Stanford University

GCEP Global Climate & Energy Project

APS Energy Research Workshop
Portland Oregon
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Carbon Dioxide Capture and Sequestration in Deep Geological Formations

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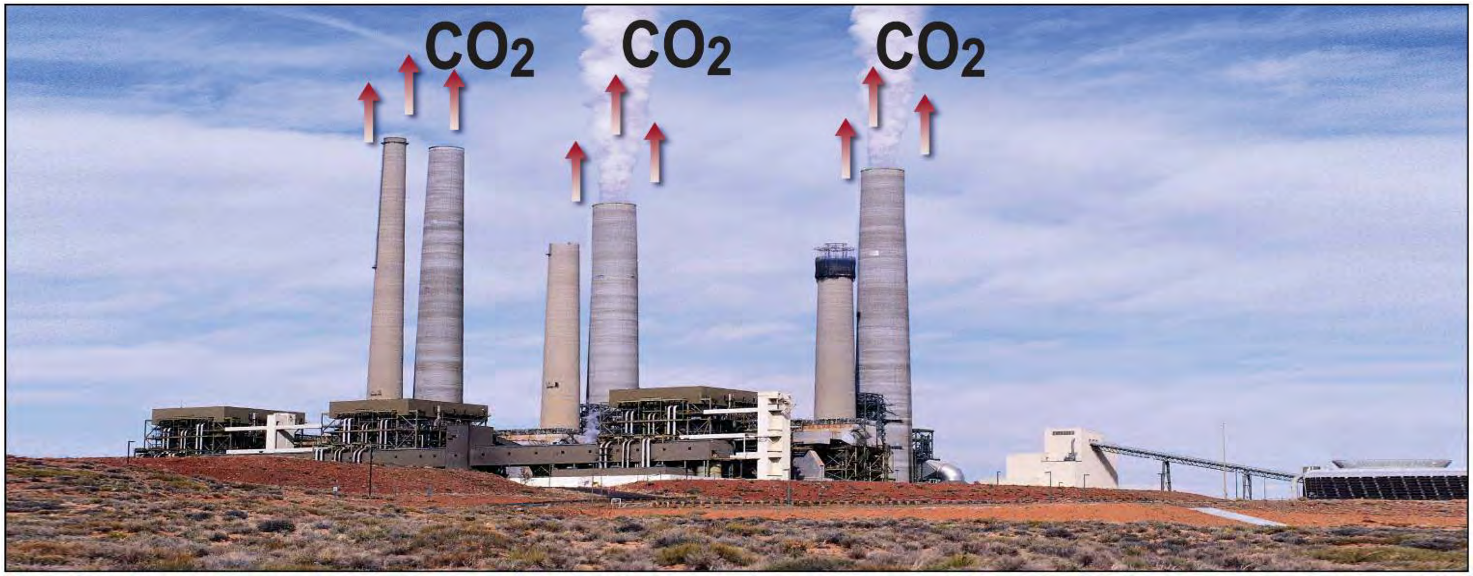
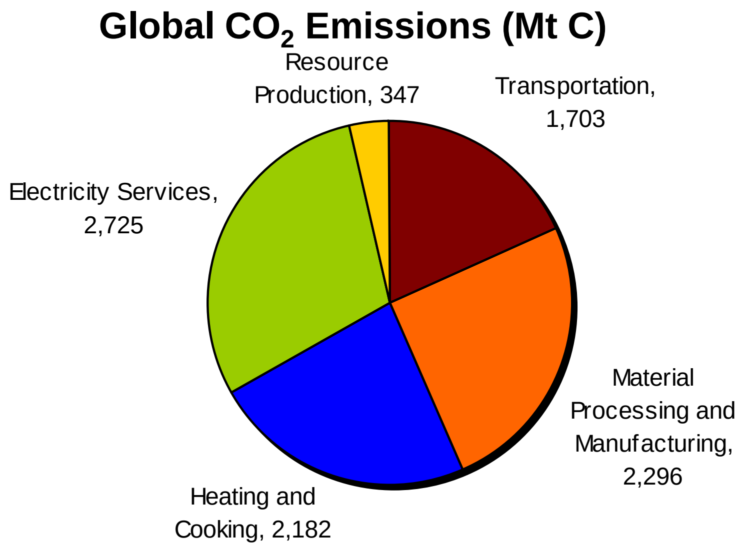
Global Challenges – Global Solutions – Global Opportunities

What is Carbon Dioxide Capture and Sequestration 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
- 85% of today's energy comes from fossil fuels and a rapid transition to low carbon energy sources is difficult and expensive
- Necessary to achieve the rapid carbon dioxide emission reductions

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



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

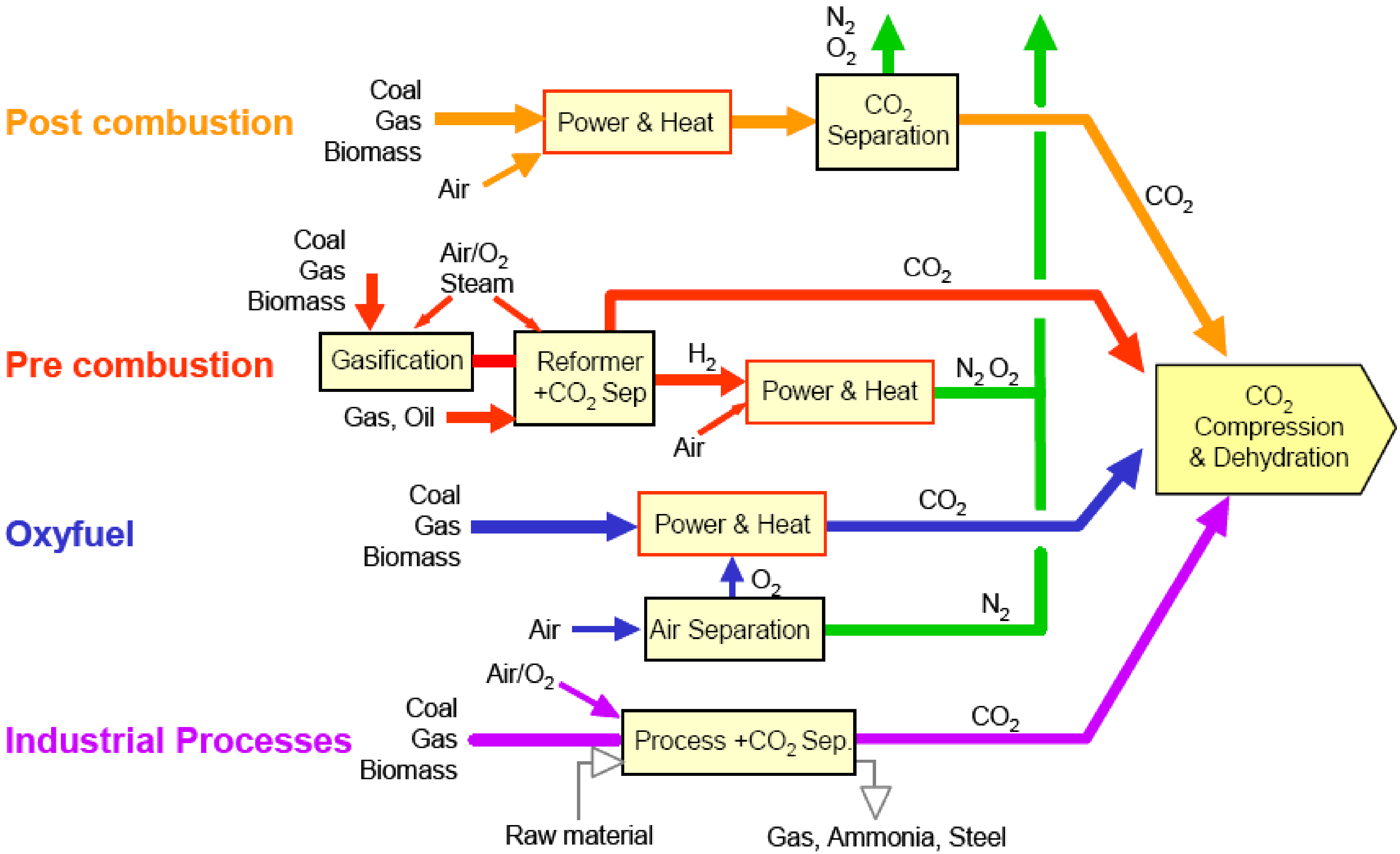
IPCC Special Report, 2005

Transportation Sector

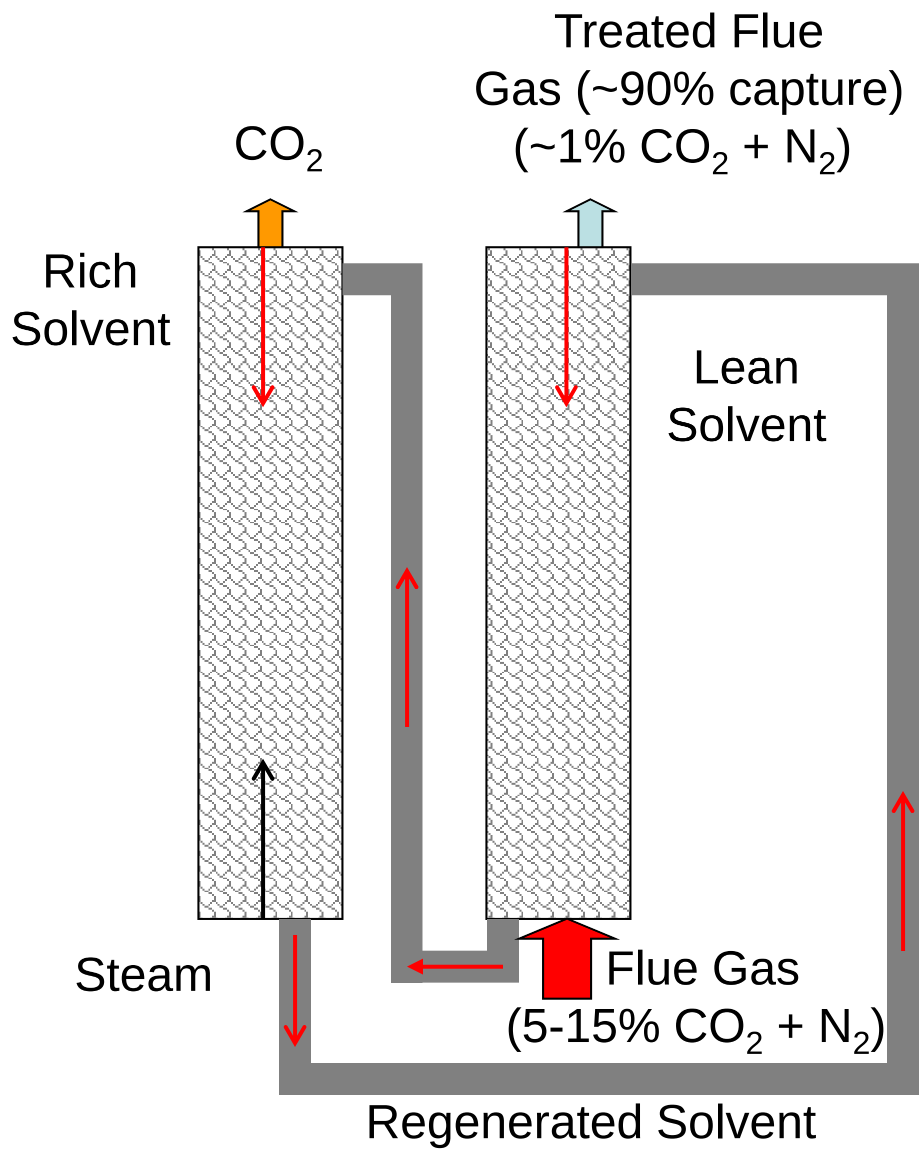
Little today.
Future Potential?

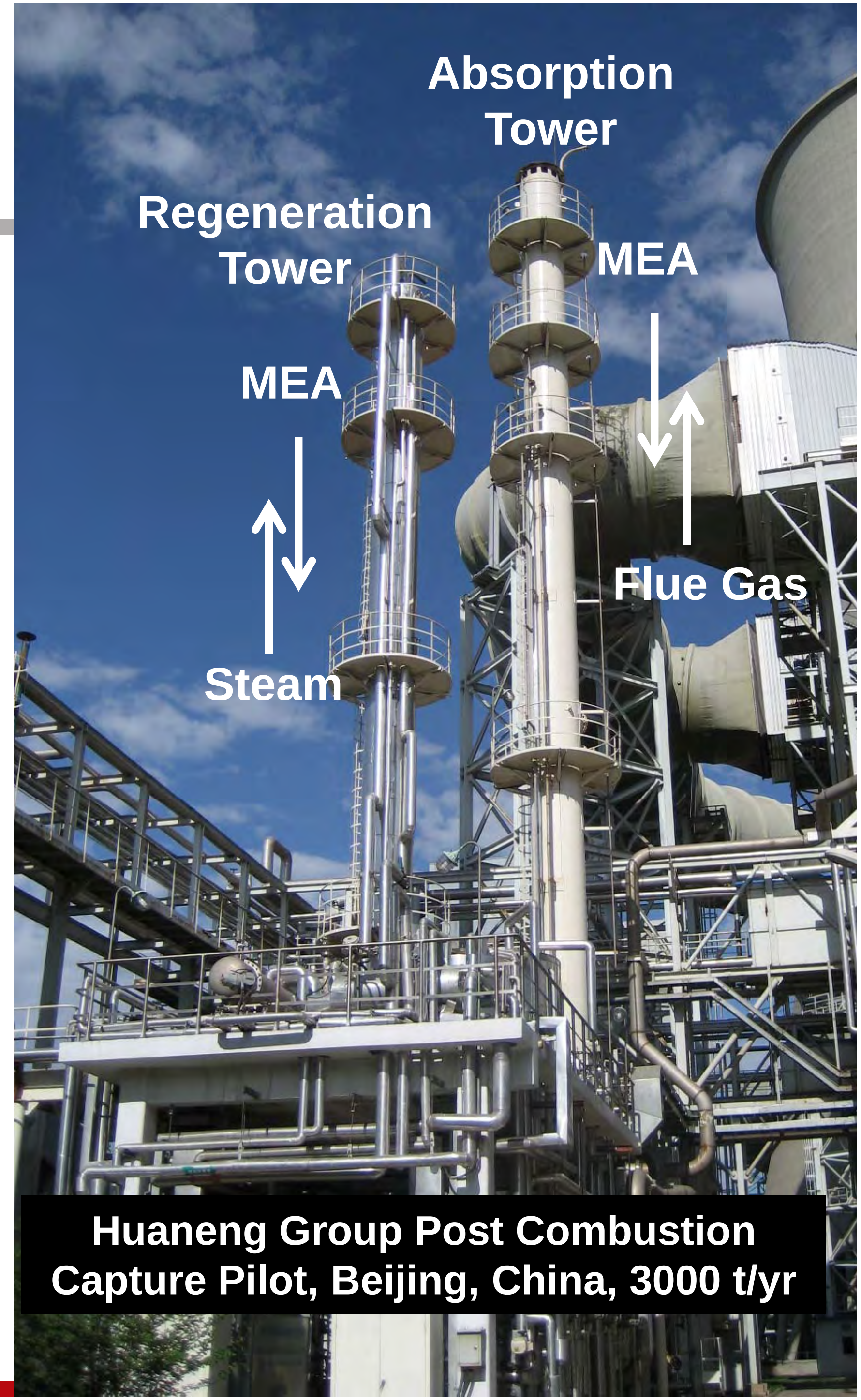
73% of U.S. light duty transport could be powered with existing fleet of power plants, Kintner-Meyer, PNNL, 2007

Options for CO_2 Capture



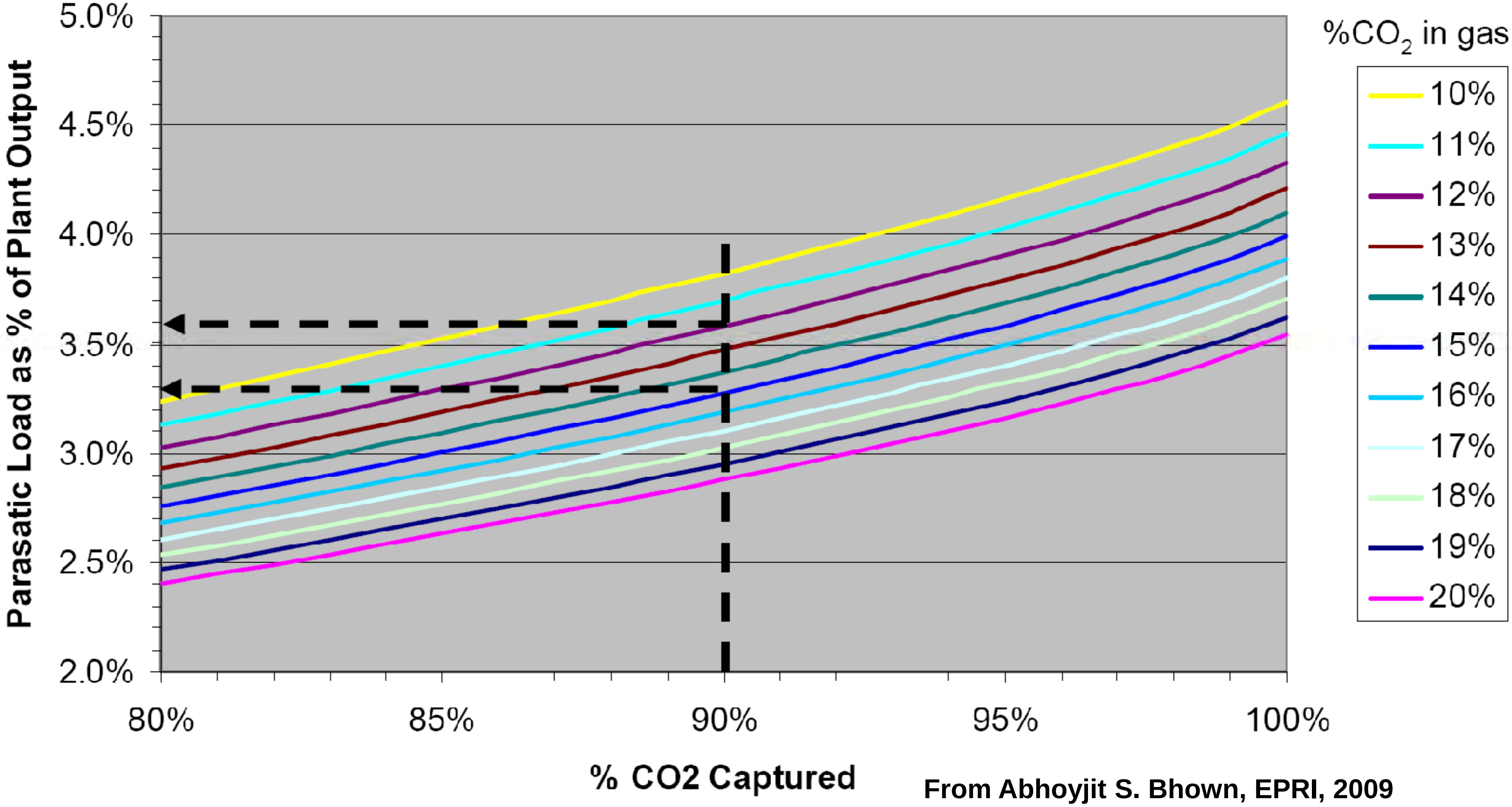
Post-Combustion Capture





Huaneng Group Post Combustion Capture Pilot, Beijing, China, 3000 t/yr

Minimum Energy For Capture



From Abhoyjit S. Bhown, EPRI, 2009

In practice, separation is about 5 to 10 times less efficient than the minimum energy requirement. A "good" process could be expected to have from 3 to 5 x minimum energy requirement.

Comparison of Capture Options

Technology	Advantages	Challenges
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	• Oxygen separation • Repowering

Today's Industrial Capture Technology

- Energy penalty: 10 to 30%
- Cost
  - $50 to $100/tonne CO_2 for the n^{th} plant
  - Significantly more for the 1^{st} plants ($150 to $250/tonne CO_2)
  - Cost of electricity generation: 50 to 100% increase
- Uncertain reliability
- R&D needed do develop new options and improve existing ones

Potential for CO_2 Reuse in the Chemical Industry is Extremely Limited

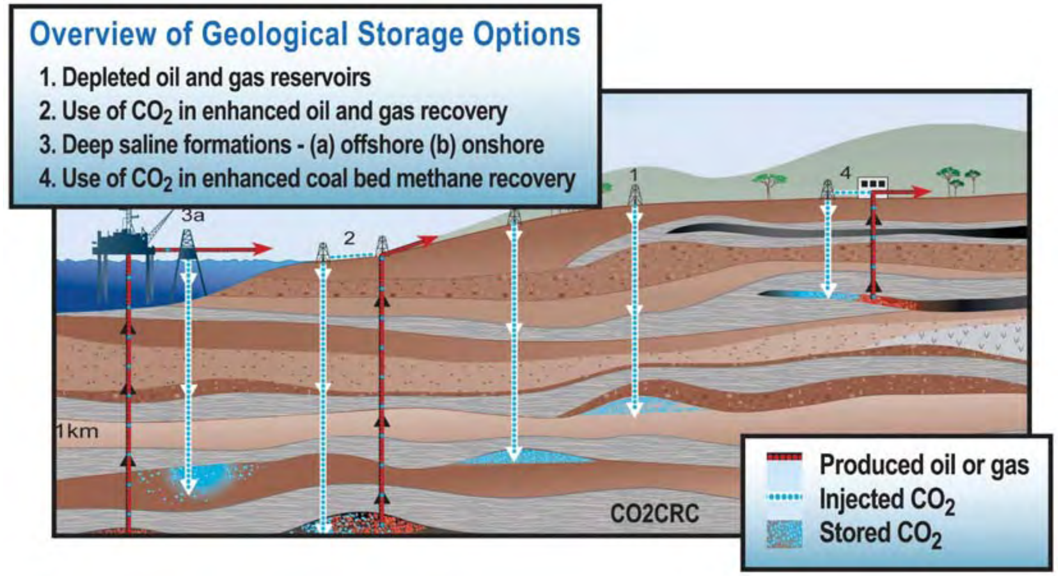
Rank	Chemical	2002 Production Mt *	Estimate +13% for 2007 Mt	Gmol	GWe if equimolar rxn with CO2 90% capture
1	Sulfuric Acid	36.65	41.54	423.54	2.74
2	Nitrogen	30.76	34.87	1244.65	8.06
3	Ethylene	23.67	26.83	838.44	5.43
4	Oxygen	22.04	24.98	890.27	5.76
5	Lime	18.42	20.87	372.24	2.41
6	Polyethylene	16.06	18.20	568.91	3.68
7	Propylene	14.46	16.38	380.27	2.46
8	Ammonia, Anydrous	13.20	14.96	878.51	5.69
9	Chlorine	11.39	12.91	182.02	1.18
10	Phosphoric Acid	10.81	12.26	125.06	0.81
95	Sodium Bicarbonate	0.54	0.61	7.24	0.05
96	Cyclohexanone	0.54	0.61	6.19	0.04
97	Propylene Glycol	0.53	0.60	7.92	0.05
98	Phthalic Anhydride	0.53	0.60	4.03	0.03
99	Sodium Sulfate	0.51	0.58	4.06	0.03
100	Potassium Hydroxide	0.47	0.54	9.55	0.06
	TOTAL	443.08	502.16	10339.12	66.95

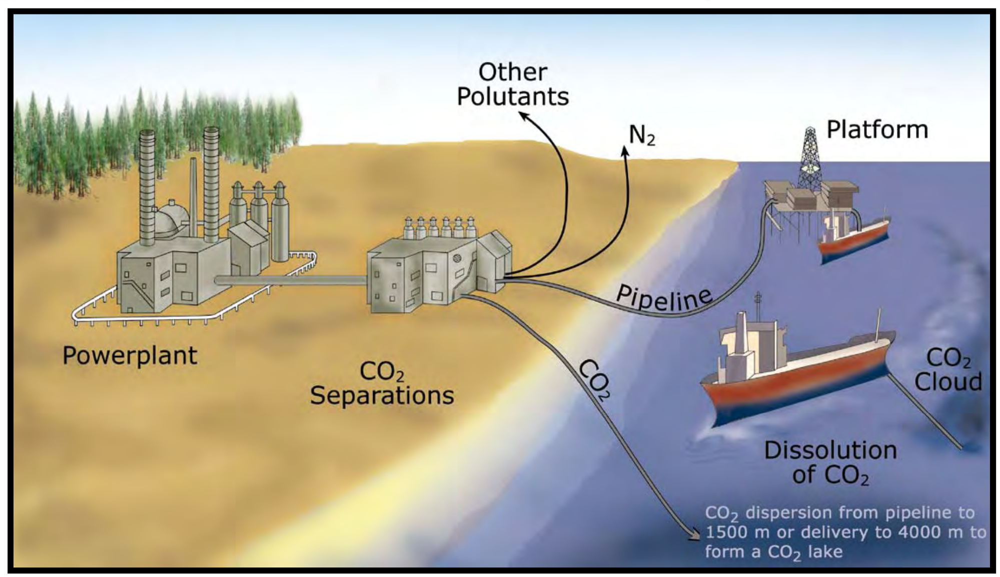
Global top 100 chemicals produce a total of 0.5 Gt/yr; CO2 emissions are 30 GT/yr. Therefore, opportunities for CO_2 reuse in the chemical industry are limited.

From Abhoyjit S. Bhown, EPRI, 2009

CO_2 Sequestration Options

- Deep geological formations
  - Oil and gas
  - Coal
  - Saline aquifers
  - Basalts
  - Deep ocean sediments
- Oceans
  - Direct injection
  - Ocean fertilization
  - Bicarbonate formation
- Solids
  - Minerals
  - Cement
  - Other





Generic Sequestration Challenges

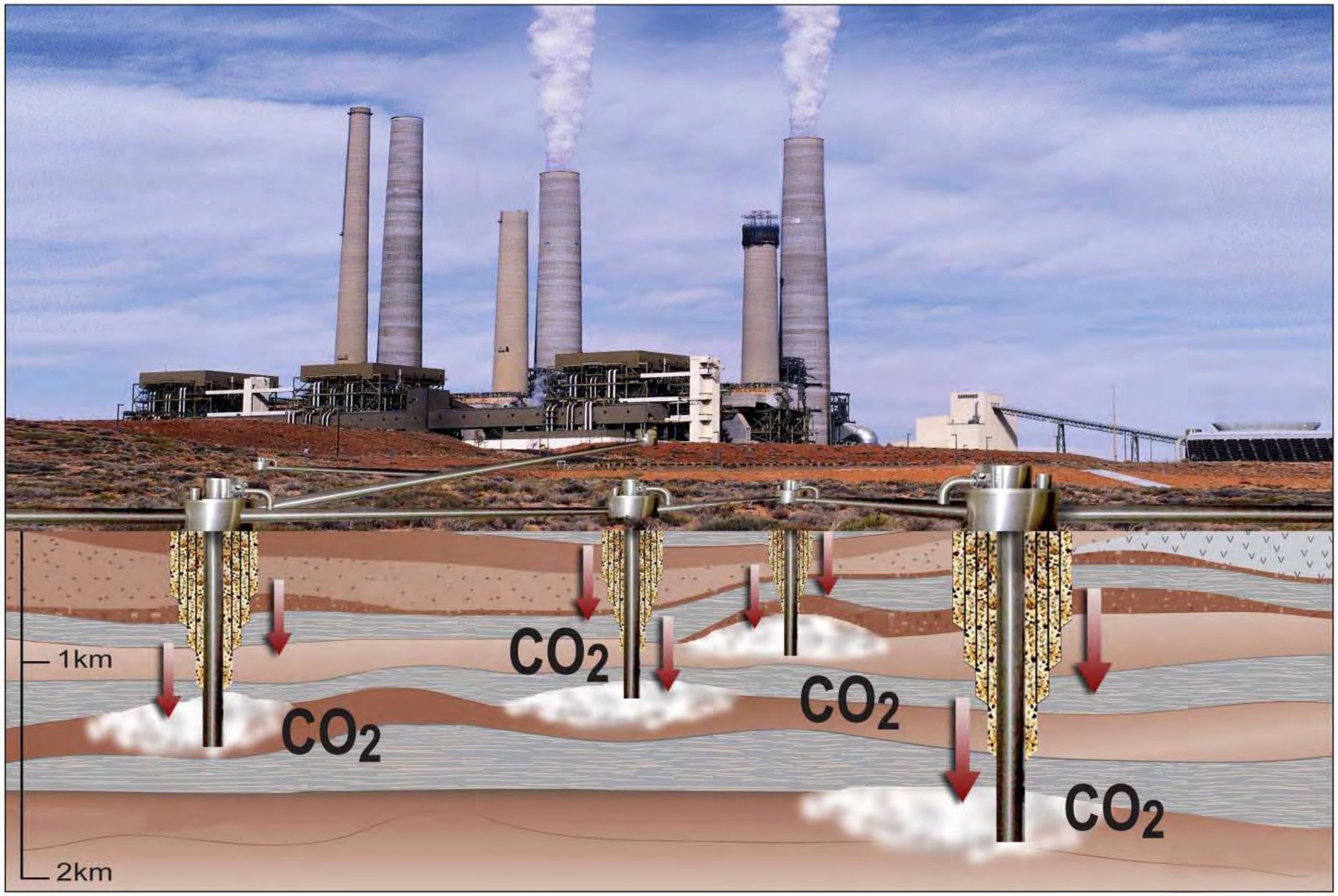
- Huge scale of emissions
  - 7 x annual petroleum production
- Establishing permanence
  - 100's to 1000's of years
- Environmental risks
- Cost
- Energy use

Comparison of Today's Sequestration Options

	Deep Geological Systems	Ocean	Solids Mineral
Permanence	M - H, depends on site selection	L- M, depends on site selection	H
Environmental and Safety Impacts	L-M, groundwater and pipelines	M-H, acidification, ecosystems	M, mining for reactants, disposal
Energy Use	M, compression cost	M, compression, shipping	H, high T or grinding for high rates
Cost	L-M, energy, capital plant	H, offshore and shipping, energy	H, energy, reactants and capital plant

H = high M = medium, L = Low

Component Technologies of Carbon Dioxide Capture and Geological Sequestration



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

Types of Rocks

- Igneous rocks
  - Rocks formed from cooling magma
  - Examples
    - Granite
    - Basalt
- Metamorphic Rocks
  - Rocks that have been subjected to high pressures and temperatures after they are formed
  - Examples
    - Schist
    - Gneiss
- Sedimentary rocks
  - Rocks formed from compaction and consolidation of rock fragments
  - Example
    - Sandstone
    - Shale
  - Rocks formed from precipitation from solution
  - Example
    - Limestone

Crystalline
Low porosity
Low permeability
Fractures

Granite

Crystalline
Low porosity
Low permeability
Fractures

Schist

Sandstone

High porosity
High permeability
Few fractures

What Types of Rocks are Suitable for CO_2 Storage?

- Igneous rocks
  - Rocks formed from cooling magma
  - Examples
    - Granite
    - Basalt
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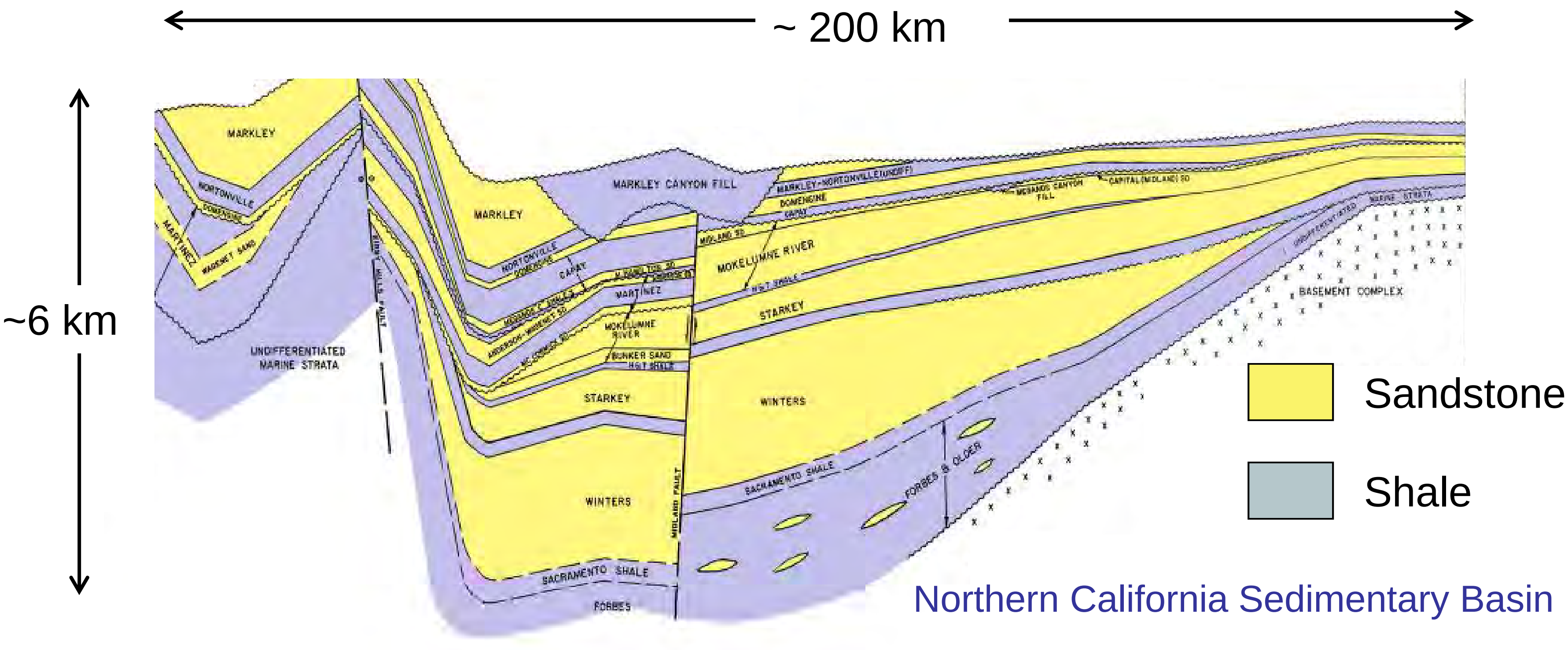
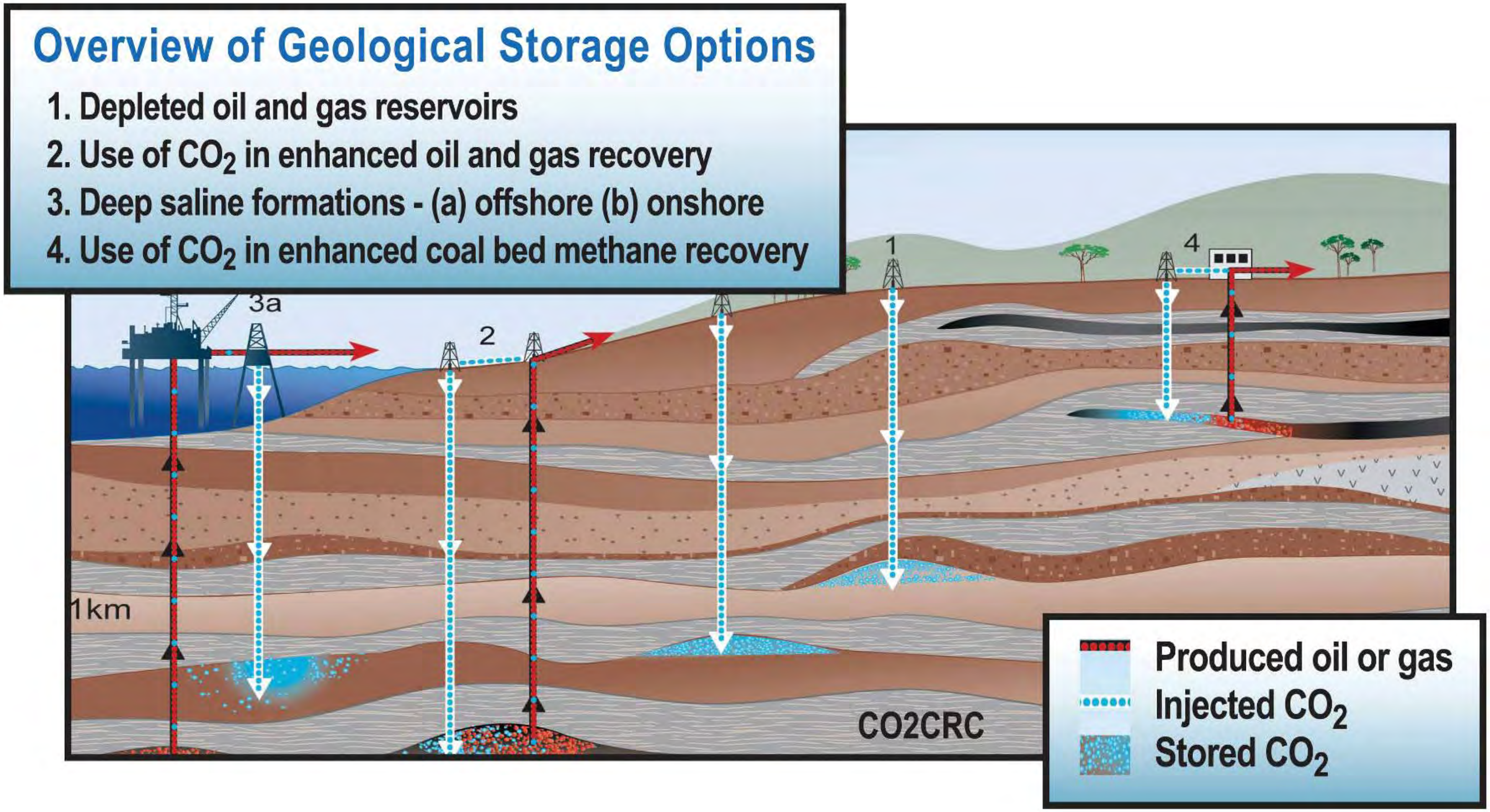
A Cross Section of Typical Sedimentary Basin

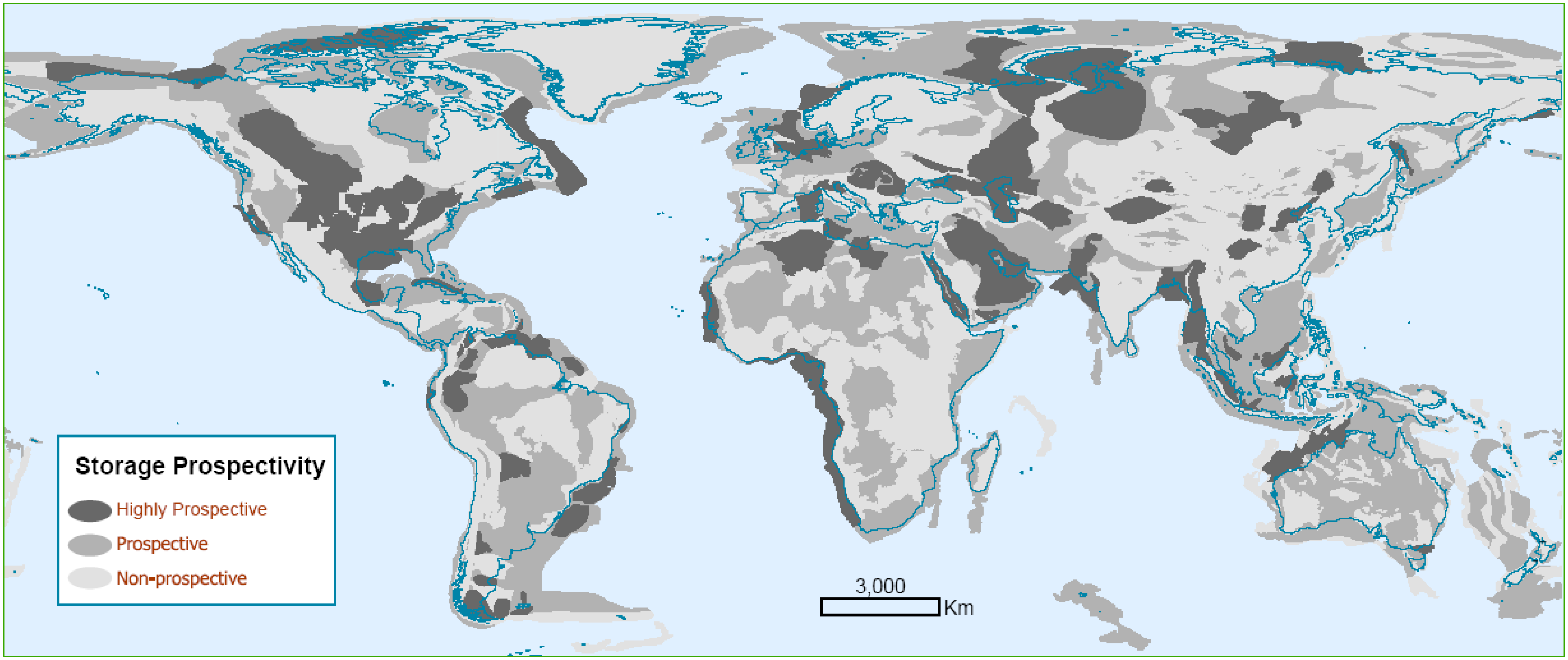


Example of a sedimentary basin with alternating layers of coarse and fine textured sedimentary rocks.

Options for Geological Storage



Global Distribution of Prospective Sequestration Sites



Potential sequestration sites are broadly distributed around the globe.

World Wide Capacity Estimates

Reservoir Type	Lower Estimate of Global Storage Capacity ($GtCO_2$)	Upper Estimate of Global Storage Capacity ($GtCO_2$)
Oil and gas fields	675[a]	900[a]
Coal seams (ECBM)	3–15	200
Saline aquifers	1,000	~ 10,000

a. Estimates would be 25% larger if undiscovered reserves were included. IPCC, 2005

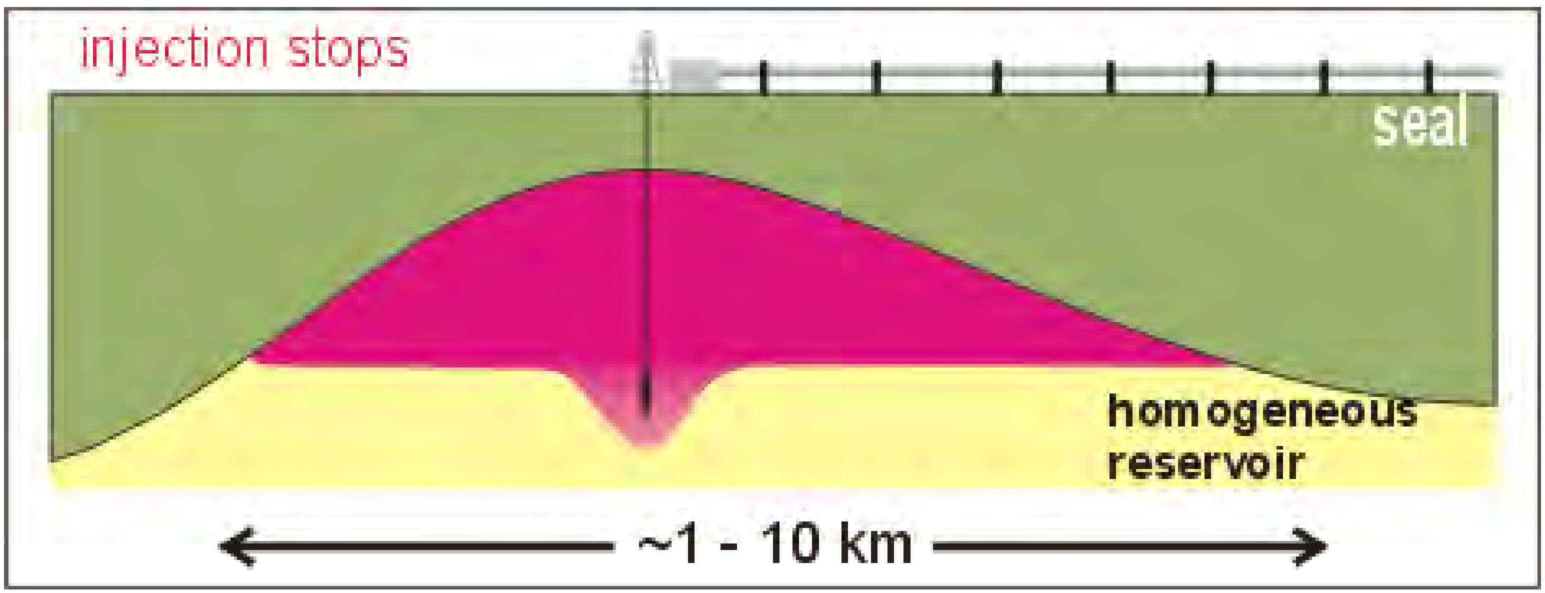
3,283 to 12,200 Gt CO_2

Current Estimates for Saline Aquifer Storage Capacity in North America (U.S. DOE)

In aggregate…sufficient for 100 years or more

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

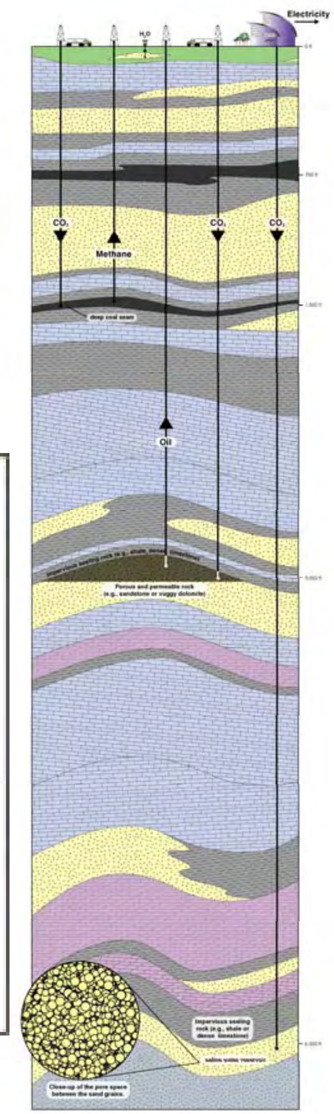
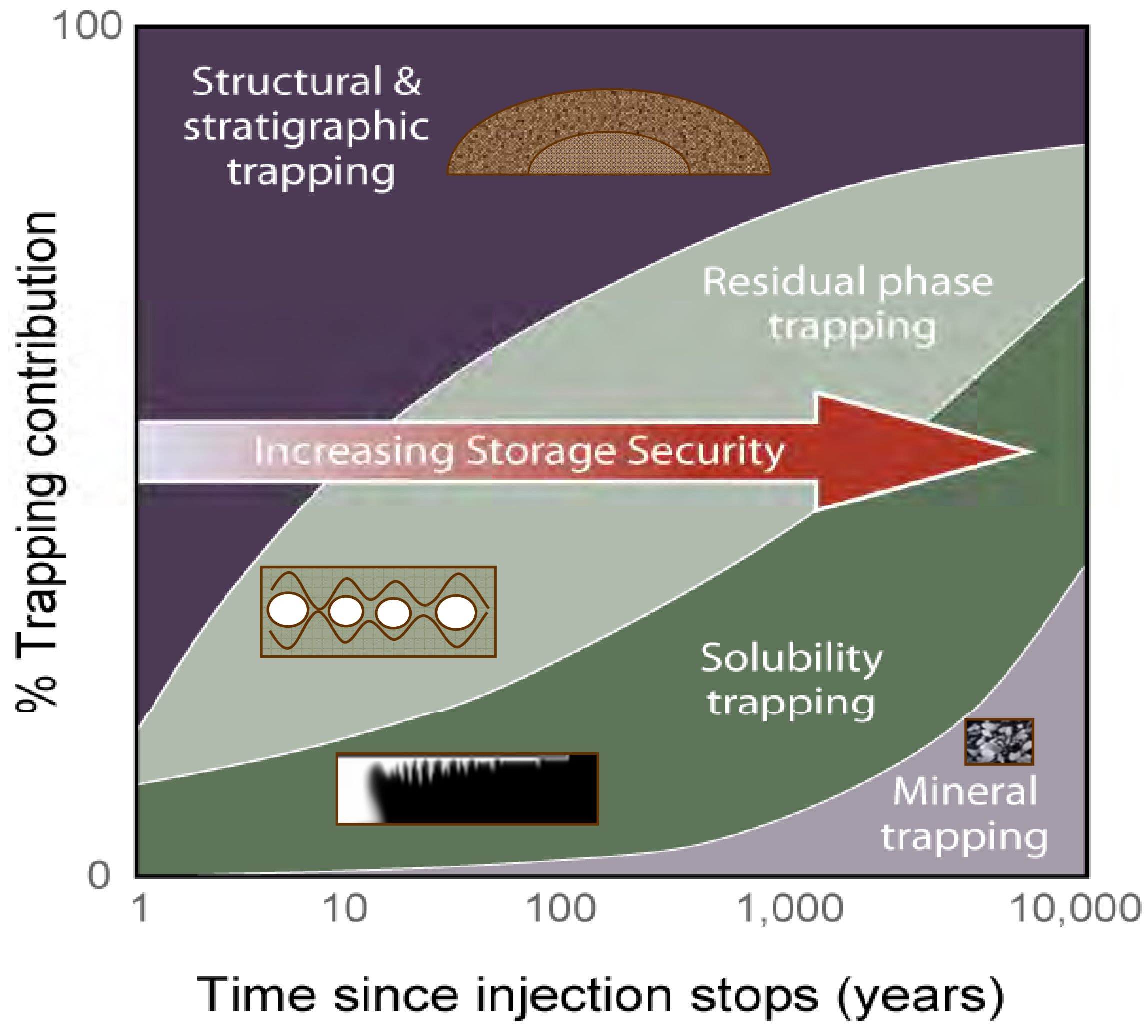


Image courtesy of ISGS and MGSC

Secondary Trapping Mechanisms Increase Over Time

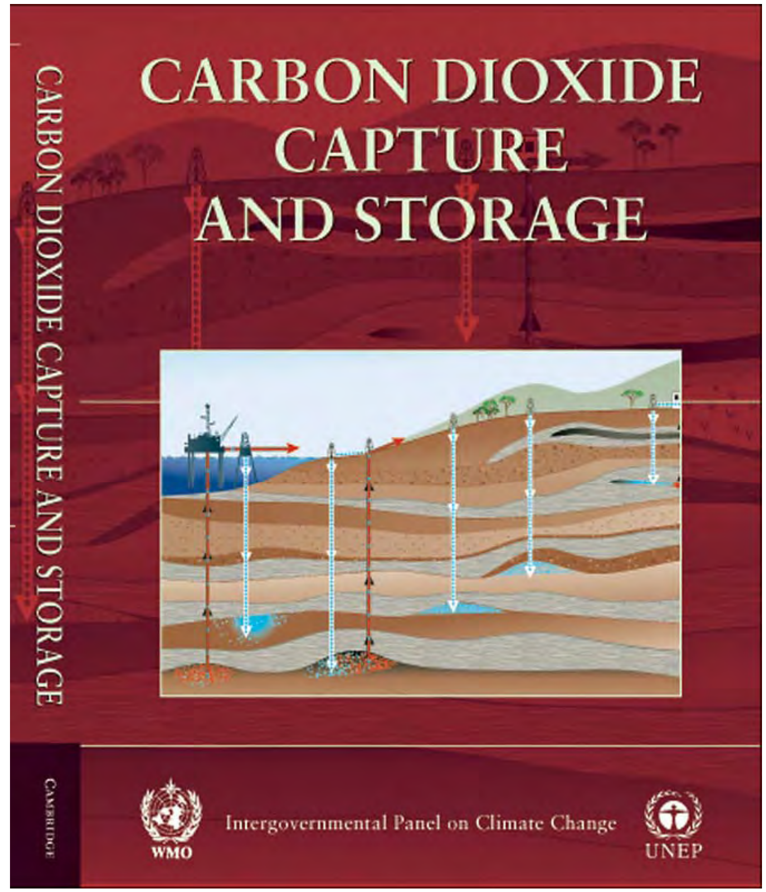
- Solubility trapping
  - CO_2 dissolves in water
- Residual gas trapping
  - CO_2 is trapped by capillary forces
- Mineral trapping
  - CO_2 converts to solid minerals
- Adsorption trapping
  - CO_2 adsorbs to coal



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."*

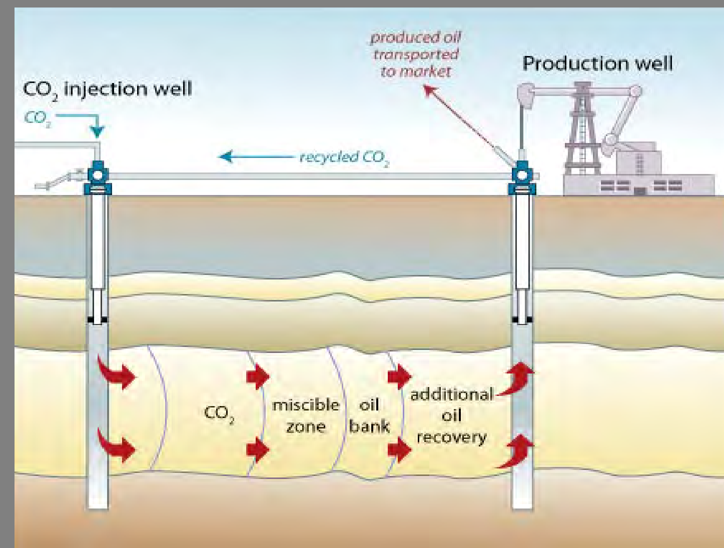
" With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO_2 releases if they arise, the local health, safety and environment risks of geological storage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

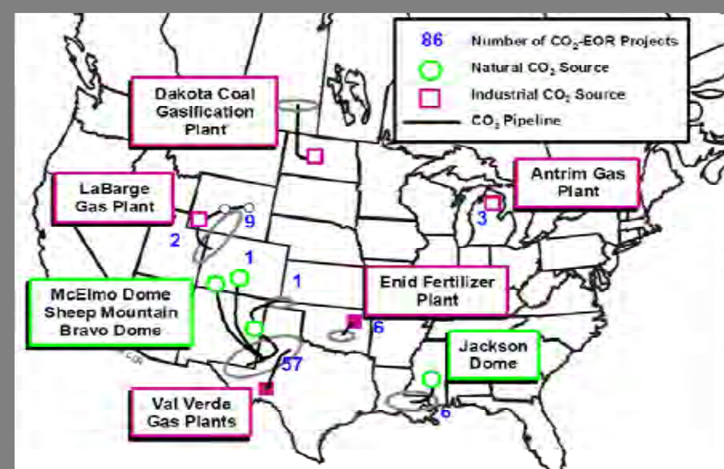


* "Very likely" is a probability between 90 and 99%.
** Likely is a probability between 66 and 90%.

Evidence to Support these Conclusions

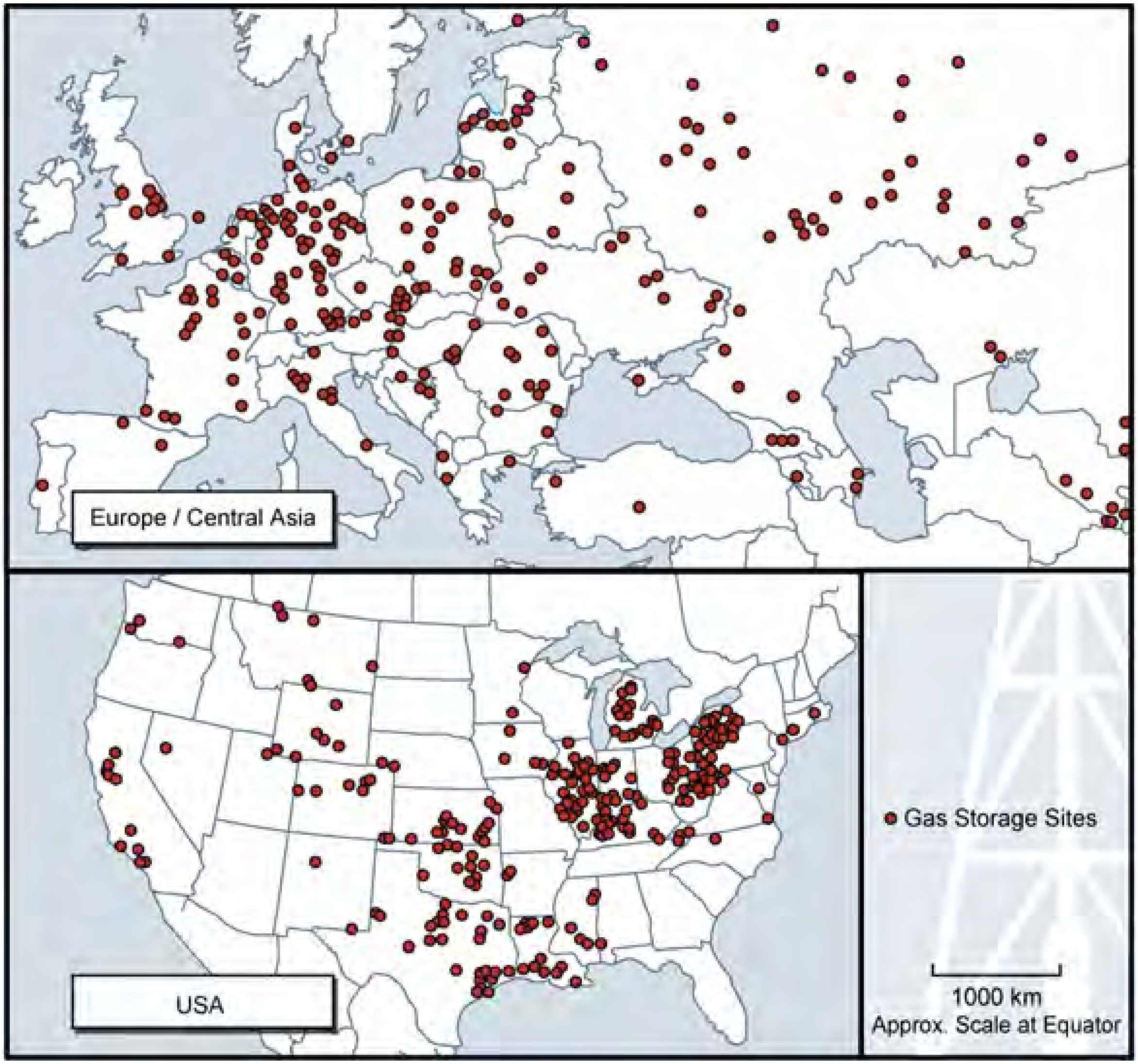
- Natural analogs
  - Oil and gas reservoirs
  - CO_2 reservoirs
- Performance of industrial analogs
  - 40+ years experience with CO_2 EOR
  - 100 years experience with natural gas storage
  - Acid gas disposal
- 25+ years of cumulative performance of actual CO_2 storage projects (~ 40 Mt injected to date)
  - Sleipner, off-shore Norway, 1996
  - Weyburn, Canada, 2000
  - In Salah, Algeria, 2004
  - Snovhit, Norway, 2008





~35 Mt/yr are injected for CO_2-EOR

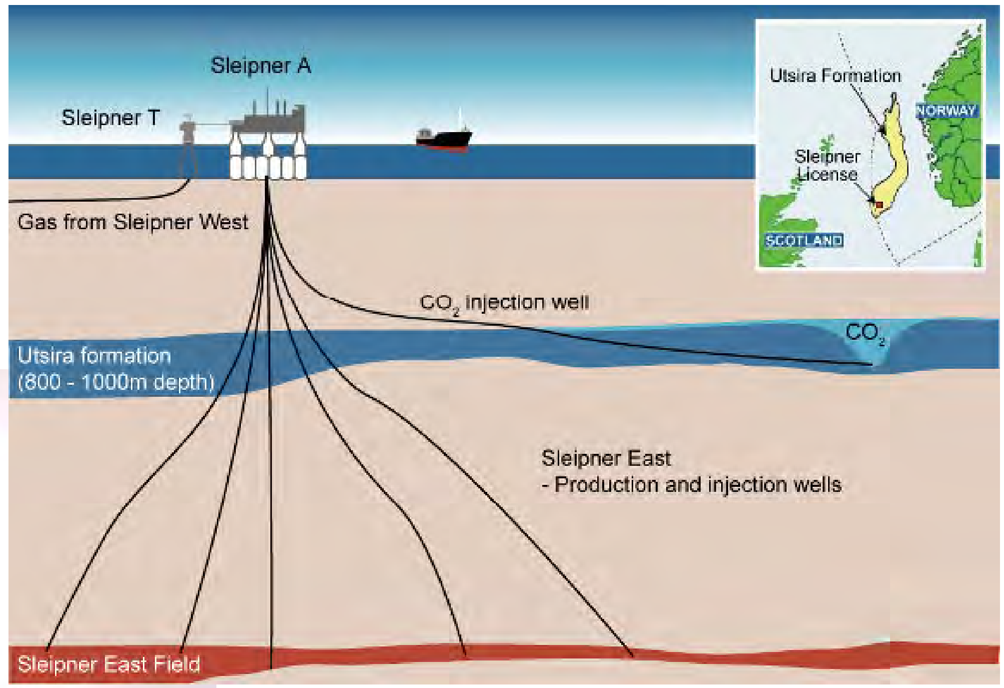
Natural Gas Storage



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

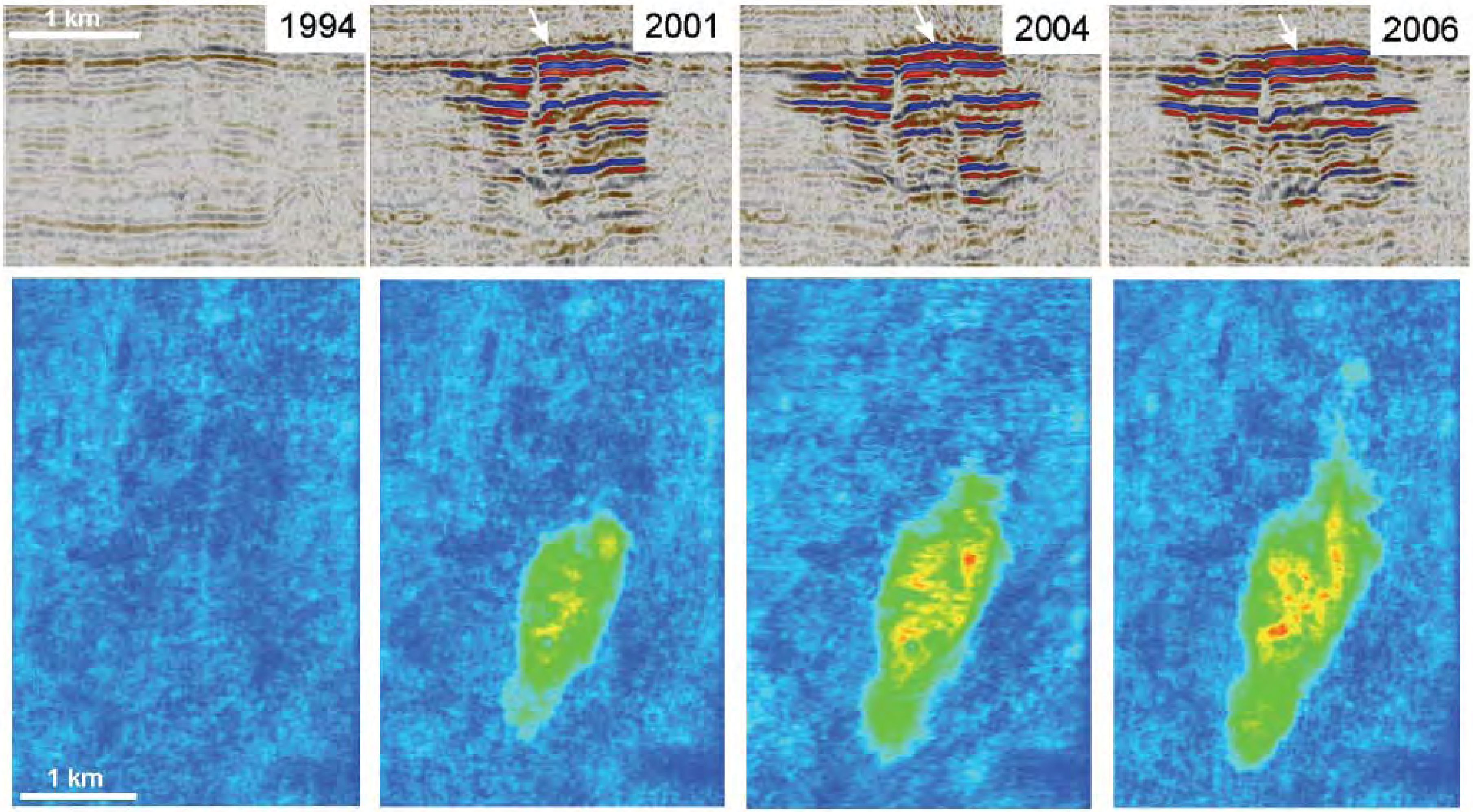
Sleipner Project, North Sea

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



Courtesy *Statoil*

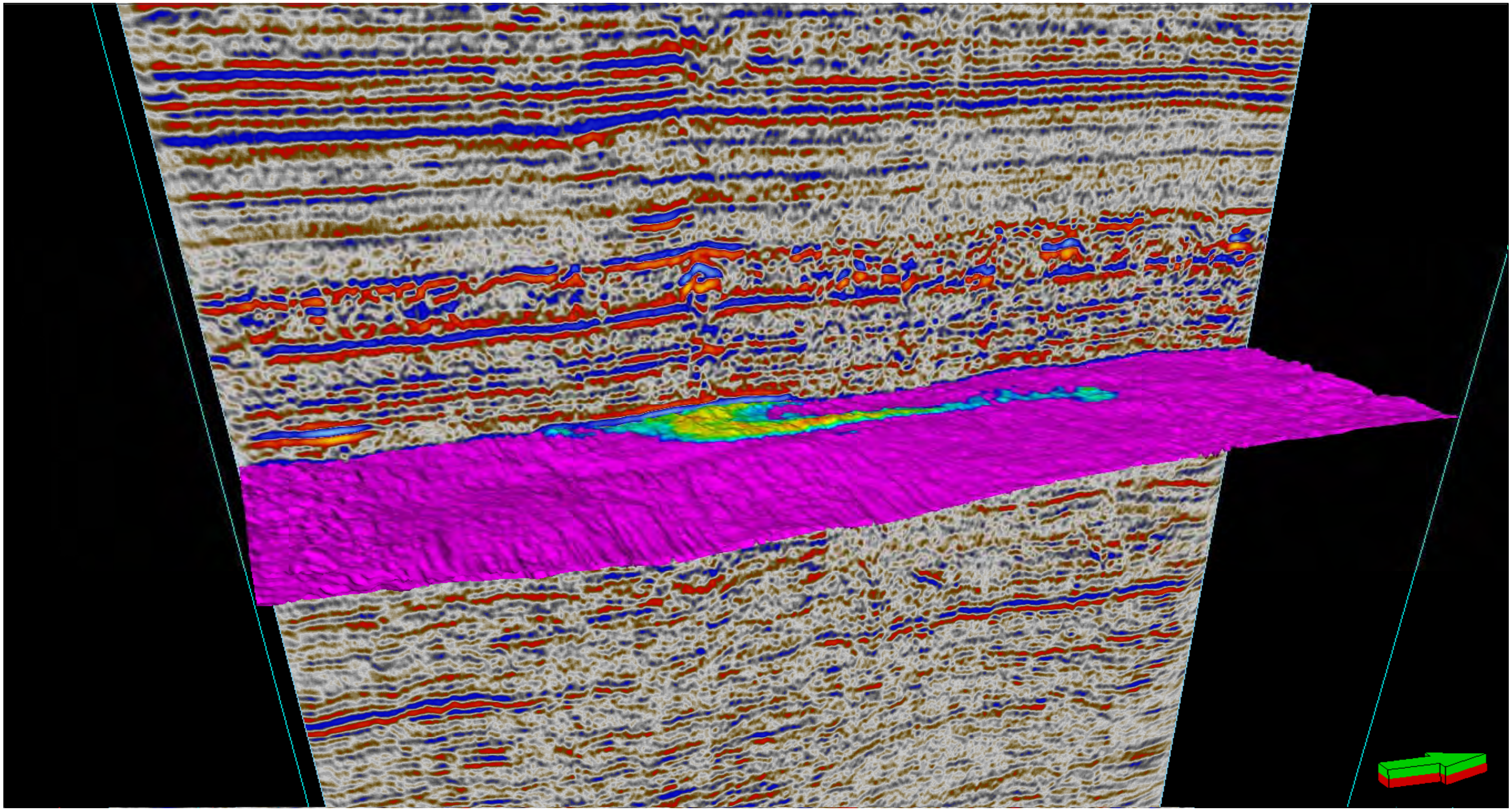
Seismic Monitoring at Sleipner



Courtesy, Andy Chadwich, BGS

Seismic imaging at Sleipner, North Sea

Plume and topmost layer 2001 - 2006



From Andy Chadwick, BGS, 2010

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

X-ray Micro-tomography at the Advanced Light Source

Micro-tomography Beamline

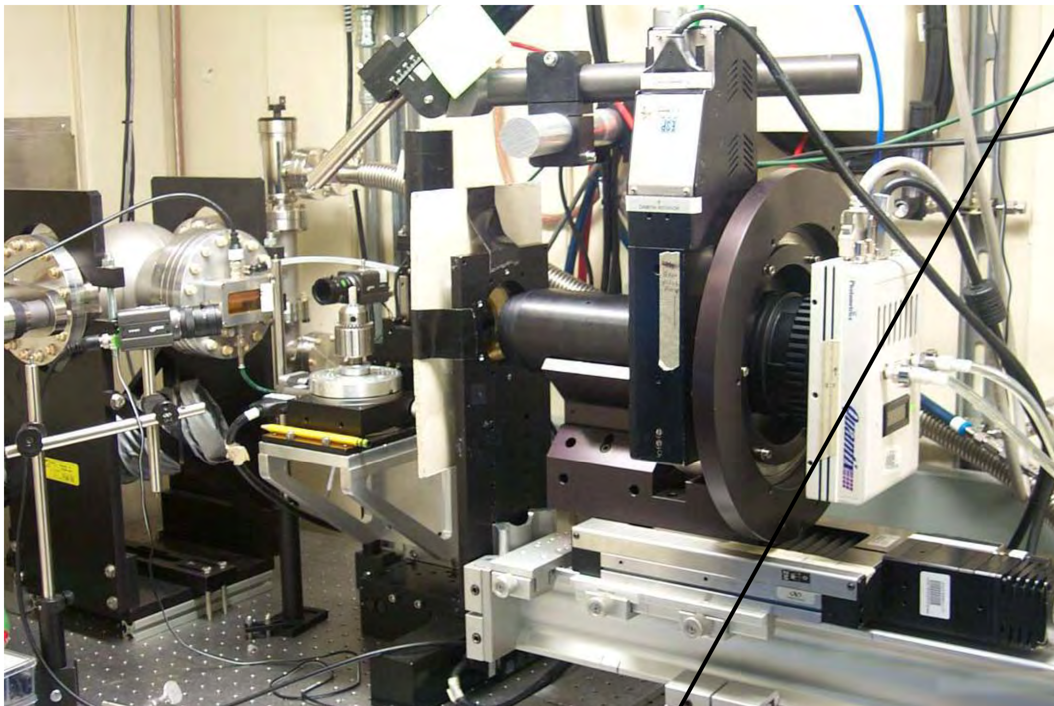
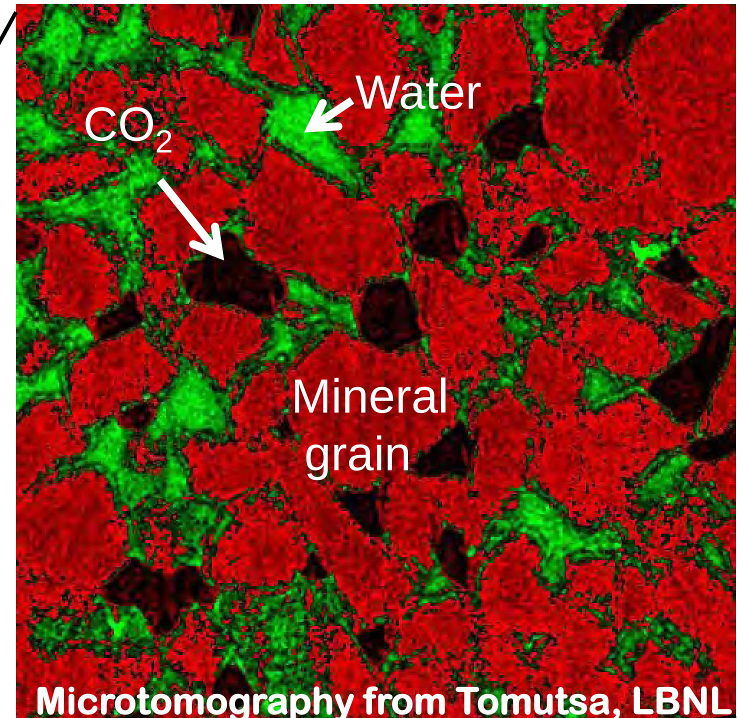


Image of Rock with CO_2



2 mm

Resolution ~ 5 μm

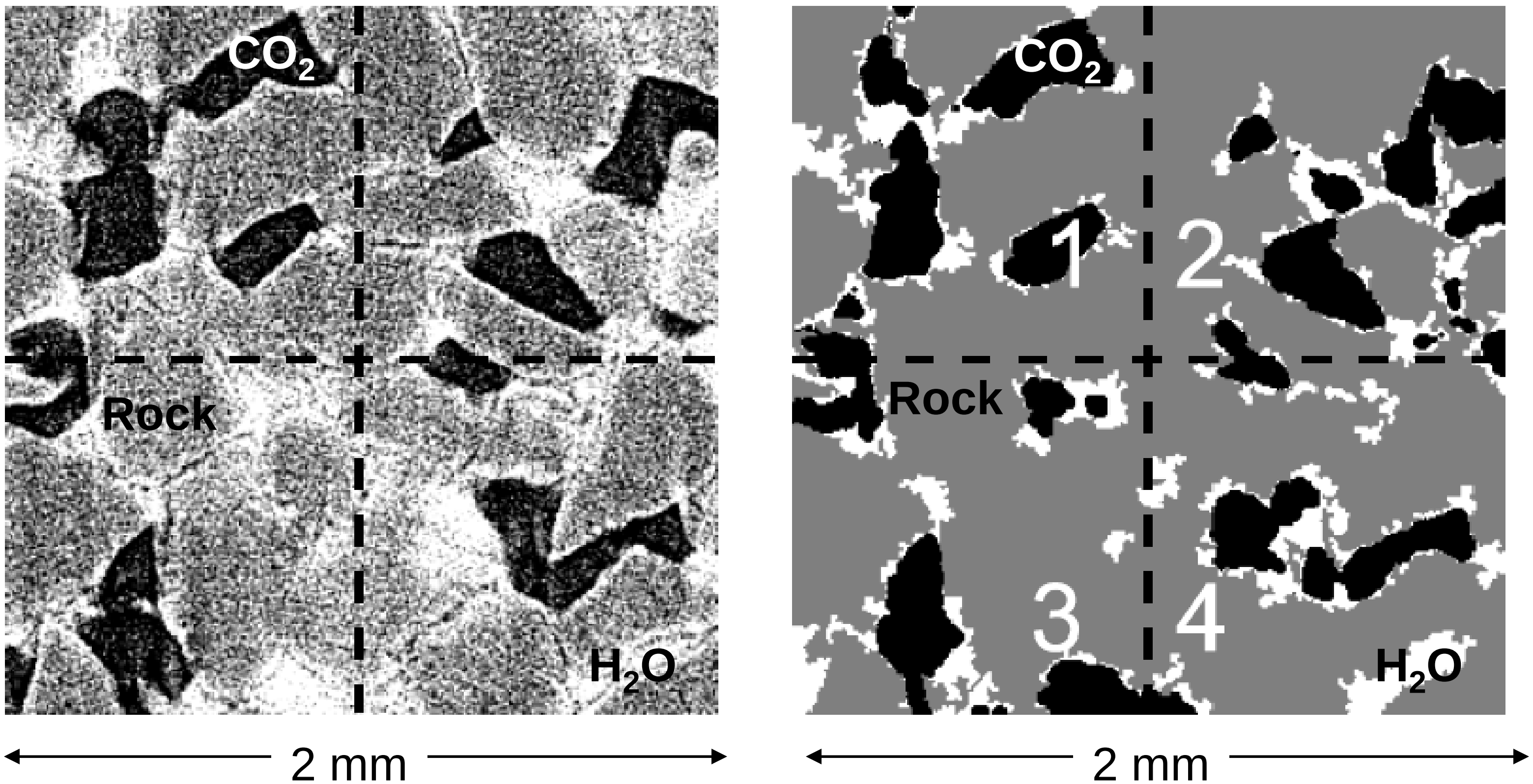
Benson et al., GHGT-8, 2007.

Pore-Scale Measurement and Modeling of Multiphase Flow of CO_2 and Brine

GCEP

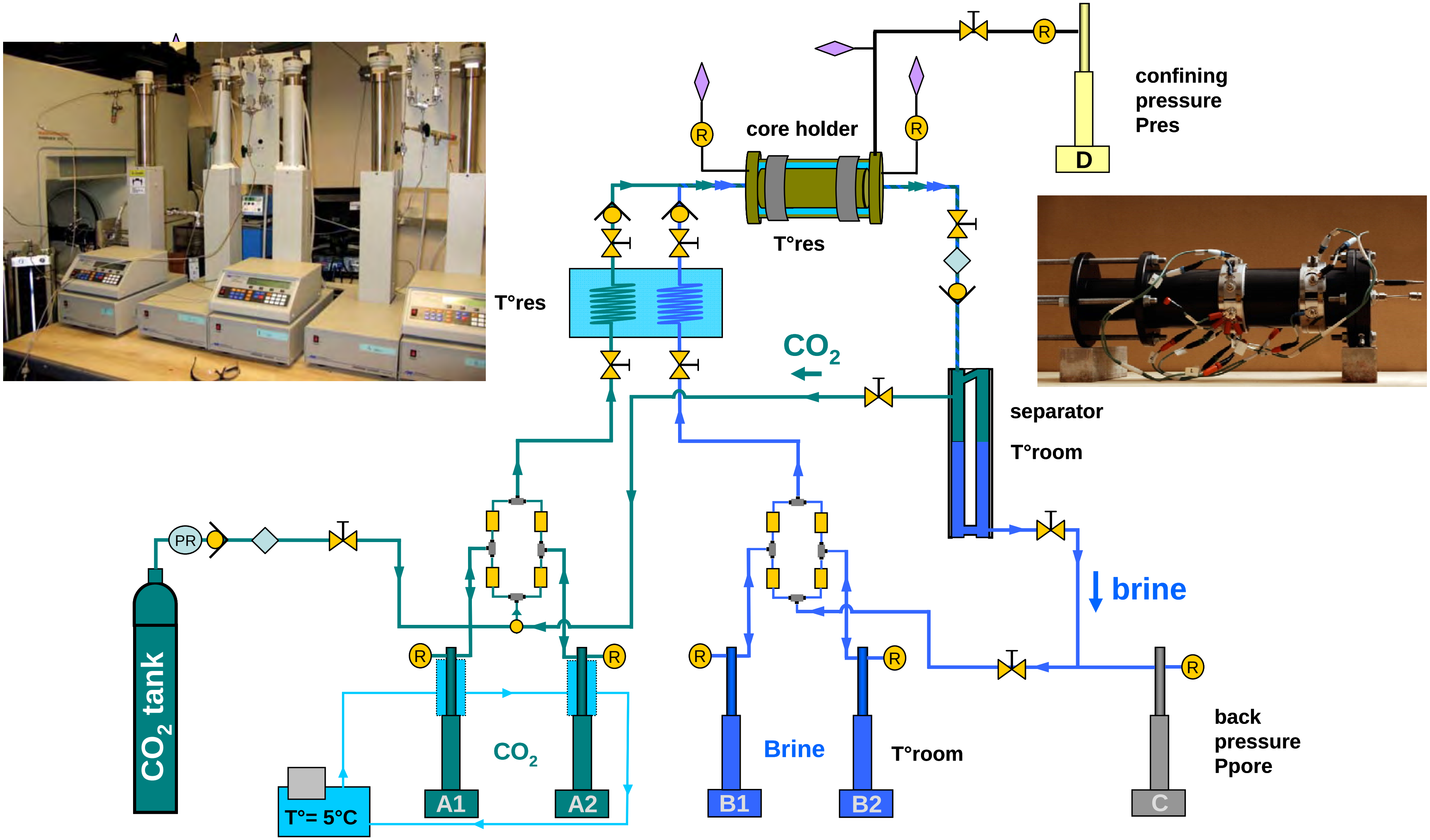
Measured at the ALS Microtomography Beamline

Calculated Using the Maximum Inscribed Spheres Method

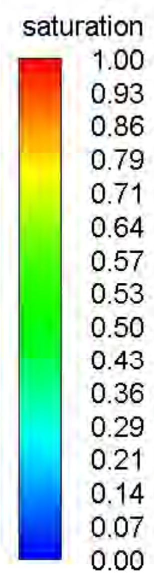


Silin, Tomutsa, Benson and Patzek, 2010. Microtomography and Pore-Scale Modeling of Two-Phase Fluid Distribution, Transport in Porous Media, Submitted.

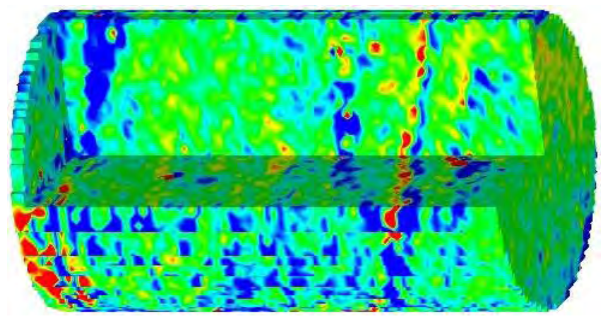
Core-Scale Multi-Phase Flow Laboratory



Multiphase Flow of CO_2 and Brine

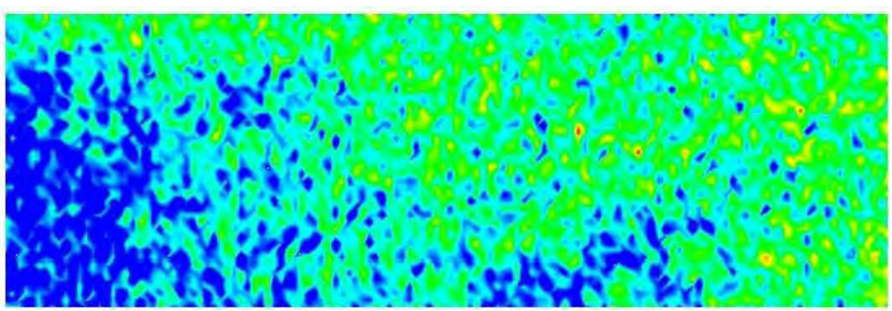


Influence of Heterogeneity



Waare C Sandstone

Influence of Buoyancy

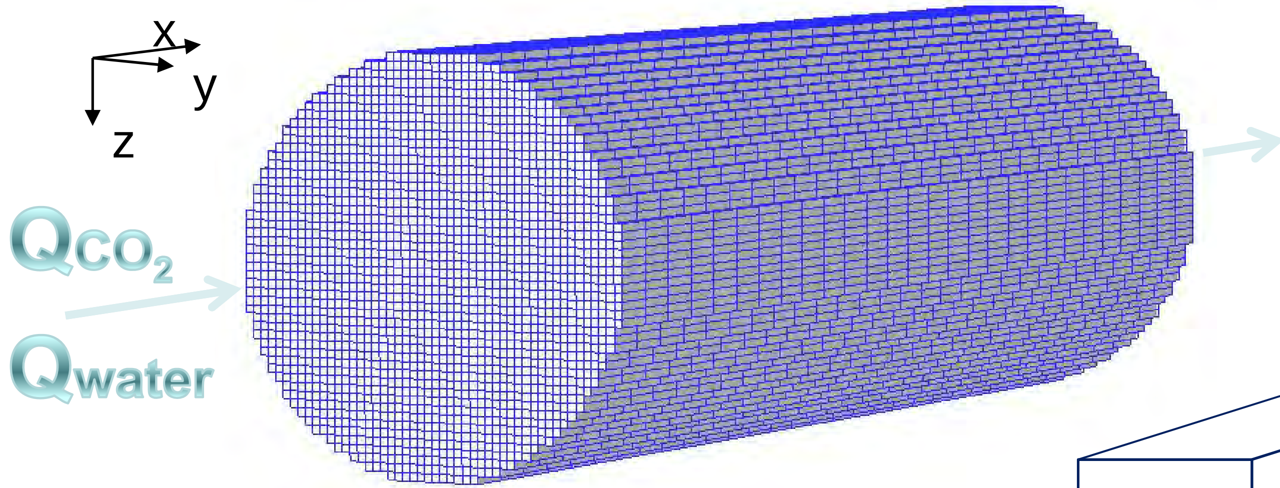


Berea Sandstone

- What fraction of the pore space will be occupied?
- What will be the footprint of the plume?
- How much dissolution and capillary trapping can be expected?

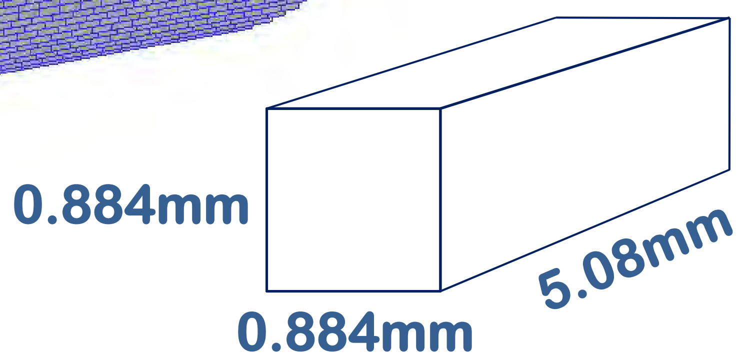
Is the current approach for simulating multiphase flow good enough to answer these questions?

Simulation Grid



T=50°C
P=12.4MPa

Grid Elements



X: 31 grid

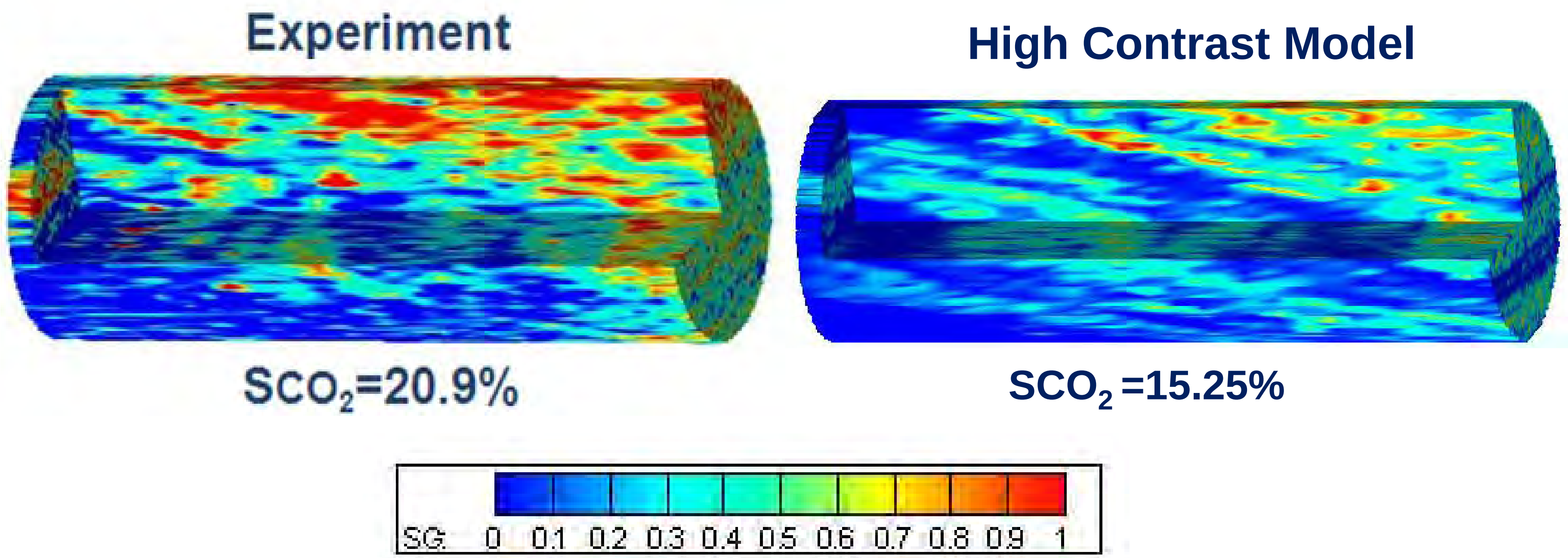
Y: 53 grid

Z: 53 grid

Total Grid = 64,635 Rectangular Elements

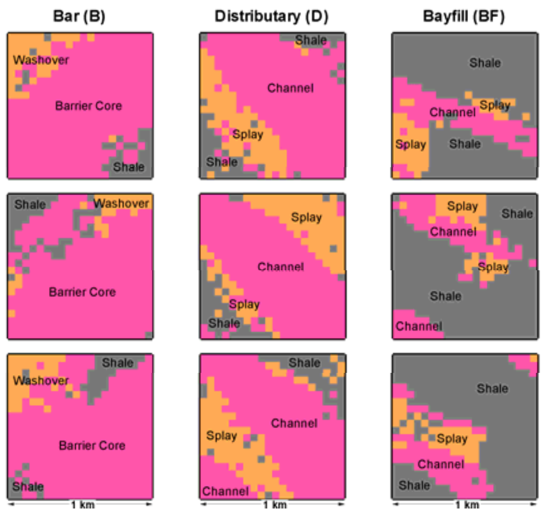
Kuo, C.-W., Krause, M. Perrin, J.C., and S. M. Benson, 2009. Effect of Small Scale Heterogeneity on Multiphase Flow of CO2 and Brine, 8th Annual NETL Carbon Sequestration Conference, Pittsburg, PA, May 5-8, 2009.

Comparison Between Models and Data



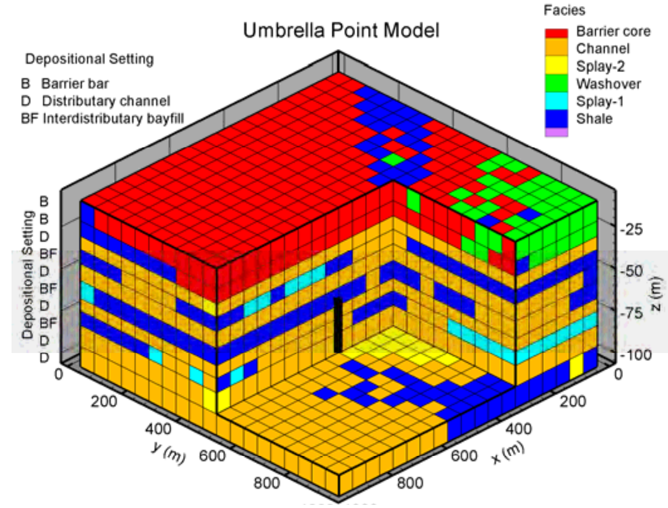
- Qualitative agreement between experiments and simulations is good
- Insights gained from core-scale experiments can improve understanding of the role of heterogeneity and buoyancy on capacity
- Improved rock properties model is needed

High Performance Computing Needed to Assess Capacity in Saline Aquifers



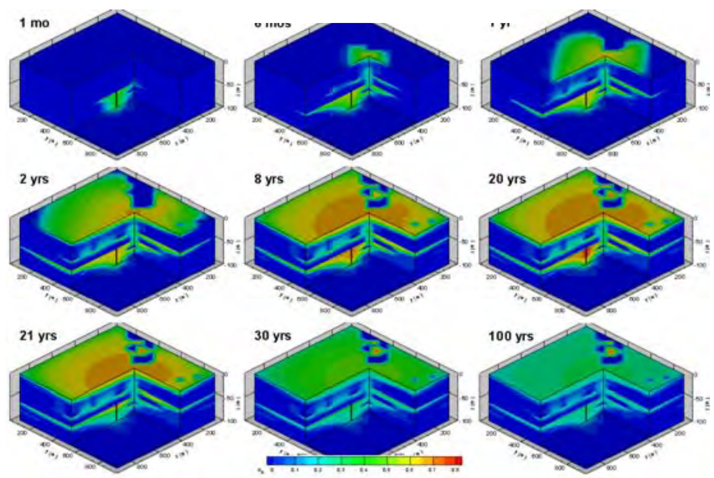
Geology

Models



Simulations

Statistics

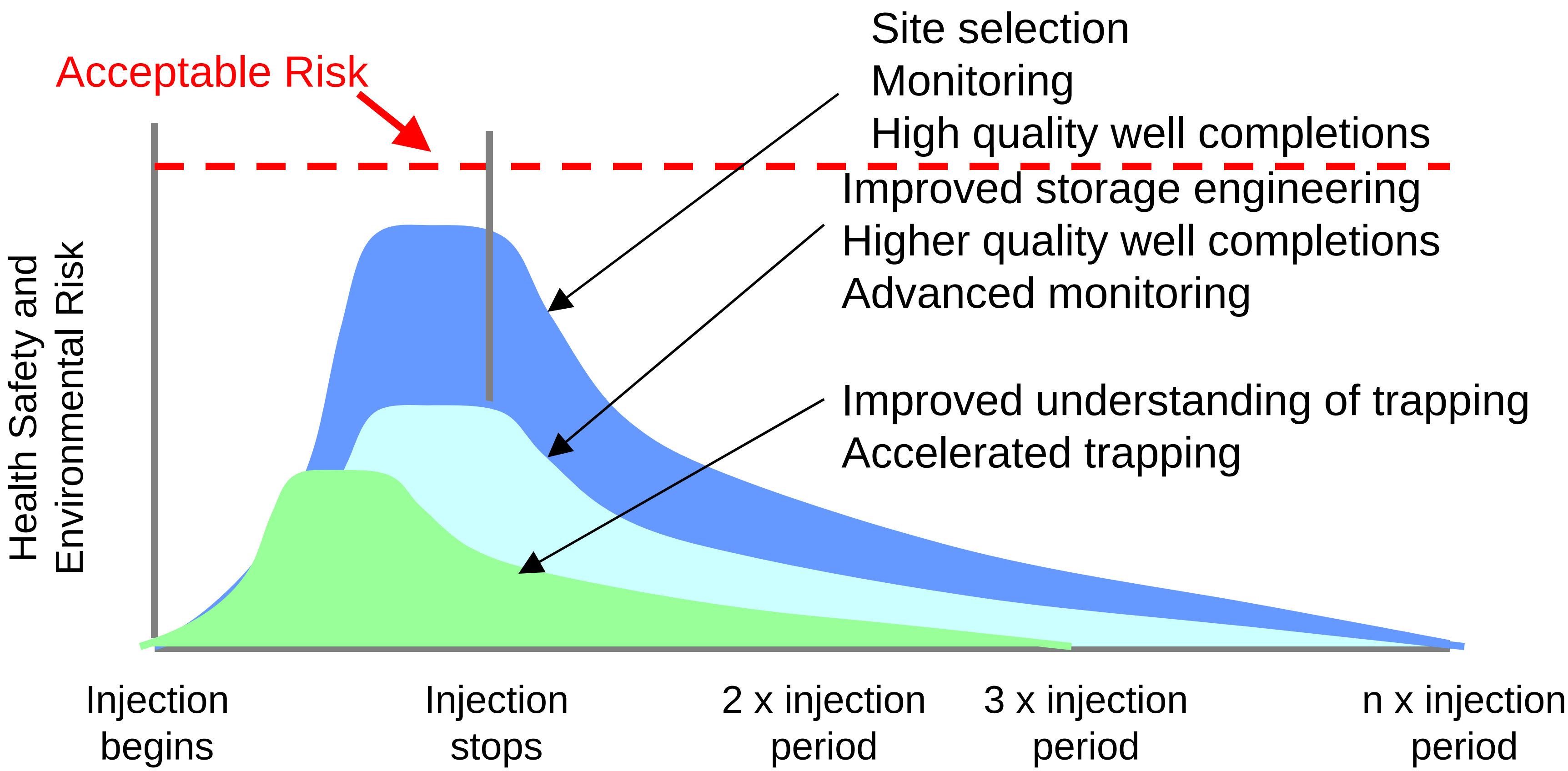


“Rules of Thumb”

CO_2 Storage Capacity = 1 to 4% Total Pore Volume[1]

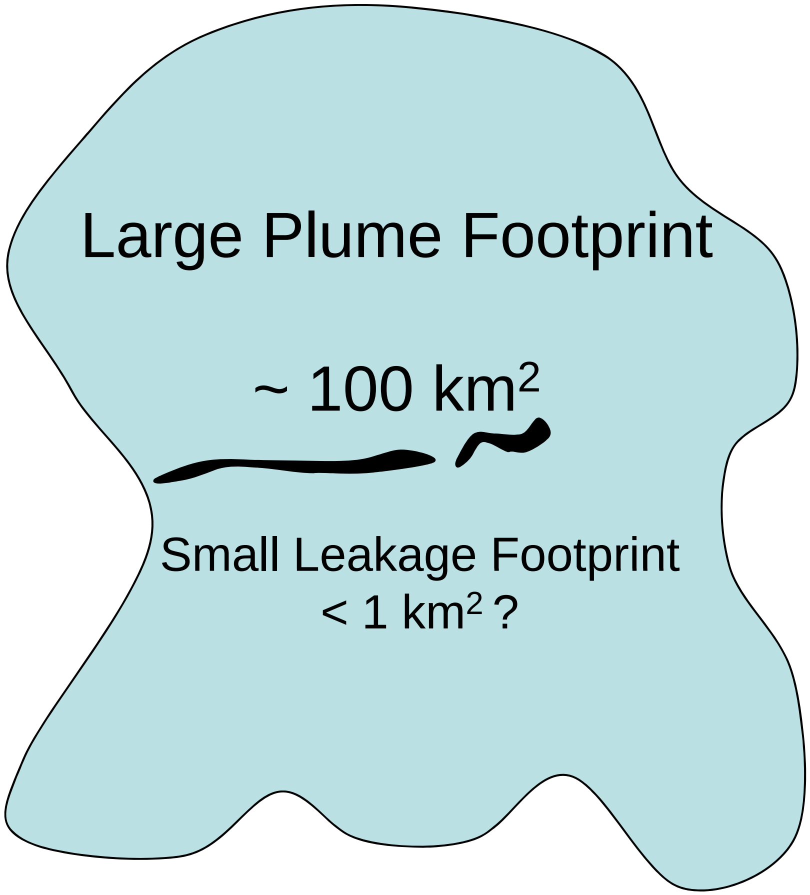
[1]*Values used in the North American Carbon Sequestration Atlas, 2008*

Storage Engineering

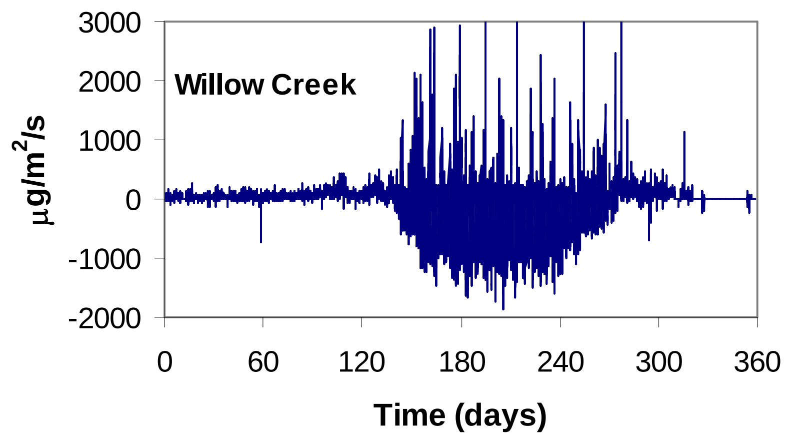


- *How can storage security be enhanced with advanced engineering?*
- *Can sub-optimal sites be used for storage with advanced storage engineering?*

Monitoring Challenges



Large Fluctuations in Background CO_2 Fluxes



Courtesy of Ken Davis and Paul Bolstad

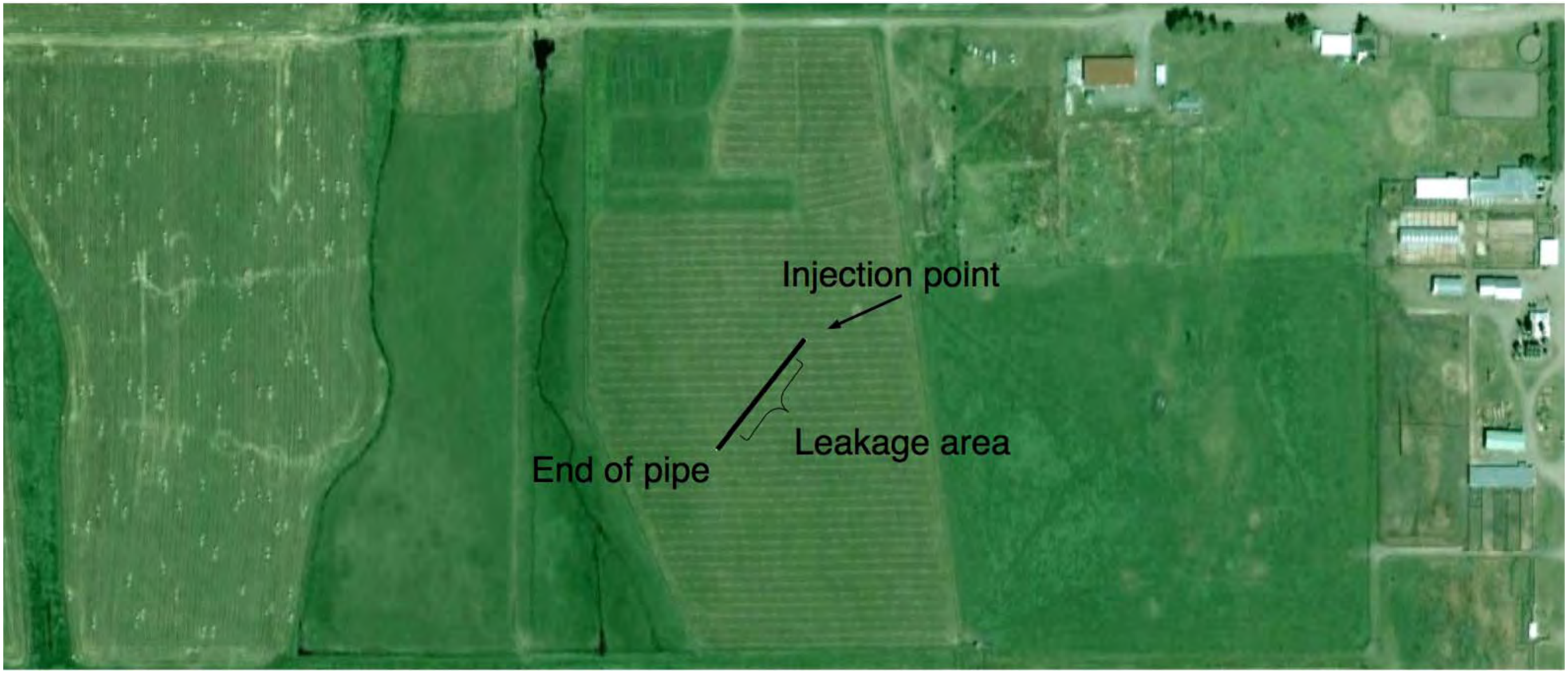
Isotope Detection Methodology

- Surveys of the site were made by traversing the site (100mX100m) at semi-regular intervals
- The gas inlet was about 10 cm above the ground
- Gas concentrations ($^{12}CO_2$, $^{13}CO_2$) were measured every 1-2 seconds along with GPS coordinates and time
- Some areas were inaccessible due to the presence of sensitive equipment

Krevor et al., 2010. International Journal of Greenhouse gas Control, in press.

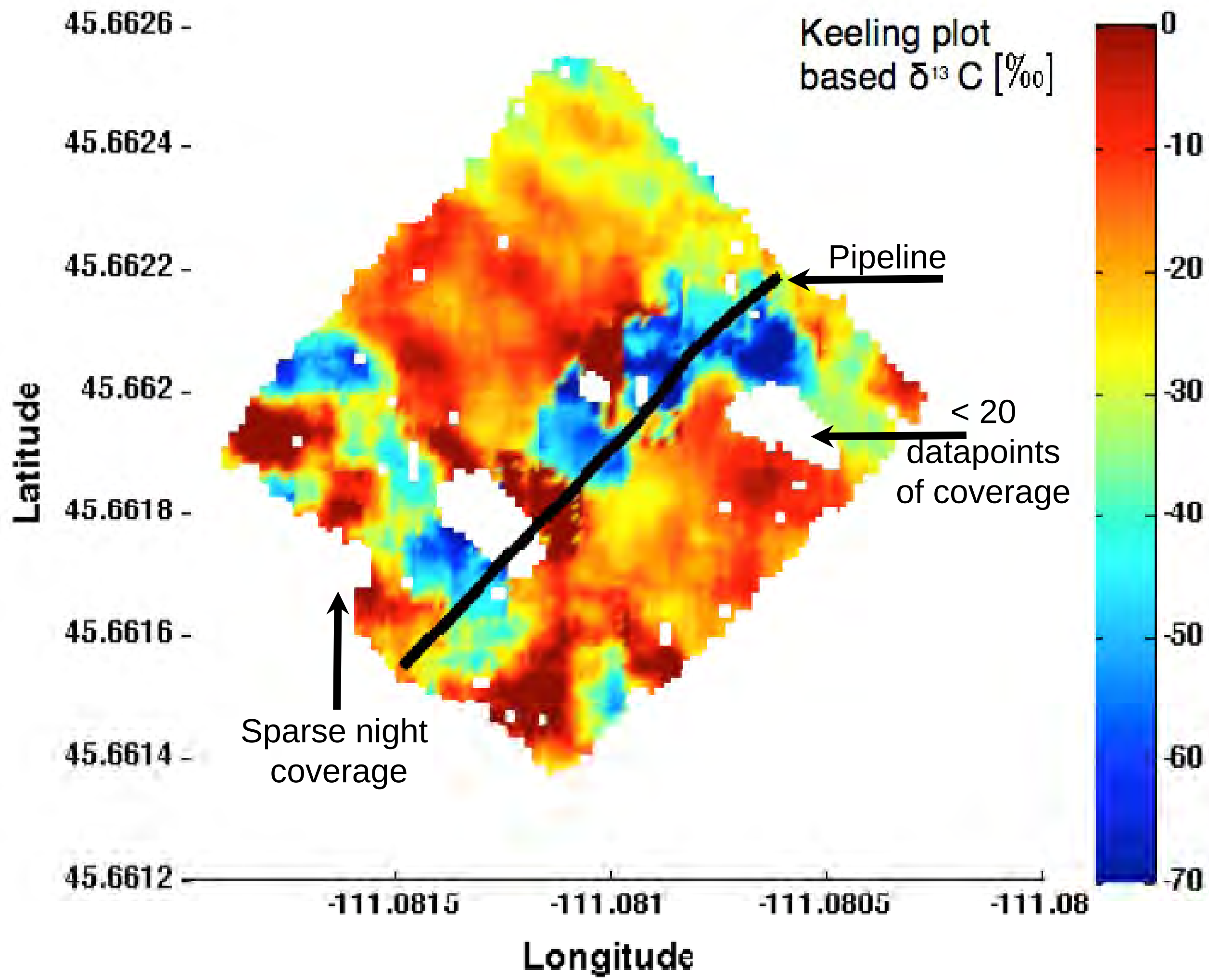
Methodology

An intentional leak of CO_2 has been designed at the ZERT experimental facility in Bozeman, Montana.



- 0.2 t/day CO_2 was released over a 30 days (.001% Leak)
- 100-meter long horizontal well
- 1-3 meters below the surface
- The injected CO_2 had a distinct $^{13}CO_2$ signature ($\delta^{13}C$ = -50) relative to atmospheric ($\delta^{13}C$ = -8) and plant respiration ($\delta^{13}C$ = -27)

Results



The plot clearly identifies a source CO_2 term with characteristically negative $\delta^{13}C$ values along the pipeline where leakage is known to occur

Institutional Issues

- 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 for CCS
- Clean Development Mechanism (CDM) credits for CCS
- Public acceptance

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

Research and Actions Needed to Accelerate Deployment of CCS

- Large scale integrated demonstration projects
- Lower the cost and decrease energy use for of all types of capture
- Increase confidence in geological storage permanence
  - Making less than ideal site adequate
- Combining biomass gasification with sequestration for negative emissions
- Finding ways to reuse CO_2 on the scale of emissions (e.g. scale of energy use)
- Address institutional issues effectively

Phases of CO_2 for CCS System