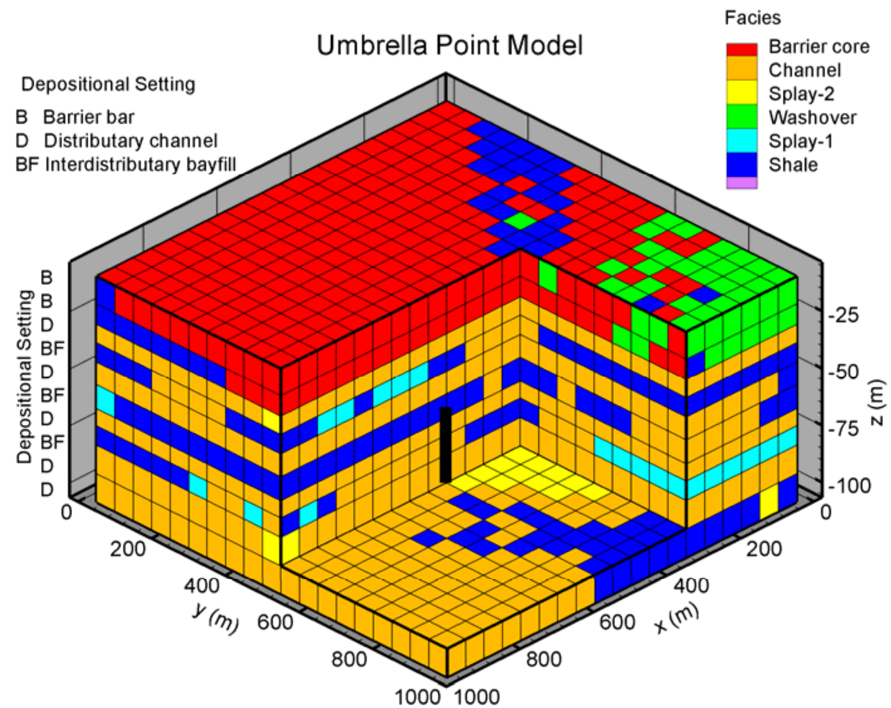




Quantifying Secondary Trapping Mechanisms

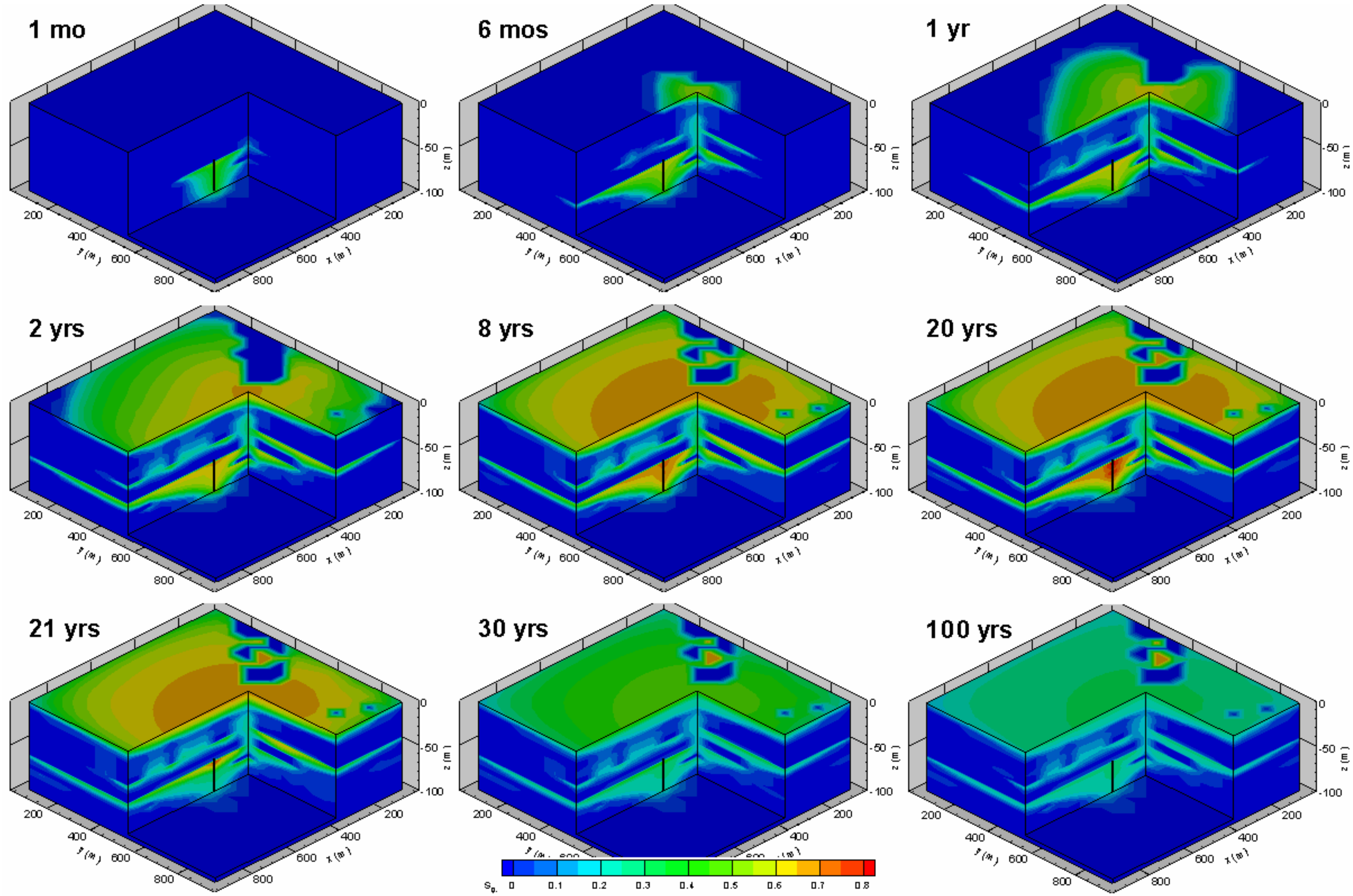


Geological Model



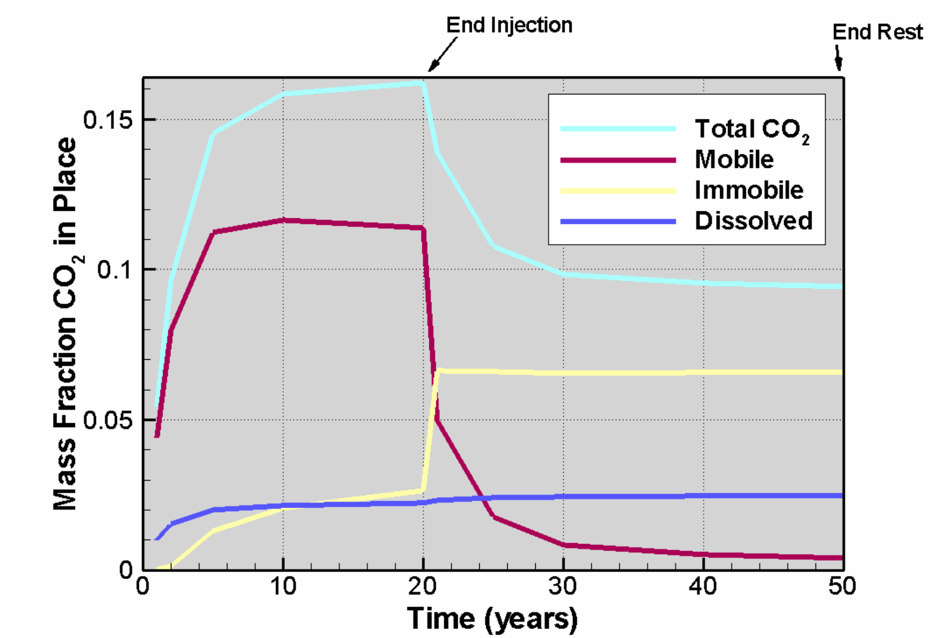
Computational Grid

Numerical Simulations of Plume Movement and Trapping

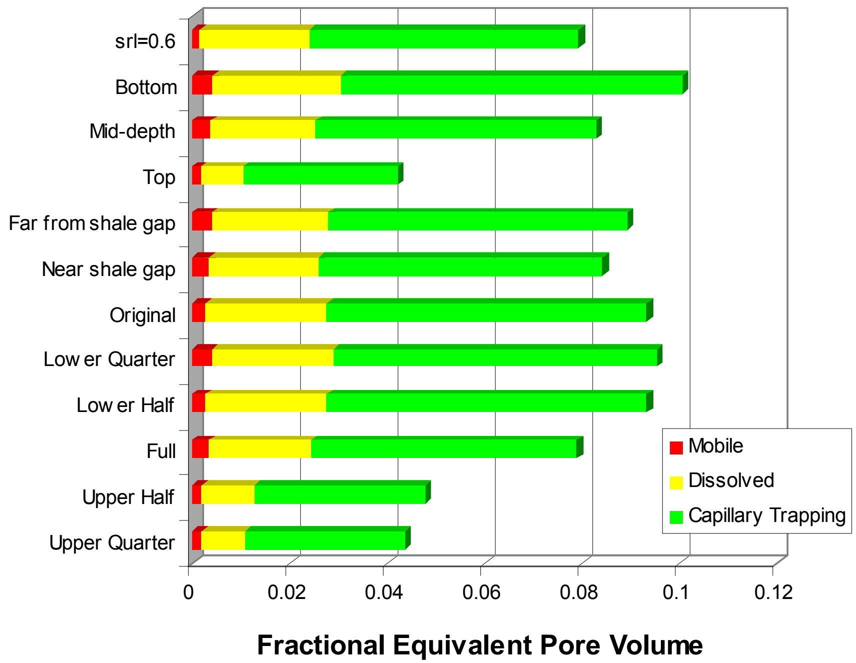


From Doughty and Benson, 2006

Trapping Rates and Efficiency

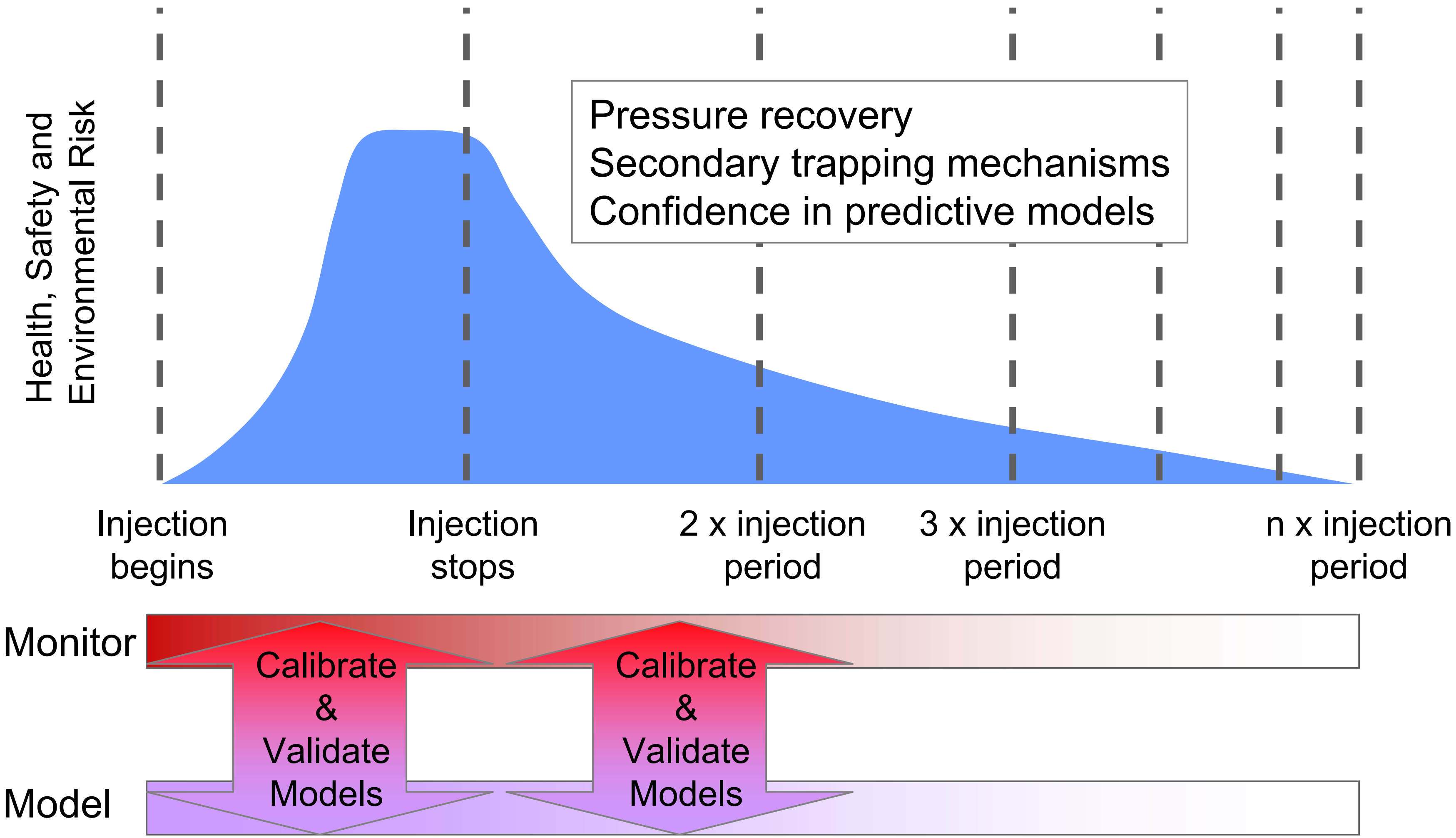


Simulated Trapping

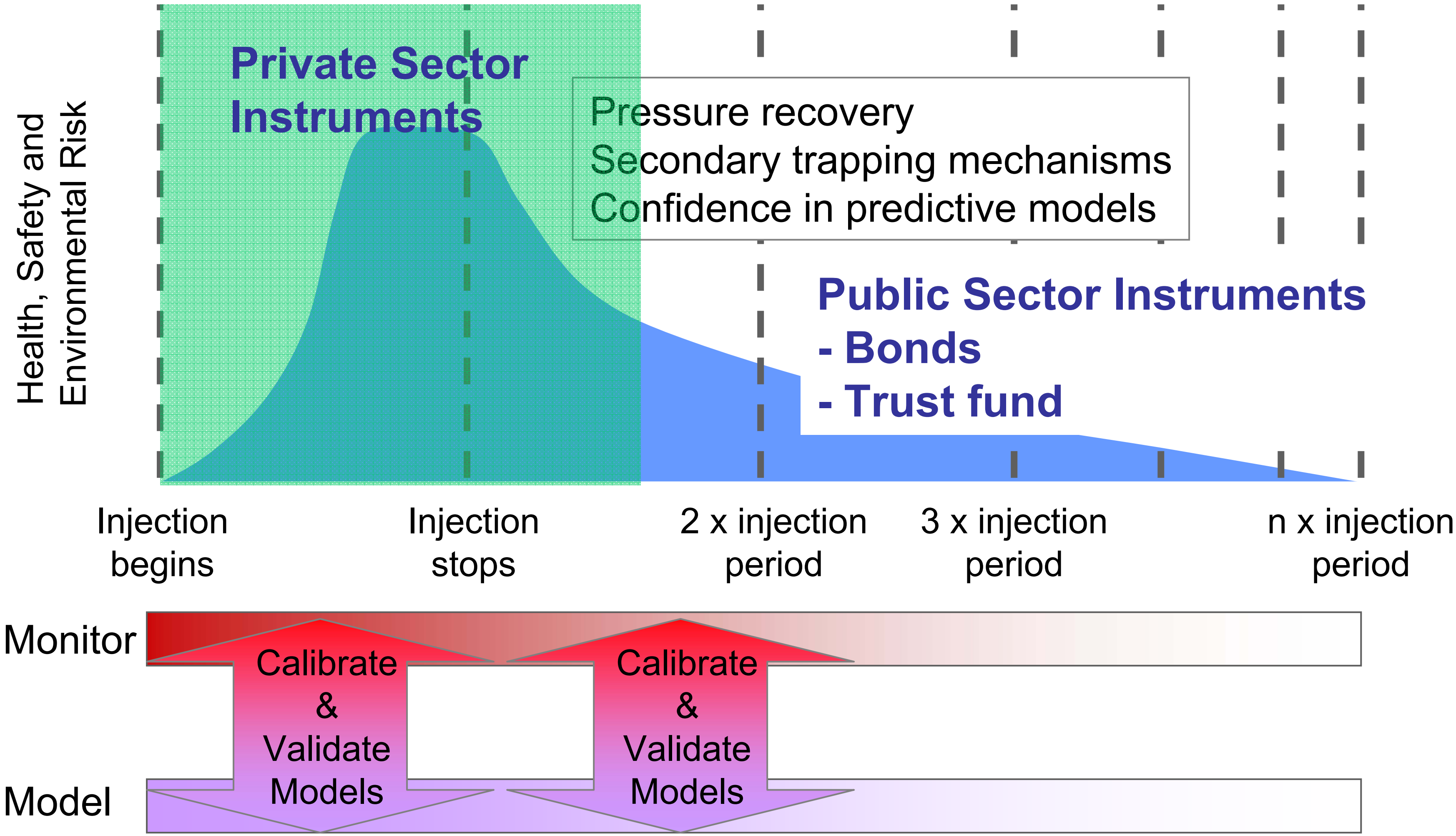


CO_2 Trapping 30-Years Post Injection

Conceptual Risk Profile for Geological Storage



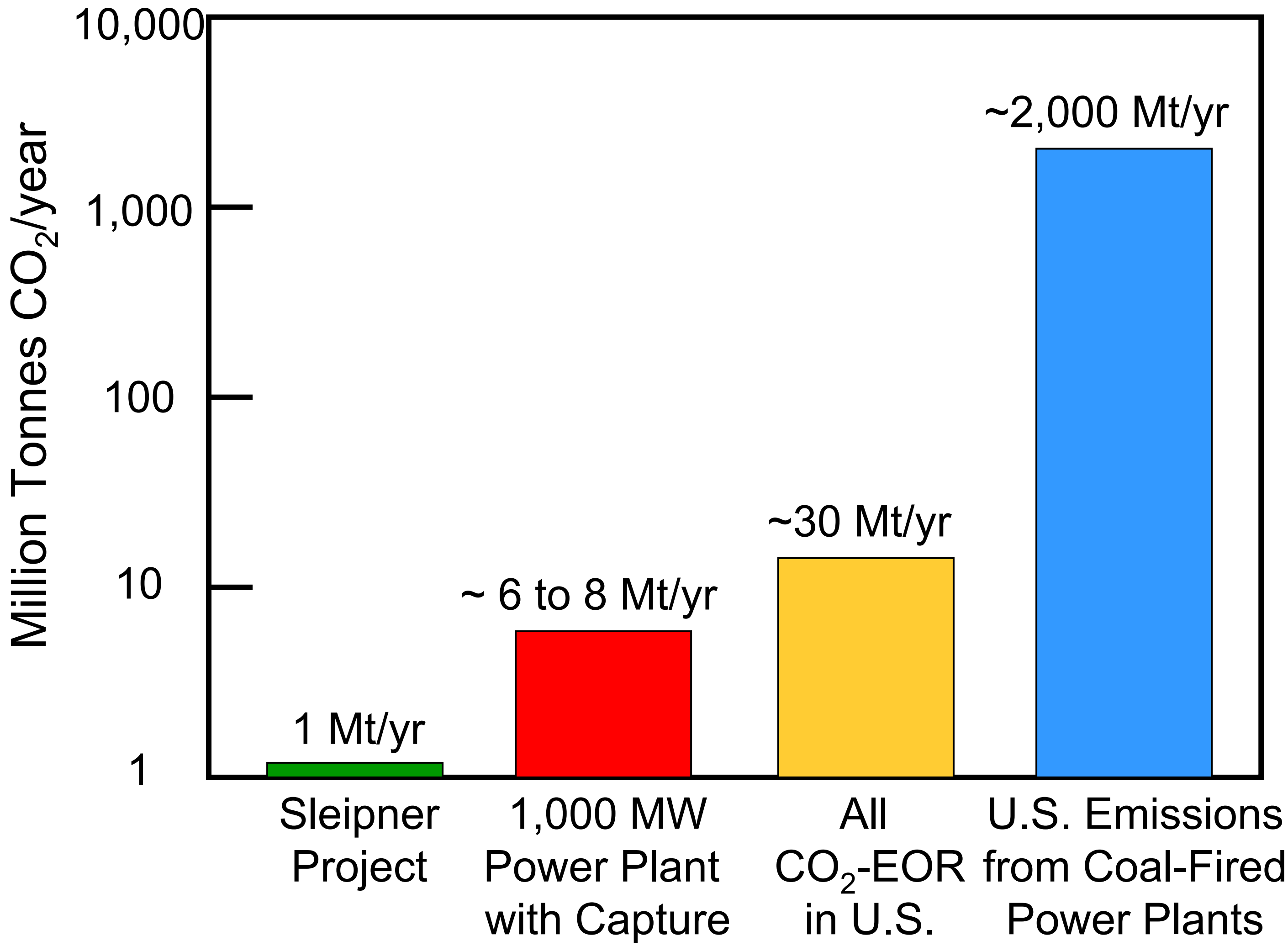
Phased Approach and Hybrid to Financial Responsibility



Fundamental Research Needs

Influence of heterogeneity at all scales on plume migration	→ Greater confidence in simulation models
Geochemical reactions and kinetics in multi-phase flow systems	→ Greater confidence in mineral trapping
Dynamic imaging of complex multi-phase flows	→ Better quality monitoring
Geomechanical and hydrological effects of large anthropogenic perturbations	→ Better knowledge of CO_2 leakage and brine migration potential
Flow and transport properties of seals, faults and fractures	→ More reliable seal assessment and site selection

The Scale is Large



Integrated Technology Development Pathway