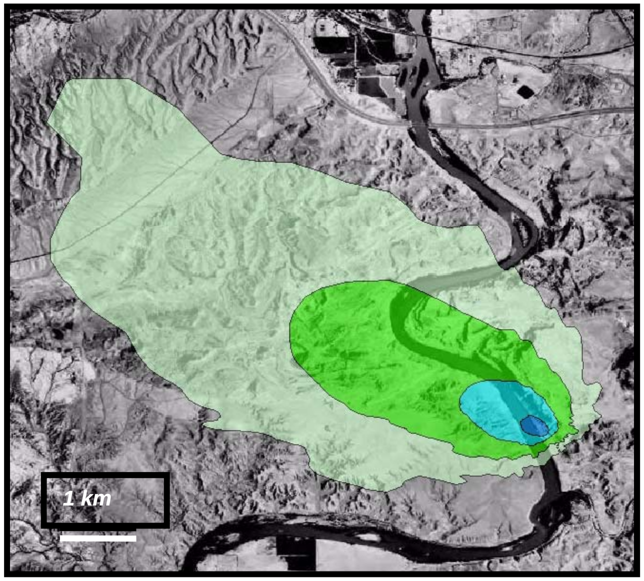
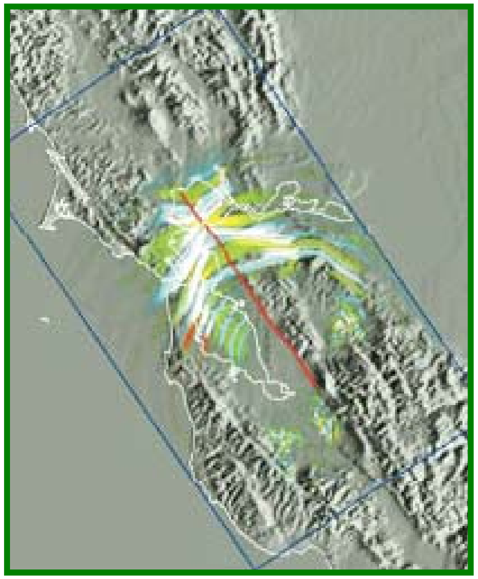
Carbon Sequestration Risks and Hazards: What we know and what we don't know





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Conclusions

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

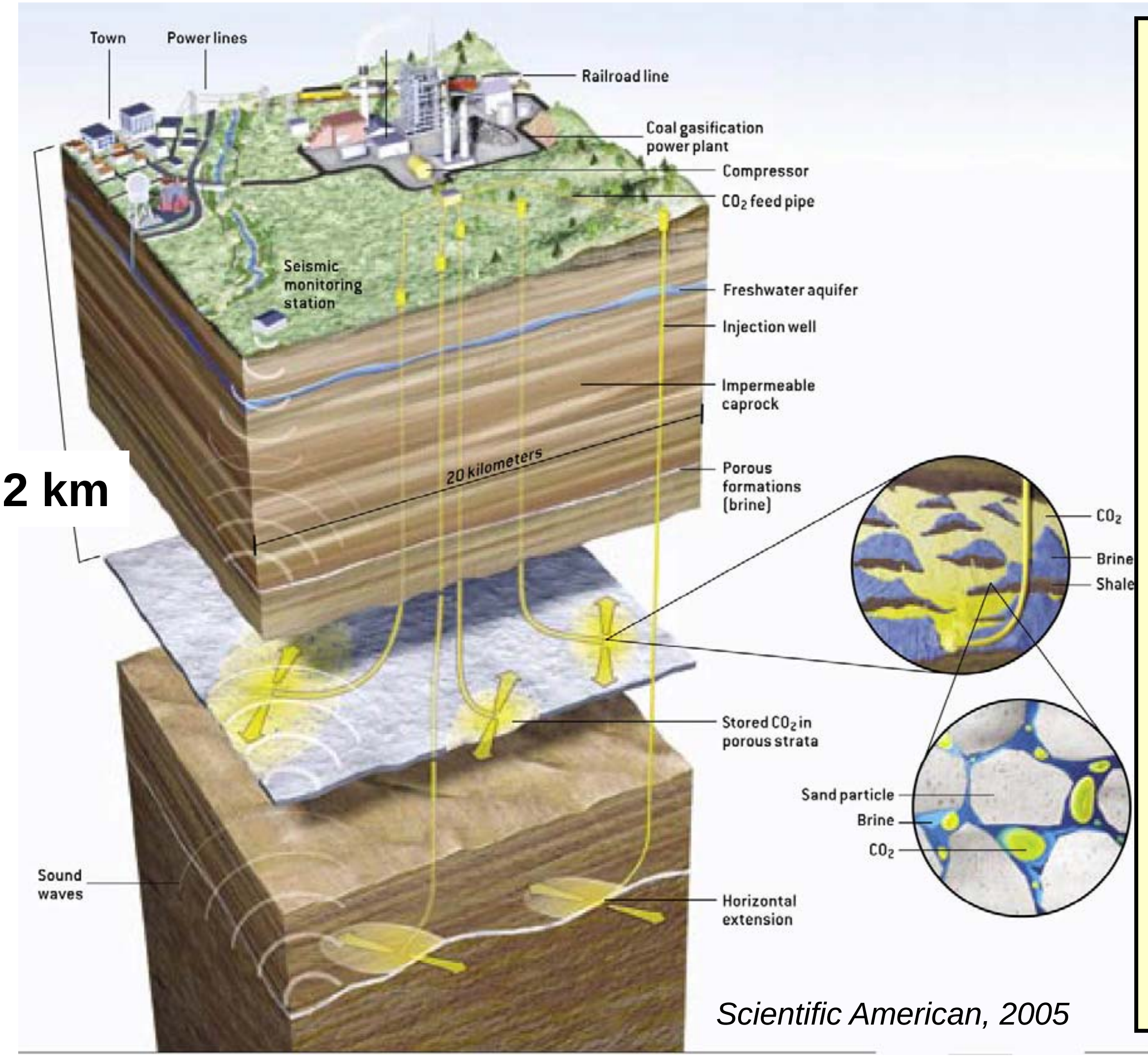
"We know enough to site a project, operate it, monitor it, and close it safely and effectively. We do not yet know enough for a full national or worldwide deployment."

The hazards of CO_2 sequestration are well defined and the associated risks appear small and manageable

Site characterization, monitoring, and hazard assessment & management are keys to safe and successful deployment

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

Geological carbon sequestration is the deep injection of CO_2 to avoid atmospheric release



Scientific American, 2005

CO_2 can be stored in deep geological formations as a pore-filling fluid:

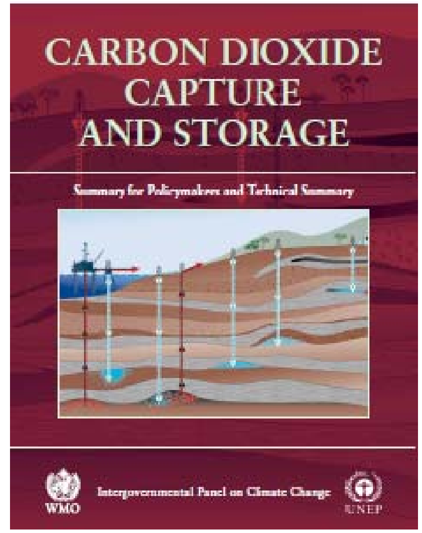
- **Saline Formations:** *largest capacity (>2200 Gt)*
- **Depleted Oil & Gas** *potential for enhanced oil and natural gas recovery*
- **Deep Coal Seams:** *potential for enhanced gas recovery as well*

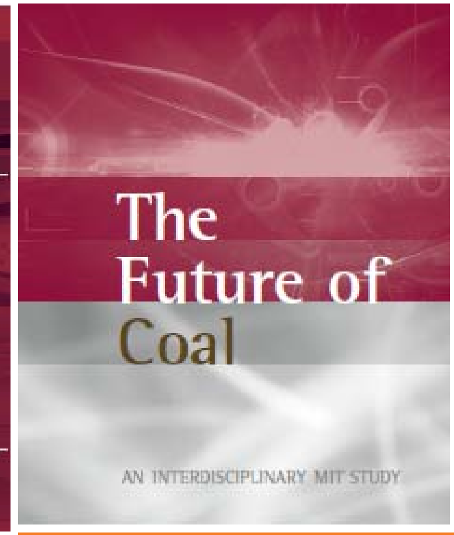
What empirical evidence is there that transport & geological storage of CO_2 can be done safely?

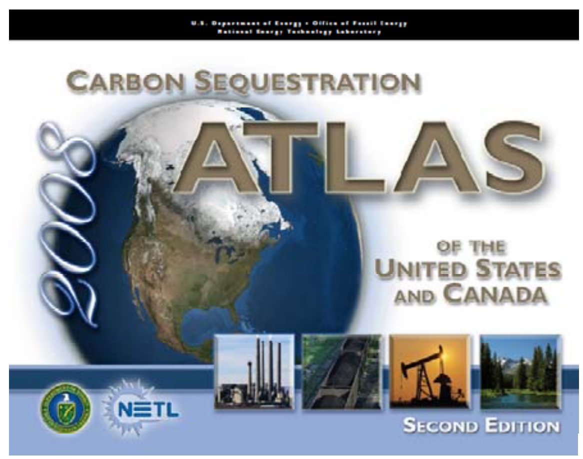
- Nature has stored oil and natural gas in underground formations over geologic timeframes, i.e. millions of years
- Gas and pipeline companies are today storing natural gas in underground formations (>10,000 facility-years experience)
- Naturally occurring CO_2 reservoirs have stored CO2-rich gas underground for millions of year, including large volumes in the US (WY, CO, TX, UT, NM, MS, WV)
- Almost 3,000 miles of CO_2 pipelines are operate in N. America, carrying over 30 million tons of CO_2 annually
- Well over 100 million tons of CO_2 have already been injected into oil reservoirs for EOR as well as into deep saline aquifers (over 80 projects have been implemented worldwide)
- Three commercial sequestration projects have demonstrably sequestered CO2 at injection rates ~ 1 million t CO_2/y for years across a wide range of geological settings

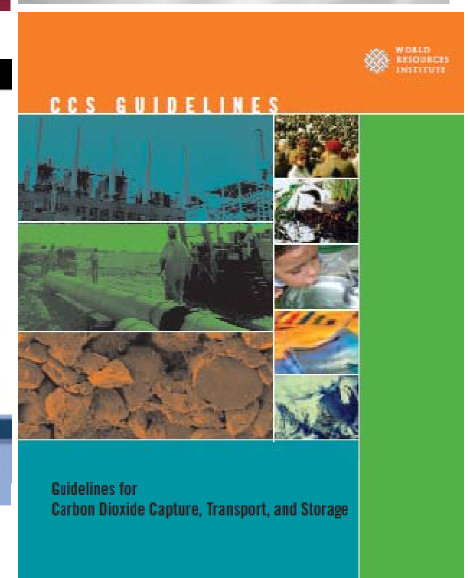
There are tremendous available resources, applicable learnings, works in progress

- **IPCC Special Report**
  - **2004 snapshot**
  - **High level of technical detail**
- **CO_2 Monography (SPE)**
- **MIT Report: Future of Coal**
- **DOE Basic Research Needs (2007)**
- **IOGCC draft guidelines (2007)**
- **NAS study (in progress)**
- **WRI CCS draft guidelines**
- **EPA draft regulations**
- **Many DOE documents**
  - **N. America CO_2 Atlas**
  - **Annual Roadmap**
  - **FutureGen selection criteria**

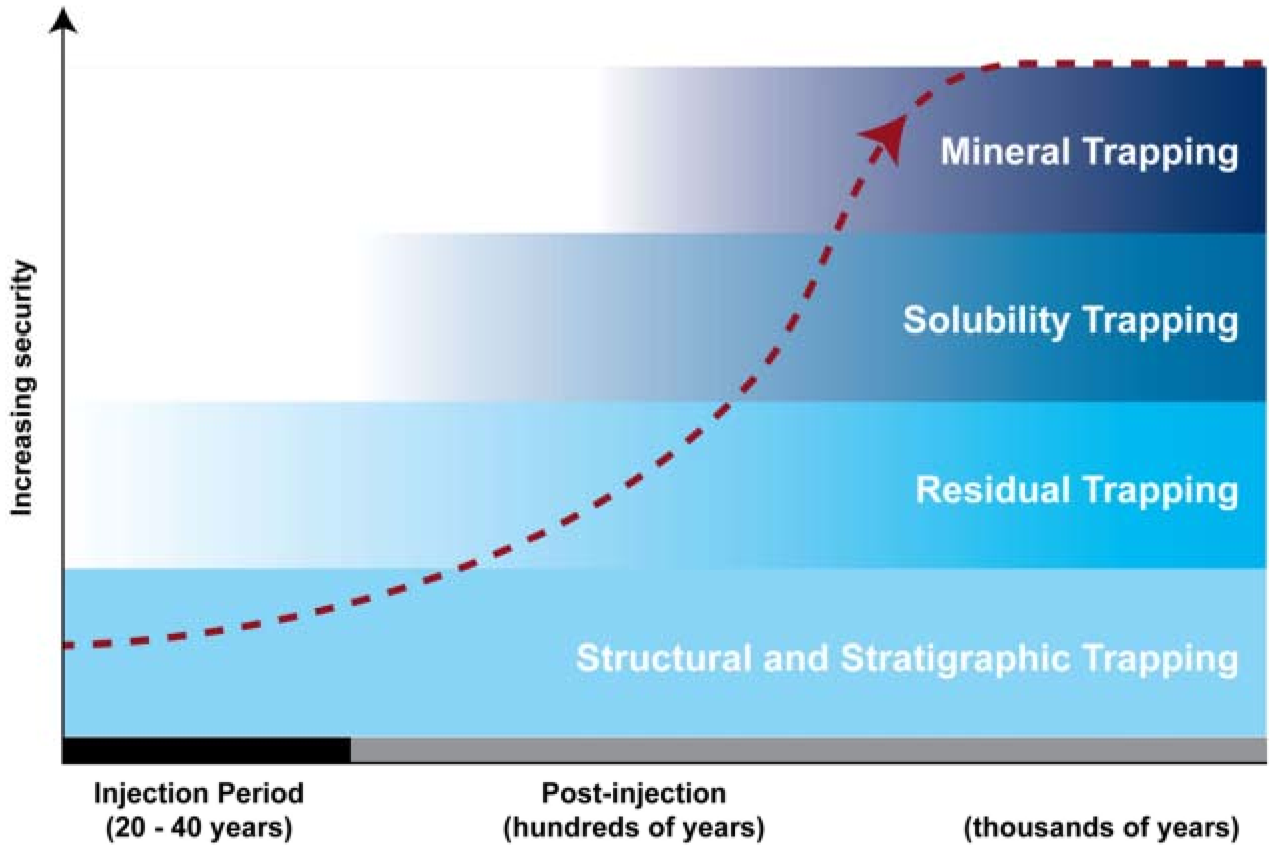








The crust is well configured to trap large CO_2 volumes indefinitely



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

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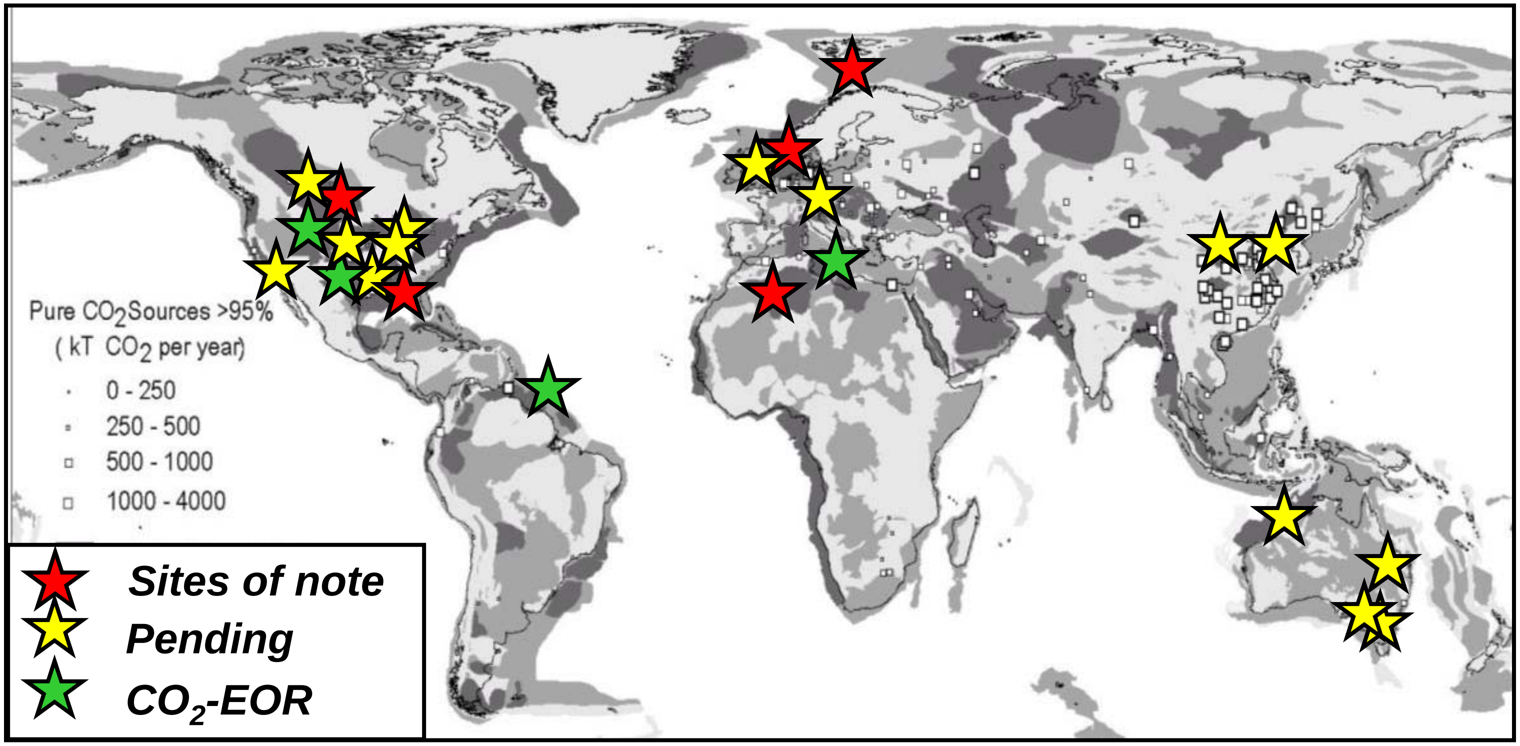
Several large projects exist, with many pending

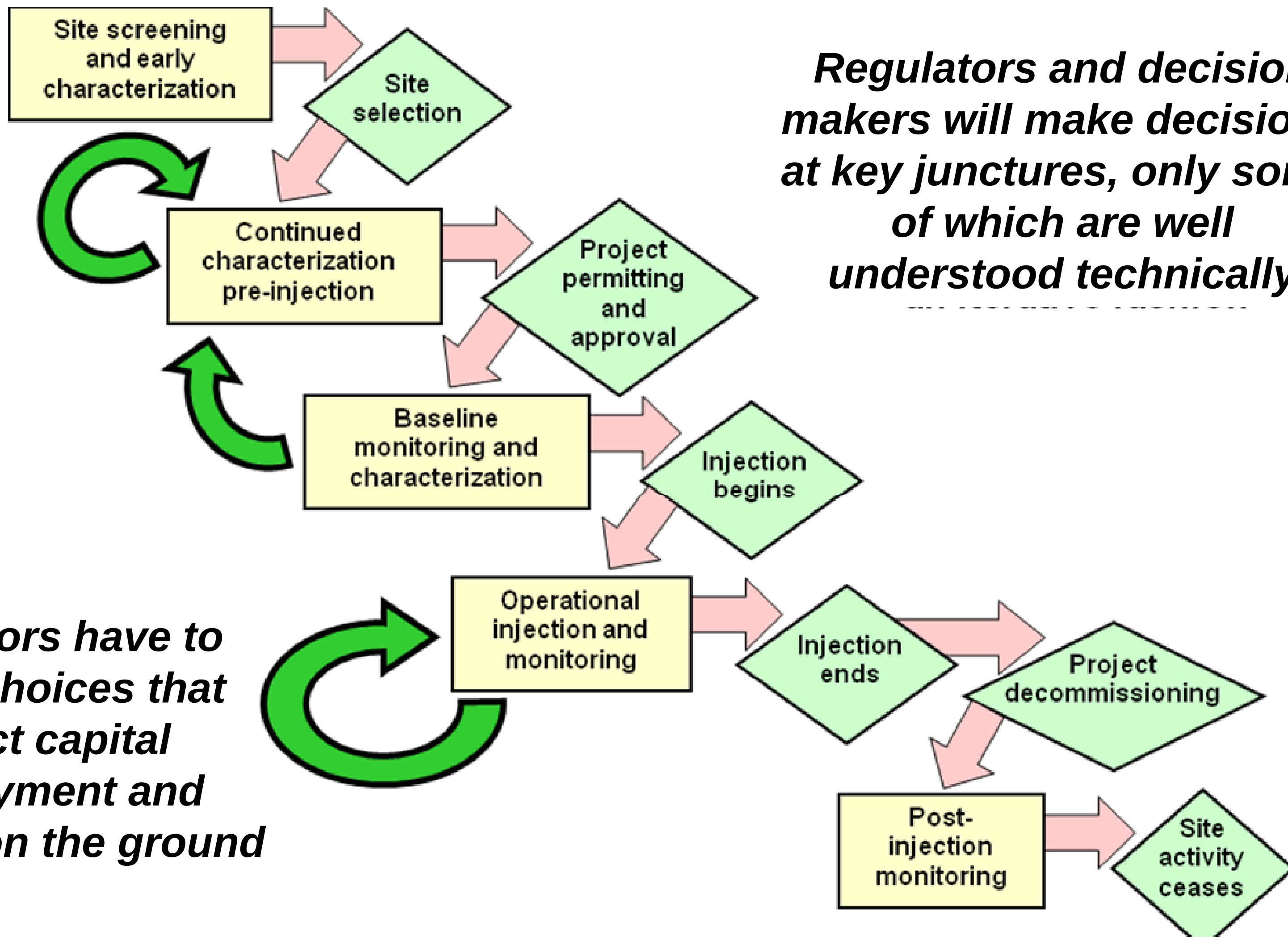
The projects, especially the three commercial sequestration projects, demonstrate the high chance of success for CCS



This experience base contributes to our knowledge regarding what is known about possible leakage hazards and risks

Deployment efforts have brought focus to CCS operations life-cycle and its key issues

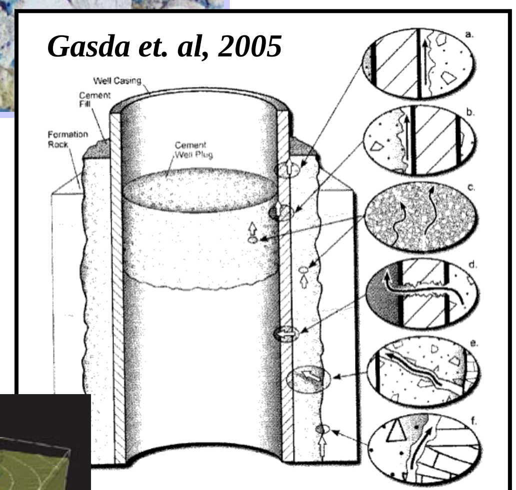
Regulators and decision makers will make decisions at key junctures, only some of which are well understood technically



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

Site characterization is the MOST important step in storage project preparation

Injectivity | **Retention** | **Capacity**



Injectivity

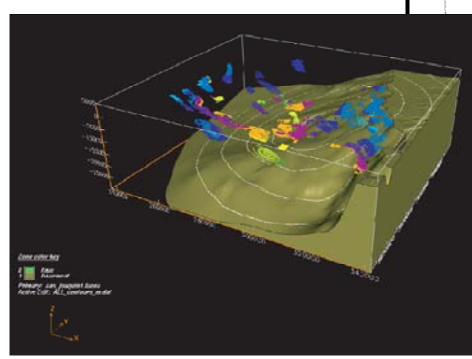
- Rate of volume injection
- Must be sustainable (months – yrs)

Retention

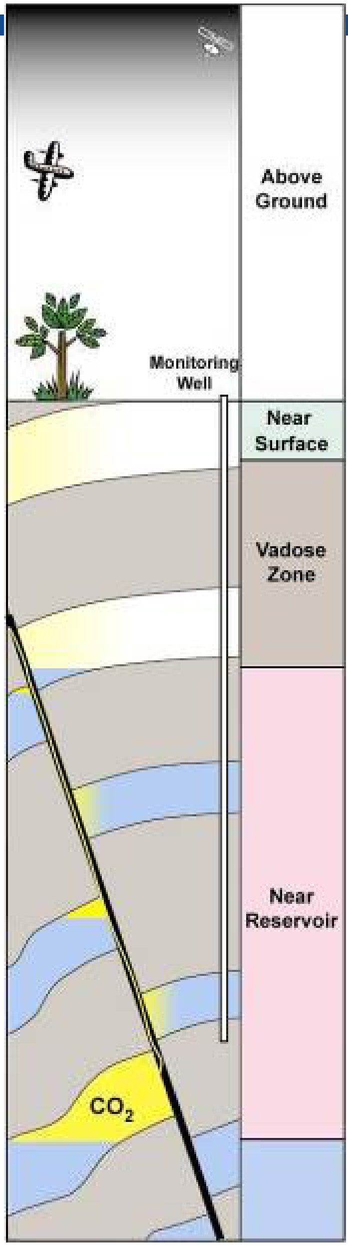
- Ability for a site to store CO_2
- Long beyond the lifetime of the project
- Most difficult to define or defend

Capacity

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



Monitoring and verification (M&V) is required, but has also been demonstrated in many settings



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

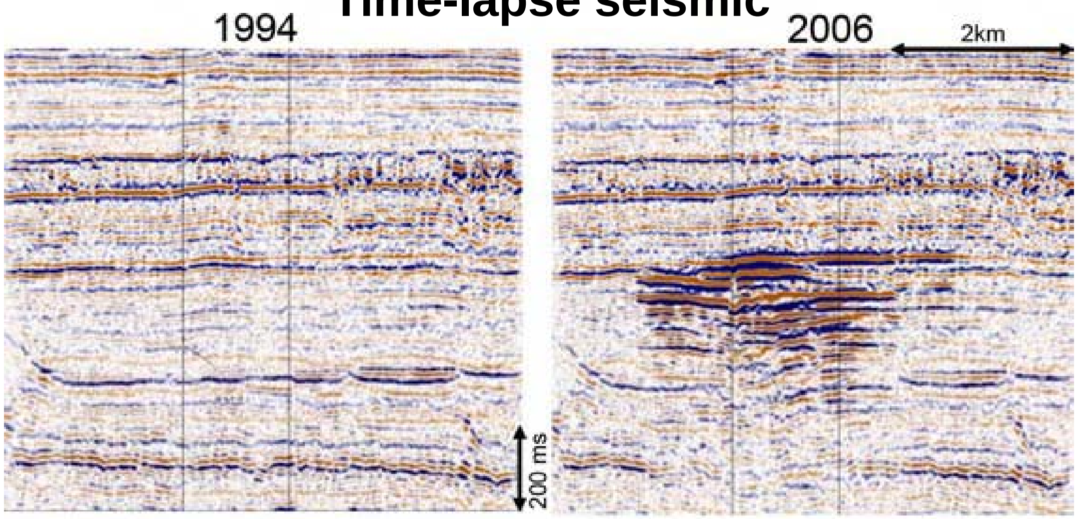
Demonstrated at:

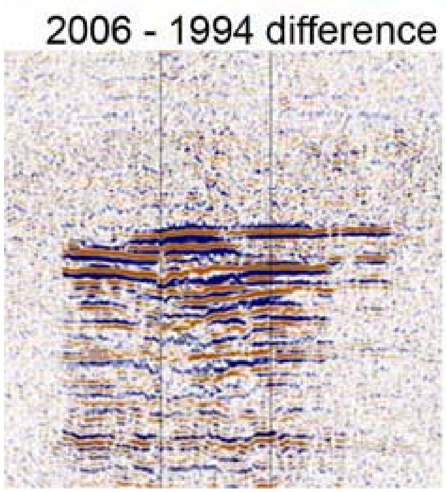
- **Sleipner, In Salah, Weyburn**
- **Frio Brine Pilot (S. Hovorka's presentation)**
- **Otway basin (Aus), Ketzin (Germ), Nagaoka (Japan)**

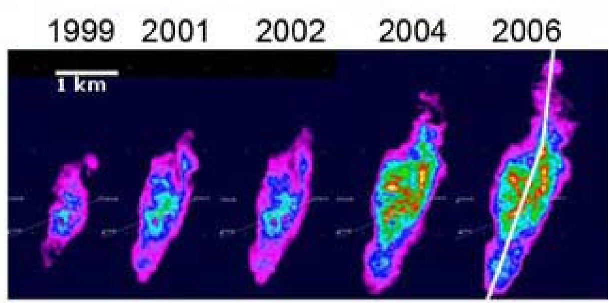
Monitoring and verification improves the operation, safety, and economic value of CCS projects

Examples of monitored projects

Sleipner Project, N. Sea
Time-lapse seismic

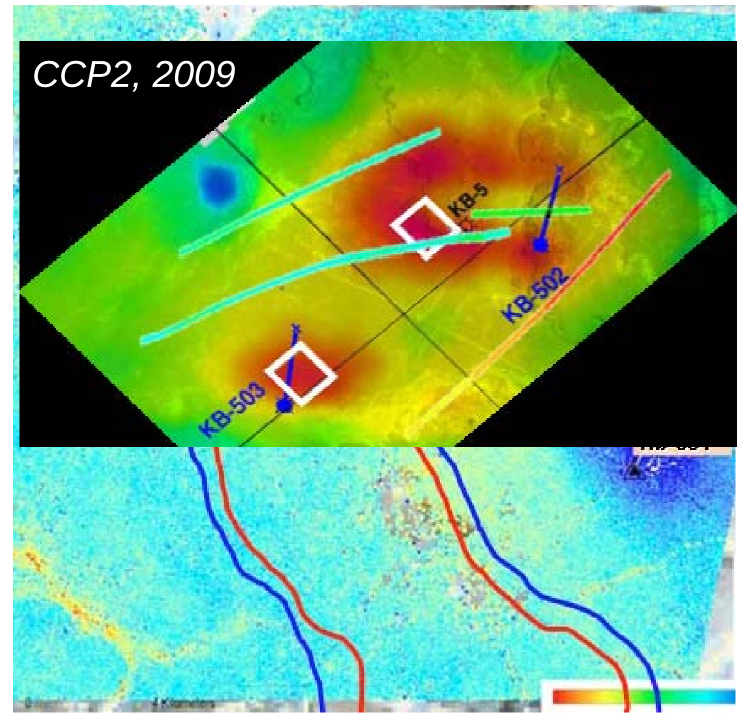






CO2 Capture project, 2009

In Salah, Algeria
InSAR



Wright et al., 2008

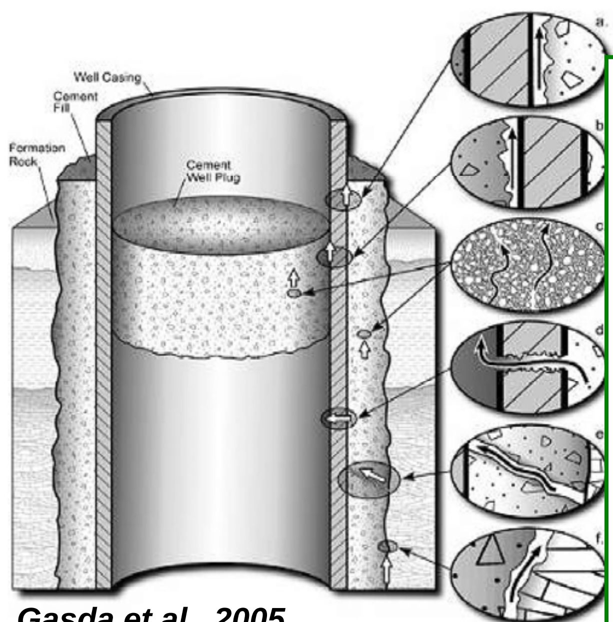
Overview Of Hazard and Risk Issues

Some basic considerations relevant to the nature and magnitude of CO_2-related risks

- CO_2 is not flammable or explosive
- CO_2 is not a dangerous gas except in very high concentrations (> 15,000 ppm)
  - Not to be confused with carbon monoxide (CO)
  - We inhale and exhale CO_2 with every breath
  - We drink carbonated (CO_2 containing) beverages
  - We buy “frozen” CO_2 for cooling (dry ice)
- We have successfully plugged and abandoned CO_2 injection wells, even badly damaged and failed wells
- Where human, animal or plant mortality has been attributable to CO_2 is due to volcanic releases in large quantities (e.g. Cameroon, Africa) or pooled in depressions or pits (Mammoth Mountain, California)

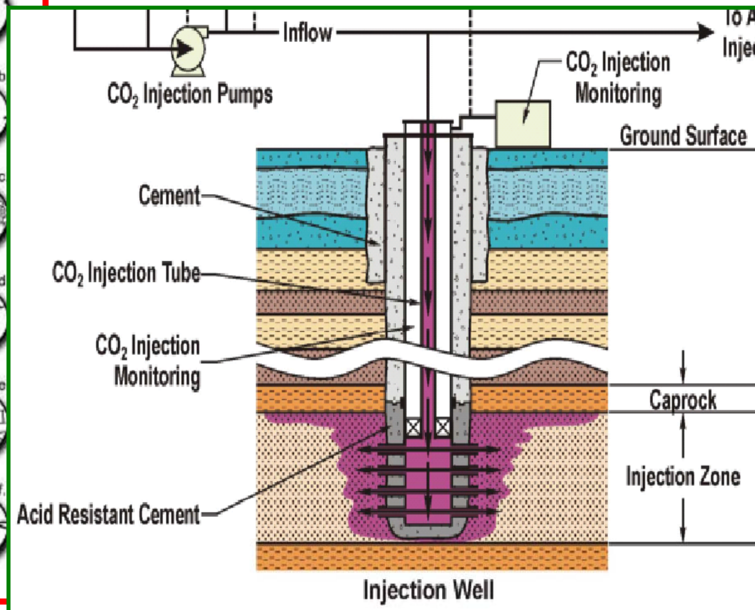
Wells represent the main hazard to GCS site integrity

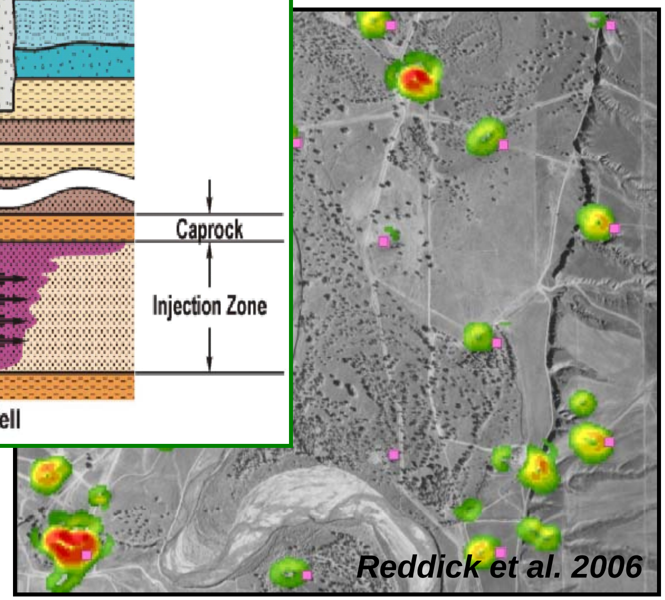
We have some understanding of well failure modes



Gasda et al., 2005

We can properly design CO_2 wells and plug failed wells





Reddick et al. 2006

We can identify and recomplete lost wells

Managing and maintaining well integrity is important to avoiding failure and risk minimization

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

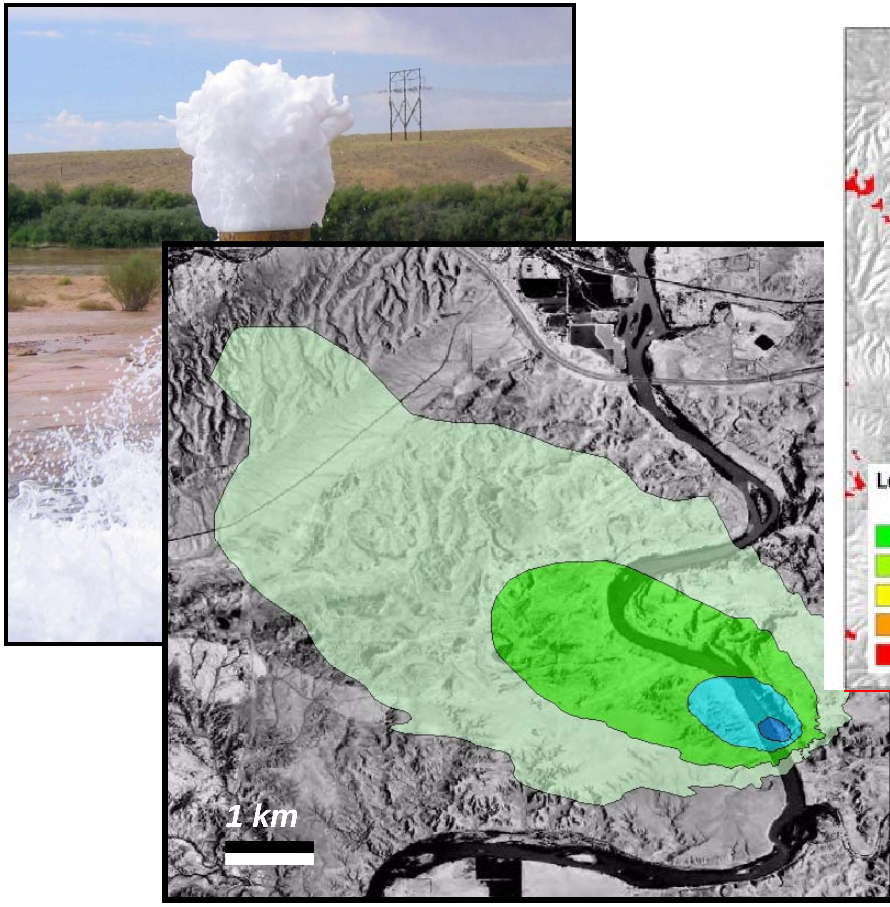
Drilled in 1936 to 801-m depth initiated CO_2 geysering.

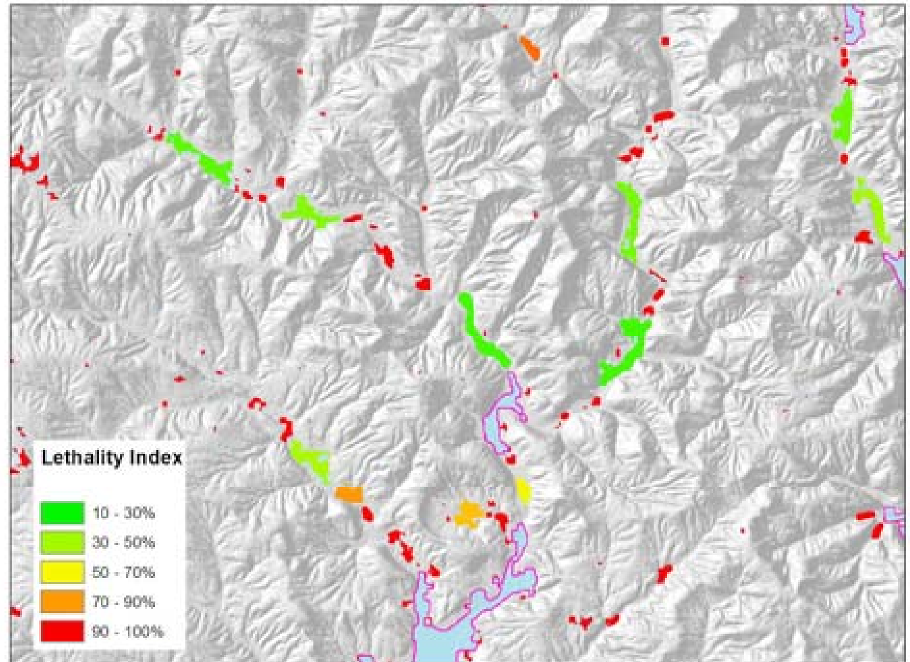
CO_2 flows from Aztec sandstone (high P&P saline aquifer)

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**

The risks of leakage appear to be both small and manageable





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

There have been other CO2 well failures with larger release rates

Location	CO_2 release rate (original units)	CO_2 release rate (kg/sec *(t/d)*)	Date	Reference
Wyoming	100 million cubic feet/day	60 *(~5000)*		S. Stinson, personal comm. 2007
Sheep Mt., CO	At least 200x10^6 scf/day	120 *(~10,000)*	March 17-April 3, 1982	Lynch *et al.* (1985)
Torre Alfina geothermal field, Italy	300 tons/hour	76 *(~6500)*	1973	Lewicki, Birkholzer, Tsang (2007)
Travale geothermal field, Italy	450 t fluid/hr	113	Jan. 7, 1972	Geothermics Lewicki et al. (2007)
Leroy Gas Storage, WY	3e6 m3/year	0.2	1976-1981	Lewicki et al. (2007)
Edmund Trust #1-33, Kingfisher, OK	45 million cubic feet of gas/month	0.9	Dec. 2005-Jan. 2006	Lewicki et al. (2007)
Crystal Geyser, UT	2.6 to 5.8 kg/sec	2.6 to 5.8	Continuing	Gouveia & Friedmann (2006)

These events were detected quickly and stopped

Simulations of the largest hypothetical event suggest leakage appears to be manageable

Max. CO_2 flow rate:
7” inside diameter well

Depth (ft)	Flow rate (kg/s)	Flow rate (ton/day)
5036	225	1944
4614	217	1875
5102	226	1952
4882	224	1935

~2x Sheep Mt. event
~50x Crystal Geyser

Simulated hypothet
Max. flow rate even
Great plains: no wi

Simulated hypothetical
Max. flow rate event
Great plains: average wind

Acute (Short-Term) Effects

	Description	(ppm) Extent Area	Population Fatalities Casualties
	>TEEL-3: Death or irreversible health effects possible.	>40,000 71.5 m 6,840 m2	0 N/A N/A
	>TEEL-2 and TEEL-1: Serious health effects or impaired ability to take protective action.	>30,000 87.3 m 9,515 m2	0 N/A N/A

Note: Areas and counts in the table are cumulative. Casualties include both Fatal and Non-Fatal effects.

The HSE consequences from catastrophic well failure do not appear to present an undue or unmanageable risk.

The Lake Nyos event is not analogous to possible CCS leakage

The worst CO_2 release event in modern history

- ***CO_2 accumulated in lake floor over 100's of years***
- ***Released all at once: >1000 people died***

Two million tons CO_2 released overnight (probably in an hour)
- ***~1000x bigger than Sheep Mt.***
- ***Several million Crystal Geysers***

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

Analog information abundant

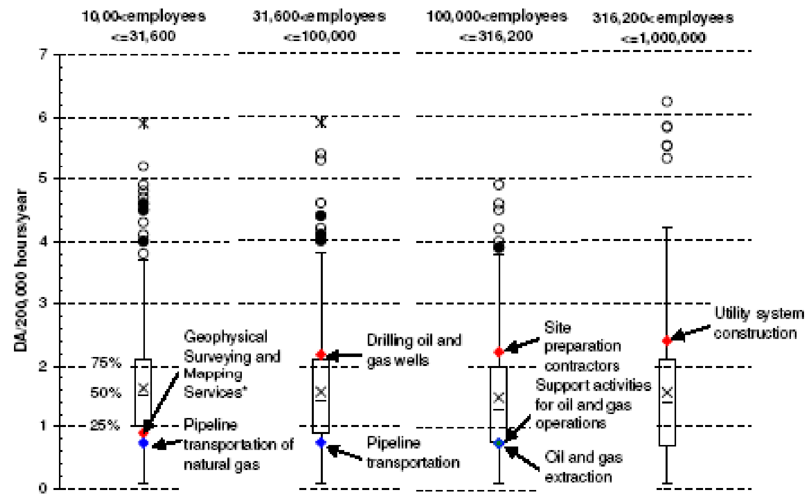
- Oil-gas exploration and production
- Natural gas storage
- Acid gas disposal
- Hazardous waste programs
- Natural and engineered analogs

Operational risks

- No greater than (probably much 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

Source: LLNL

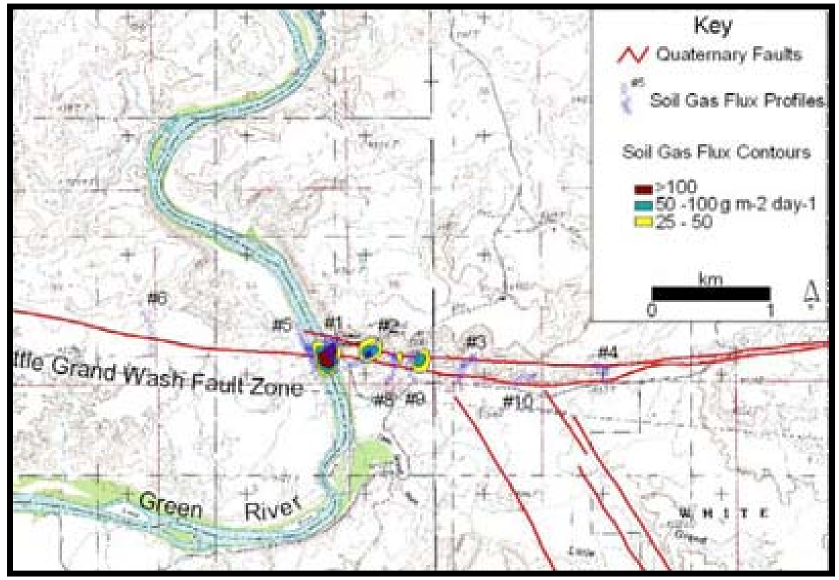
Little Grand Wash Fault soil surveys suggest fault leakage flux rates are extremely small

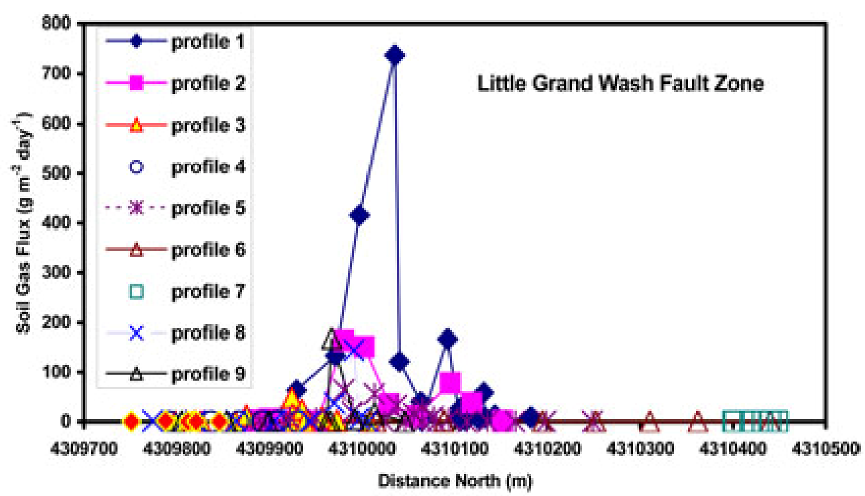
Allis et al. (2005) measured soil flux along the LGW fault zone.

Overall, concentrations were <0.1 kg/m^2/d.

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

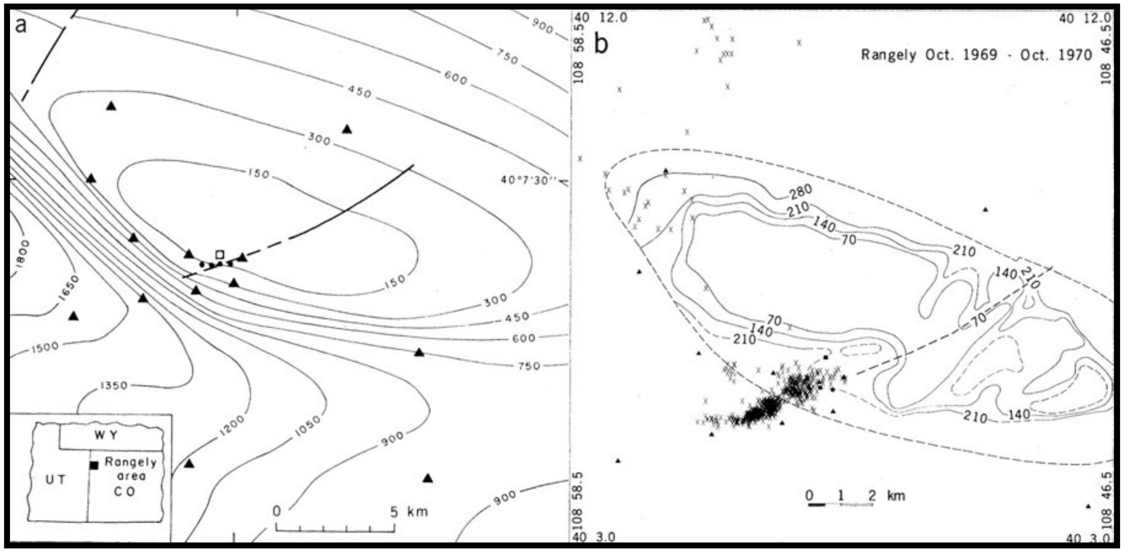
At Crystal Geyser, it is highly likely that all fault-zone leakage is at least two orders of magnitude less than the well. This may be too small to detect with many surface monitoring approaches





Allis et al., 2005

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



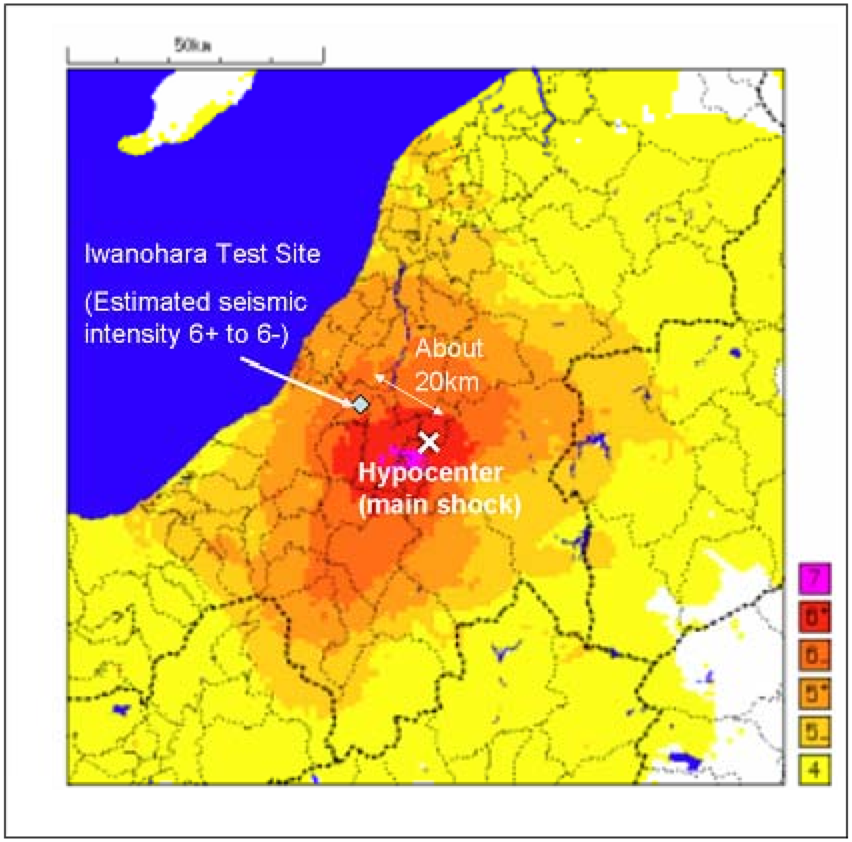
Raleigh et al., 1976

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

The M6.8 Chuetsu earthquake did not cause leakage at the Nagaoka CO2 injection project



http://www.rite.or.jp/English/lab/geological/demonstration.html

To identify the earthquake's impact on the storage site, the conditions of the wells, the reservoir, and the injection facility were inspected and tested

Following these tests & inspections, the conditions of the wells, reservoir, and facility were found intact after the earthquake, and injection was resumed.

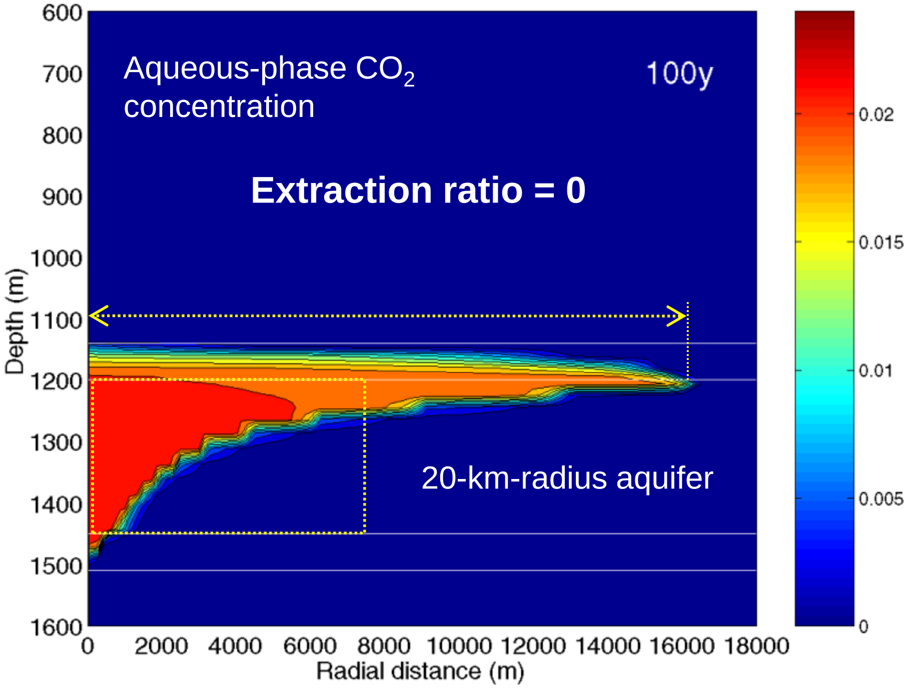
- ***Oct 23, 2004, 17:56***
Mid-Niigata Chuetsu Earthquake occurred.
- ***Automatic halt of injection due to loss of power supply***
(Cumulative amount at the time of injection halt: approx. 8,950 t- CO2)

One can also actively manage the reservoir through producing and treating water

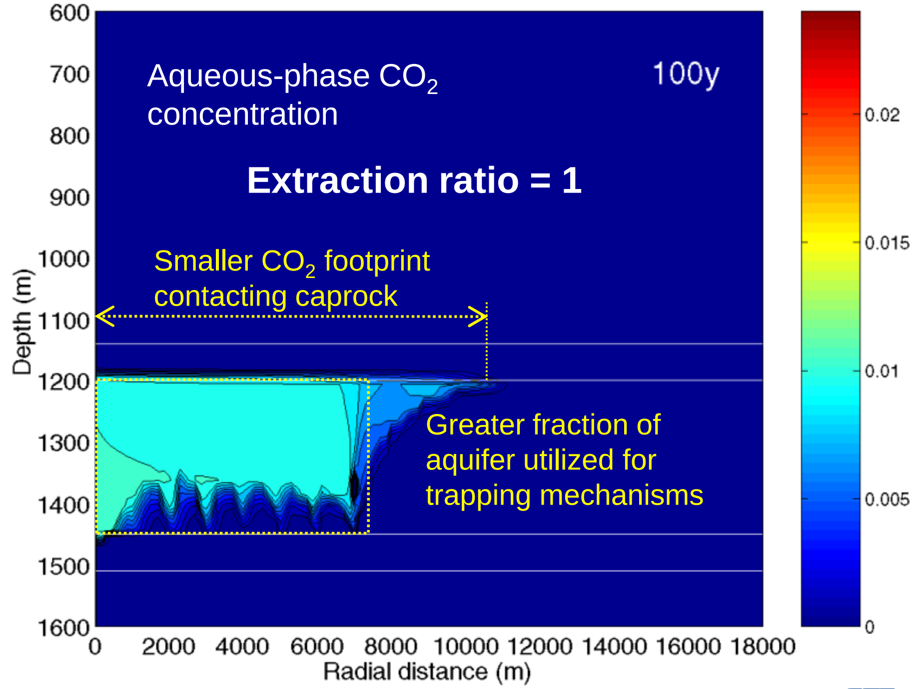
Active CO_2 Reservoir Management provides several **benefits**

- Reduces CO_2 plume footprint and increases resource use
- Greatly reduces pressure buildup and attendant risks (e.g., seismicity)
- Allows for **Enhanced Water Recovery**

Passive CO_2 Reservoir Management



Active CO_2 Reservoir Management



We can produce water at sequestration sites for low cost, reducing environmental footprint and adding value

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Modern 1 GW IGCC plant's CO_2: 7.5 million m^3

How much water are we talking about?

3 million tons = 4 million m^3 water

- **3000 acre-feet**
- **Serve 5000 homes**
- **Irrigate 1000 acres of crops**
- **Provide all the cooling water needed for 1000 MW natural gas plant with CCS**

1. **Produce water from neighboring well**
2. **Desalinate**
3. **Reinject the concentrate**

Treating 7.5 M m^3 of displaced brine to make fresh water could:

- **Help manage pressure in the saline aquifer**
- **Provide half the plant's operating fresh water (includes cooling)**

Current cost estimate: \$400-600/acre-foot (1/2 of conventional R/O)

Potential to manage and reduce pressure risk is great; important engineering and reservoir issues must be studied

Conclusions

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

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