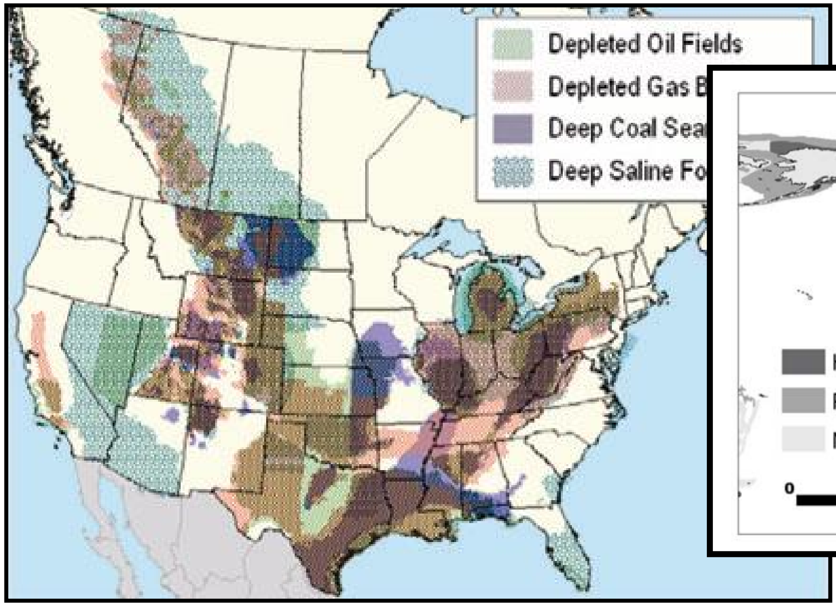
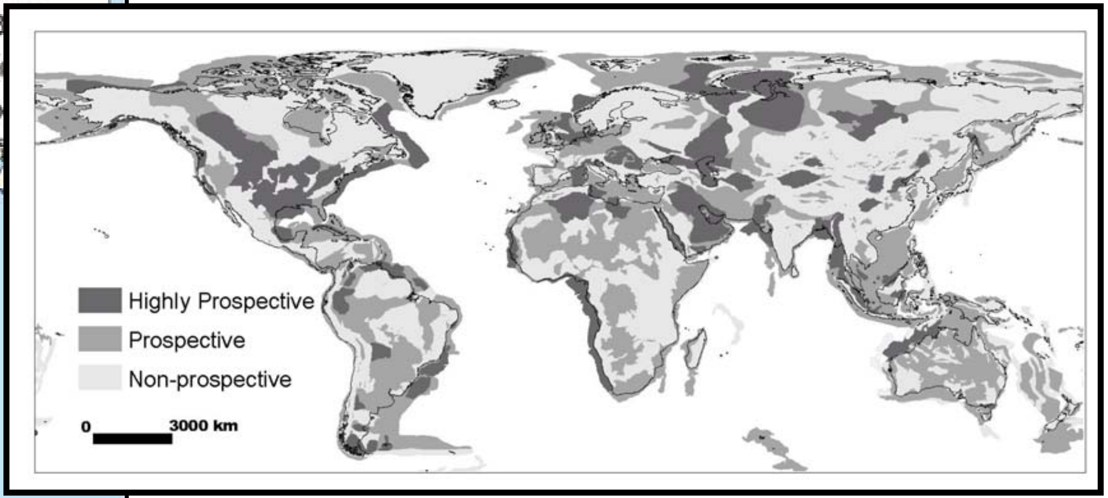
Overview of Carbon Capture & Sequestration

Current status, critical gaps, and recommendations for deployment





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Conclusions

Current knowledge strongly supports carbon sequestration as a successful technology to dramatically reduce CO2 emissions.

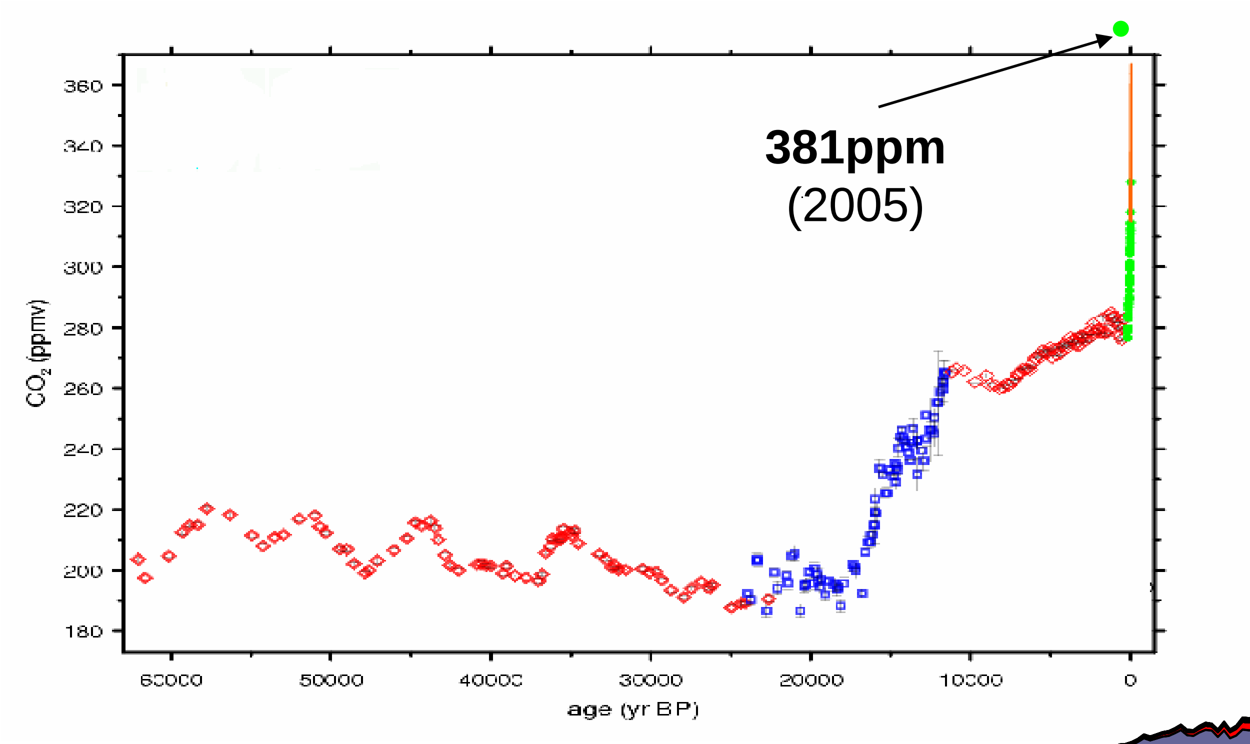
Current science and technology gaps appear resolvable

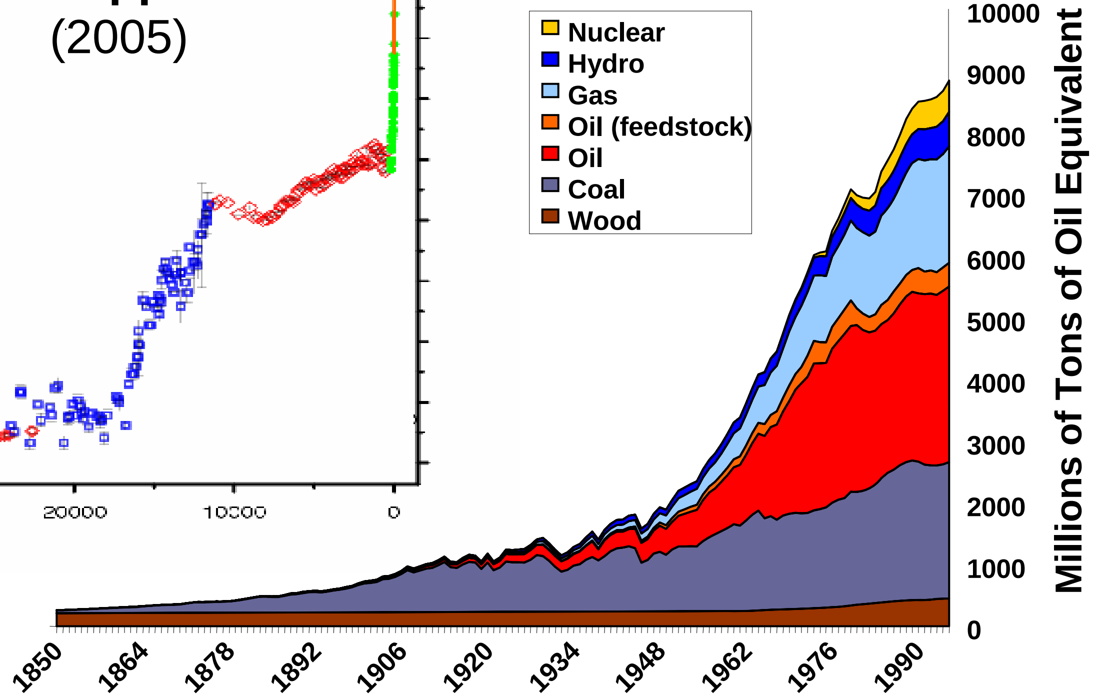
Deployment issues, including regulatory, legal, and operational concerns, can be addressed through development of operational protocols advised by science

LARGE SCALE tests are crucial to understanding successful deployment of carbon capture and sequestration (CCS) and creating appropriate policy/economic structures.

No test active to date is sufficient with respect to scale, duration, monitoring, and analysis.

The dominant energy trends are increased fuel use and increased CO_2 emissions

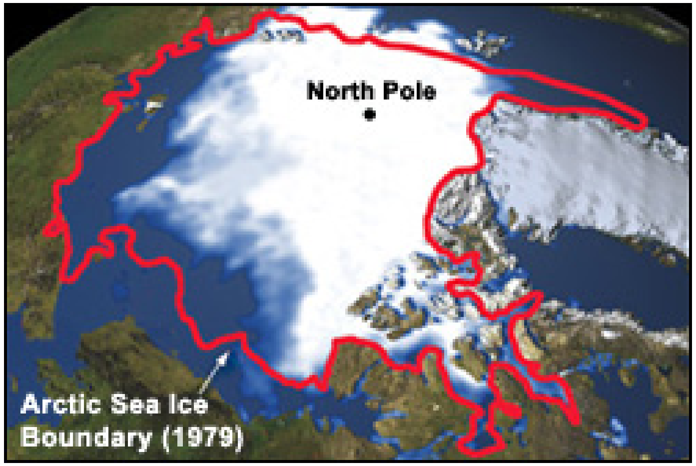




The Times They Are a-Changing…

Climate Science: Greater sureness, broader consensus

- Clearer delineation of traditional risks (e.g., Greenland ice sheet)
- Greater willingness to quantify attribution
- New studies on satellite data
- New risks (e.g., ocean acidification)



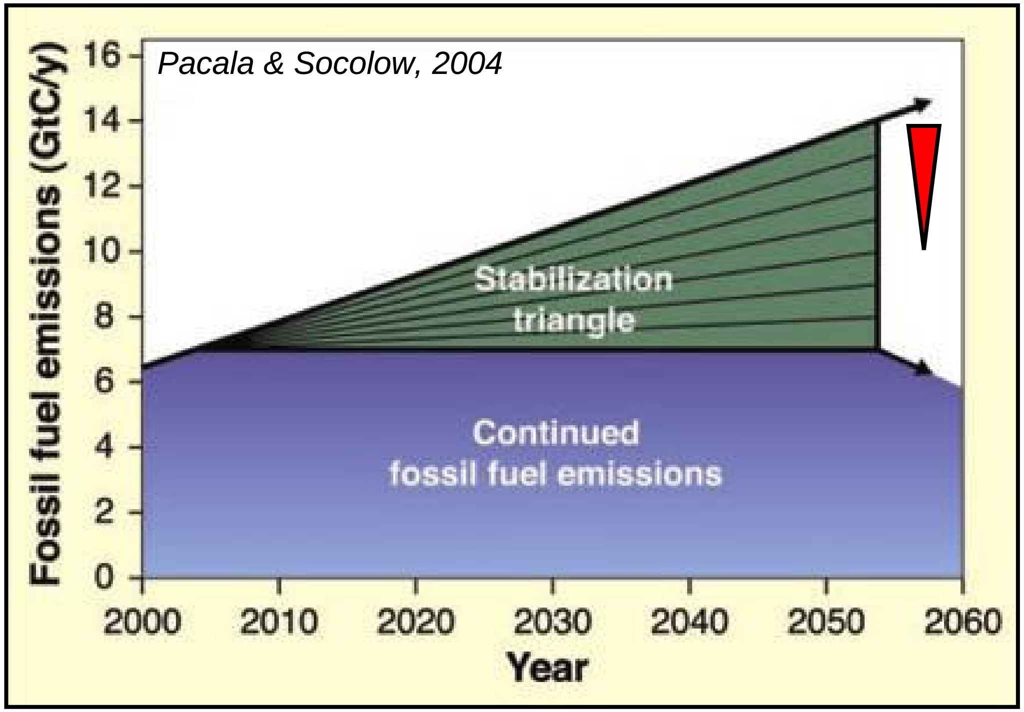
Major Policy Shifts:

- Kyoto in force; Bush acknowledges signal
- State actions (CA, RGGI); WGA
- CA: SB1368, AB32
- Sense of the Senate resolution; Title XVI of EPA2005
- New Asian-Pacific Partnership

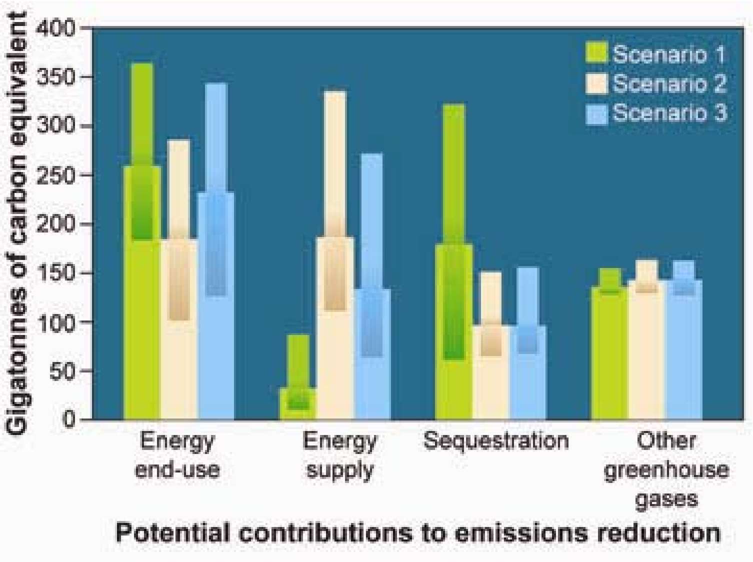
Major Industrial Changes and Actions:

- BP's new decarbonized fuels business unit
- GE's major effort (Ecomagination)
- Major generating, energy, coal companies
- Emerging CO_2 markets
- Insurance and financial companies engaged

CO_2 Capture & Storage (CCS) represents an attractive pathway to substantial GHG reductions

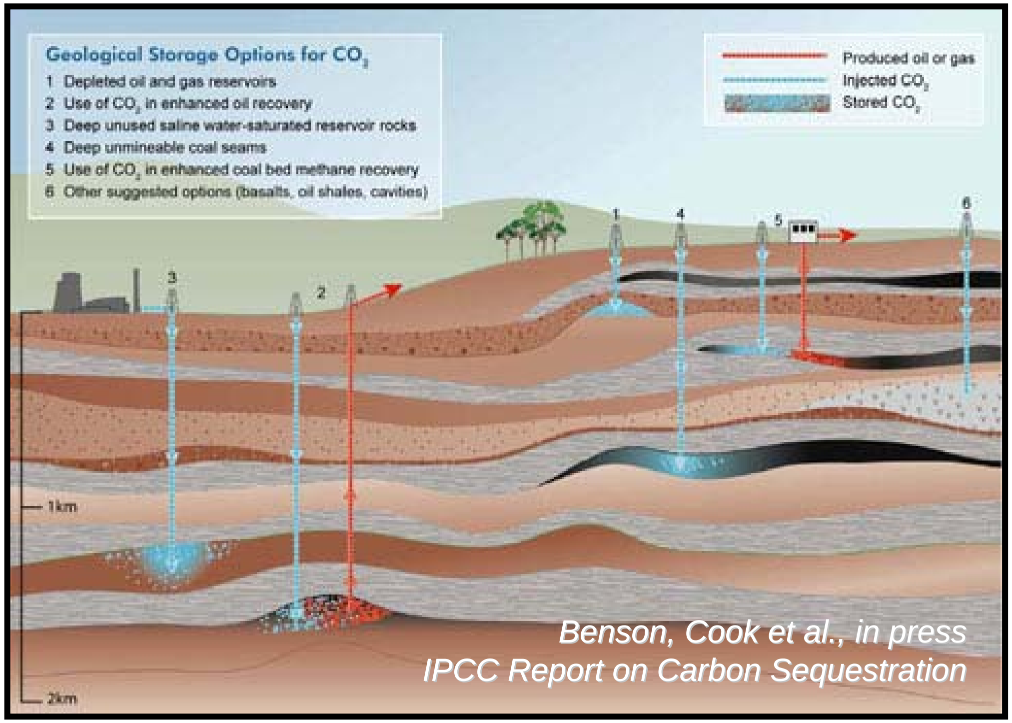


- A key portfolio component (with efficiency, conservation, renewables)
- Cost competitive to other carbon-free options (e.g., wind, nuclear)
- Uses existing technology



CCS appears at once an ACTIONABLE, SCALEABLE, RELATIVELY CHEAP, BRIDGING TECHNOLOGY

Carbon dioxide can be stored in several geological targets, usually as a supercritical phase



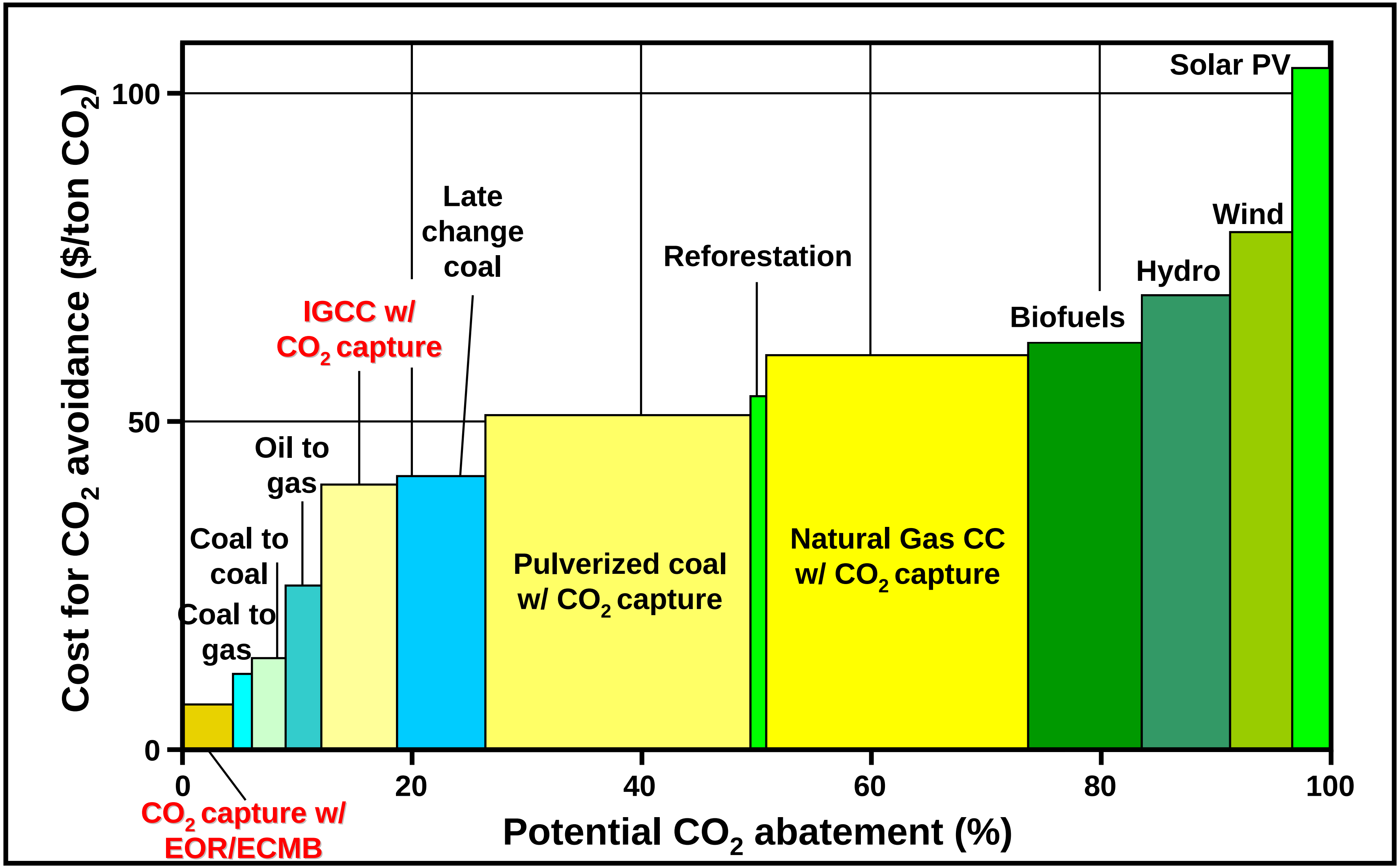
Benson, Cook et al., in press
IPCC Report on Carbon Sequestration

Saline Aquifers
Depleted Oil & Gas fields
(w/ or w/o EOR and EGR)
Unmineable Coal Seams
(w/ or w/o ECBM)
Other options
(e.g., oil shales, basalts)

The storage mechanisms vary by reservoir type

EOR/Depleted Oil & Gas fields are early actors
Saline aquifers hold the largest storage capacity
There is both overlap and distinctiveness between them

CCS Costs today appear competitive



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Adapted from Lars Stromberg, Vattenfall AB, Electricity Generation, Sweden, 2001; SPA Pacific

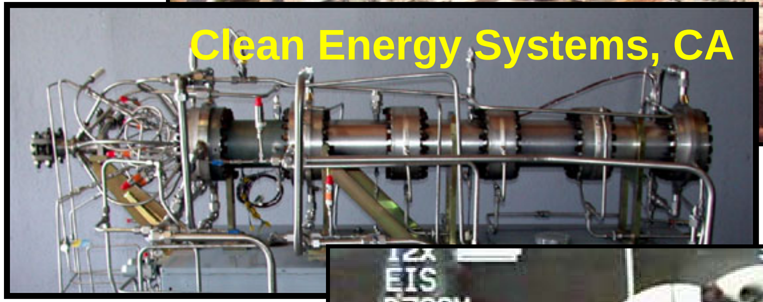
High purity (>95%) CO_2 streams are required for storage

Mostly natural sources (e.g., CO_2 domes)

Capture devices on standard existing plants (e.g., PC) are relatively high in cost.

Refineries, fertilizer & ethanol plants, polygeneration, cement plants, and gas processing facilities are cheapest.

Typical PC plant	**\$40-60/t CO_2**
Typical gasified plant	**\$30-40/t CO_2**
Oxyfired combustion	**\$30-40/t CO_2***
Low-cost opportunities	**\$ 5-10/t CO_2**



At present, all three approaches to carbon capture and separation appear equally viable

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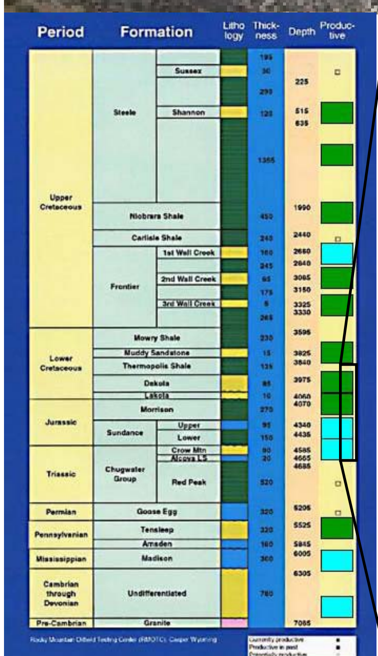
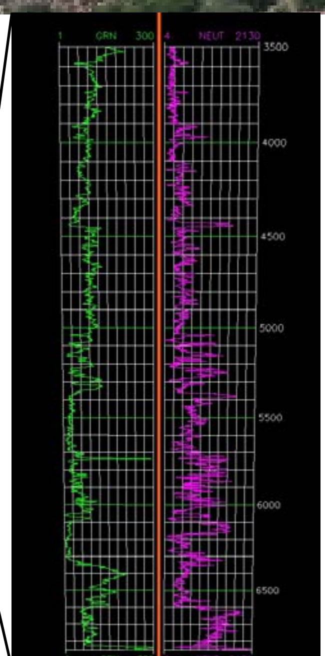
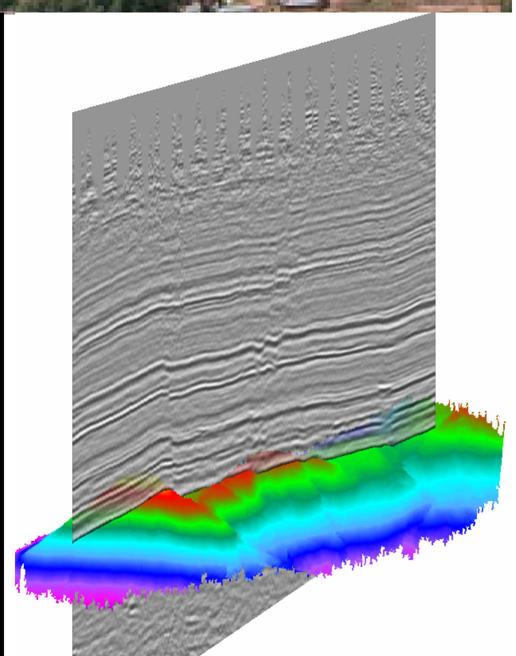
** Not yet ready for prime time*

Storage mechanisms: physical

It's not rocket science – it's rock science



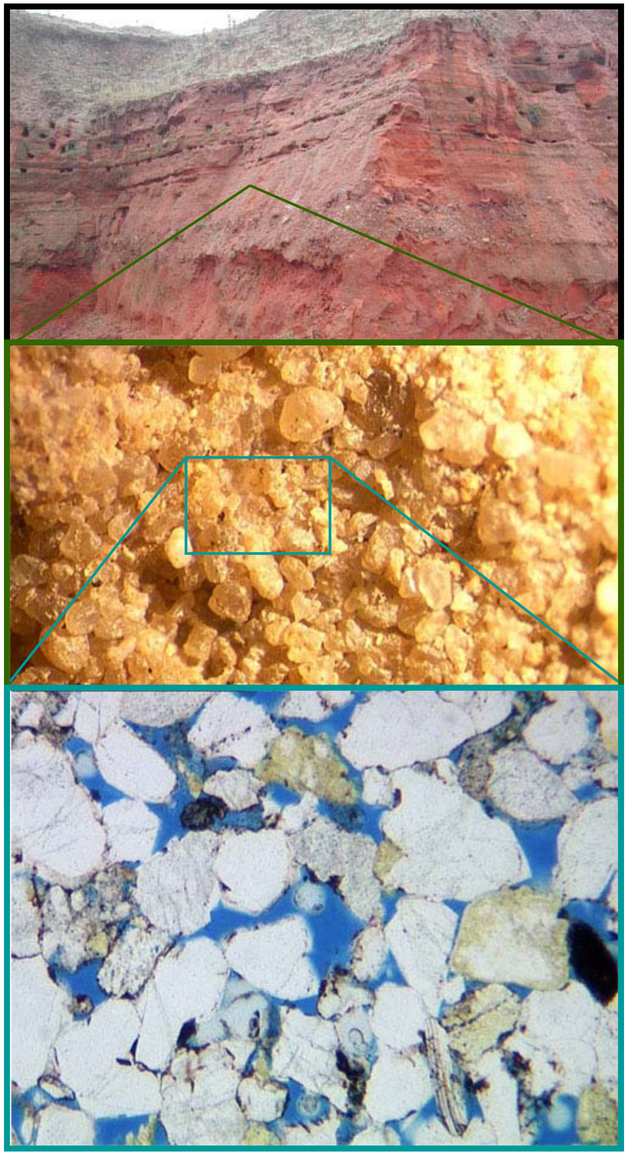


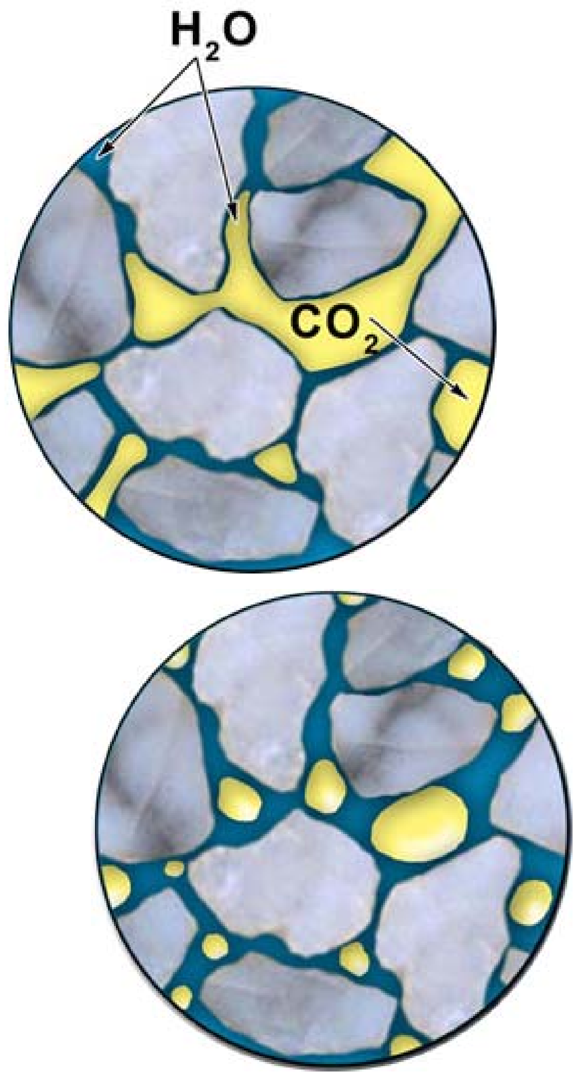


Supercritical CO_2 I buoyant, and will flow to the surface without a physical barrier. This commonly has a geometric component (e.g., 4-way closure) and a physical component.

For all relevant cases, this involves an impermeable unit above the injection zone. This mechanism is effective unless the physical barrier is breached (e.g., faults, wells)

Storage mechanisms: residual trapping

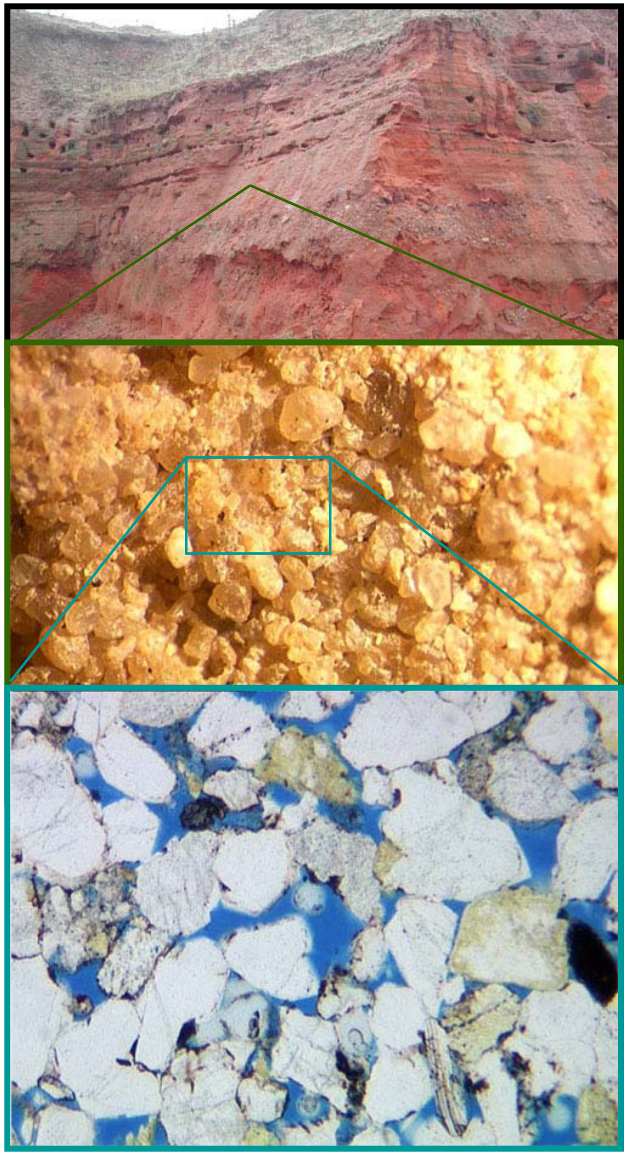


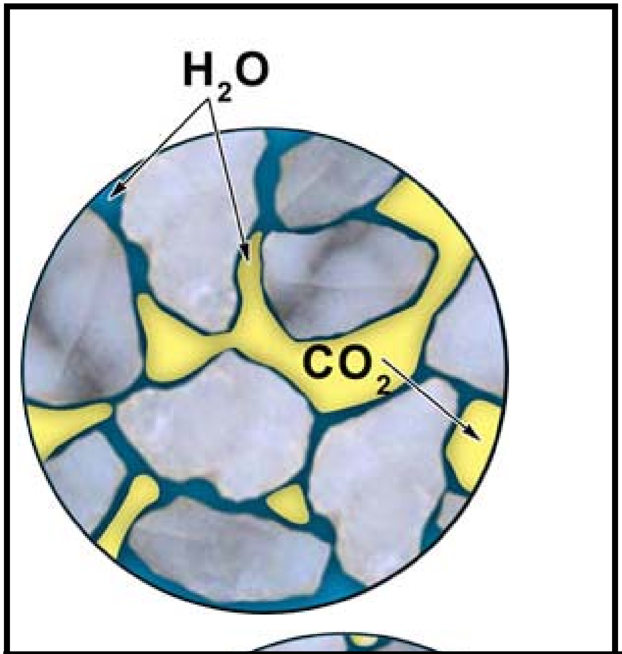


At high pore saturations, CO_2 is mobile and can move as a supercritical phase. At low saturations, CO_2 is trapped by the capillary forces, and will only move by intervention.

In general, one can only determine the residual saturation experimentally. For reservoirs of interest, roughly 10-25% of the CO_2 could be fixed as a residual phase.

Storage mechanisms: residual trapping





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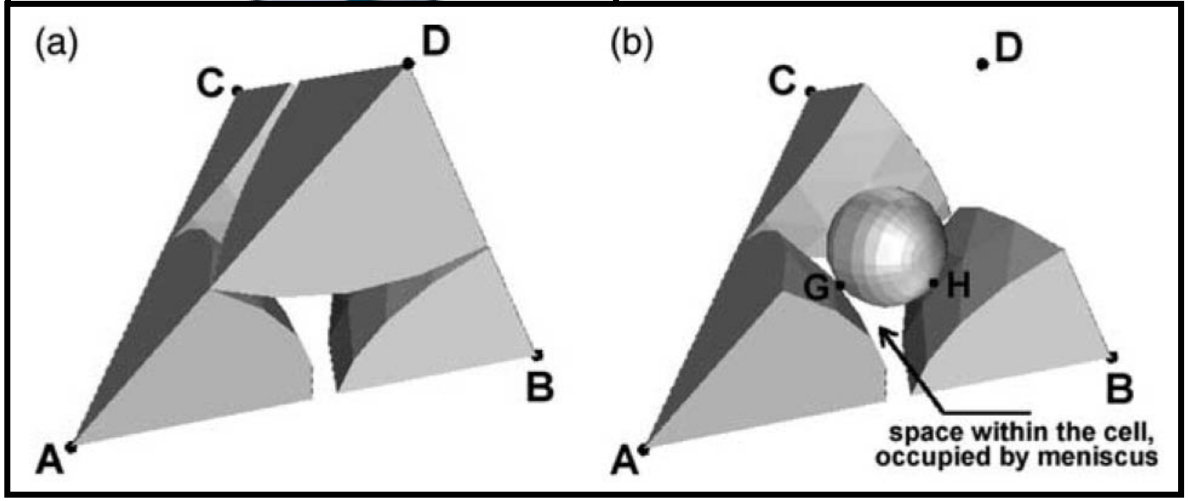
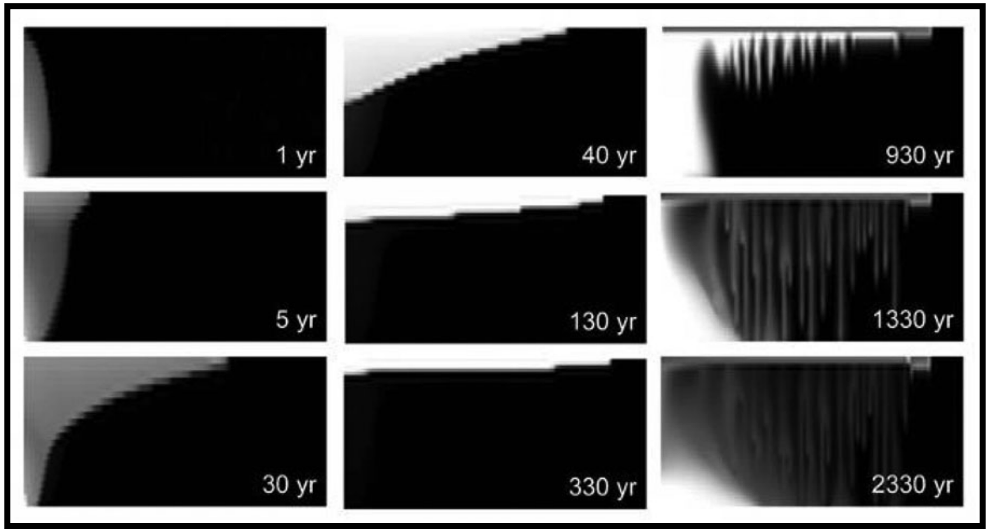
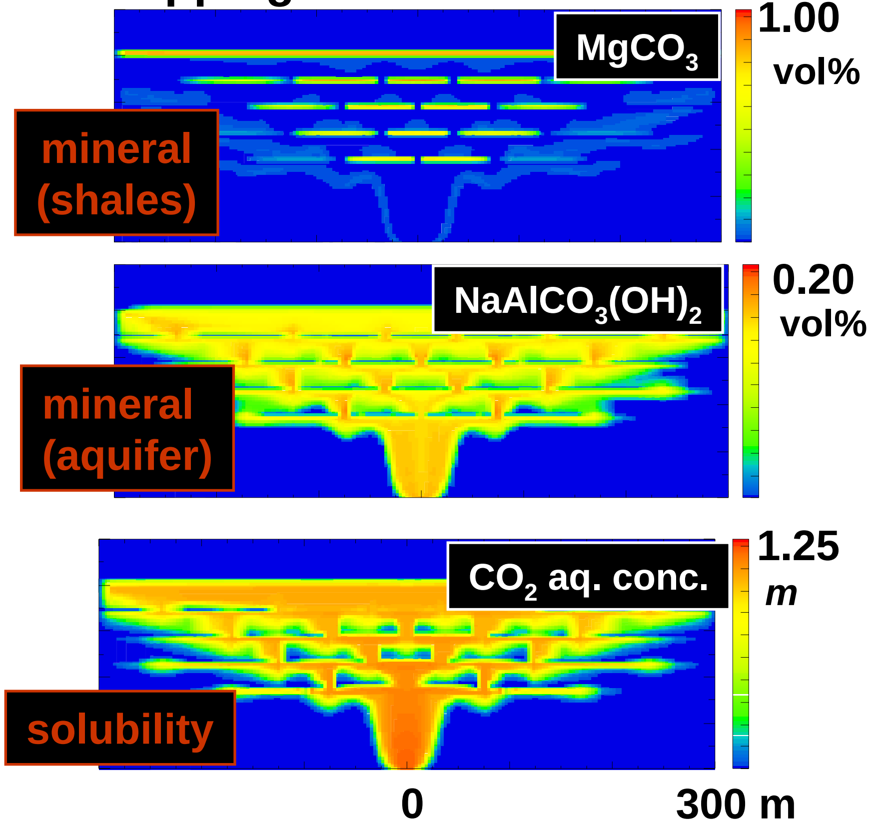


Storage mechanisms: dissolution/mineralization and permanence



Over time, the CO_2 will dissolve into the brine & hydrocarbons. The brine fraction becomes dense, which may set up convection cells

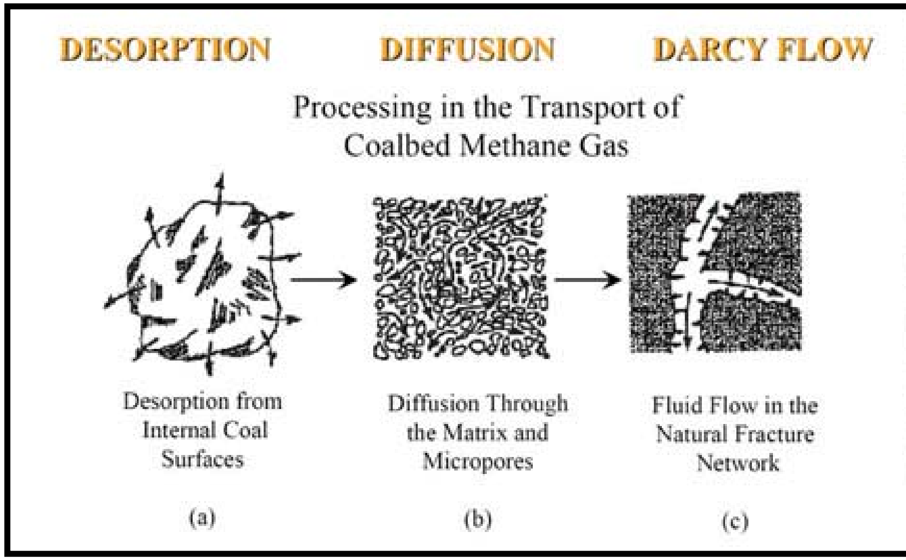
Trapping mechanisms



The dissolved fraction becomes carbonic acid, liberating bicarbonate ion. This can react with free radicals and minerals to dissolve and precipitate minerals. In many circumstances, carbonate minerals will precipitate, fixing CO_2 permanently.

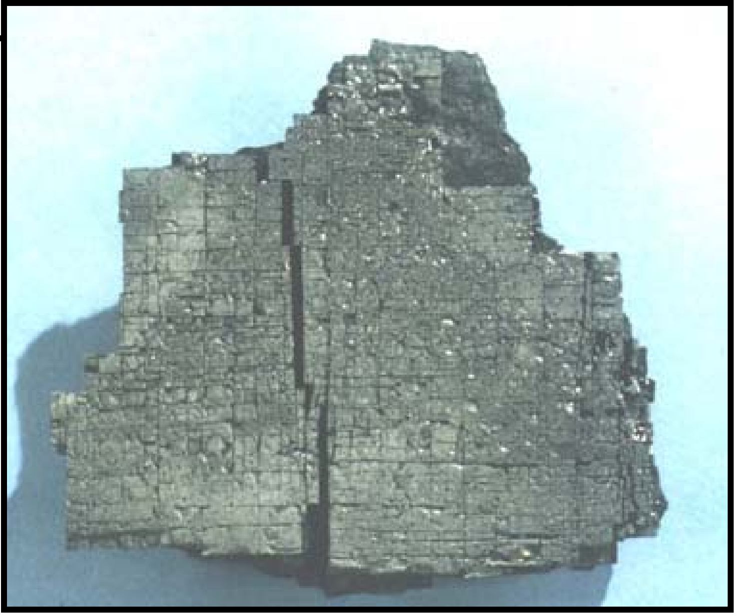
Both dissolved & mineralized CO_2 are permanently fixed.

Storage mechanisms: coals

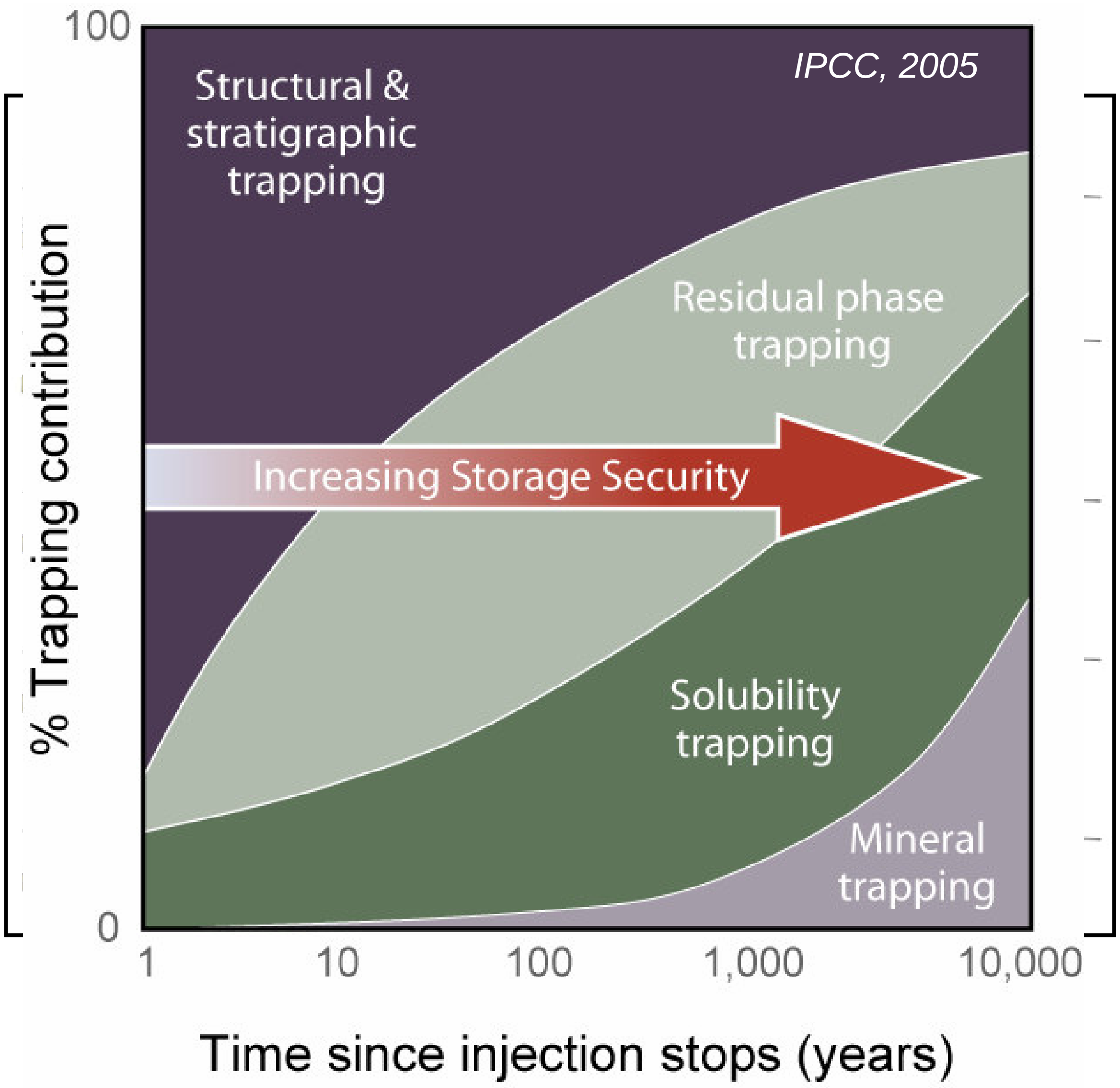


Coal storage (and ECBM) are fundamentally different. Here, CO_2 adsorbs to the organic mineral surface. In doing so, it may liberate CH_4 at ~2:1. The CO_2 is not mobile and does not need to be supercritical.

Coals are low-permeability rocks, and the effective capacity will be a function of cleat geometry. ***This is NOT ready for prime time***



The crust is well configured to trap large CO2 volumes indefinitely

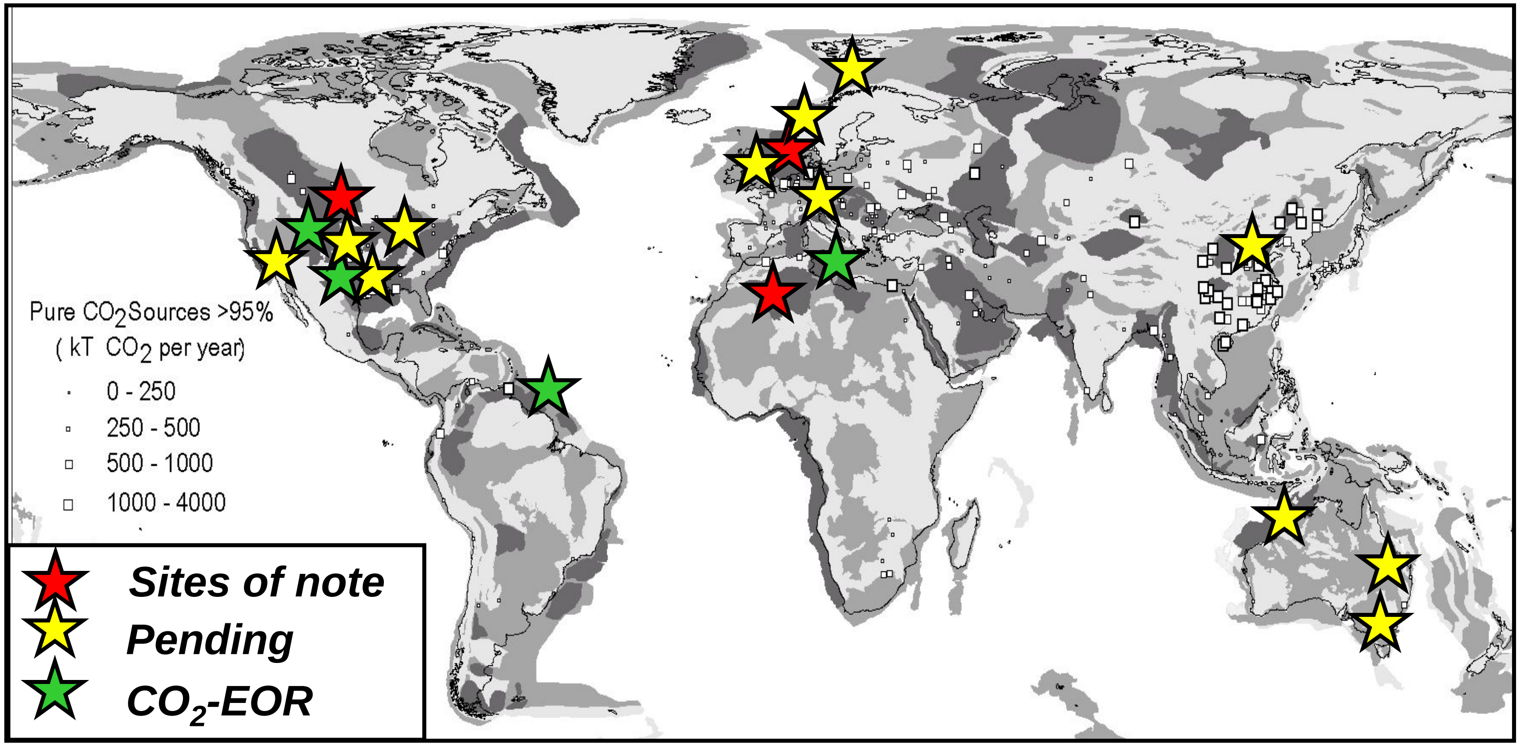


Because of multiple storage mechanisms working at multiple length and time scale, the shallow crust should attenuate mobile free-phase CO_2 plumes, trap them residually, & ultimately dissolve them

This means that over time risk decreases and permanence increases

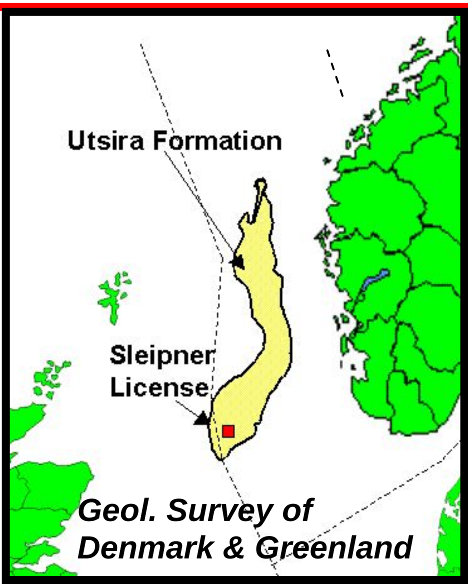
Several large projects exist, with many pending

The projects demonstrate the high chance of success for CCS



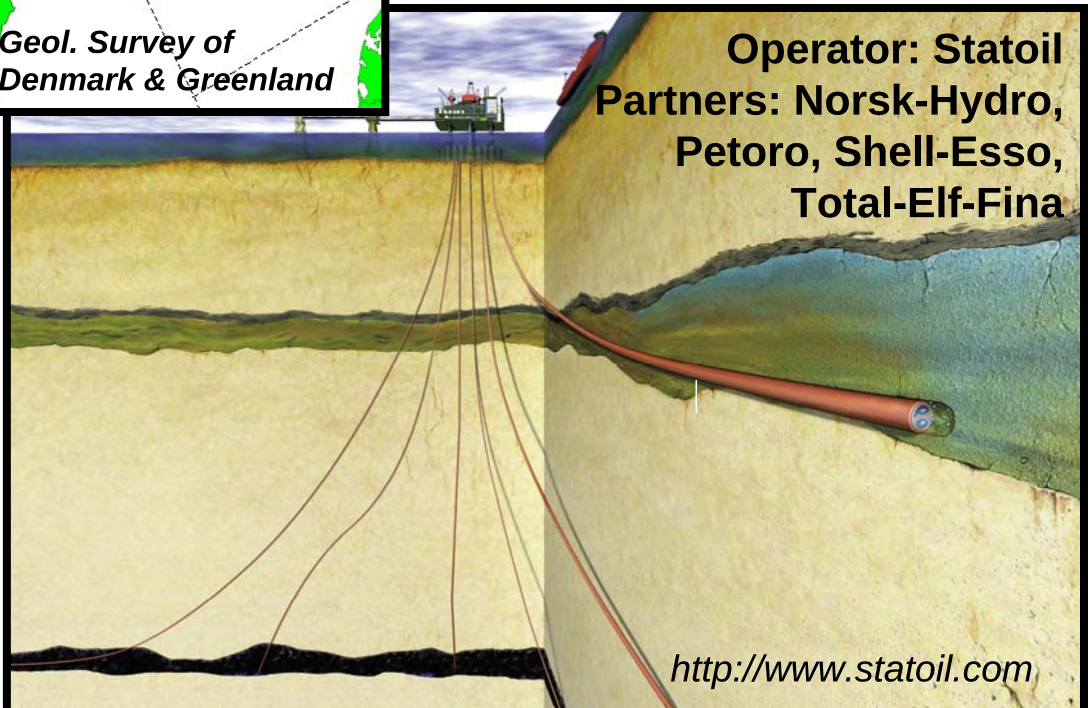
These studies are still not sufficient to provide answers to all key technical questions or to create a regulatory structure

Sleipner Vest project demonstrates 1st order viability of commercial storage



FIRST major attempt an large volume CO_2 sequestration, offshore Norway. Active since 1996. Monoethanolamine (MEA) capture

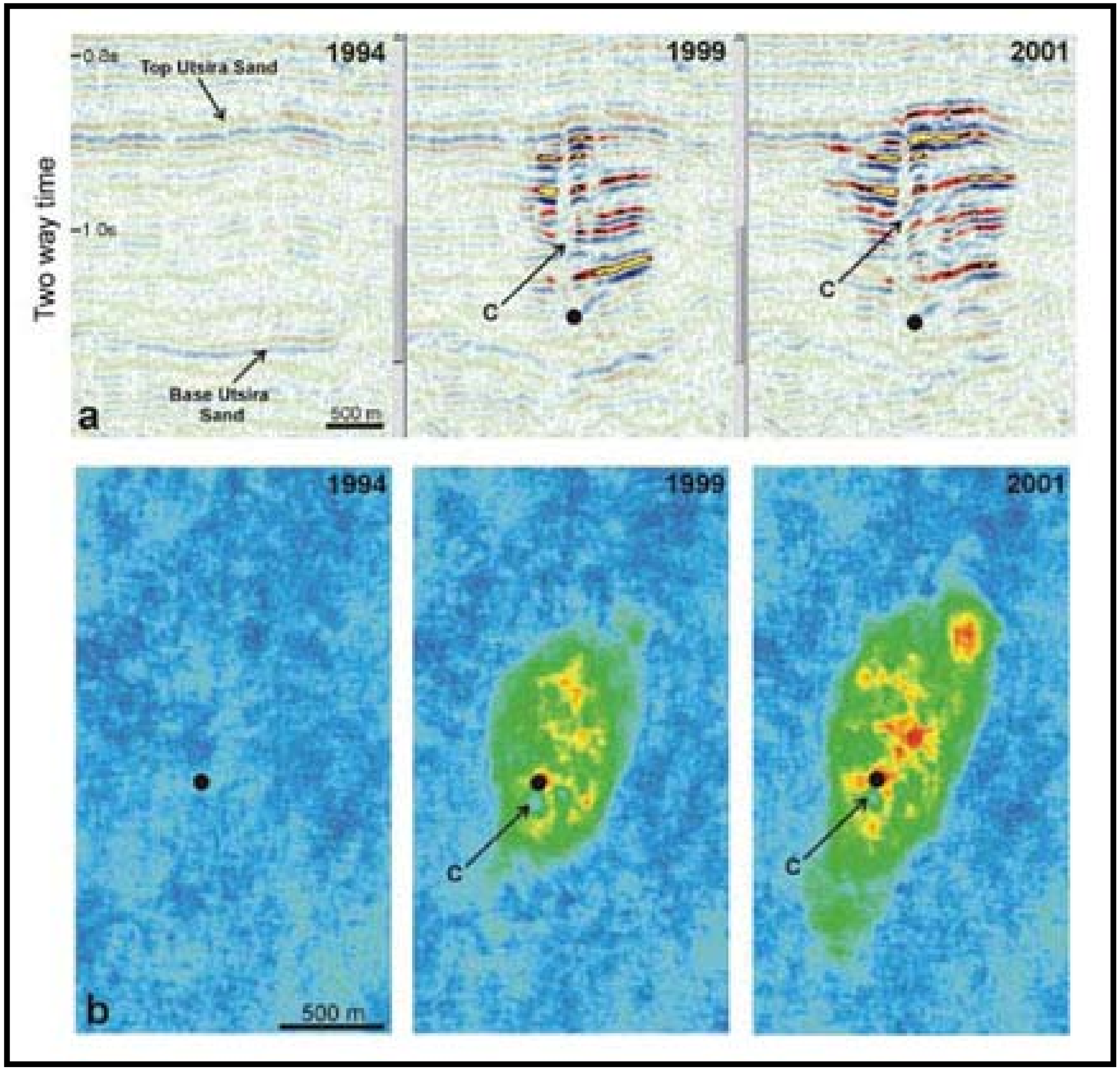
Economic driver: Norwegian carbon tax on industry ($50/ton C)
Cost of storage: $15/ton C



Target: 1 MM t CO_2/yr.
So far, 10 MM t

Miocene Aquifer: DW fan complex
- **30-40% porosity, 200 m thick**
- **high perm. (~3000 mD)**
- **between 15-36 ^{o}C – w/i critical range**

Sleipner monitoring supports the interpretation that CO_2 can be imaged and has not escaped



The CO_2 created impedance contrasts that revealed thin shale baffles within the reservoir.

This was a surprise.

This survey has sufficient resolution to image 10,000 t CO_2, if collected locally as a free-phase.

Although powerful, 4D seismic is no panacea

Chadwick et al., 2004

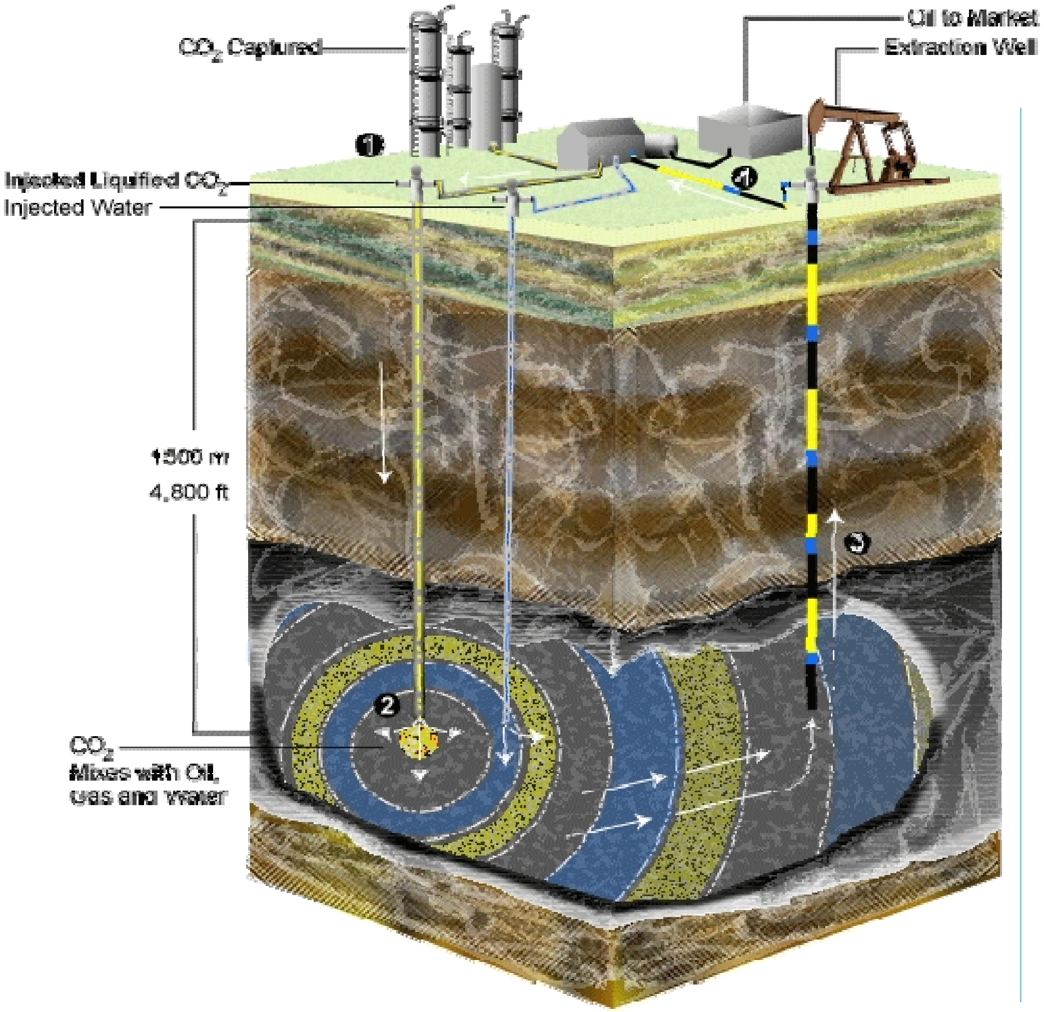
Weyburn: Transport from North Dakota gasification plant to EOR field

CO_2 Delivery

- **200 miles of pipe**
- **Inlet pressure 2500 psi; delivery pressure 2200 psi**
- **5,000 + metric tonnes per day**
- **Deliver to Weyburn and now Midale**

Weyburn field

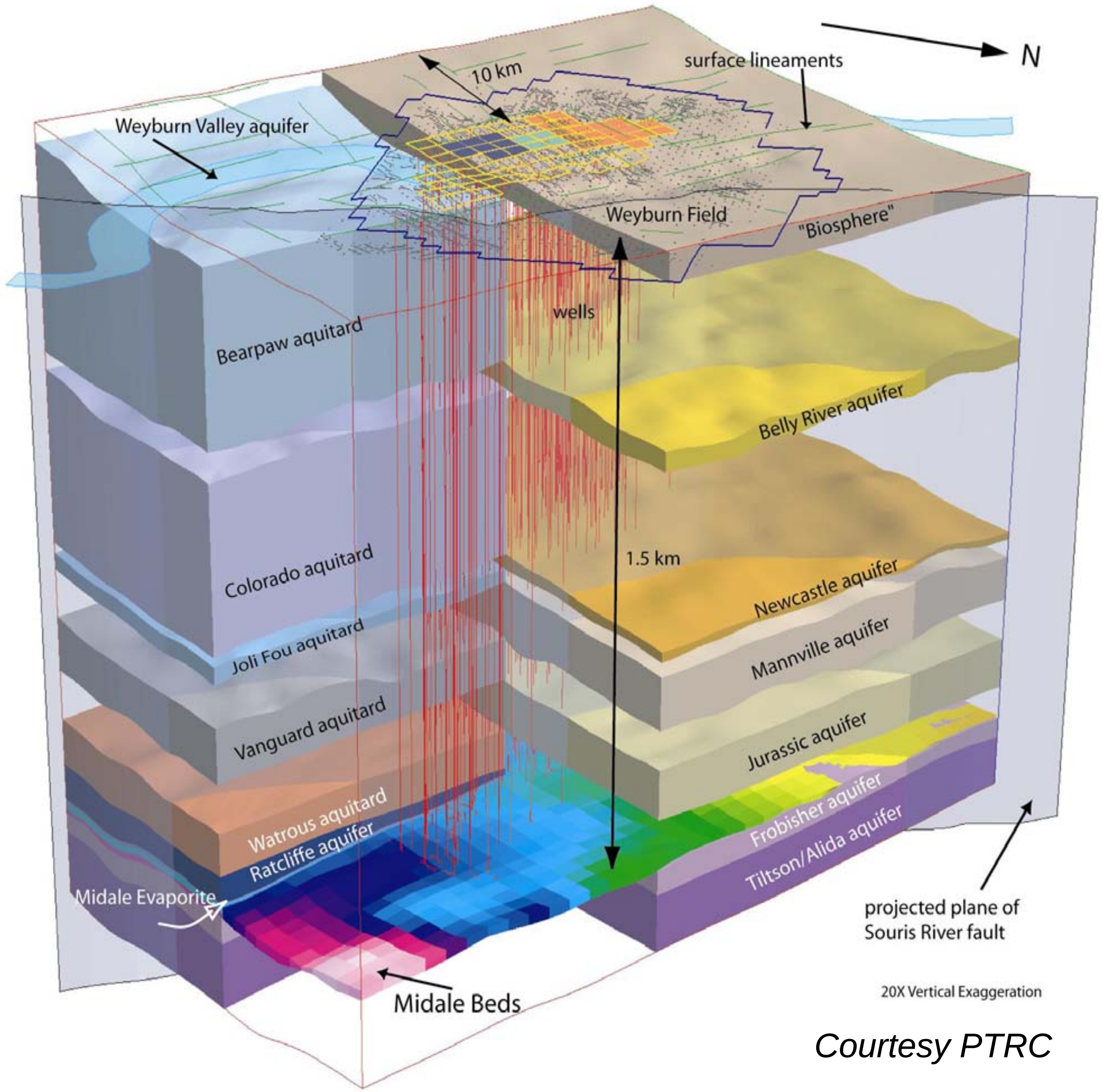
- **Discovered: 1954**
- **>2.0 Gbbl OOIP**
- **Additional recovery ~130 MM barrels**
- **>26 M tons CO2 stored**
- **4 year, $24M science project; expand to second phase**



Courtesy PTRC

Geological Model

- Areal extent 10 km beyond CO_2 flood limits
- Geological architecture of system
- Properties of system
  - lithology
  - hydrogeological characteristics
  - faults
- Can be tailored for different RA methods and scenario analyses

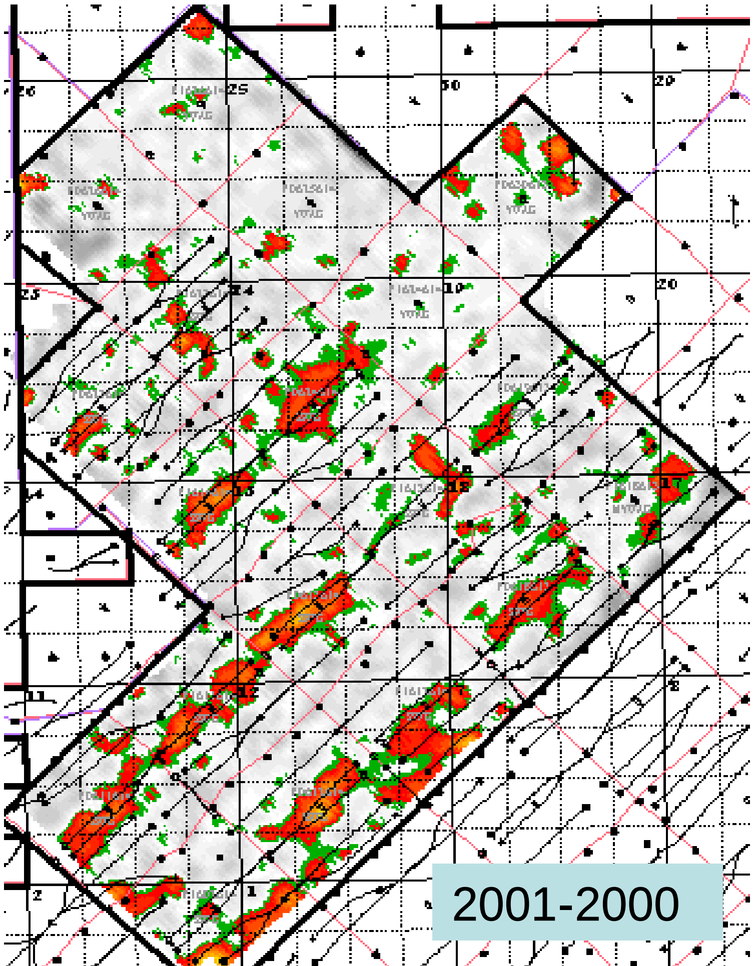


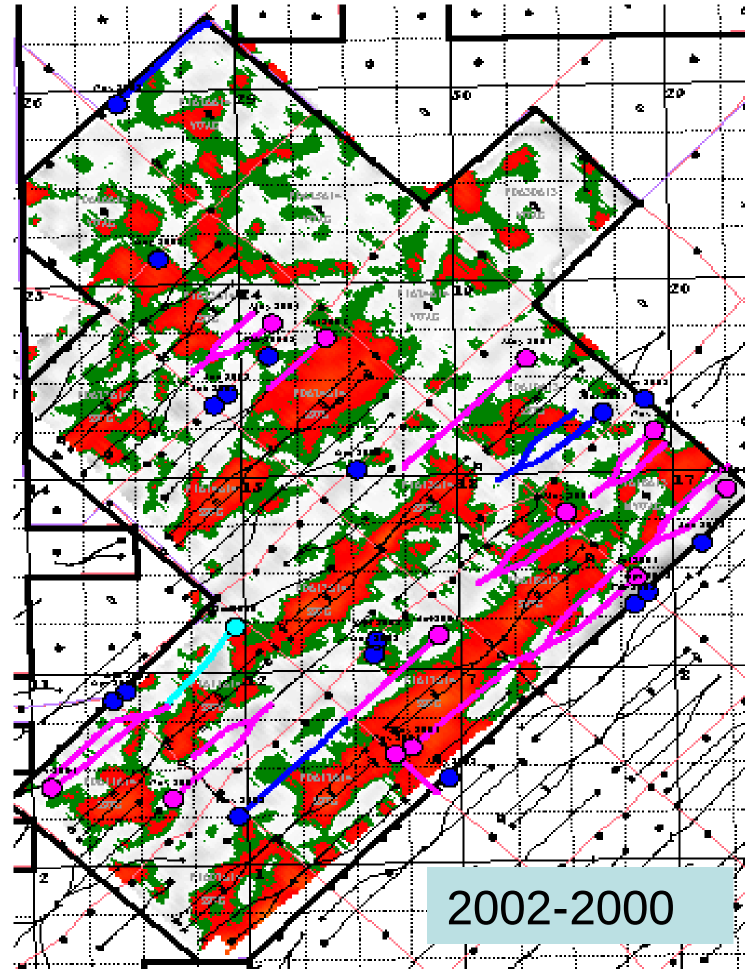
Courtesy PTRC

4D-3C Time-Lapse Seismic Surveys

vs. Baseline survey (Sept. 2000)

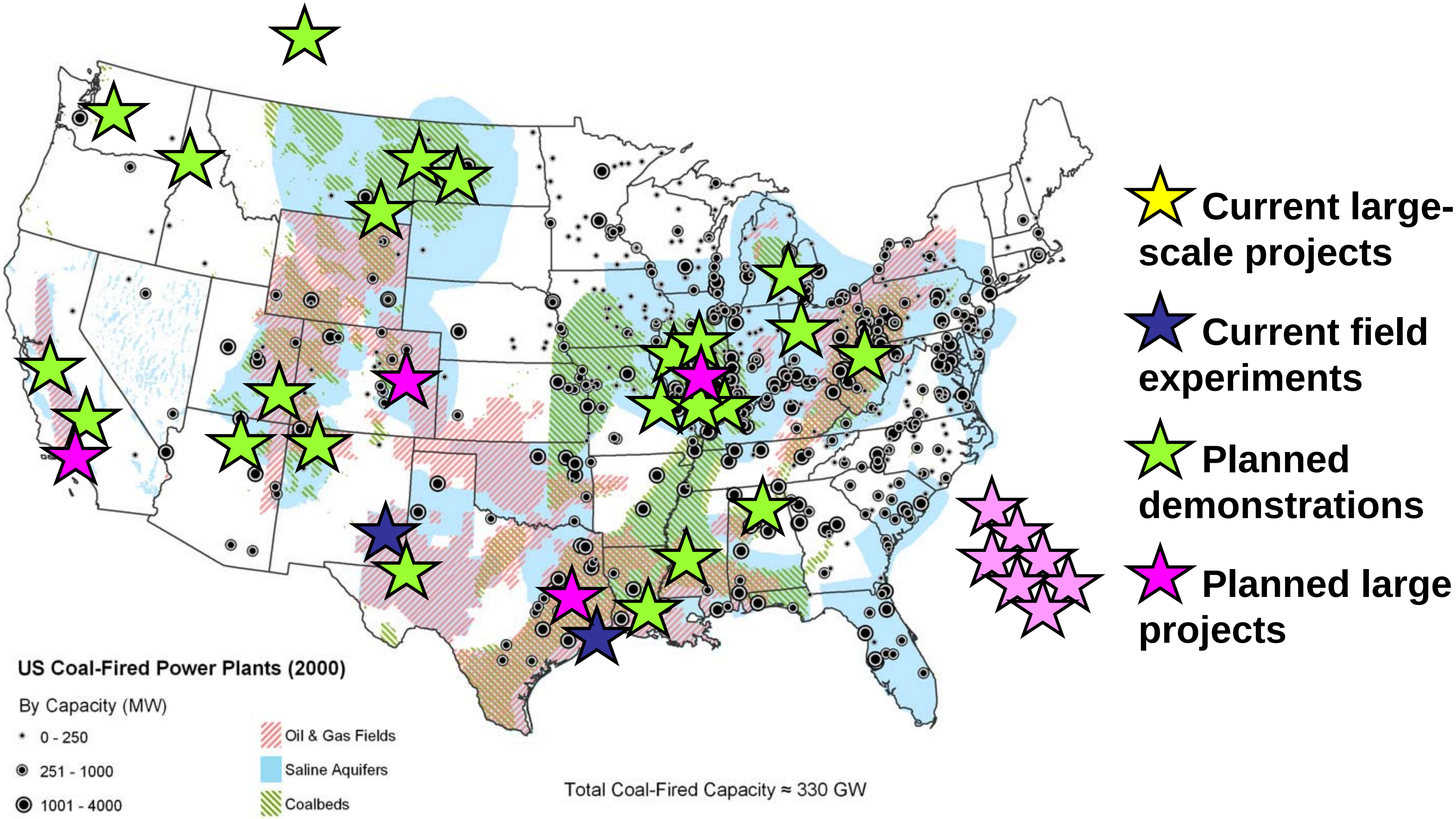
Marly Zone





Wilson & Monea 2004

In the US, small projects have begun and large projects almost begun



MIT, in press

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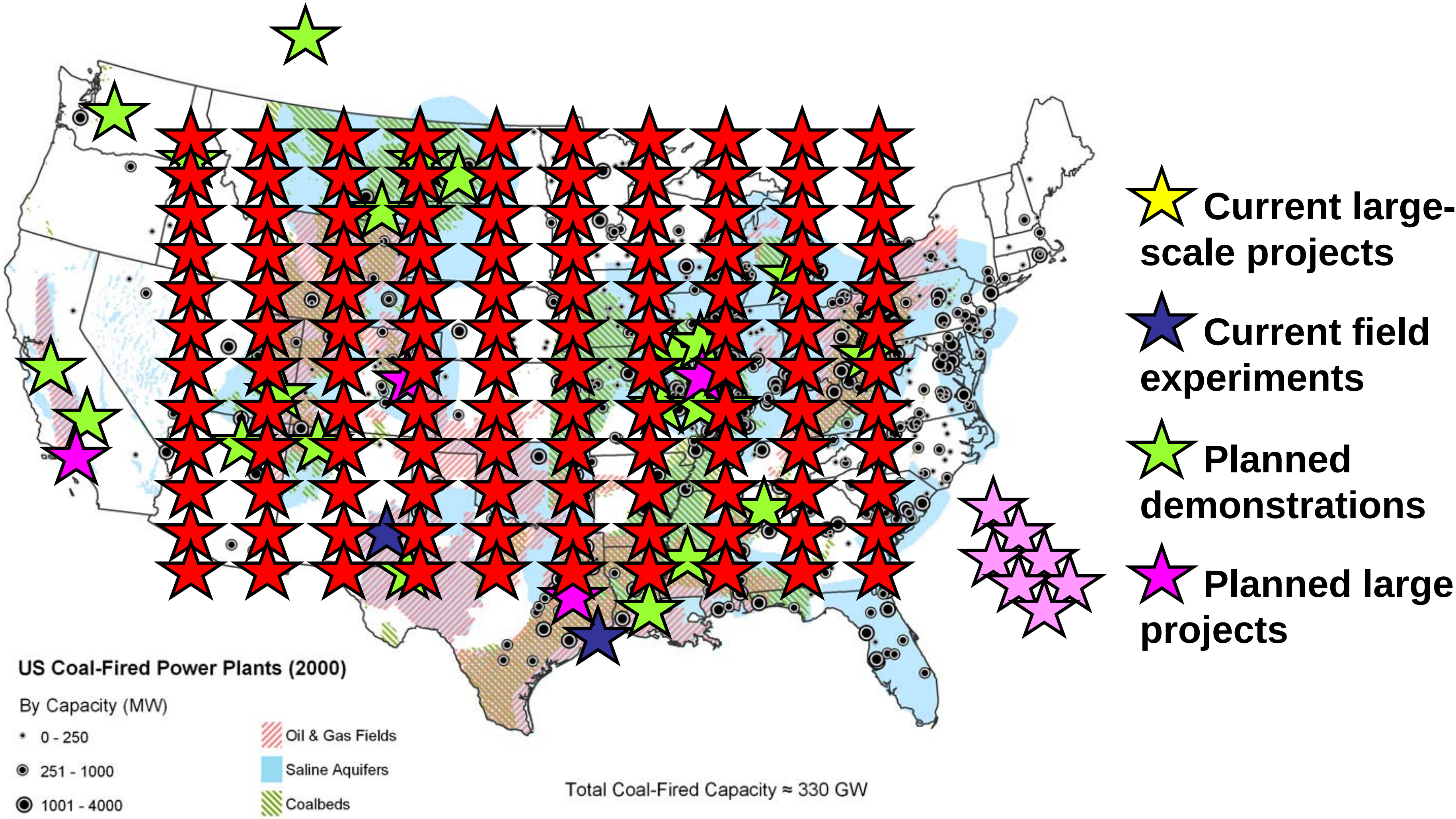
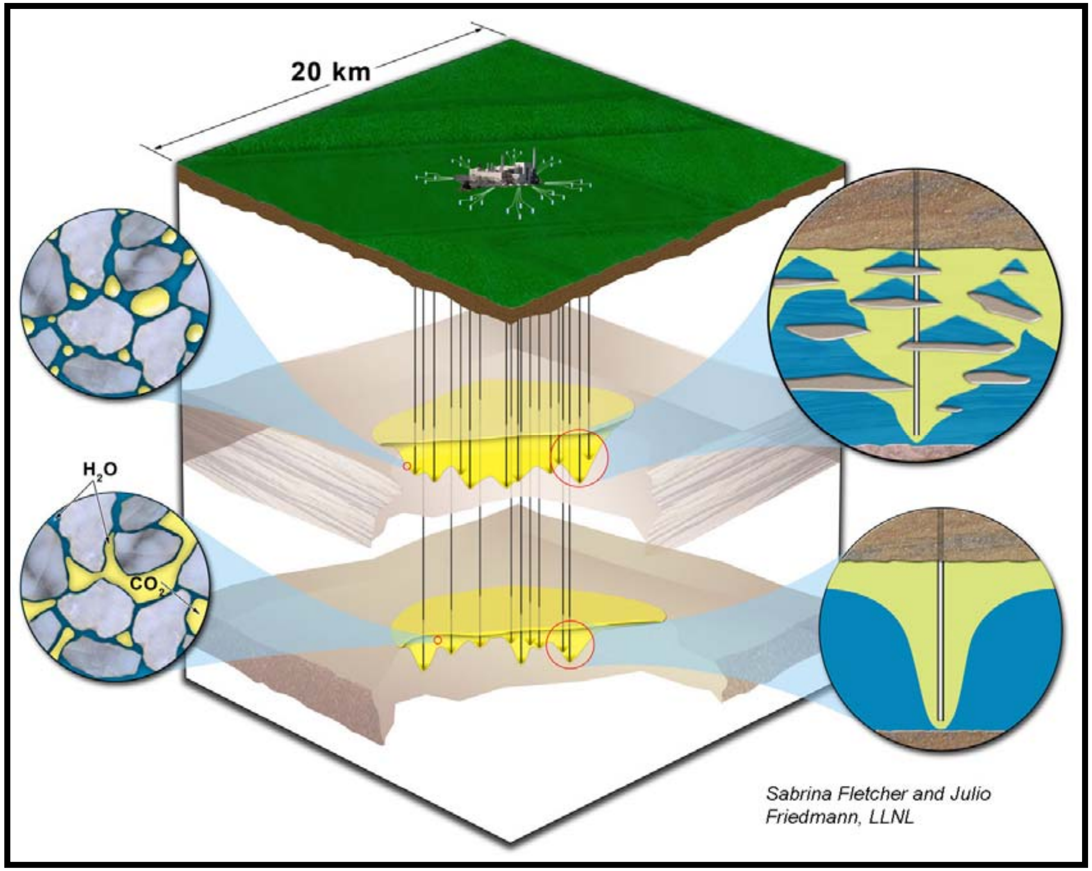


MIT, in press

The true scope of large-scale CCS deployment is the primary challenge and source for concerns.

Let's agree that by 2020, all new coal plants will be fitted for CO_2 capture and storage. The scope and scale of injection from a single plant and many plants must be considered.



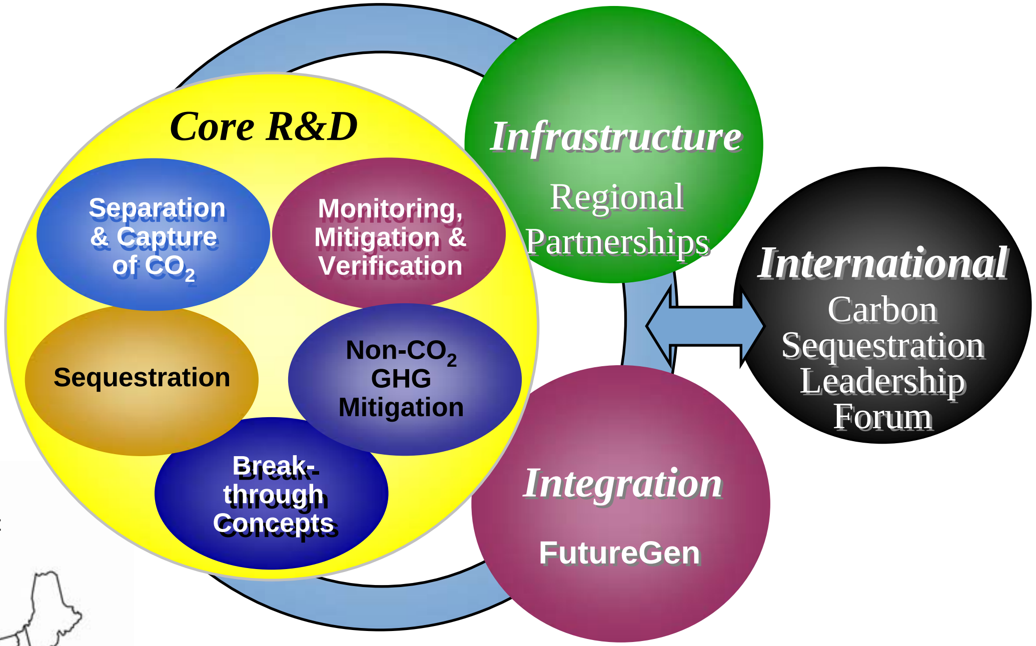
MIT, in press

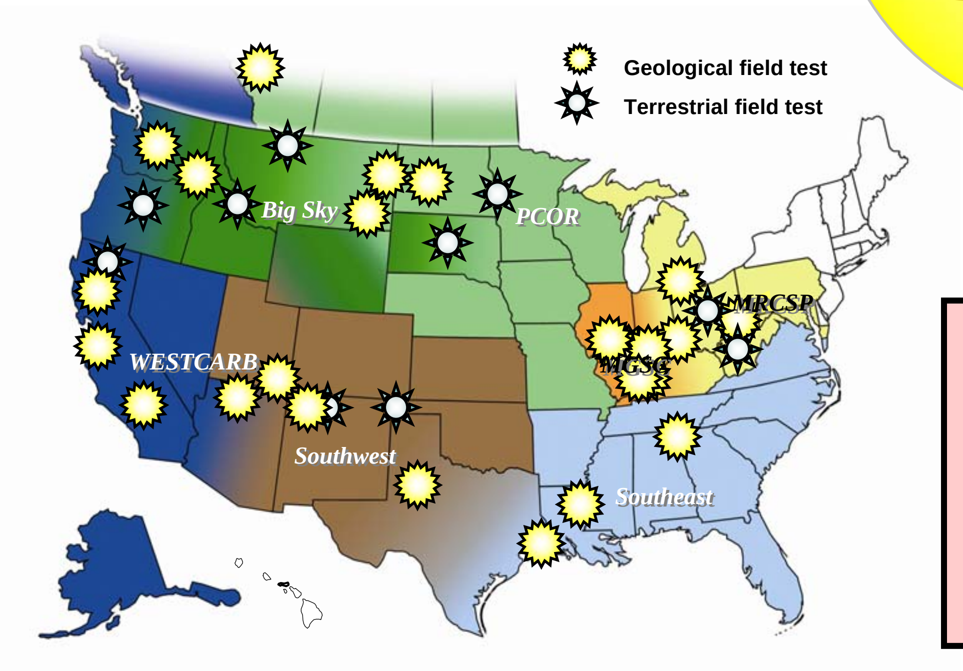
One 1000 MW plant:
- **6 MM t CO_2/yr**
- **100,000 bbl/d**
- **After 50 year, 2 G bbls**
- **CO_2 plume at 10y, ~10 km radius: at 50 yrs, ~30 km radius**
- **Many hundreds of wells**
- **Likely injection into many stacked targets**

One Gt/y C abatement requires 600 projects of this size (3600 Sleipners)

To address CCS challenges, the DOE Clean Coal Program has run an aggressive research effort

The US program ($67M/y) has three main planks: FutureGen, Core R&D, and the Regional Partnerships.

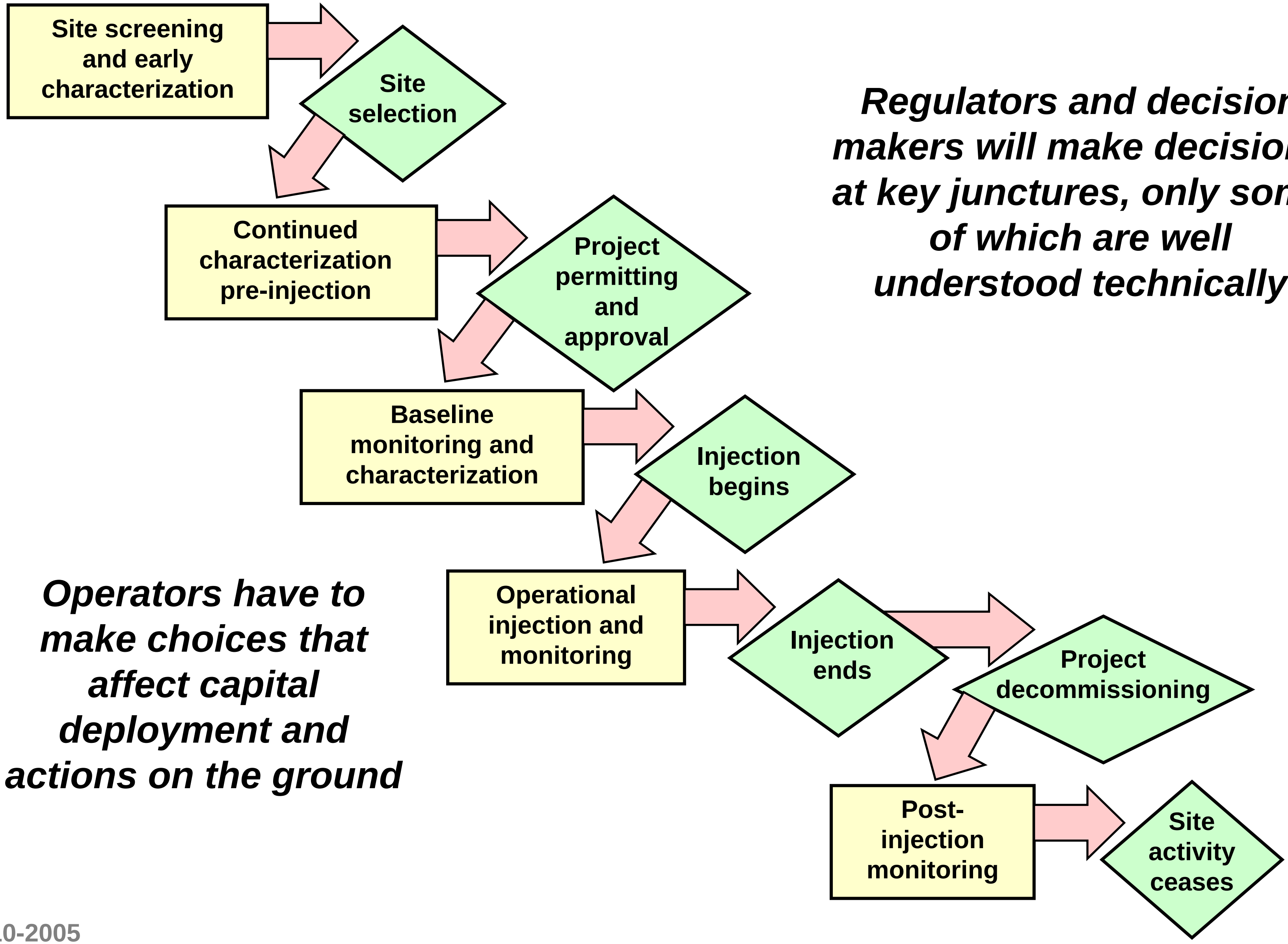




The partnerships work in 40 states and 4 provinces, with members from industry, government, academia, and FFRDCs

Courtesy US DOE

The drive to deployment has brought focus on the life-cycle of CCS operations and its key issues



Regulators and decision makers will make decisions at key junctures, only some of which are well understood technically

Operators have to make choices that affect capital deployment and actions on the ground

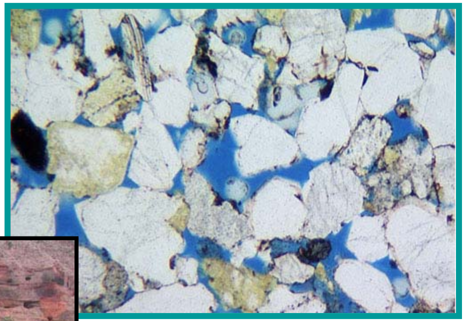
Site selection due diligence requires characterization & validation of ICE

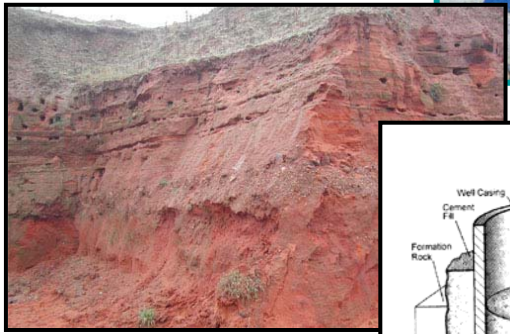
Injectivity ***Capacity*** ***Effectiveness***

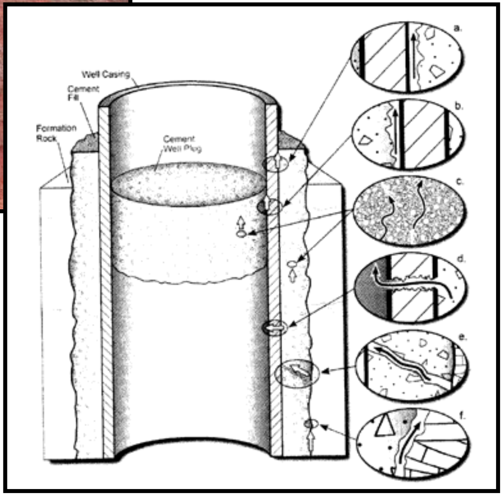
Injectivity
- **Rate of volume injection**
- **Must be sustainable (months – years)**

Capacity
- **Bulk (integrated) property**
- **Total volume estimate**
- **Sensitive to process**

Effectiveness
- **Ability for a site to store CO_2**
- **Long beyond the lifetime of the project**
- **Most difficult to define or defend**





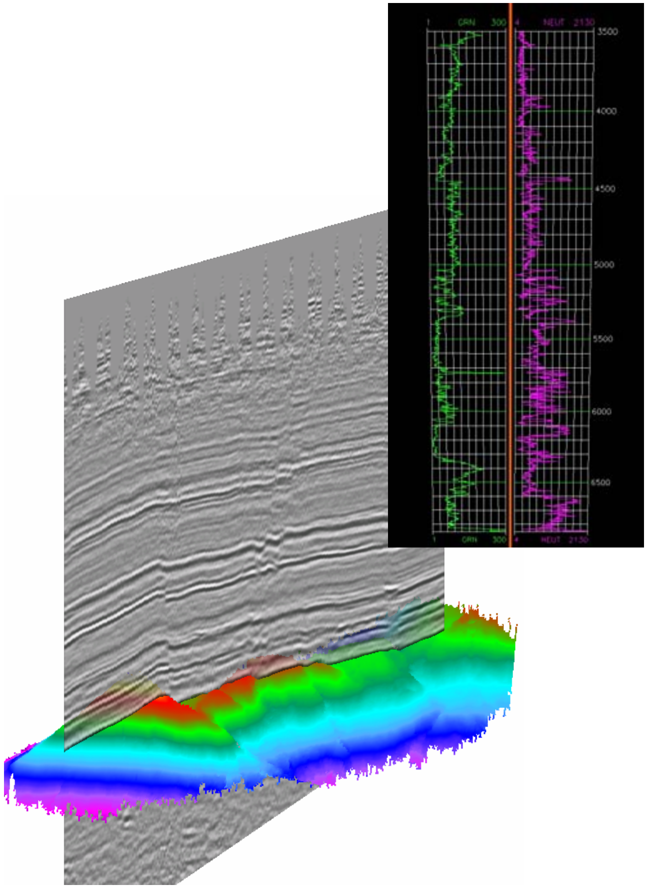


Gasda et. al, 2005

Site selection should require due diligence in characterization & validation

Injectivity
Capacity
Effectiveness

Ideally, project site selection and certification would involve detailed characterization. In most cases, this will require new geological and geophysical data sets.



For Depleted Oil & Gas Fields:

- **Injectivity & capacity well established**
- **Objective measures of effectiveness exist**

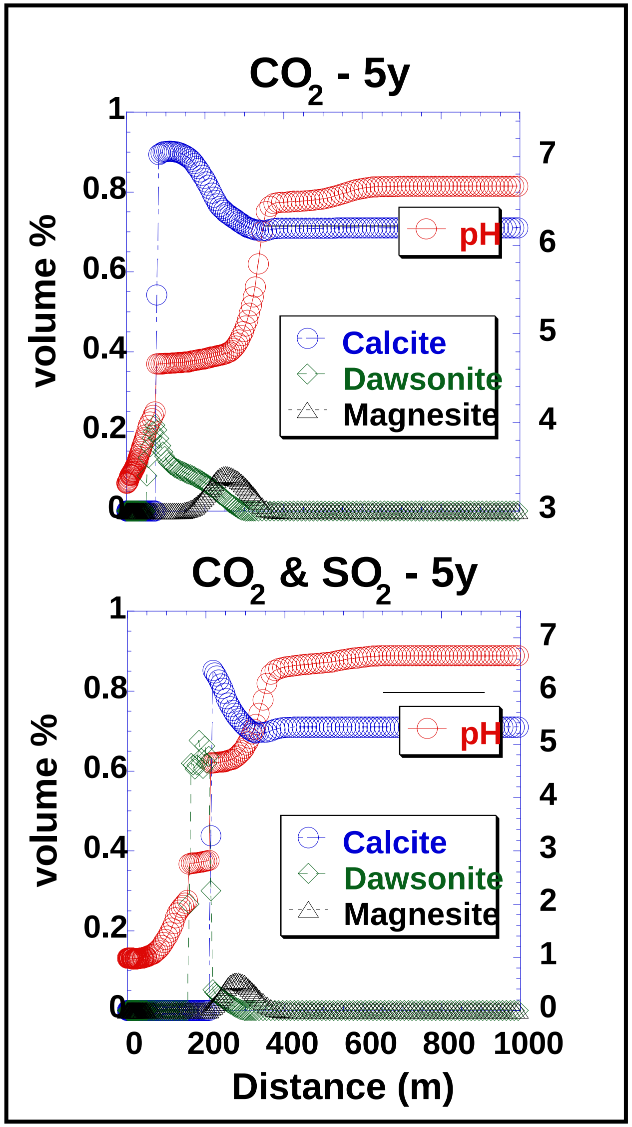
For Saline Aquifers:

- **ICE could be estimated; would probably require exploratory wells and 3D seismic**
- **Include cores, followed by lab work**

For Unmineable Coals:

- **Injectivity could be tested**
- **Capacity is poorly understood**
- **Effectiveness is not well understood or demonstrated**

Co-contaminant storage may reduce COE and capture costs; effects are site specific

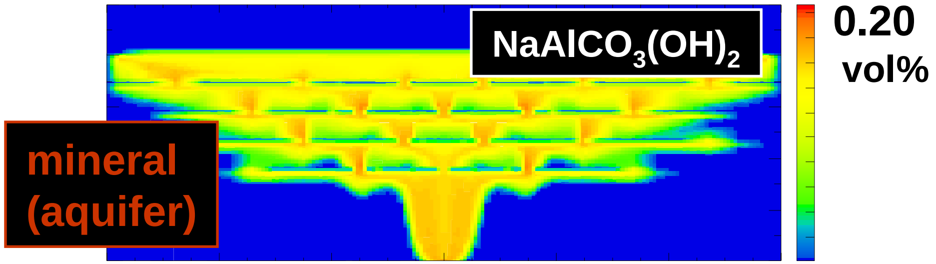


Knauss et al., 2005

Substantial cost reductions for new plants may be possible if CO_2, SO_x, and NO_x can be co-stored, esp. w/ oxyfiring combustion.

Preliminary geochemical models and experiments suggest that while H_2S has a small geochemical effect, SO_x has dramatic effect, greatly reducing pH and changing the mineral reactions.

More work is needed to understand site-specific risks and fates.



Johnson et al., 2005

Open issues in site selection

For Depleted Oil & Gas Fields:

- **Incremental cost concerns in most cases**

For Saline Aquifers:

- **Approximation of potential fast-paths to surface**
- **Accurate rendering of reservoir heterogeneity and residual saturation**
- **Understanding of local stress tensor and geomechanics**

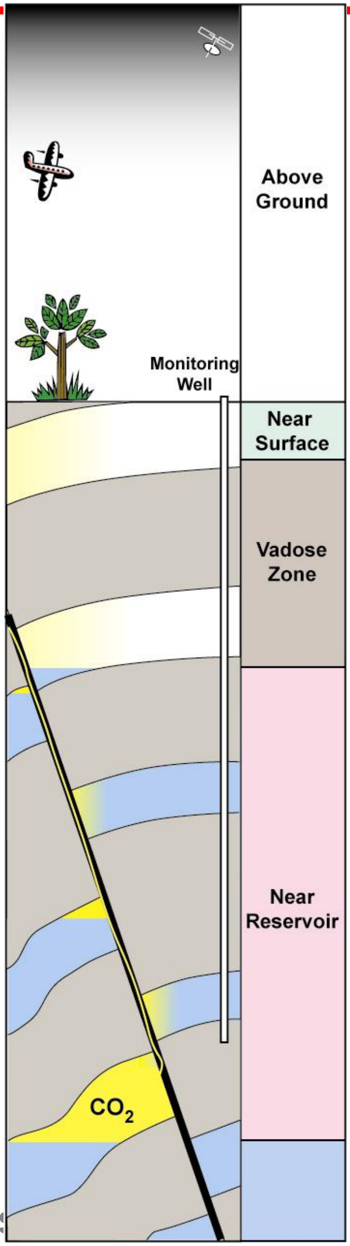
For Unmineable Coals:

- **Understand transmissivity between fracture and matrix pore systems.**
- **Understanding sealing architecture near seam**
- **Understand cleat structure and its response to pressure transient**

The threshold for validation is different for each site and reservoir class.

Policy is needed to establish a regulatory framework aimed at appropriate validation of selected sites for certification

Once injection begins, measurement, monitoring, and verification (MMV) is required



MMV serves these key roles:

- Understand key features, effects, & processes
- Injection management
- Delineate and identify leakage risk and leakage
- Provide early warnings of failure
- Verify storage for accounting and crediting

Currently, there are abundant viable tools and methods; however, only a handful of parameters are key

- Direct fluid sampling via monitoring wells (e.g., U-tube)
- T, P, pH at all wells (e.g., Bragg fiberoptic grating)
- CO_2 distribution in space: various proxy measures
  (Time-lapse seismic clear best in most cases)
- CO_2 saturation (ERT, EMIT likely best)
- Surface CO_2 changes, direct or proxy
  (atmospheric eddy towers best direct; LIDAR may surpass)
  (perfluorocarbon tracing or noble gas tracing best proxies)
- Stress changes (tri-axial tensiometers)

Effective (MMV) for a typical site should focus on near surface and near reservoir in four stages

Practical monitoring programs should be (1) crafted around utility, robustness, and automation, (2) based on a sound understanding of local geology and geography, and (3) *formally integrated*

Assessment and planning

- Site characterization
- Simulation & forward modeling
- Array design and planning

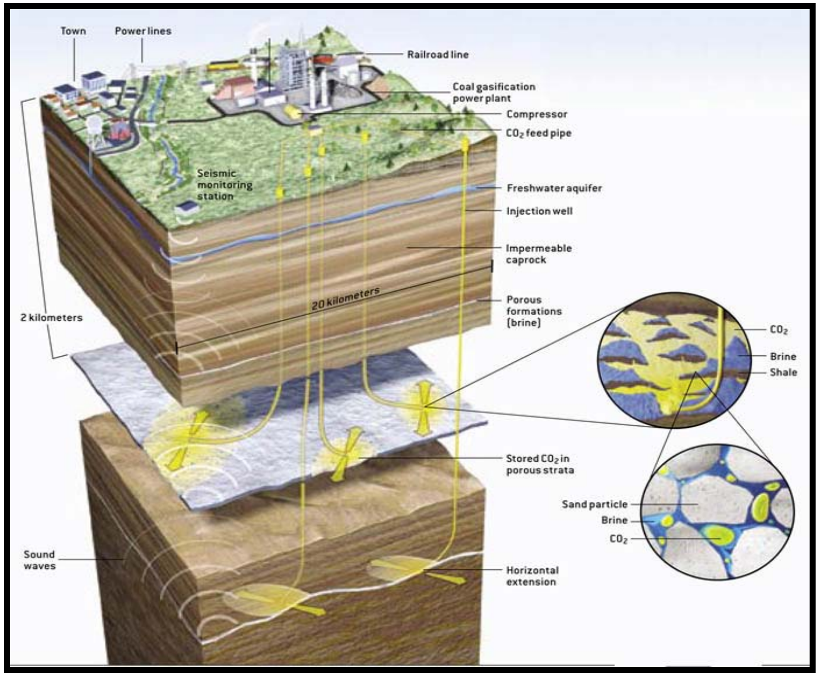
Baseline monitoring

- May take days to years
- May require reworking wells

Operational monitoring during injection

Array monitoring during and after injection

- Surface & subsurface components
- May have additional tools along high-risk zones
- Recurrence and duration determined by site parameters
- *Need for formal integration*



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Open issues in MMV

By what means can we formally integrate and compare the results of orthogonal MMV surveys?

What are likely durations of monitoring after injection stops?

Detection limits:

- **What are detection thresholds for individual technologies?**
- **What limits detection as a function of subsurface or surface concentration, location, and distribution?**

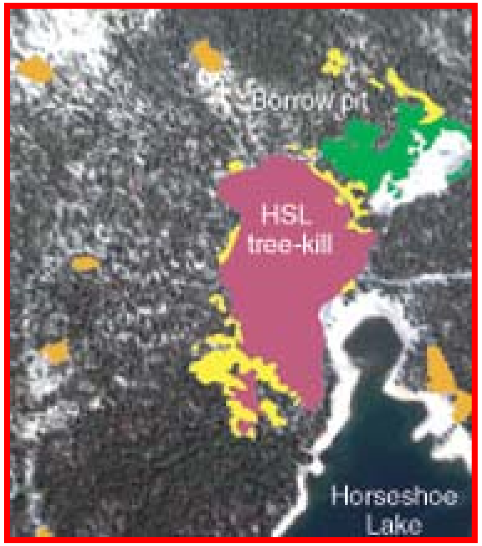
Need to focus on surface detection methods and approaches:

- **How can one measure flux above background?**
- **How can one configure a surface array to answer key questions**
- **How can one optimize an array given a geography and geology?**

Coordinated field tests are needed to compare and contrast methods in terms of efficacy. Multiple field tests can serve as the basis for policy and regulation.

Leakage risks remain a primary concern

1) High CO_2 concentrations (>15,000 ppm) can harm environment & human health.
2) There are other potential risks to groundwater, environment
3) Concern about the effectiveness & potential impact of widespread CO_2 injection
4) Economic risks flow from uncertainty in subsurface, liability, and regulations

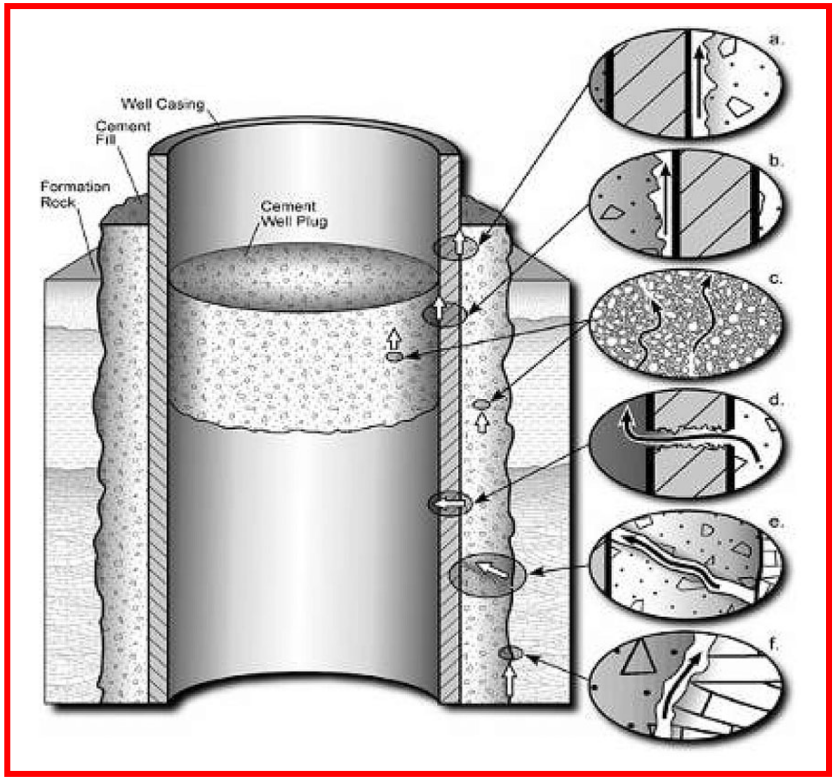


Elements of risk can be prioritized

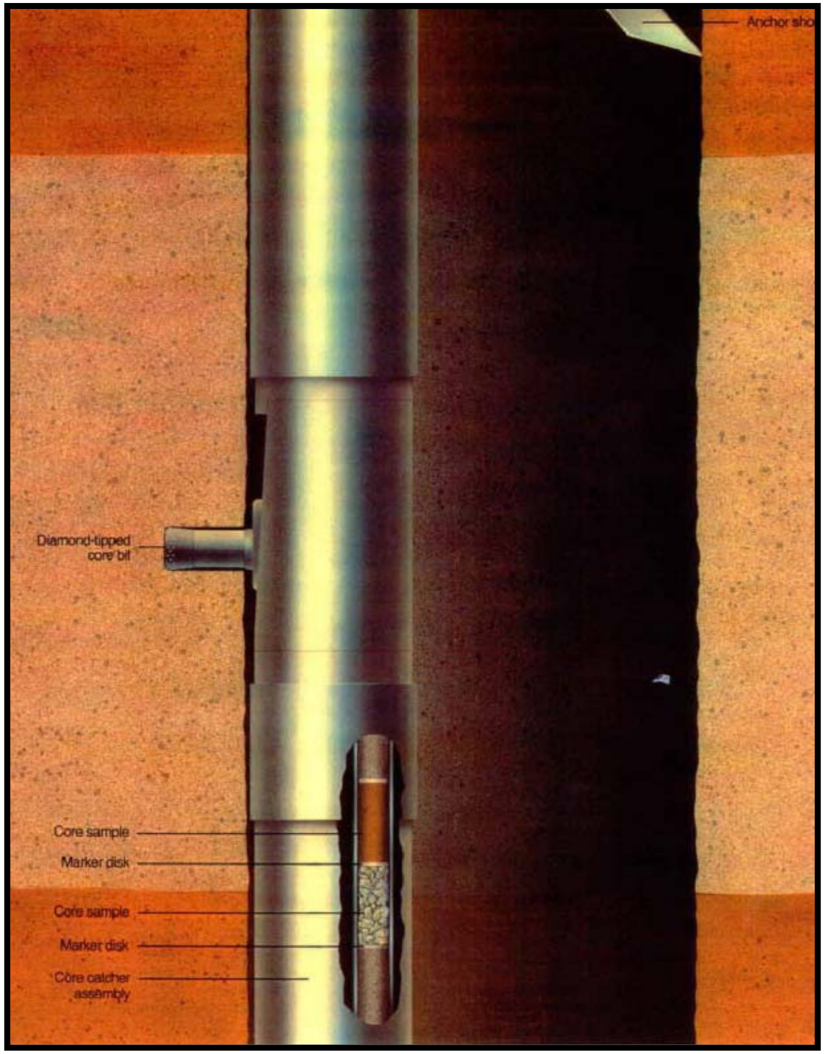
- Understanding high-permeability conduits (wells and faults)
- Predicting high-impact effects (asphyxiation, water poisoning)
- Characterizing improbable, high-impact events (potential catastrophic cases)

Well-bore integrity remains a key risk element requiring technology development

Investigators, regulators, and modelers need empirical and statistical data sets to condition risk of complete well failure.



Gasda et al., 2005



Courtesy Schlumberger

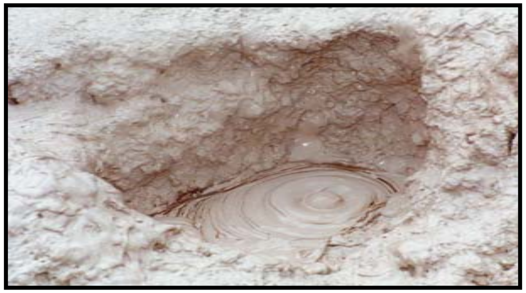
Plugs remain a key concern, particularly for old wells (orphaned and abandoned)

Plug technology has improved over time due to regulation

http://fotos.naturspot.de/bilder/11-336.html

1850's – 1920's

- Animal Carcasses
- Mud
- Debris
- Nothing



http://www.richardseaman.com/Travel/NewZealand/NorthIsland/Rotorua/MudPools/SunkenMudPool.jpg

1930's – 1953

- Mud
- Cement with no additives

http://www.hardwarestore.com/media/product/221101_front200.jpg

1953 – present

- Standard Portland Cement
- Cement with additives

Ide et al., 2006

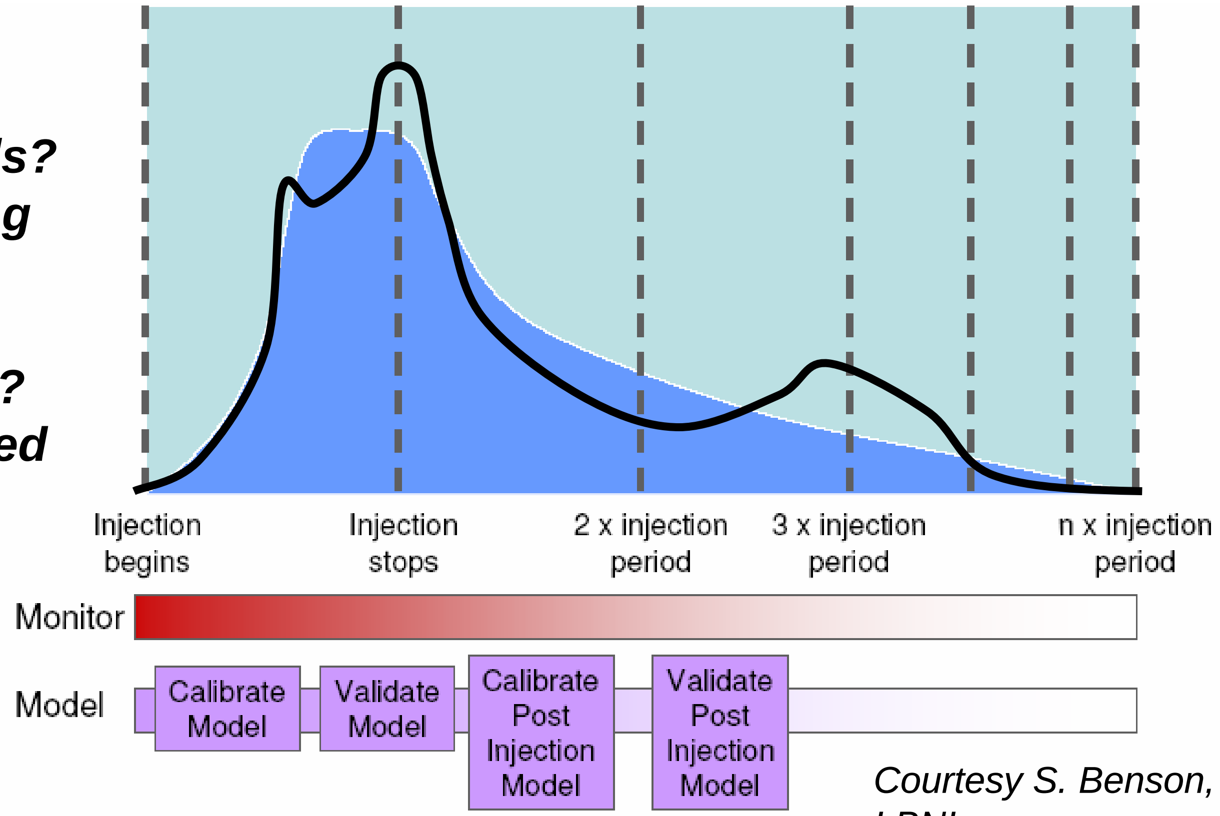
These wells present a challenge to integrity and monitoring which could be resolved through

Site closure remains a poorly circumscribed problem from operational and regulatory views

Uncertainties persist in key aspects:

- ***What are proper abandonment protocols?***
- ***When does monitoring cease?***
- ***When does liability transfer to a new party?***
- ***Are there unanticipated long-term concerns?***
- ***What are the real magnitudes of these risks?***

Conceptual Risk Profile



Courtesy S. Benson, LBNL

These uncertainties impede commitment of capitol to operational projects today

Work remains to develop a hazard risk framework that can be regularly employed

The hazards are a set of possible environments, mechanisms, and conditions leading to failure at some substantial scale with substantial impacts.

Atmospheric release	Groundwater degradation	Crustal deformation
Well leakage	Well leakage	Well failure
Fault leakage	Fault leakage	Fault slip/leakage
Caprock leakage	Caprock leakage	Caprock failure
Pipeline/ops leakage		
		Induced seismicity
		Subsidence/tilt

The hazards must be fully identified, their risks quantified, and their operational implications clarified

Friedmann, in press

Because of local nature of hazards, prioritization (triage) is possible for any case

Hypothetical Case: Texas GOM coast

Atmospheric release hazards	Groundwater degradation hazard	Crustal deformation hazards
Well leakage	Well leakage	Well failure
Fault leakage	Fault leakage	Fault slip/leakage
Caprock leakage	Caprock leakage	Caprock failure
Pipeline/ops leakage		
Pink = highest priority Orange = high priority Yellow = moderate priority		Induced seismicity
		Subsidence/tilt

Part of protocol design is to provide a basis for this kind of local prioritization for a small number of classes/cases

It is worth noting that the risks at present appear to be very small and manageable

Analog information abundant

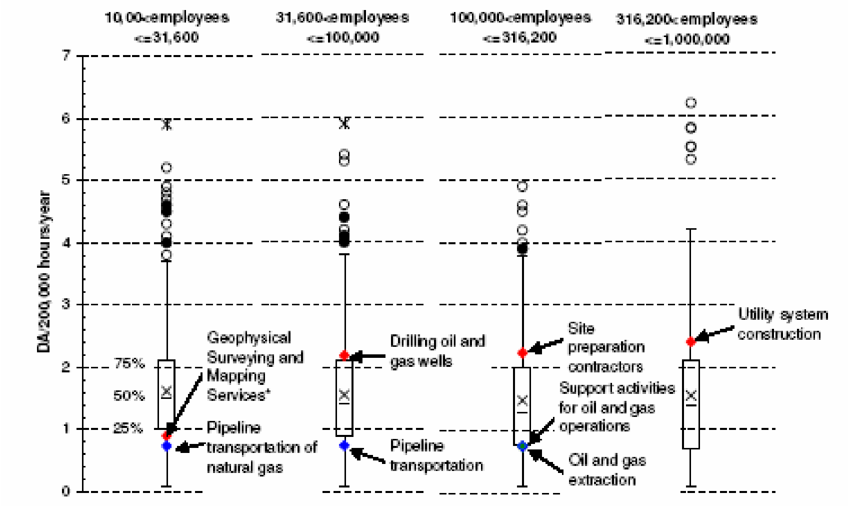
- Oil-gas exploration and production
- Natural gas storage
- Acid gas disposal
- Hazardous waste programs
- Natural and engineered analogs

Operational risks

- No greater than (probably less than) oil-gas equivalents
- Long experience with tools and methodologies

Leakage risks

- Extremely small for well chosen site
- Actual fluxes likely to be small (HSE consequences also small)
- Mitigation techniques exist



Benson, 2006

Bogen et al., 2006

Analog for the worst case scenario

Crystal Geyser, UT

Crystal Geyser, UT represents a strong analog for well leakage, fault leakage, & soil leakage

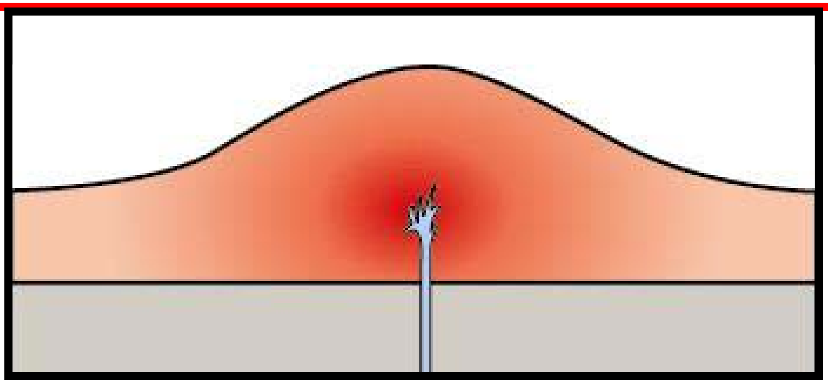
Drilled in 1936 to 801-m depth initiated CO_2 geysering.

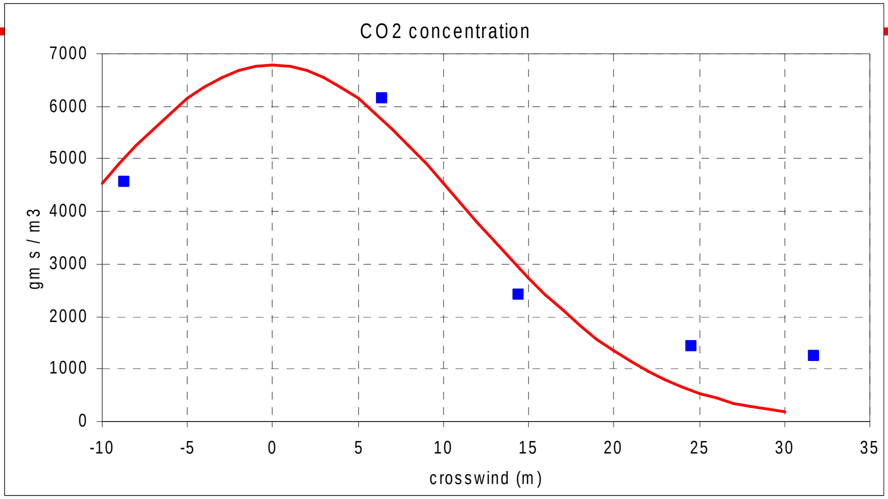
CO_2 flows from Aztec sandstone (high P&P saline aquifer)

Oct. 2004, LLNL collected flux data

- **Temperature data**
- **Meteorological data**
  - **Low wind (<2 m/s)**
- **5 eruptions over 48 hrs**
- **Four eruptions and one pre-eruption event sampled**

Crystal Geyser emission data results

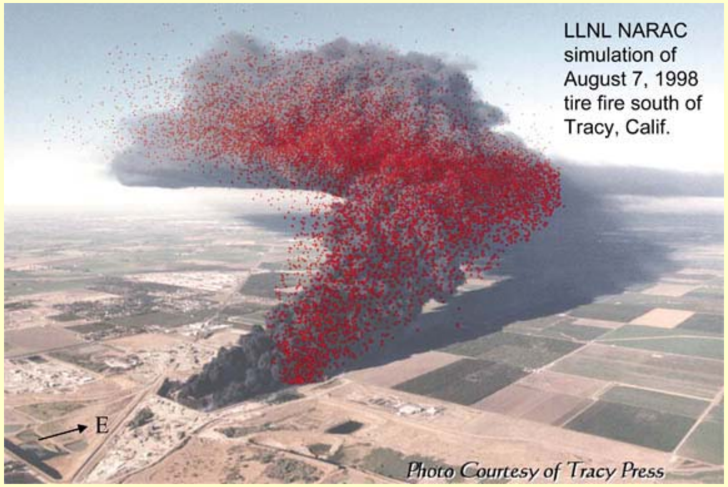




		Eruption Interval	CO_2 emission data during eruption	
Eruption	**Eruption Character**	**Duration (hr:min)**	**Total (metr. ton)**	**Rate (m.t./ min)**
1	moderate	0:07	1.1	0.15
2	*(no observations)*[&]	0:15	*N/A*	*N/A*
3	moderate	2:02	41	0.34
4	explosive	0:10	1.7	0.16
5a[*]	(pre-eruptive)	0:11	0.11	0.010
5	moderate	0:24	1.6	0.07

Short eruptions < 1 ton : Long eruption ~ 41 ton
Daily flux: ~10-25 t (5-41 t)
Annual flux: ~5000-9000 t (<1% of 1 MM t/yr injection)
Never above ~12500 ppm (up to 15000 ppm, no harm at all)

Atmospheric dispersion models of Crystal Geyser match source term characteristics



LLNL's NARAC facility is prepared to provide a plume prediction for any location in the US within 15 minutes. It accounts for topography, weather, infrastructure, and calculates risk based on health standards

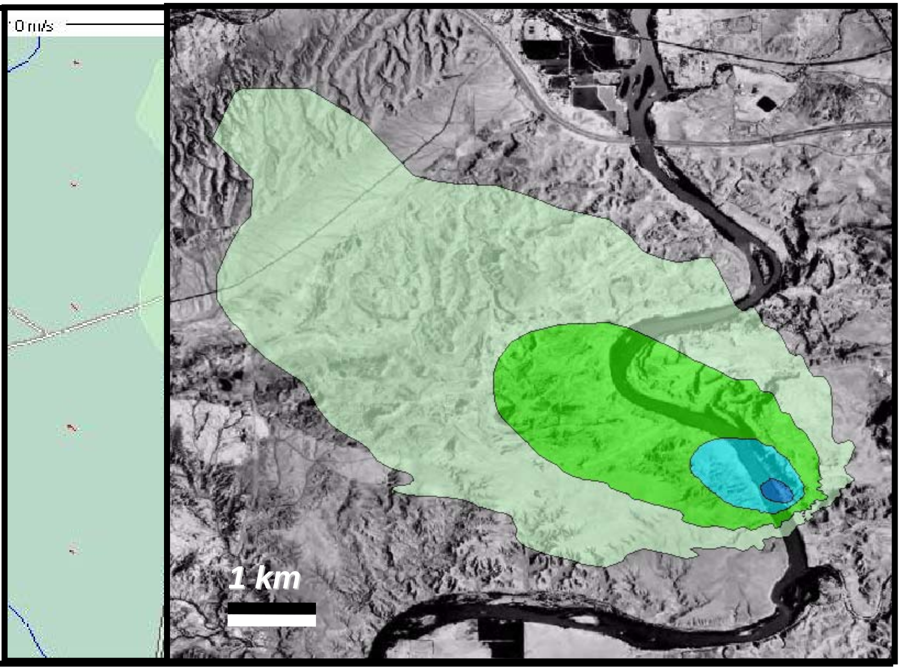
3-D NARAC models of CO_2 release from Crystal Geyser set limits on concentrations (i.e., health & safety thresholds) that can guide regulation and monitoring planning.

>100 ppm; 0.05km^2

>10 ppm; 0.6km^2

>1 ppm; 4.4 km^2

>0.1 ppm; 0.05km^2

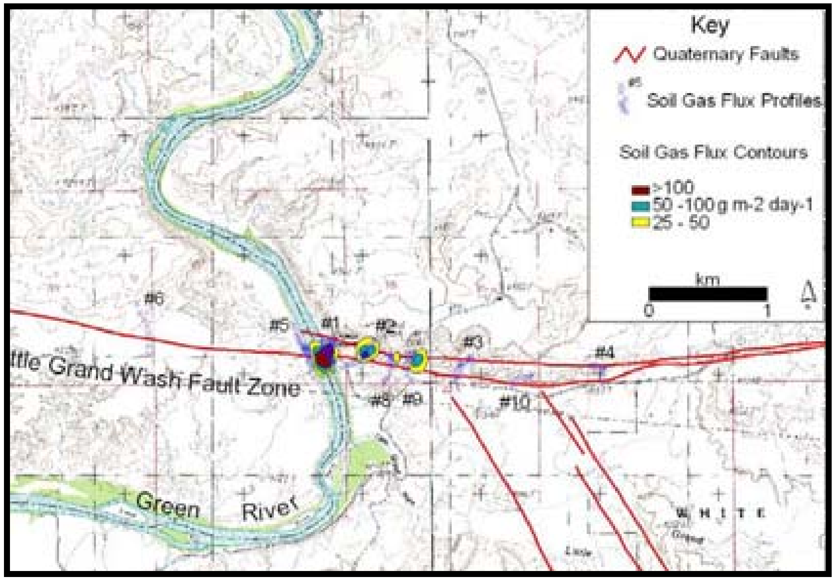


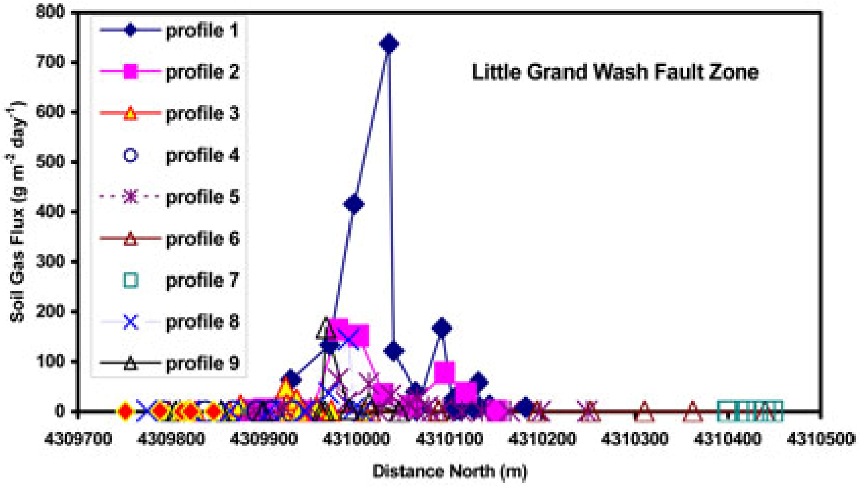
Little Grand Wash Fault soil surveys suggest fault leakage flux rates are extremely small

Allis et al. (2005) measured soil flux along the LGW fault zone.

Overall, concentrations were <0.1 kg/m²/d.

Integrated over the fault length and area, this is unlikely approach 1 ton/day.

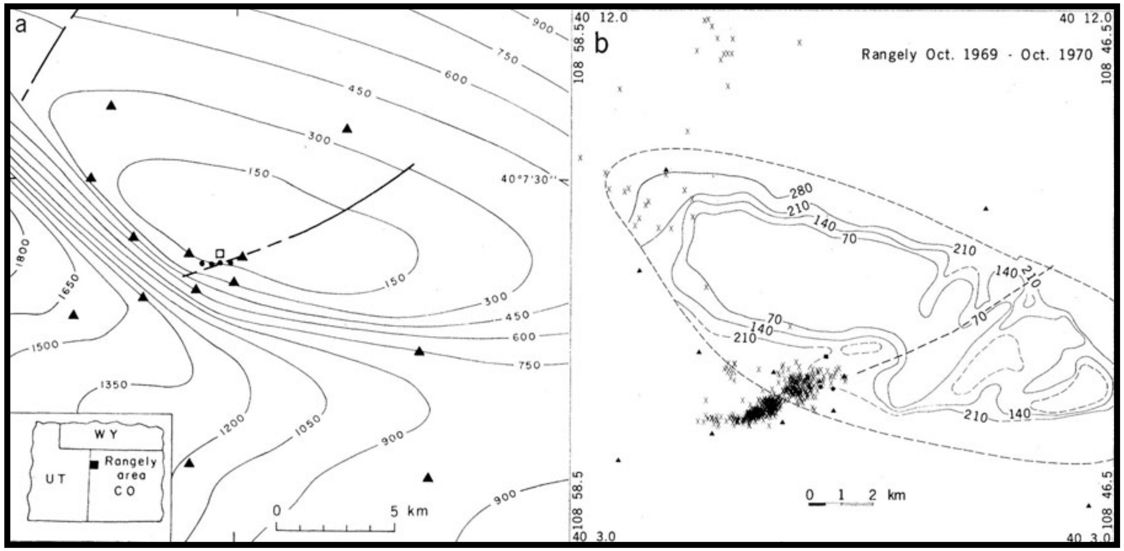




At Crystal Geyser, it is highly likely that all fault-zone leakage is at least two orders of magnitude less than the well. At the very least, this creates a challenge for MMV arrays

Allis et al., 2005

Initial concerns about induced seismicity and associated leakage are likely to be misplaced



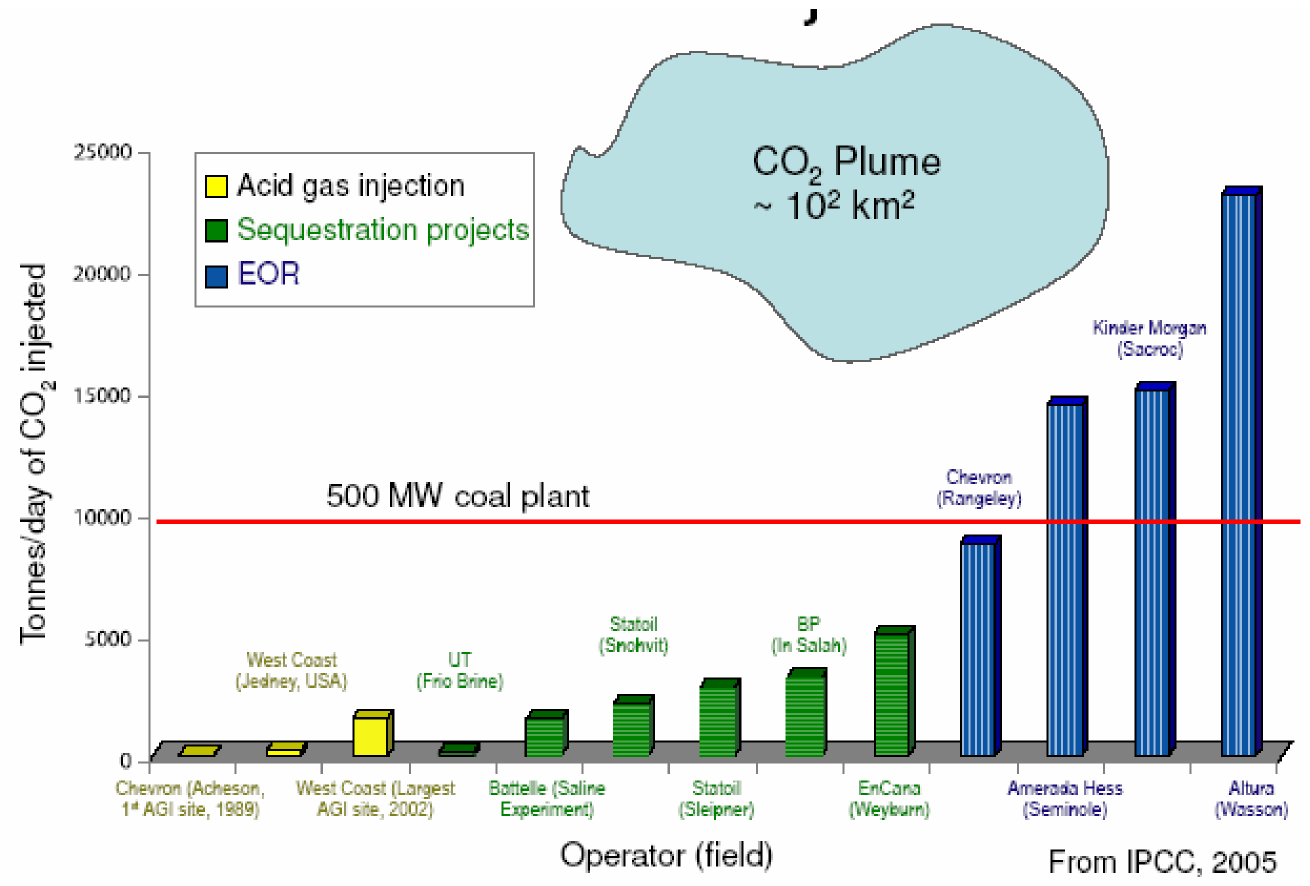
An experiment at Rangely field, CO, attempted to induce earthquakes in 1969-1970. It did so, but only after enormous volumes injected over long times on a weak fault

- ***Mean permeability: 1 mD***
- ***Pressure increase: >12 MPa (1750 psi) above original***
- ***Largest earthquake: M3.1***

There were no large earthquakes
The seal worked, even after 35 years of water and CO_2 injection
Most injection sites are less severe than this one
This phenomenon can only be studied at scale

Raleigh et al., 1976

Ultimately, more experience is needed through targeted study of large projects



The costs of this effort are small compared to the projected cost of plants, pipelines, or global warming impacts

Conclusions

Current knowledge strongly supports carbon sequestration as a successful technology to dramatically reduce CO_2 emissions.

> ***Current science and technology gaps appear resolvable***

Deployment issues, including regulatory, legal, and operational concerns, can be addressed through development of operational protocols advised by science

LARGE SCALE tests are crucial to understanding successful deployment of carbon capture and sequestration (CCS) and creating appropriate policy/economic structures.

> ***No test active to date is sufficient with respect to scale, duration, monitoring, and analysis.***