Stanford University

GCEP Global Climate & Energy Project

Caltech

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Reducing Greenhouse Gas Emissions: The Role of Geologic Storage of CO_2

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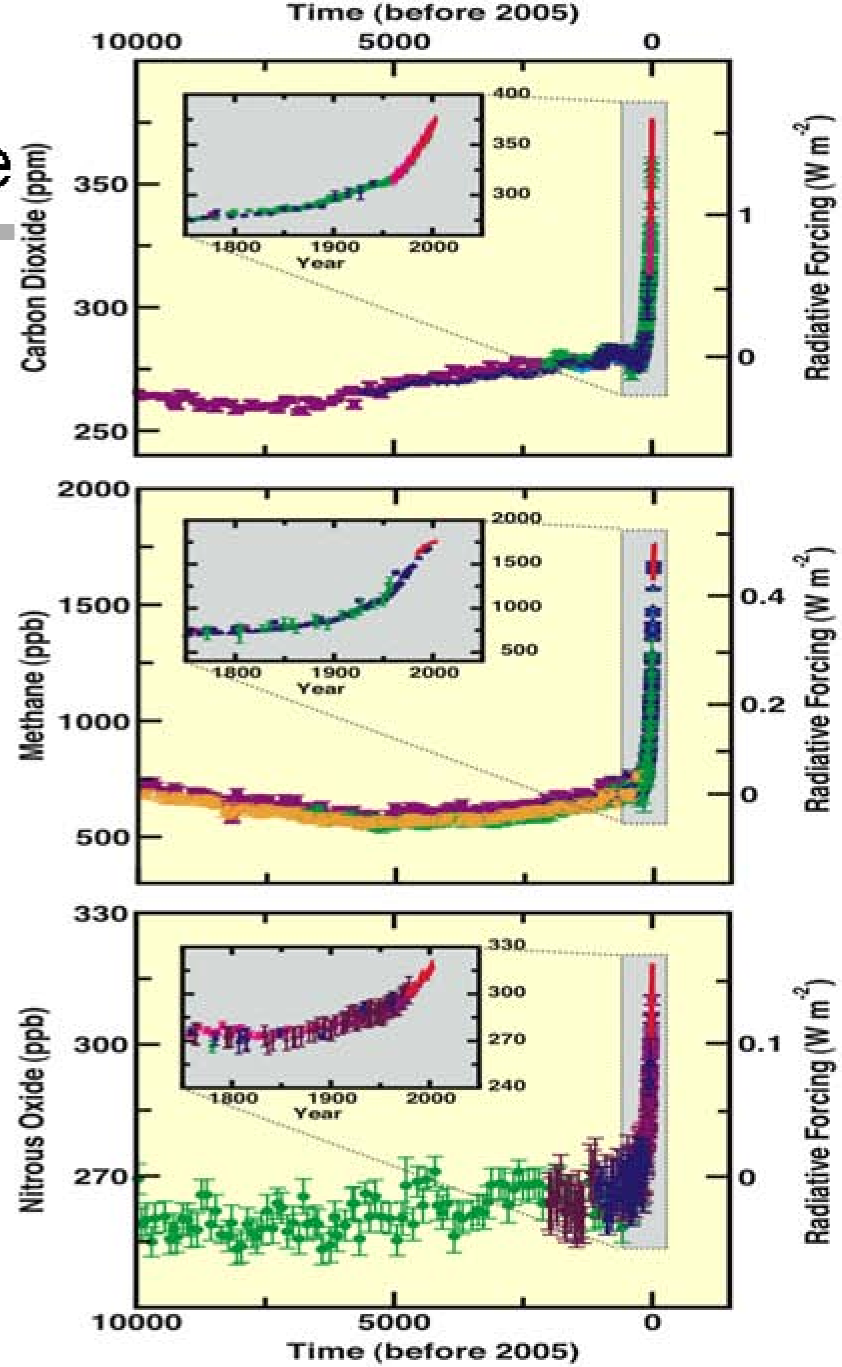
Human and Natural Drivers of Climate Change

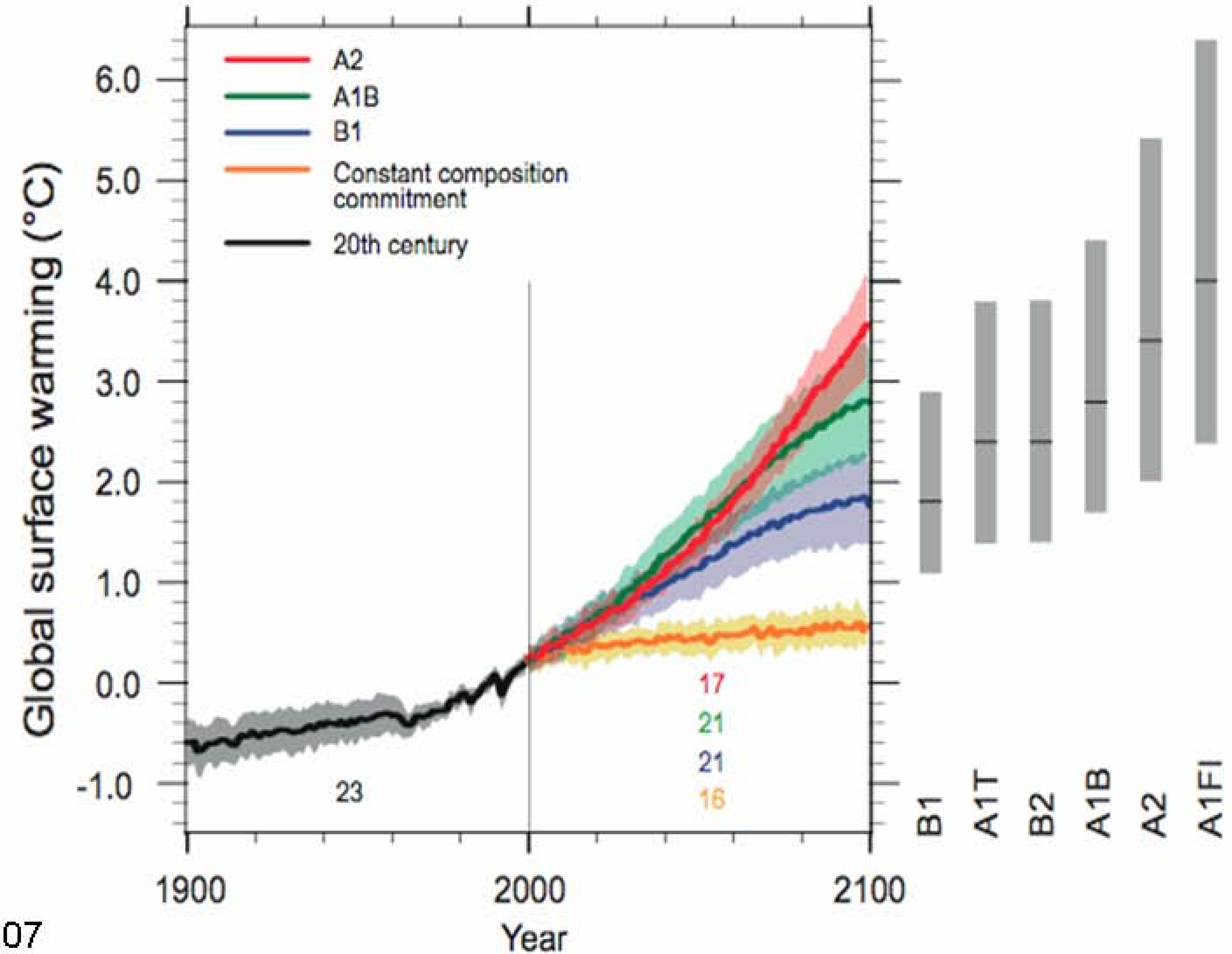
CO_2, CH_4 and N_2O Concentrations

- far exceed pre-industrial values
- increased markedly since 1750 due to human activities

Relatively little variation before the industrial era



Predicted Global Average Temperature



Source: IPCC, 2007

The Oceans in a High CO_2 World

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The oceans have taken up ~400 Gt of fossil fuel CO_2. Global surface oceans now remove 20-25 Mt CO_2/day.

Decline in pH (0.1 since industrial revolution) affects bicarbonate, carbonate ion concentrations, rates of fixation of $CaCO_3$ by assorted critters in the trophic chain, potential for feedbacks with temperature change.

Source: Oceanography Vol.17, No.3, Sept. 2004

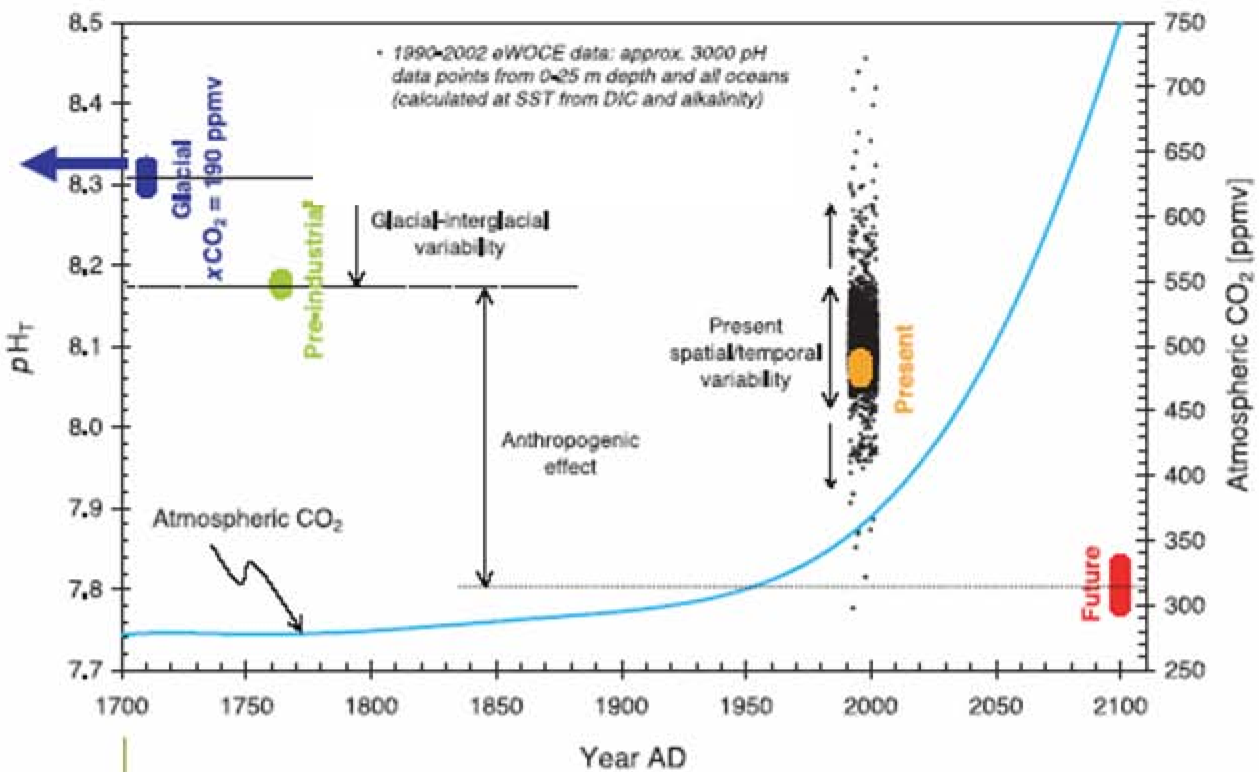


Figure 2. Present (1990-2002) surface seawater pH_T values from all oceans (3000 data points from the upper 25 m, pH_T were calculated from measured dissolved inorganic carbon and alkalinity). The majority of the data fall into a rather narrow pH range of 8.1 ± 0.1. Also shown

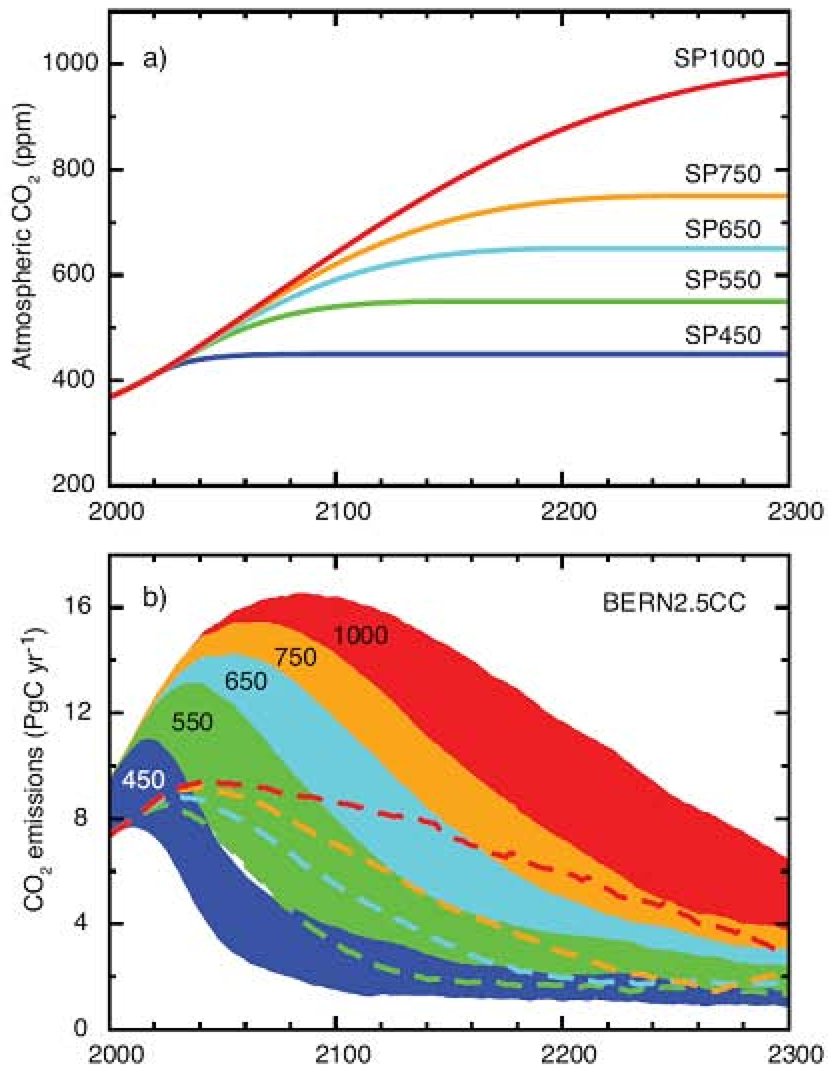
The Need for Technology

Concentrations of CO_2 will rise above current values (380 ppm), even under the most optimistic scenarios.

Stabilization will require that emissions peak and then decline. Peak timing depends on the stabilized concentration.

Improvements in efficiency, introduction of renewables, nuclear power, … all help.

New technology will be needed for the really deep reductions.

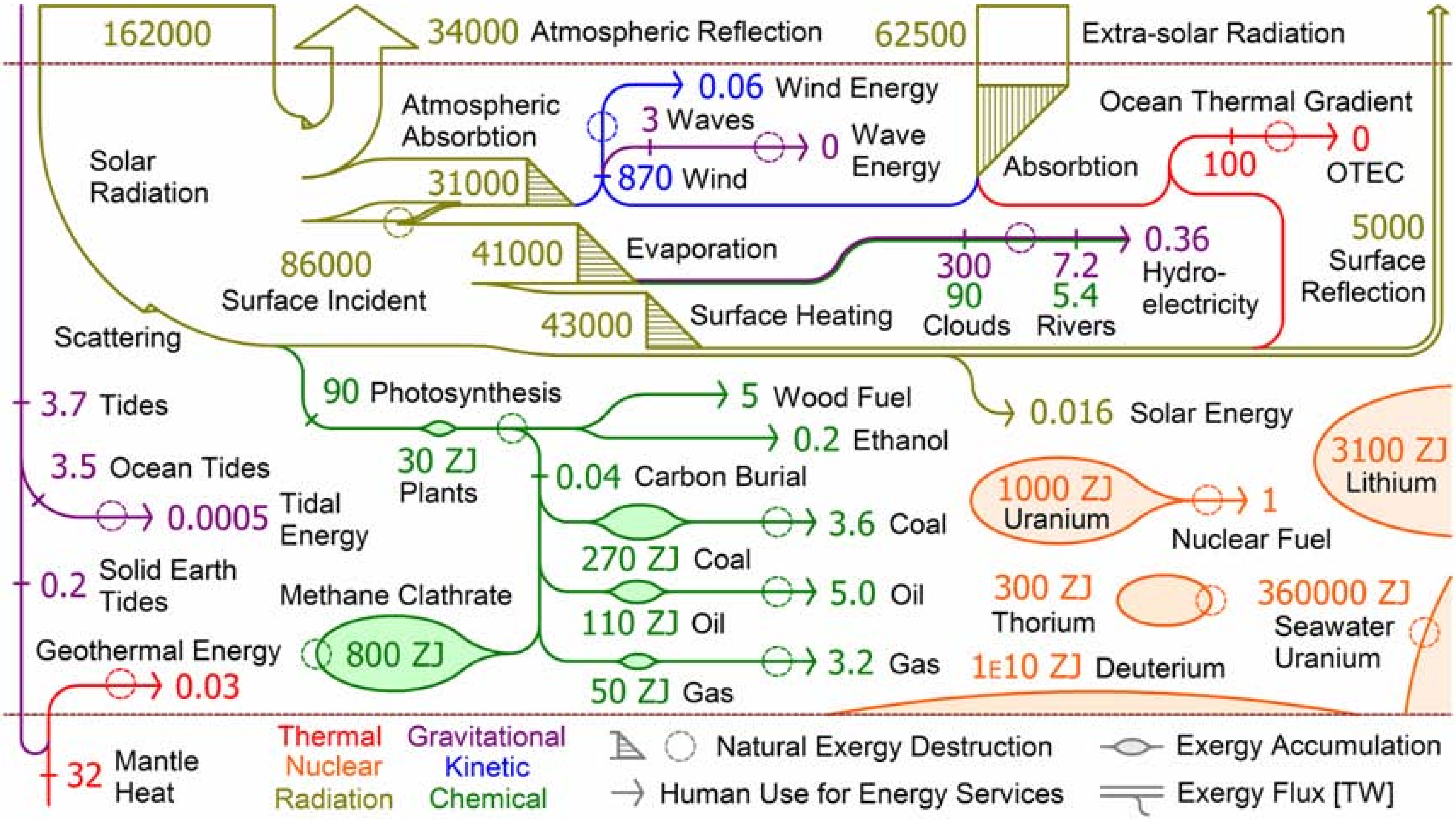


Source: IPCC 2007

So what do we do about this?

- Look for energy efficiency at every turn – there is plenty of room for efficiency improvement with technologies we have today, especially in the US.
- But growth in demand, particularly in the developing world will require that new technologies be brought on line if greenhouse gas emissions are to be reduced at the same time.
- Engage in a vigorous research effort to lay foundations for future energy technologies.
- Use a portfolio approach: guessing now the shape of the energy mix and markets 30-50 years in the future is doomed to failure.

Exergy Flow of Planet Earth (TW)

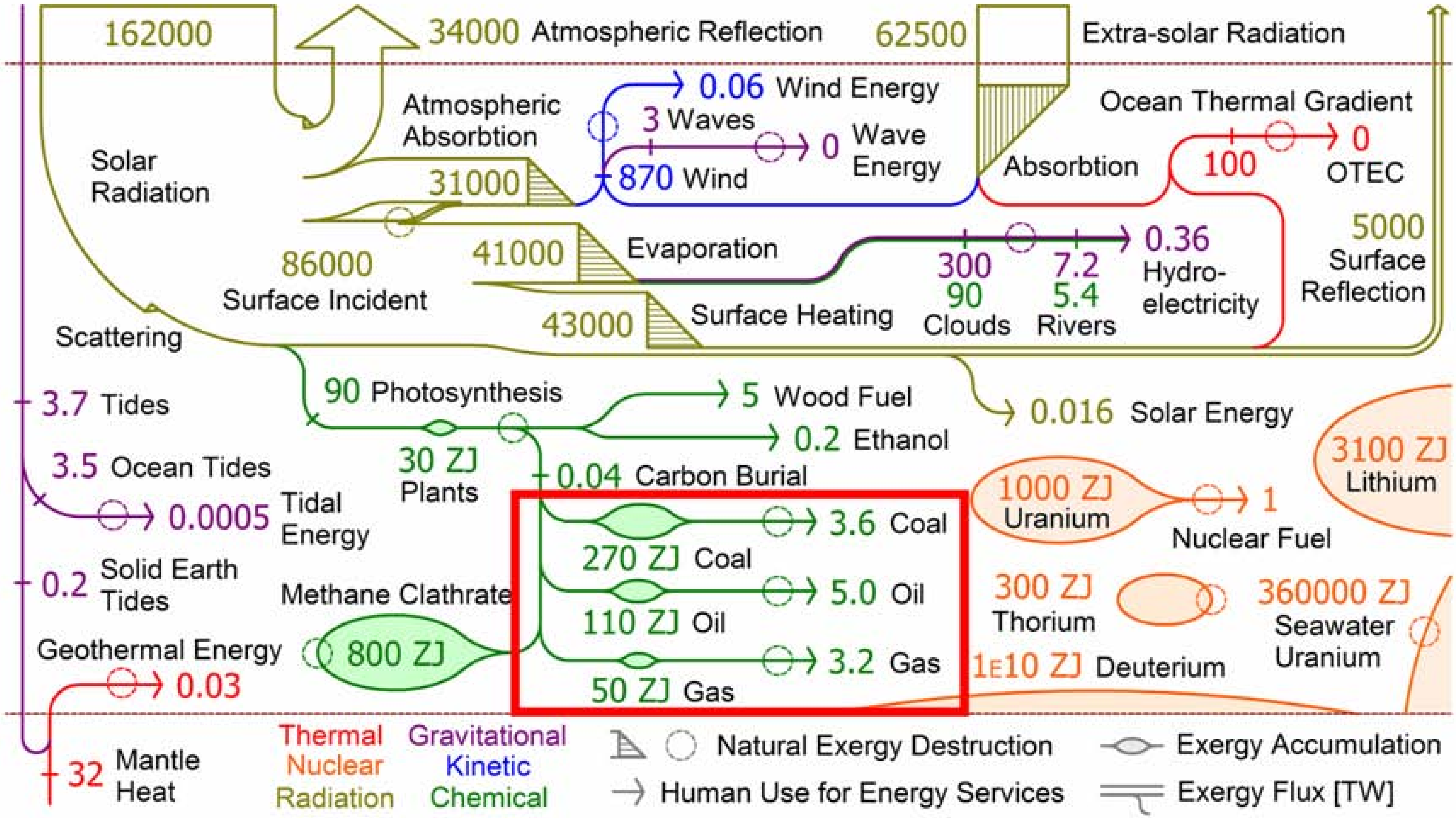


Current Global Exergy Usage Rate ~ 15 TW (0.5 ZJ per year)

(1 ZJ = 10^{21}J) ~86000/15 = ~5700

Source: W. Hermann, GCEP Systems Analysis Group 2004.

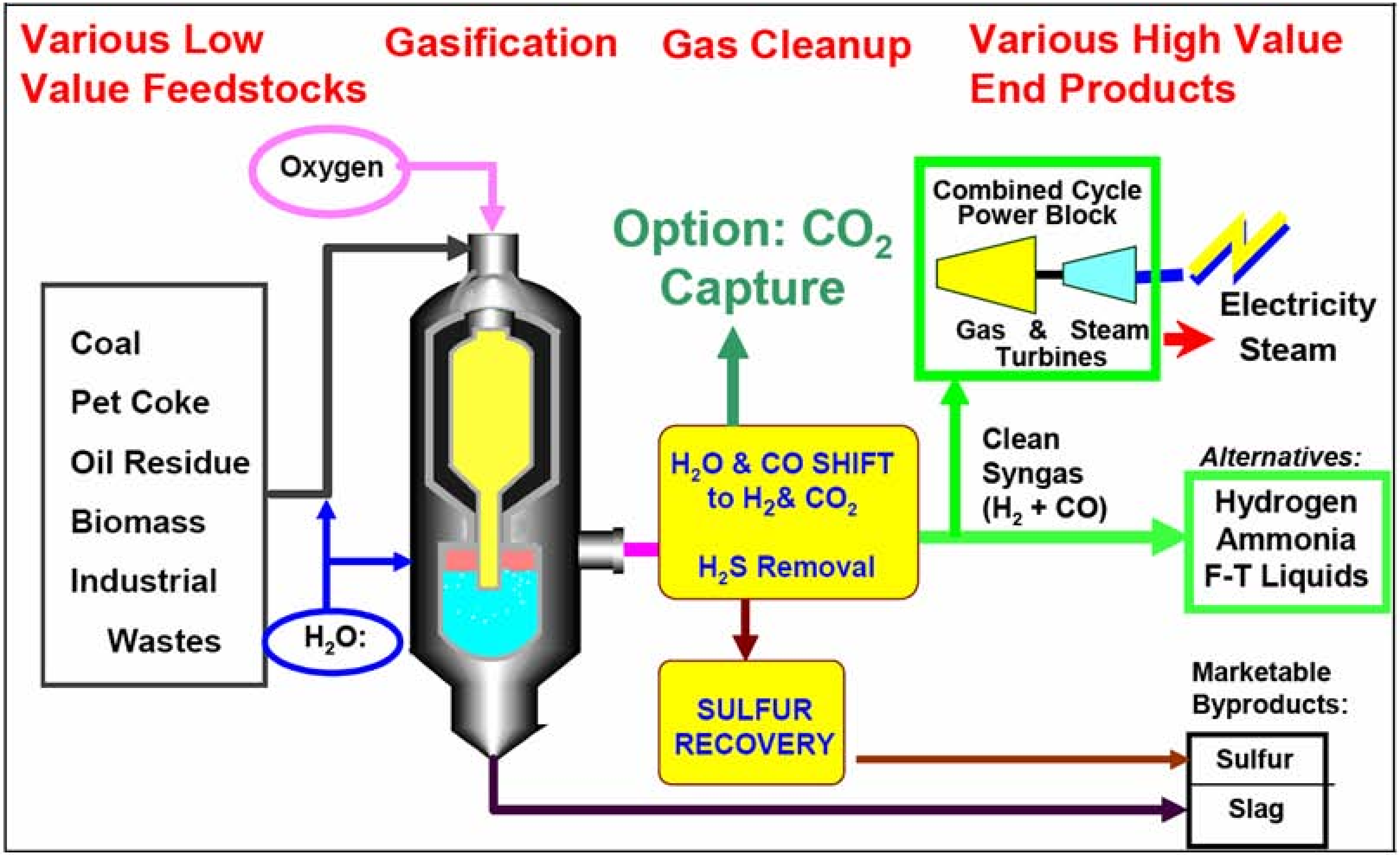
Exergy Flow of Planet Earth (TW):
Fossil Hydrocarbon Resource



(1 ZJ = 10^{21}J)

Source: W. Hermann, GCEP Systems Analysis Group 2004.

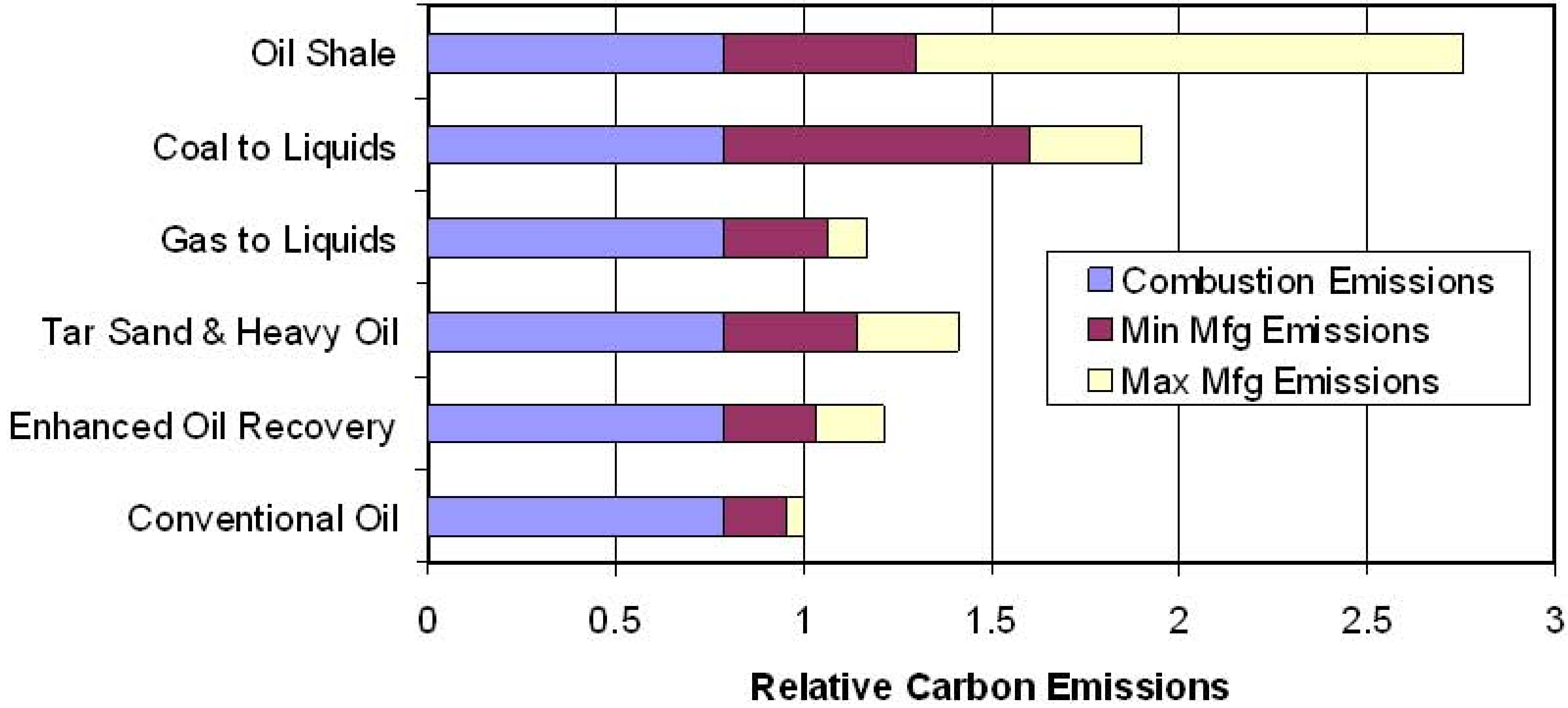
Gasification Options



Issues: Cost, operating reliability, overall efficiency if CO_2 recovered

Time scale: in use now, but not at large scale

Relative Carbon Emissions of Alternative Hydrocarbon Fuels



- Production of alternative liquid fuels from coal, tar sands, or oil shales increases GHG emissions significantly
- Volumes of CO_2 storage required to mitigate the upstream emissions will be very large if coal, tar sands and heavy oils are used to offset a significant fraction of conventional hydrocarbon use.

Source: Farrell & Brandt, Env. Res. Let. 1, 2006

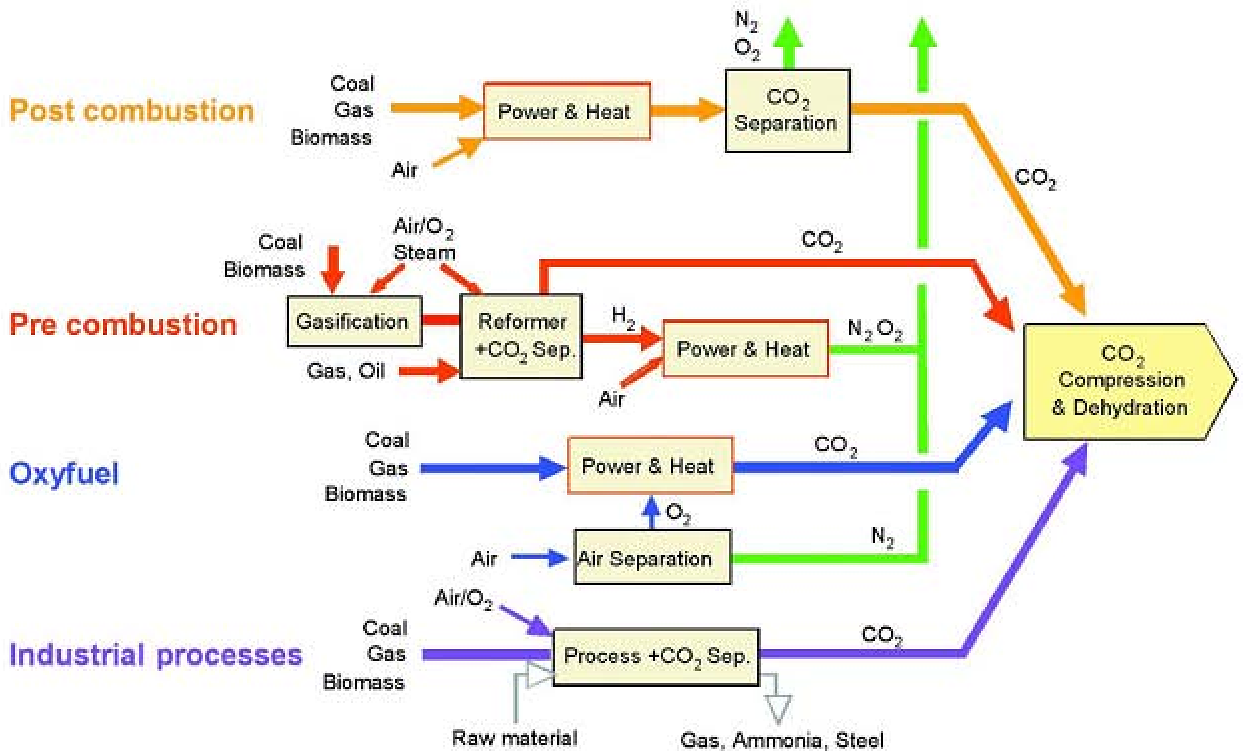
Geologic Storage of CO_2?

- Can we capture the CO_2? Efficiently? Cost?
- Do we have enough variety of geologic settings for storage?
- Is there sufficient volume available in the subsurface to store enough CO_2 to have an impact?
- Do we know enough about the physical mechanisms that will trap the CO_2 in the subsurface to design safe storage projects that won't leak?
- Do we have enough experience with actual operations to undertake storage at scale?

There are multiple routes for capturing CO_2 (but it's expensive!)

- Gas separation processes are available for commercial scale
- CO_2 is routinely separated from natural gas (amines, physical solvents)
- Early storage field tests have used CO_2 that must be separated anyway (Sleipner, In Salah, Weyburn)

Overview of CO2 capture processes and systems



SRCCS Figure TS-3

Source: IPCC Special Report Carbon Capture & Storage, 2006

Efficiency and Cost

- Typical efficiencies for the solvent/amine separations are low: about 15% of the energy expended is required by the thermodynamics – the rest is lost to entropy creation and heat transfer losses.
- Est. costs (2002 $ per tonne CO_2 avoided), efficiency (LHV)
  - New natural gas combined cycle: $37-74 47-50%
  - New pulverized coal: $29-51 30-35%
  - New IGCC $13-37 31-40%
  - New H_2 $ 2-56 52-68%
- Cost of CO_2 capture is the largest component in cost of storage. A breakthrough in separations technology would make a big difference.

Source: IPCC Special Report on CCS, 2005

What Types of Rock Formations are Suitable for Geological Storage?

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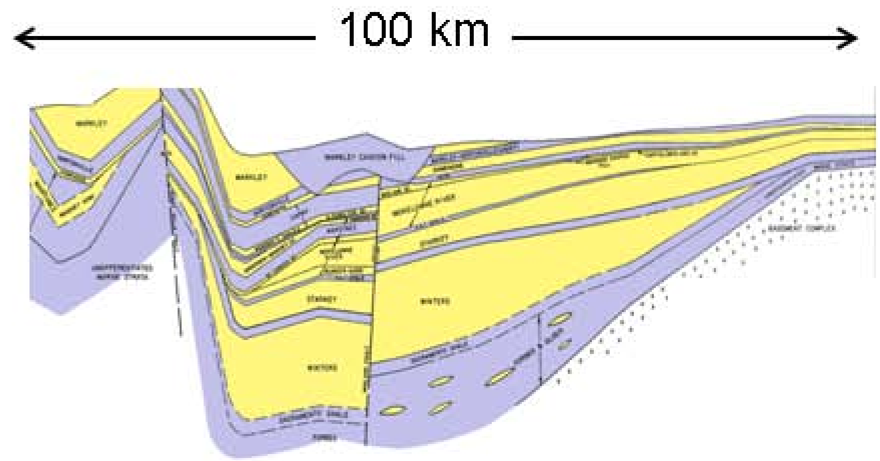
Rocks in deep sedimentary basins with barriers to vertical flow are suitable for CO_2 storage.

Map showing world-wide sedimentary basins



Northern California Sedimentary Basin

Specific formation types

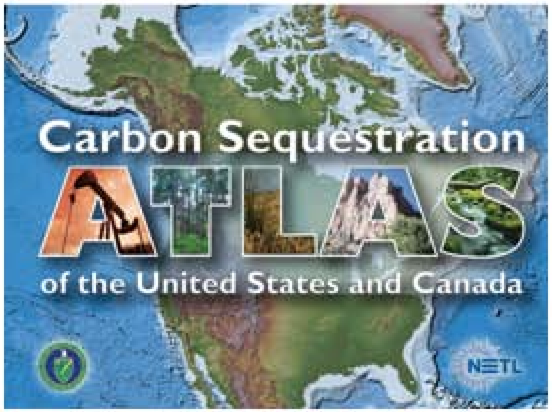
- Oil reservoirs
- Gas reservoirs
- Saline aquifers
- Deep, unminable coal beds

What about CO_2 storage in basalt?

This is an unproven technology that is the subject of ongoing research.

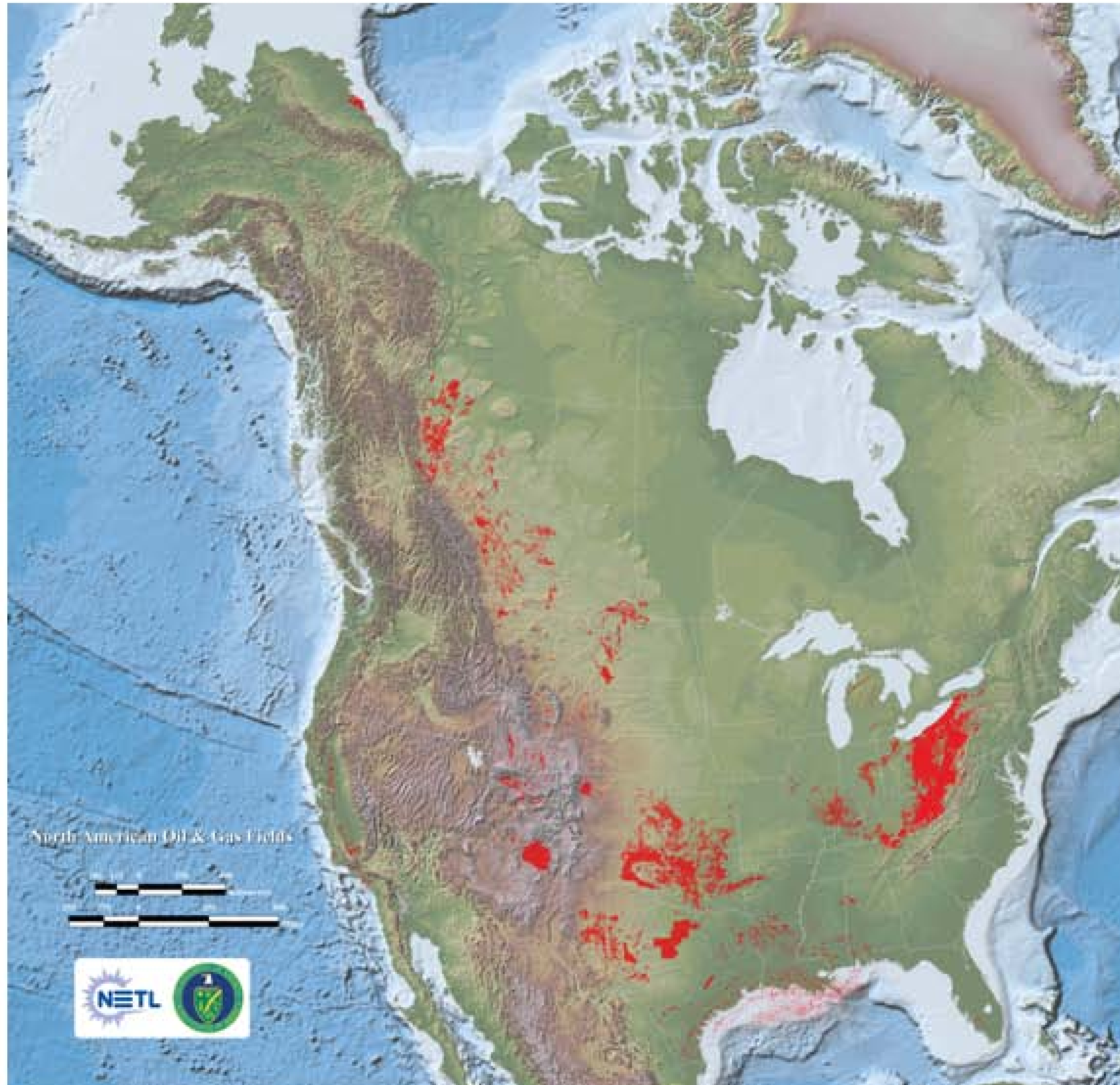
Source: S.M. Benson, GCEP

Location of Storage Sites I
North America: Oil and Gas Fields



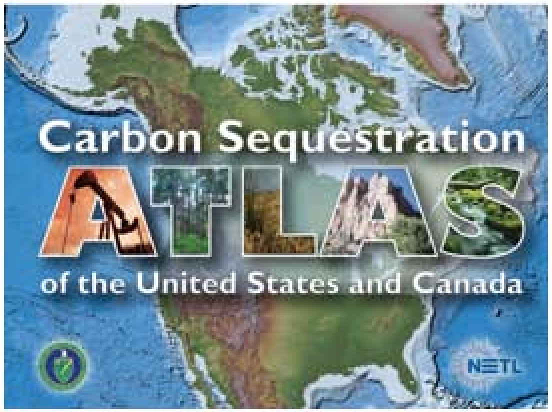
First North American Carbon Sequestration Atlas, 2006

CO_2 Storage Capacity (Billion Metric Tons)	
Big Sky	0.8
MGSC	0.4
MRCSP	2.5
PCOR	19.6
SECARB	32.4
SOUTHWEST	21.4
WESTCARB	5.3
TOTAL	82.4



Source: S.M. Benson, GCEP

Location of Storage Sites in North America: Saline Aquifers



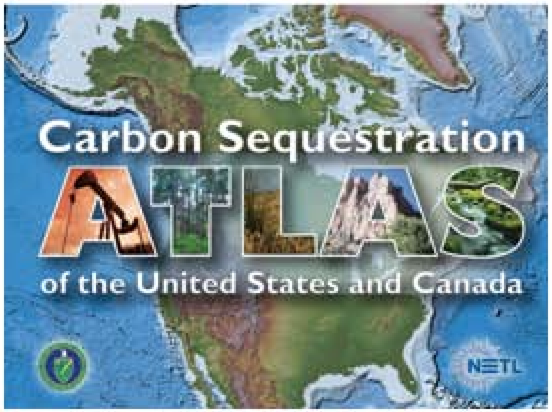
First North American Carbon Sequestration Atlas, 2006

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

Source: S.M. Benson, GCEP

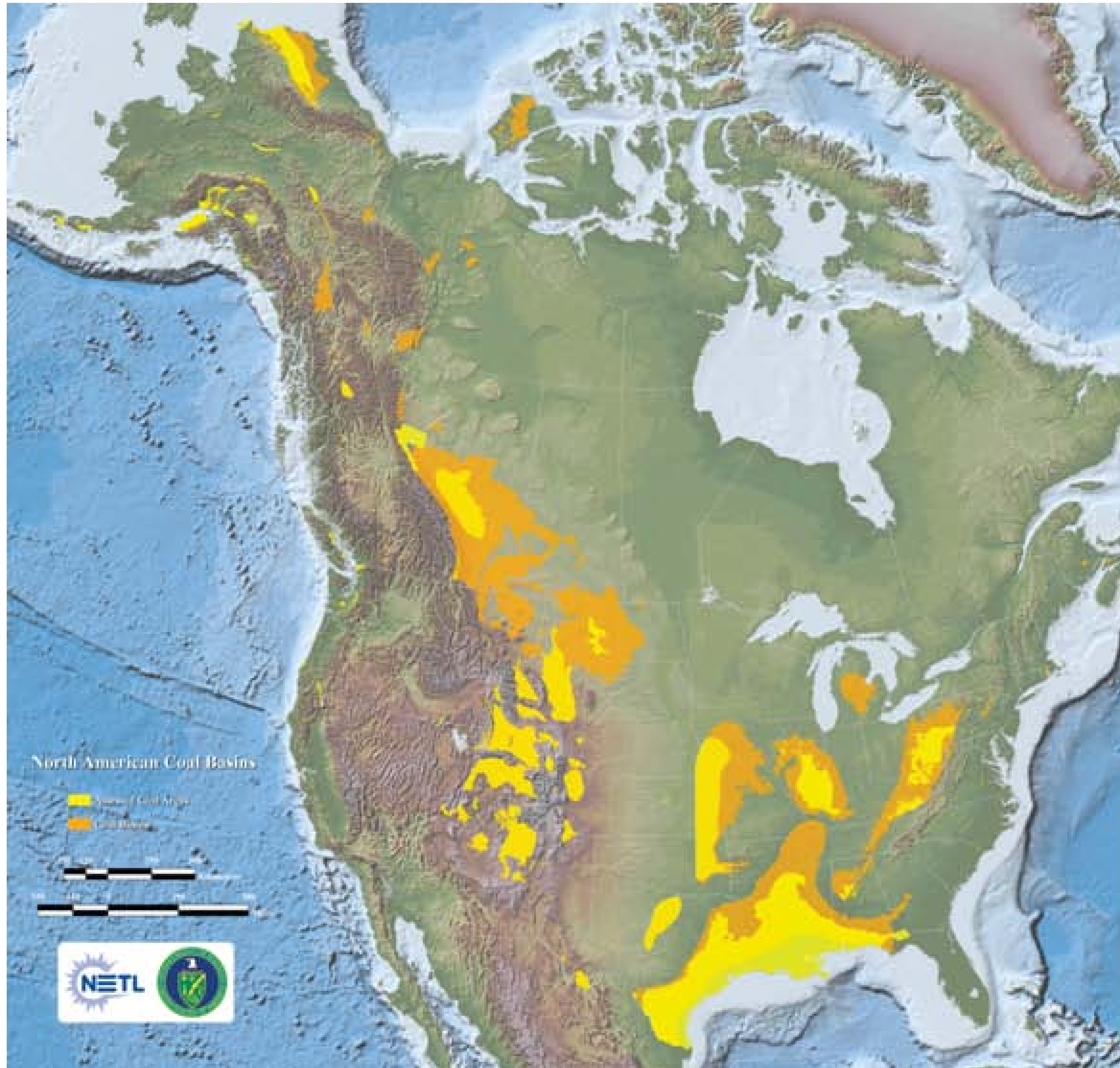
Location of Storage Sites in North America: Coal



First North American Carbon Sequestration Atlas, 2006

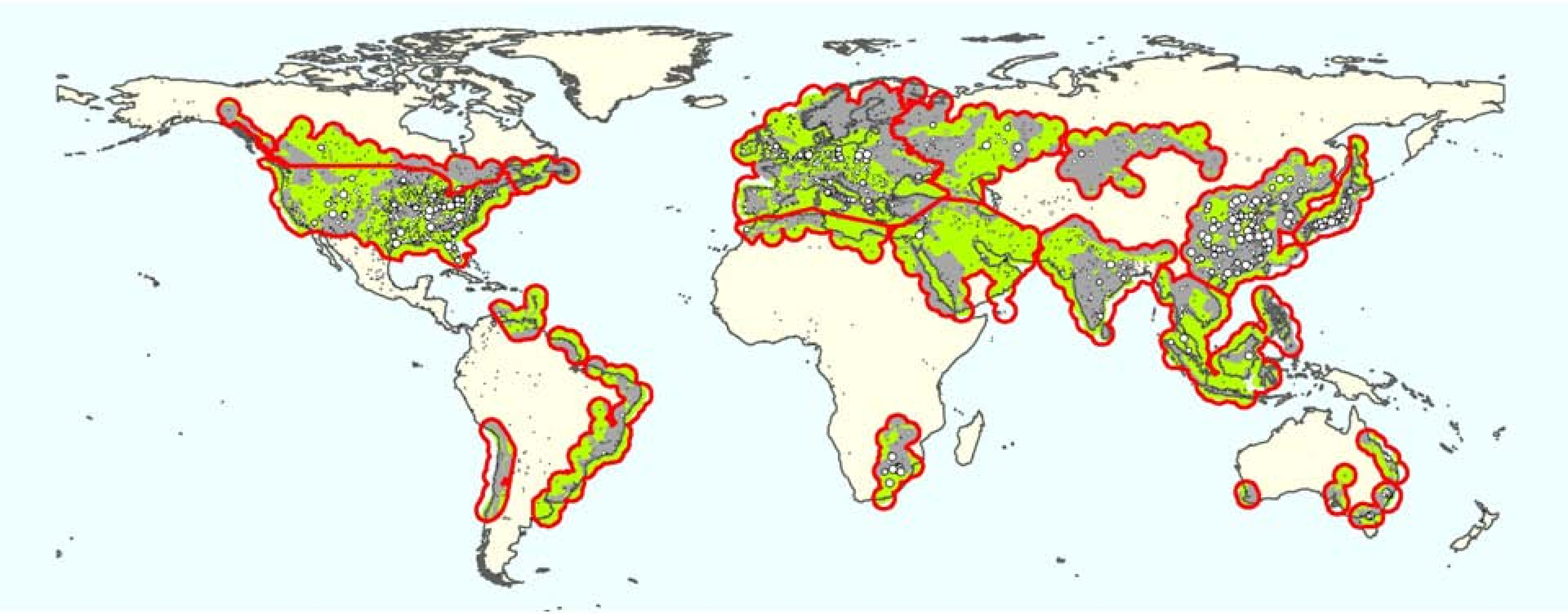
CO_2 Storage Capacity
(Billion Metric Tons CO_2)

Big Sky	NA	NA
MGSC	2.3	3.3
MRCSP	0.7	1.0
PCOR	8.0	8.0
SECARB	57	82
SOUTHWEST	0.9	2.3
WESTCARB	87	87
TOTAL	**156**	**183**



Source: S.M. Benson, GCEP

World Regional CO_2 Storage Opportunities



Emission regions (300 km buffer)

Prospective basins

Non- Prospective provinces

Source: John Bradshaw, Geoscience Australia

Physical Mechanisms of Storage

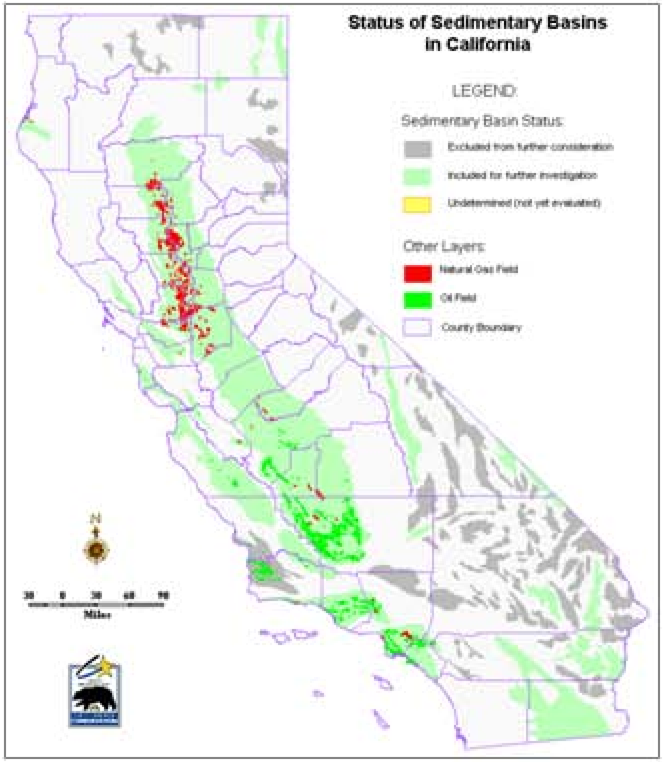
- How far does injected CO_2 propagate (where will we need to monitor)?
- How long does it take to immobilize the CO_2 by some mechanism?
- What is the ultimate fate of the CO_2?
- What fraction of the CO_2 has the potential to escape (as a function of time)?
- Can we design injection processes that reduce the potential for leakage?

The state of knowledge differs for the three main types of potential storage sites. Considerable simulation capability exists (but questions of large scale and long term mechanisms remain).

Regional and reservoir scale characterization will be needed

Site Selection and Characterization:

- Are the seals continuous over the storage reservoir?
- What is the 3-D geometry of faults and fractures?
- Are faults seals or fluid conduits?
- How much overpressure can the seals sustain?
- What is the injectivity of the storage formation?
- What is the storage capacity?



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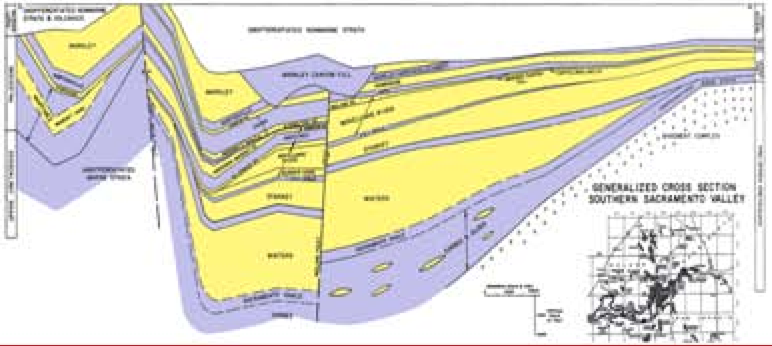
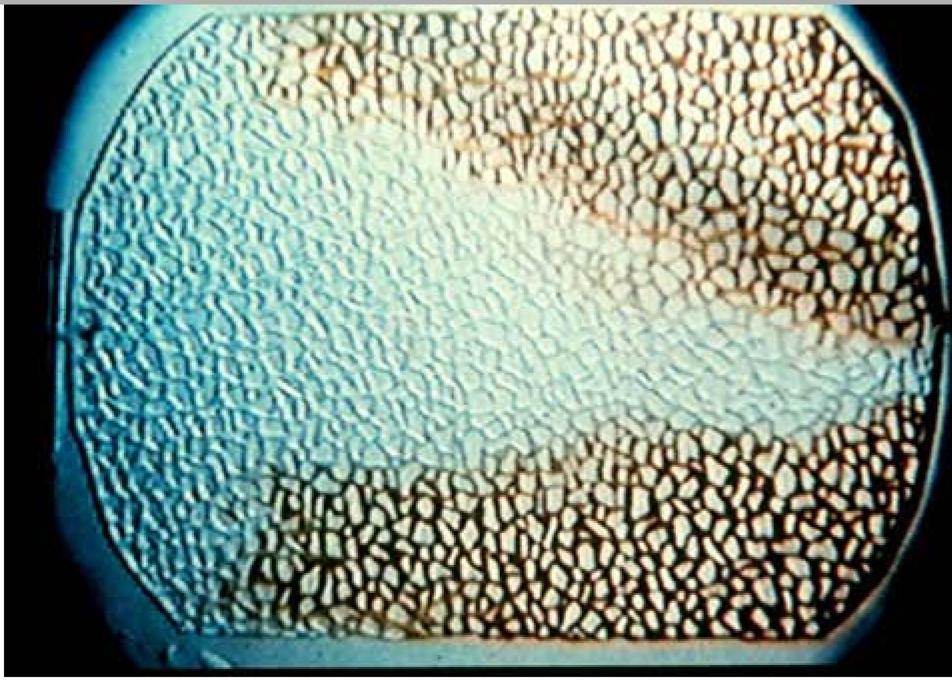
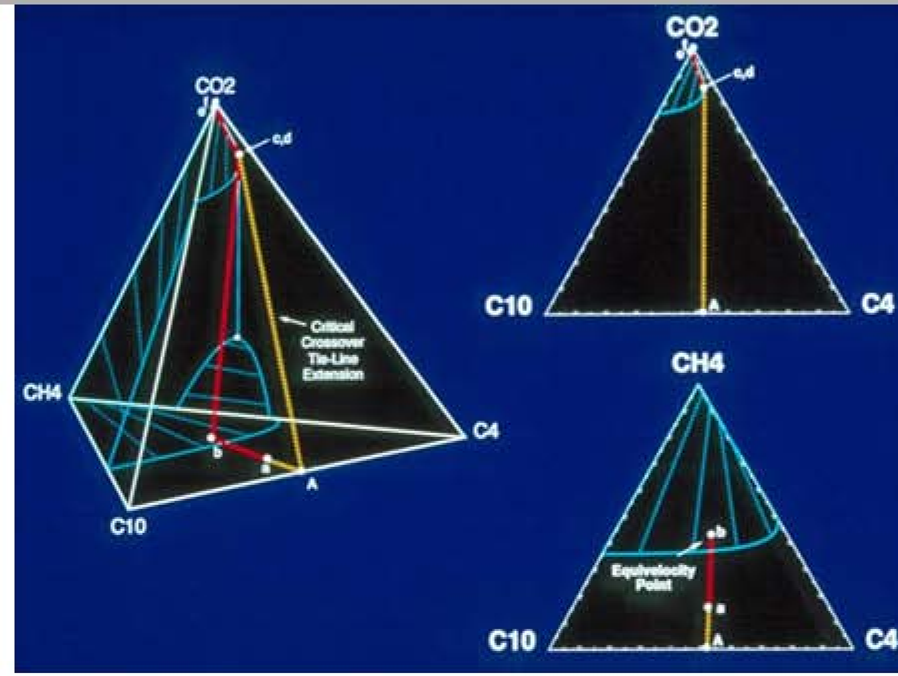


Source: S. M. Benson

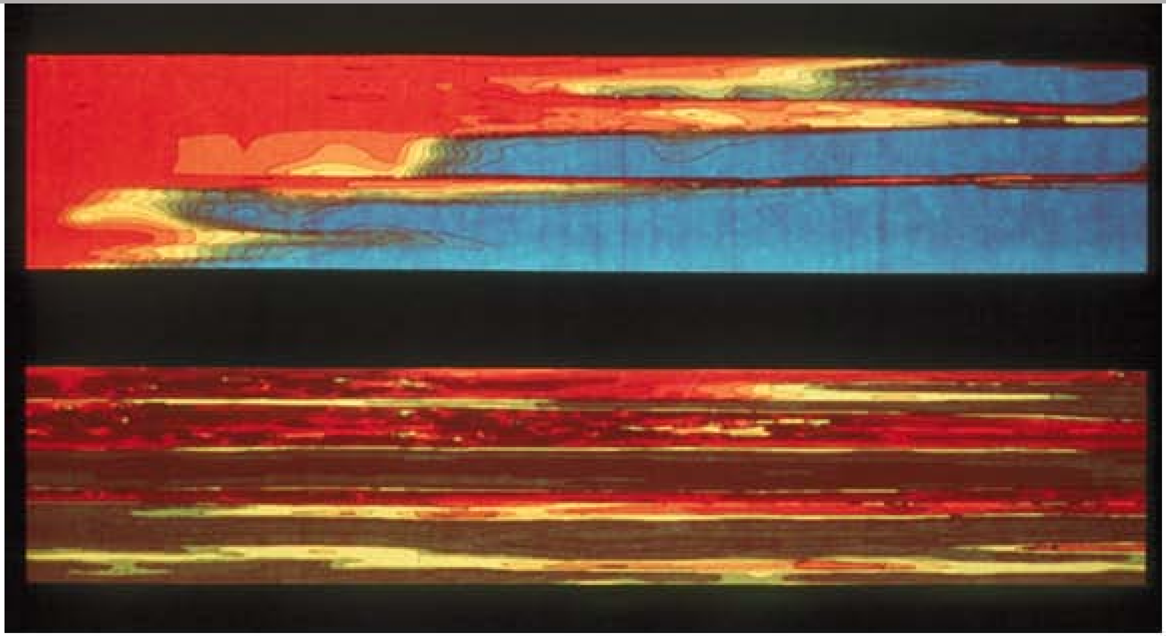
Why CO_2 for EOR?





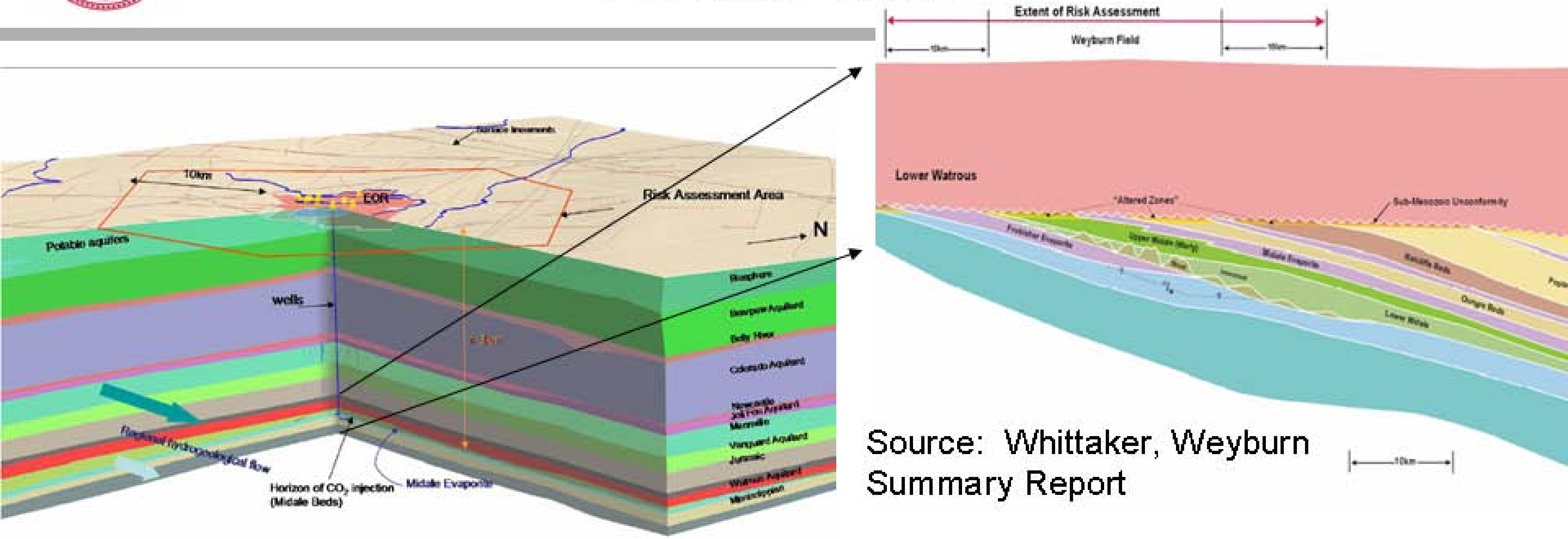
- If pressure is high enough, oil is displaced very efficiently due to chromatographic separations that occur during flow of two phases with different compositions.
- The displacement is efficient if the composition path approaches the critical locus.

Reservoir Displacement



- Heterogeneity and gravity strongly influence well-to-well flow of injected gas.
- Extremes of permeability dominate the flow.
- Low viscosity CO_2 will find the easy flow paths between wells.
- Breakthrough of injected CO_2 limits sweep efficiency and recovery.
- Opportunity to optimize for storage and recovery.

Weyburn: multiple barriers to vertical flow



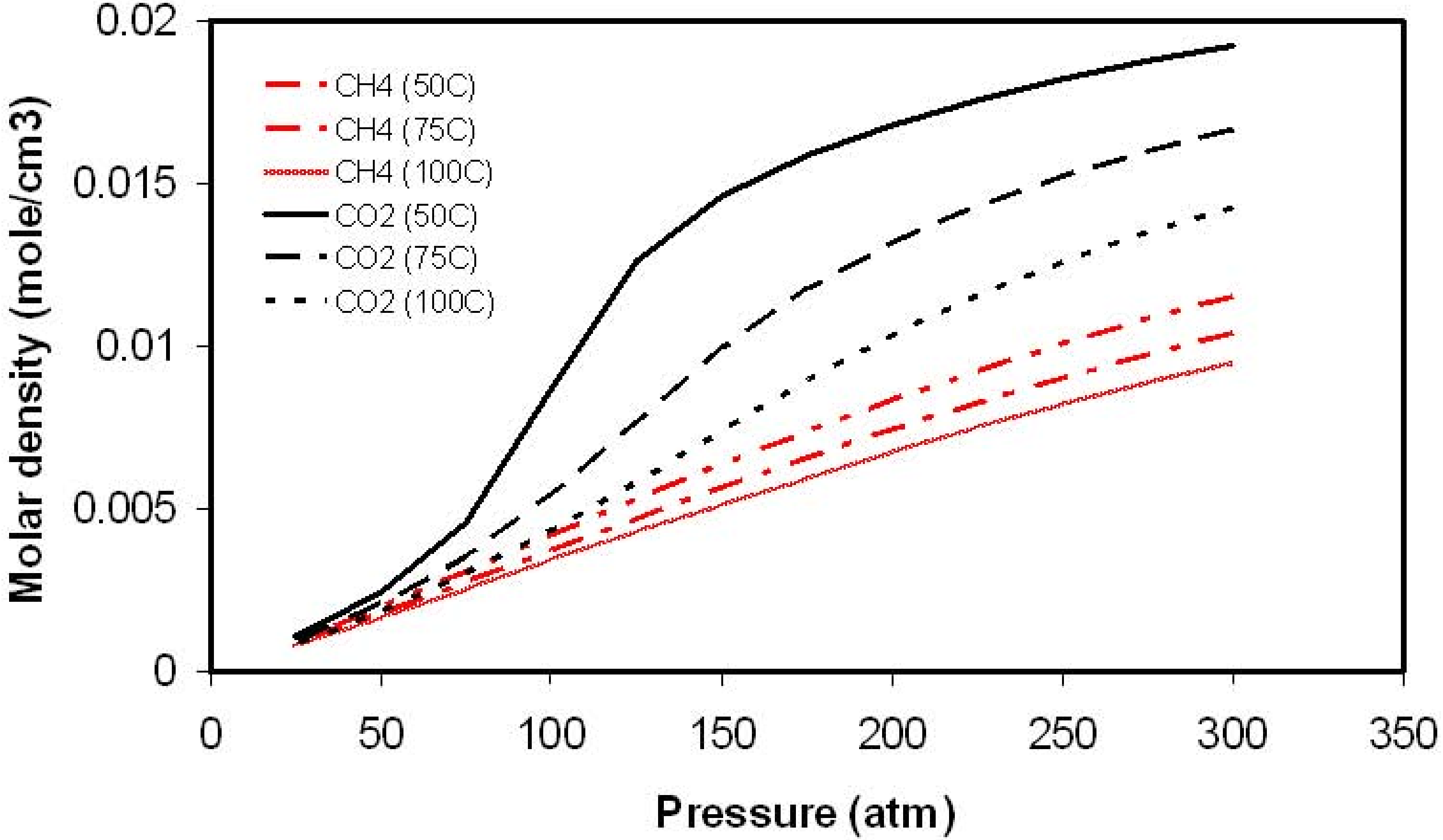
Source: Whittaker, Weyburn Summary Report

- The deep formations containing salt water and oil are separated from shallow aquifers by multiple, thick, low permeability formations.
- Even if the oil were not present at Weyburn, it would be a good place to store CO_2. But the oil indicates that there is a trap with a good seal. Storage in oil and gas settings relies on the existence of a seal in the long term.

CO_2 injection in gas reservoirs

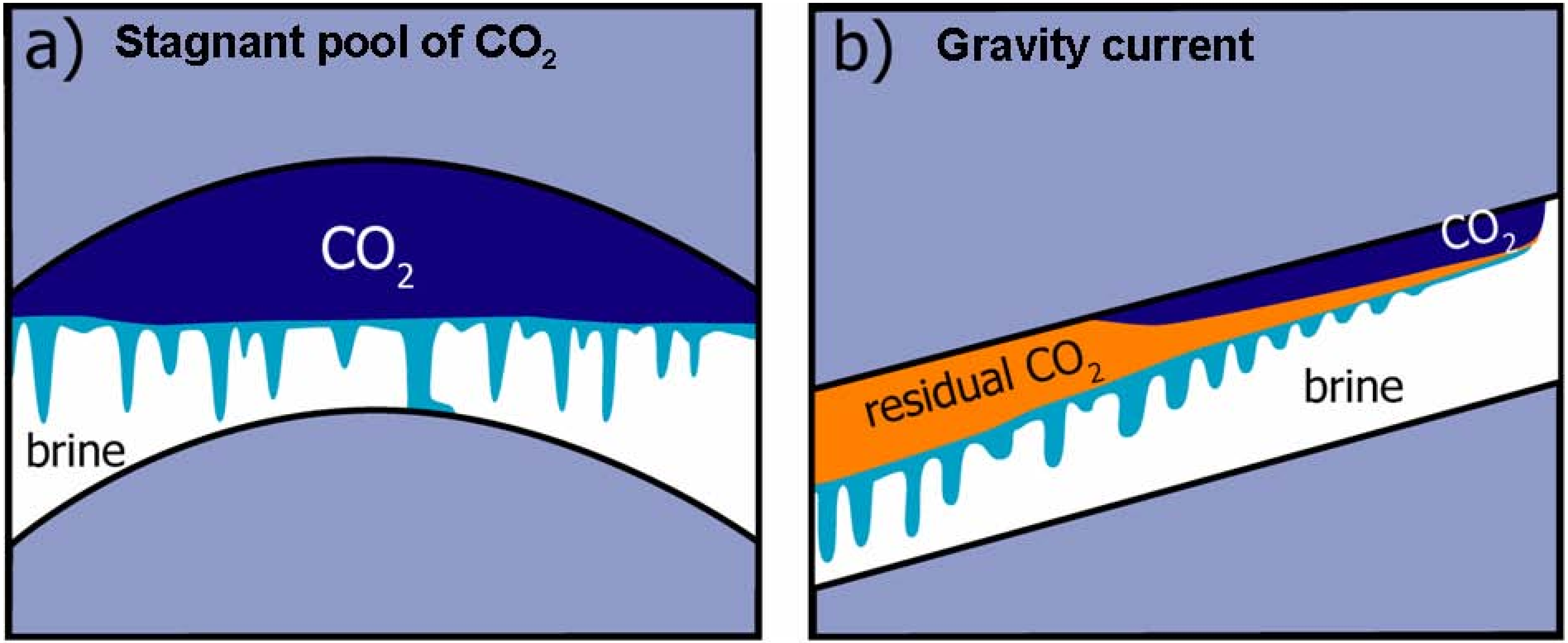
- CO_2 could be used for pressure maintenance or condensate vaporization in gas reservoirs. First test underway in the Netherlands
- At a given temperature and pressure, CO_2 is always more dense than CH_4. Injection low in the reservoir would limit vertical mixing.
- CO_2 is slightly more viscous than CH_4.
- CO_2 is an effective injection fluid for condensate vaporization.
- Issues include breakthrough of injected CO_2 in production wells (well-to-well flow still dominates, diffusional mixing.
- Driving force for upward migration remains indefinitely.

Density of CO_2 and CH_4



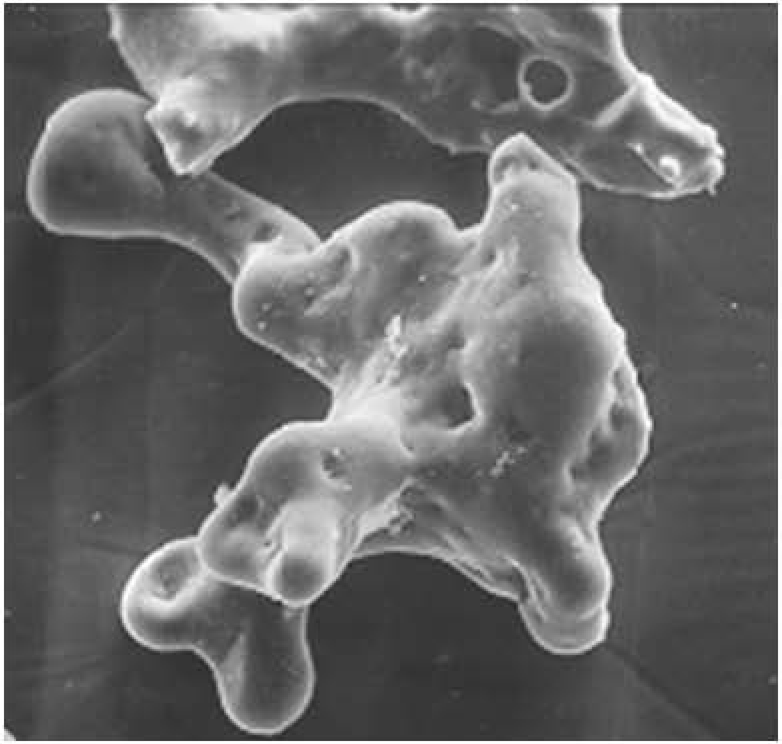
Methane could be removed from a gas field, oxidized, and reinjected. Pressure would decline because CO_2 is less dense than CH_4.

Schematic of CO_2 in an aquifer



Mechanisms: immobilize CO_2 by capillary trapping

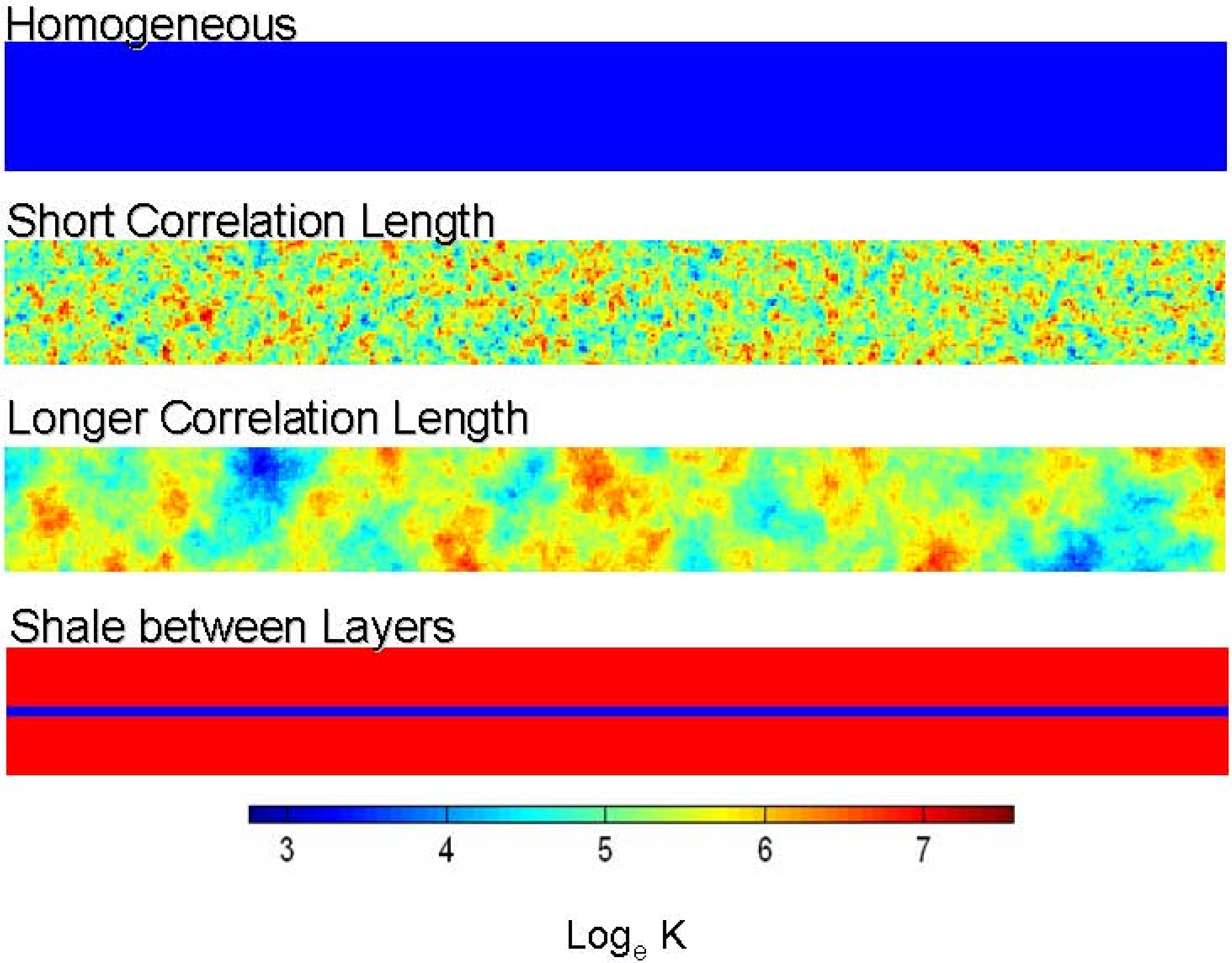
- Pushing CO_2 with water, causes CO_2 bubbles to be isolated in the tiny pores in the rock.
- These trapped bubbles are very difficult to move.
- Can we make use of trapping to design injection schemes that trap the CO_2 effectively?



Trapped bubbles (after removal of the rock)
(Image: N. R. Morrow)

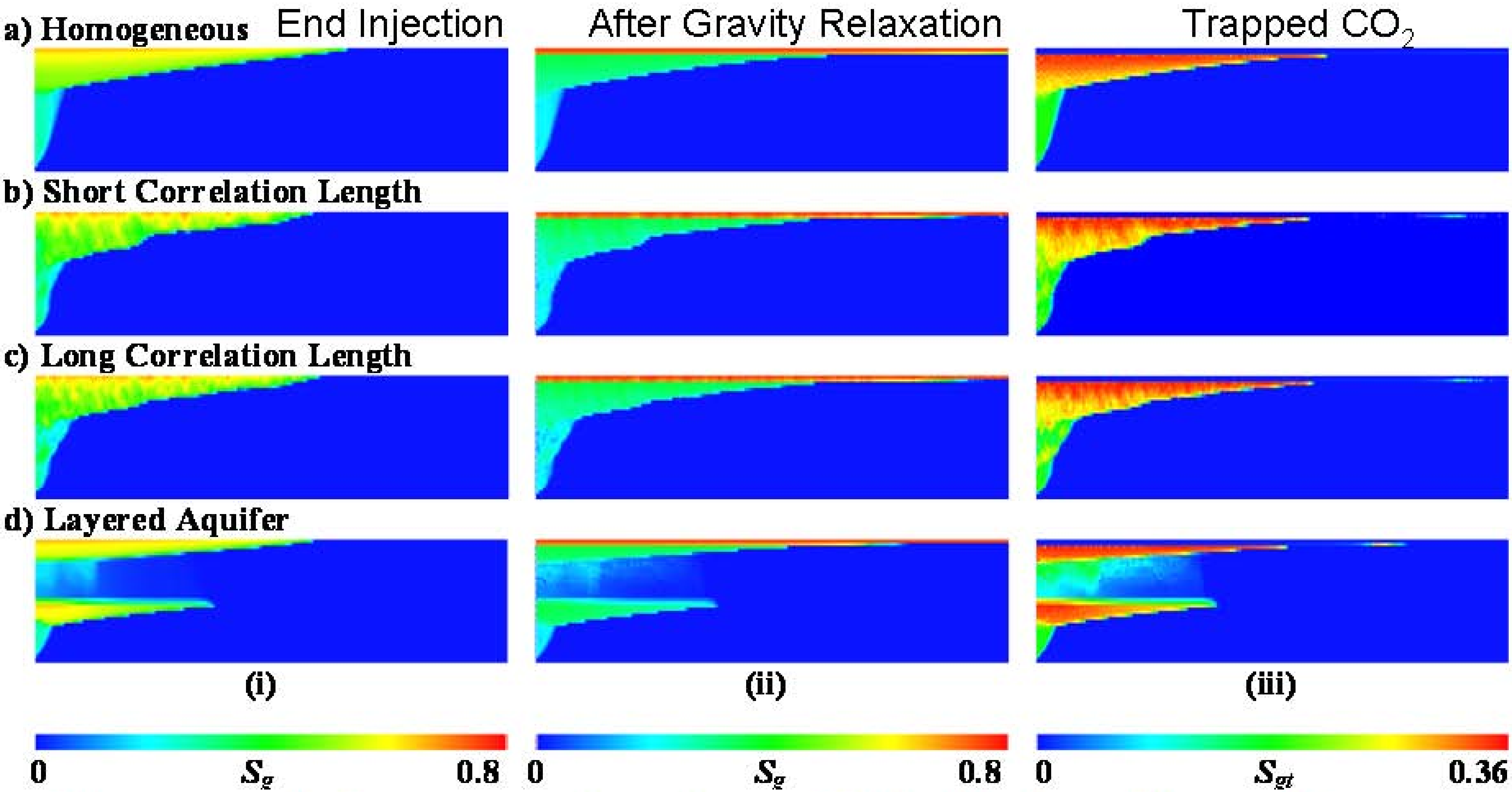
Capillary trapping can immobilize CO_2 relatively quickly. If the CO_2 is trapped, it can't leak during the time required for it to dissolve. Once dissolved, it does not move upward in the rocks.

Permeability distributions for simulations



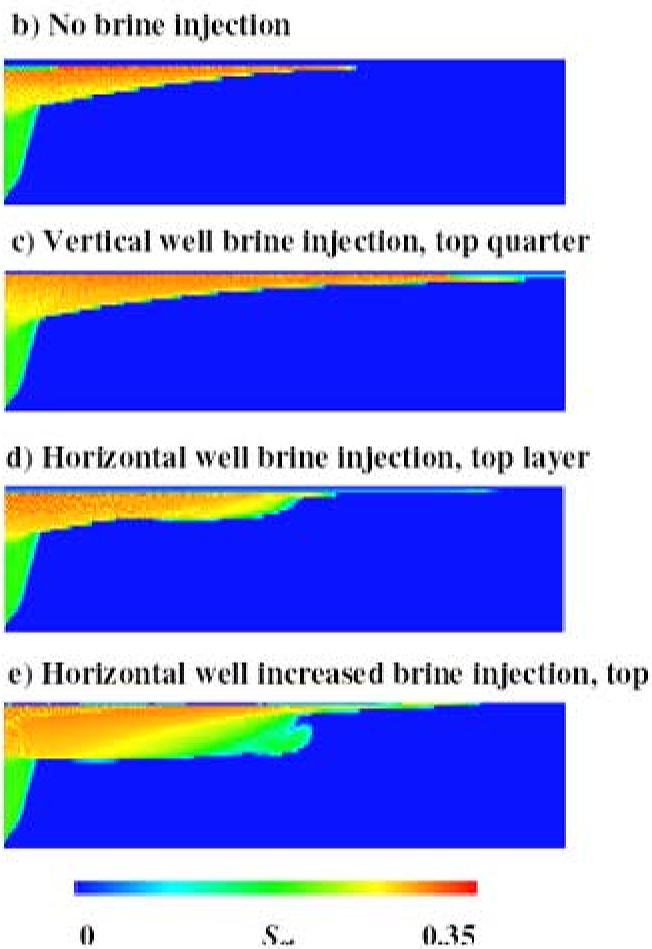
Gravity-Dominated Displacements

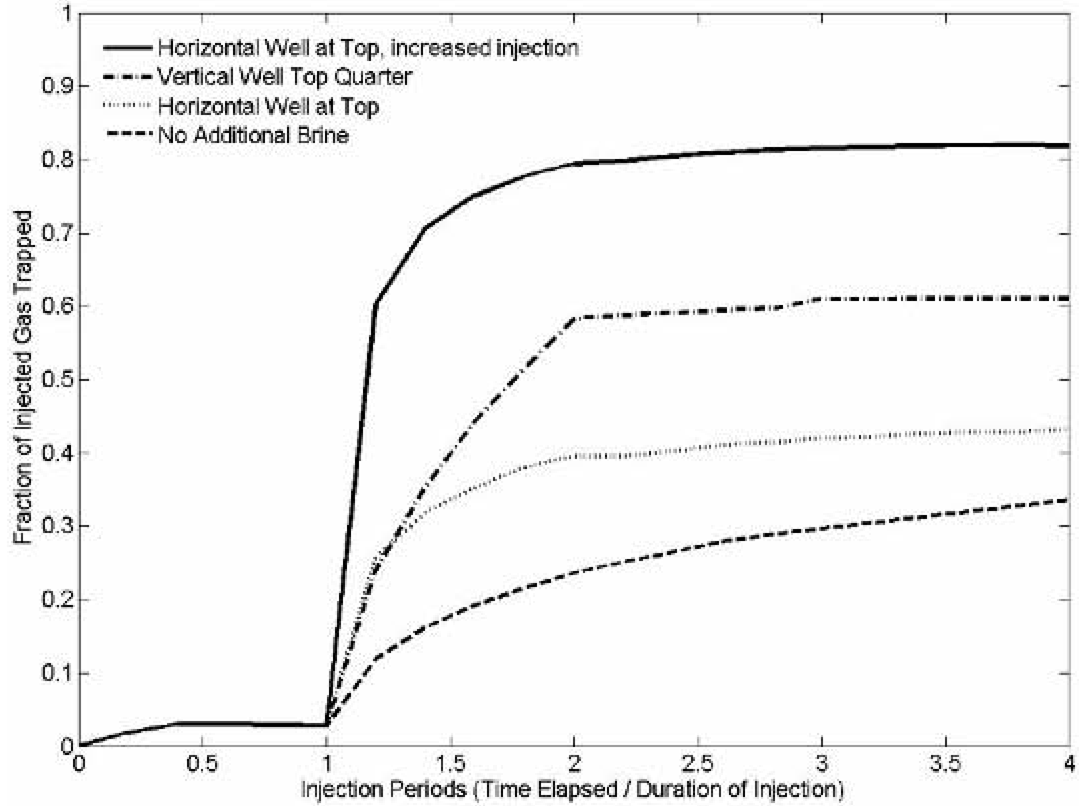
N_{gv}= 55, P_c= 0



Strong gravity forces move less dense CO_2 to the top of the aquifer. Capillary trapping occurs at the base of the gravity tongue as brine invades behind gas during gravity relaxation after injection ceases.

Water injection to trap CO_2



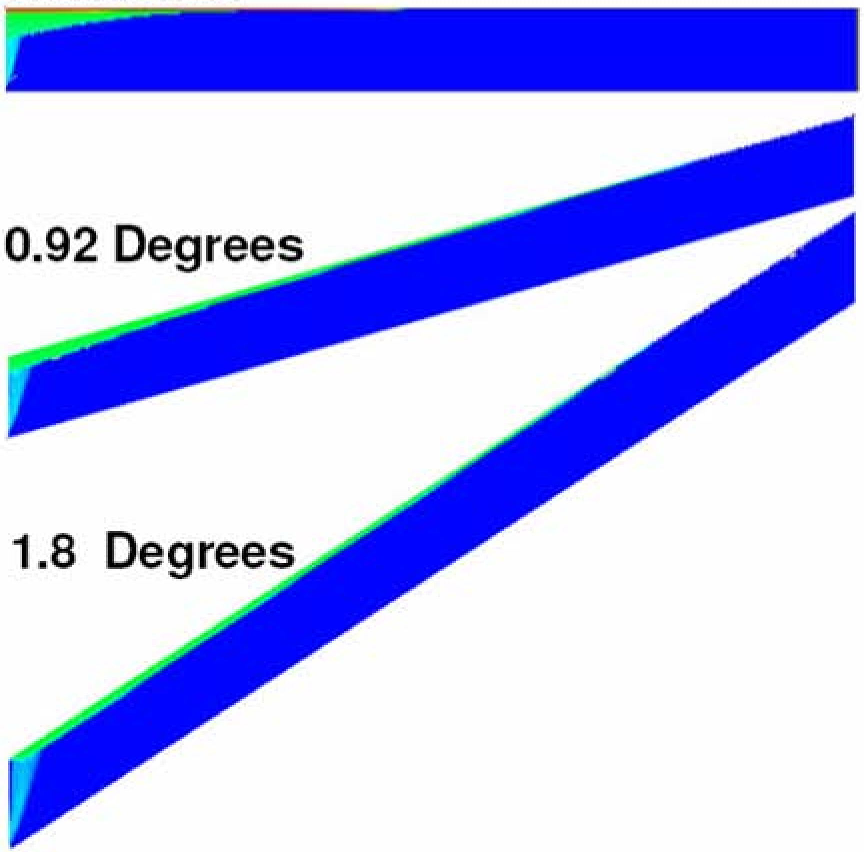


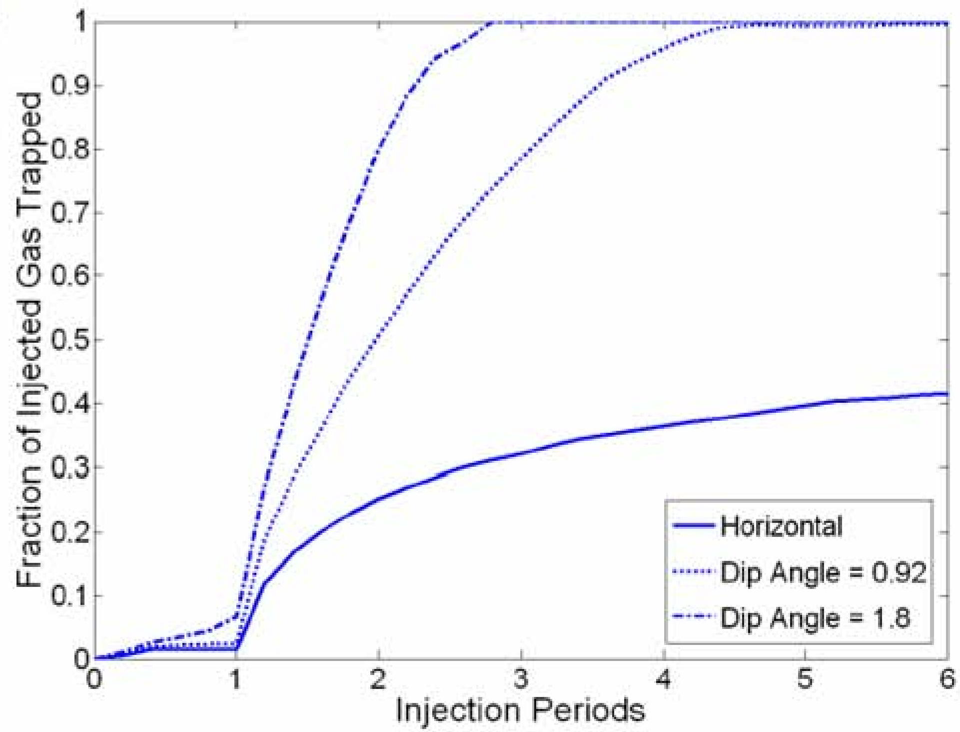
Injecting water after the CO_2 can trap part of it relatively quickly.

Small Amounts of Dip Enhance Trapping

Rel Perm Hysteresis, No P_c, N_{gv} = 55.6, Homogeneous

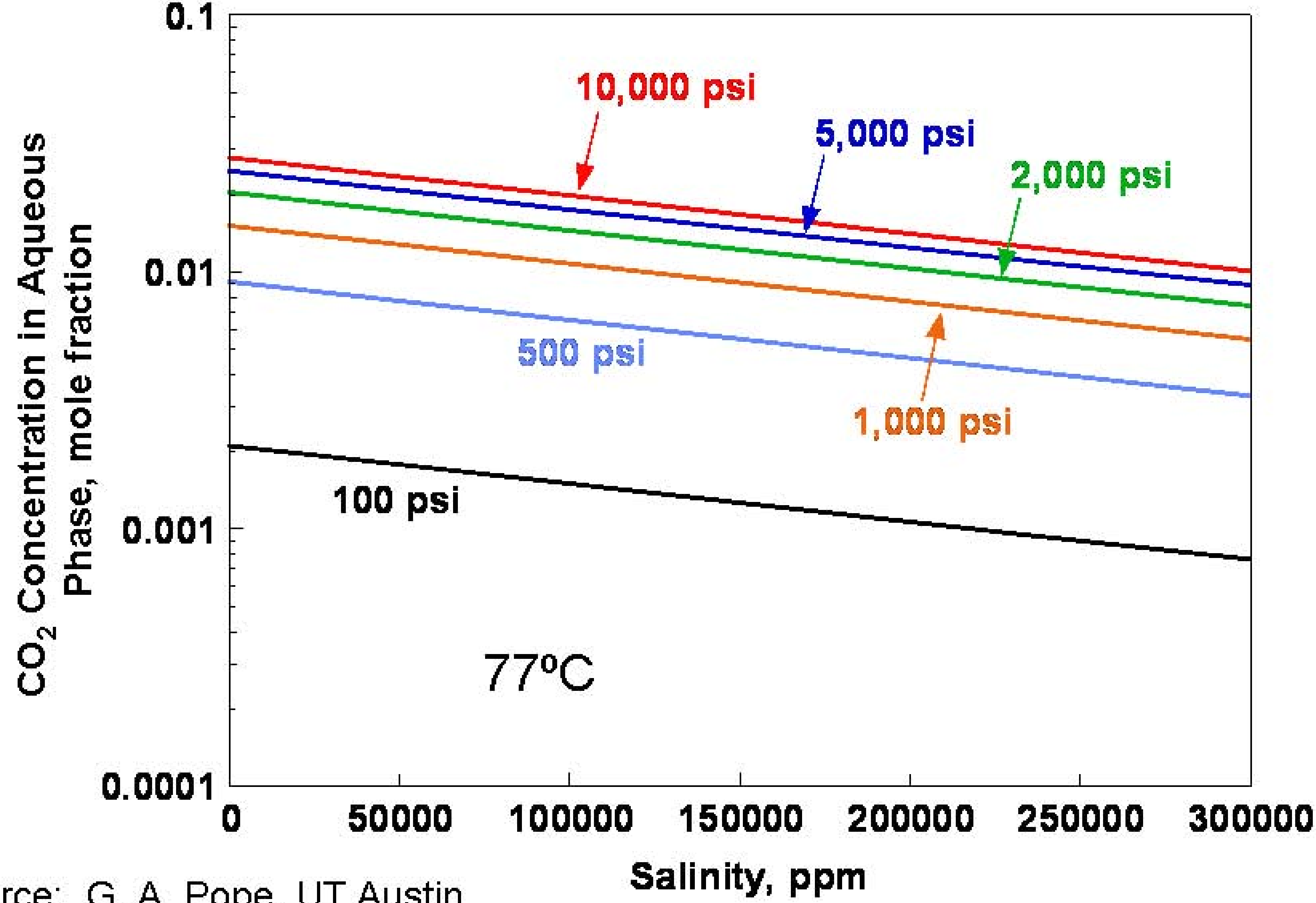
Horizontal





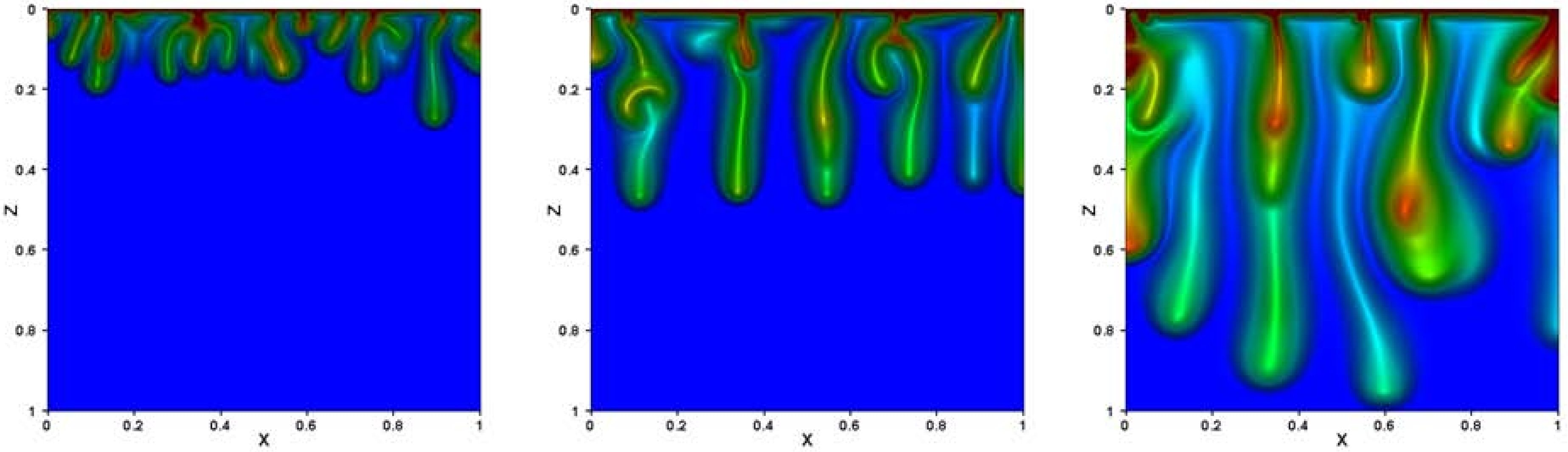
Tilting the reservoir enhances trapping efficiency (amount and rate)

Increasing brine salinity reduces CO_2 solubility in aqueous phase



Source: G. A. Pope, UT Austin

Mechanisms: dissolution of CO_2 in brine



24 years | 52 years | 108 years

- Diffusion of CO_2 into brine creates more dense brine at the upper interface.
- That configuration is unstable, and gravity-driven fingers develop (but the fingers move slowly).
- More capillary snap-off as CO_2 dissolves.

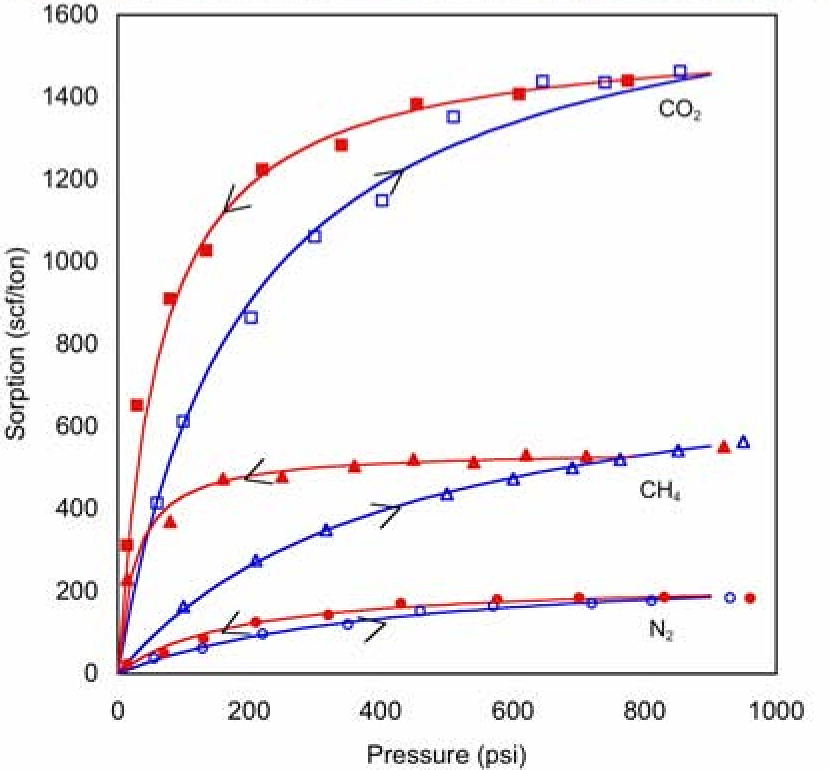
The combination of capillary trapping and dissolution immobilizes much of the injected CO_2, but not instantly.

Storage security increases with time.

Source: Riaz, Hesse, Tchelepi & Orr, J Fluid Mech 2006

Storage in Coal Beds

- Storage mechanism is adsorption of CO_2 on coal
- CO_2 adsorbs more strongly than does CH_4 or N_2
- Complex flow in fractured coals
- Adsorbed gas reduces permeability – managing permeability reduction will be essential
- Very limited field experience to date



Separation of CO_2 from N_2 with coal

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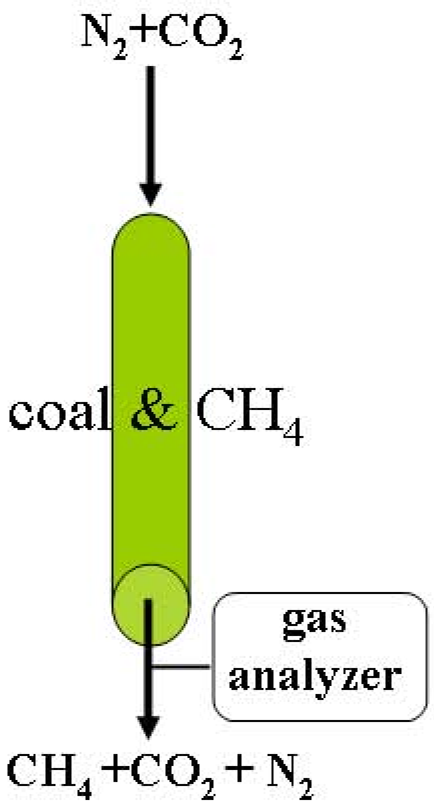
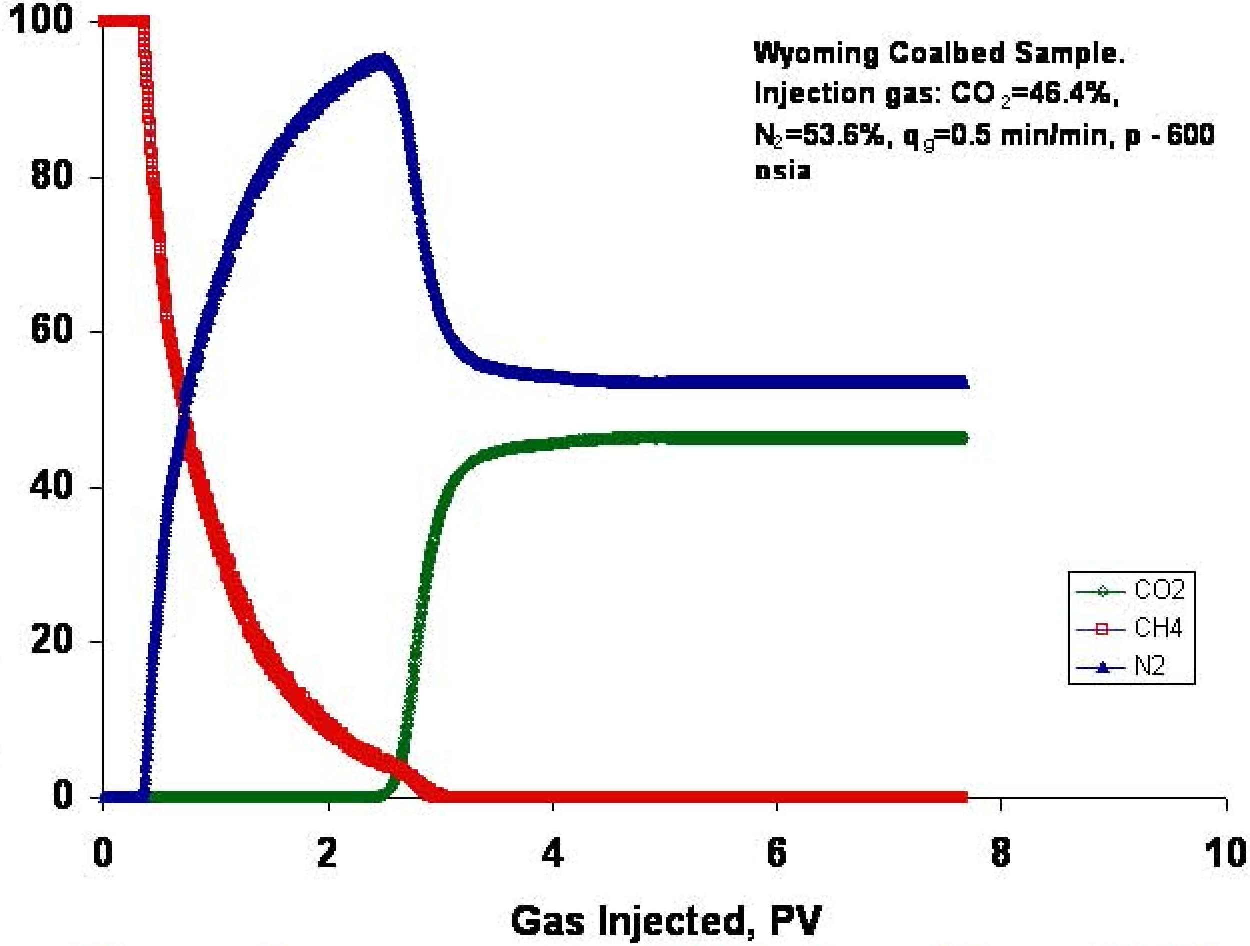
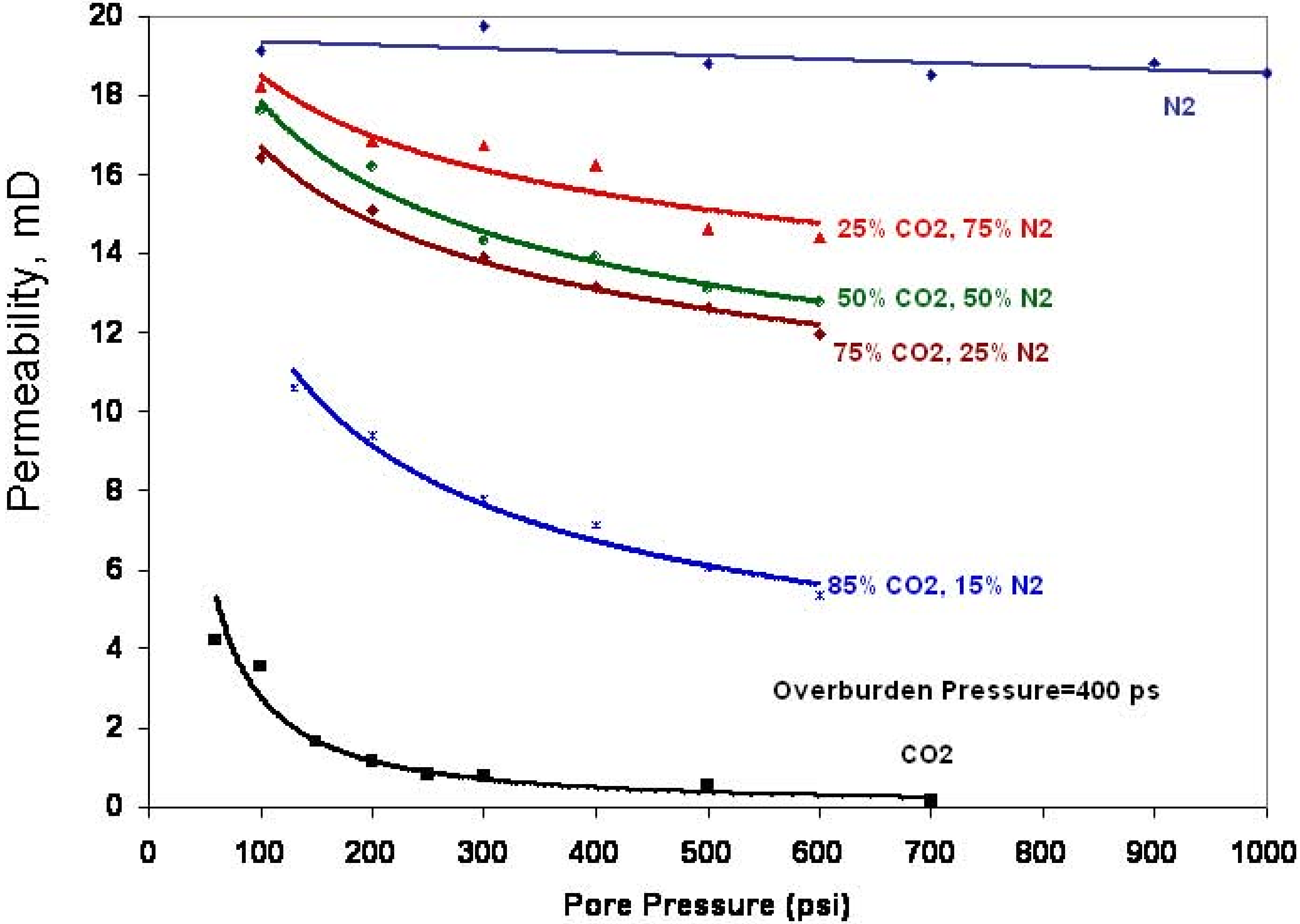




Adsorption chromatography separates CO_2 from N_2 as it flows through the coal.

Coal permeability increases as CH_4 desorbs, declines as CO_2 adsorbs



Experience: Oil and Gas Reservoirs

- Known geologic seal (otherwise the oil or gas would not be there.
- Data needed for flow prediction available from geology, producing history.
- 30+ years of experience with injection of CO_2 for enhanced oil recovery provides significant practical experience.

Figure 3. Existing CO_2 Pipelines and Sources in the Permian Basin

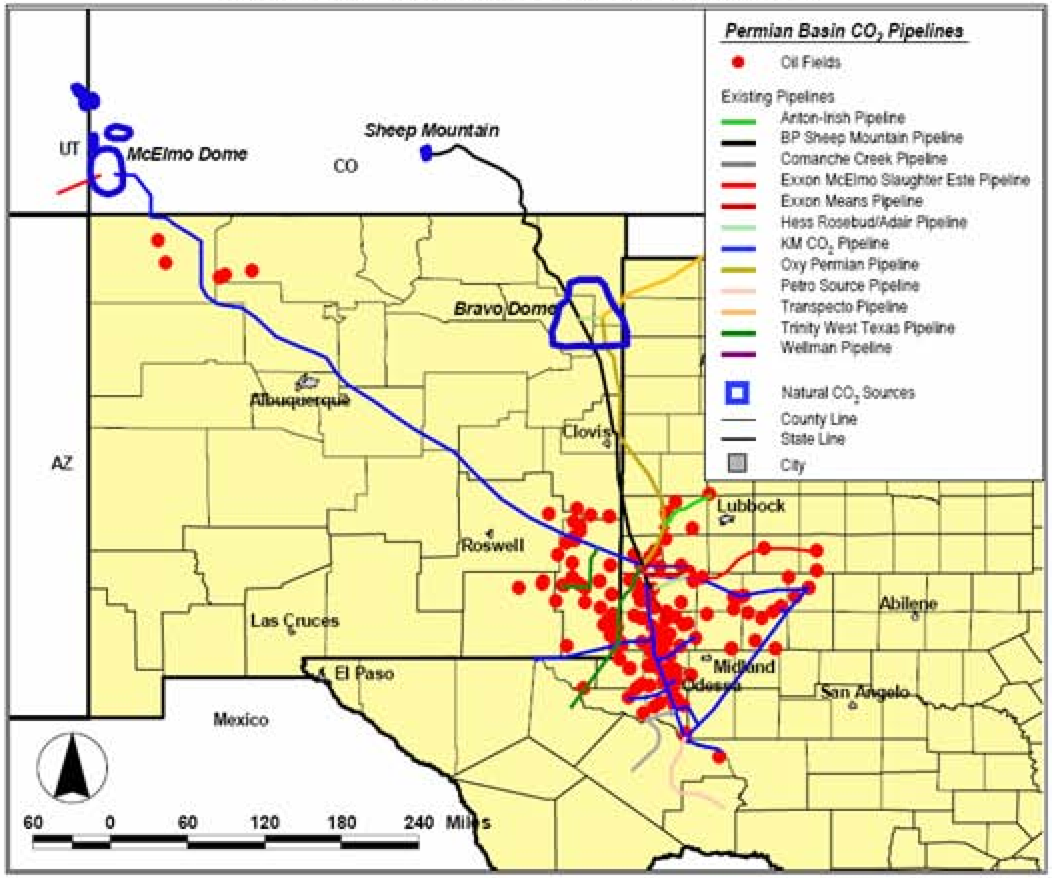
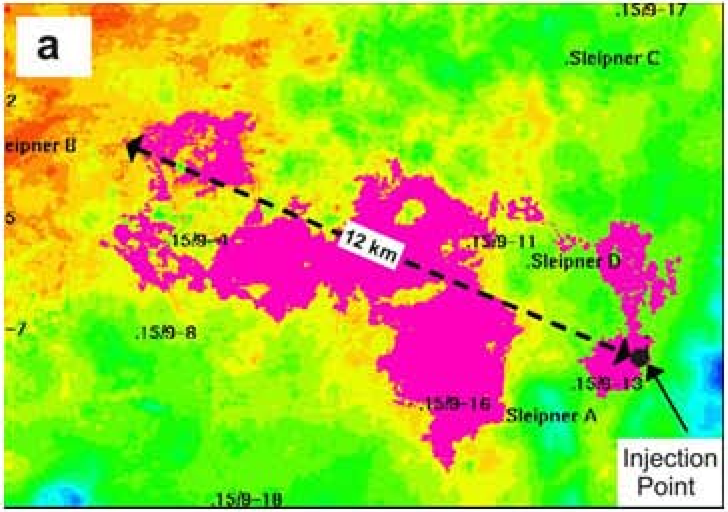
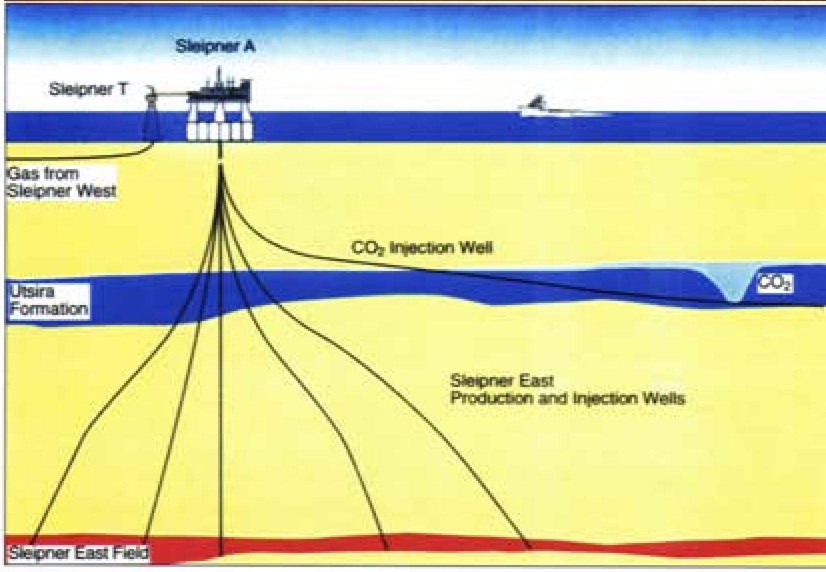


Image: DOE Basin Oriented Studies for EOR, Permian Basin, 2006

Experience: aquifer injection in the North Sea

- Sleipner West: 1 million tonnes/yr injection.
- CO_2 separated from produced gas.
- About 10 million tonnes injected so far.
- CO_2 has been retained well in the target formation.





San Juan Basin CO_2 Injection Test

One project has been performed in the US, others underway in Europe, Japan.

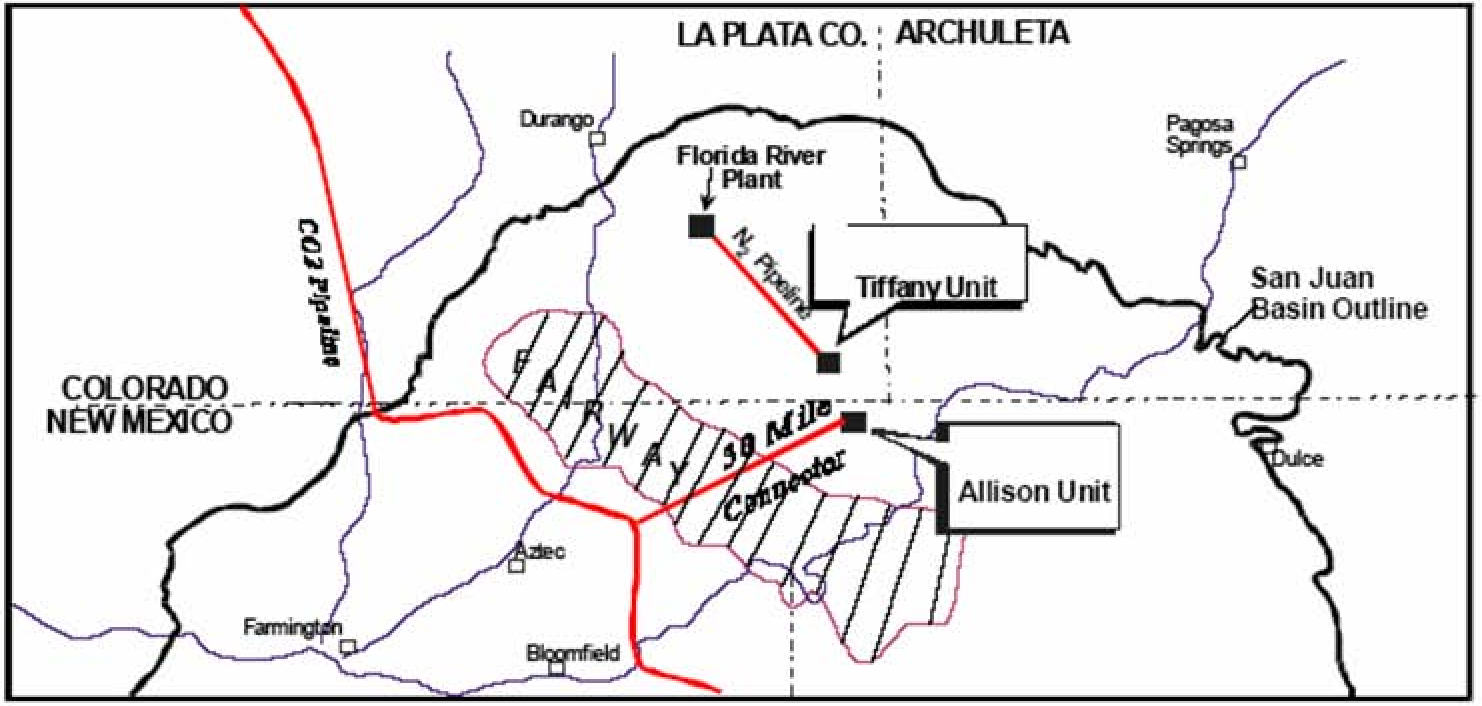
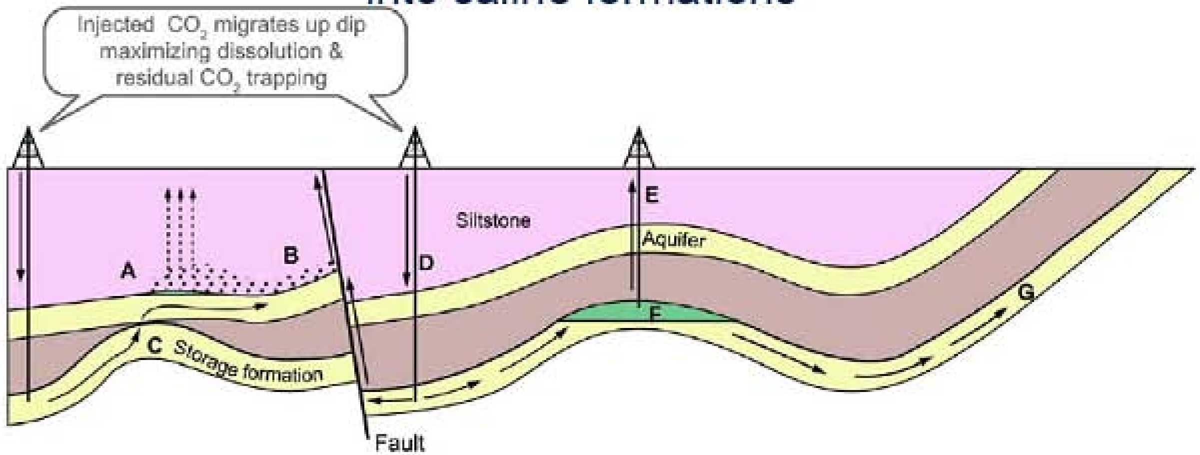


Figure 2: Location of the Allison Unit, San Juan Basin

Source: Reeves, US DOE DE-FC26-00NT40924, Feb 2003

Potential for leakage?

Potential leakage routes and remediation techniques for CO2 injected into saline formations



Potential Escape Mechanisms

A. CO_2 gas pressure exceeds capillary pressure & passes through siltstone	**B.** Free CO_2 leaks from A into upper aquifer up fault	**C.** CO_2 escapes through 'gap' in cap rock into higher aquifer	**D.** Injected CO_2 migrates up dip, increases reservoir pressure & permeability of fault	**E.** CO_2 escapes via poorly plugged old abandoned well	**F.** Natural flow dissolves CO_2 at CO_2 / water interface & transports it out of closure	**G.** Dissolved CO_2 escapes to atmosphere or ocean

Remedial Measures

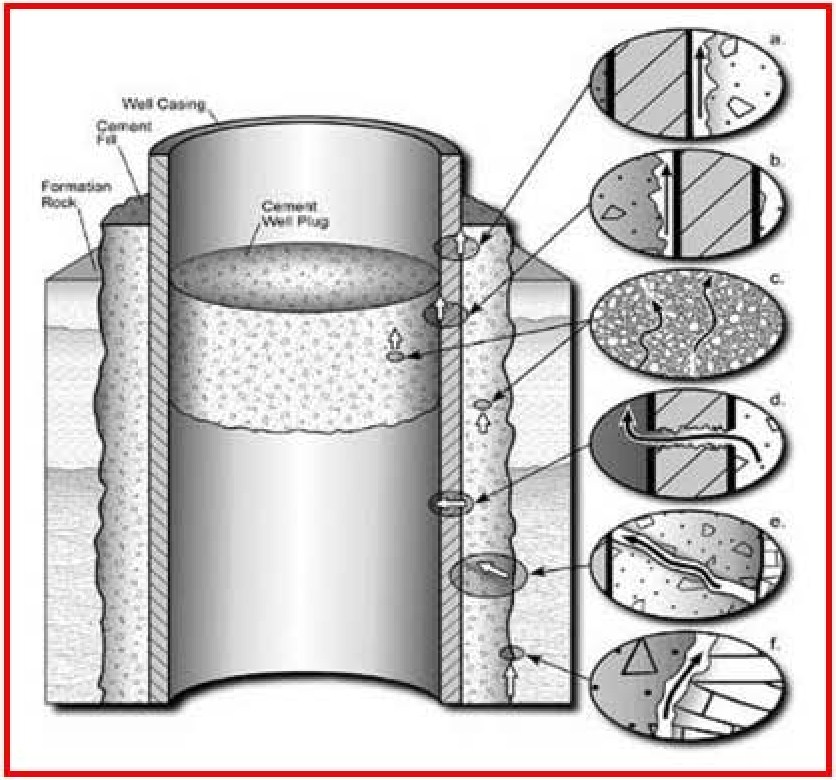
***A.** Extract & purify ground-water*	***B.** Extract & purify ground-water*	***C.** Remove CO_2 & reinject elsewhere*	***D.** Lower injection rates or pressures*	***E.** Re-plug well with cement*	***F.** Intercept & reinject CO_2*	***G.** Intercept & reinject CO_2*

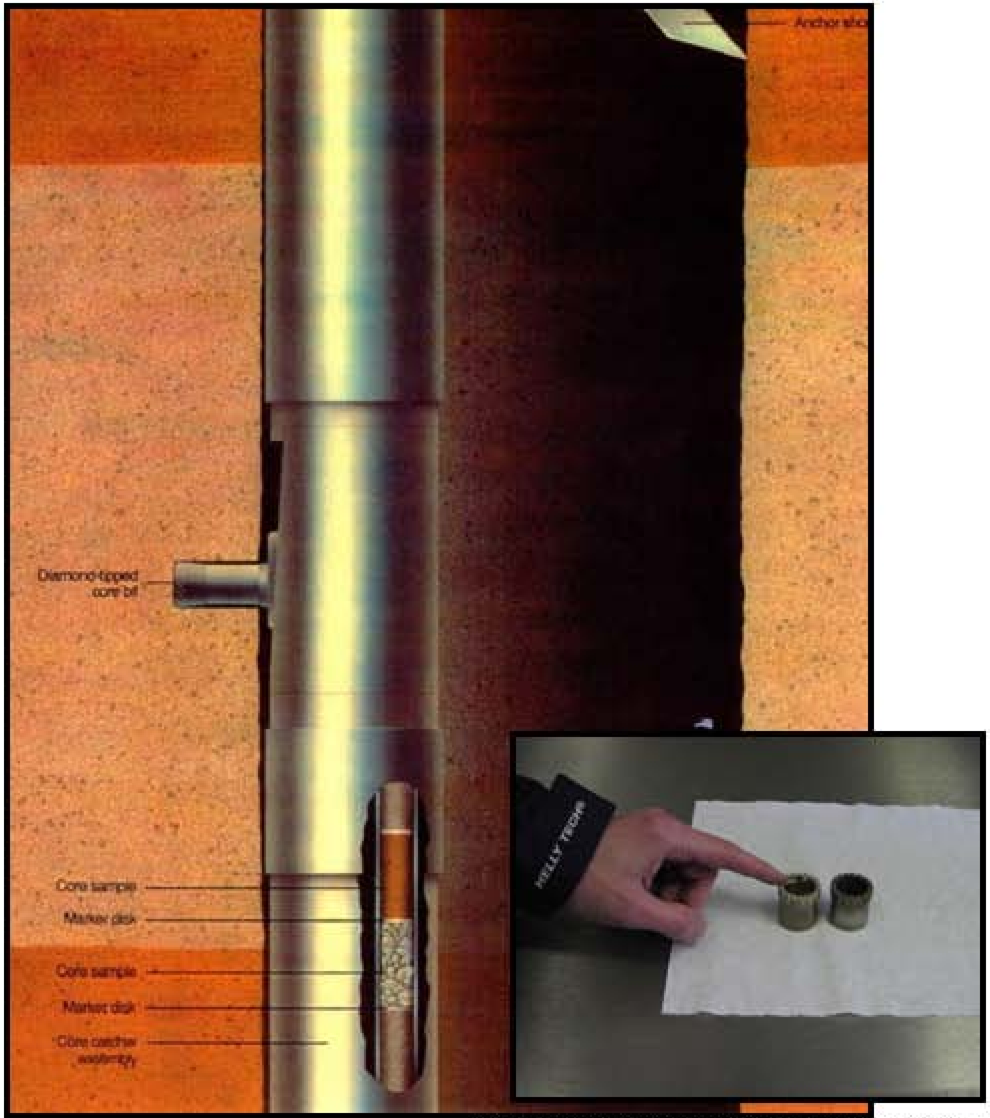
Careful site selection, good injection design, careful operation will be required.

Source: IPCC Special Report Carbon Capture & Storage, 2006

Well-bore integrity is the most important risk issue

Cements used to seal wells are subject to attack by low pH brine. Poorly plugged wells that have been abandoned could also provide leak pathways.





Source: J. Friedmann, LLNL *After Gasda et al., 2004* *Princeton Environmental Institute*

Estimated Costs for Geologic Storage (2002 $/tonne)

- Onshore saline aquifers:
  - Australia $0.2 – 5.0
  - Europe $1.9 – 6.2
  - USA $0.4 – 4.5
- Offshore saline aquifers
  - Australia $0.5 – 30.2
  - North Sea $4.7 – 12
- Depleted Oil Fields
  - USA $0.5 – 4
- Depleted Gas Fields
  - USA $0.5 – 12.2
- Enhanced Oil Recovery
  - USA $-92 – 66.7
    (depends strongly on oil price)
- Enhanced Coalbed CH_4:
  - Australia $-20 – 150
    (depends strongly on gas price)

There is considerable uncertainty in the cost estimates – but storage at costs well below the cost of CO_2 separation appears possible at significant scale

Source: IPCC Special Report on CCS, 2005

Reality check: the volumes are very large!

- At a CO_2 density of 500 kg/m^3 (1000 m depth at 50°C), injection of 1 billion tonnes/yr of CO_2 is equivalent to ~ 35 million barrels/day.
- At a CO_2 density of 700 kg/m^3, 1 Gt CO_2 is equivalent to ~ 25 million barrels/day.
- Worldwide emissions of CO_2, ~ 25 Gt/yr:
  ~ 625 – 825 million barrels/day!
- World oil production is currently ~85 million barrels/day.
- These volumes are large enough that it is clear that CO_2 storage in geologic formations will be but one of a variety of ways to reduce CO_2 emissions to the atmosphere.

CO_2 Storage – Underway or Proposed

Source: Peter Cook, CO2CRC

Do we know enough to undertake large-scale geologic storage?

- Can we capture the CO_2? Yes, though cost is an issue.
- Do we have enough variety of potential geologic settings for storage? Yes, in the US, at least.
- Is there sufficient volume available in the subsurface to store enough CO_2 to have an impact? Yes.
- Do we know enough about the physical mechanisms that will trap the CO_2 in the subsurface to design safe storage projects that won't leak? Yes for oil and gas, better quantification needed for aquifers, no for coal storage.
- Do we have enough experience with actual operations to undertake storage at scale? Yes for oil and gas, not yet but beginning for aquifers, no for coal beds.

Conclusions

- In this century, we humans need to demonstrate that we can learn to live on this planet in a way that protects its essential systems.
- Energy is one of the prime ways we interact with planetary systems.
- Building our capability to limit the impact, carbon and otherwise, is just the sort of challenge we should all tackle!
- This is just the sort of challenge students and faculty at Caltech should tackle, so let's get to work!