Stanford University

GCEP Global Climate & Energy Project

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Geological Sequestration: A Primer

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Global Challenges – Global Solutions – Global Opportunities

Transition to a Sustainable Energy System for the 21st Century and Beyond

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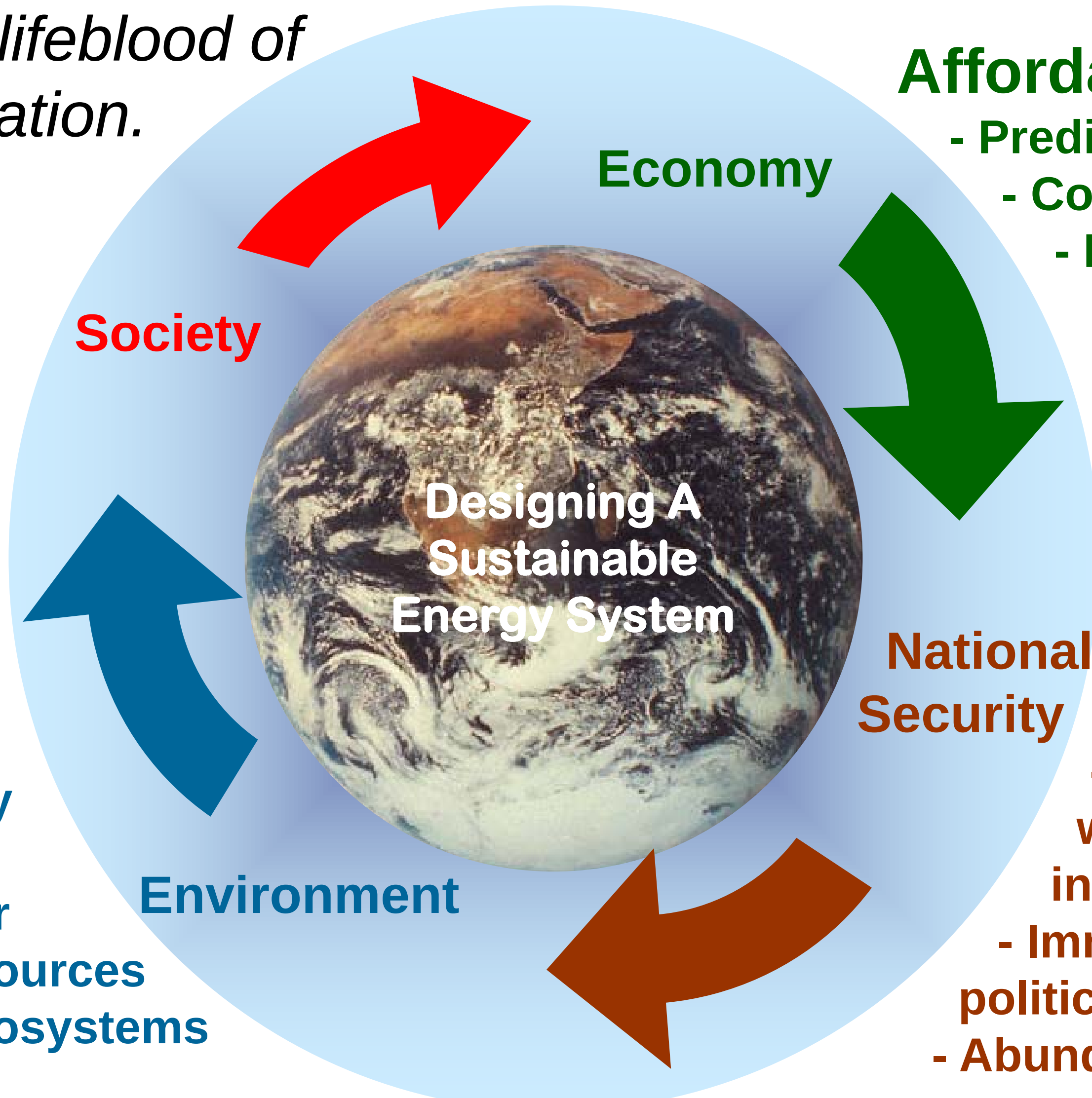
Energy is the lifeblood of modern civilization.



Accessible
- Reliable
- Useful
- Equitable

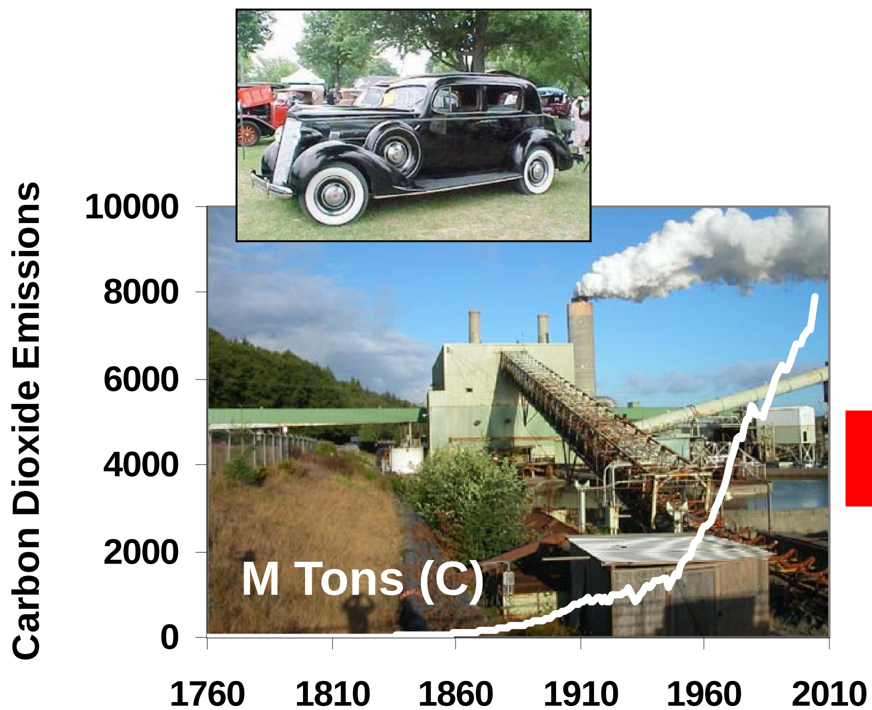
Affordable
- Predictable
- Competitive
- Resilient
- Profitable

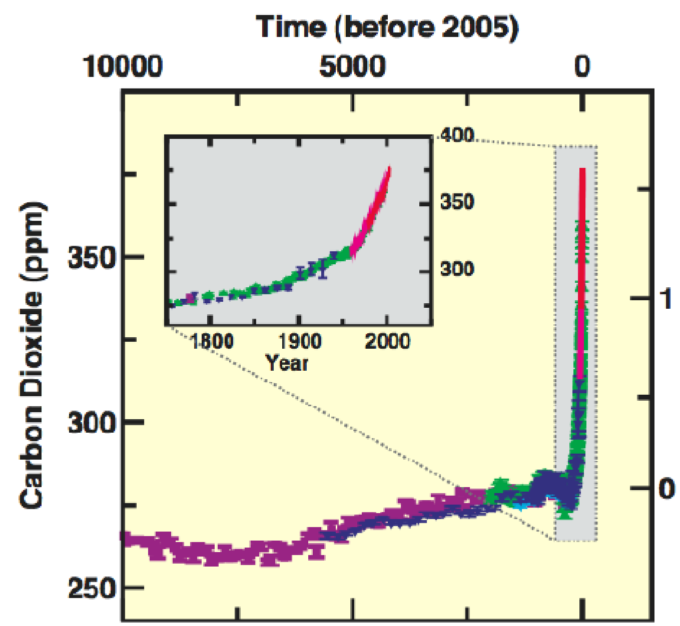
Secure
- Compatible with National interests
- Immune from political manipulation
- Abundant

Protective
- Air Quality
- Climate
- Water Resources
- Ecosystems

Carbon Dioxide in the Atmosphere

Carbon dioxide emissions have risen dramatically over the past two hundred years…

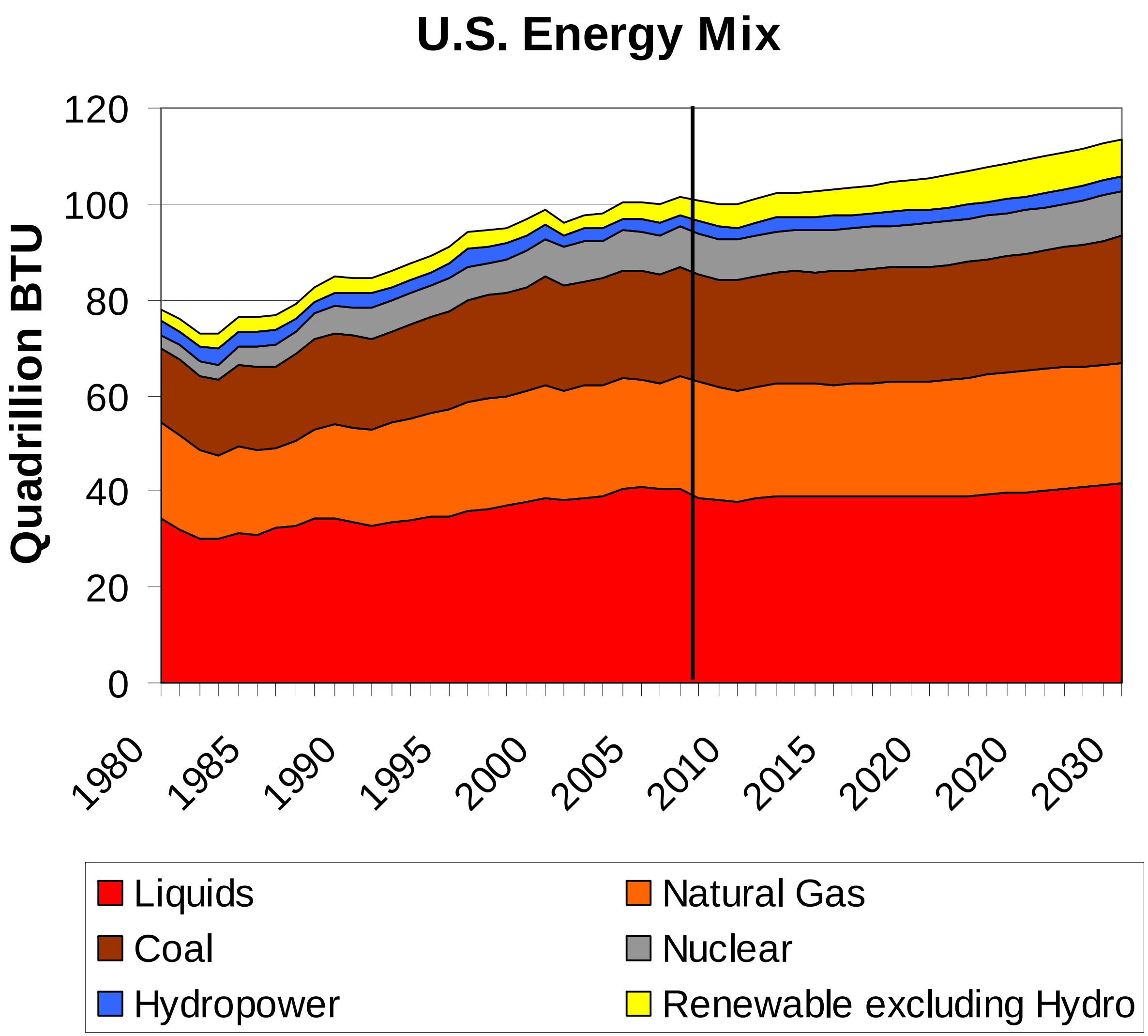




IPCC, 2007

… leading to the buildup of carbon dioxide in the atmosphere,
… global warming, and
… ocean acidification.

Today's Energy Mix

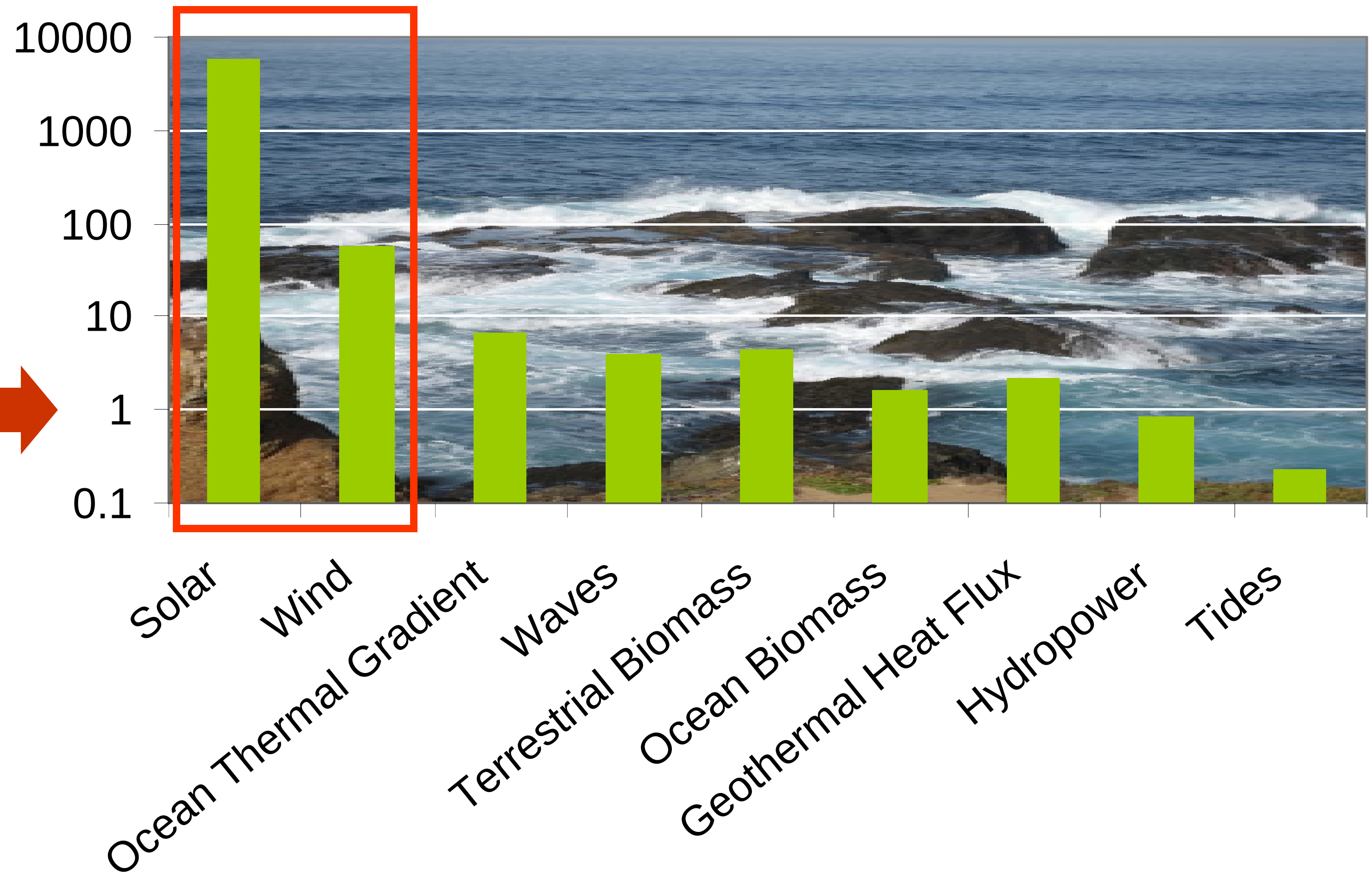


Source: EIA Reference Case, 2009

- 85% of U.S. energy supply from fossil fuels
- 80% of U.S. energy supply projected by 2030
- Reductions of CO_2 and other greenhouses gases of 50 to 80% are needed by 2050
- Low carbon emission electricity options
  - Renewable energy (sun and wind)
  - Nuclear power
- Growth of these is unlikely to be fast enough to achieve needed emission reductions

Renewable Global Energy Flows

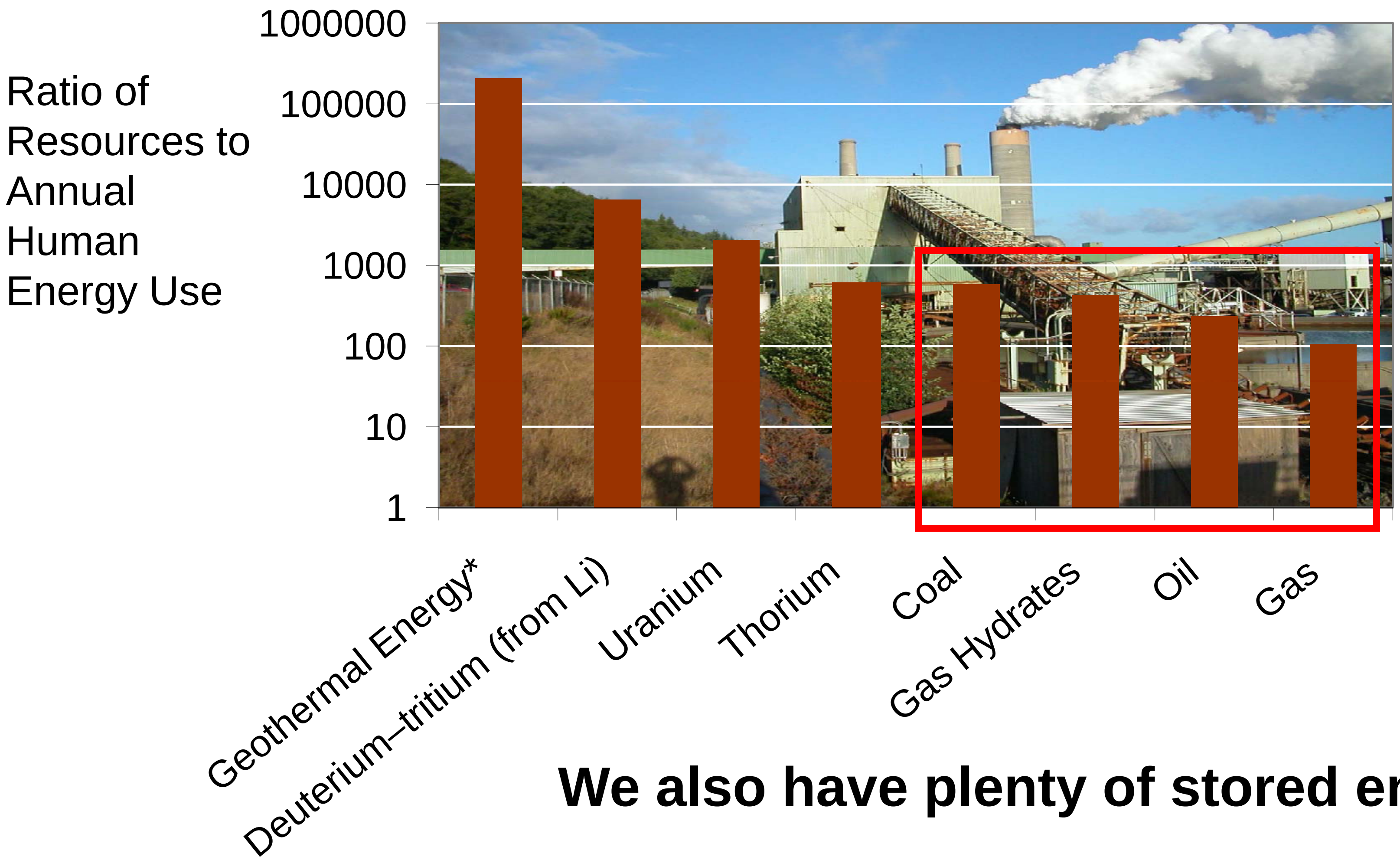
Human Use of Energy (15 TW)



The solar and wind energy resources are large compared to human energy use.

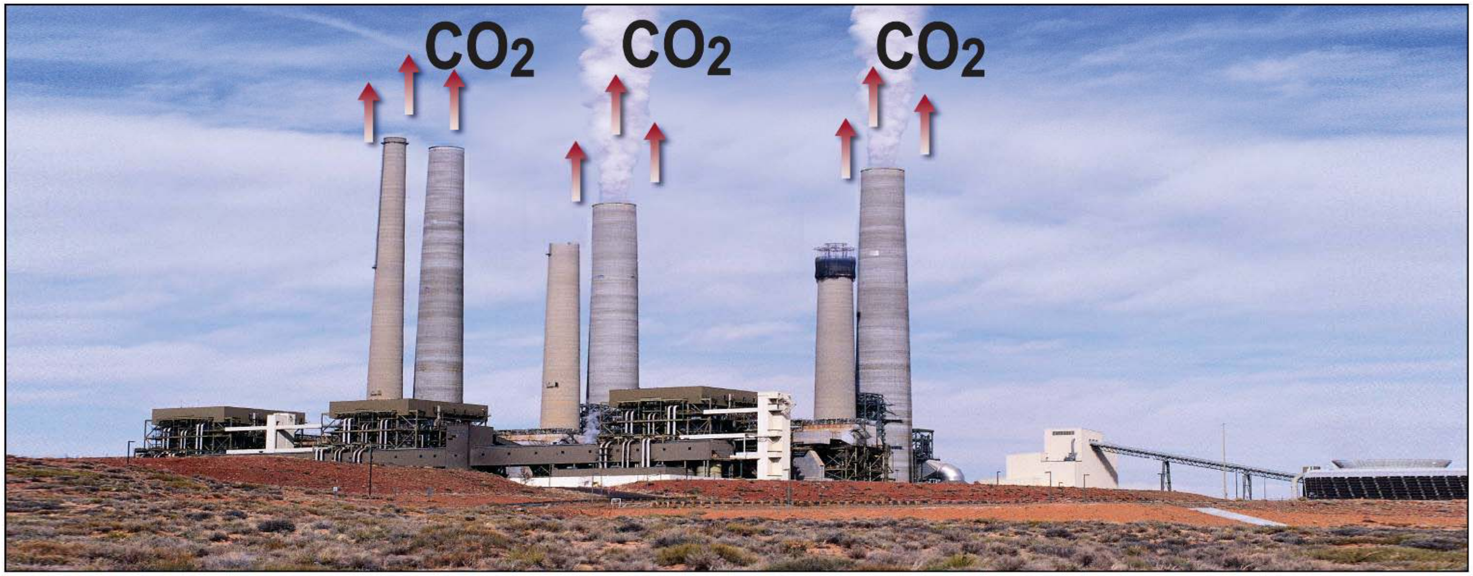
Energy Stored in the Earth's Crust

Energy Stores



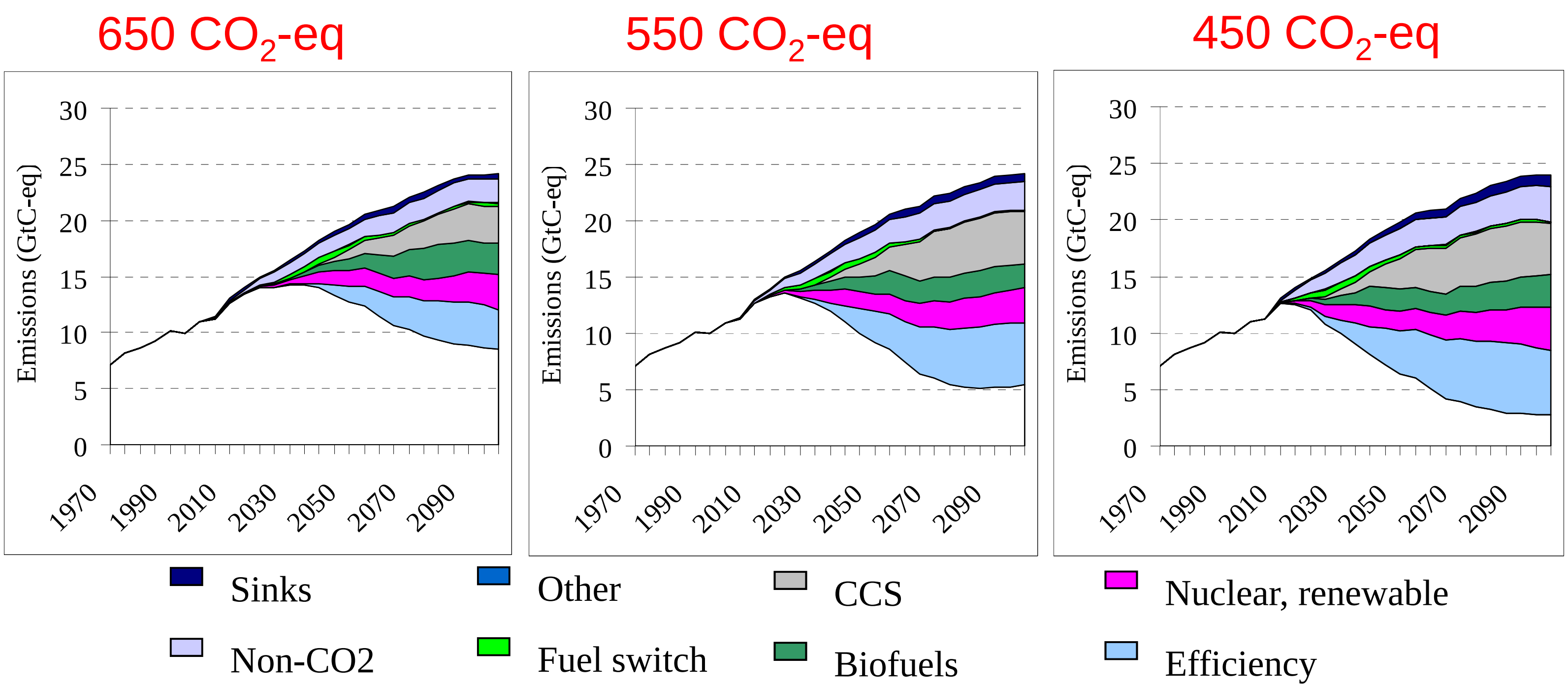
We also have plenty of stored energy.

What is Carbon Dioxide Capture and Storage and Why is it Important?



- Carbon dioxide capture and storage technology can slow global warming by reducing carbon dioxide emissions into the atmosphere
- Applicable to the 60% of emissions which come from stationary sources such as power plants
- Necessary to achieve the rapid carbon dioxide emission reductions

CCS is Needed for Large CO_2 Emission Reduction



Expected contributions to GHG emissions with carbon prices in the range of \$20 to \$100/tCO_2-eq.

From IPCC, 2007:WG III

Current Worldwide Sources and Emissions (~7,500 total > 0.1 MT/yr)

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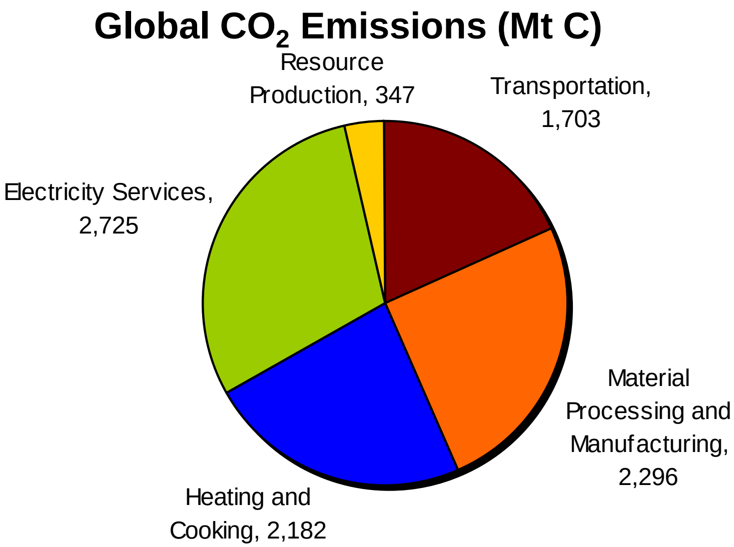


Electricity Sector

Fuel	# of Sources	Average Emissions per Source (MT/source)
Coal	2025	3.9
Nat. Gas	1728	0.8 – 1.0
Fuel Oil	1108	0.6 – 1.3

IPCC Special Report, 2005

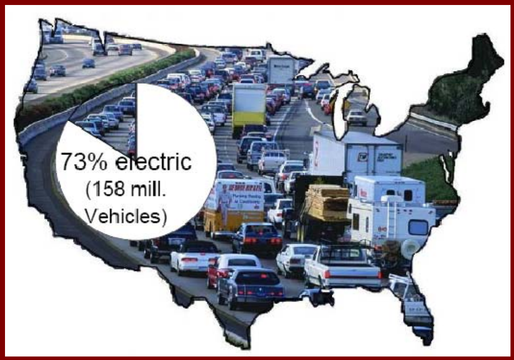
Material Processing & Manufacturing

Source	# of Sources	Average Emissions per Source (MT/source)
Cement	1175	0.8
Refining	638	1.35
Other	736	0.15 – 3.5

IPCC Special Report, 2005

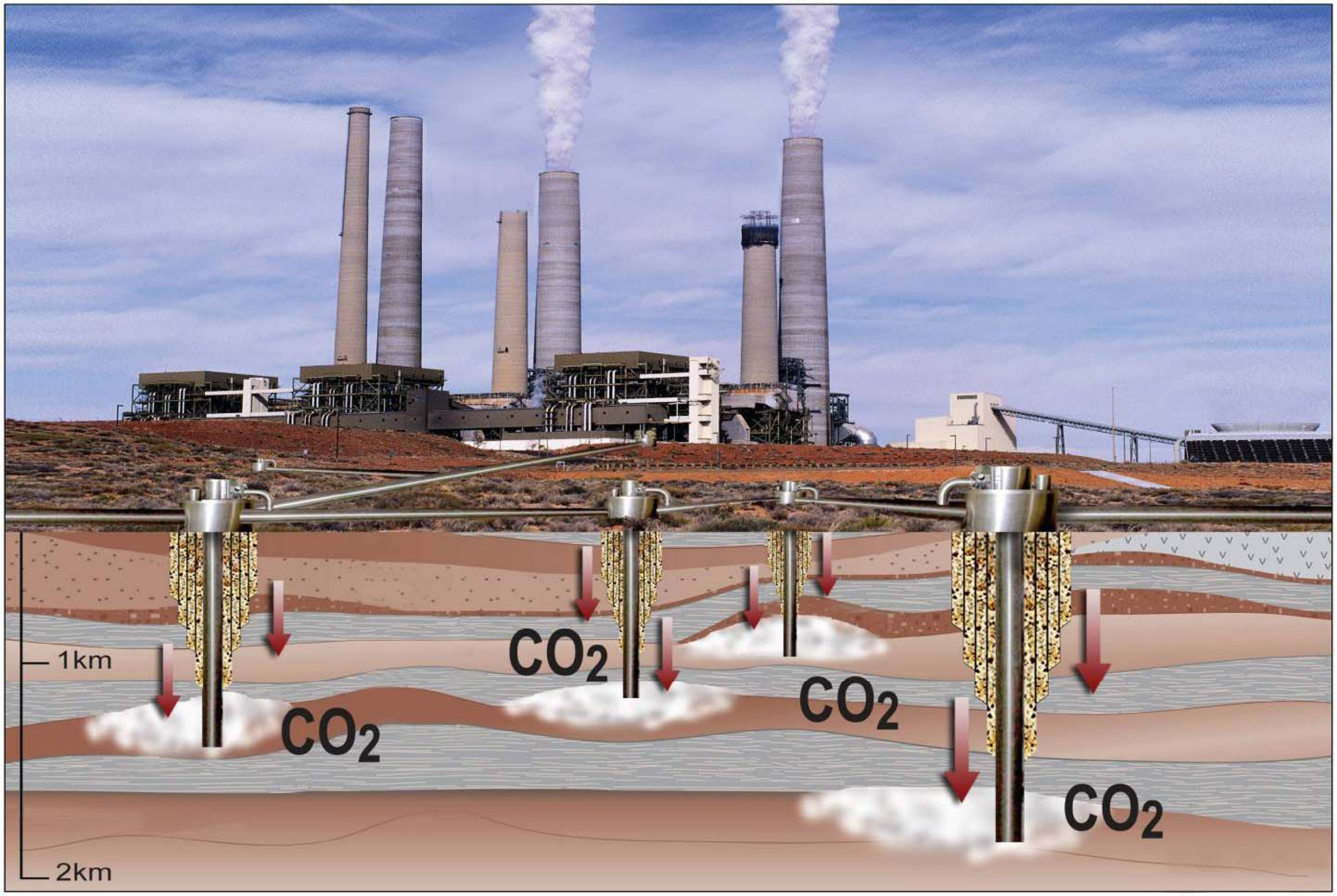
Transportation Sector

Little today.
Future Potential?



73% of U.S. light duty transport could be powered with existing fleet of power plants, Kintner-Meyer, PNNL, 2007

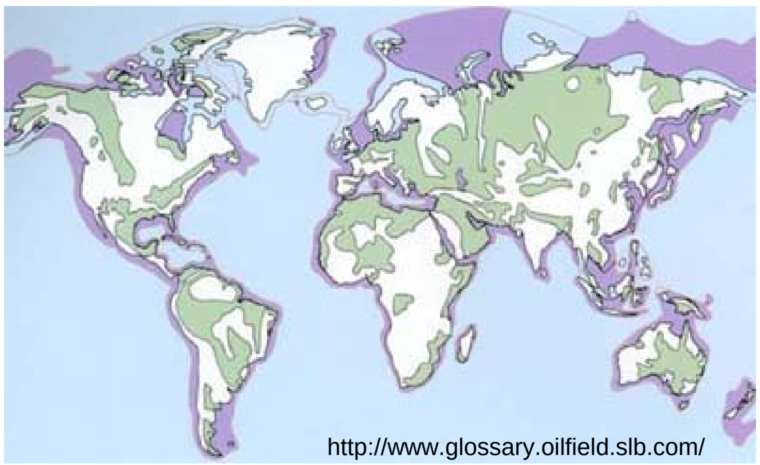
Carbon Dioxide Capture and Storage Involves 4 Steps



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

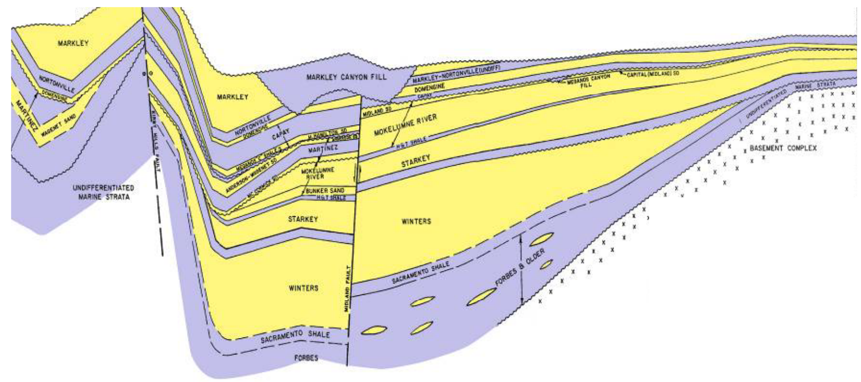
What Types of Rock Formations are Suitable for Geological Storage?

Rocks in deep sedimentary basins are suitable for CO_2 storage.



Map showing world-wide sedimentary basins

100 km



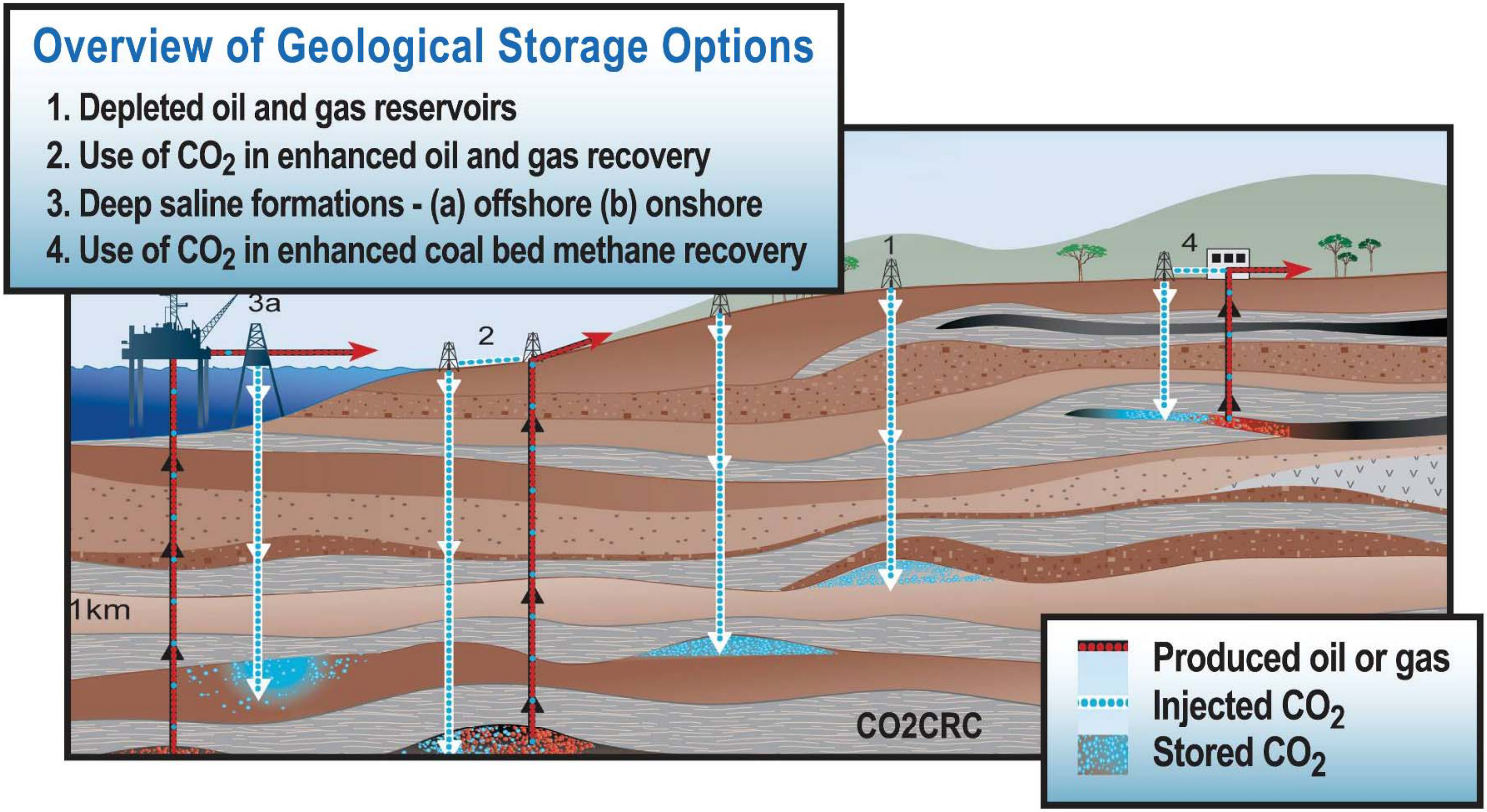
Northern California Sedimentary Basin

1 inch

Sandstone

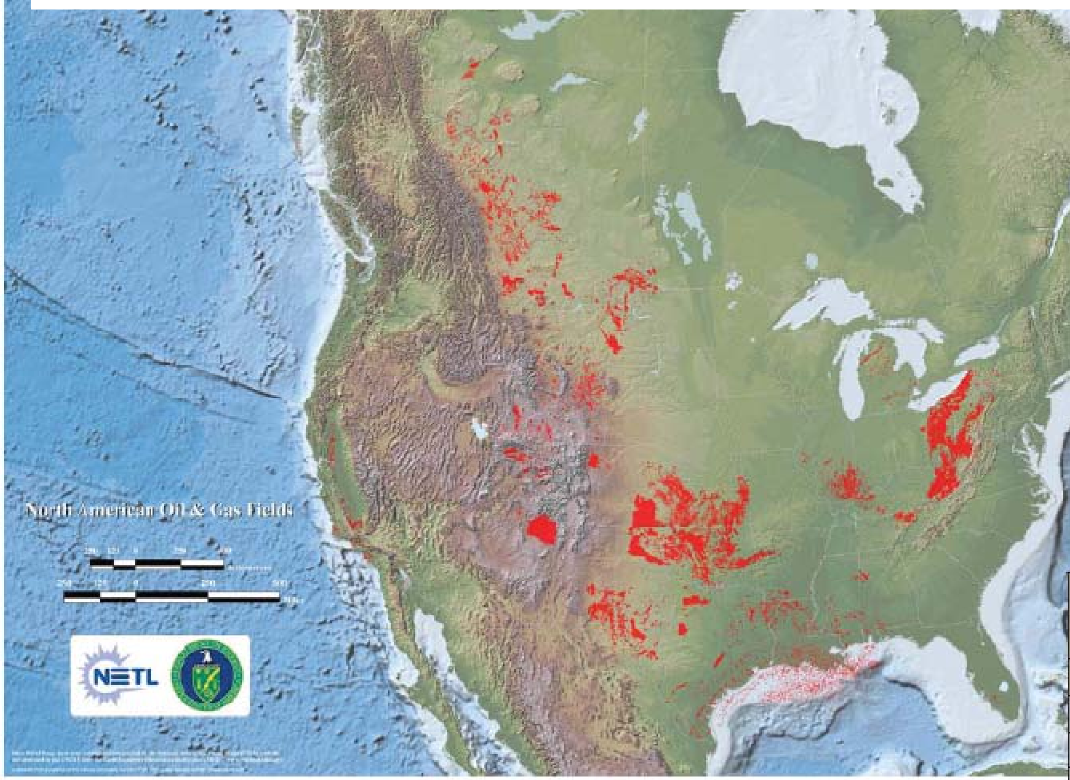
Example of a sedimentary basin with alternating layers of sandstone and shale.

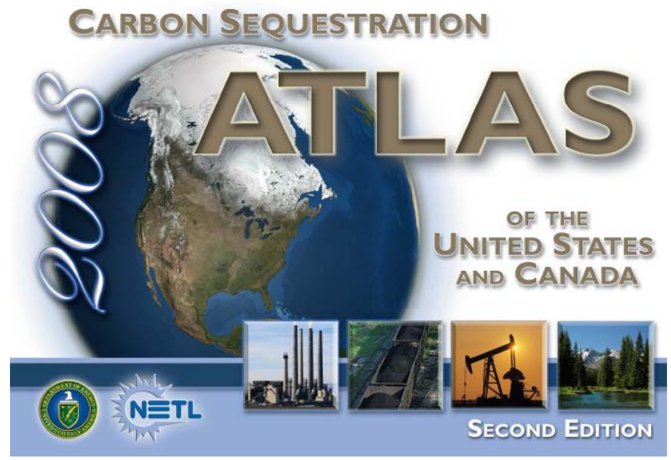
Options for Geological Storage



Storage Resources in Oil and Gas Reservoirs

Oil and gas reservoirs could potentially store about 60 years of current emissions from power generation.

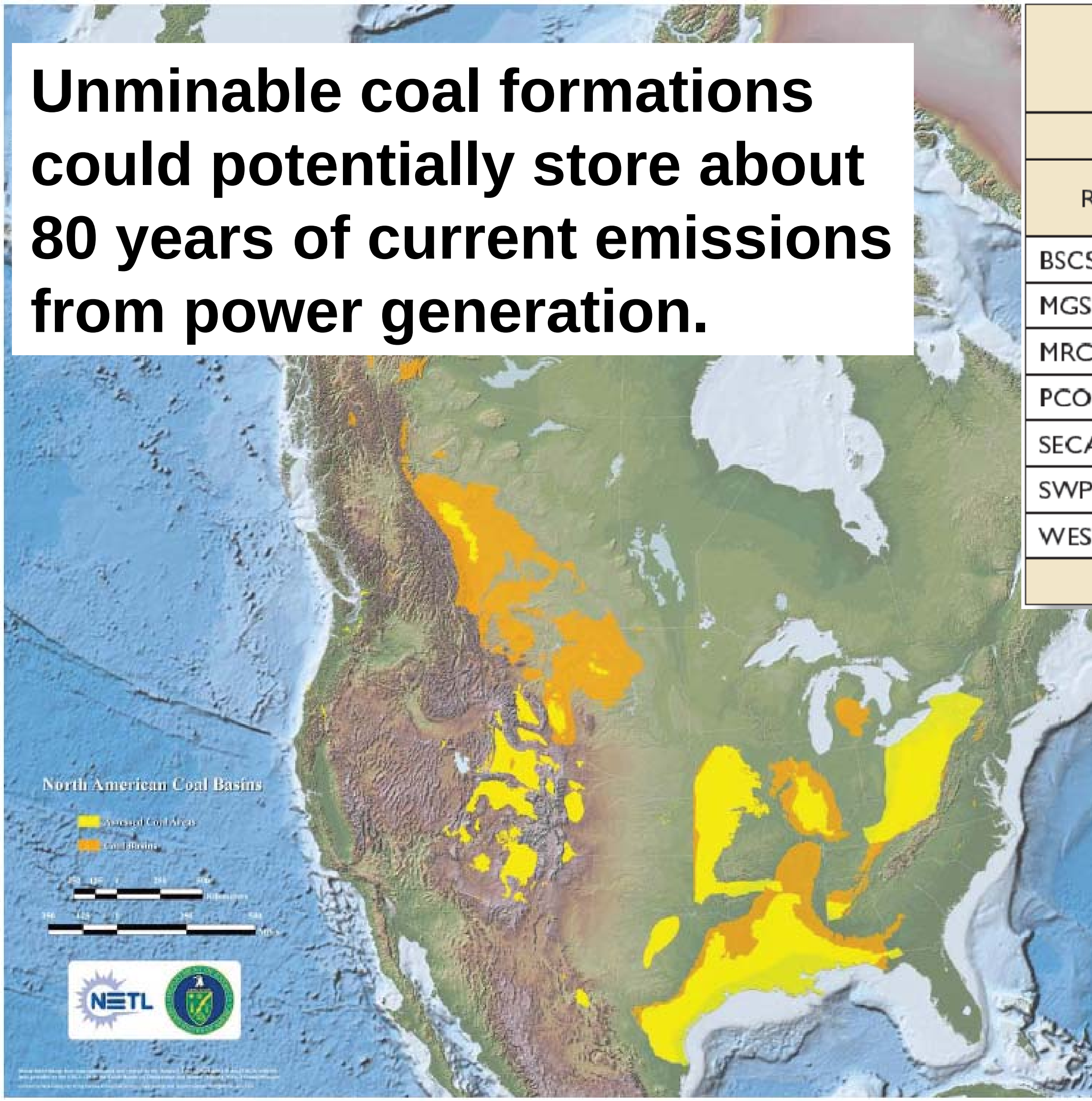




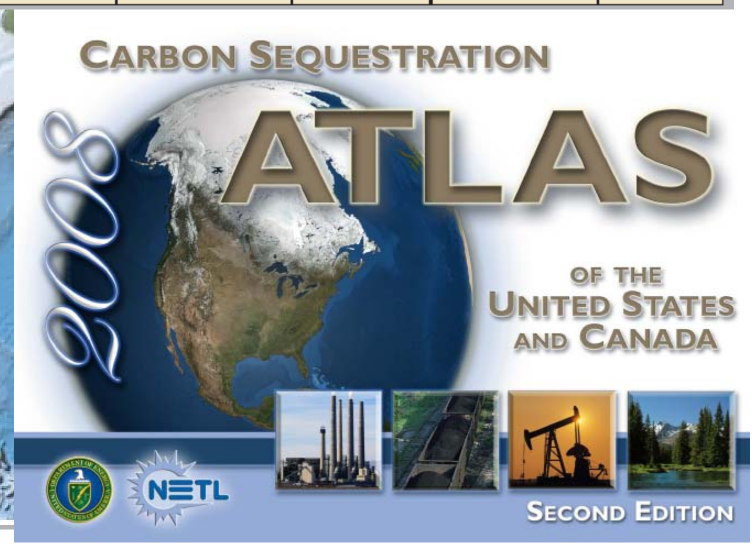
CO_2 Resource Estimates by Regional Carbon Sequestration Partnership for Oil and Gas Reservoirs		
RCSP	Billion Metric Tons	Billion Tons
BSCSP	1.5	1.6
MGSC	0.4	0.4
MRCSP	8.4	9.3
PCORP	24.1	26.5
SECARB	27.1	29.9
SWP	62.3	68.7
WESTCARB	5.8	6.4
TOTAL	129.6	142.9

Storage Resources in Coal Beds

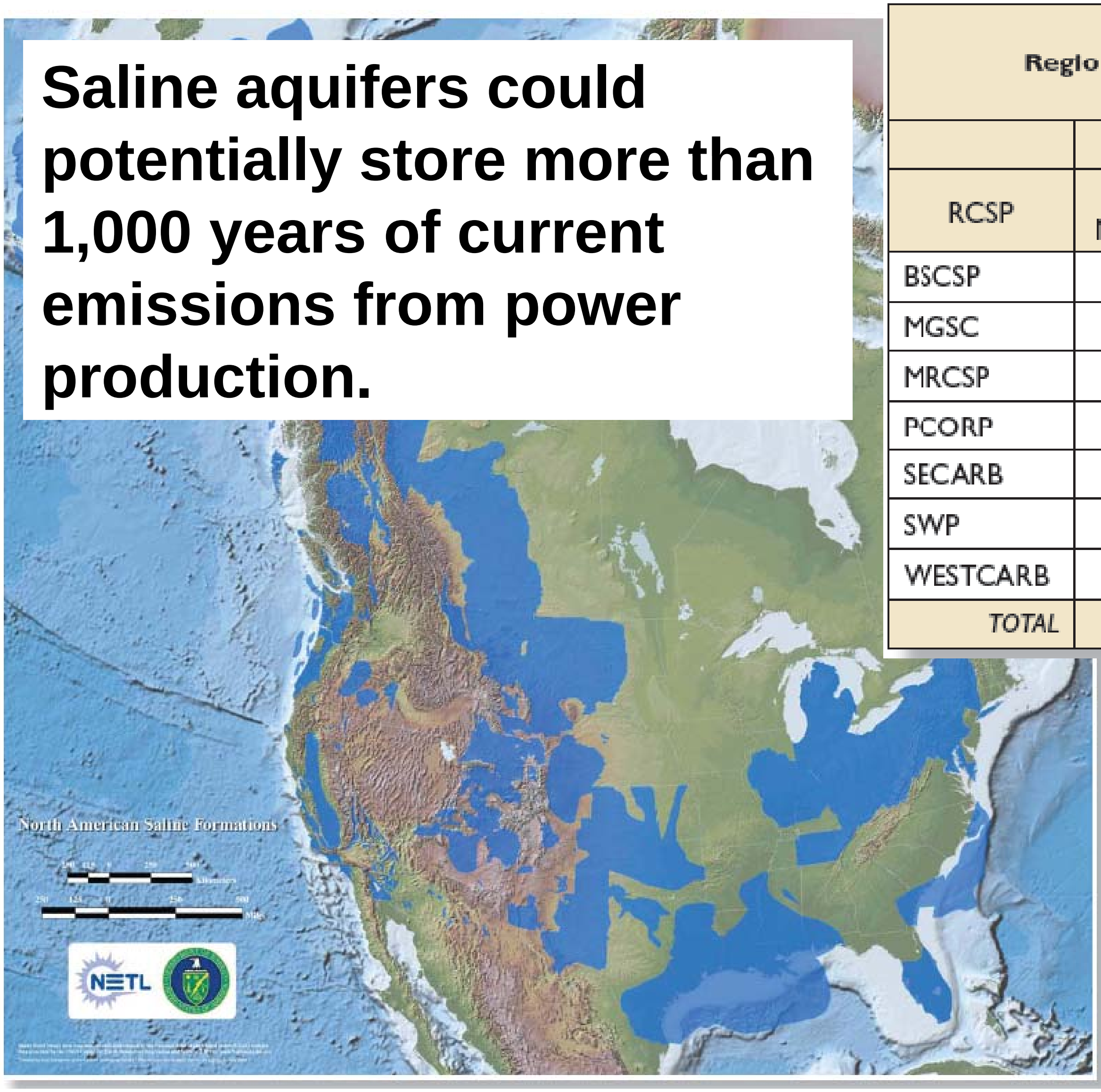
Unminable coal formations could potentially store about 80 years of current emissions from power generation.



CO_2 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



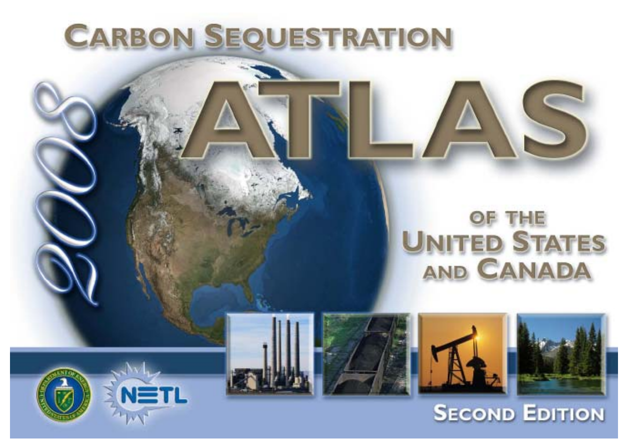
Saline Aquifers



Saline aquifers could potentially store more than 1,000 years of current emissions from power production.

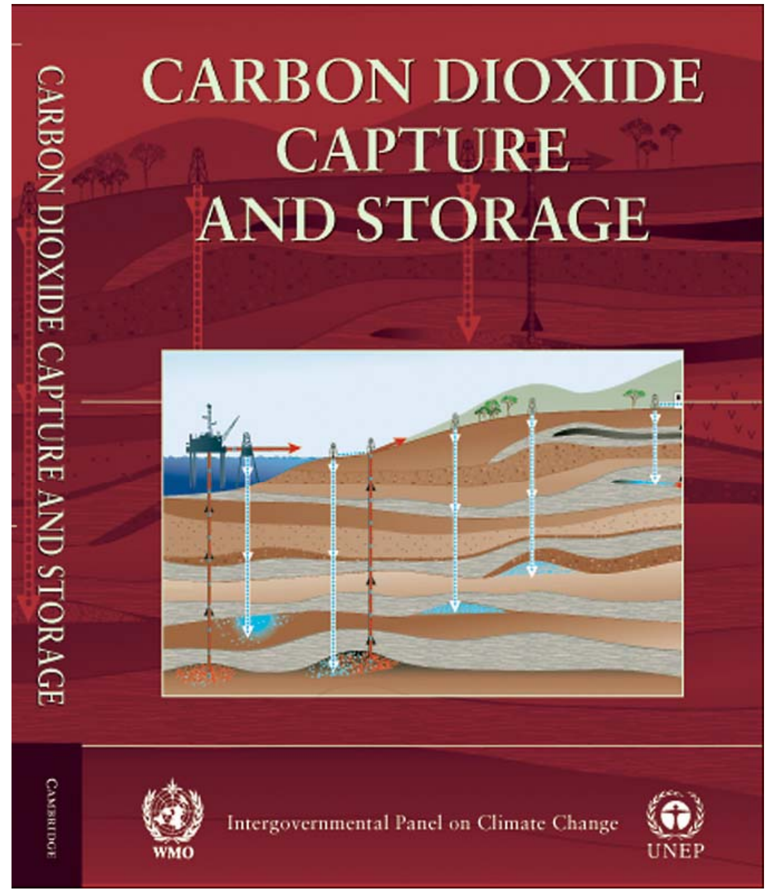
CO_2 Resource Estimates by Regional Carbon Sequestration Partnership for Saline Formations

	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."*



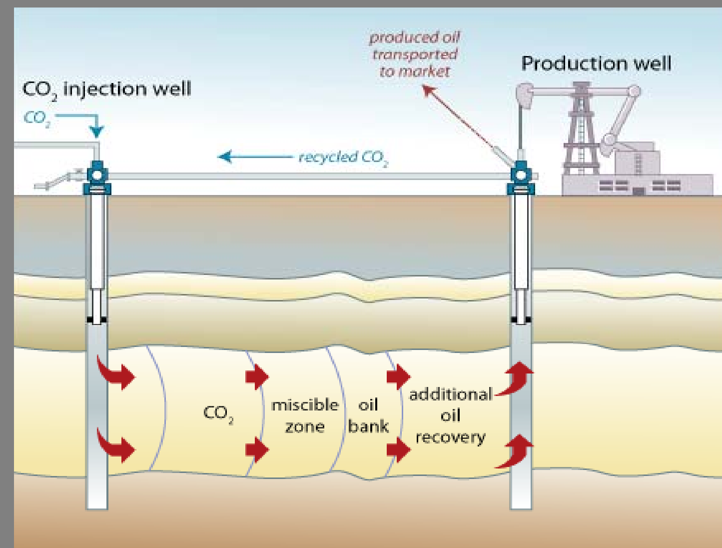
" With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO_2 releases if they arise, the local health, safety and environment risks of geological storage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

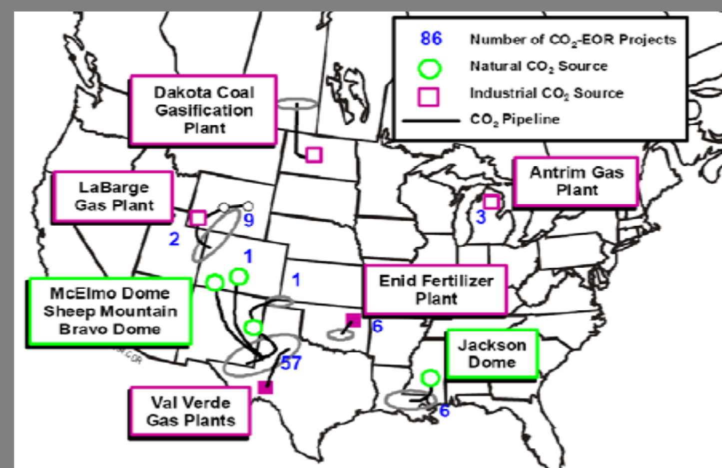
* "Very likely" is a probability between 90 and 99%.

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

Evidence to Support these Conclusions

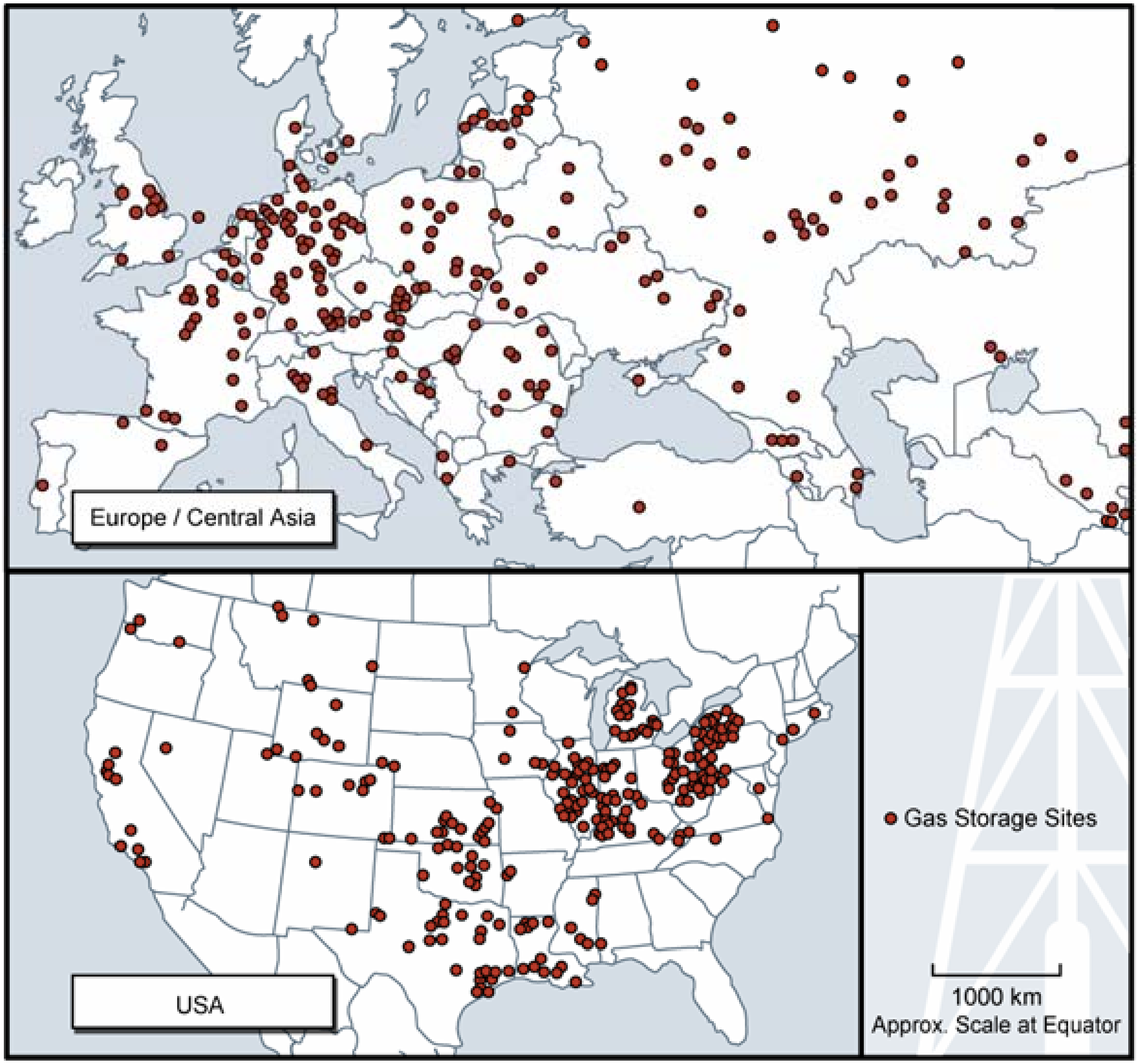
- Natural geological analogs
  - Oil and gas reservoirs
  - CO_2 reservoirs
- Performance of industrial analogs
  - 30+ years experience with CO_2 EOR
  - 100 years experience with natural gas storage
  - Acid gas disposal
- 25+ years of cumulative performance of actual CO_2 storage projects
  - Sleipner,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





~35 Mt/yr are injected for CO_2-EOR

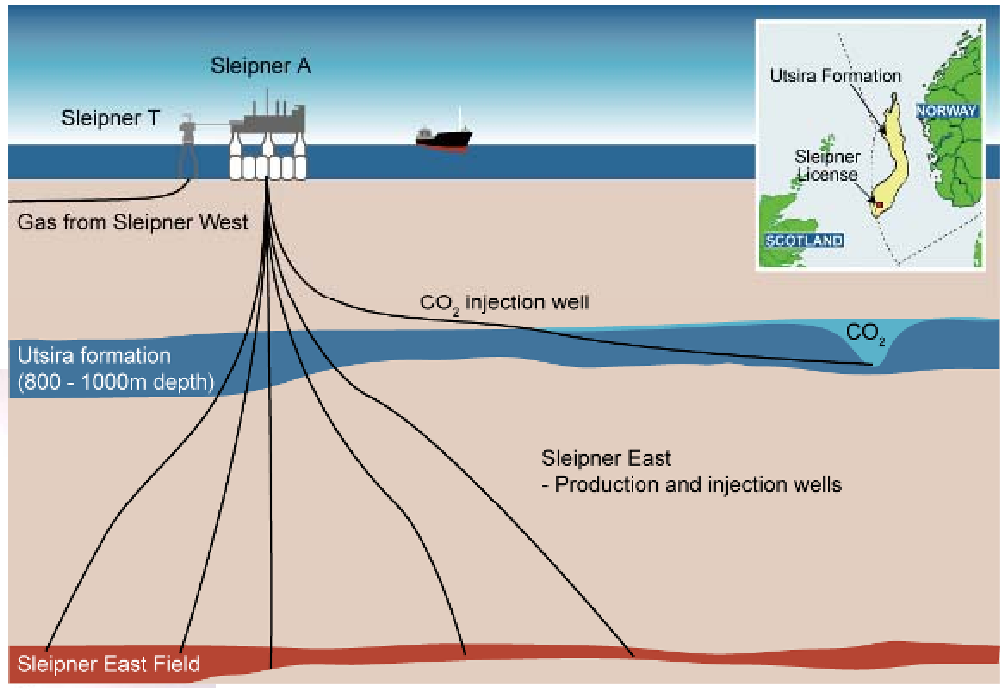
Natural Gas Storage



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

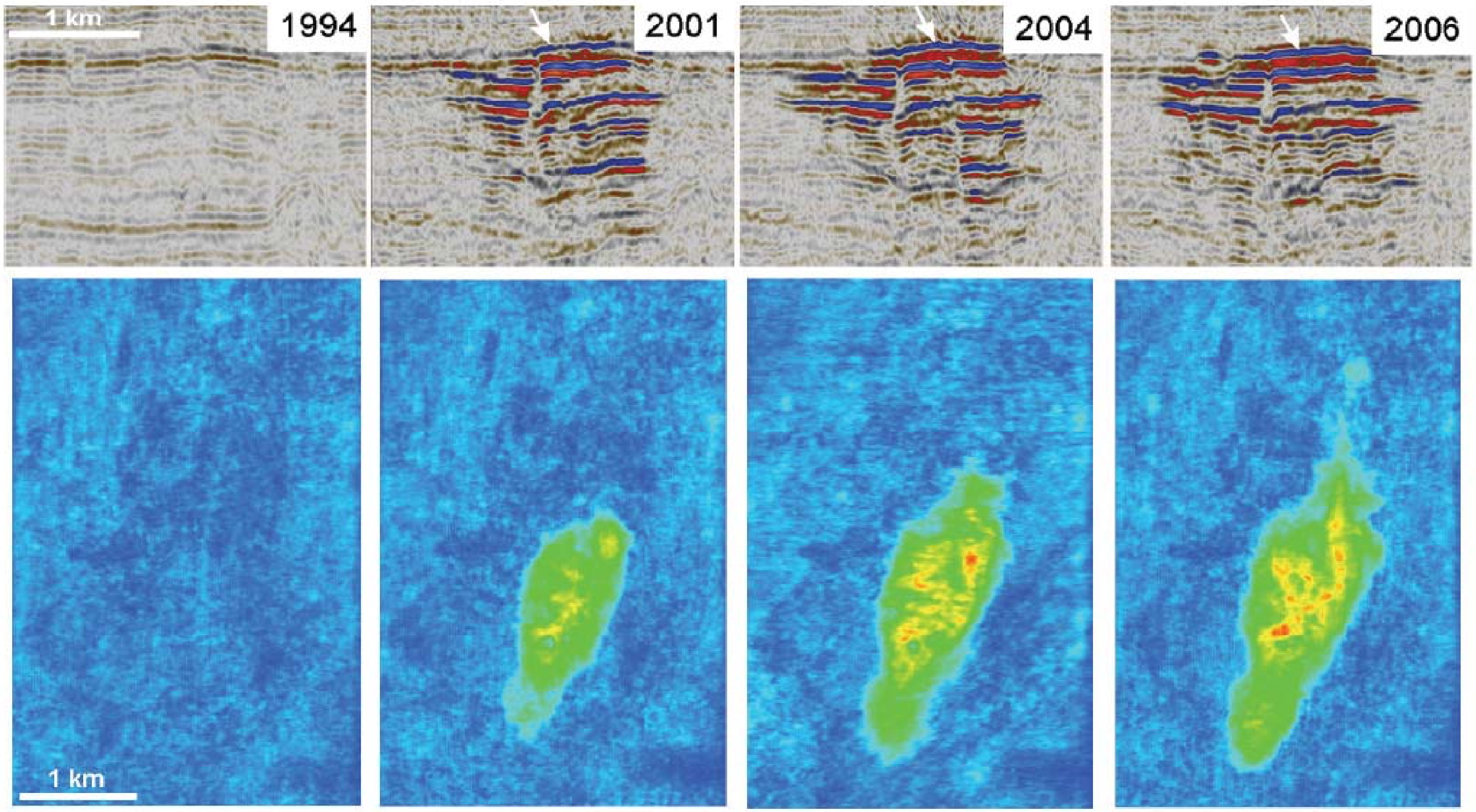
Sleipner Project, North Sea

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



Courtesy *Statoil*

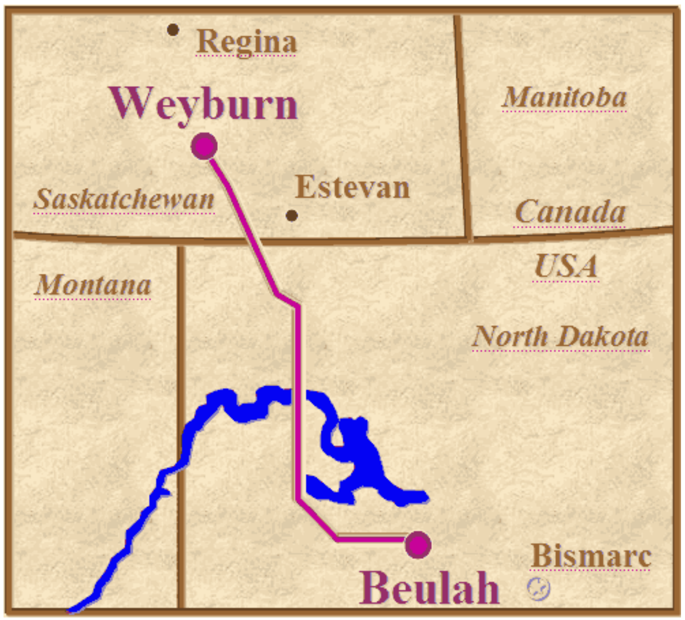
Seismic Monitoring Data from Sleipner



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

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.



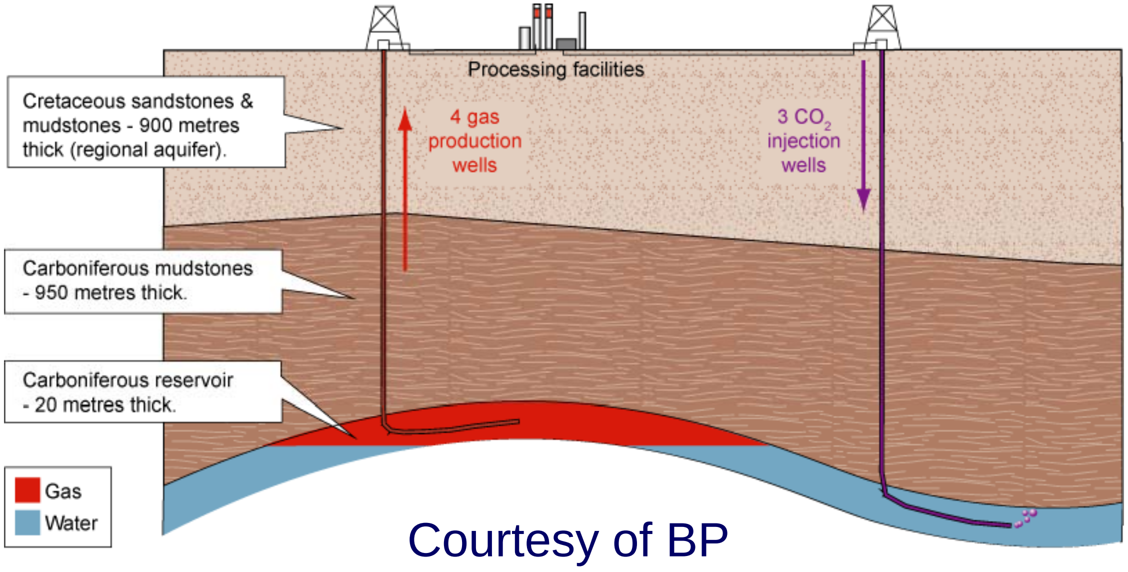
In Salah Gas Project

In Salah Gas Project
- Krechba, Algeria

Gas Purification
- Amine Extraction

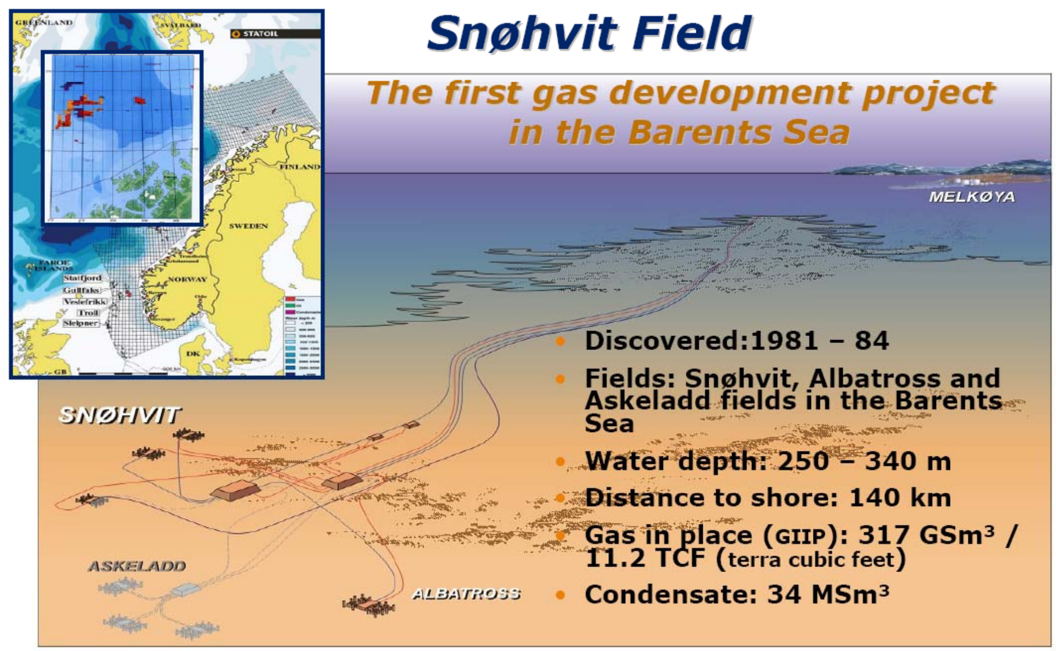
1 Mt/year CO_2 Injection

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…"

Long Term Stewardship and Financial Responsibility

Regulatory Oversight

Remediation

Monitoring

Safe Operations

Storage Engineering

Site Characterization and Selection

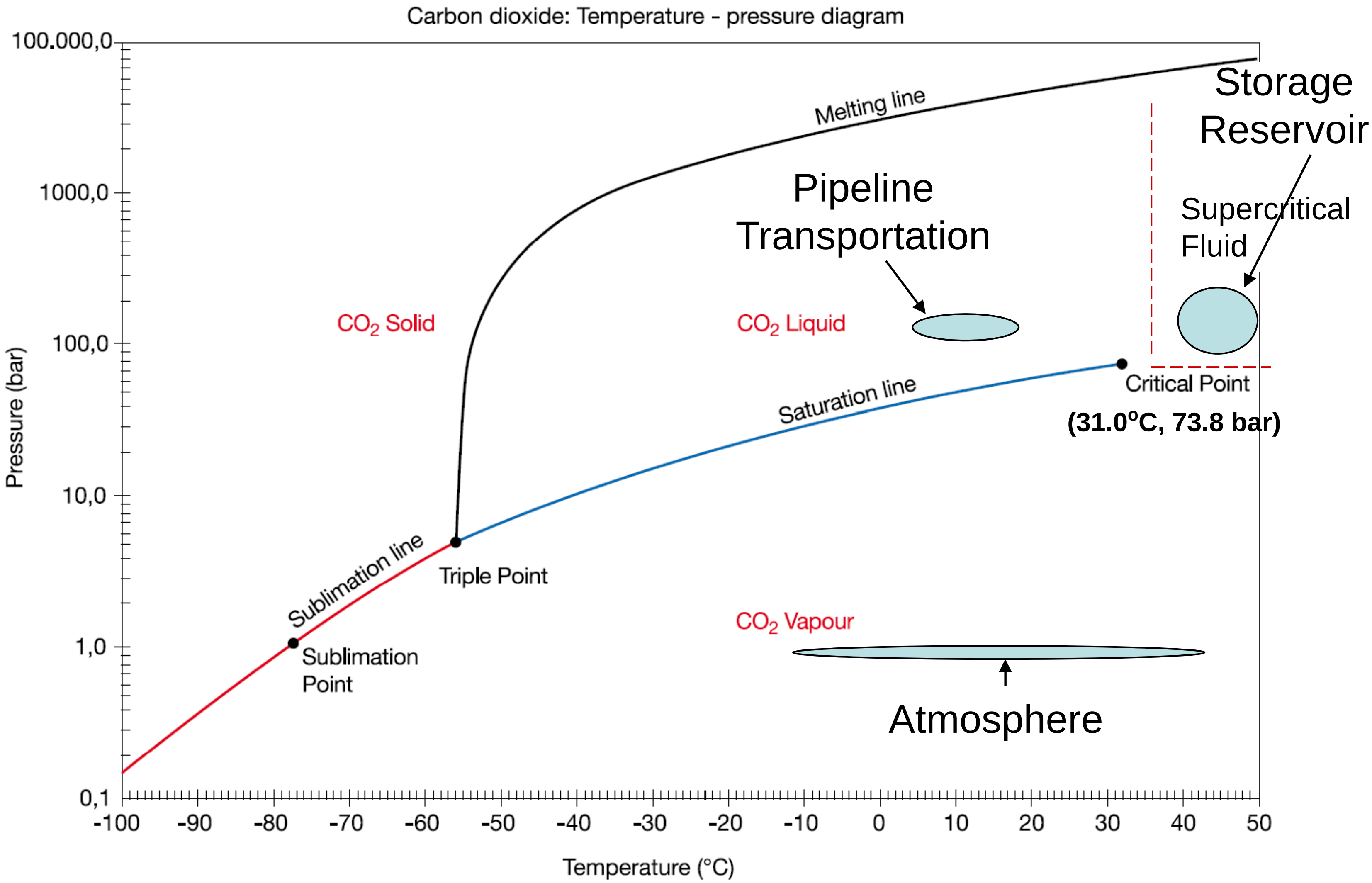
Fundamental Storage and Leakage Mechanisms

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

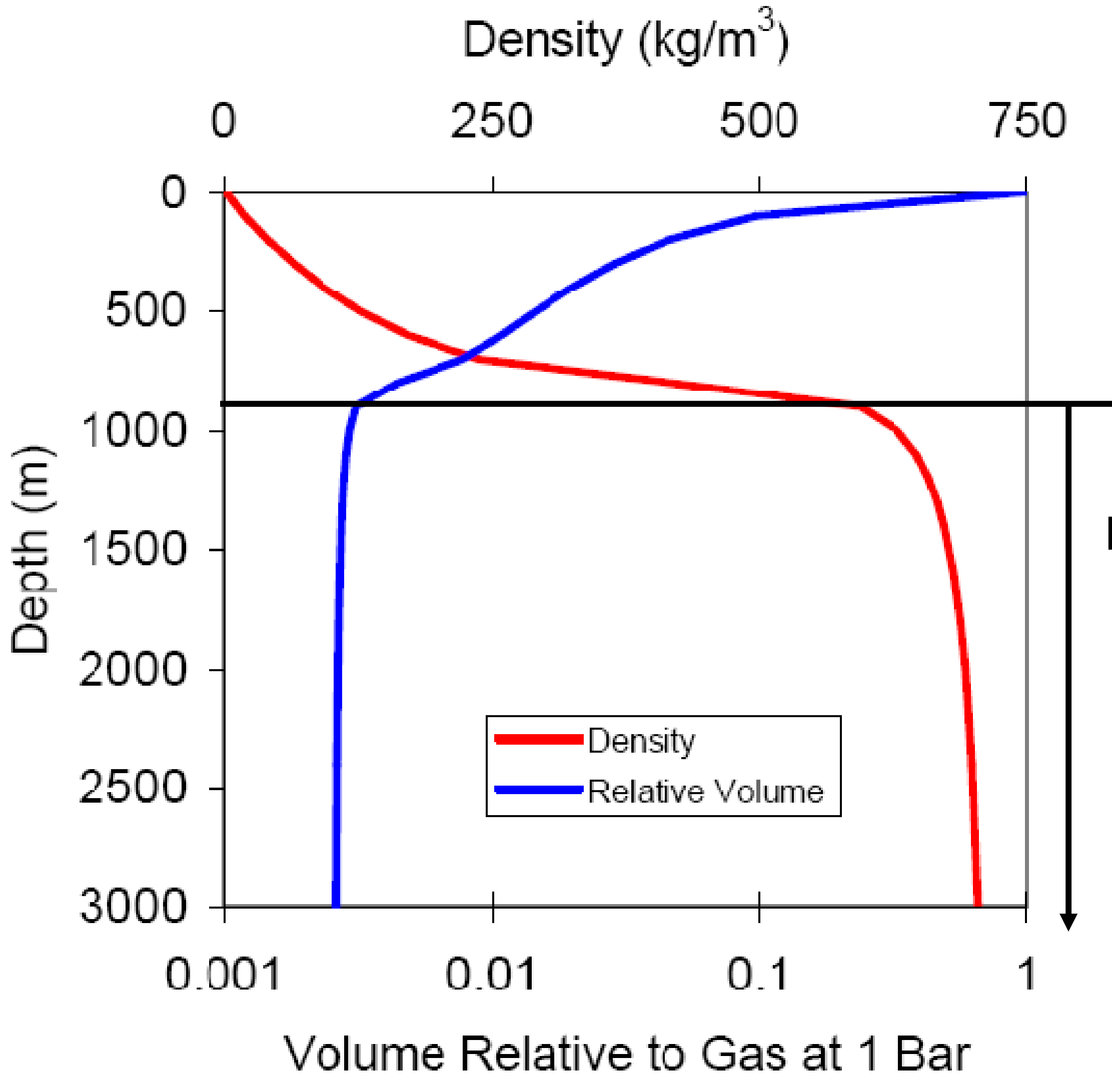
"… the fraction retained is likely to exceed 99% over 1,000 years."

IPCC, 2005

Fluid Properties of Carbon Dioxide



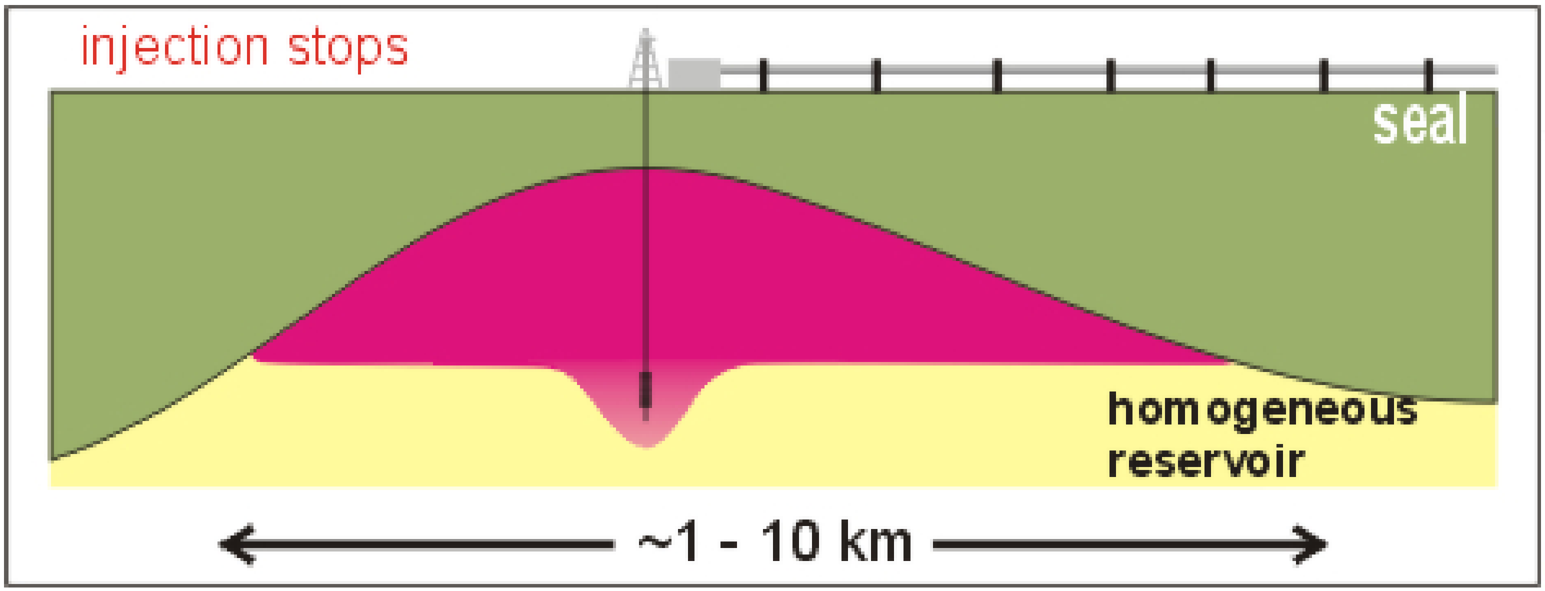
Density of Carbon Dioxide



Storage at Depths Greater than 1,000 m (3,000 ft)

Basic Concept of Geological Sequestration of CO_2

- Injected at depths of 1 km or deeper into rocks with tiny pore spaces
- Primary trapping
  - Beneath seals of low permeability rocks



Courtesy of John Bradshaw

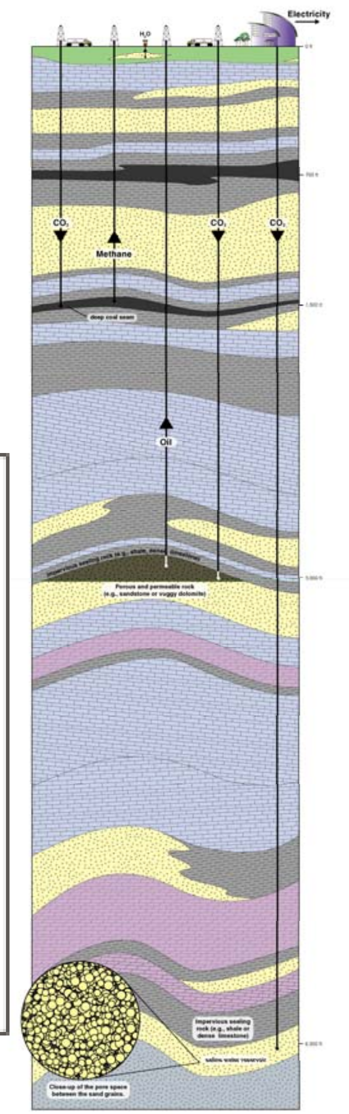


Image courtesy of ISGS and MGSC

X-ray Micro-tomography at the Advanced Light Source

Micro-tomography Beamline

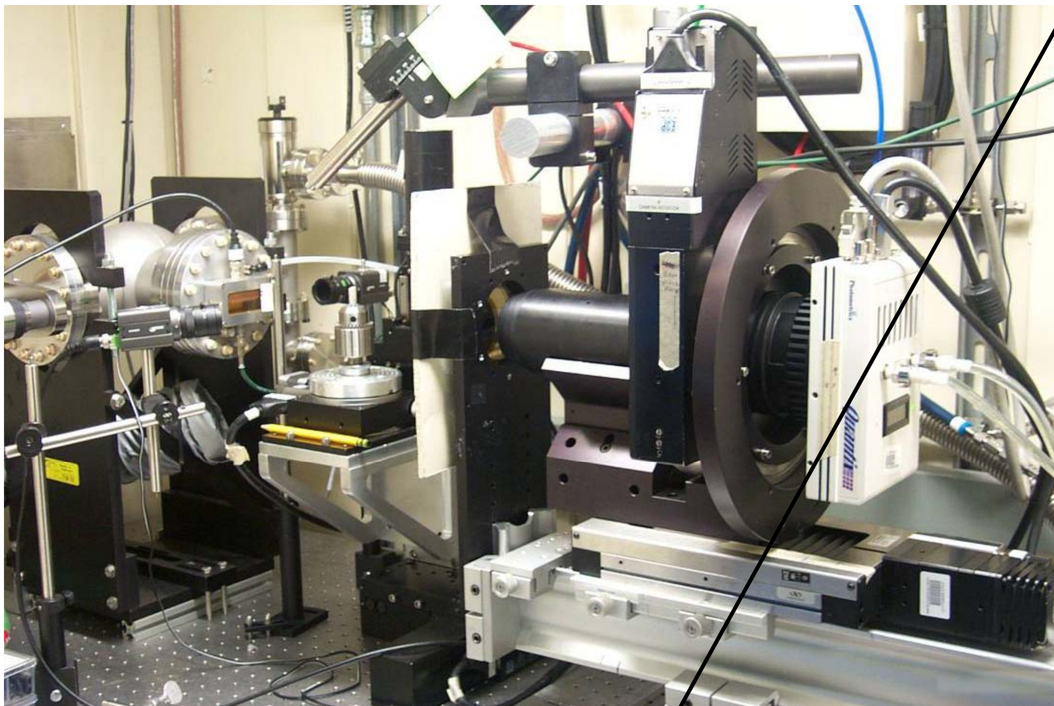
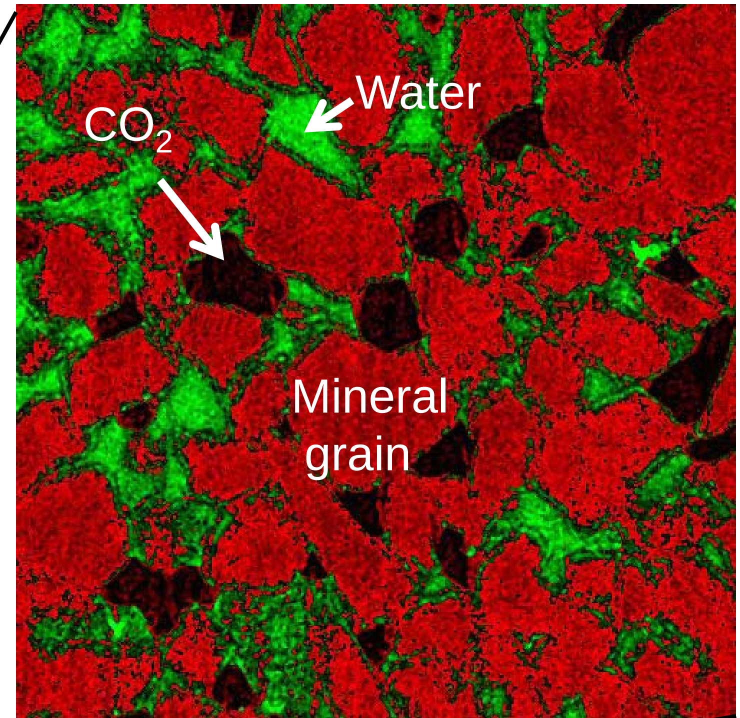


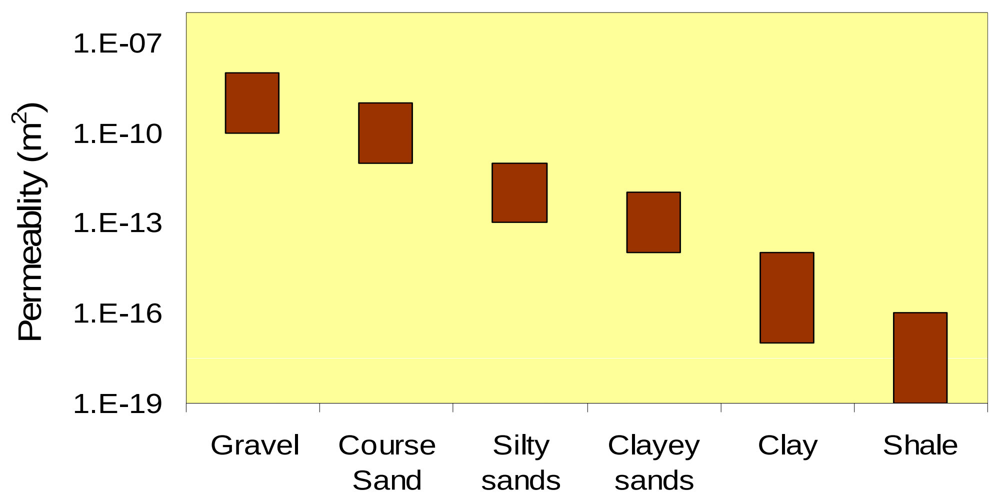
Image of Rock with CO_2



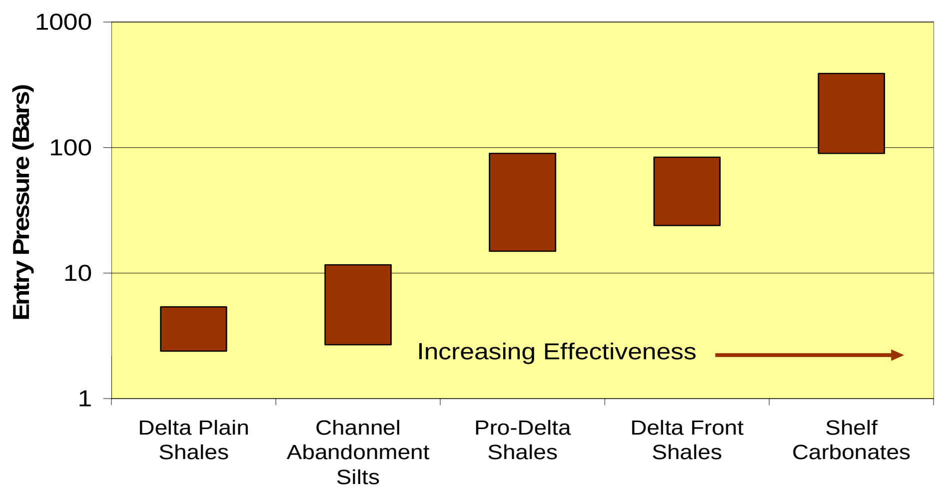
2 mm

Seal Rocks and Trapping Mechanisms

- Seal rock geology
  - Shale
  - Clay
  - Carbonates
- Two trapping mechanisms
  - Permeability barriers to CO_2 migration
  - Capillary barriers to CO_2 migration

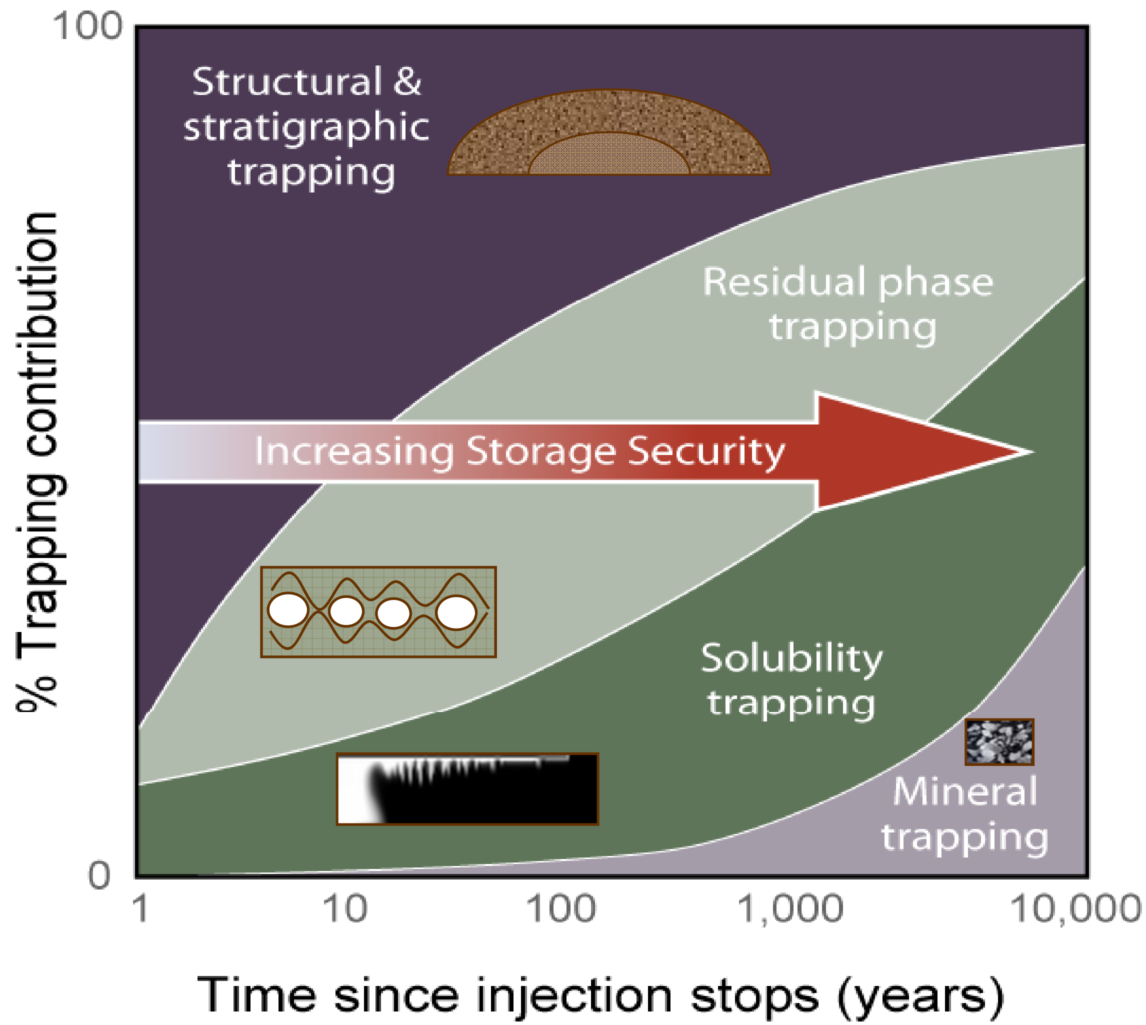


Capillary Barrier Effectiveness

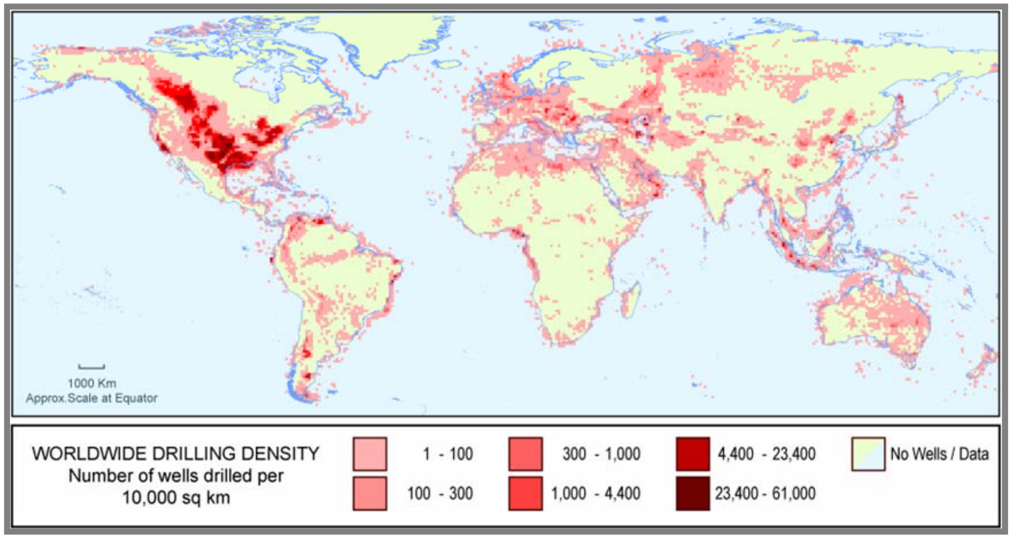


Secondary Trapping Mechanisms Increase Over Time

- Solubility trapping
  - CO_2 dissolves in water
- Residual gas trapping
  - CO_2 is trapped by capillary forces
- Mineral trapping
  - CO_2 converts to solid minerals
- Adsorption trapping
  - CO_2 adsorbs to coal



What Could Go Wrong?



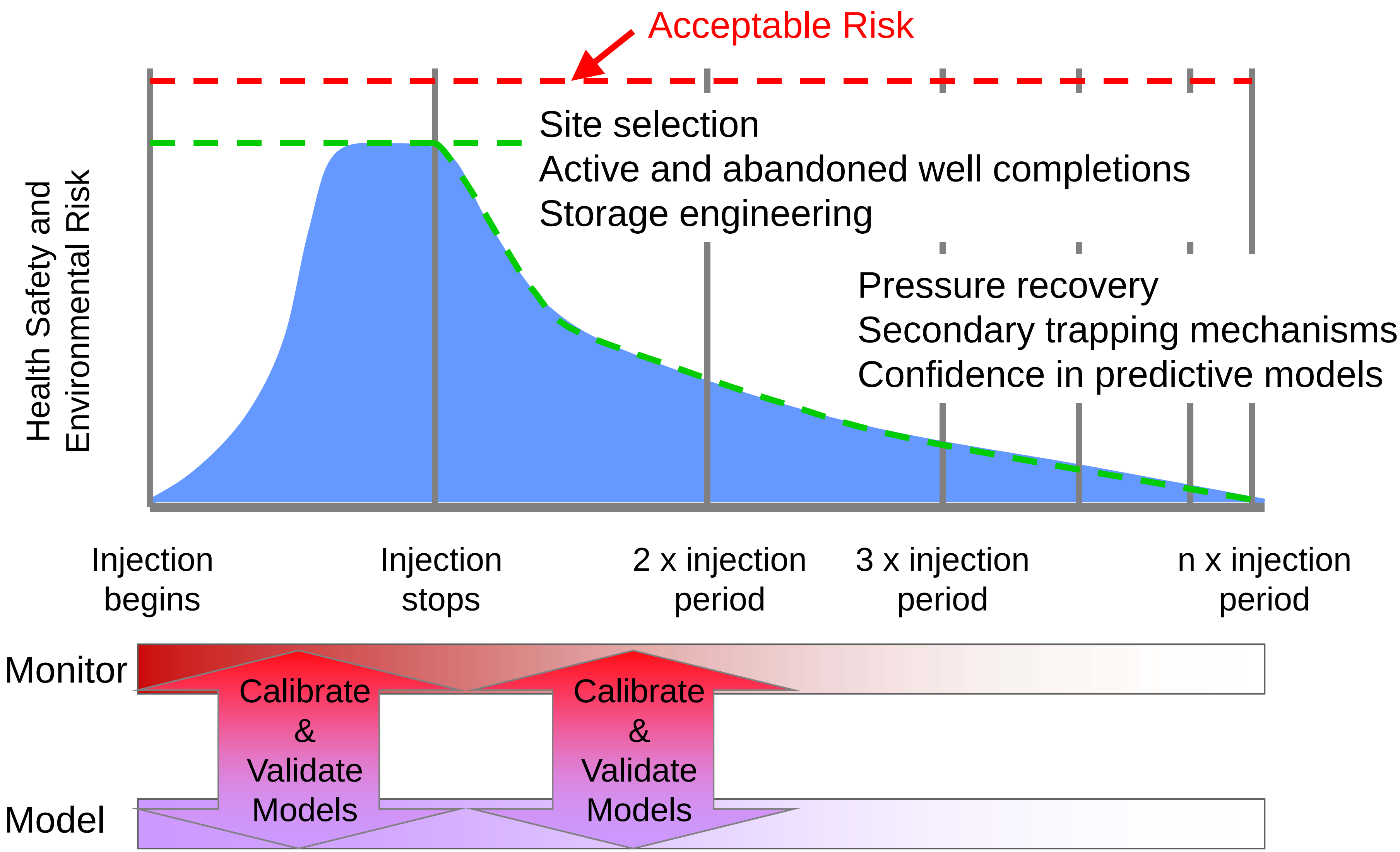
Potential Consequences

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

Potential Release Pathways

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

Risk Management



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

Concluding Remarks

- CCS is an important part of solving the global warming problem
- Progress on CCS proceeding on all fronts
  - Industrial-scale projects
  - Demonstration plants
  - Research and development
- Technology is sufficiently mature for commercial projects with CO_2-EOR and for large scale demonstration projects in saline aquifers
- Research is needed to support deployment at scale
  - Capture: Lower the cost and increase reliability
  - Sequestration: Increase confidence in permanence
- Institutional issues and incentives need to be addressed to support widespread deployment