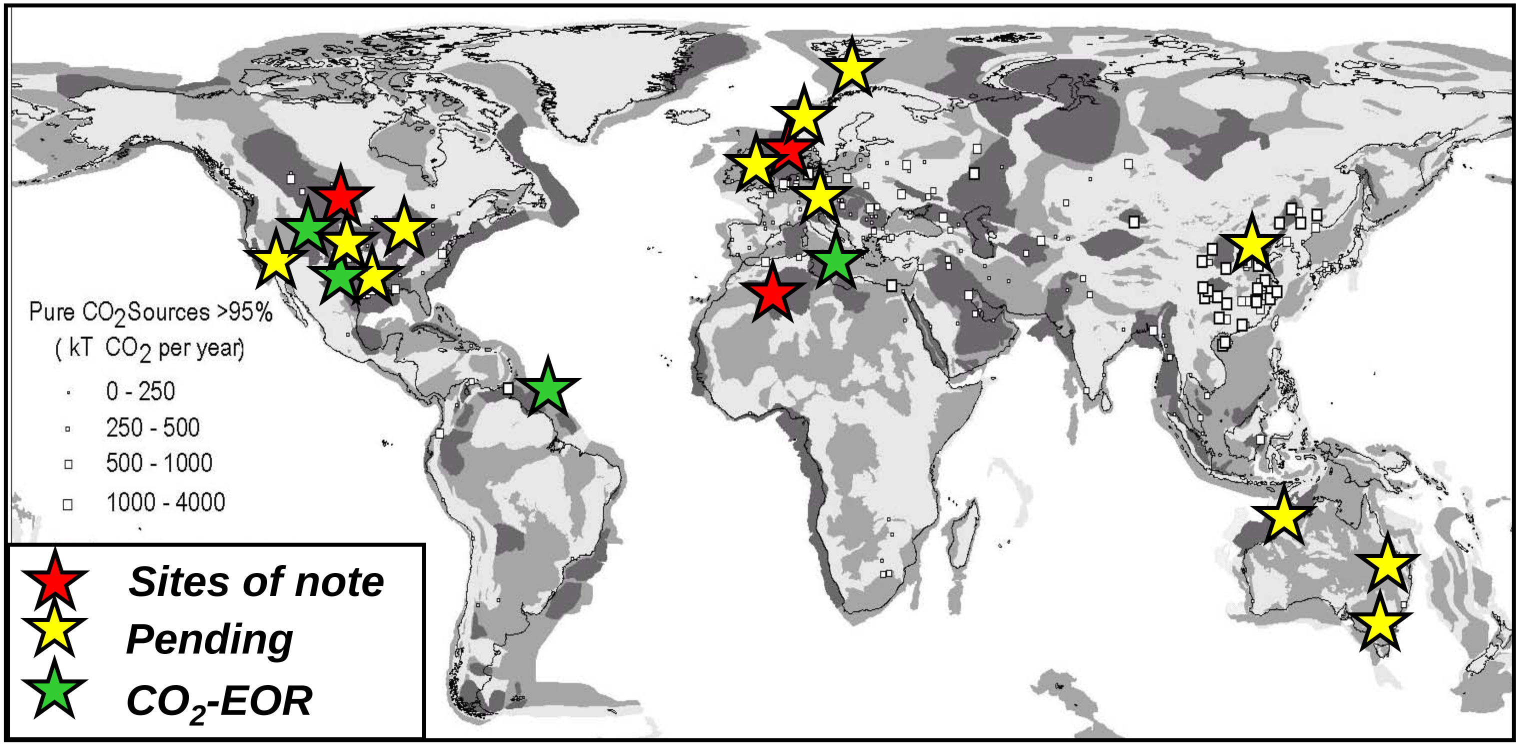
Carbon Capture and Sequestration

As a major greenhouse gas abatement option



S. Julio Friedmann

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Conclusions

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

Current science and technology gaps appear resolvable at scale

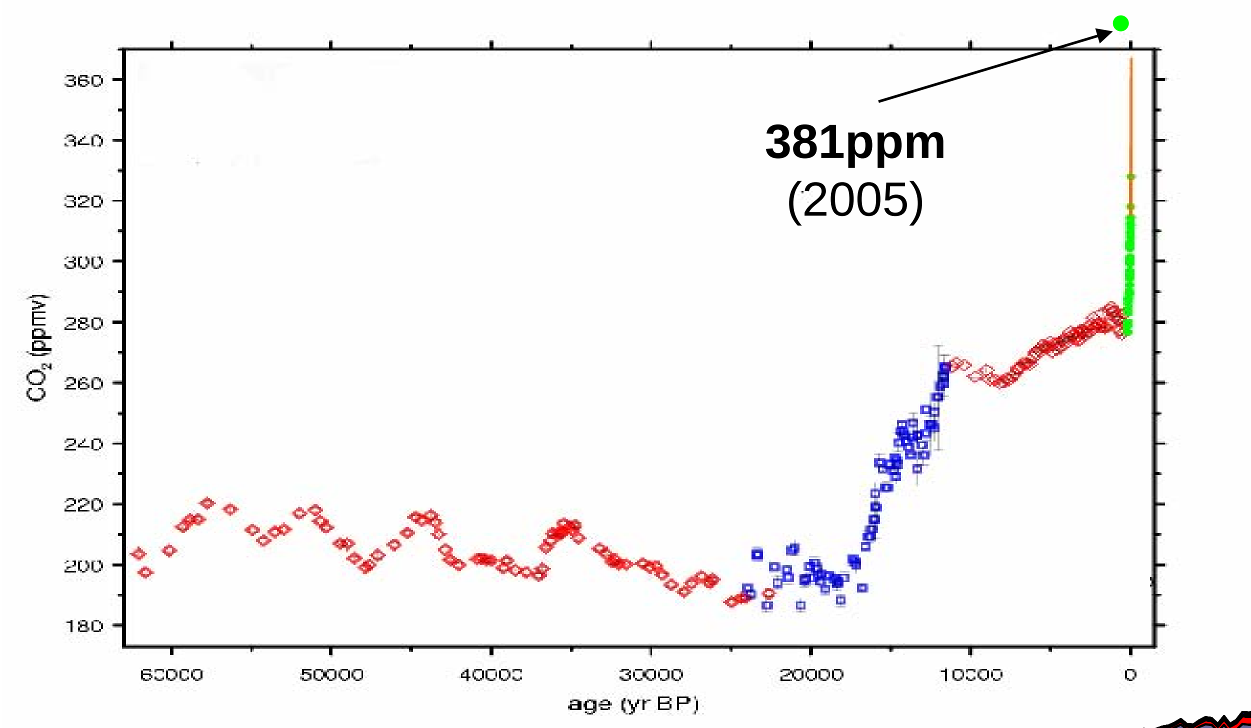
"We know enough to site a project, operated it, monitor it, and close it safely and effectively. We do not yet know enough for a full national or worldwide deployment."

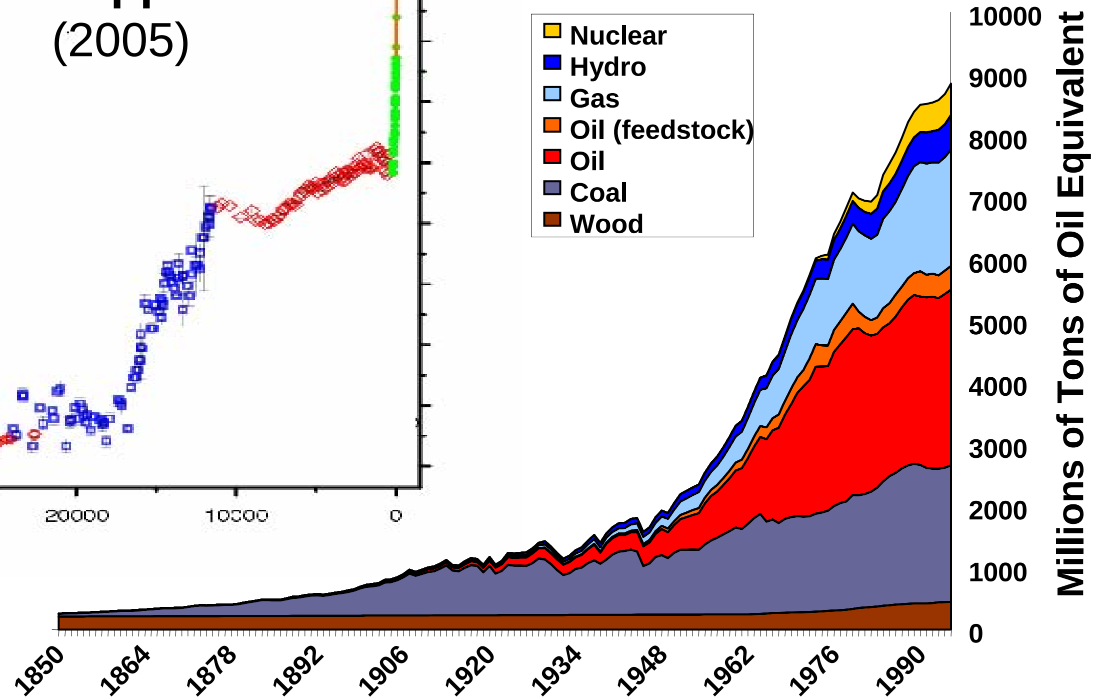
Deployment issues, including regulatory, legal, and operational concerns can be addressed through development of operational protocols advised by science IN LARGE PROJECTS

Site characterization, monitoring, and hazard assessment & management are keys to commercial success

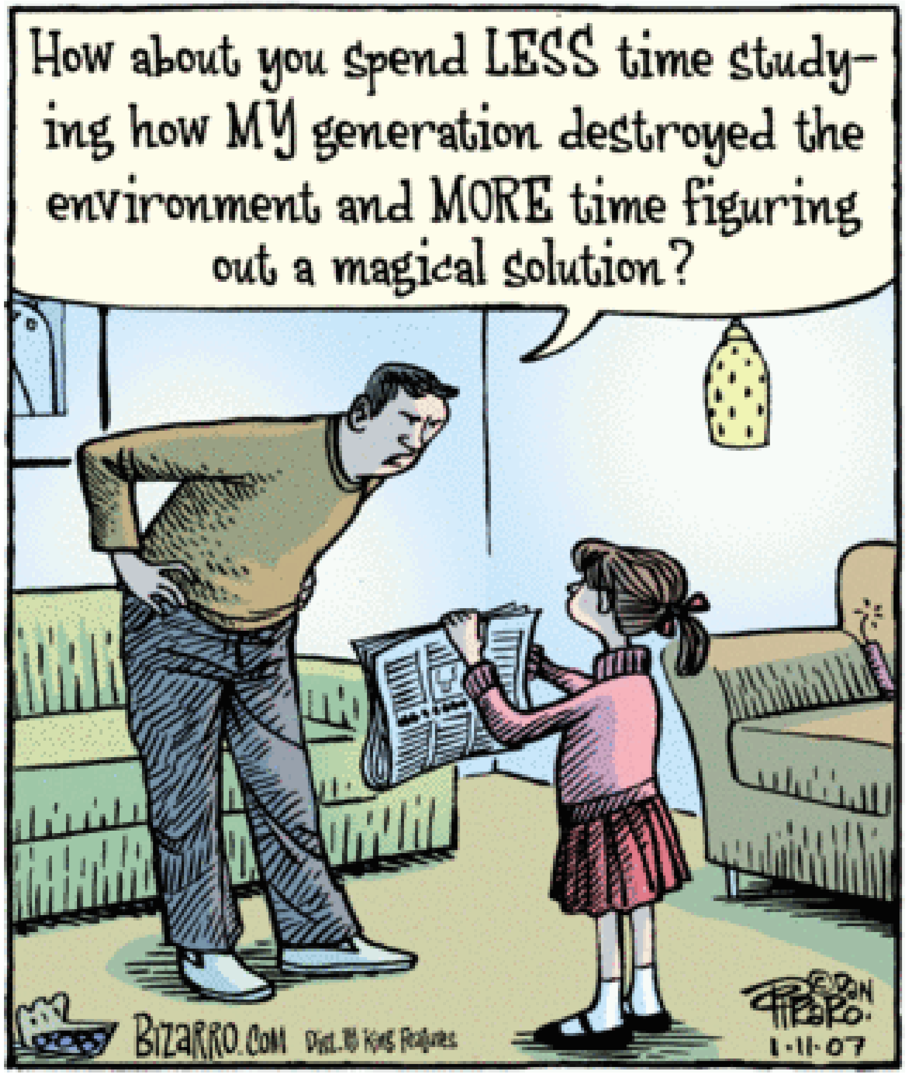
This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

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





The Need for Speed



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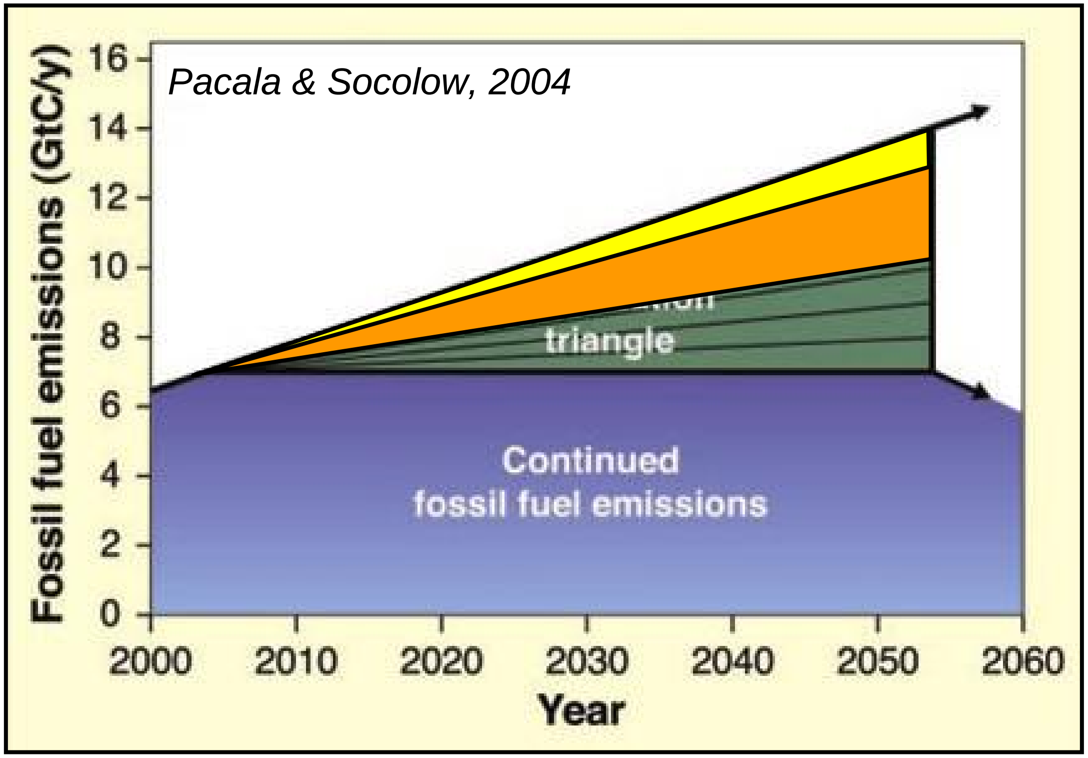
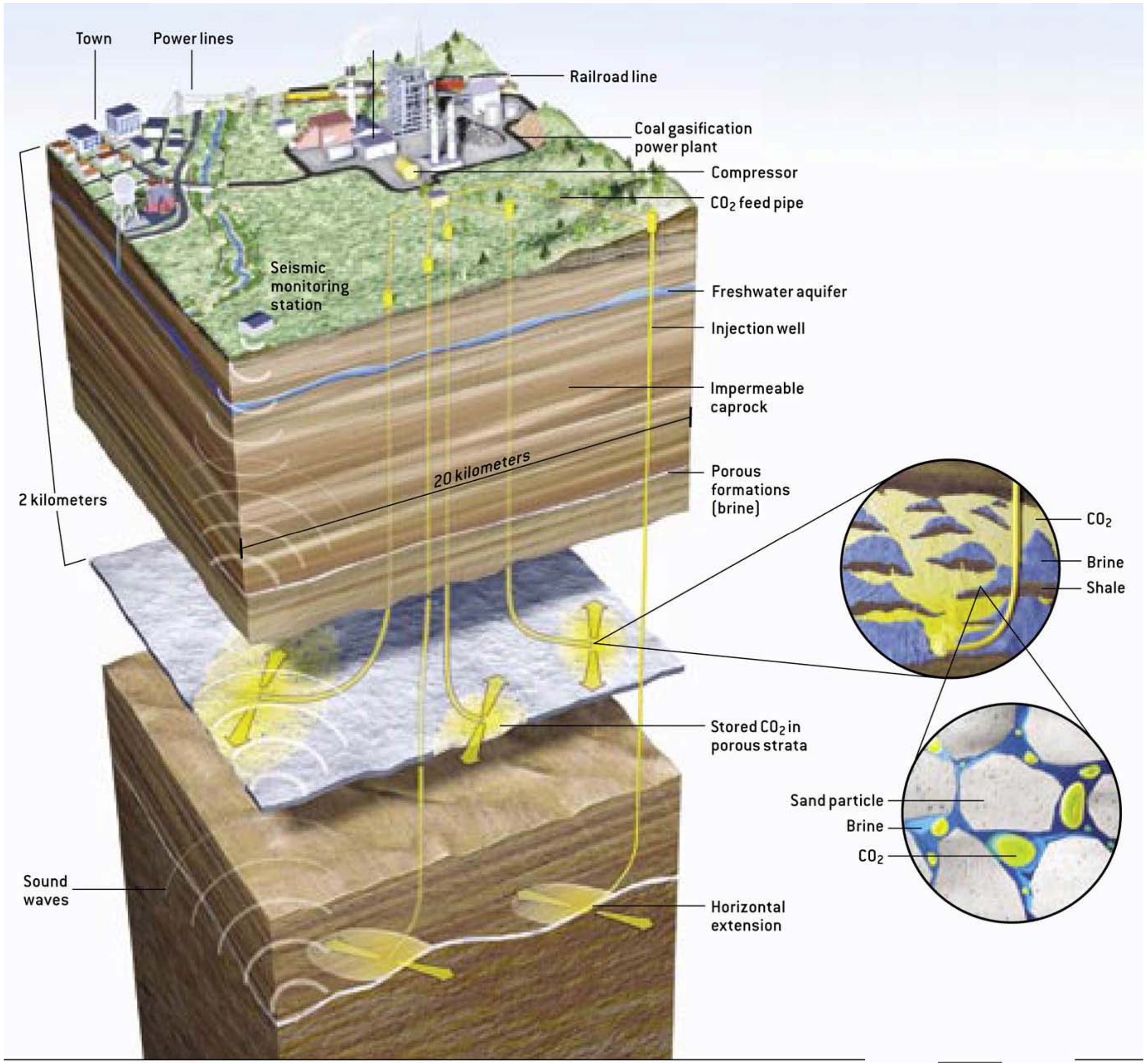
CO_2 Capture & Sequestration (CCS) can provide 15-50% of global GHG reductions



- ***ACTIONABLE***
- ***SCALEABLE***
- ***COST-EFFECTIVE***

- **A key portfolio component (w/ cons., effic., nuclear, renew.)**
- **Cost competitive to other carbon-free options (enables others, like hydrogen)**
- **Uses proven technology**
- **Applies to existing and new plants**
- **Room for cost reductions (50-80%)**

Carbon dioxide can be stored in deep geological formations as a dense, pore-filling fluid

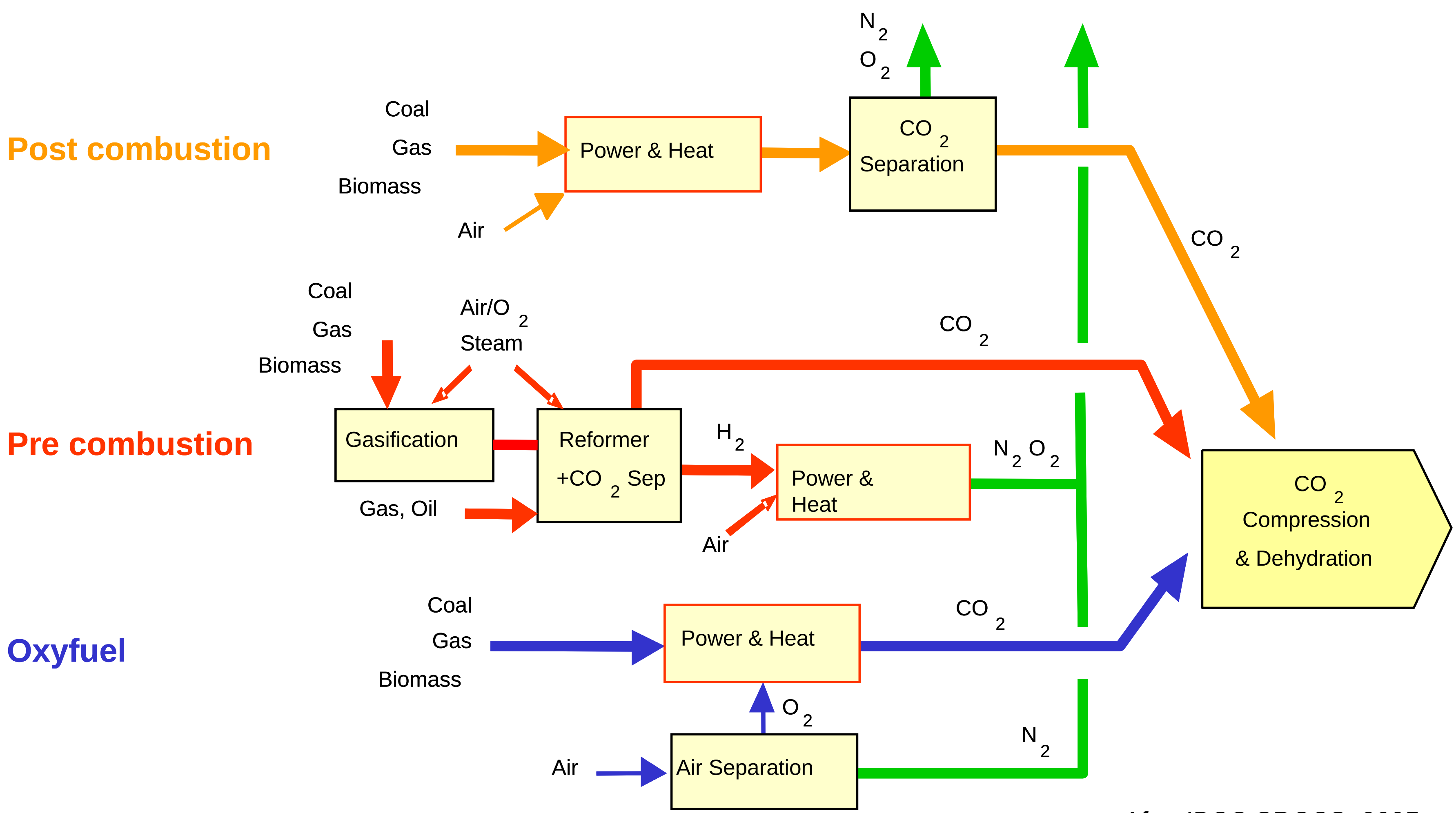


- **Saline Formations:** ***largest capacity (>2200 Gt)***
- **Depleted Oil & Gas fields:** ***potential for enhanced oil and natural gas recovery***

Scientific American, 2005

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

Three technology pathways can capture and separate large volumes of CO_2



After IPCC SRCCS, 2005

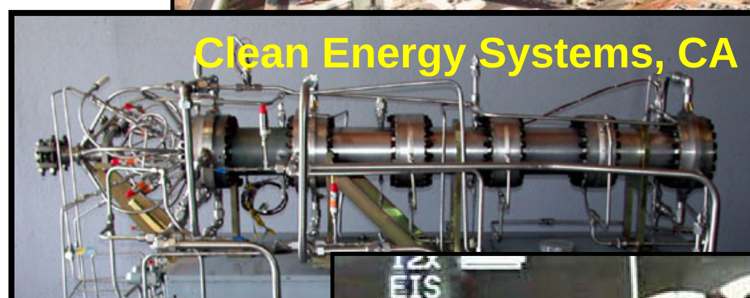
High purity (>95%) CO_2 streams are required for storage

Capture devices for standard existing plants are relatively high in cost.

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

Typical PC plant	**\$40-60/t CO_2**
Typical gasified plant	**\$30-45/t CO_2**
Oxyfired combustion	**\$40-60/t CO_2***
Low-cost opportunities	**\$ 5-10/t CO_2**

Refineries, fertilizer & ethanol plants, polygeneration, cement plants, and gas processing facilities are cheapest. Pursuit of coal-to-liquids, H_2 fuel production, and oil shales will make additional high concentration streams



***** Not yet ready for prime time***

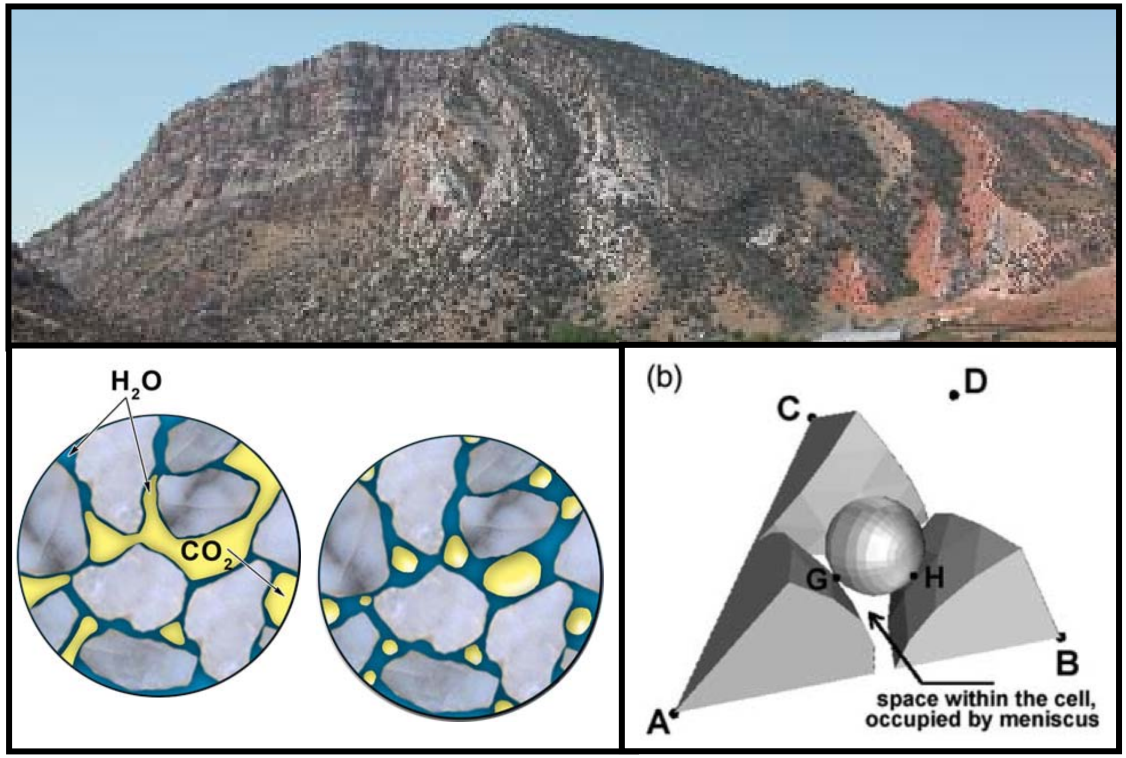
Storage mechanisms are sufficiently well understood to be confident of effectiveness

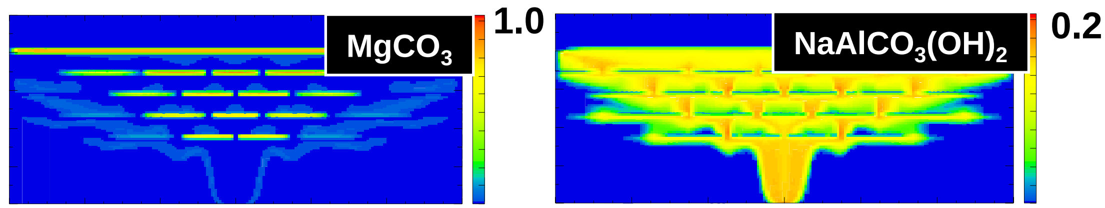
Physical trapping
- Impermeable cap rock
- Either geometric or hydrodynamic stability

Residual phase trapping
- Capillary forces immobilized fluids
- Sensitive to pore geometry (<25% pore vol.)

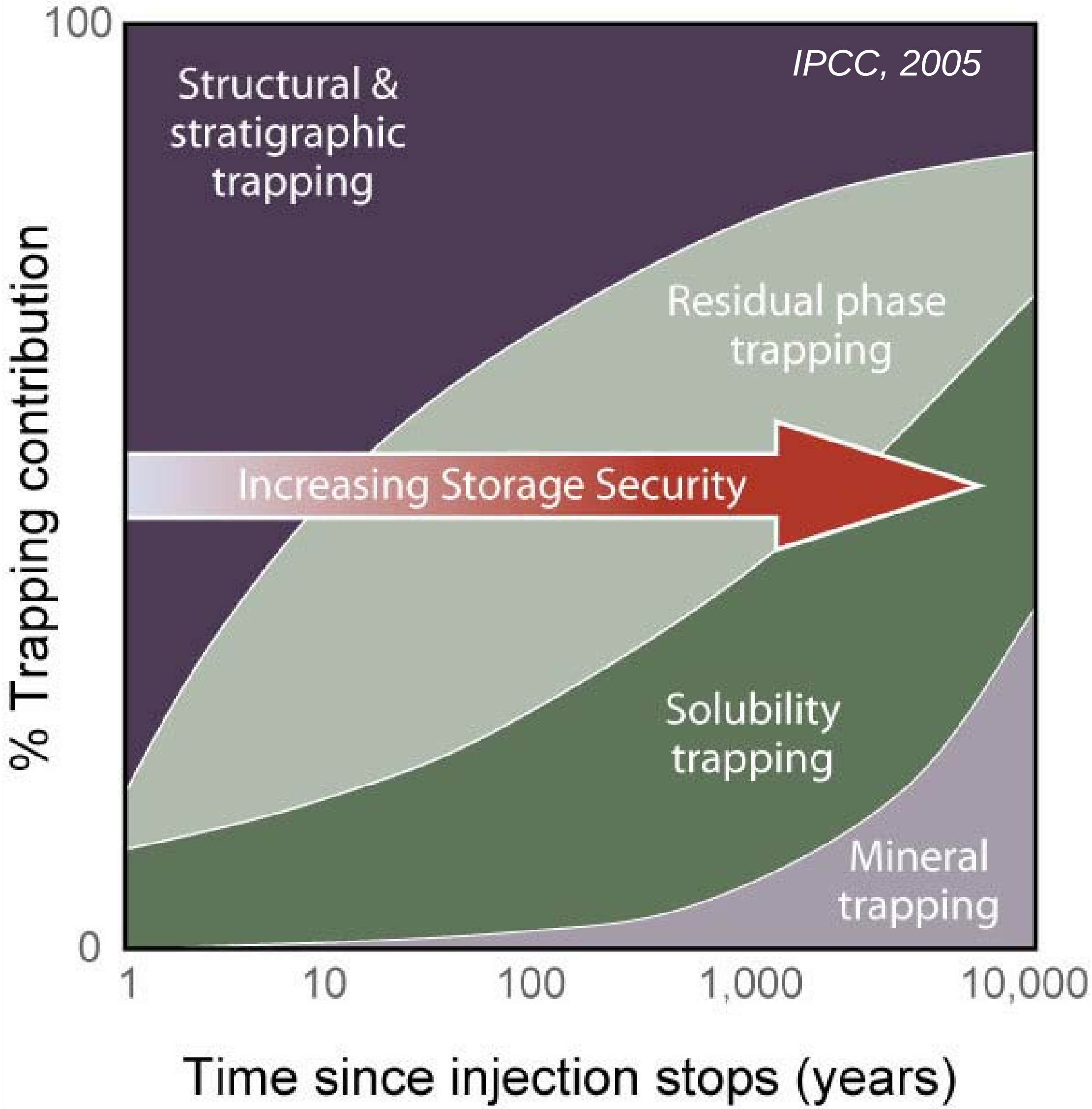
Solution/Mineral Trapping
- Slow kinetics
- High permanence

Gas adsorption
- For organic minerals only (coals, oil shales)





The crust is well configured to trap large CO_2 volumes indefinitely

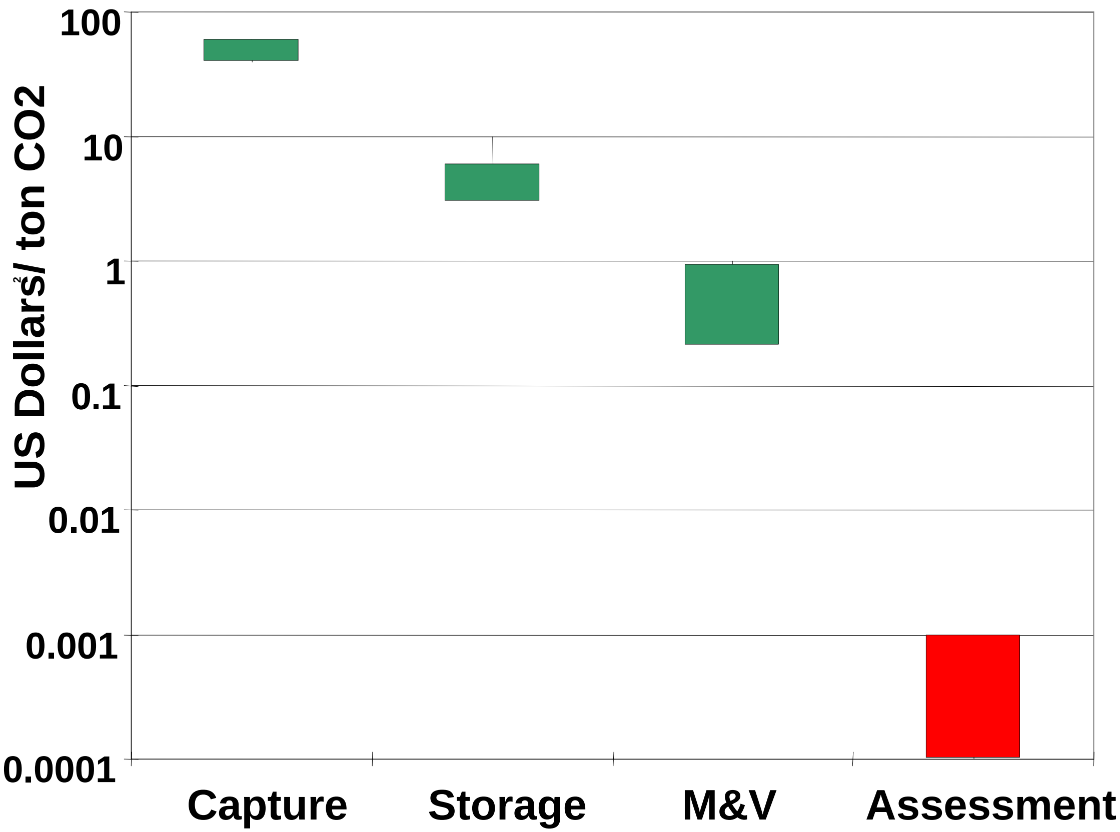


Because of multiple storage mechanisms working at multiple length and time scale, the shallow crust should attenuate mobile free-phase CO_2 plumes, trap them residually, & ultimately dissolve them

This means that over time risk decreases and permanence increases

Assessments represent the lowest cost, highest impact step in CCS

Expected Costs of CCS Technology Elements



Friedmann et al., 2006

Capture: \$40-80/t CO_2
Storage: \$3-8/t CO_2
M&V: \$0.2-\$1.0/t CO_2
Assessment: <\$0.01/t CO_2

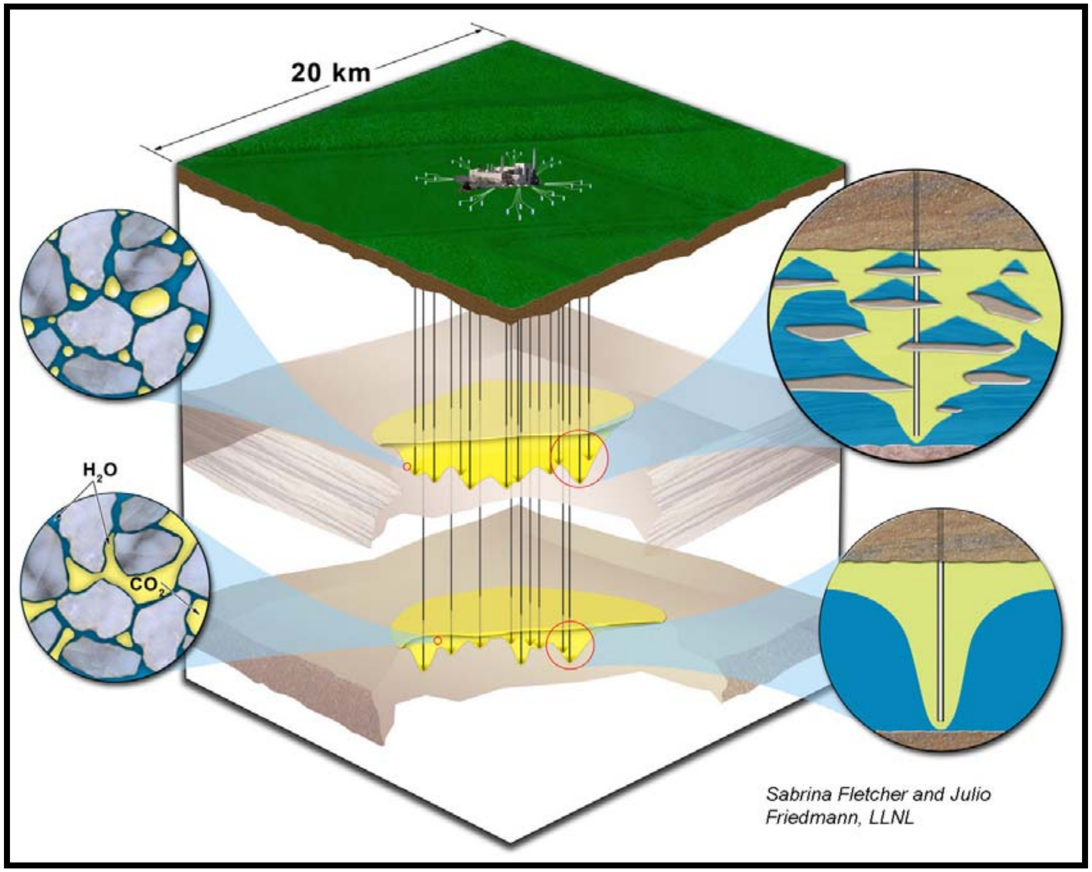
IN GENERAL TERMS, CCS **is cost competitive with new nuclear and wind.**

Locally, this will vary considerably

For any large injection volume, local assessment is extremely low in cost and can be executed with conventional technology

The true scope of large-scale CCS deployment is the primary challenge

Let's suggest that by 2020, all new coal plants will be fitted for CO_2 capture and storage *(watch this space)*. The scope and scale of injection from a single plant must be considered.



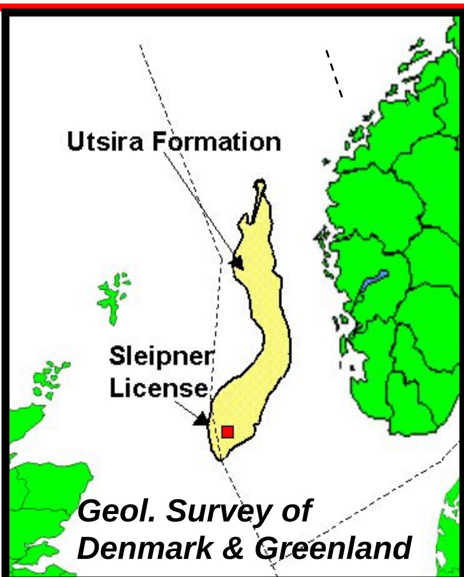
Sabrina Fletcher and Julio Friedmann, LLNL

One 1000 MW coal plant, 85% c.f., 90% capture:

- **5-8 MM t CO_2/yr**
- **120,000-200,000 bbl/d (as supercritical phase)**
- **After 60 year, 2.8-4 G bbls**
- **CO_2 plume at 10y, ~10 km radius: at 50 yrs, ~30 km**
- **Tens to hundreds of wells**
- **Likely injection into many stacked targets**

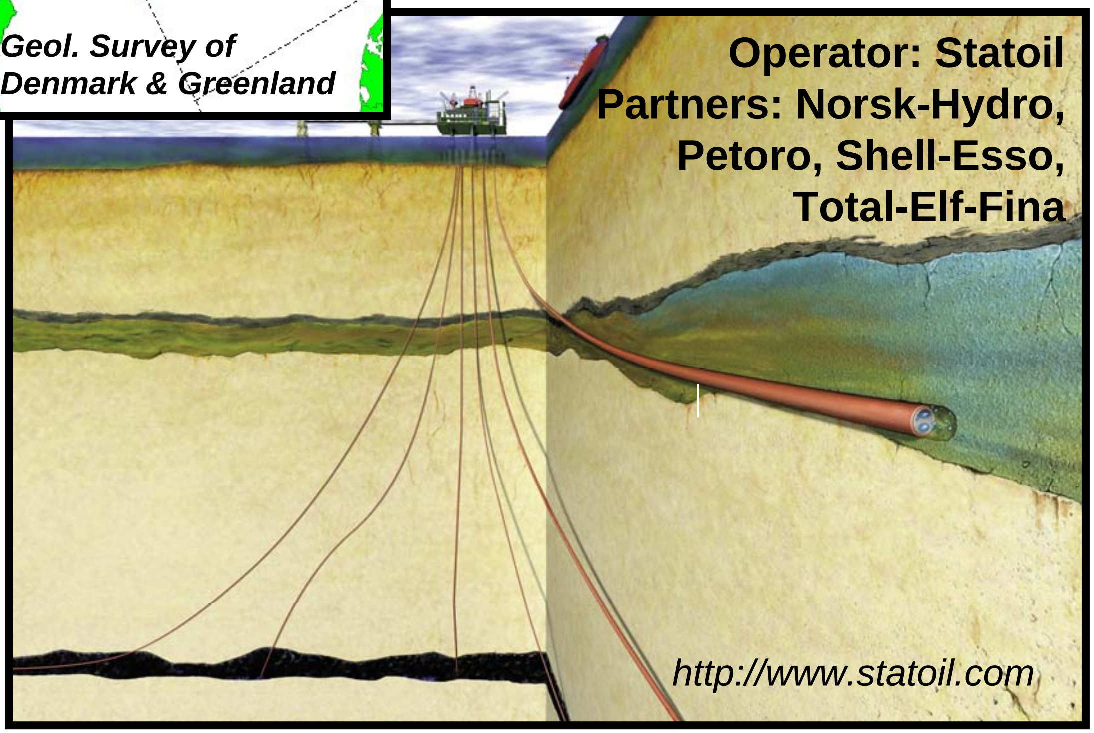
One wedge is 700 of these

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

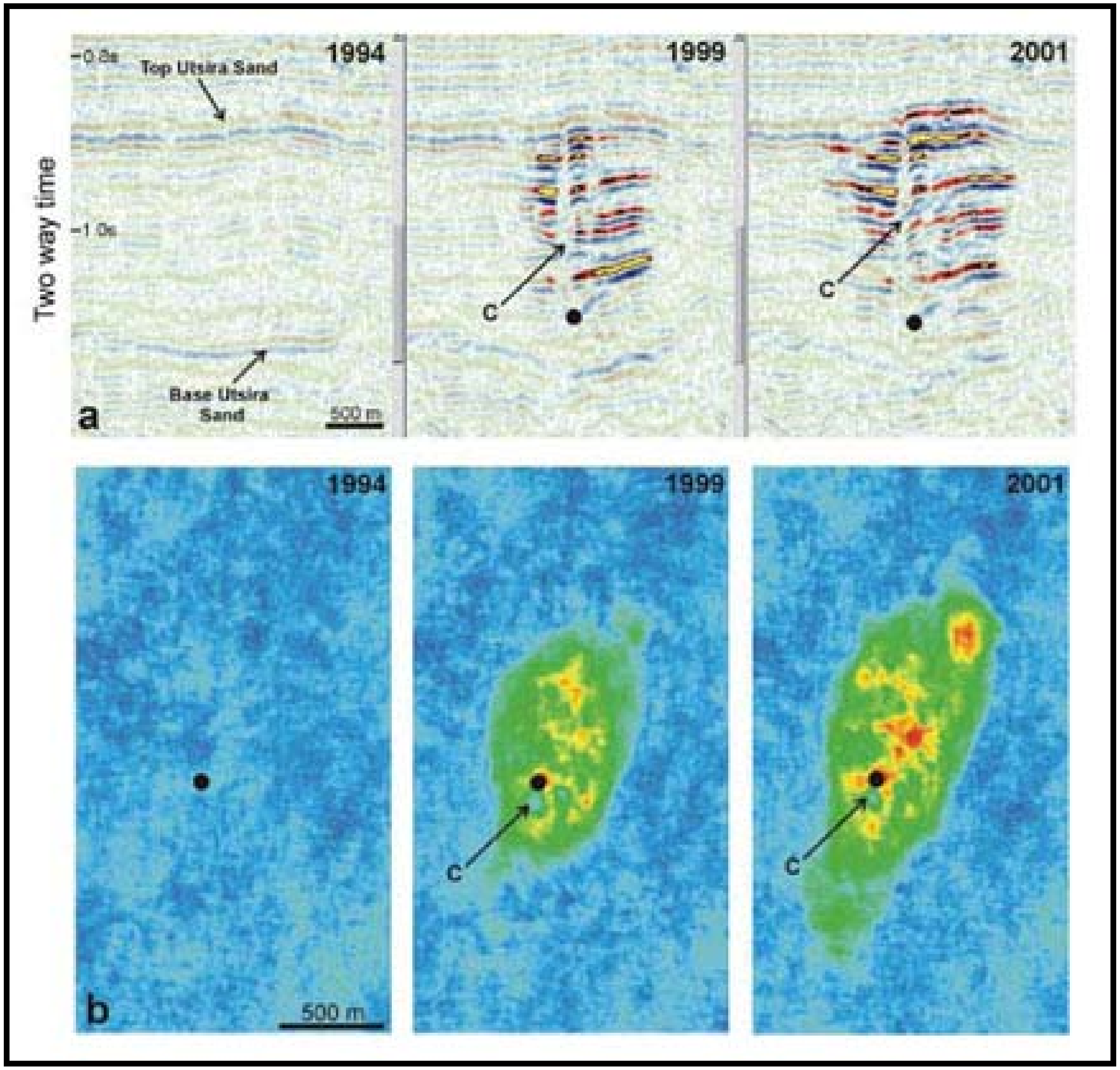


Target: 1 MM t CO_2/yr. So far, 10 MM t

Miocene Aquifer: DW fan complex

- **30-40% porosity, 200 m thick**
- **high perm. (~3000 mD)**
- **between 15-36 °C – w/i critical range**

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



Chadwick et al., 2004

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.

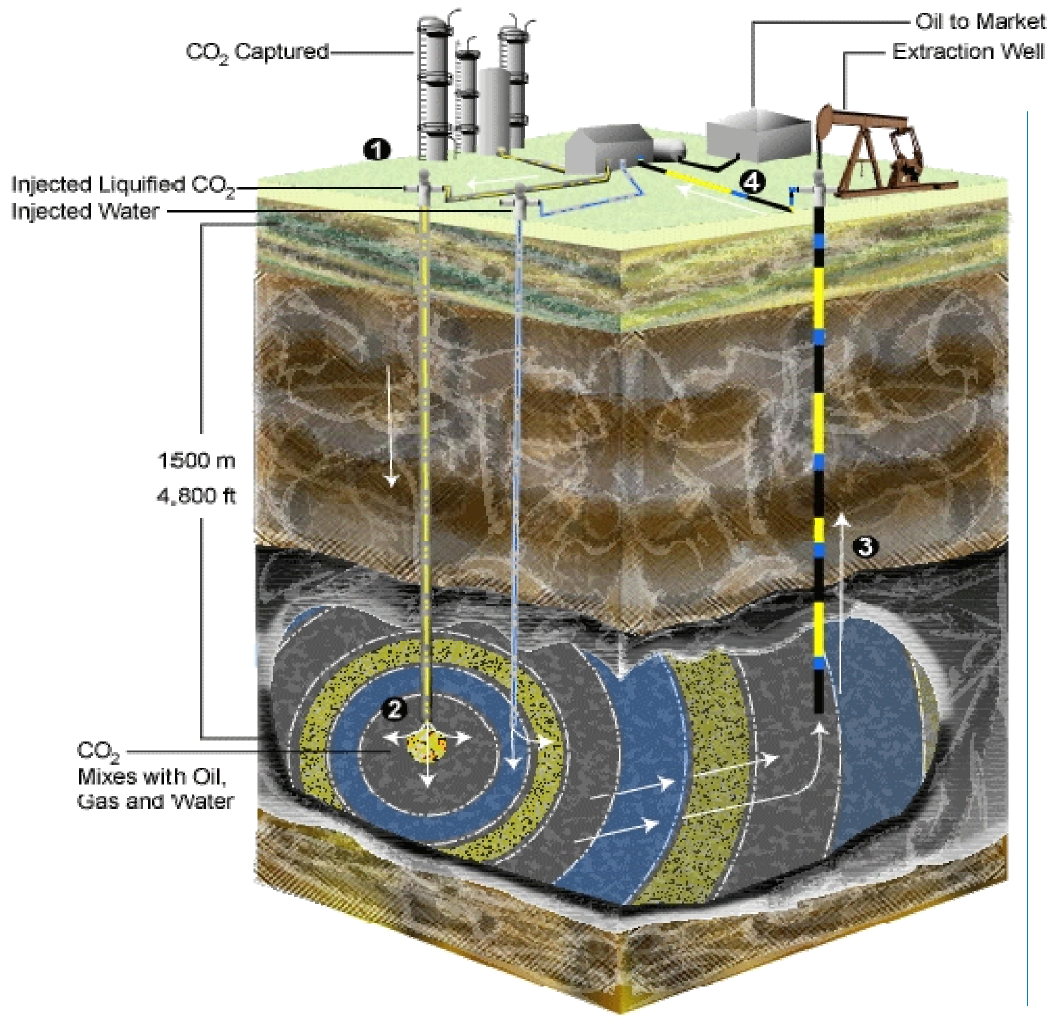
Weyburn: Transport from North Dakota gasification plant to EOR field

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

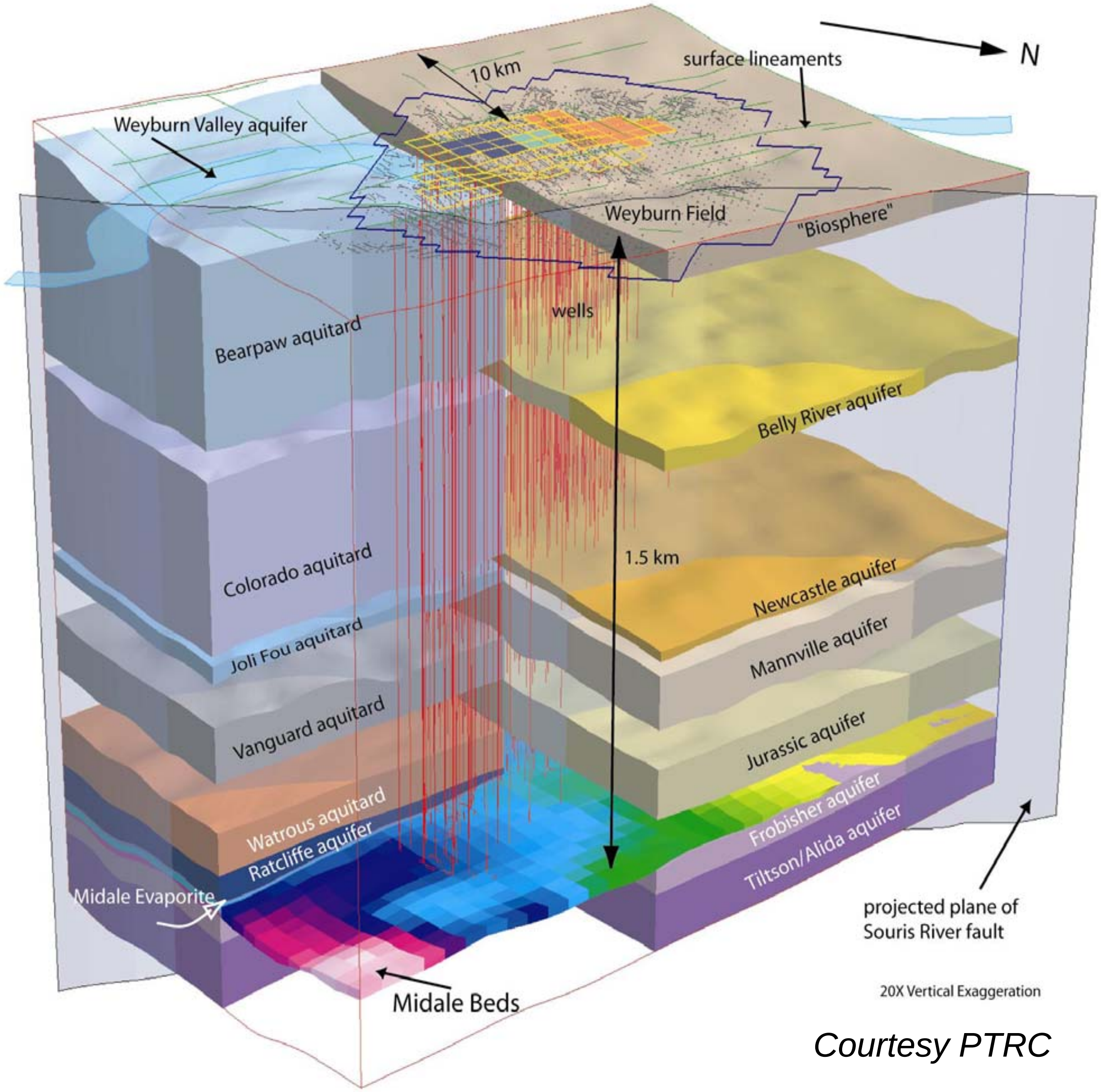
- **Discovered: 1954**
- **>2.0 Gbbl OOIP**
- **Additional recovery ~130 MM barrels**
- **>26 M tons CO2 stored**
- **4 year, $24M science project; expand to second phase**



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

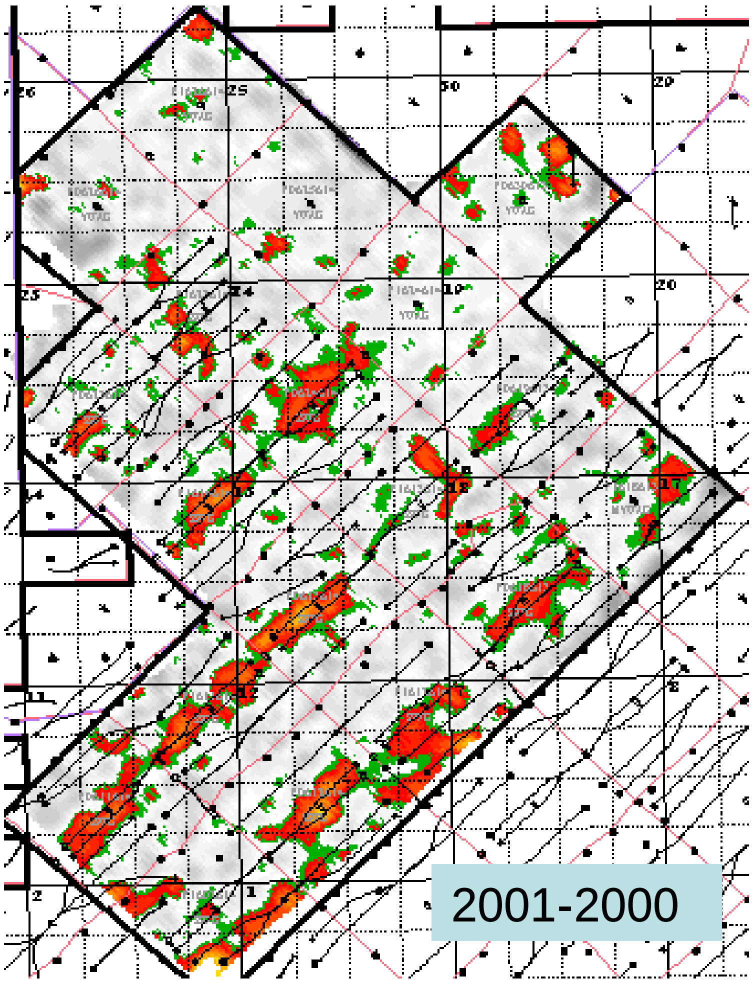


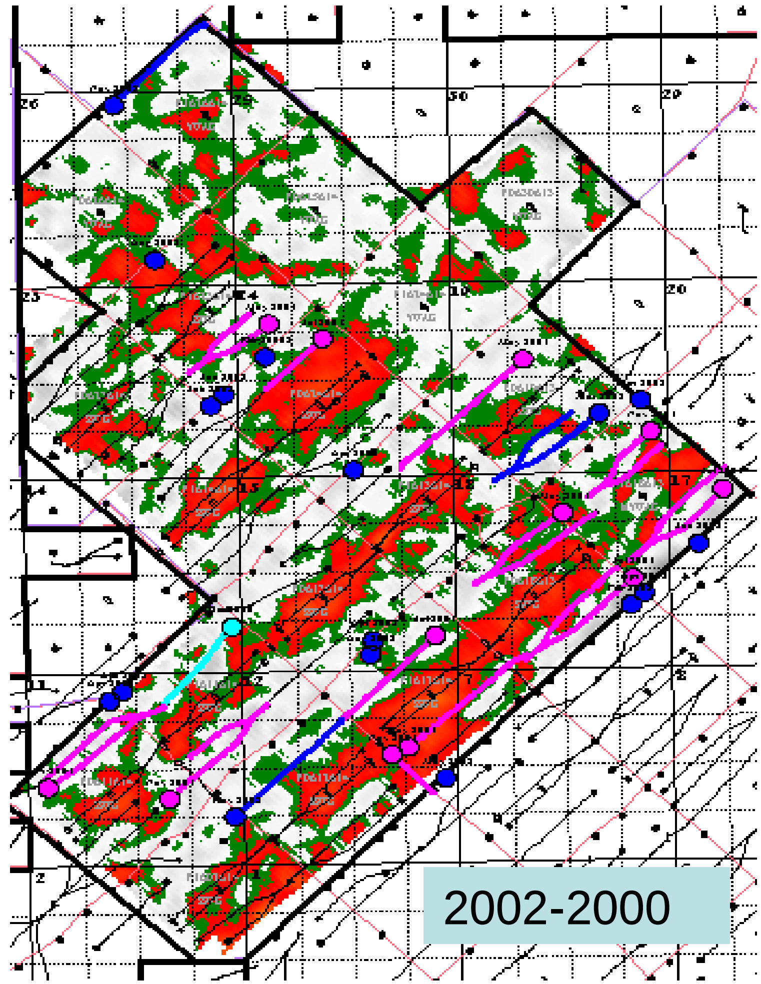
Courtesy PTRC

4D-3C Time-Lapse Seismic Surveys

vs. Baseline survey (Sept. 2000)

Marly Zone

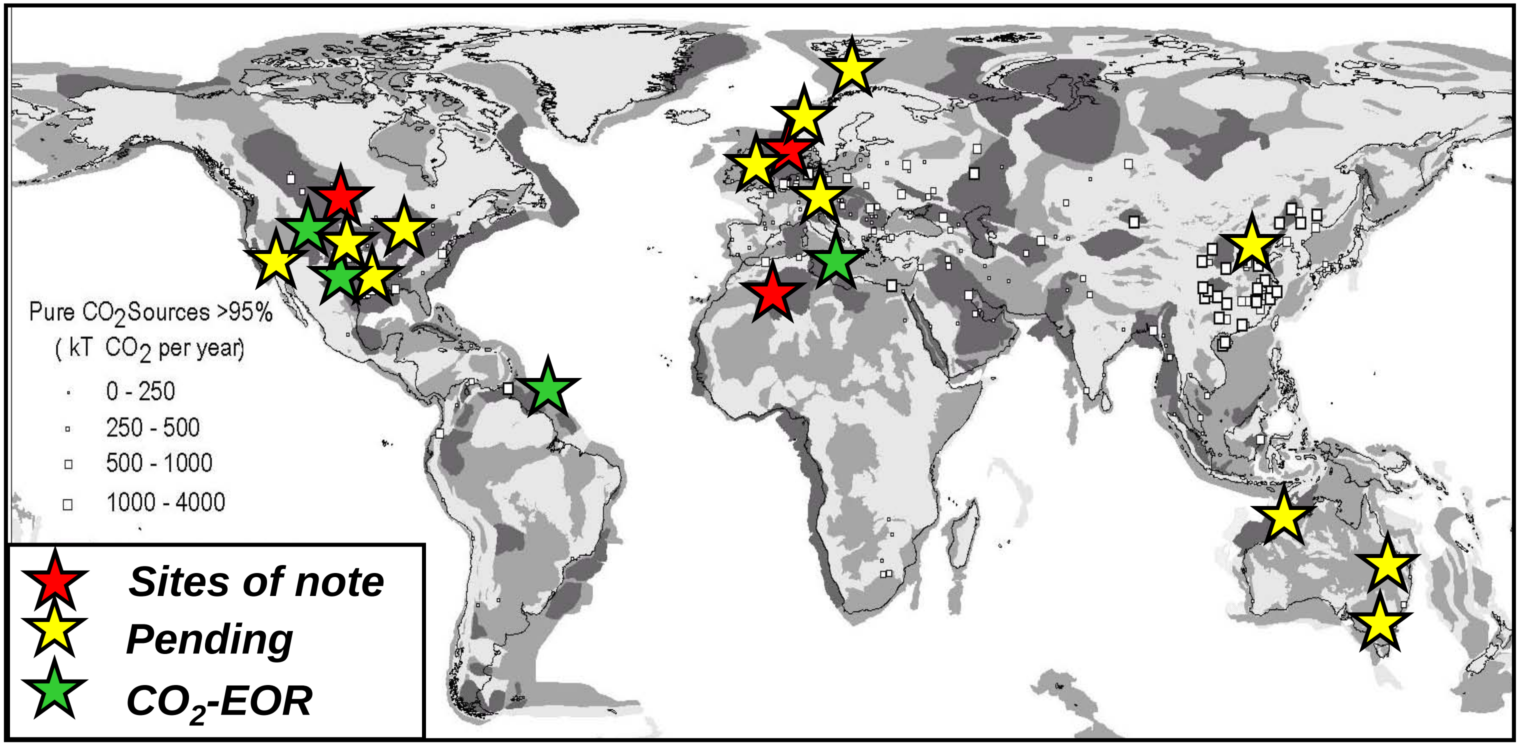




Wilson & Monea 2004

We need large projects to give the technical basis regulation and legal frameworks

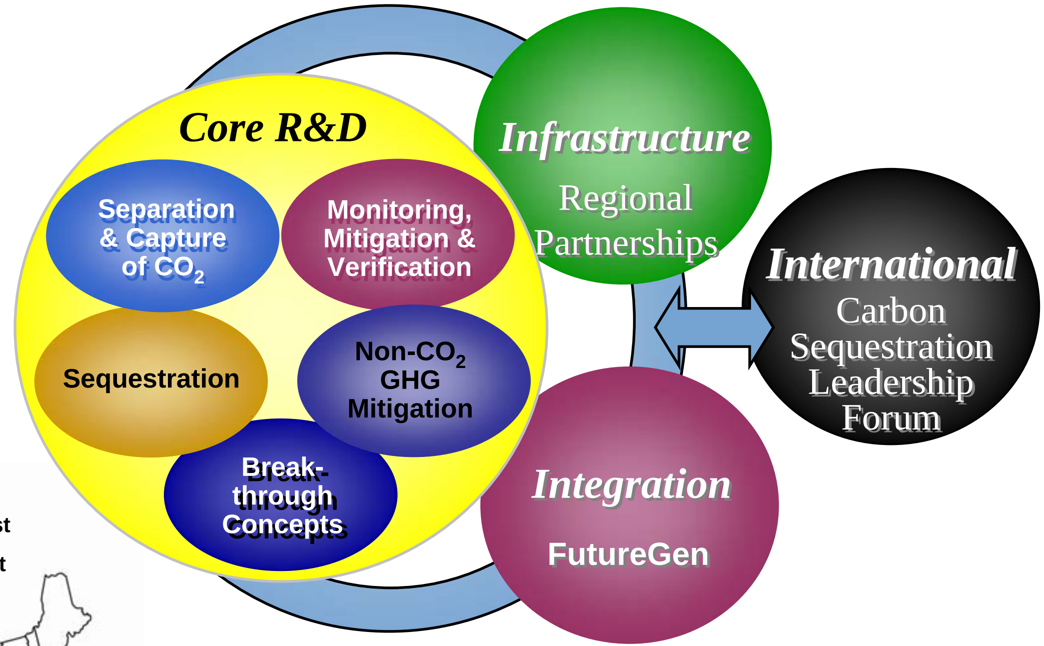
The projects demonstrate the high chance of success for CCS

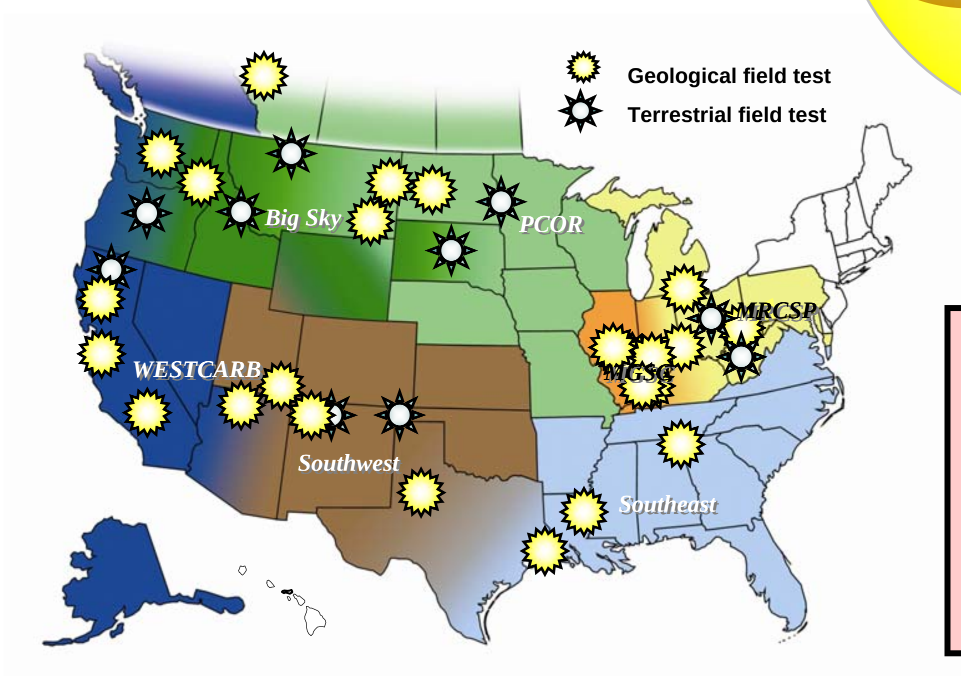


These studies are still not sufficient to provide answers to all key technical questions or to create a regulatory structure

To address CCS challenges, the DOE Clean Coal Program has built a substantial research effort

The US program ($100M/y) has three main planks: FutureGen, Core R&D, and the Regional Partnerships.

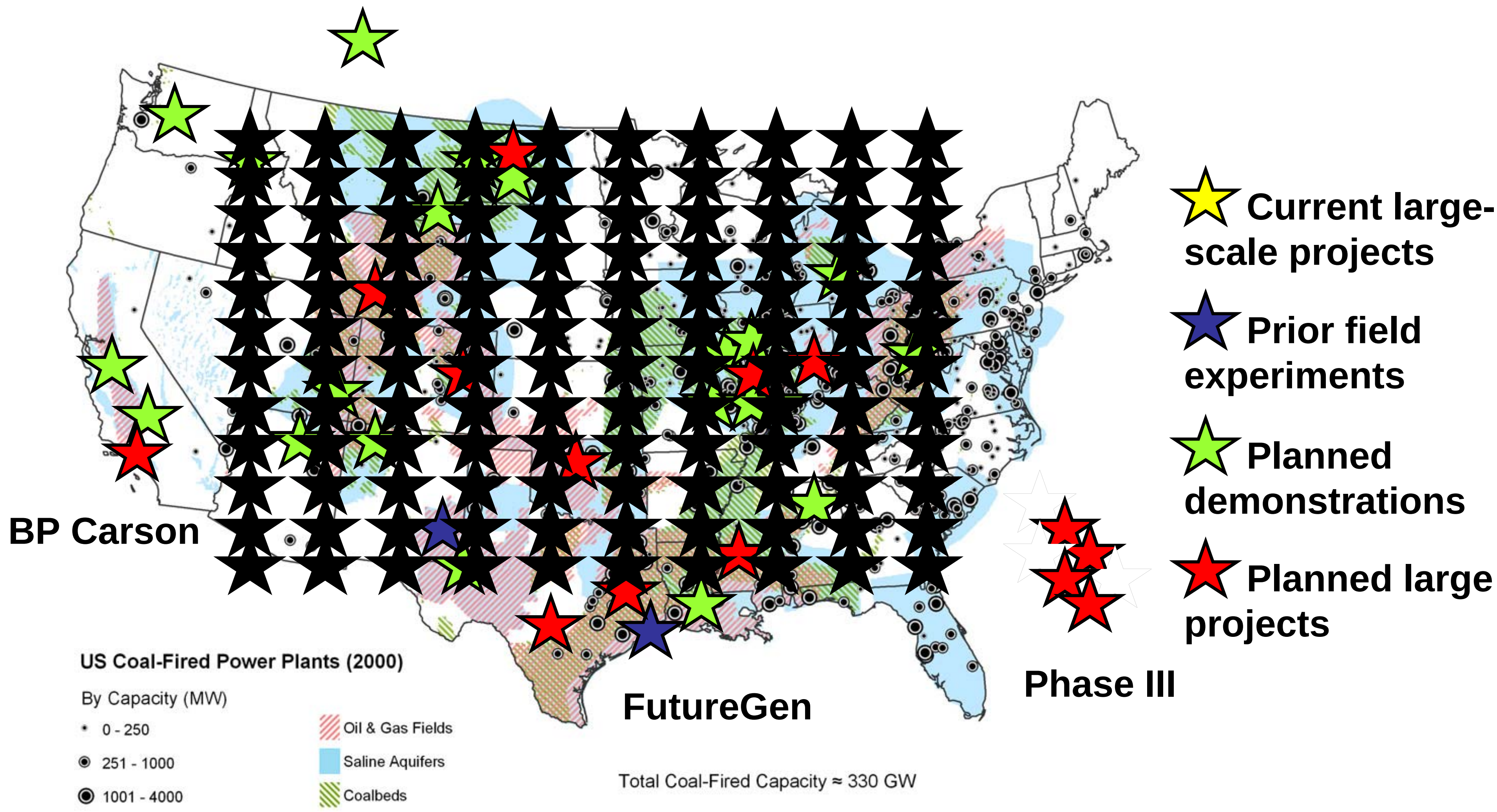




The partnerships work in 42 states and 5 provinces, with members from industry, government, academia, and FFRDCs

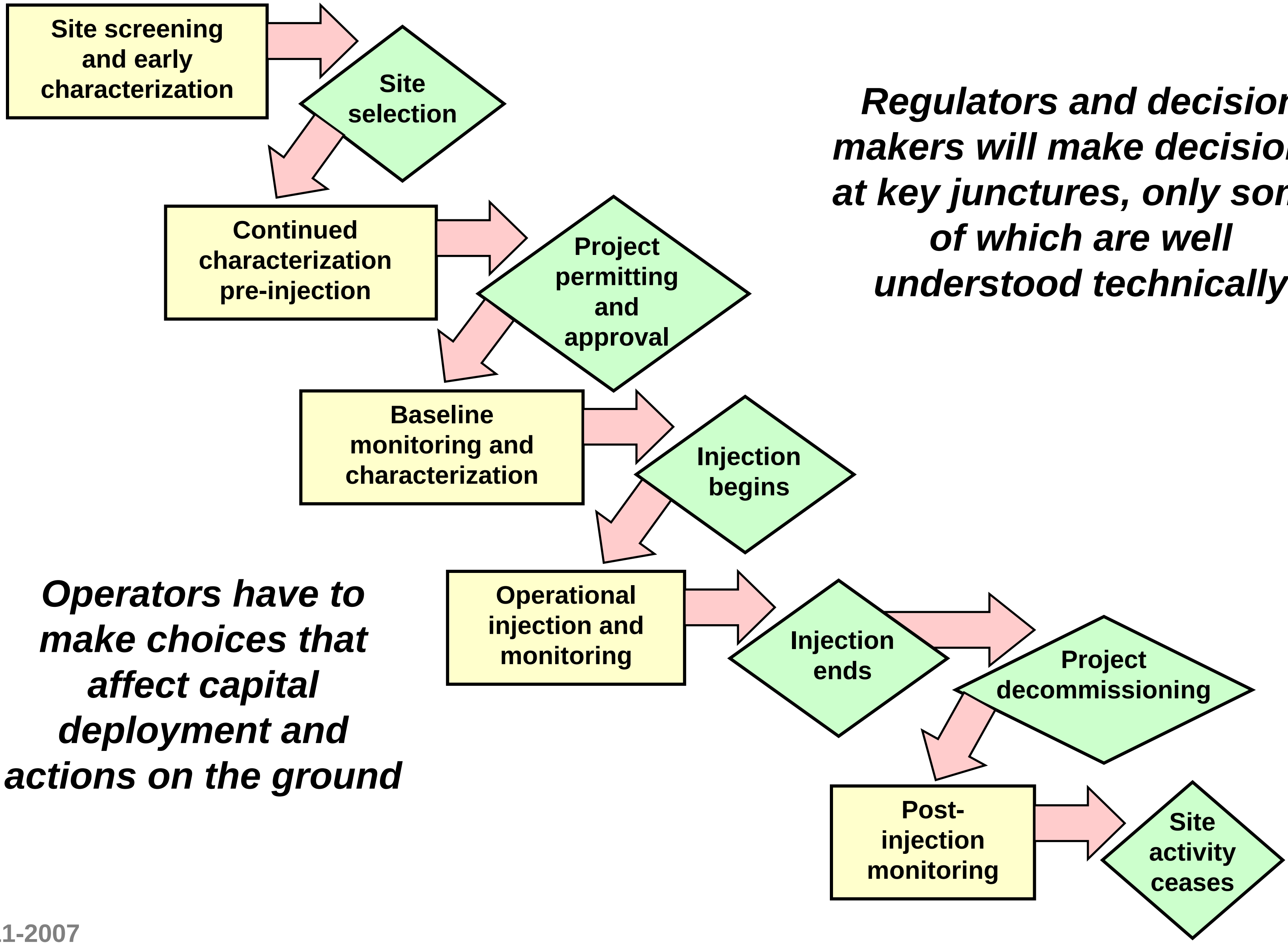
Courtesy US DOE

Large projects in the US are announced from many parties in many regions



These projects are proceeding with great uncertainty

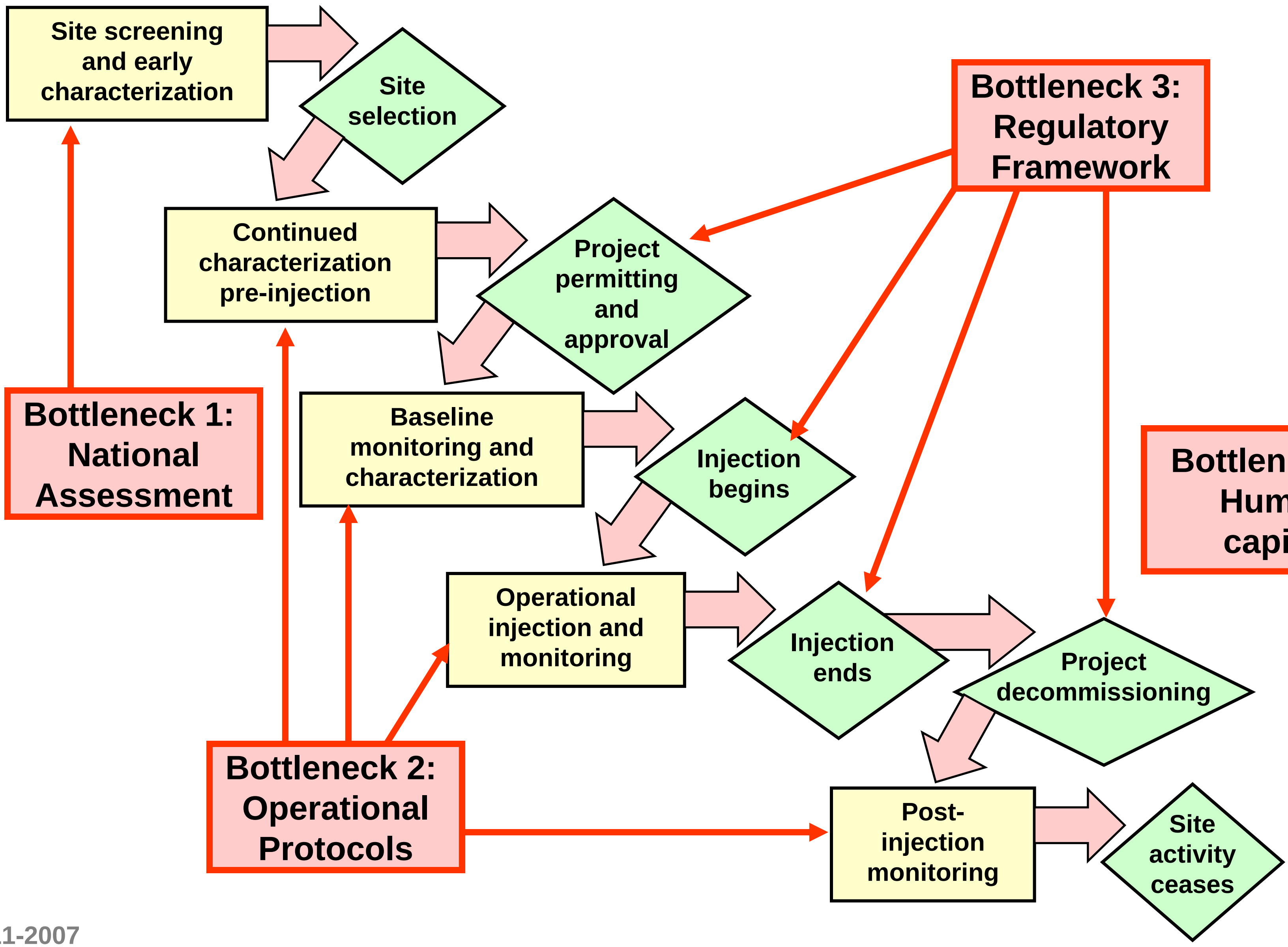
The drive to deployment has brought focus on life-cycle of CCS operations and its key issues



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

CCS deployment will be limited by bottlenecks in information, knowledge, and expertise



Site selection due diligence requires characterization & validation of ICE

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

Injectivity

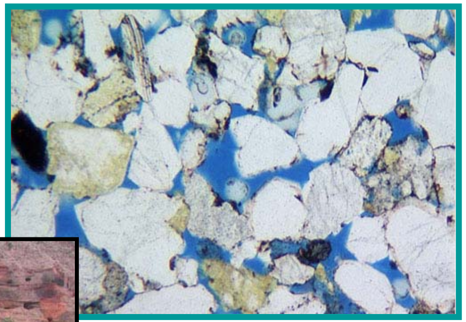
- **Rate of volume injection**
- **Must be sustainable (months – years)**

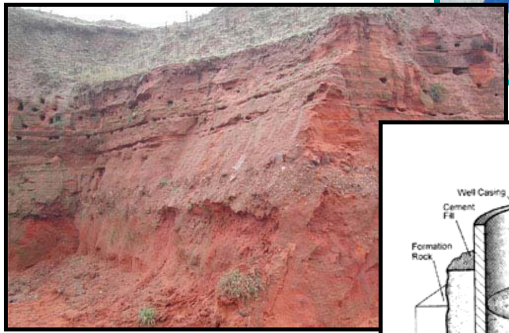
Capacity

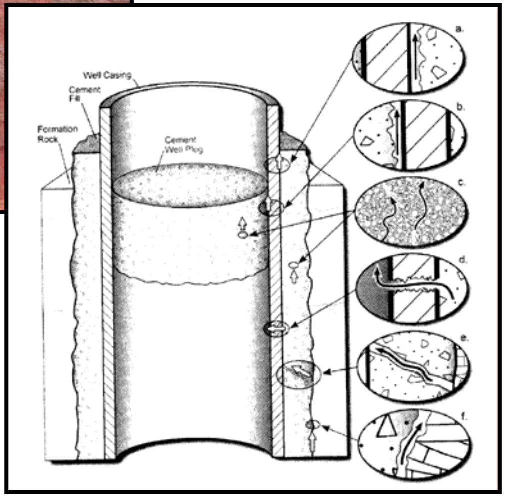
- **Bulk (integrated) property**
- **Total volume estimate**
- **Sensitive to process**

Effectiveness

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



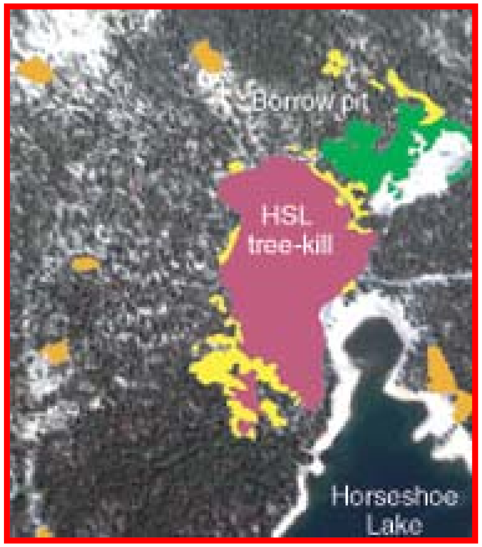




Gasda et. al, 2005

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)

The focus for CO_2 storage operations should be HAZARDS first, RISKS second

HAZARDS are easily mapped & understood, providing a concrete basis for action

RISK = Probability * consequence

RISKS are often difficult to determine

- **Hard to get probability or consequence from first principles**
- **Current dearth of large, well-studied projects prevents empirical constraint**

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, 2007

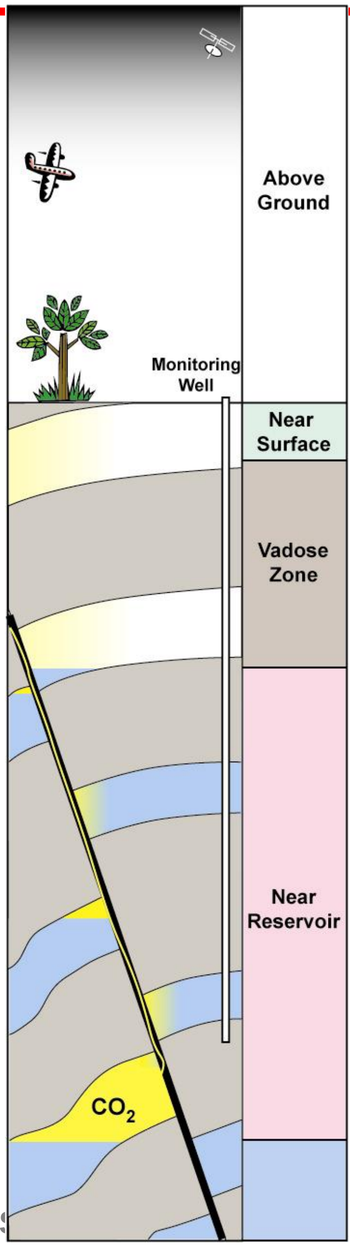
Because of local nature of hazards, prioritization (triage) is possible for any case

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

Once injection begins, monitoring & verification (M&V) is required



M&V serves these key roles:

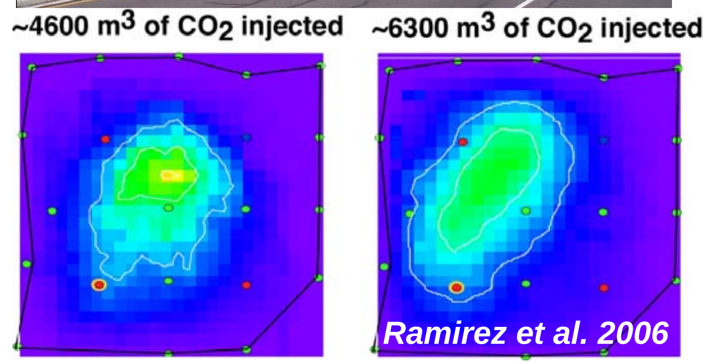
- Understand key features, effects, & processes
- Injection management
- Delineate and identify leakage risk and leakage
- Provide early warnings of failure
- Verify storage for accounting and crediting

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

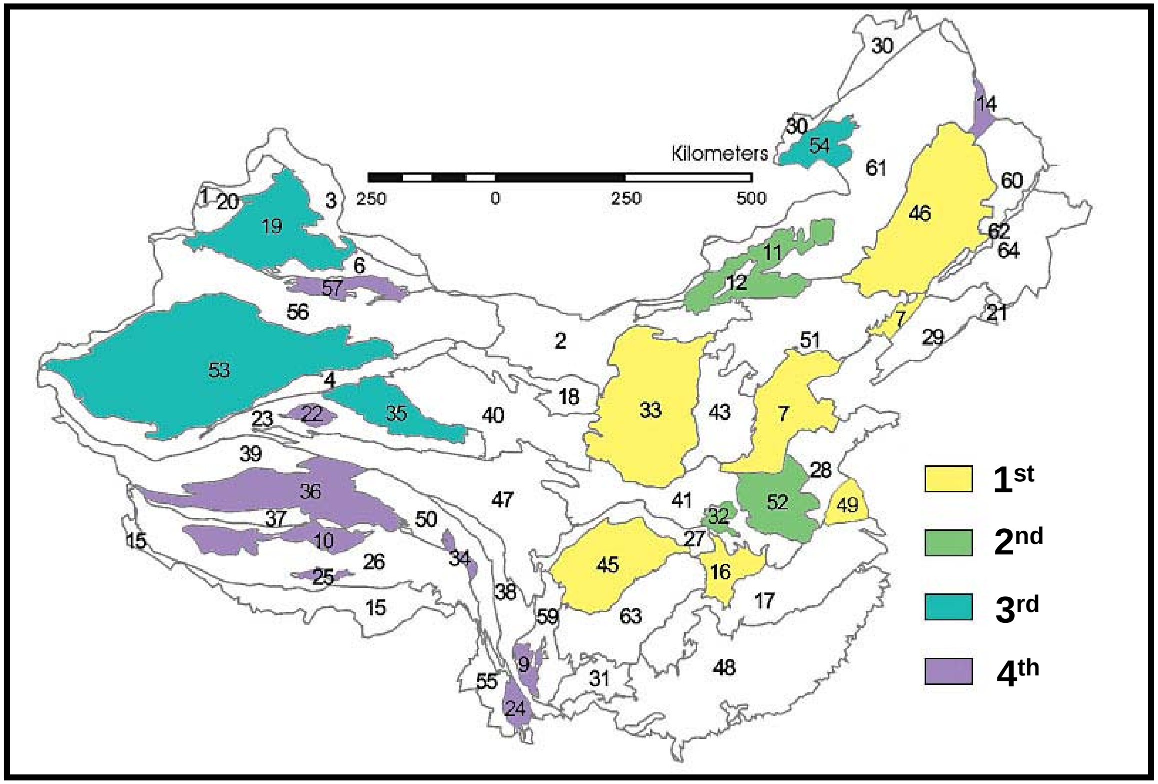
- Direct fluid sampling via monitoring wells (e.g., U-tube)
- T, P, pH at all wells (e.g., Bragg fiberoptic grating)
- CO_2 distribution in space: various proxy measures
  (Time-lapse seismic clear best in most cases)
- CO_2 saturation (ERT, EMIT likely best)
- Surface CO_2 changes, direct or proxy
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

Many tools exist to monitor & verify CO_2 plumes

Parameter	Best tool	Other tools
Fluid composition	Direct sample	(Surface sampling + simulation)
T, P fieldwide	Thermocouples & pres. sensors	Fiberoptic Bragg grating
Subsurface pH monitoring	pH sensors	
CO_2 distribution	Time-lapse seismic	(microseismic, tilt, VSP, electrical methods)
CO_2 saturation	Electrical methods (ERT)	(advanced seismic)
Surface detection	Soil gas, PFC tracing	(Atmos. eddy towers, FTIRS, LIDAR, hyperspectral)
Stress/strain changes	(Tri-axial tensiometers)	Bragg grating, tilt, InSAR



China capacity & opportunities can be quickly assessed and pursued



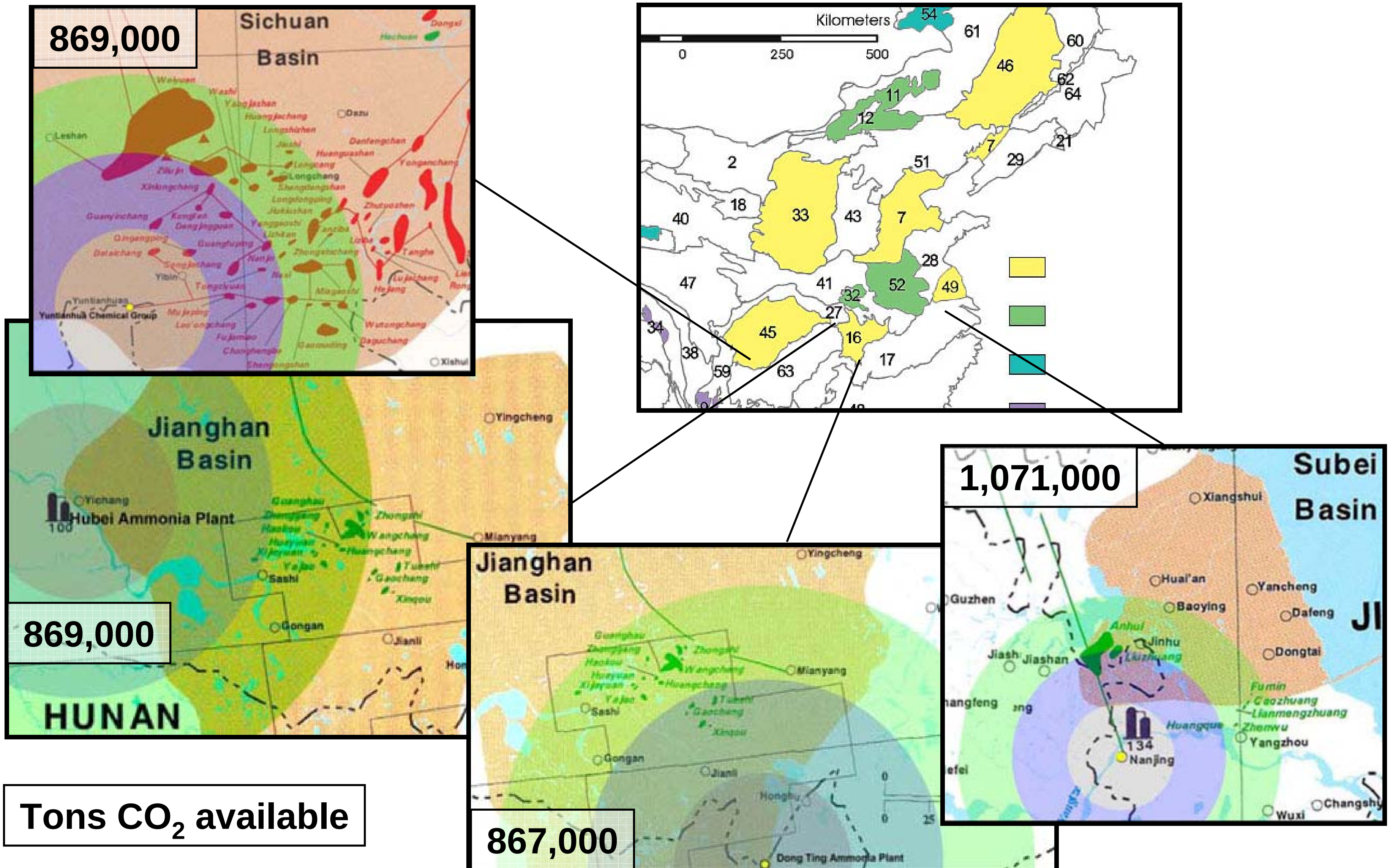
China is geologically very complex, requiring a long, large-scale effort at capacity assessment.

However, only a few of basins matter the most due to source proximity. These could be assessed fairly quickly and easily given proper cooperation and data access

- Songliao
- Bohainan-Liaodong
- Sichuan
- Jianghan
- Ordos
- Subei

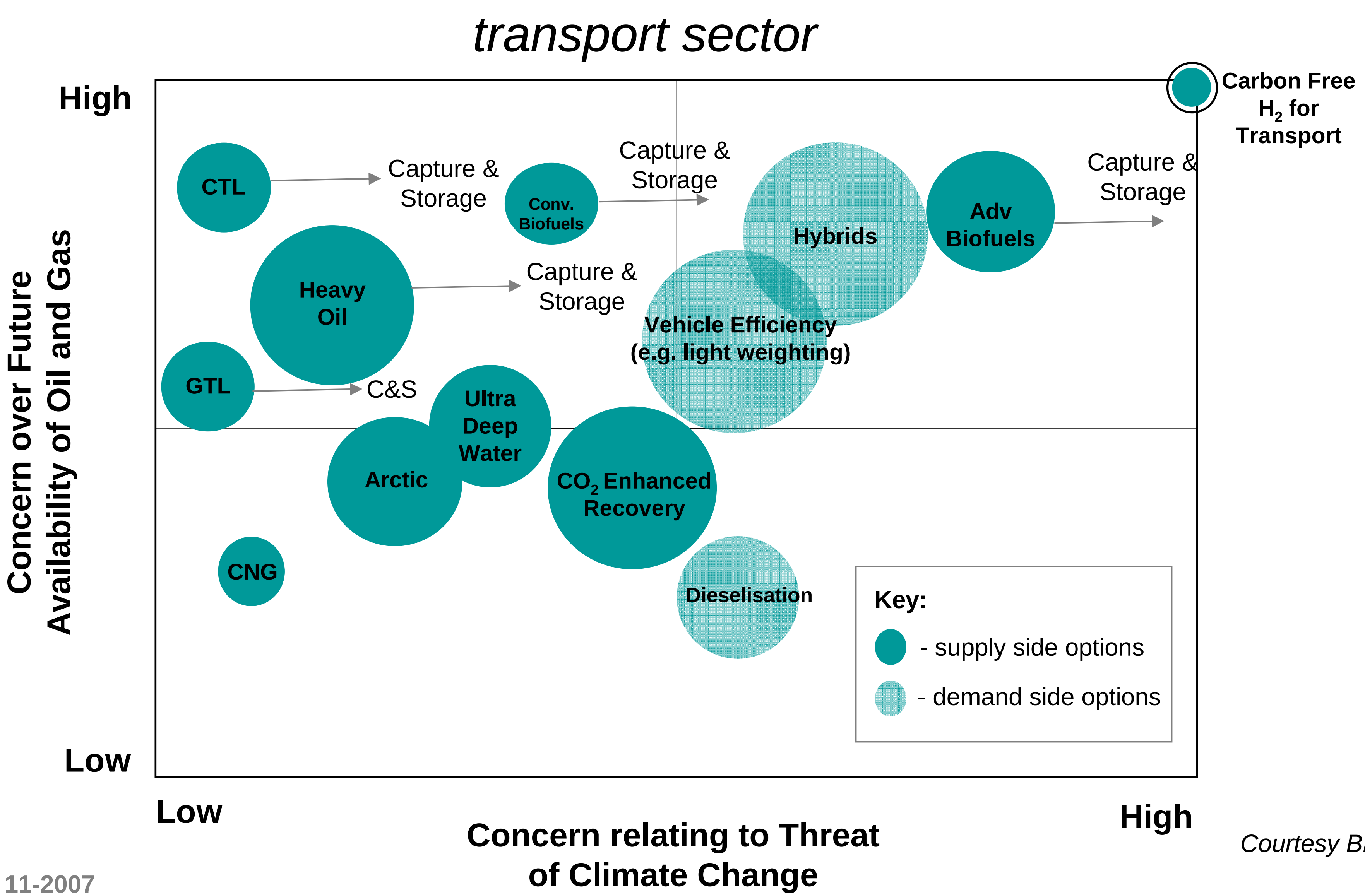
These basins lie near large, concentrated CO_2 sources and contain a relevant range of geology. Assessments, short pipelines, and wells could be completed at low cost.

Low-cost, value-added targets in Eastern China would help demonstrate effectiveness quickly



Meng et al., 2005

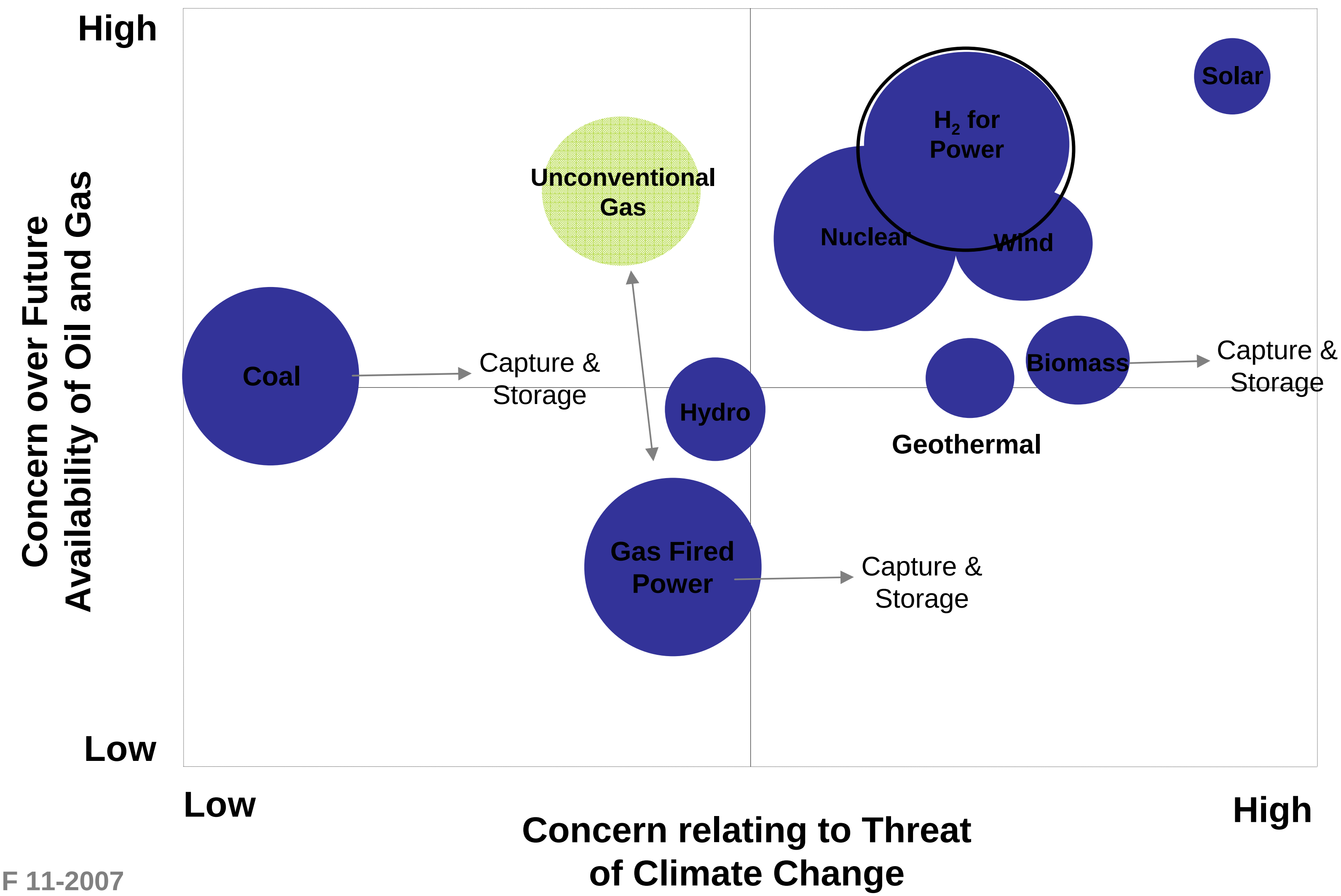
CCS can reduce the carbon footprint for transportation energy options



Courtesy BP

CCS can reduce the footprint of power options

power sector



Courtesy BP

Conclusions

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Current science and technology gaps appear resolvable at scale

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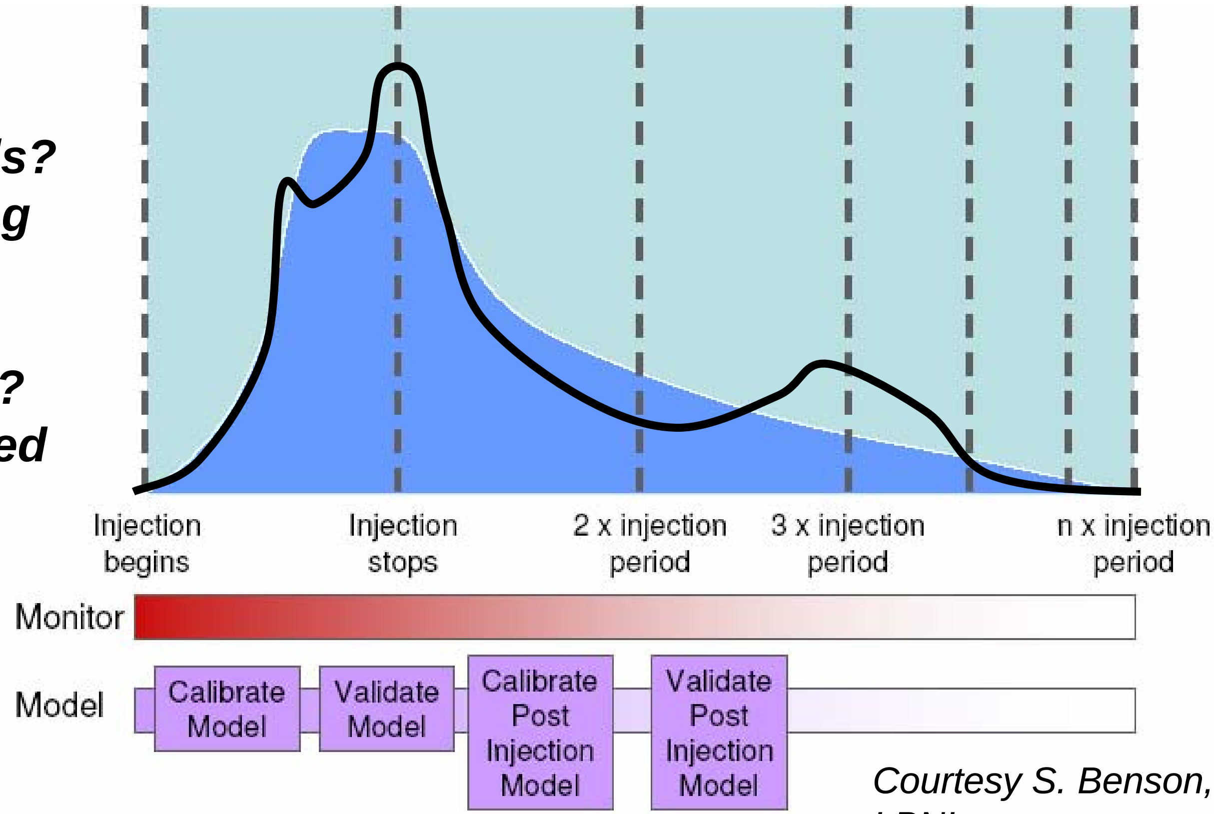
Site closure remains a poorly circumscribed problem from operational and regulatory views

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?***

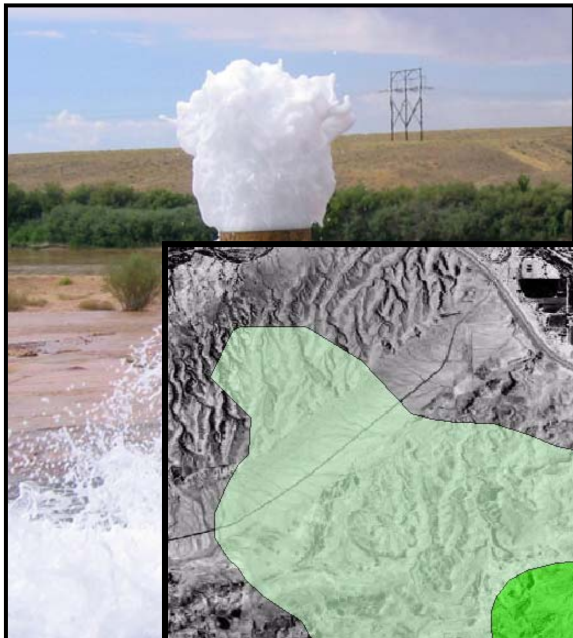
Conceptual Risk Profile

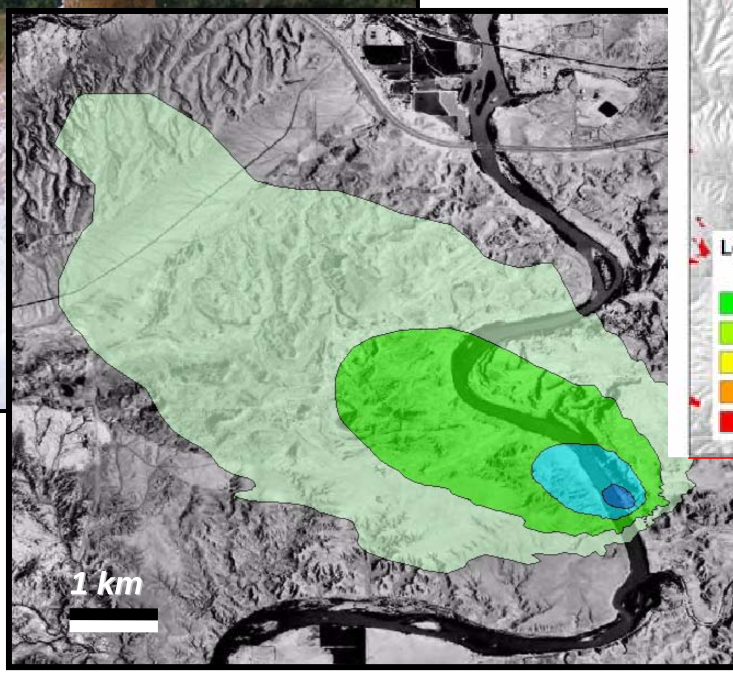


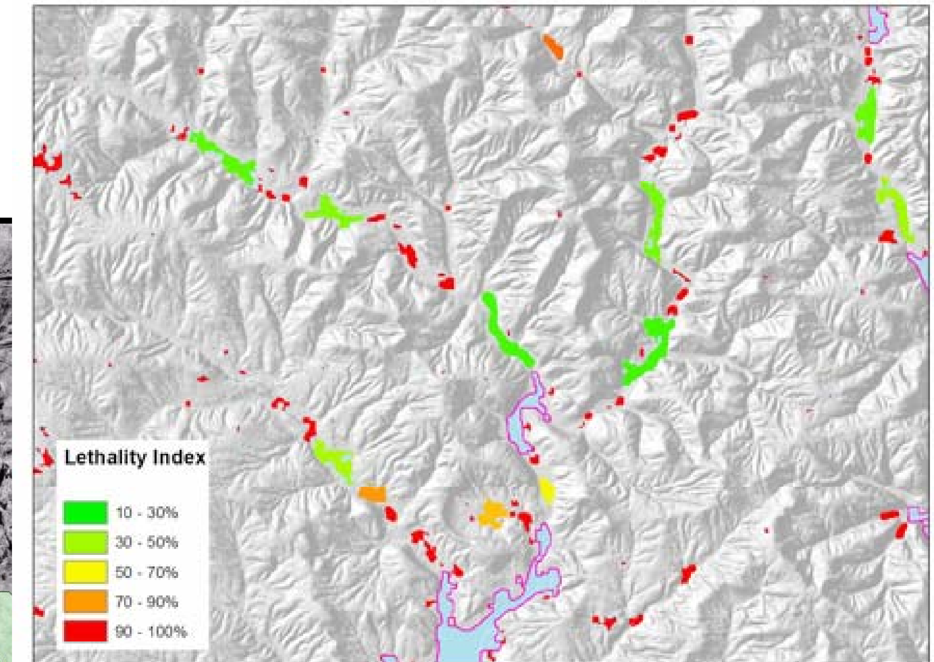
Courtesy S. Benson, LBNL

These uncertainties impede commitment of capitol to operational projects today

Managing leakage hazards should be FAST
Flexible, Actionable, Simple, and Transparent







Wells present a challenge to integrity and monitoring which could be resolved through technology application & regulation