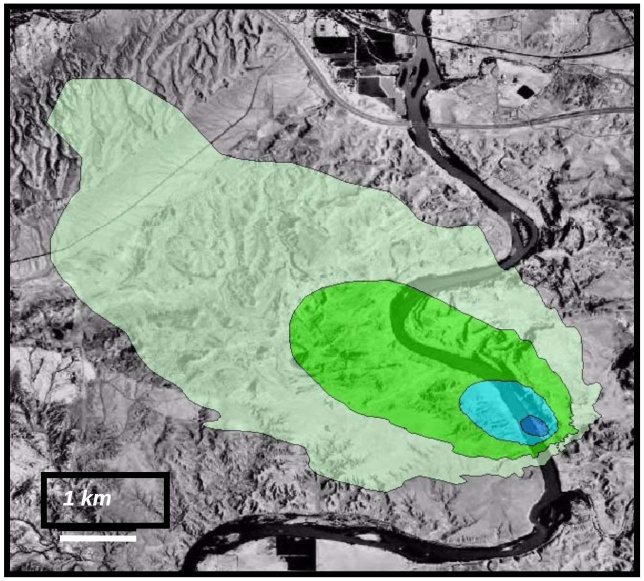
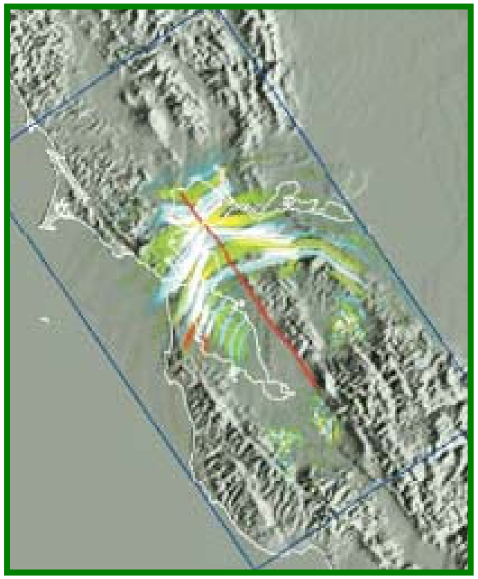
Carbon Sequestration Risks and Hazards: What we know and what we don't know





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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."

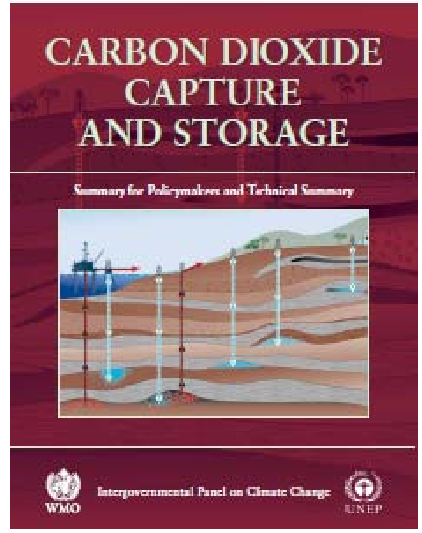
The hazards of CO_2 sequestration are well defined and the associated risks appear small and manageable

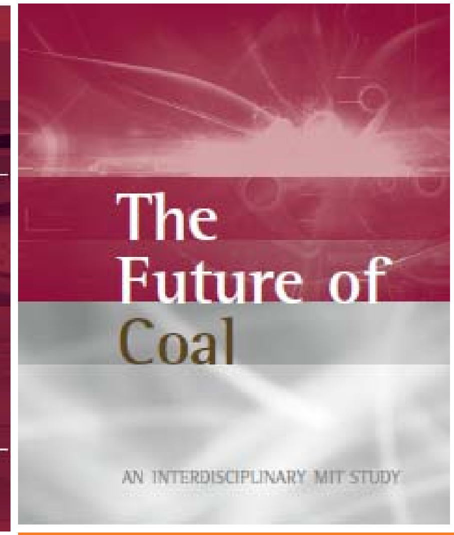
Site characterization, monitoring, and hazard assessment & management are keys to safe and successful deployment

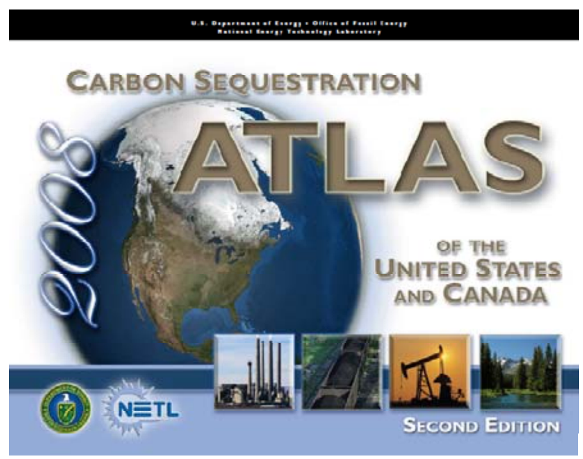
This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

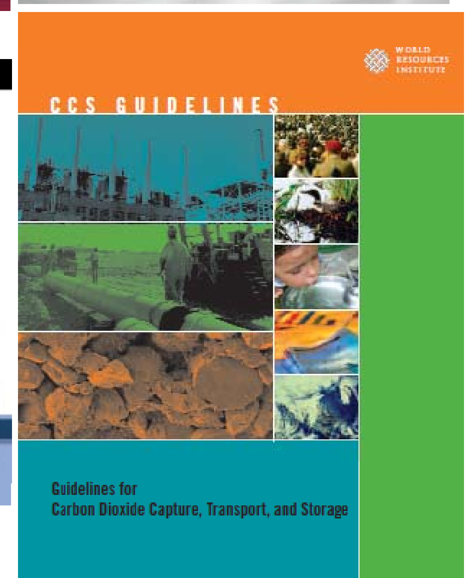
There are tremendous available resources, applicable learnings, works in progress

- **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**

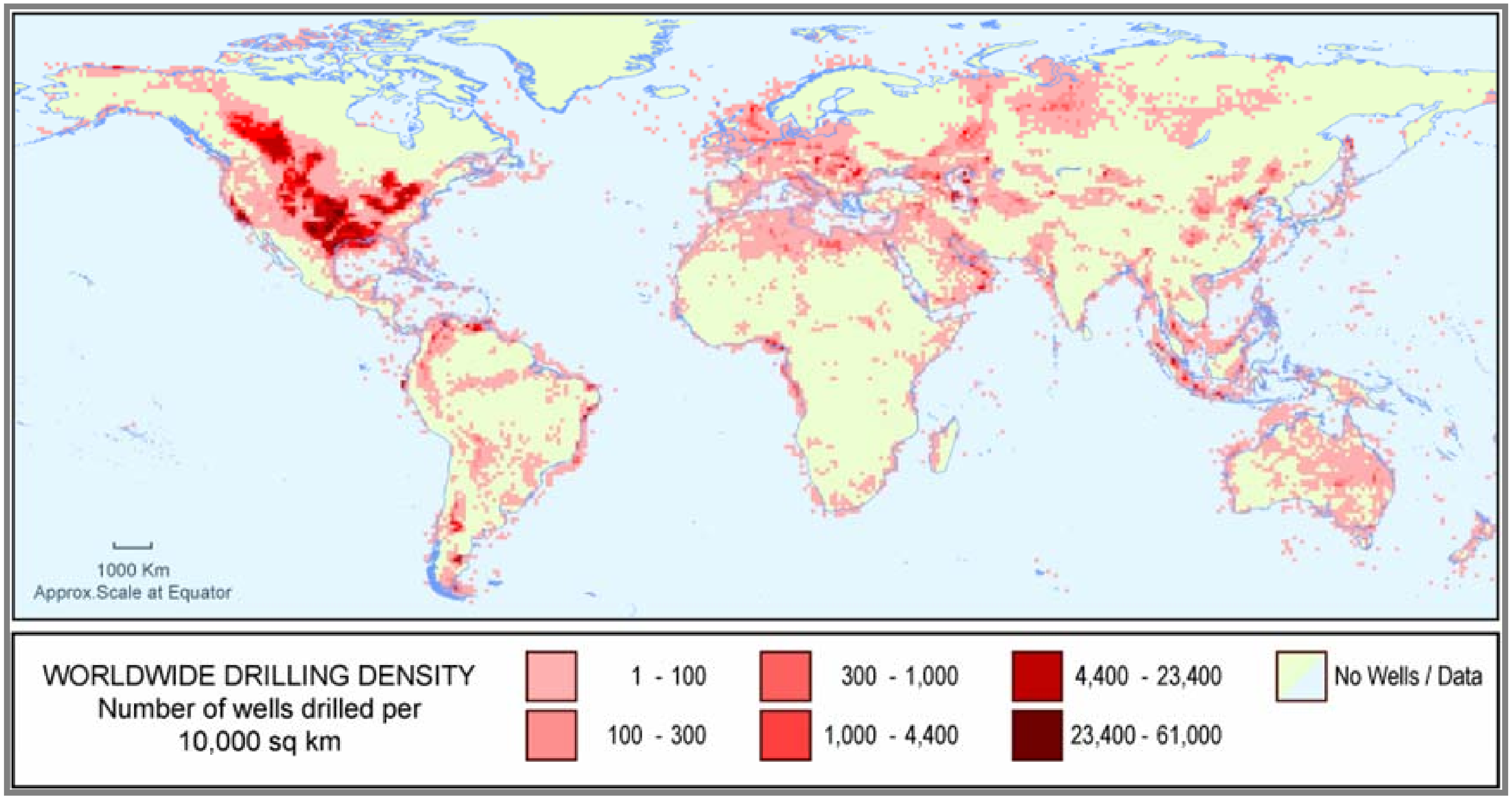








What Could Go Wrong?



Potential Release Pathways

- Well leakage (injection and abandoned wells)
- Poor site characterization (undetected faults)
- Excessive pressure buildup damages seal

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

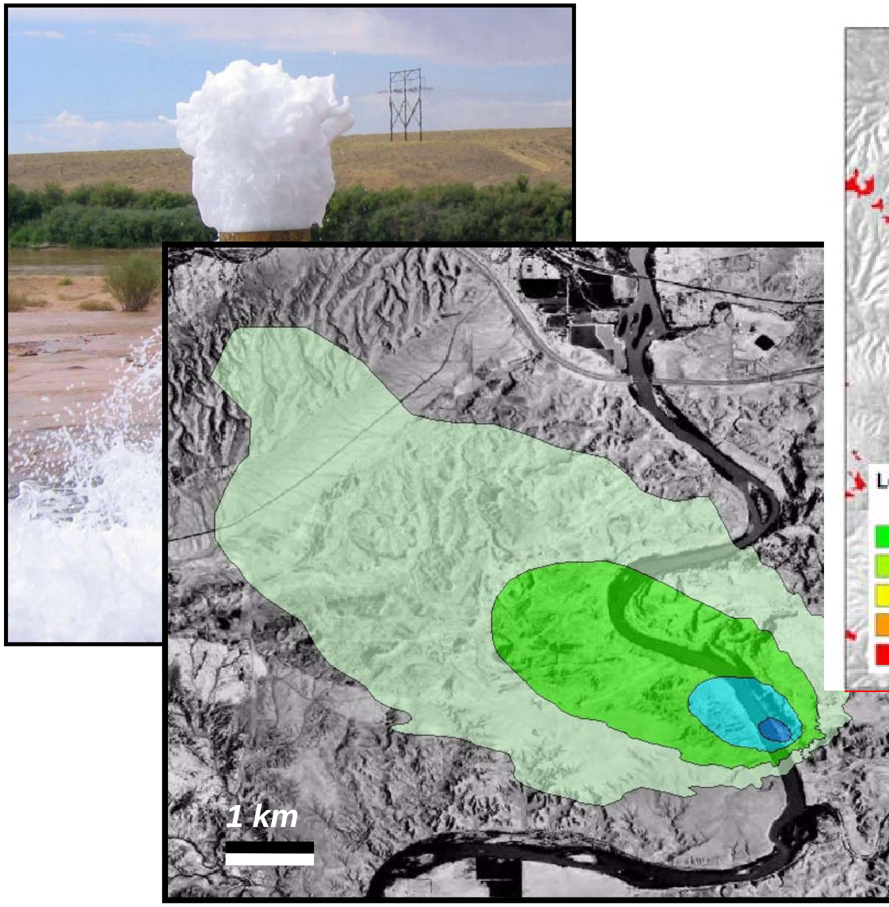
Drilled in 1936 to 801-m depth initiated CO_2 geysering.

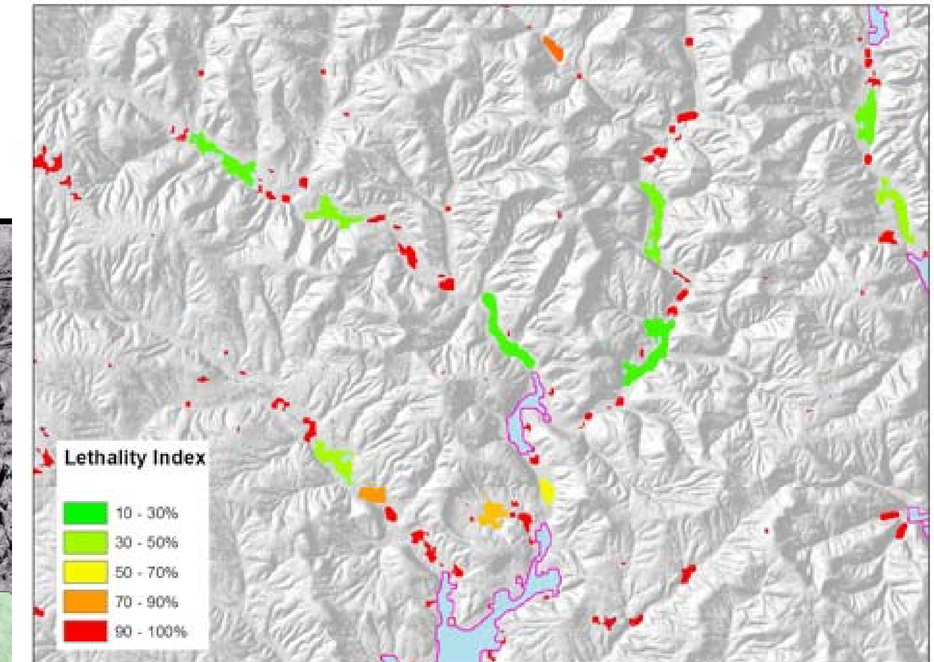
CO_2 flows from Aztec sandstone (high P&P saline aquifer)

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 CO_2 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)

Almost all 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 hypothetical
Max. flow rate event
Great plains: no wind

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

Acute (Short-Term) Effects

	Description	(ppm) Extent Area	Population Fatalities Casualties
(red)	>TEEL-3: Death or irreversible health effects possible.	>40,000 71.5 m 6,840 m2	0 N/A N/A
(orange)	>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

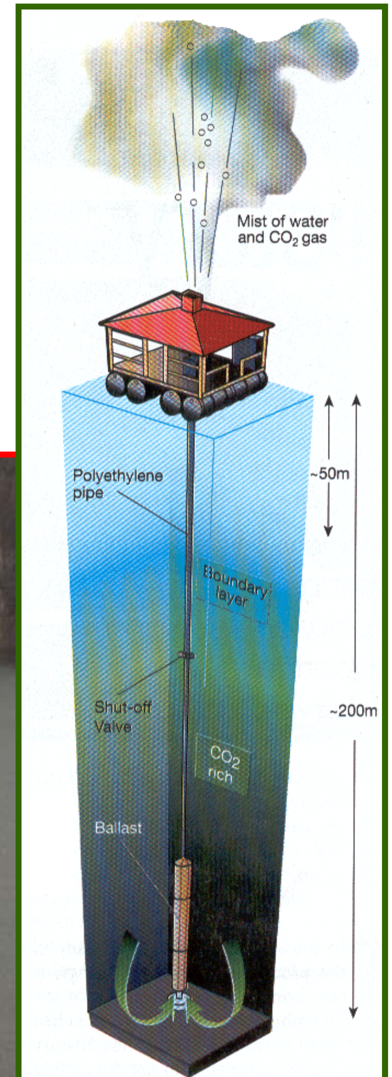
The worst CO_2 release event in modern history

- ***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***

The Lake Nyos event is not analogous to possible CCS leakage

- ***The crust has great strength and great mass***
  - ***catastrophic overturning not possible***
  - ***flow rates from geological formations can't be this fast***
- ***No deep lakes exist near any potential storage site in any OECD country***
- ***This type of occurrence is easily detected and mitigated***

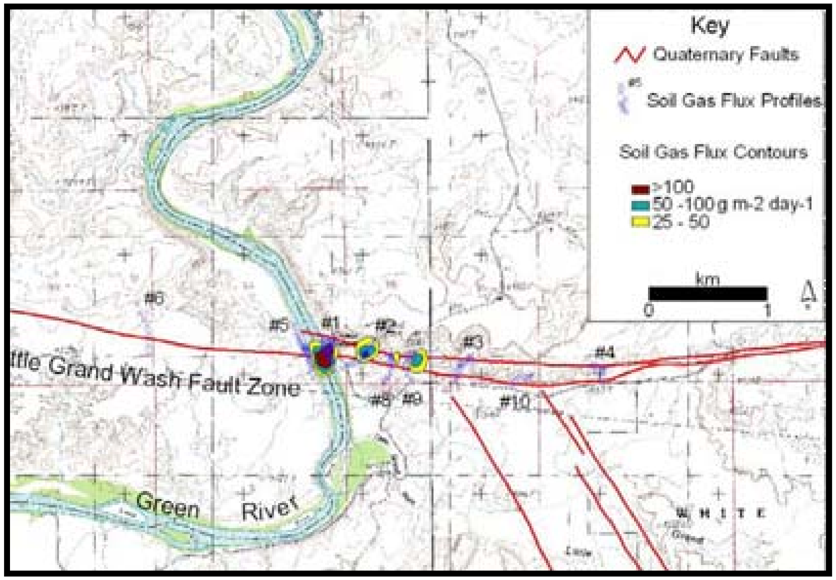


Little Grand Wash Fault soil surveys suggest fault leakage flux rates are extremely small

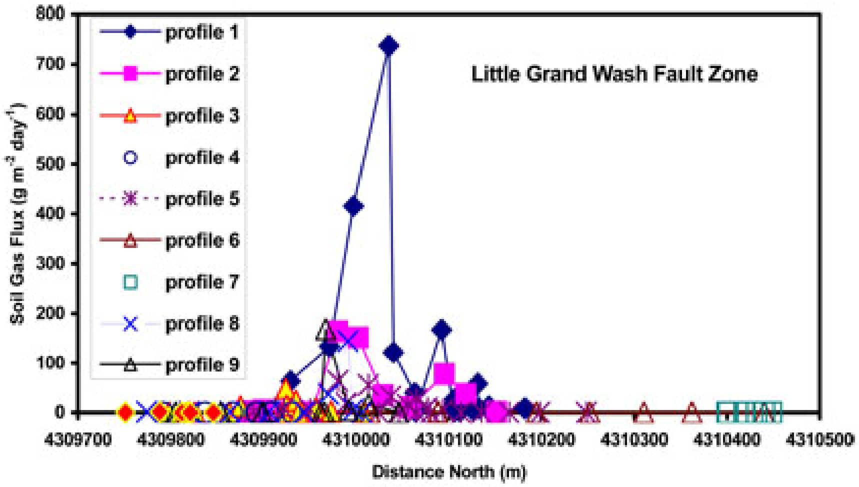
Allis et al. (2005) measured soil flux along the LGW fault zone.

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. This may be too small to detect with many surface monitoring approaches



Allis et al., 2005

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

Analog information abundant

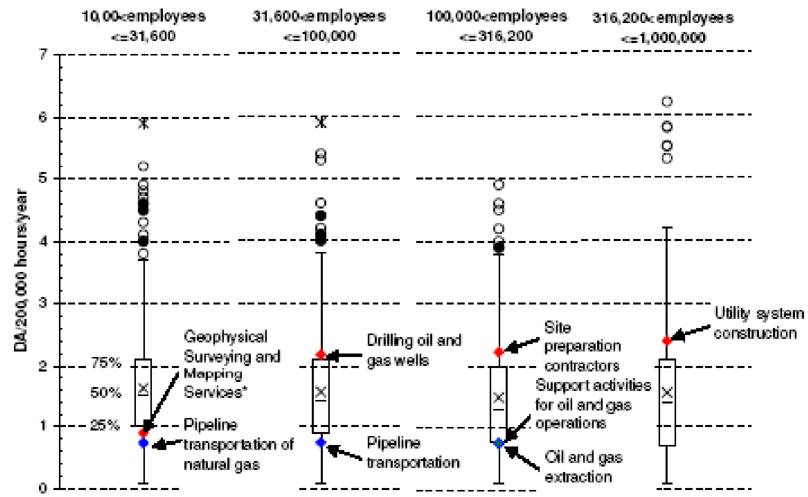
- Oil-gas exploration and production
- Natural gas storage
- Acid gas disposal
- Hazardous waste programs
- Natural and engineered analogs

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

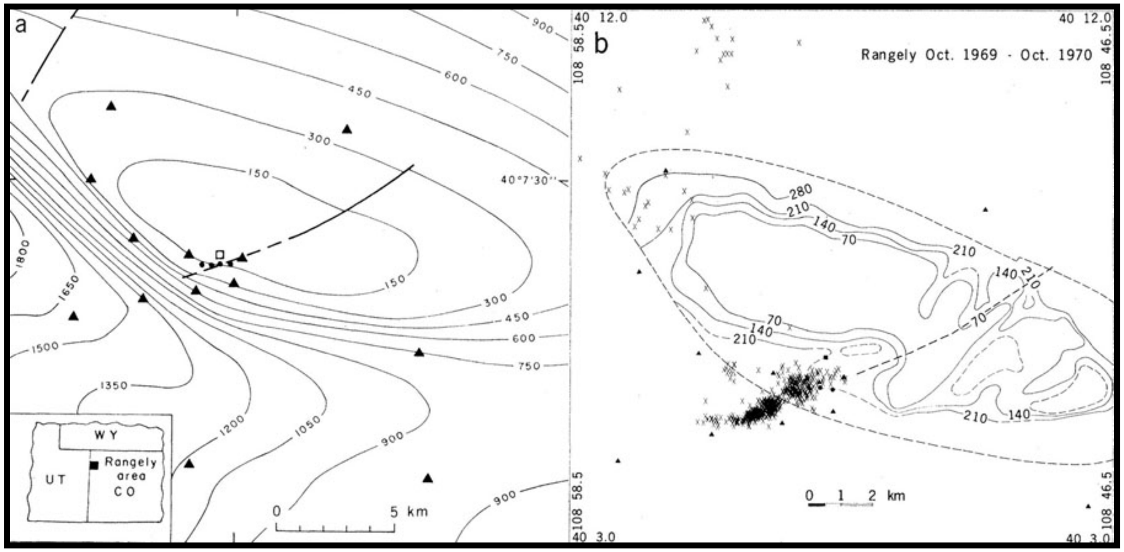


Benson, 2006

Bogen et al., 2006

Source: LLNL

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



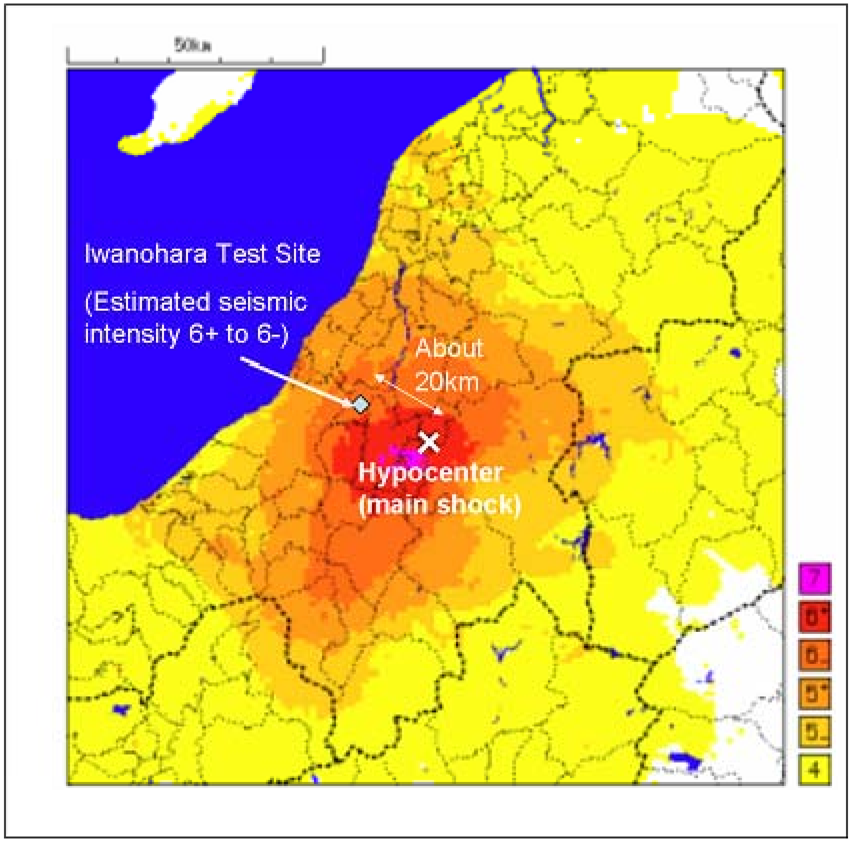
Raleigh et al., 1976

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 CO_2 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- CO_2)***

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