Stanford University

GCEP Global Climate & Energy Project

Public Workshops on Carbon Capture and Sequestration
Bloomberg National Headquarters, NY and
Rayburn House Office Bldg., Washington, DC
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Carbon Dioxide Capture and Sequestration in Deep Geological Formations

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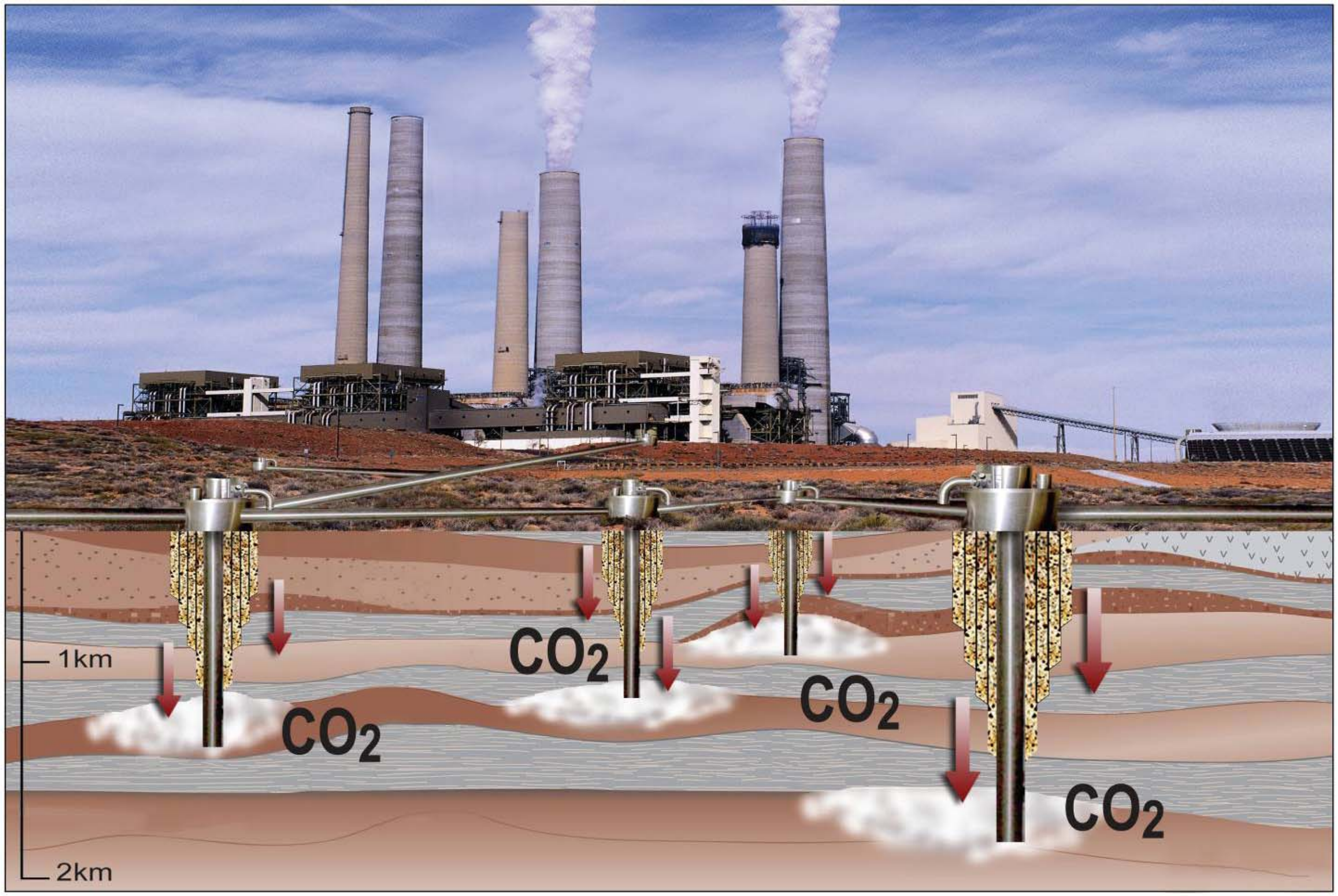
Science and technology for a low GHG emission world.

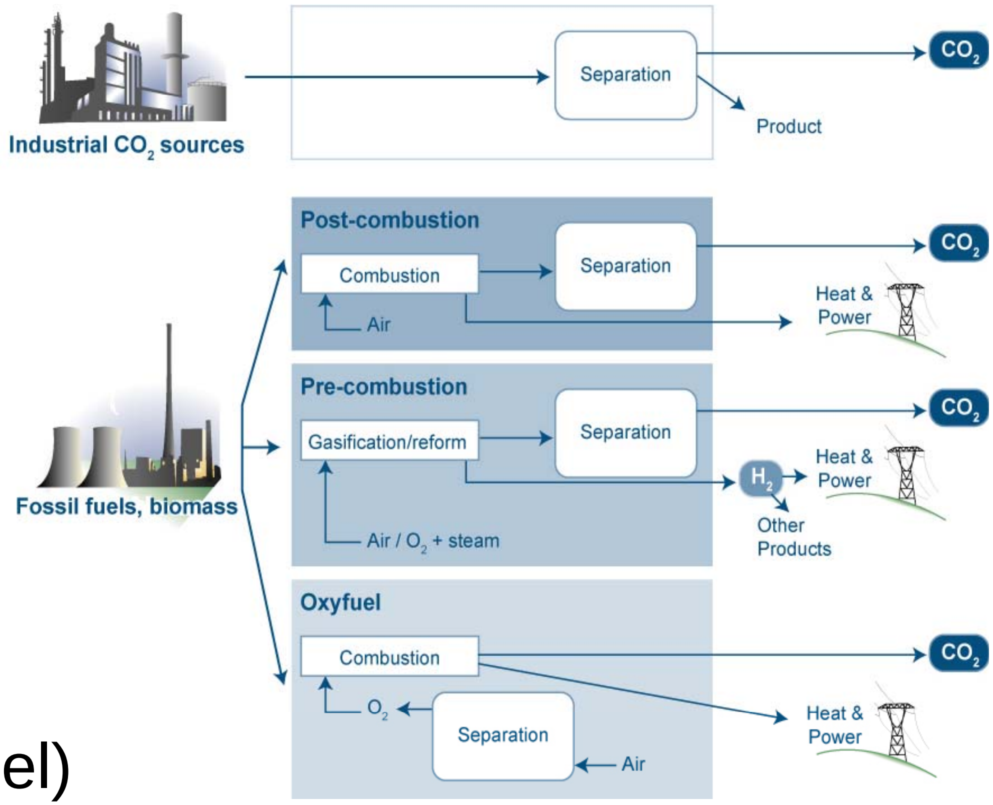
Carbon Dioxide Capture and Geologic Storage



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

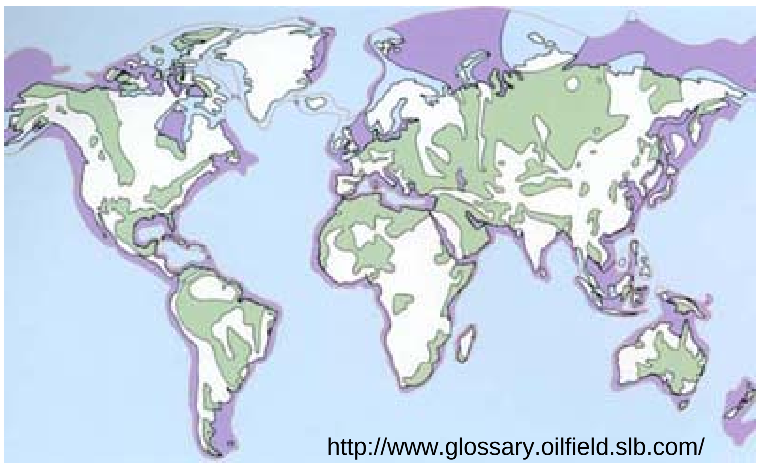
Options for CO_2 Capture

- Post-combustion
  - Scrub CO_2 after combustion
  - Established technology
- Pre-combustion (IGCC)
  - Convert coal to a gas before combustion
  - Established technology for other applications
  - Not demonstrated for power production
- Oxygen combustion (Oxy-fuel)
  - Use O_2 instead of air for combustion
  - Not demonstrated for power production

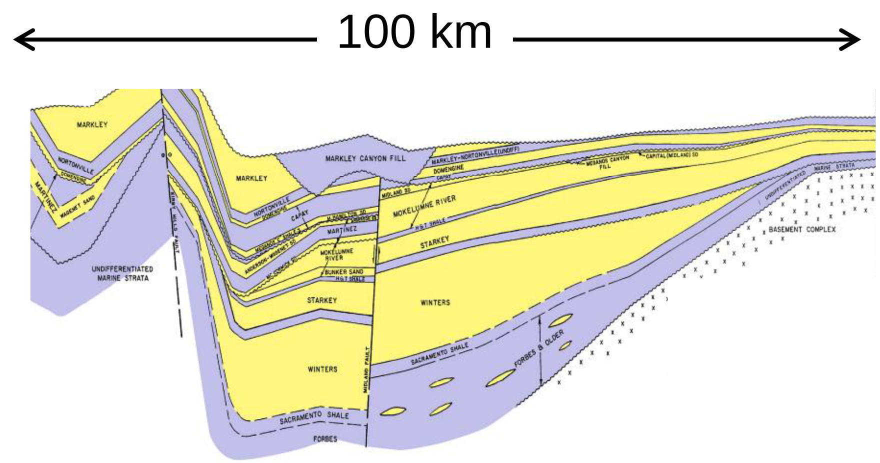


What Types of Rock Formations are Suitable for Geological Storage?

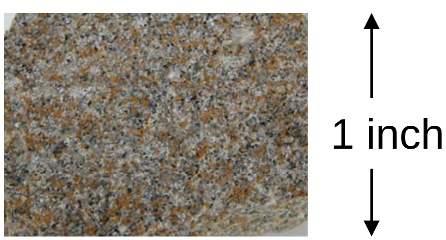
Rocks in deep sedimentary basins are suitable for CO_2 storage.



Map showing world-wide sedimentary basins



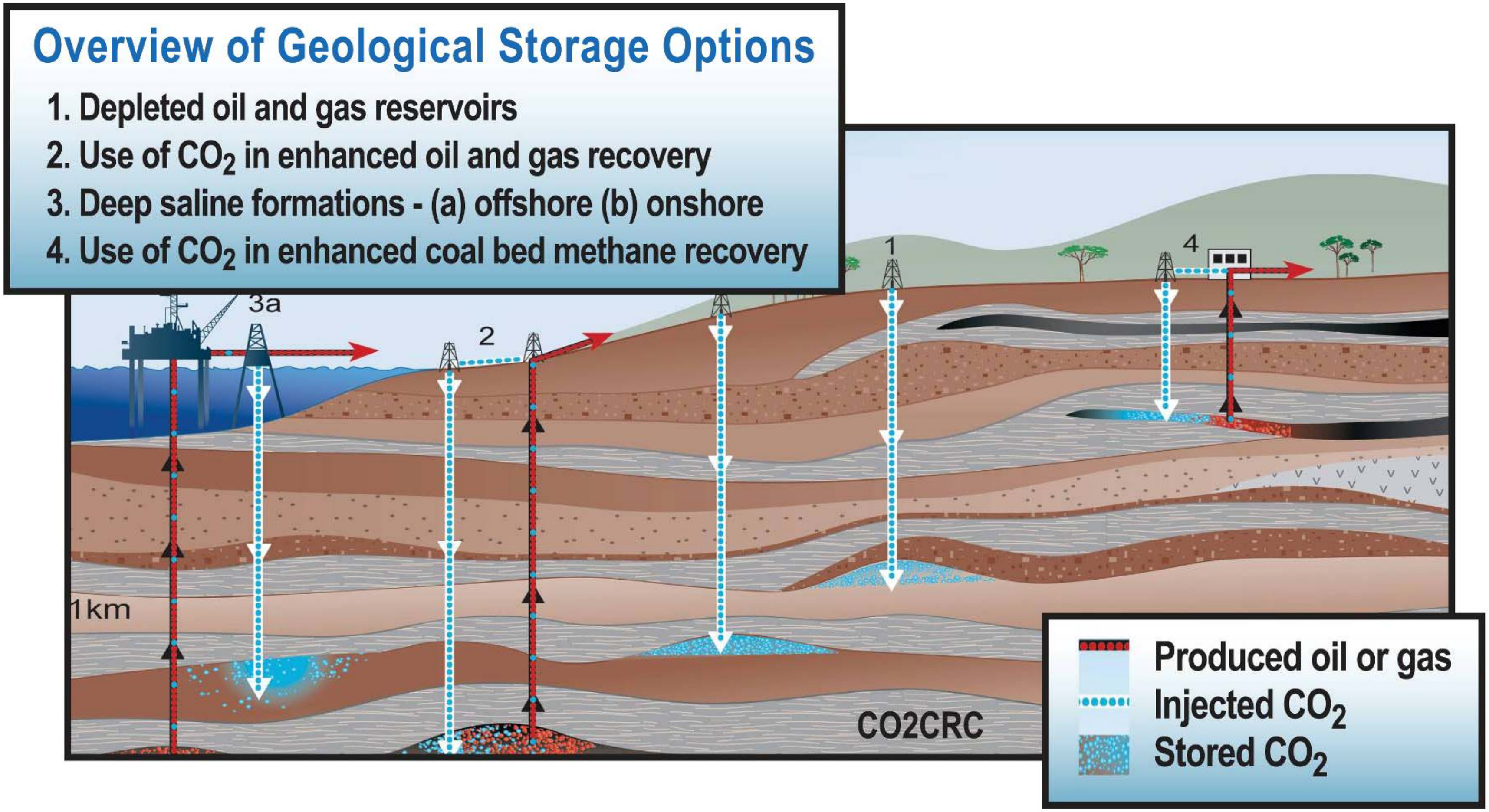
Northern California Sedimentary Basin



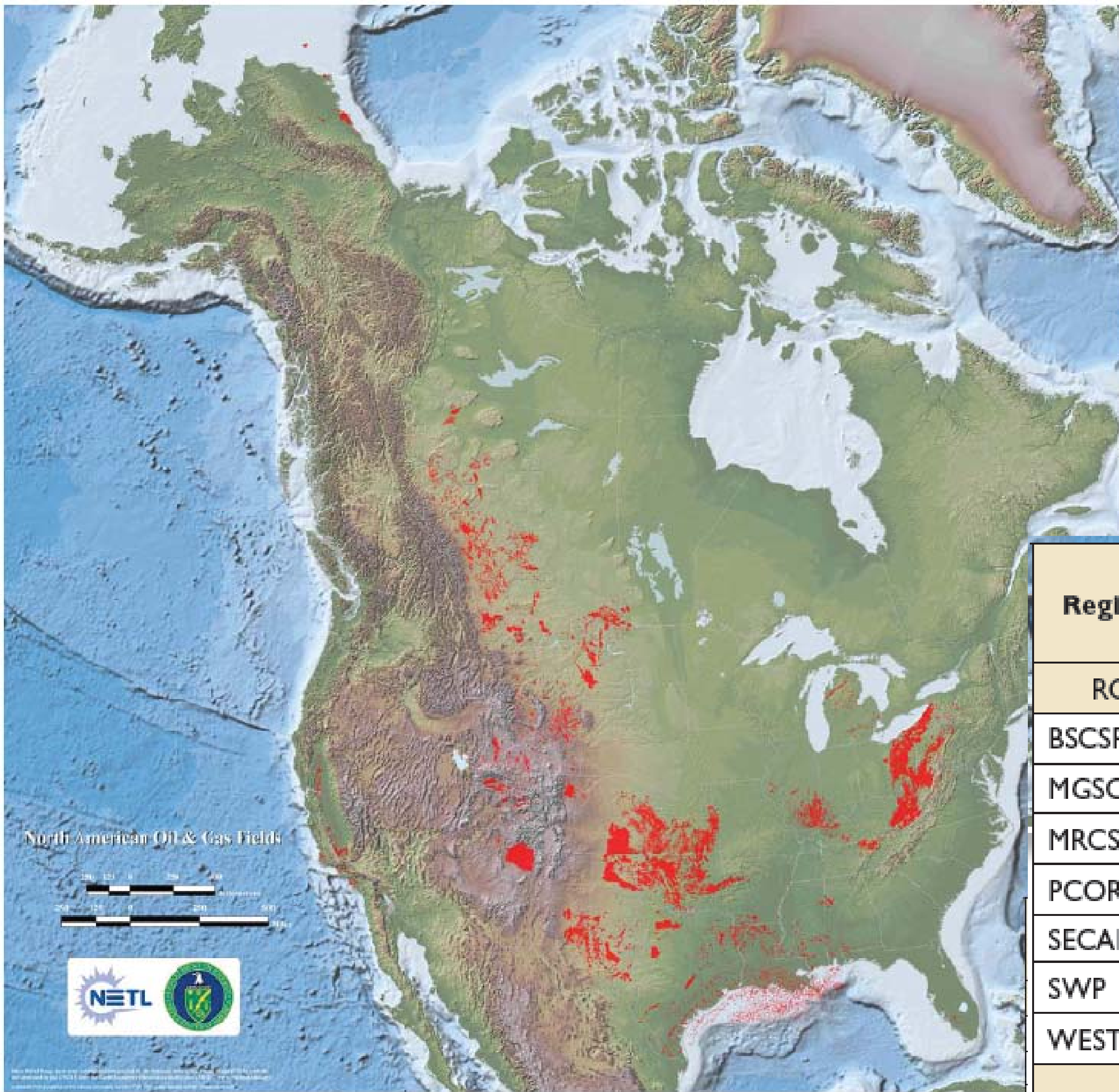
Sandstone

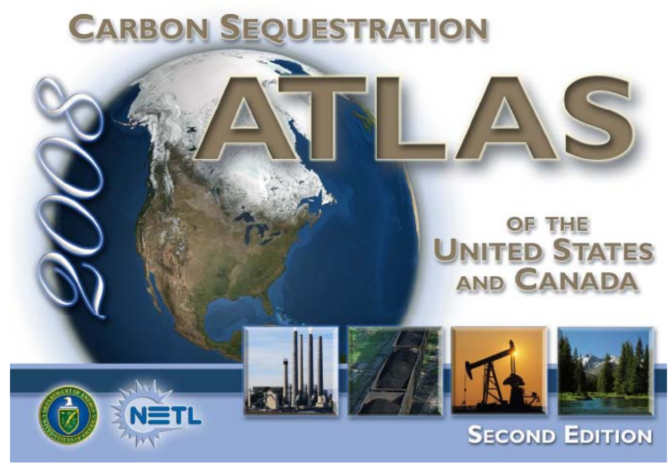
Example of a sedimentary basin with alternating layers of sandstone and shale.

Options for Geological Storage



Oil and Gas Reservoirs

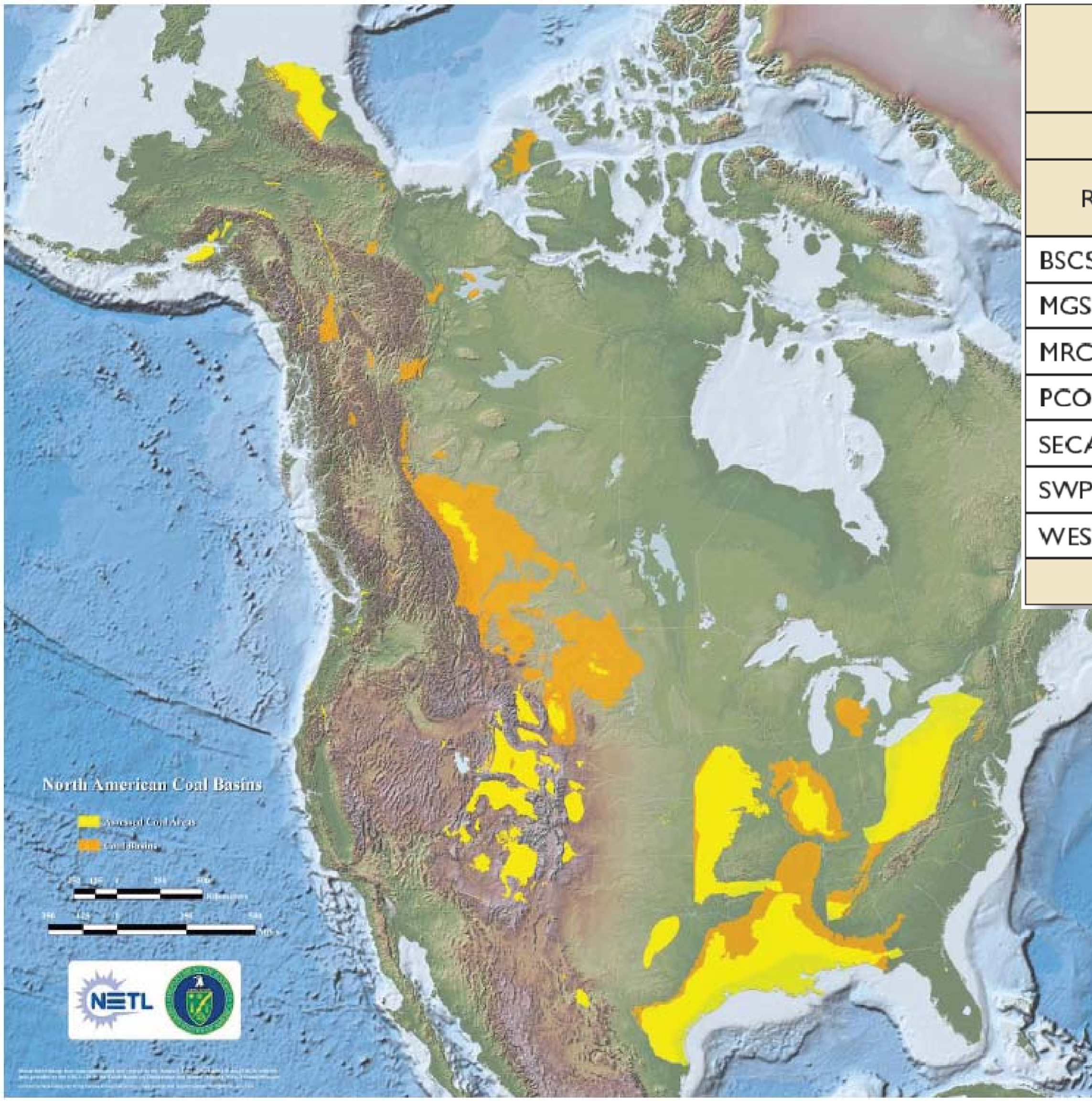




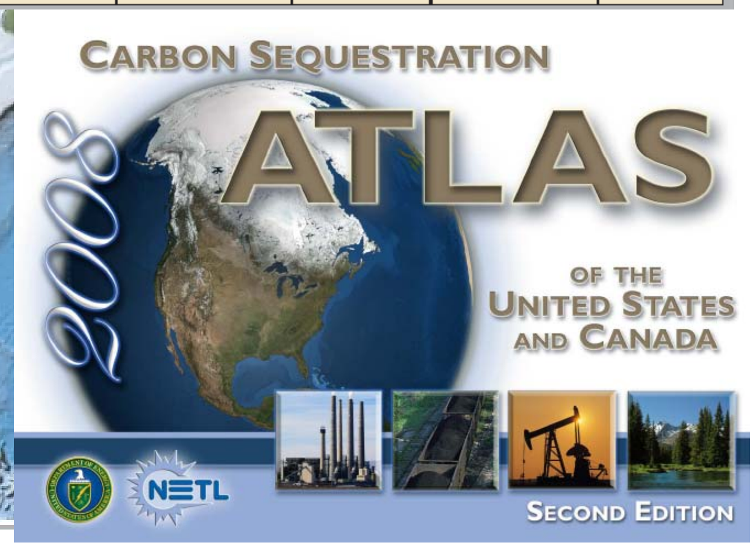
CO_2 Resource Estimates by Regional Carbon Sequestration Partnership for Oil and Gas Reservoirs

RCSP	Billion Metric Tons	Billion Tons
BSCSP	1.5	1.6
MGSC	0.4	0.4
MRCSP	8.4	9.3
PCORP	24.1	26.5
SECARB	27.1	29.9
SWP	62.3	68.7
WESTCARB	5.8	6.4
TOTAL	129.6	142.9

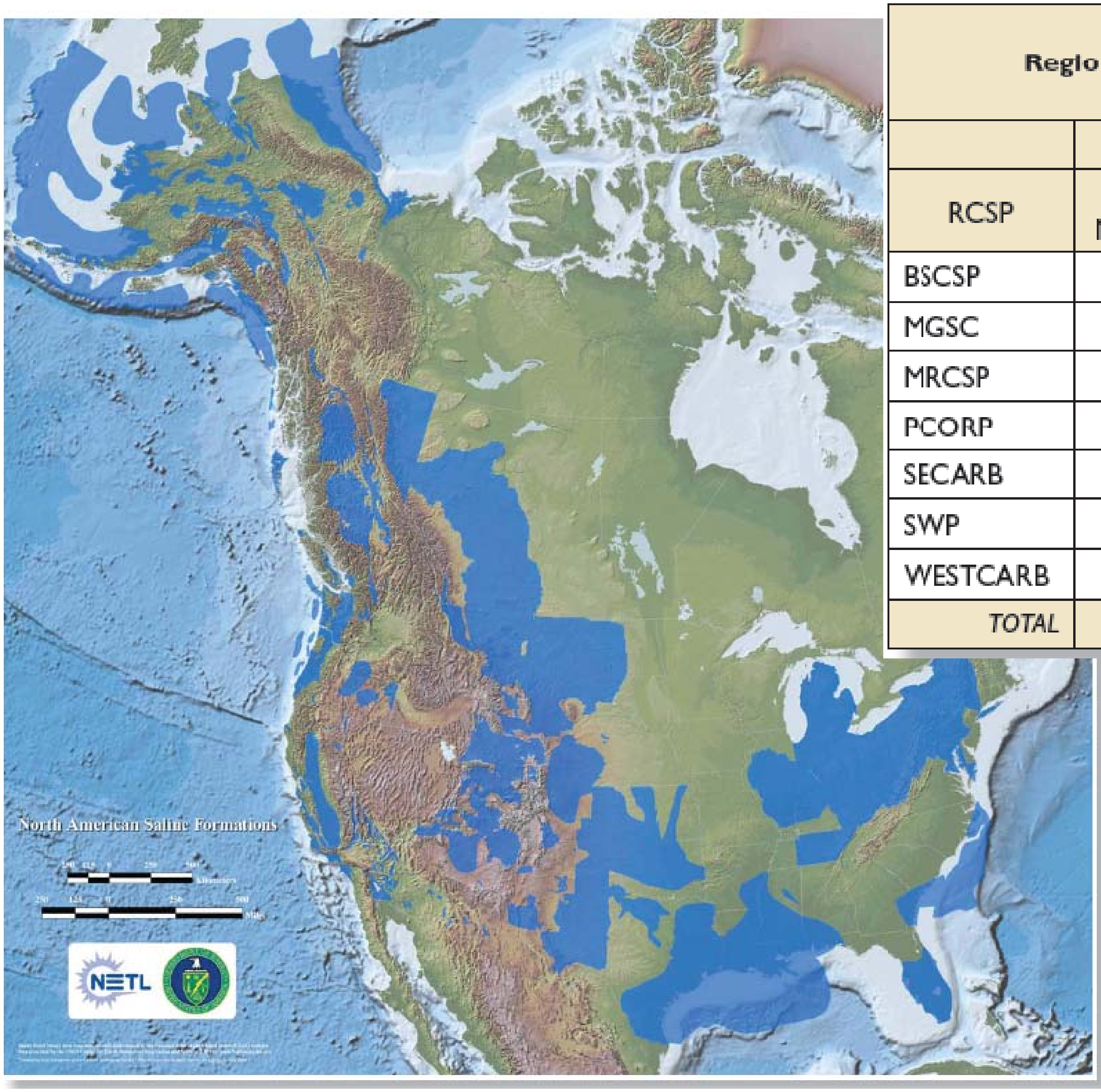
Coal Beds



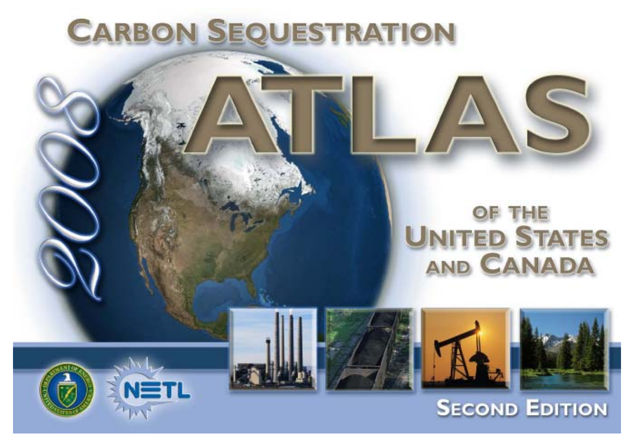
CO₂ Resource Estimates by Regional Carbon Sequestration Partnership for Unmineable Coal Seams				
	Low		High	
RCSP	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	12.1	13.3	12.1	13.3
MGSC	1.7	1.8	2.4	2.6
MRCSP	0.8	0.9	0.8	0.9
PCORP	10.7	11.8	10.7	11.8
SECARB	57.8	63.7	82.8	91.3
SWP	0.7	0.8	1.8	2.0
WESTCARB	86.8	95.7	86.8	95.7
TOTAL	170.6	188.0	197.3	217.5



Saline Aquifers



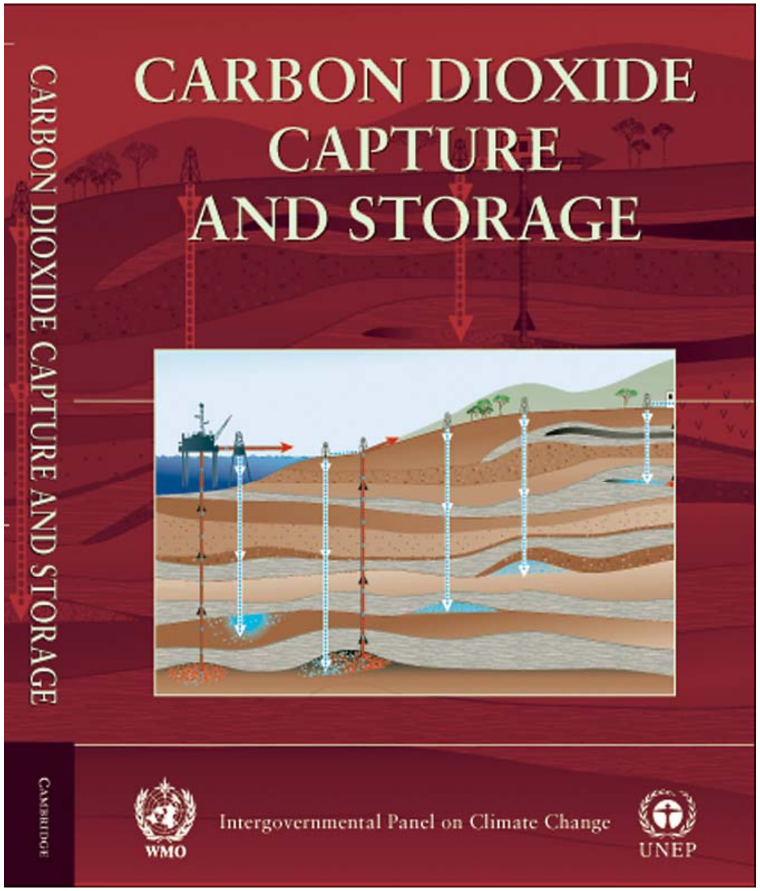
CO$_2$ Resource Estimates by Regional Carbon Sequestration Partnership for Saline Formations				
	Low		High	
RCSP	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	460.9	508.0	1,831.5	2018.9
MGSC	29.2	32.1	116.6	128.6
MRCSP	117.8	129.8	117.8	129.8
PCORP	185.6	204.6	185.6	204.6
SECARB	2,274.6	2,507.3	9,098.4	10029.3
SWP	10.7	11.8	42.6	47.0
WESTCARB	204.9	225.9	817.3	900.9
TOTAL	3,283.6	3,619.5	12,209.8	13459.0



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."

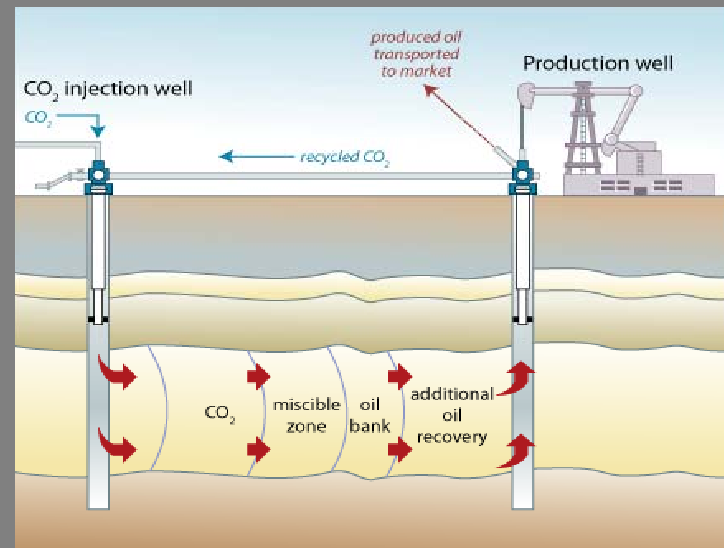


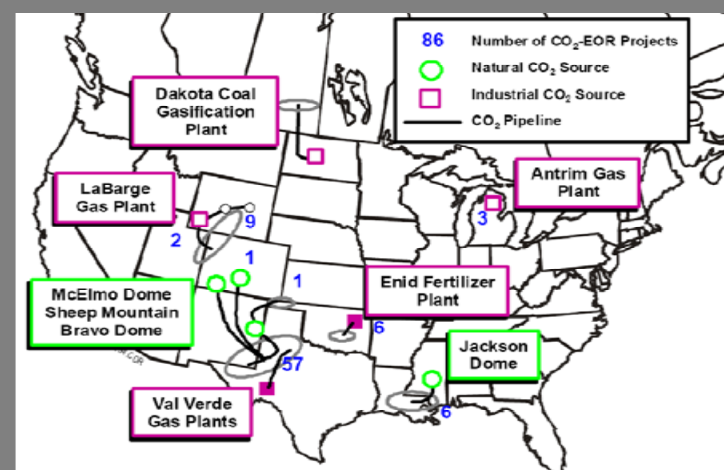
* "Very likely" is a probability between 90 and 99%.

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

Evidence to Support these Conclusions

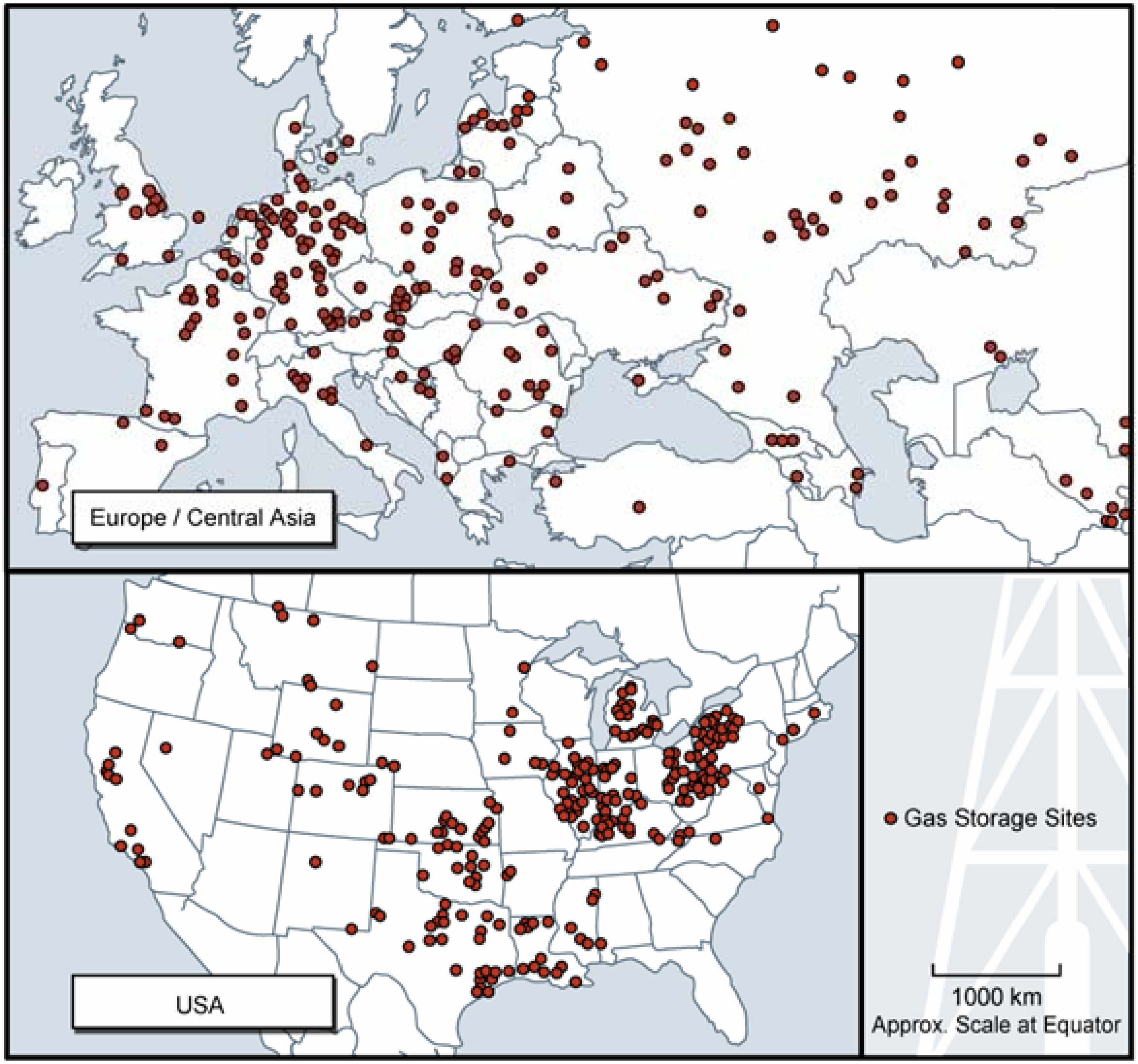
- Natural analogs
  - Oil and gas reservoirs
  - CO_2 reservoirs
- Performance of industrial analogs
  - 30+ years experience with CO_2 EOR
  - 100 years experience with natural gas storage
  - Acid gas disposal
- 25+ years of cumulative performance of actual CO_2 storage projects
  - Sleipner, off-shore Norway, 1996
  - Weyburn, Canada, 2000
  - In Salah, Algeria, 2004
  - Snovhit, Norway, 2008





~35 Mt/yr are injected for CO_2-EOR

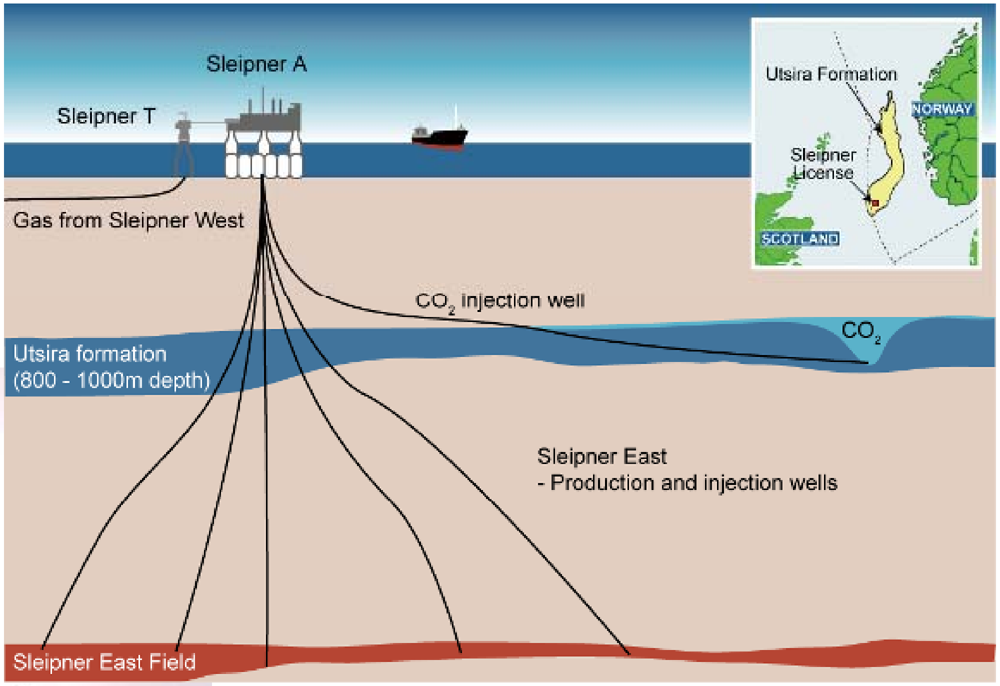
Natural Gas Storage



- Seasonal storage to meet winter demands for natural gas
- Storage formations
  - Depleted oil and gas reservoirs
  - Aquifers
  - Caverns

Sleipner Project, North Sea

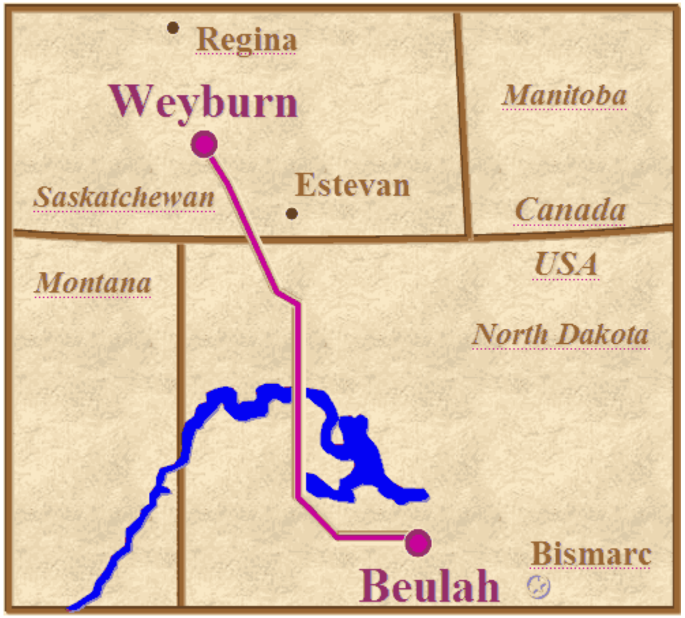
- 1996 to present
- 1 Mt CO_2 injection/yr
- Seismic monitoring



Courtesy *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.



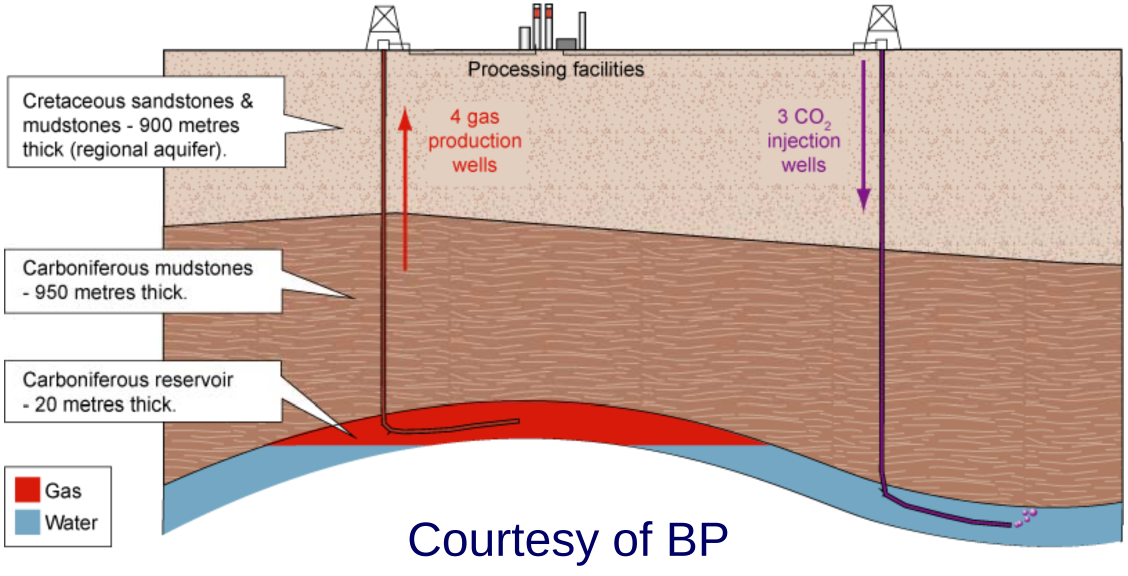
In Salah Gas Project

In Salah Gas Project
- Krechba, Algeria

Gas Purification
- Amine Extraction

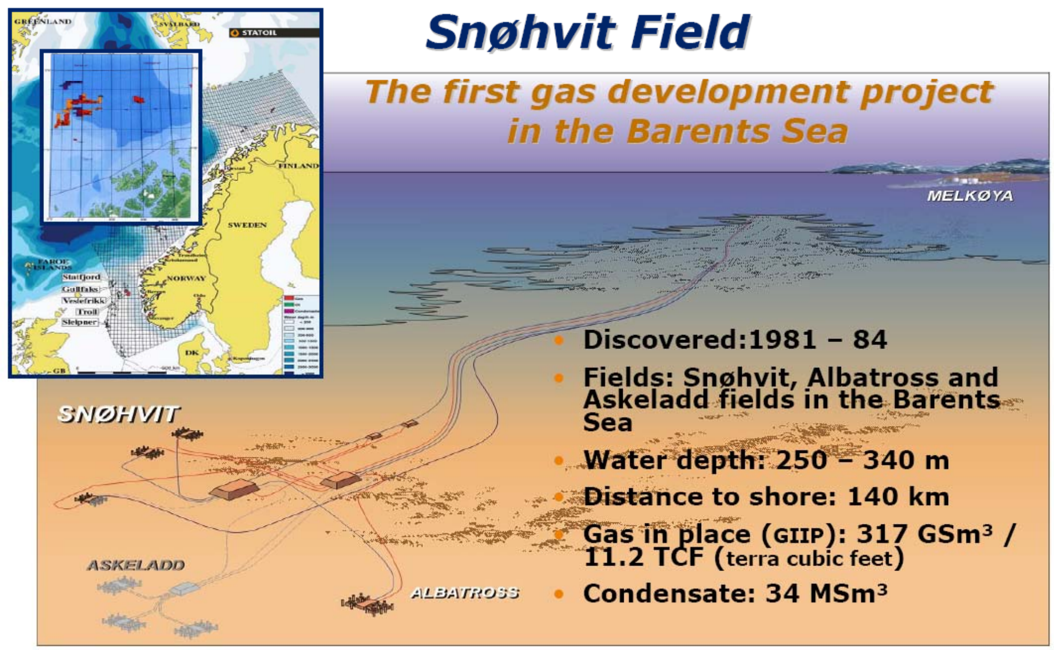
1 Mt/year CO_2 Injection

Operations Commence
- June, 2004



Snohvit, Norway

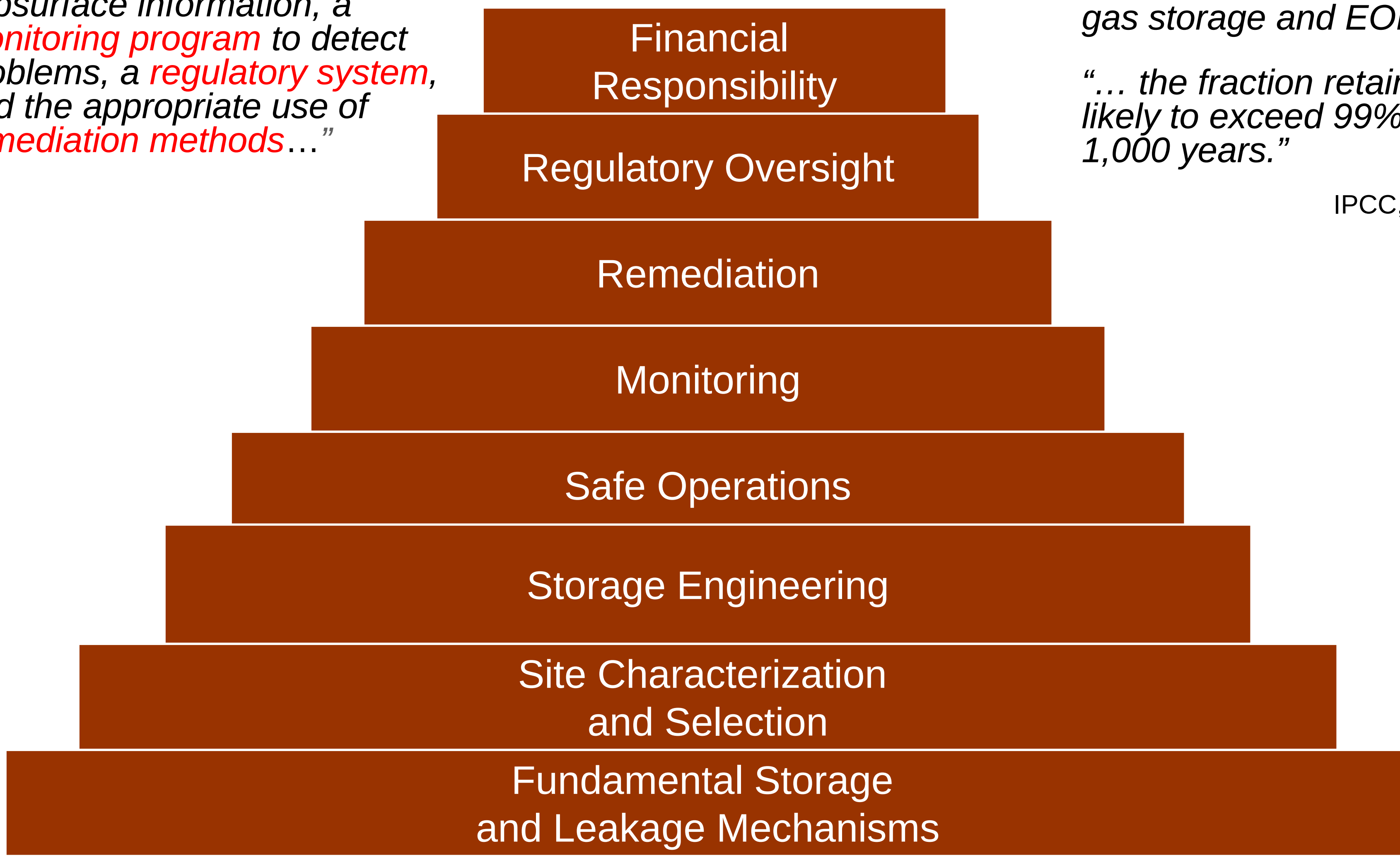
- Snohvit Liquefied Natural Gas Project (LNG)
  - Barents Sea, Norway
- Gas Purification (removal of 5-8% CO_2)
  - Amine Extraction
- 0.7 Mt/year CO_2 Injection
  - Saline aquifer at a depth of 2,600 m (8530 ft) below sea-bed
- Sub-sea injection
- Operations Commence
  - April, 2008



Courtesy StatoilHydro

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*…"

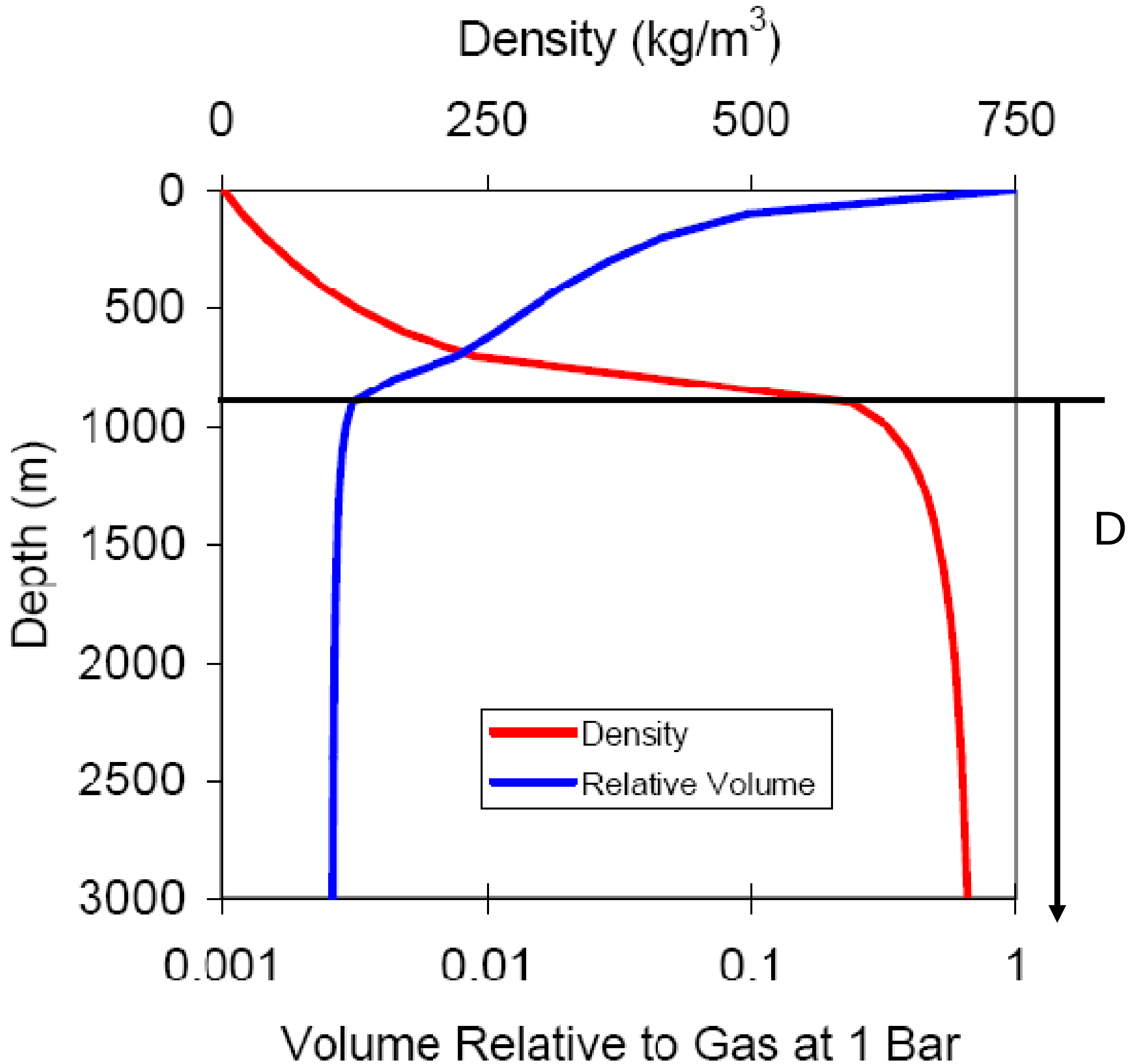


"… risks similar to existing activities such as natural gas storage and EOR."

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

IPCC, 2005

Density of Carbon Dioxide



Storage at Depths Greater than 800 m (2,600 ft)

Sequestration 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

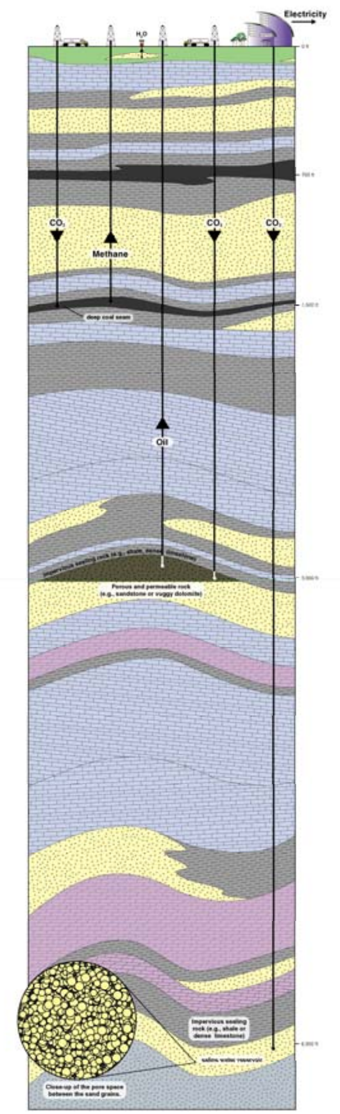


Image courtesy of ISGS and MGSC

X-ray Micro-tomography at the Advanced Light Source

Micro-tomography Beamline

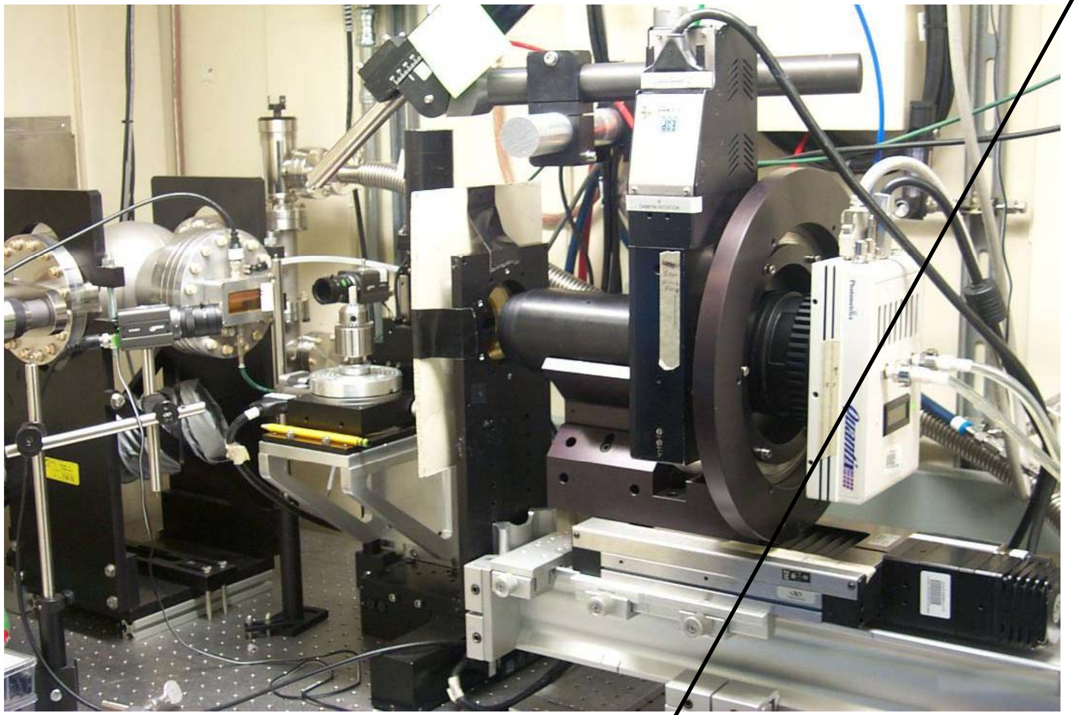
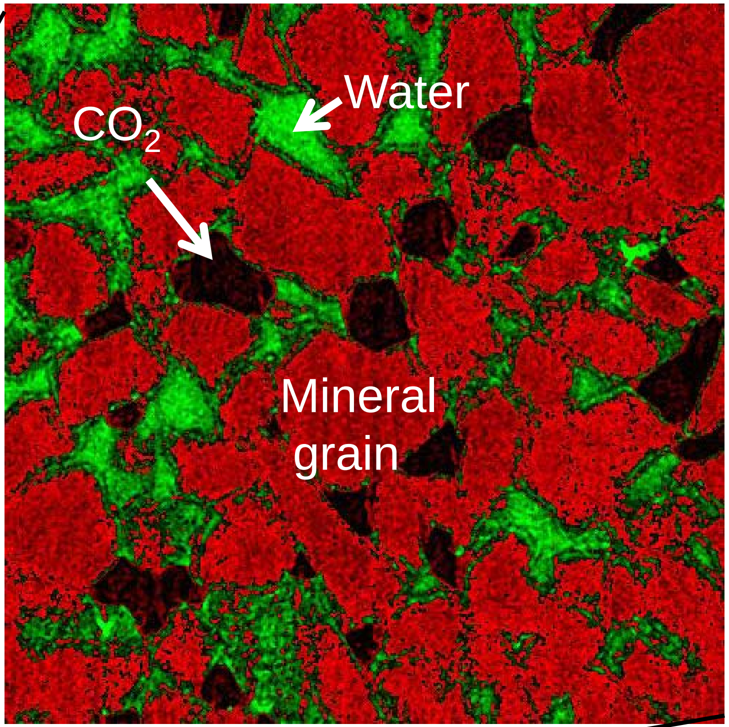


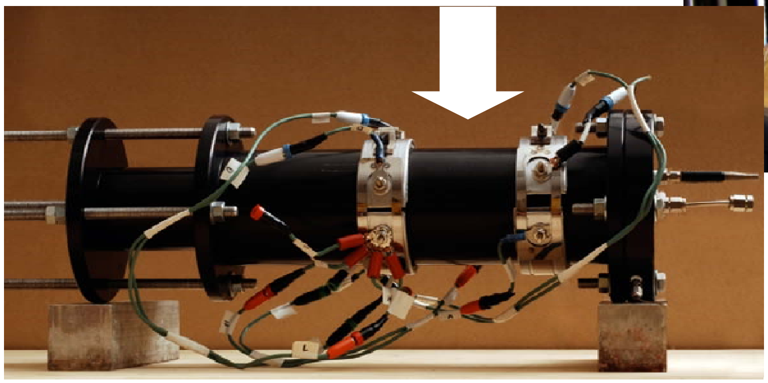
Image of Rock with CO_2



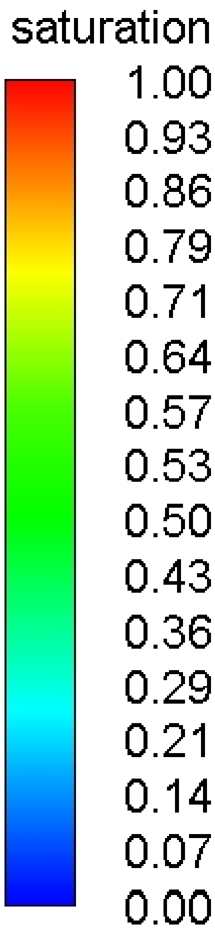
2 mm

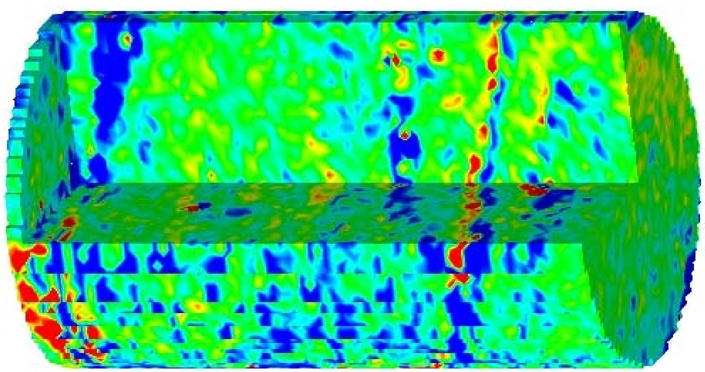
Multi-Phase Flow Laboratory

Replicate *in situ* conditions
- Pressure
- Temperature
- Brine composition



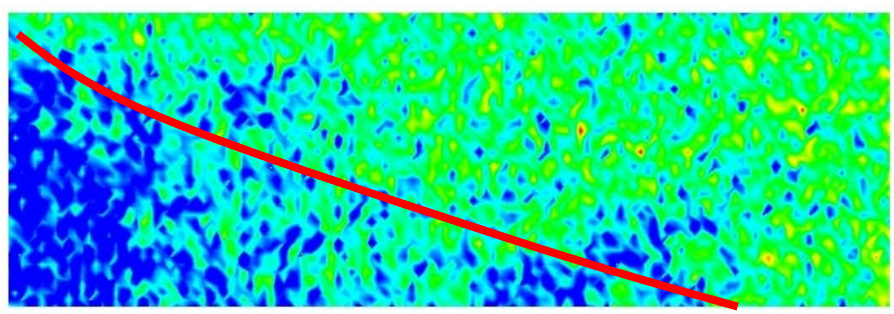
Multiphase Flow of CO_2 and Brine





Waare C Sandstone

Influence of Heterogeneity

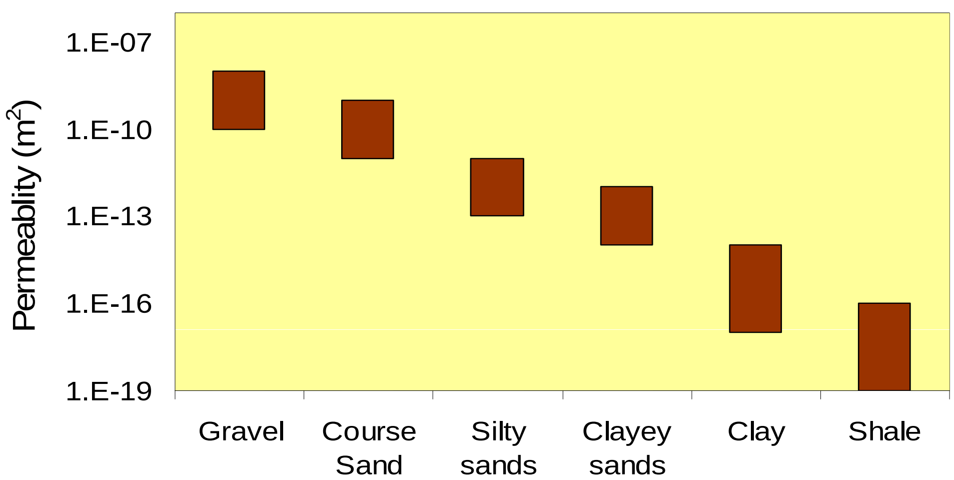


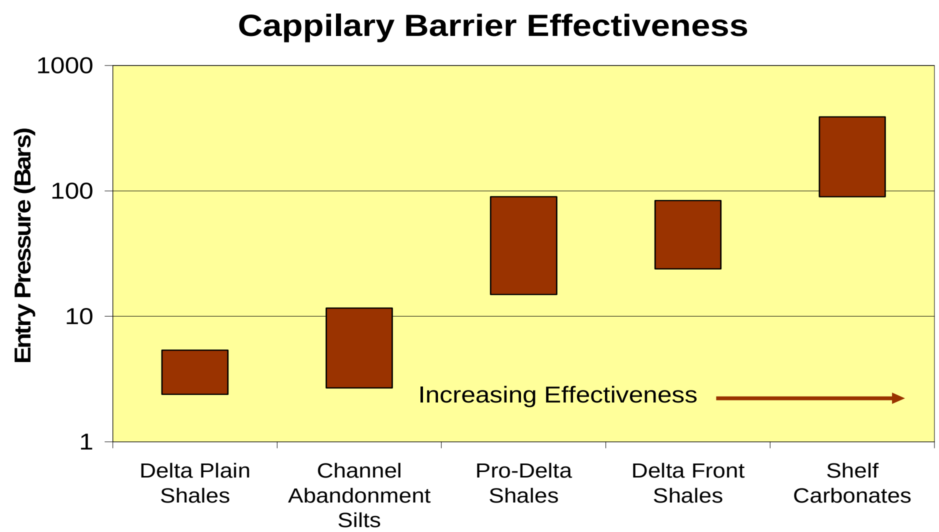
Berea Sandstone

Influence of Buoyancy

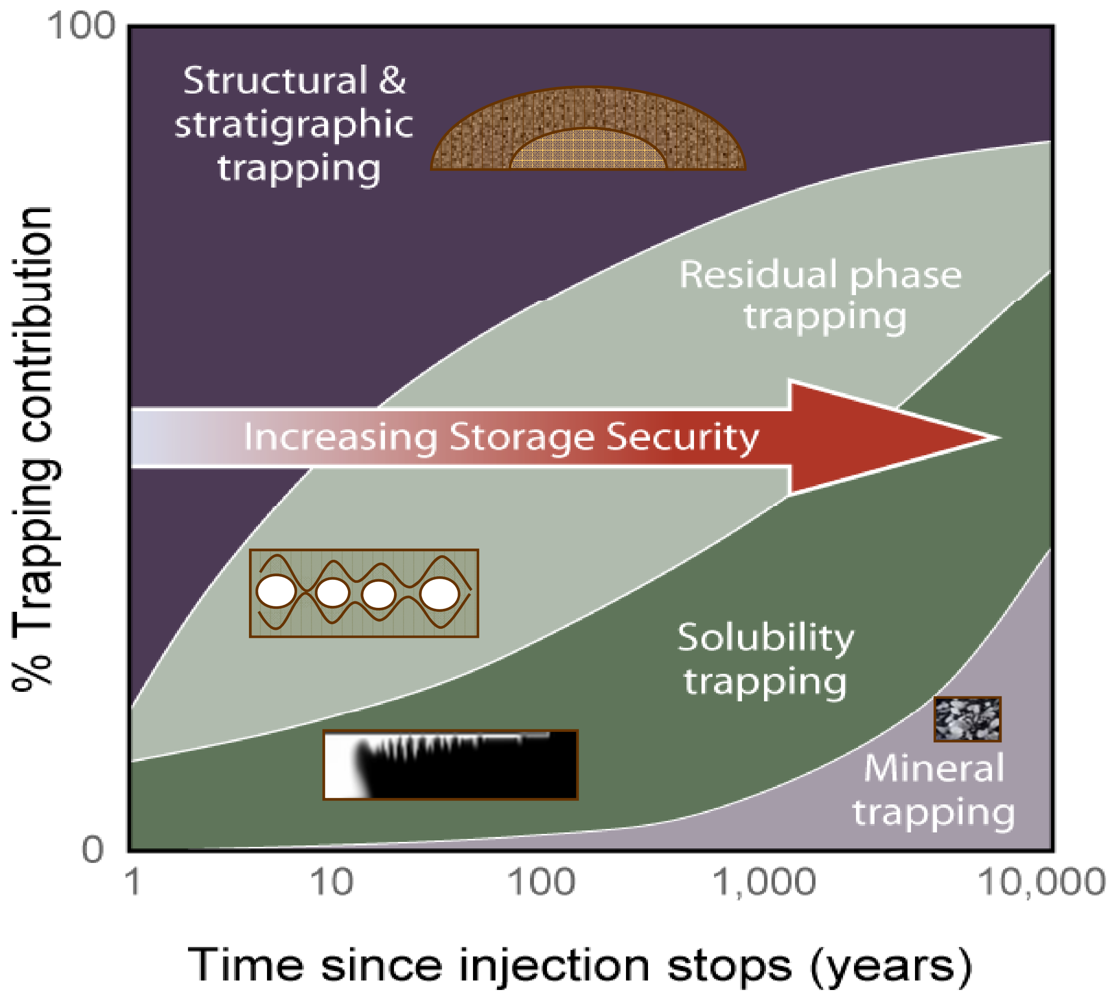
Seal Rocks and Mechanisms

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

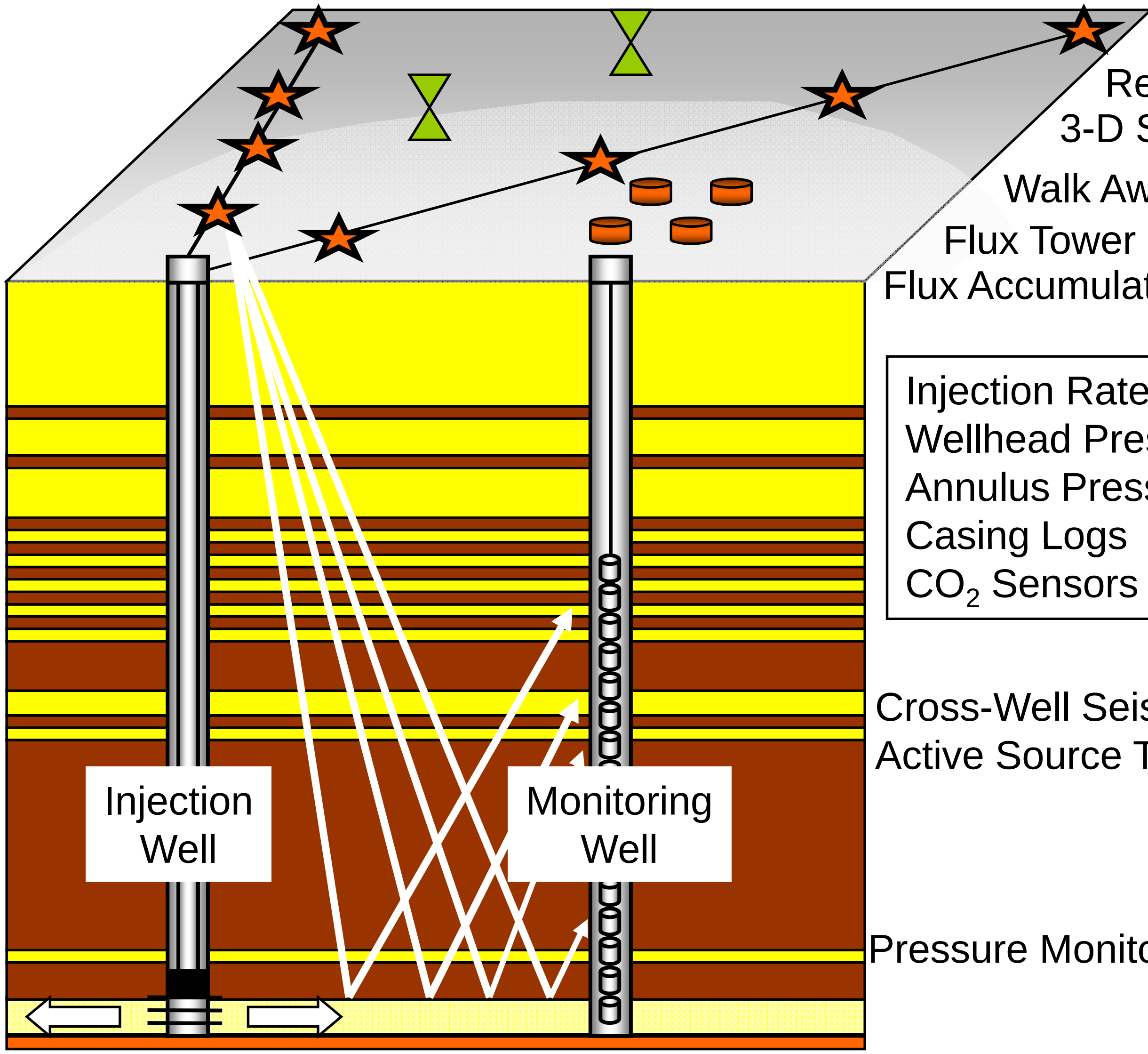




Secondary Trapping Mechanisms Increase Over Time



Many Monitoring Methods are Available

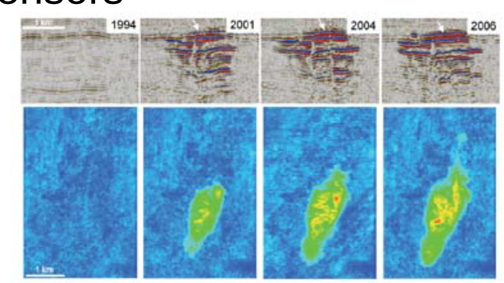


Satellite land surface deformation
Remote sensing of vegetative stress
3-D Seismic
Walk Away VSP
Flux Tower
Flux Accumulation Chamber

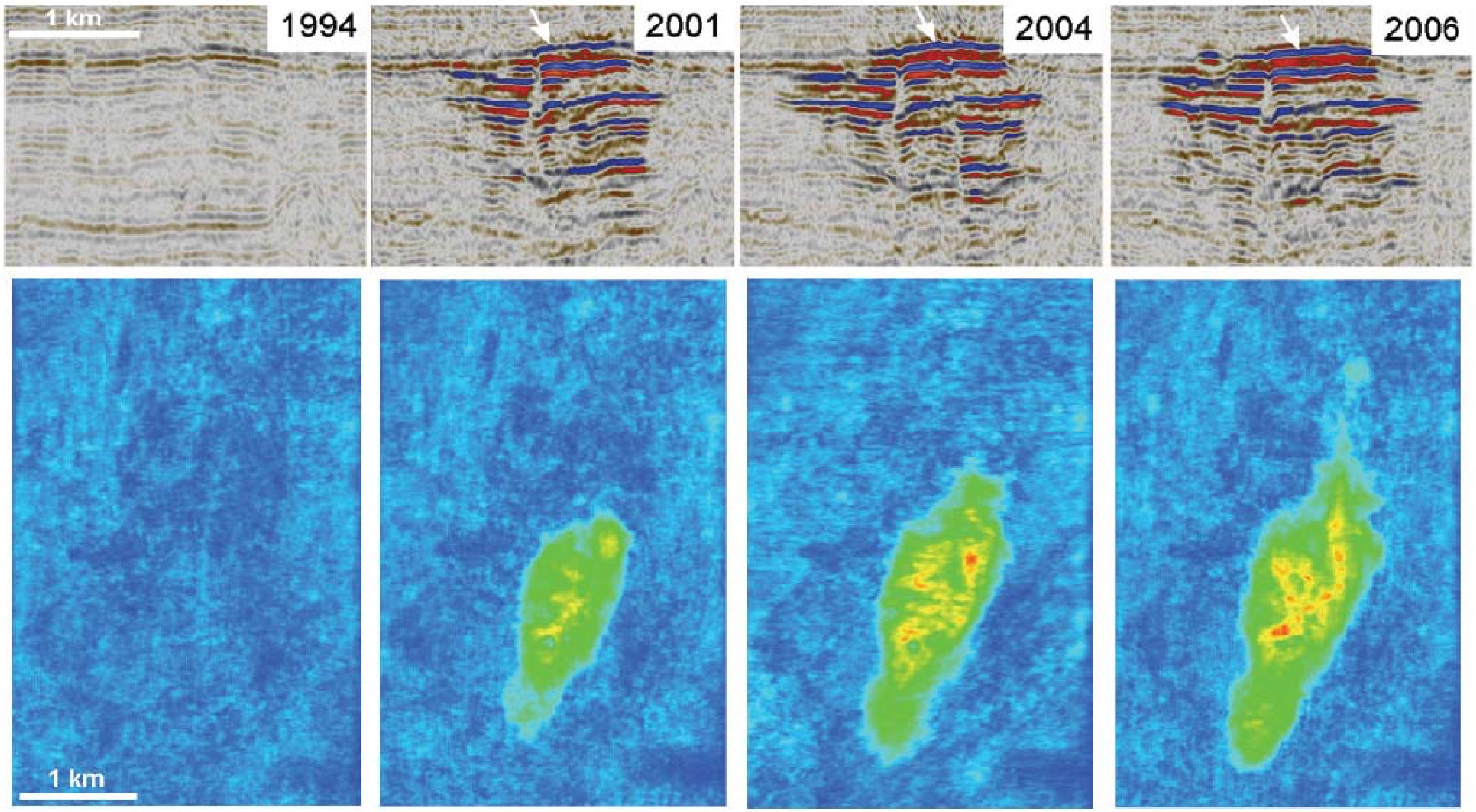
Injection Rate
Wellhead Pressure
Annulus Pressure
Casing Logs
CO_2 Sensors

Cross-Well Seismic
Active Source Thermal Sensors

Pressure Monitoring



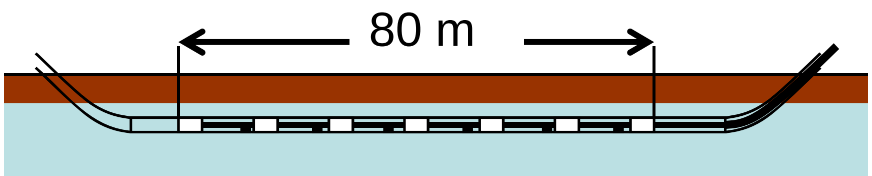
Seismic Monitoring Data from Sleipner

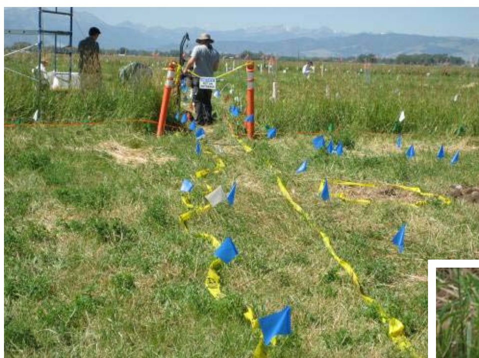


From Chadwick et al., GHGT-9, 2008.

Surface Monitoring

Detection Verification Facility (Montana State University)





Field Site

Horizontal Injection Well

Flow Controllers

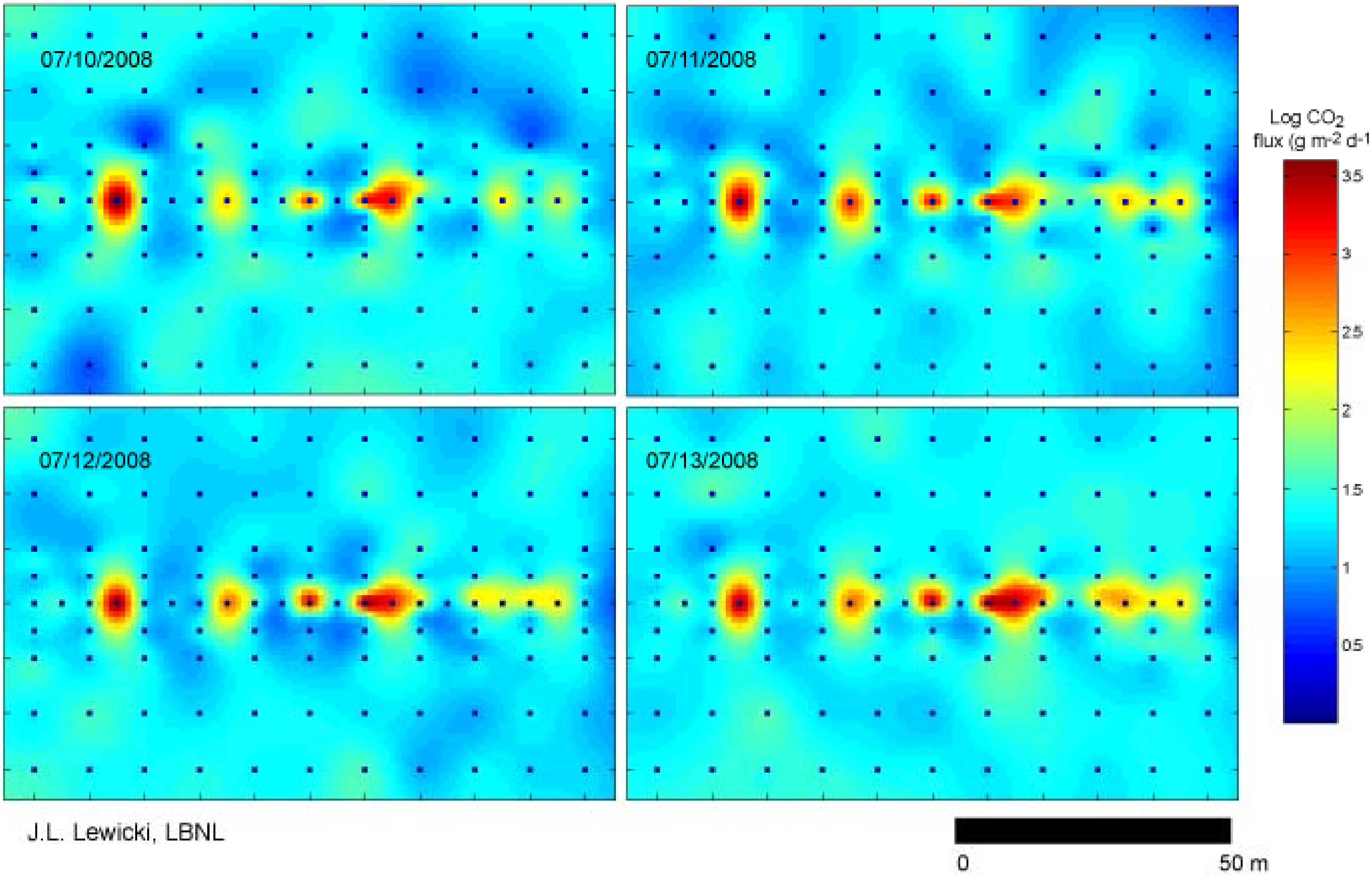
Flux Tower

Hyperspectral Imaging of Vegetation

Soil Gas

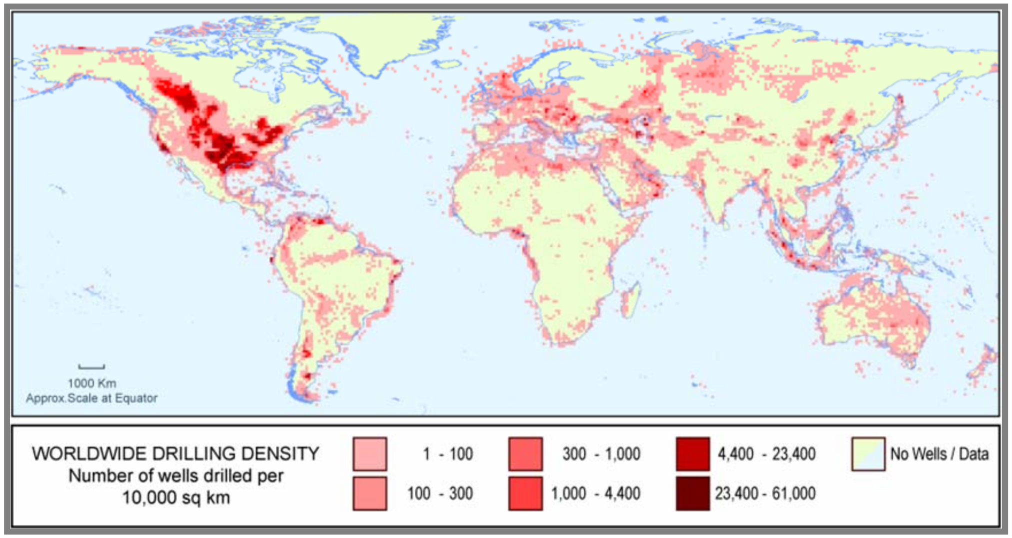
Flux accumulation chamber

Leak Detection Using Flux Accumulation Chambers



J.L. Lewicki, LBNL

What Could Go Wrong?



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

Potential Consequences

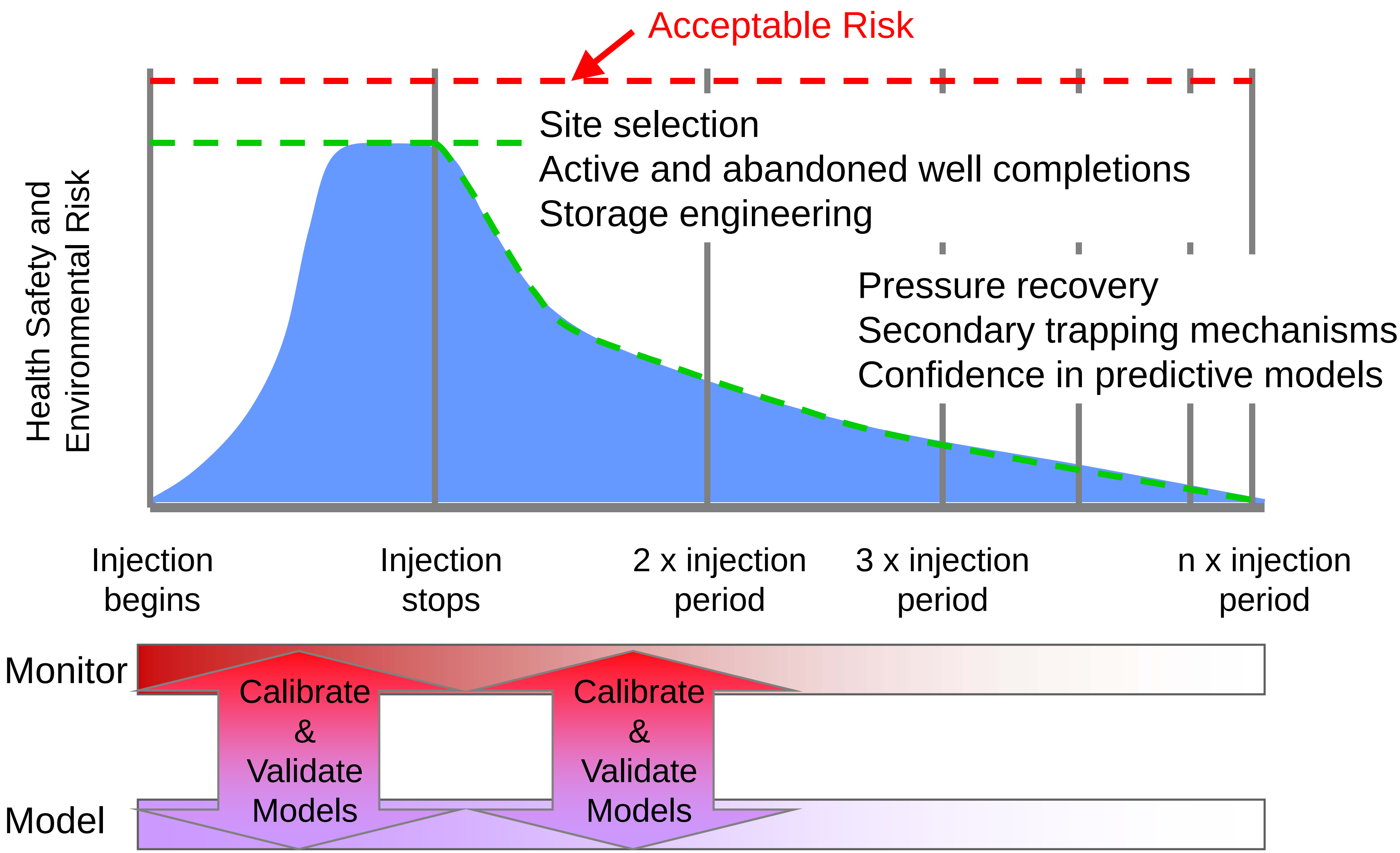
1. Worker safety
2. Groundwater quality degradation
3. Resource damage
4. Ecosystem degradation
5. Public safety
6. Structural damage
7. Release to atmosphere

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

Storage Security: Long Term Risk Profile



Maturity of CCS Technology

- 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

Institutional Issues

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

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

Concluding Remarks

- 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
  - Research and development
- 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: Lower the cost and increase reliability
  - Sequestration: Increase confidence in permanence
- Institutional issues need to be resolved to support widespread deployment