Stanford University

GCEP Global Climate & Energy Project

Google Energy Seminar
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Carbon Dioxide Capture and Sequestration: Hype or Hope?

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Science and technology for a low GHG emission world.

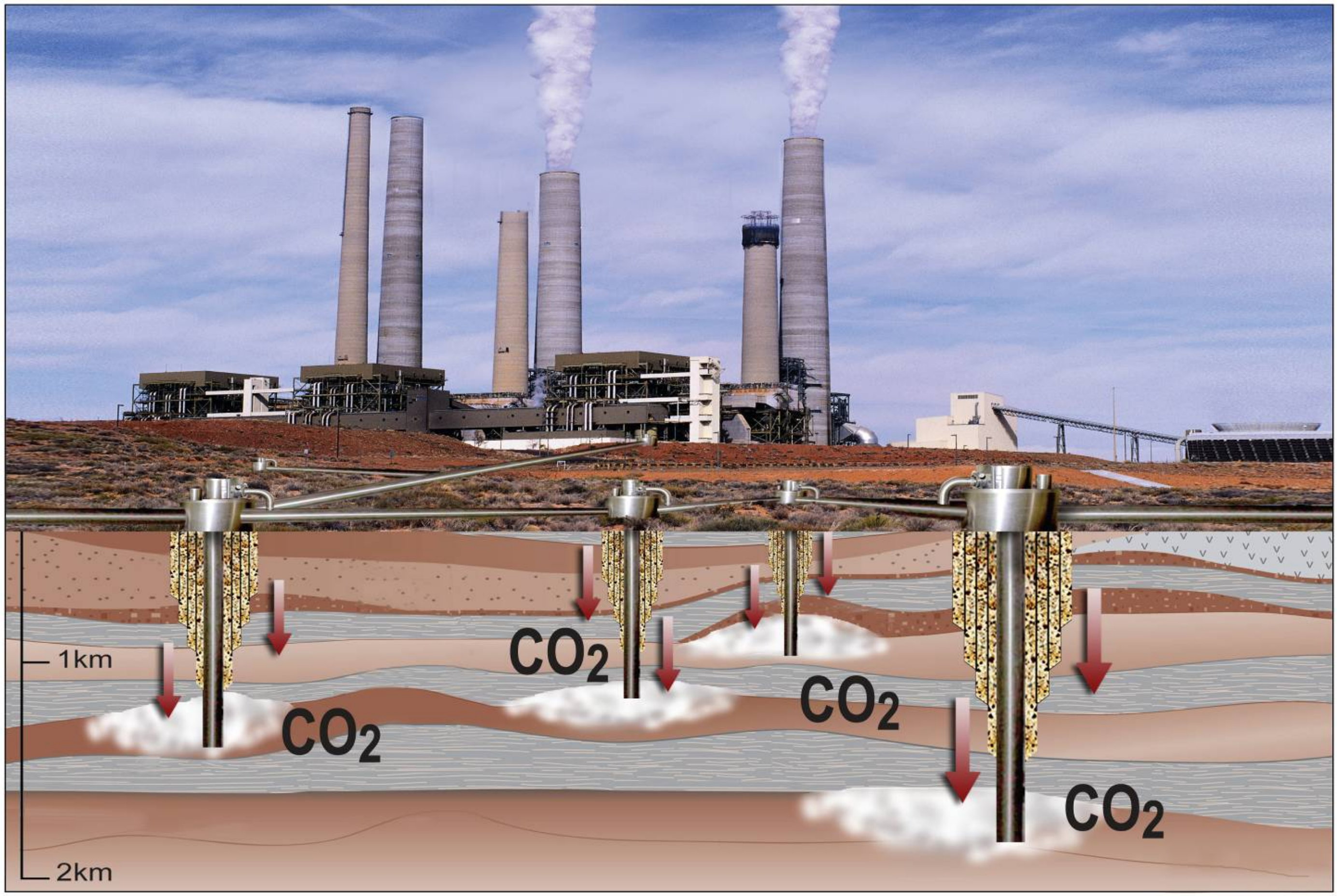
Contradicting Views About CCS

- Hope?
  - CCS can result in 20% of needed emissions reductions over the next 100 years
  - Without CCS, were in trouble
  - All components of CCS technology are available today, we just need to put them together
  - We’ve been doing this for 30 years in oilfields
  - Just do it!
- Hype?
  - CCS is extremely expensive
  - Environmental risks are unacceptably high
  - CO_2 will leak back to the surface
  - Institutional barriers are too high

Key Questions

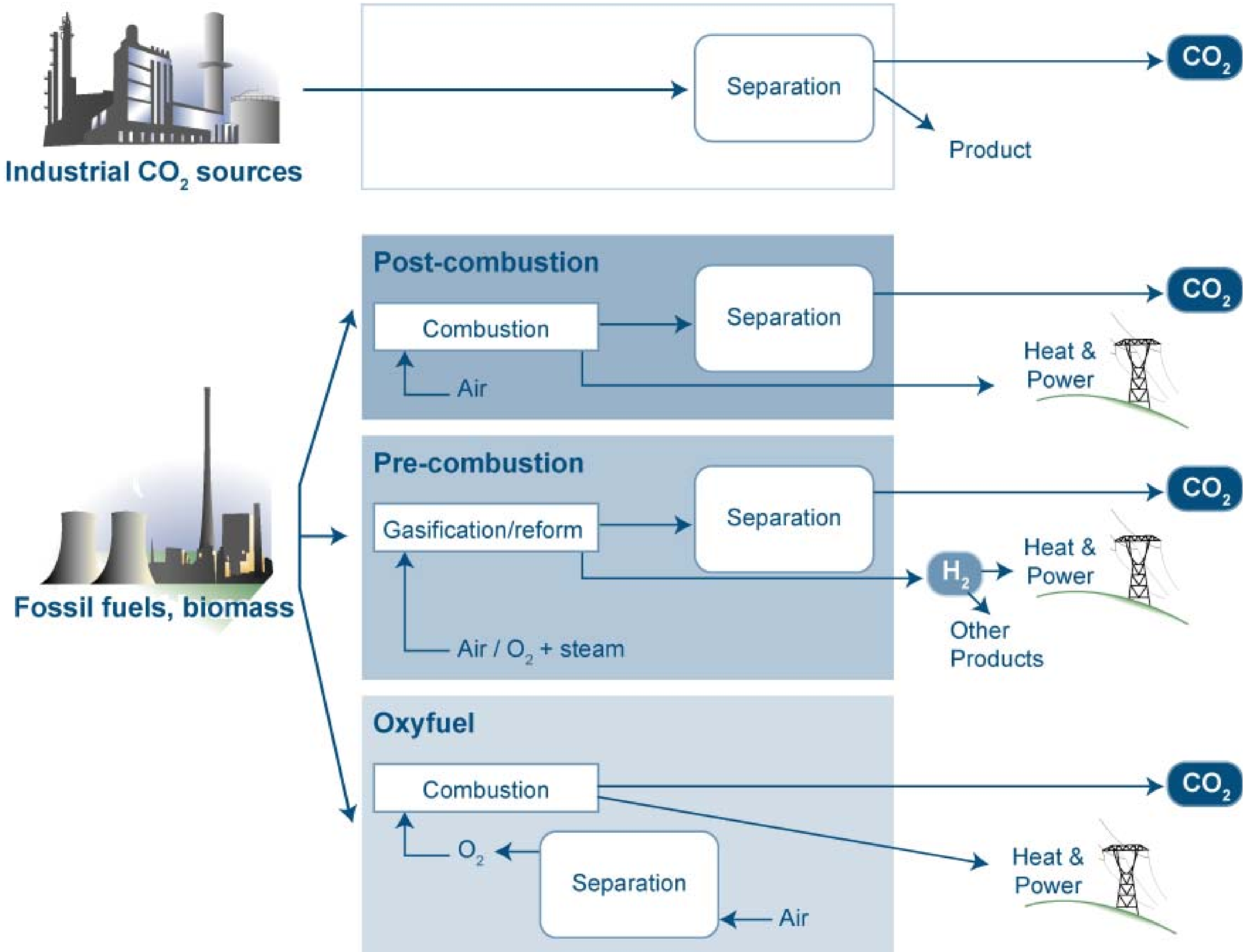
- Is capture technically feasible?
- Will CO_2 leak back to the surface?
- Will CO_2 storage create unacceptable environmental hazards?
- Is there enough storage capacity?
- Will CCS be too costly to implement?
- Will non-technical issues impede deployment?

Carbon Dioxide Capture and Geologic Storage



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

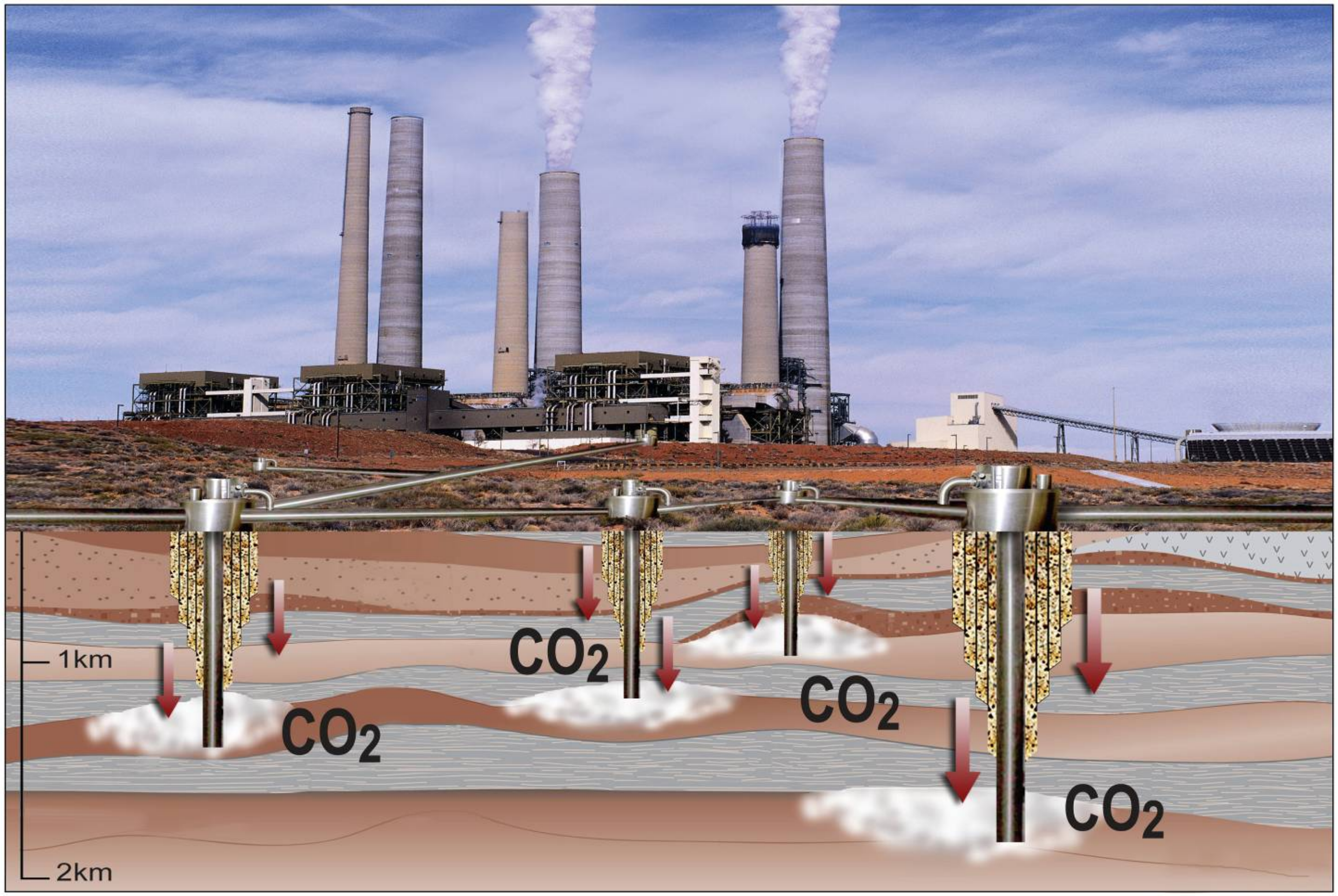
Options for CO_2 Capture



Comparison of Capture Options

Technology	Advantages	Drawbacks
Post-Combustion	• Mature technology • Standard retrofit	• High energy penalty (~30%) • High cost for capture
Pre-Combustion (IGCC)	• Lower costs than post-combustion • Lower energy penalties (10-15%) • H_2 production	• Complex chemical process • Repowering • Large capital investment
Oxygen-Combustion	• Avoid complex post-combustion separation • Potentially higher generation efficiencies	• New materials • Oxygen separation • Repowering

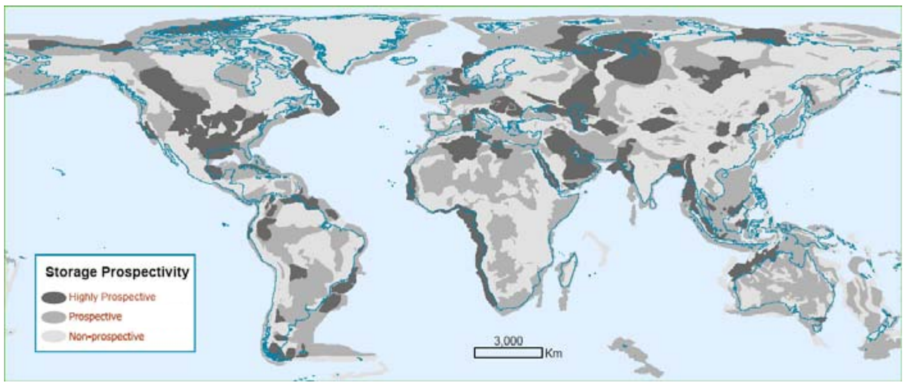
Carbon Dioxide Capture and Geologic Storage



Capture → Compression → Pipeline Transport → Underground Injection

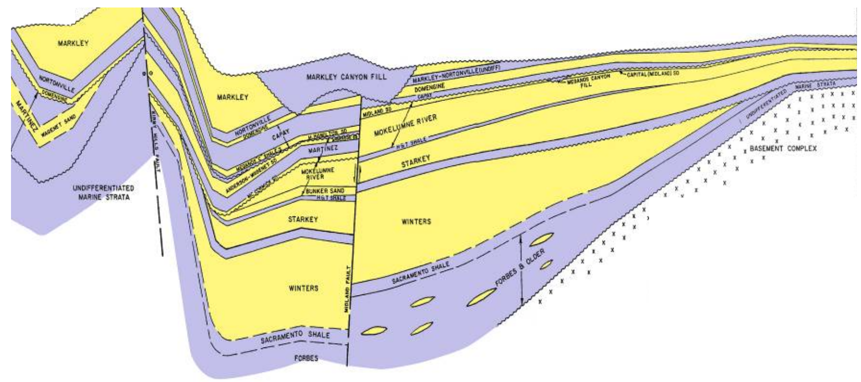
What Types of Rock Formations are Suitable for Geological Storage?

Rocks in deep sedimentary basins are suitable for CO_2 storage.



Map showing world-wide sedimentary basins ranked according to prospectivity for storage

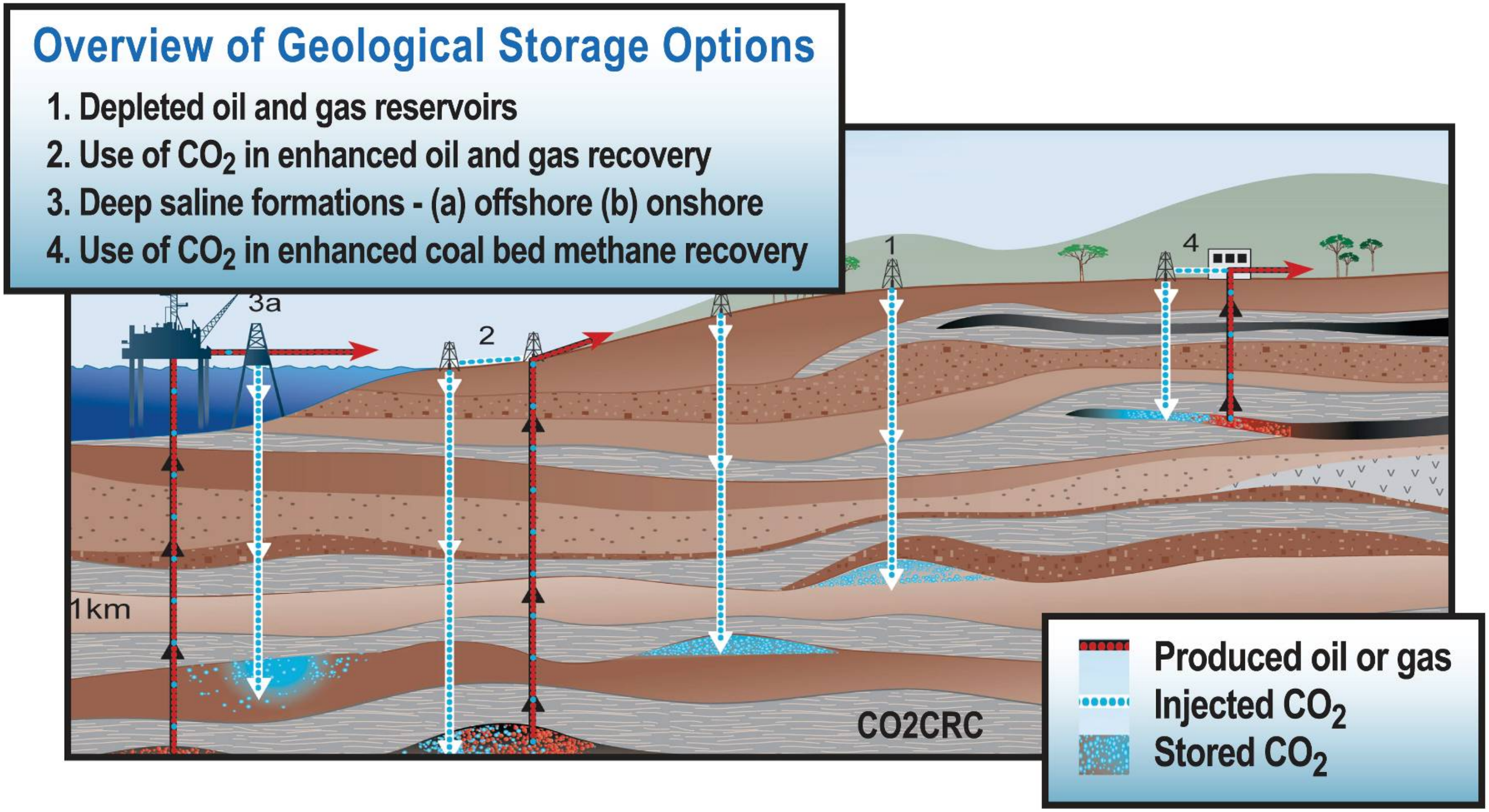
← 100 km →



Northern California Sedimentary Basin

Example of a sedimentary basin with alternating layers of coarse and fine textured sedimentary rocks.

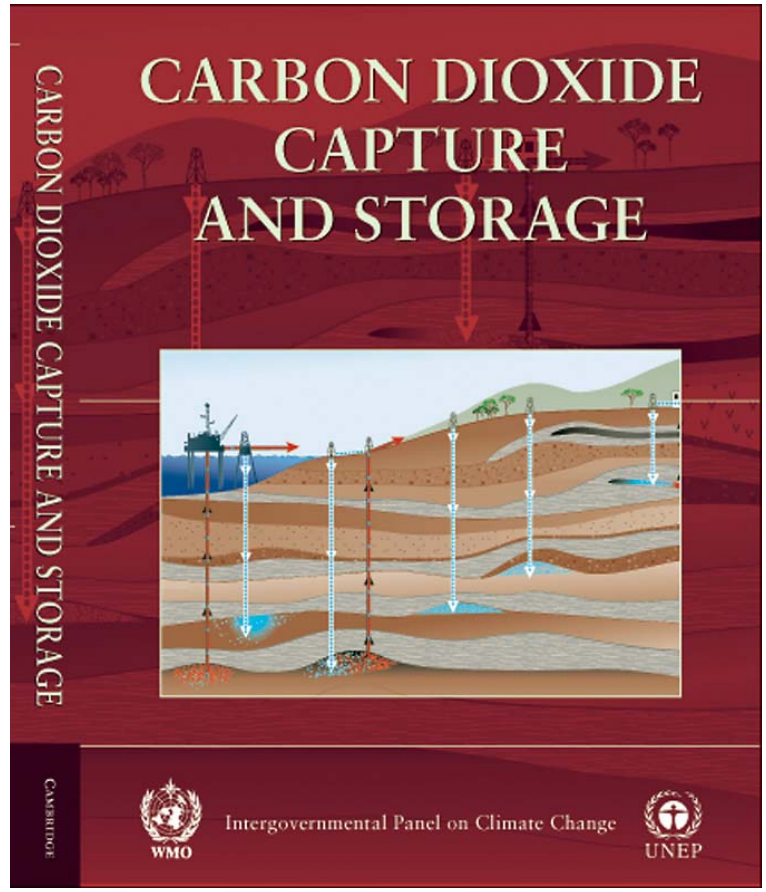
Options for Geological Storage



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."

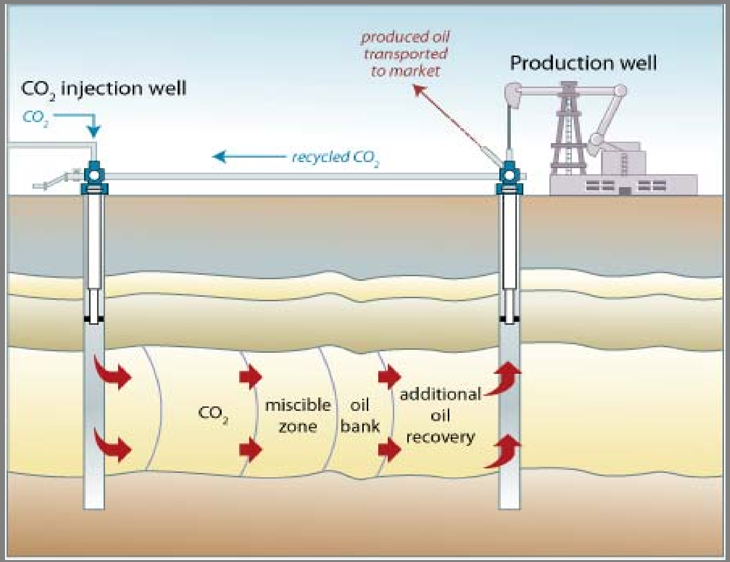


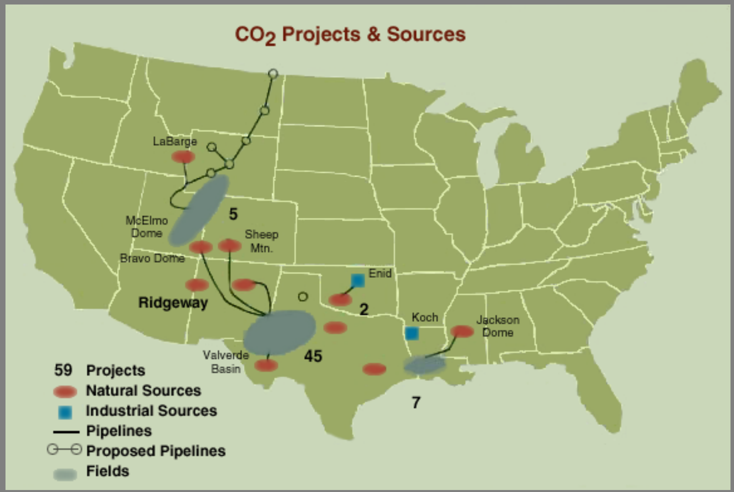
* "Very likely" is a probability between 90 and 99%.

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

Evidence to Support these Conclusions

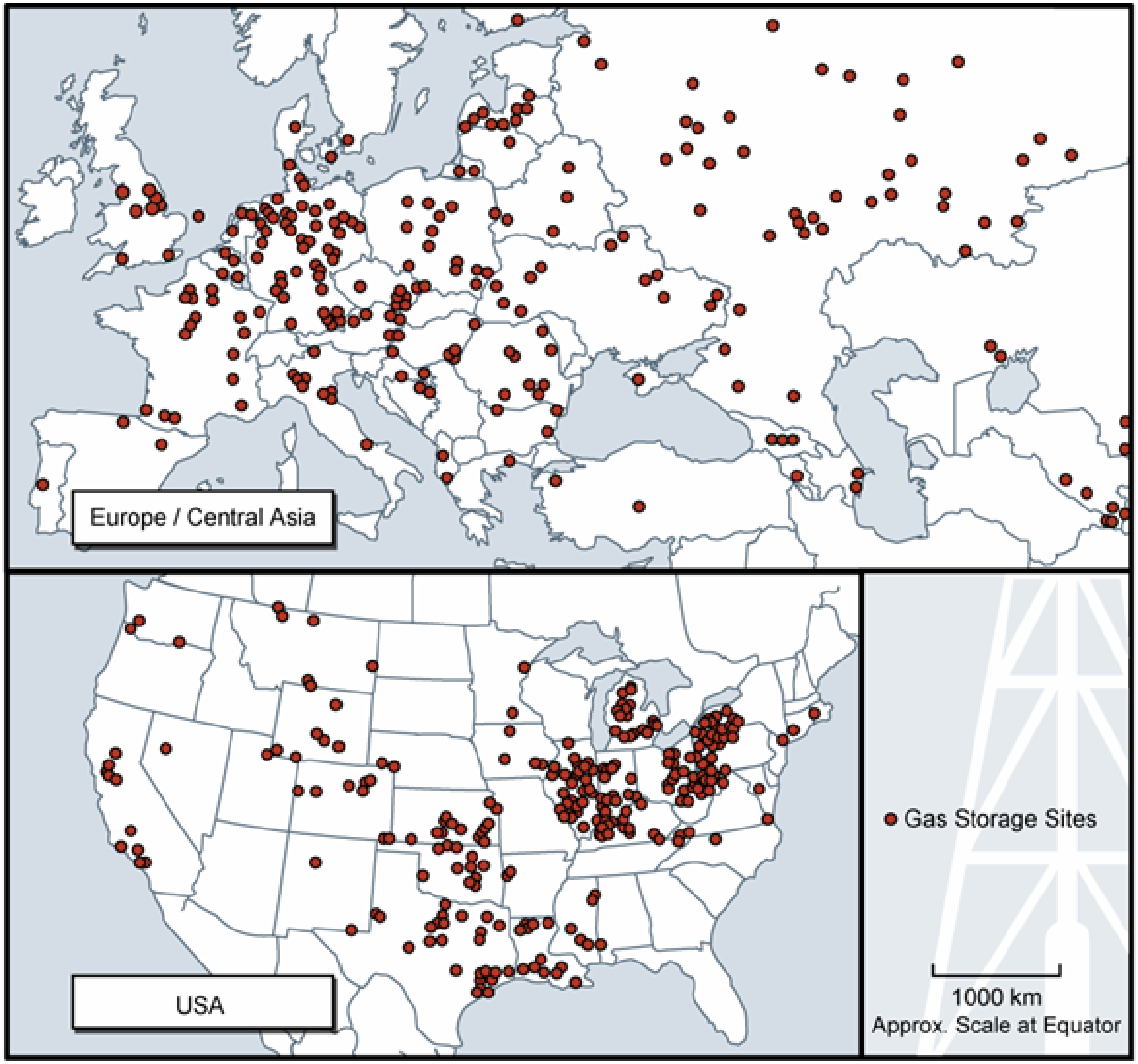
- Natural analogs
  - Oil and gas reservoirs
  - CO_2 reservoirs
- Performance of industrial analogs
  - 30+ years experience with CO_2 EOR
  - 100 years experience with natural gas storage
  - Acid gas disposal
- 20+ years of cumulative performance of actual CO_2 storage projects
  - Sleipner, off-shore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





~35 Mt/yr are injected for CO_2-EOR

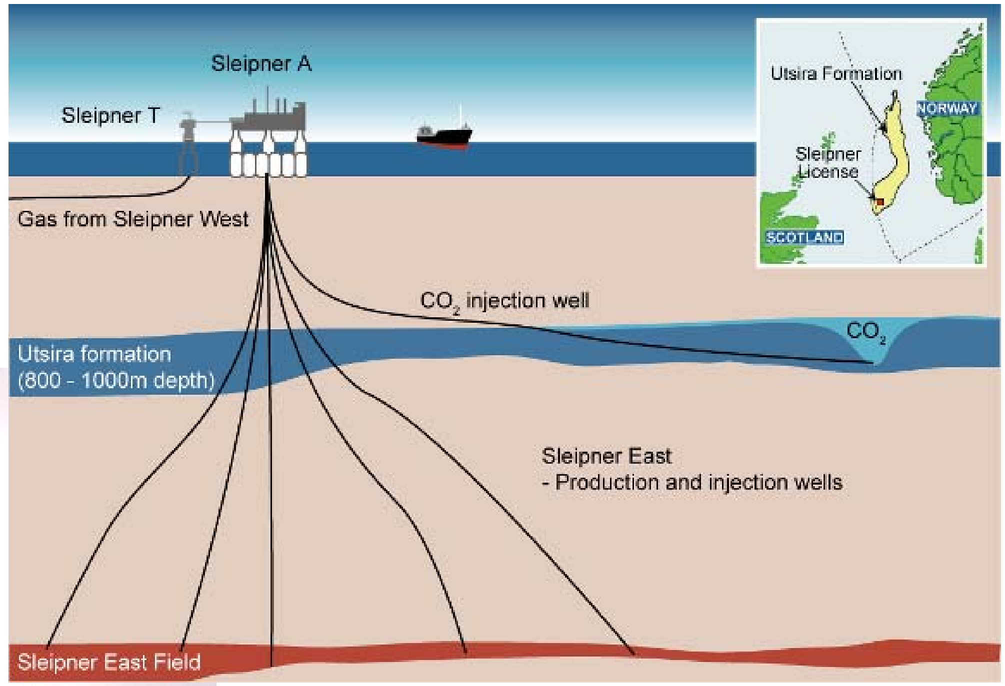
Natural Gas Storage



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

Sleipner Project, North Sea

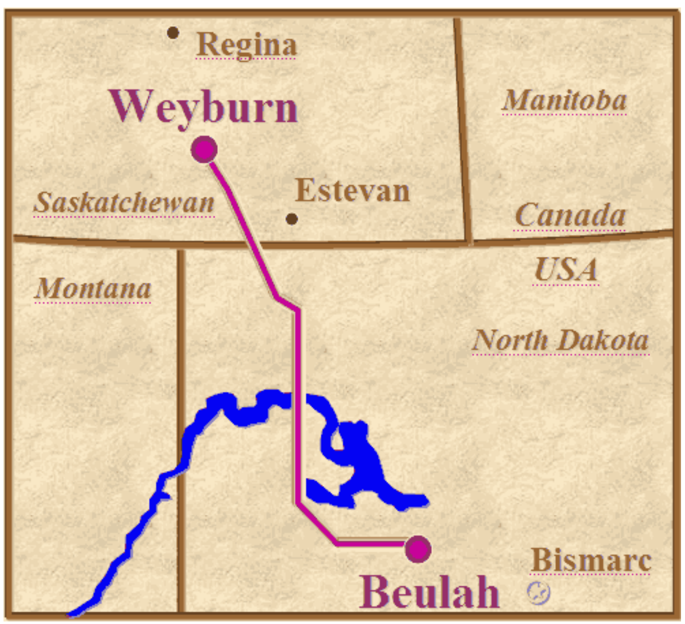
- 1996 to present
- 1 Mt CO_2 injection/yr
- Seismic monitoring



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.



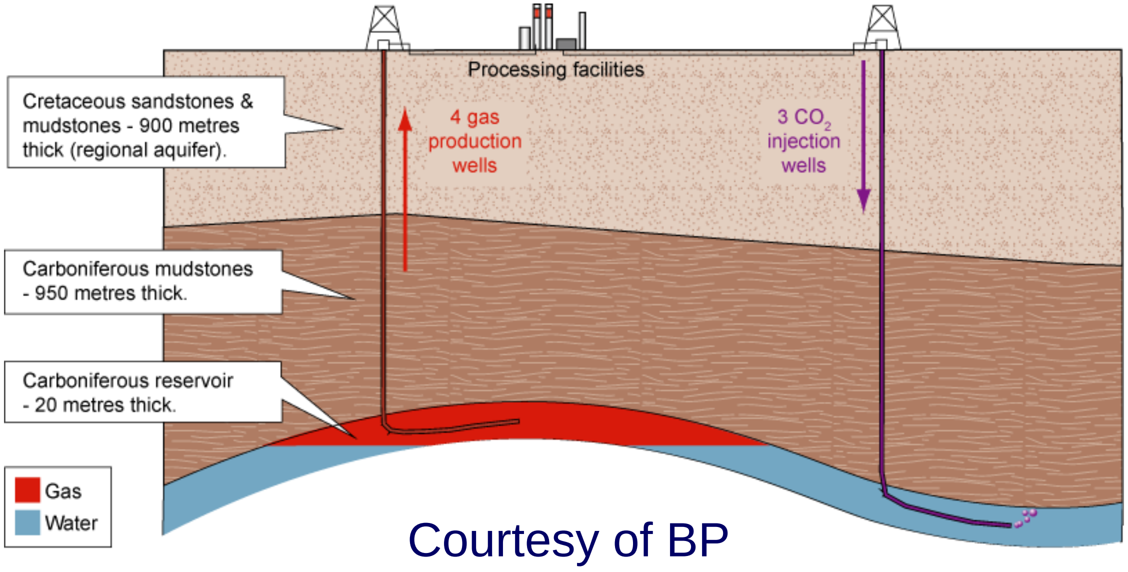
In Salah Gas Project

In Salah Gas Project
- Krechba, Algeria

Gas Purification
- Amine Extraction

o.6 Mt/year CO_2 Injection

Operations Commence
- June, 2004



Key Elements of a Geological Storage Safety and Security Strategy

" 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*…"

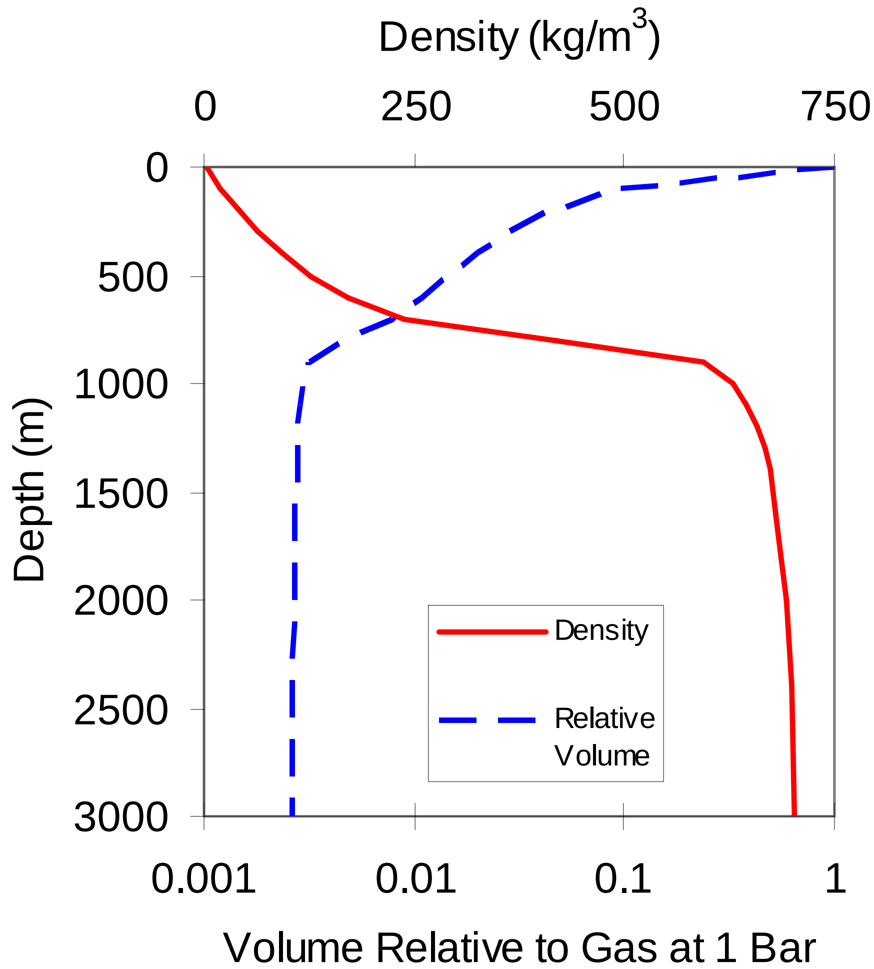
- Financial Responsibility
- Regulatory Oversight
- Remediation
- Monitoring
- Safe Operations
- Storage Engineering
- Site Characterization and Selection
- Fundamental Storage and Leakage Mechanisms

"… risks similar to existing activities such as natural gas storage and EOR."

"… the fraction retained is likely to exceed 99% over 1,000 years."

IPCC, 2005

Variation with Depth and Geothermal Regime of Carbon Dioxide Density



X-ray Micro-tomography at the Advanced Light Source

Micro-tomography Beamline

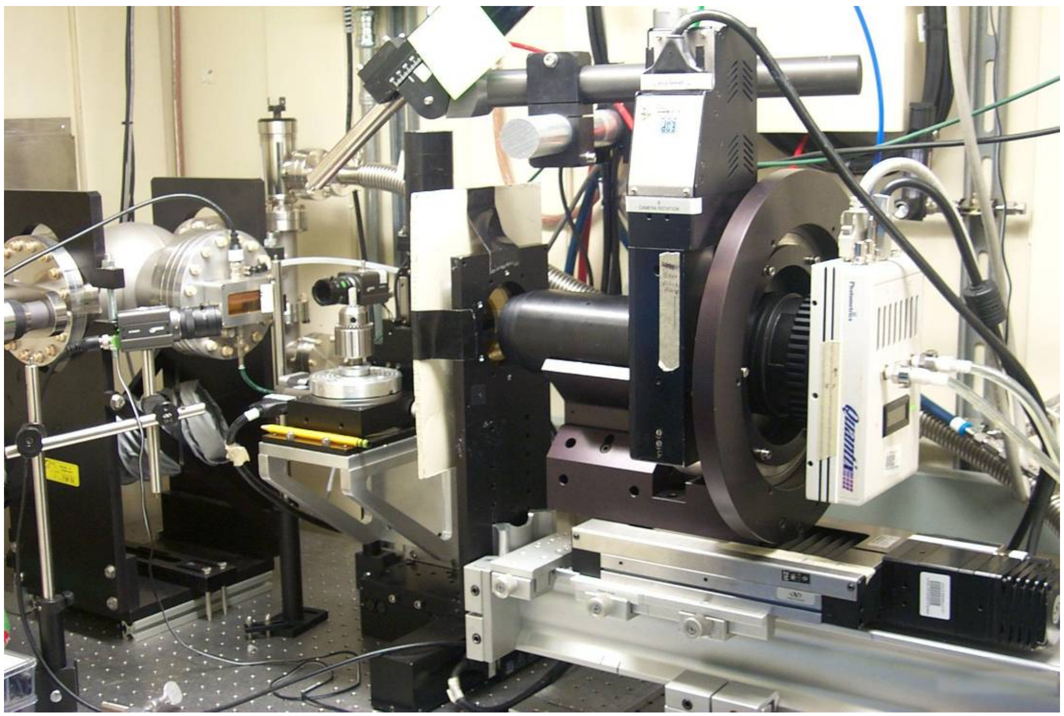
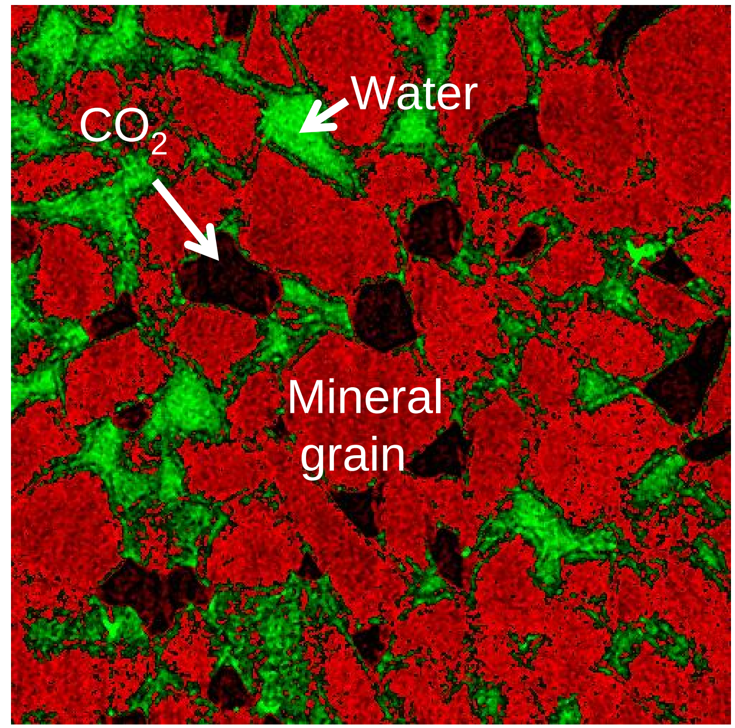


Image of Rock with CO_2



2 mm

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

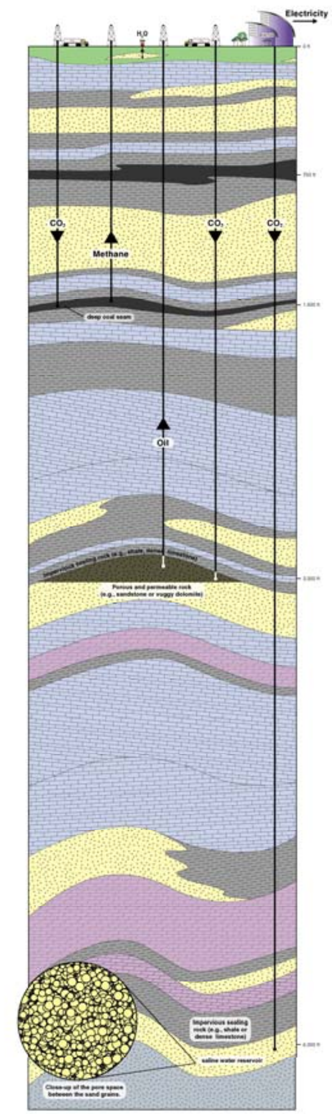
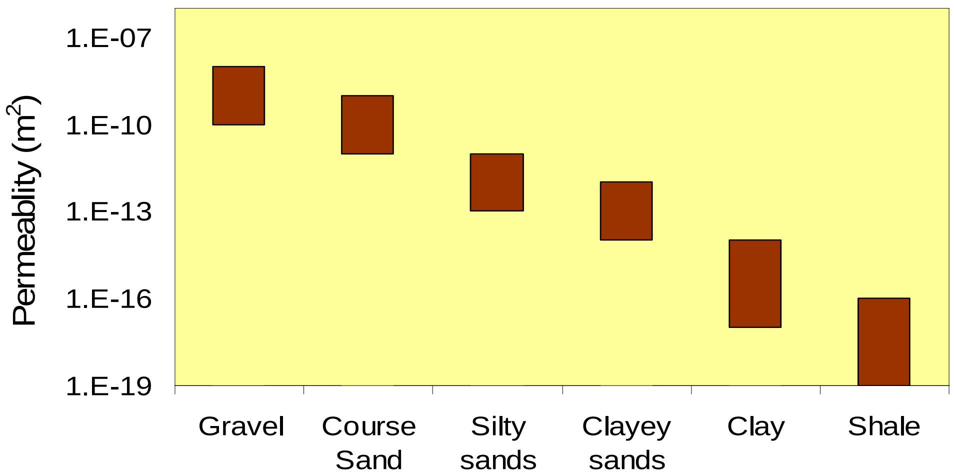
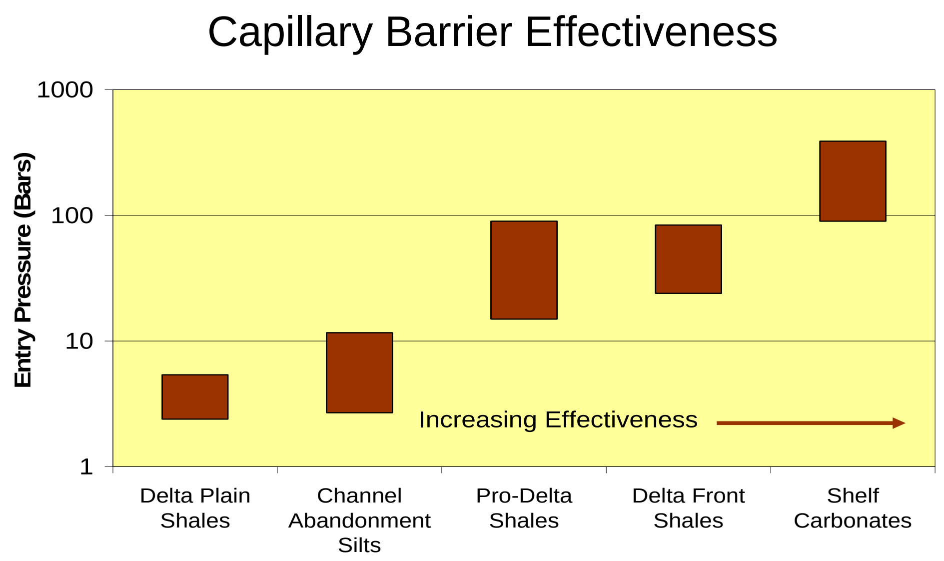


Image courtesy of ISGS and MGSC

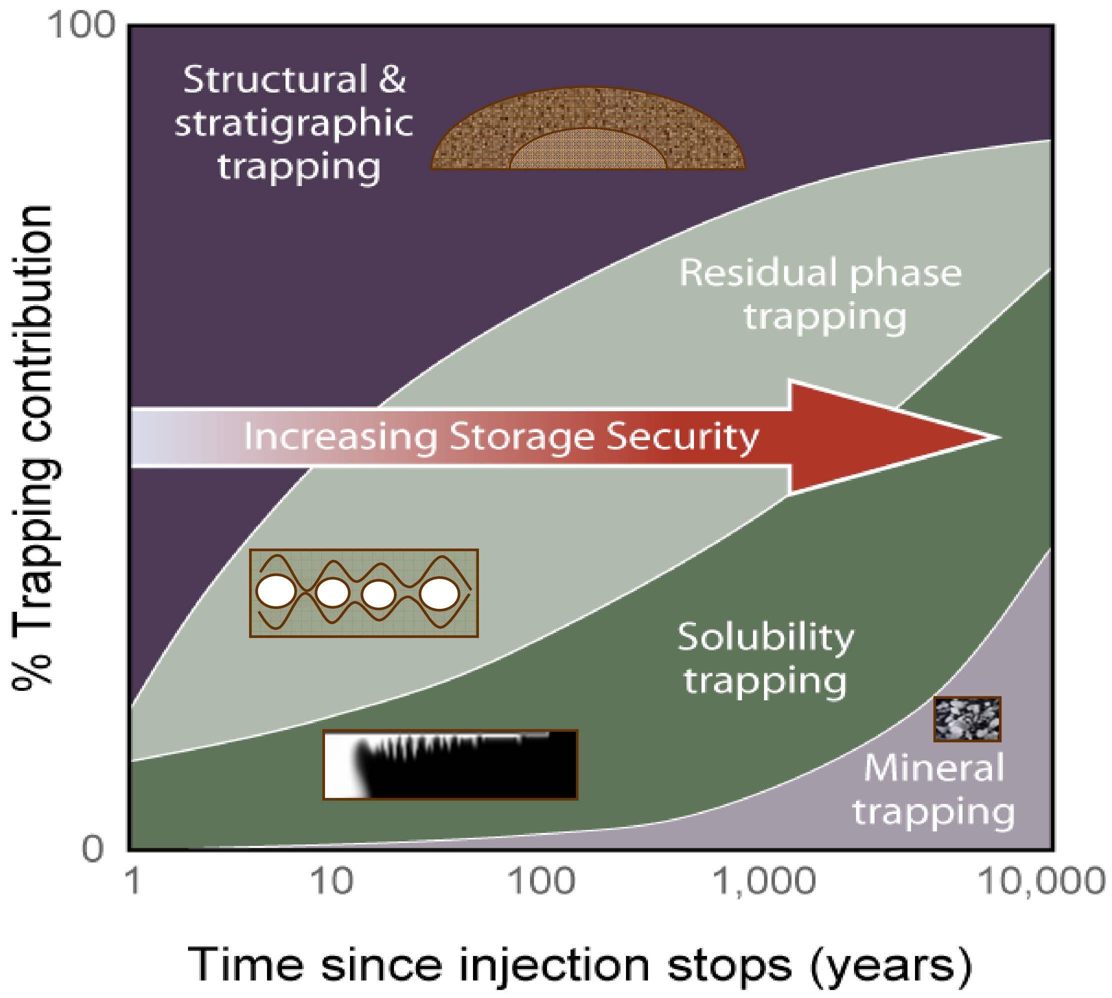
Seal Rocks and Mechanisms

- Shale, clay, and carbonates
- Permeability barriers to CO_2 migration
- Capillary barriers to CO_2 migration

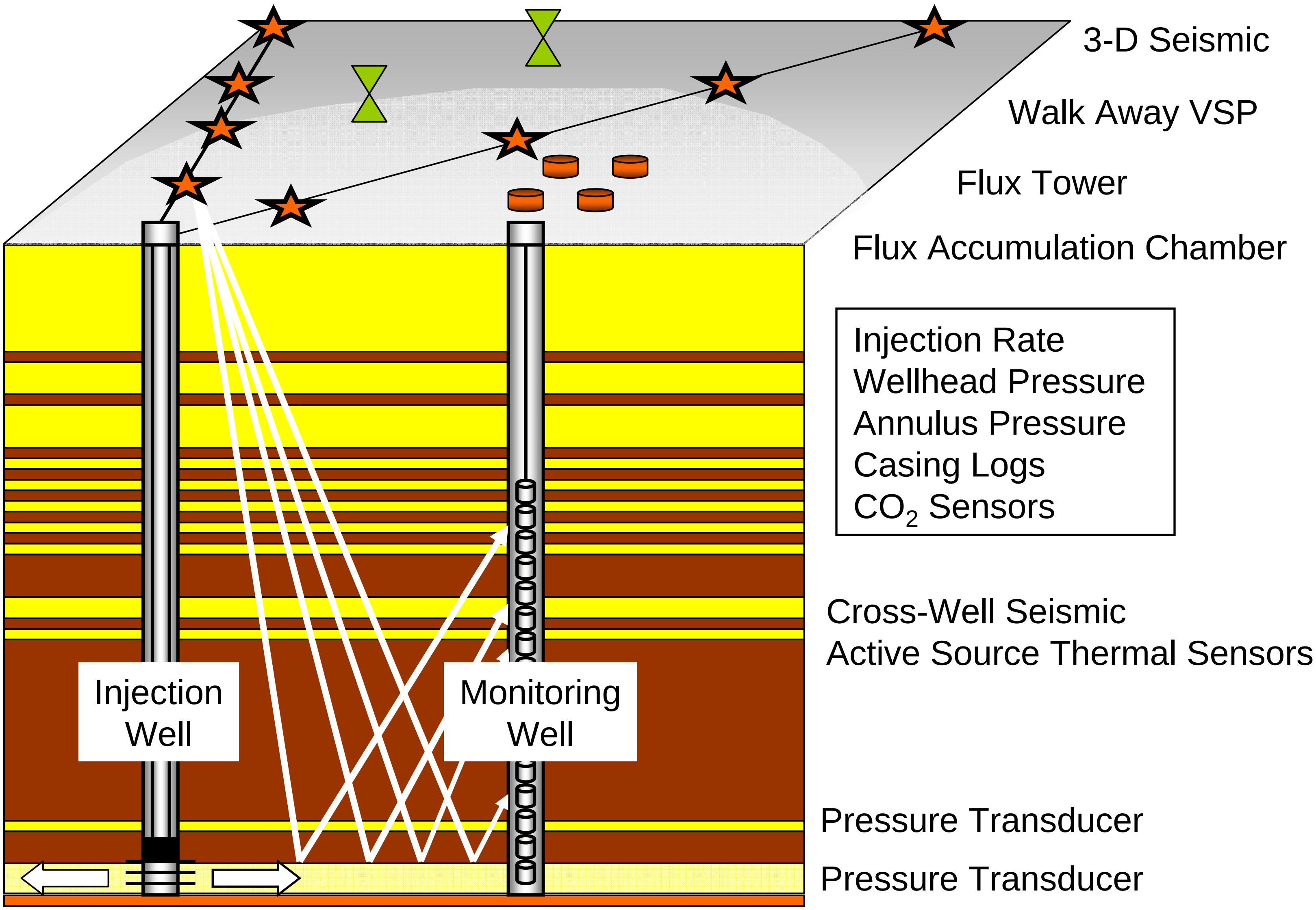




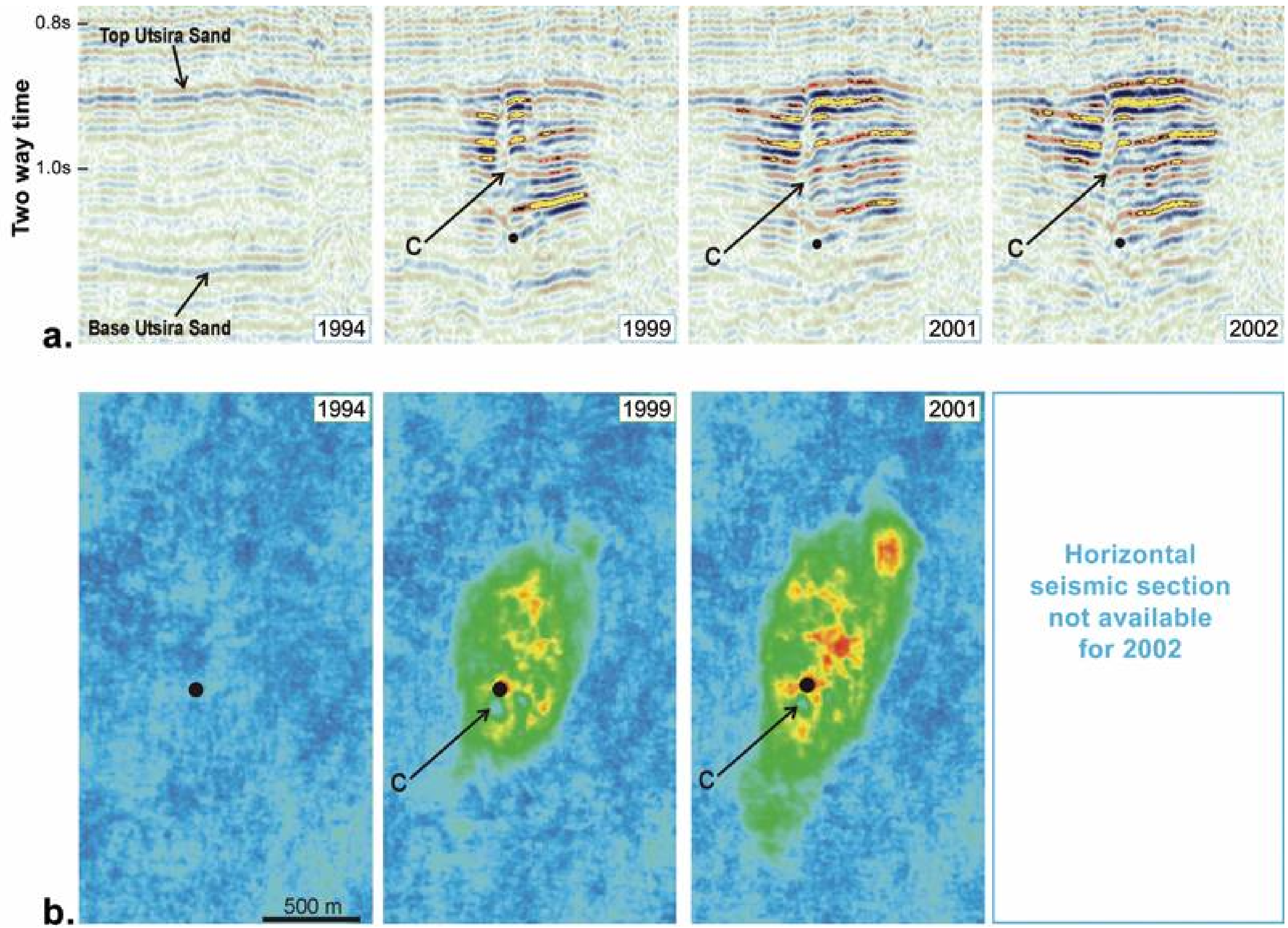
Secondary Trapping Mechanisms Increase Over Time



Monitoring Methods



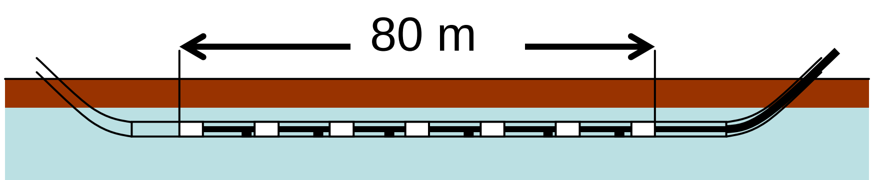
Seismic Monitoring Data from Sleipner

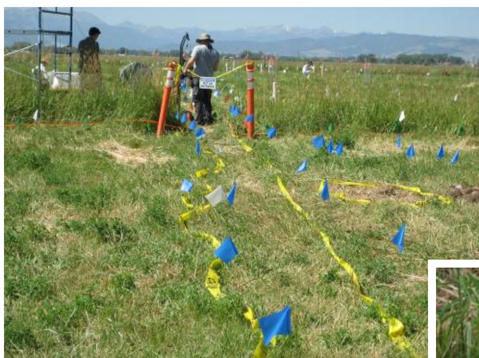


From Andy Chadwick, 2004

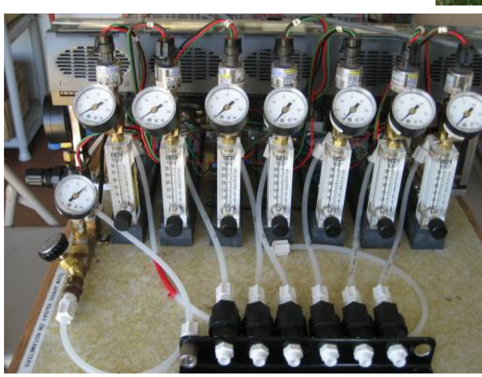
Surface Monitoring

Detection Verification Facility (Montana State University)




Field Site


Horizontal Injection Well


Flow Controllers

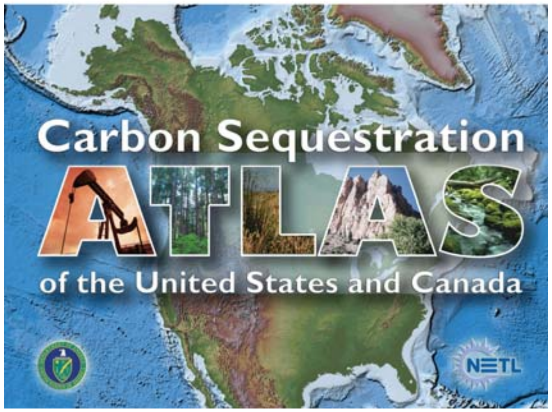

Flux Tower


Hyperspectral Imaging of Vegetation


Soil Gas


Flux accumulation chamber

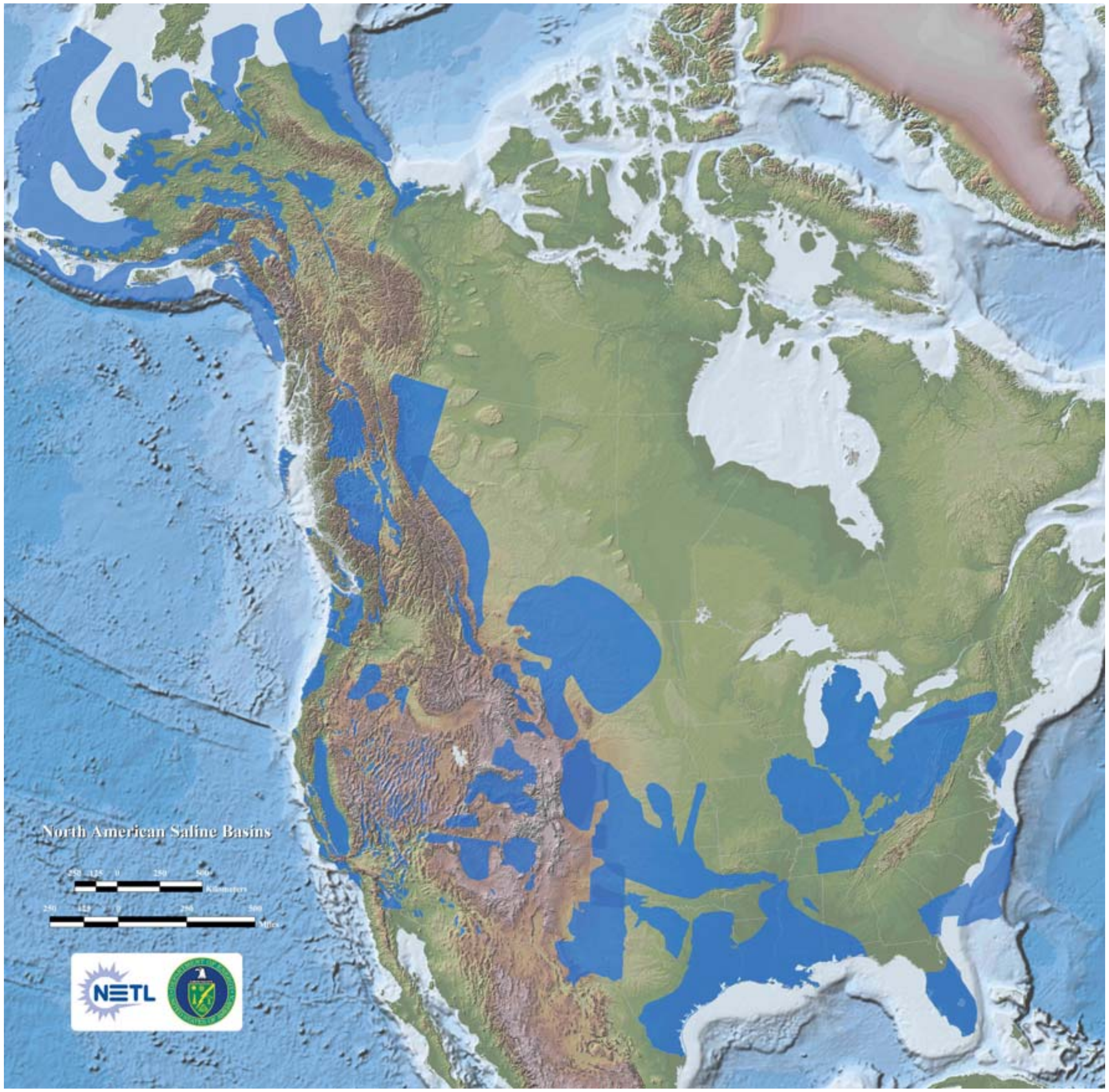
Location of Storage Sites in North America: Saline Aquifers



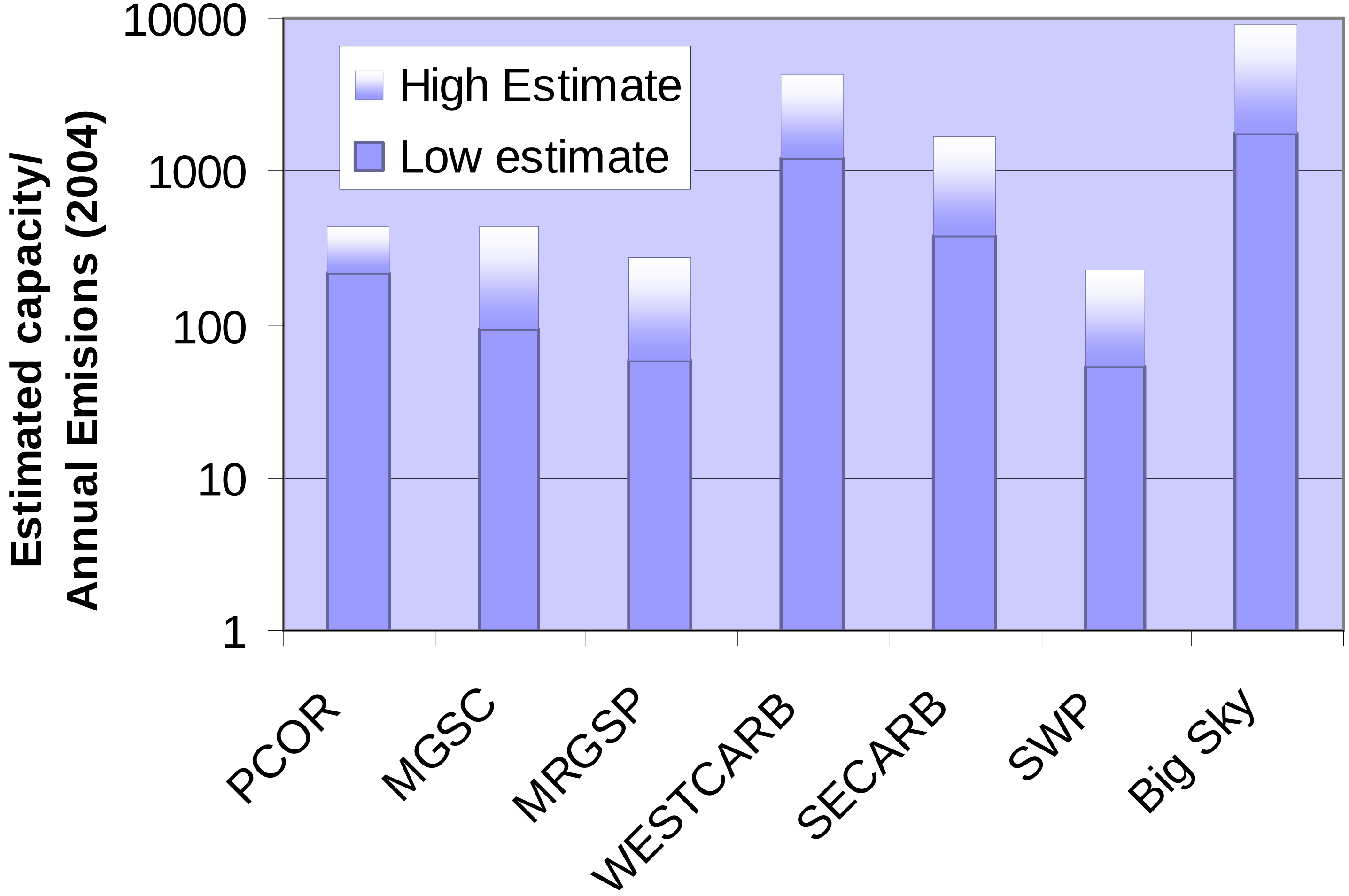
First North American Carbon Sequestration Atlas, 2006

CO_2 Storage Capacity
(Billion Metric Tons)

Big Sky	271	1,085
MGSC	29	115
MRCSP	47	189
PCOR	97	97
SECARB	360	1,440
SOUTHWEST	18	64
WESTCARB	97	288
TOTAL	919	3,378



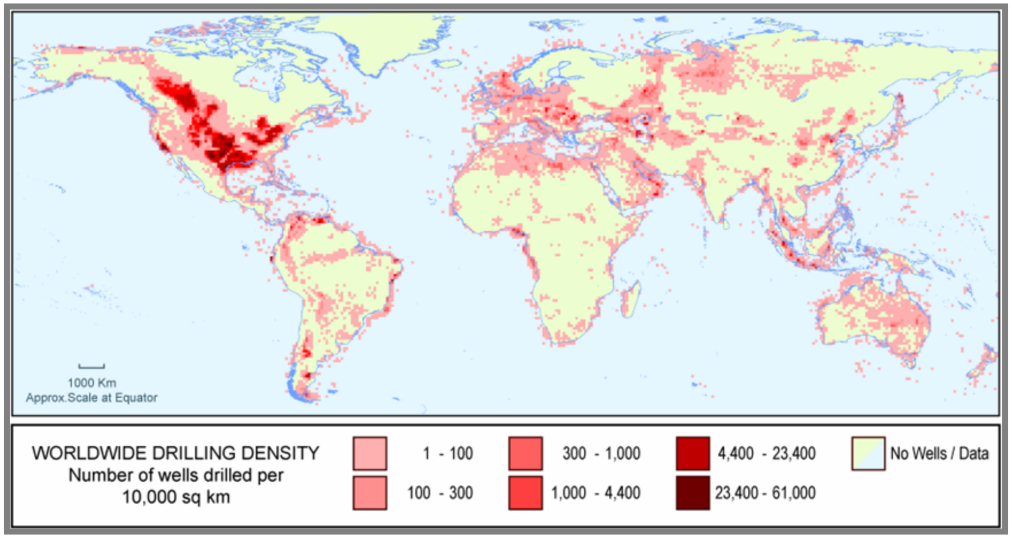
Capacity Varies Widely by Region



Theoretical capacity estimates range from 50 to over 1,000 times annual emissions (from stationary sources), depending on location.

What Could Go Wrong?

World Map of Active and Abandoned Wells



Potential Release Pathways

- Well leakage (injection and abandoned wells)
- Poor site characterization (undetected faults)
- Excessive pressure buildup damages seal

Potential Consequences

1. Worker safety
2. Groundwater quality degradation
3. Resource damage
4. Ecosystem degradation
5. Public safety
6. Structural damage
7. Release to atmosphere

What about a catastrophic release, like what happened at Lake Nyos in Cameroon?

Risk Management

Financial Responsibility	Financial mechanisms and institutional approaches for long term stewardship (e.g. monitoring and remediation if needed)
Regulatory Oversight	Oversight for site characterization and selection, storage system operation, safety, monitoring and contingency plans
Remediation	Active and abandoned well repair, groundwater cleanup, and ecosystem restoration
Monitoring	Monitoring plume migration, pressure monitoring in the storage reservoir and above the seal, and surface releases
Safe Operations	Well maintenance, conduct of operations, well-field monitoring and controls
Storage Engineering	Number and location of injection wells, strategies to maximize capacity and accelerate trapping, and well completion design
Site Characterization and Selection	Site specific assessment of storage capacity, seal integrity, injectivity and brine migration
Fundamental Storage and Leakage Mechanisms	Multi-phase flow, trapping mechanisms, geochemical interactions, geomechanics, and basin-scale hydrology

Are We Ready?

- State-of-the-art is well developed, scientific understanding is excellent and engineering methods are mature
- Sufficient knowledge is available but practical experience is lacking, economics may be sub-optimal, scientific understanding is good
- Demonstration projects are needed to advance the state-of-the art for commercial scale projects, scientific understanding is limited
- Pilot projects are needed to provide proof-of-concept, scientific understanding is immature
- New ideas and approaches are needed

Status of Geological Storage

GCEP

	Oil and Gas	Saline Aquifers	Coalbeds
Financial Responsibility			
Regulatory Oversight			
Remediation			
Monitoring			
Safe Operations			
Storage Engineering			
Site Characterization and Selection			
Fundamental Storage and Leakage Mechanisms			

Maturity Summary

- Are we ready for CCS?

Oil and gas reservoirs

Saline aquifers

Coalbeds

State-of-the-art is well developed, scientific understanding is excellent and engineering methods are mature

Sufficient knowledge is available but practical experience is lacking, economics may be sub-optimal, scientific understanding is good

Demonstration projects are needed to advance the state-of-the art for commercial scale projects, scientific understanding is limited

Pilot projects are needed to provide proof-of-concept, scientific understanding is immature

Cost of CCS

Type of power plant with CCS	Natural Gas Combined Cycle reference plant	Pulverized Coal reference plant
	US$/t$CO_2$ avoided	US$/t$CO_2$ avoided
Power plant with capture and geological storage		
Natural Gas Combined Cycle	40 – 90	20 – 60
Pulverized Coal	70 – 270	30 – 70
Integrated Gasification Combined Cycle	40 – 220	20 – 70

Source: IPCC, 2005

McKinsey, 2008:

- $77 to $116/t$CO_2$ avoided for early projects
- $39 to $58/t$CO_2$ avoided after learning lowers cost

Cost of Electricity Production with CCS

Power plant system	Natural Gas Combined Cycle (US$/kWh)	Pulverized Coal (US$/kWh)	Integrated Gasification Combined Cycle (US$/kWh)
Without capture (reference plant)	0.03 - 0.05	0.04 - 0.05	0.04 - 0.06
With capture and geological storage	0.04 - 0.08	0.06 - 0.10	0.05 - 0.09

IPCC, 2005

Increase electricity production costs by 50 to 100%
U.S. DOE Goal: 10% increase in cost, likely to change to 35% increase

Contradicting Views About CCS

- Hope?
  - CCS can result in 20% of needed emissions reductions over the next 100 years (yes)
  - Without CCS, were in trouble (probably)
  - All components of CCS technology are available today, we just need to put them together (not quite that simple)
  - We've been doing this for 30 years in oilfields (but more than oilfields will be needed, experience will be needed for saline aquifer storage)
  - Just do it! (yes, for large scale demonstration projects)
- Hype?
  - CCS is extremely expensive (compared to what?)
  - Environmental risks are unacceptably high (no, not if done carefully)
  - CO_2 will leak back to the surface (no, not if done carefully)
  - Institutional barriers are too high (possibly, if the government and private sector do not work together quickly and effectively)

Institutional Issues

- Policy and regulations to limit carbon emissions
- Long term liability for stored CO_2
- Legal framework for access to underground pore space
- Regulations for storage: siting, monitoring, performance specifications
- Carbon trading credits
- Clean development mechanism (CDM)
- Public acceptance

None is likely to be a show stopper, but all require effort to resolve.

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 and commercial projects with CO_2-EOR
- Research is needed to support deployment at scale
  - Capture: Reduce costs and improve reliability
  - Storage: Improve storage security and avoid unintentional environmental impacts
- Institutional issues need to be resolved to support widespread deployment