CO_2 Sequestration Checklist: Criteria for Carbon Sequestration Project Success

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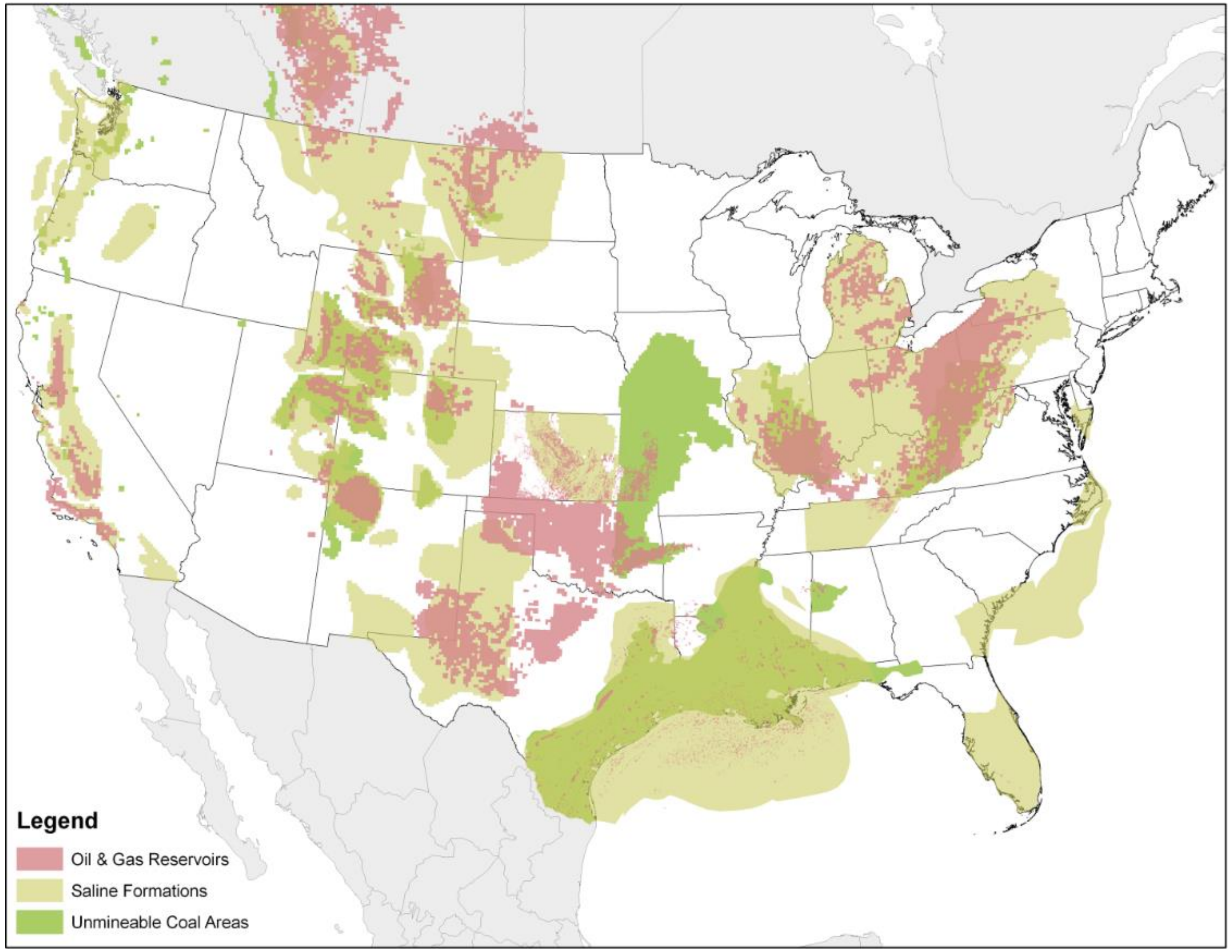
The carbon capture, utilization, and sequestration (CCUS) industry is gaining momentum as governments and investors show increasing support. Sequestering carbon dioxide (CO_2) in the subsurface for permanent disposal shares many similarities with modern oil and gas practices. As a result, the oil and gas industry is well-suited in operating CCUS projects and understanding the risks associated with subsurface exploration.

Based on experience and research from large-scale industry pilot projects supported by federal governments and academic researchers, we have identified the primary criteria and risks that should be considered throughout the entire development lifecycle of a CO_2 sequestration project. These criteria and risks include:

01	Subsurface storage space does not guarantee a viable project.
02	Projects need long-term access to reliable, economic carbon emissions.
03	Utilizing existing infrastructure can help support CO_2 transport from source to sink.
04	Projects need to build early community support though engagement and education.
05	Nearby surface use, population centers, and environmental impact can be detrimental to project progress.
06	Class VI well permitting is still an evolving regulatory risk.
07	Certain types of structural trapping used in oil and gas prospecting are difficult to assess for sequestration use.
08	Drilling wells in previously unexplored regions could lead to delays and project complications.
09	Class VI wells have more stringent requirements than typical oil and gas wells.
10	Well cementing is essential in ensuring long-term storage of sequestered CO_2.
11	Injectivity of the target storage reservoir determines both injection rate and total storage potential.
12	Fractures and faults in the subsurface are major concerns for CO_2 leakage and unexpected migration.
13	Improper CO_2 injection can induce earthquakes.
14	Legacy wells are a major concern for CO_2 leakage.
15	Fluid migration in undeveloped regions may have high uncertainty.
16	Reservoir seals can fail from changes in subsurface stress during injection.
17	Surface and well monitoring can ensure safety through a sequestration project but doesn't limit project risk.
18	Once properly injected into the subsurface, CO_2 should become less likely to leak with time.

1. Subsurface Storage Formations

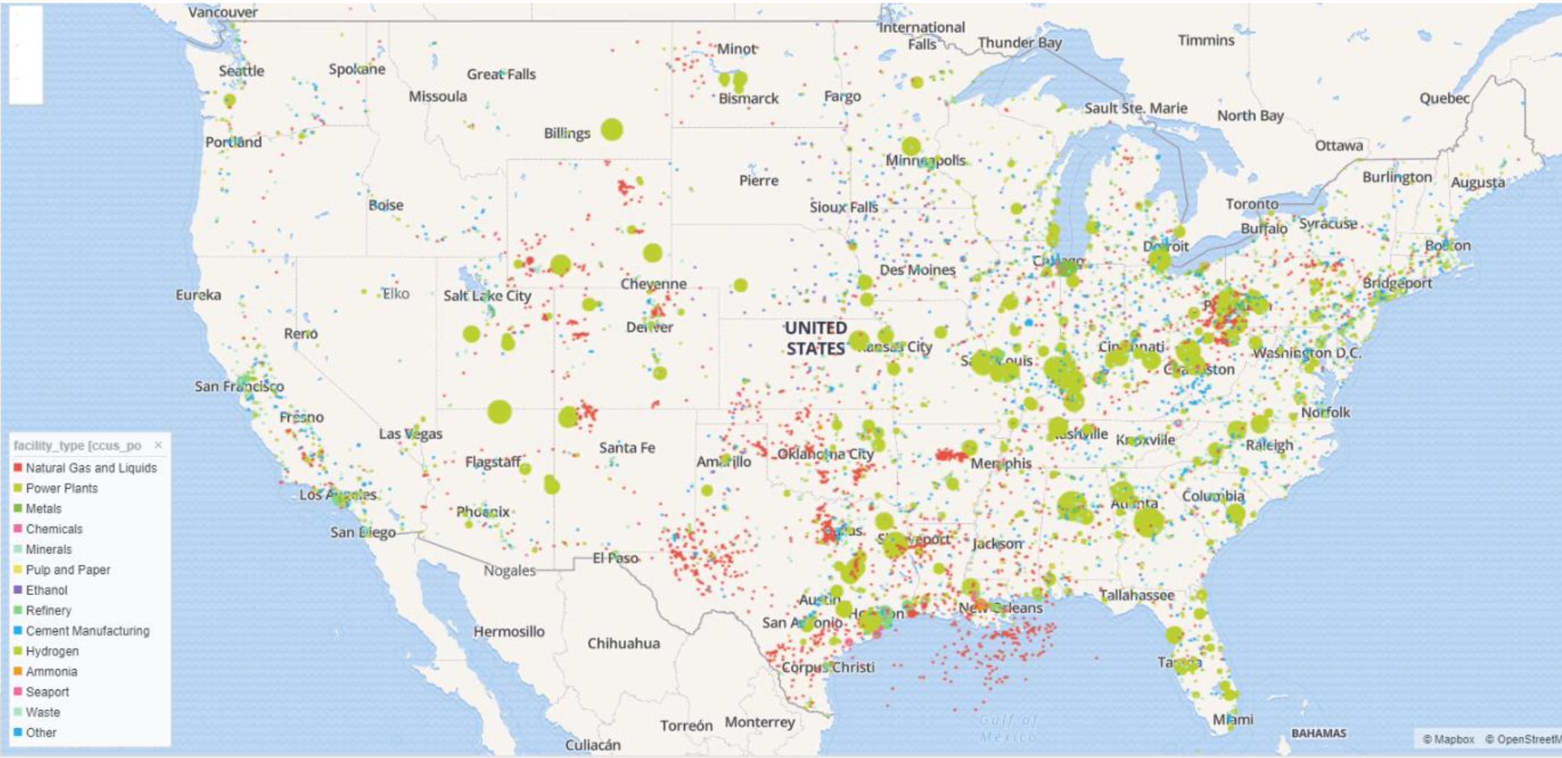
- Multiple regions across the United States have been identified as suitable for CO_2 sequestration:
  - Deep Saline Formations
  - Depleted Oil and Gas Reservoirs
  - Unmineable Coal Formations
- These locations however are largely identified from previous work in subsurface exploration and often coincide with regions of high fossil fuel consumption.
- Although a subsurface location may appear promising, it does not necessarily qualify as a suitable site for sequestration.
- The numerous other aspects that affect the feasibility of a sequestration project are discussed in this report.



Ideal formations for CO_2 sequestration across the United States. A sizable portion has the subsurface pore space available for sequestration, but this is not the only criteria for a successful sequestration site. (Source: NETL)

2. CO_2 Point Source Emissions

- Access to large quantities of carbon dioxide is essential for successful sequestration projects.
- This map shows the location of large point source emissions across the United States.
- Multiple CO_2 emissions offtake agreements adds complexity, but also increases flexibility in project development.
  - Injection wells seem to be coalescing around 1 million metric tons per year (MMtpa) per well.
  - Most CO_2 emission sources are below 1 MMtpa, requiring aggregation.
- Cost of CO_2 capture varies by industry.
- Coal power generation stations are favoring ceasing operations rather than considering CO_2 capture installations from:
  - Grandfathered air quality permits.
  - Underwhelming performance of pilot capture facilities.
  - High capture costs.



US Map of large emissions sources colored by each industry with the size of each dot scaled by CO_2 emissions volume per year. Locating sequestration sites around concentrated regions of large emissions sources will decrease project risks compared to a single emissions source. (Source: Orennia)

3. Use and Repurposing of Existing Infrastructure

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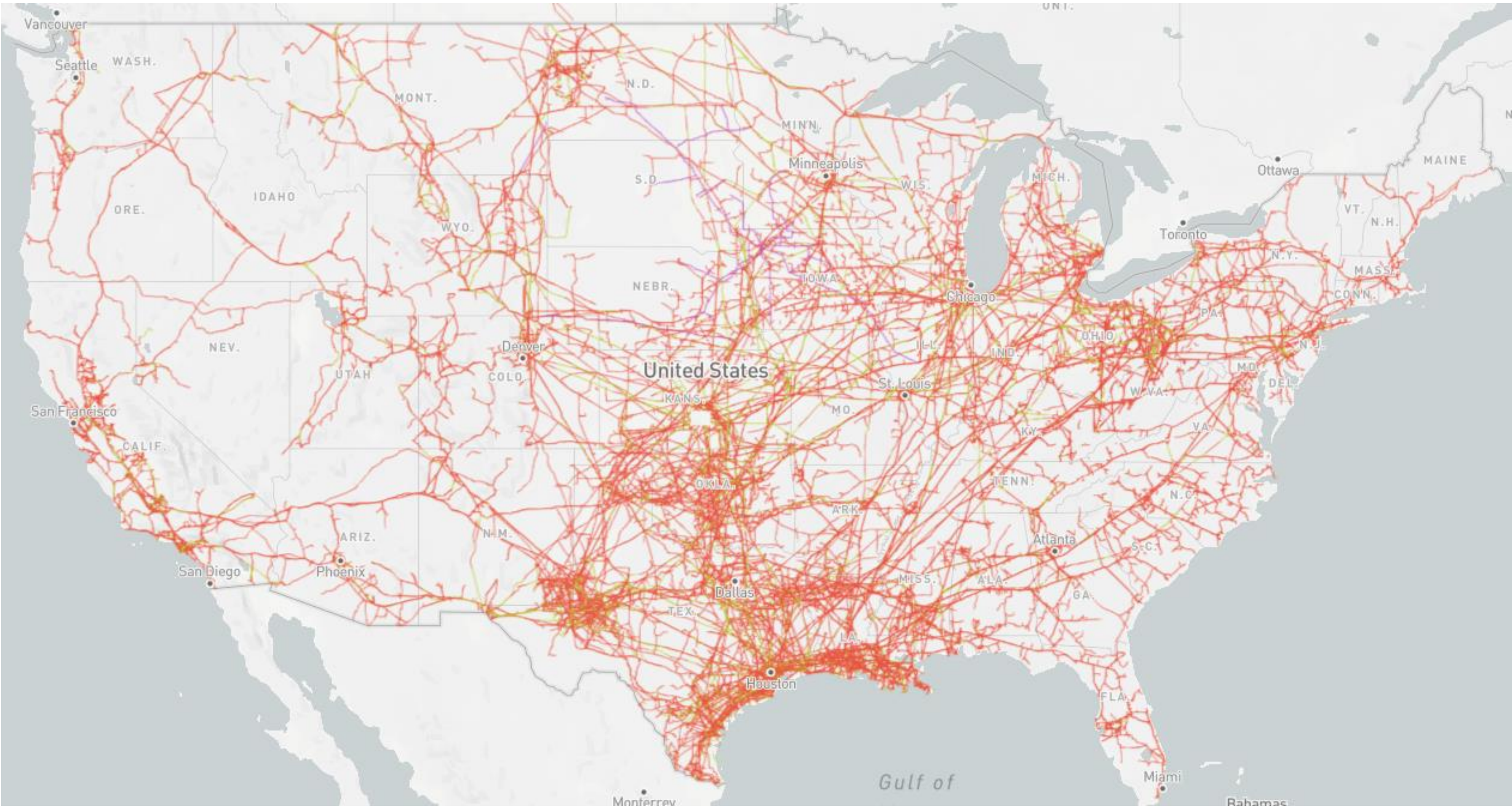
- Massive amounts of infrastructure development have been needed for energy usage in the US.
- This map shows the developed pipeline infrastructure of the US.
- A similar development of CO_2 transport is unlikely from:
  - Increased public opposition with political and legislative sympathy.
  - Losses of economic efficiency from long-distance waste transport.
- Several companies are pursuing pipeline conversions from underutilized lines to solve demand for CO_2 transport.
- Pipeline commodity conversion is feasible, but requires significant investment in safety improvements.



Existing pipeline network across the United States. Only a limited number of these pipelines shown in green are designated for CO_2. Local access to existing infrastructure significantly reduces project costs and avoids potential delays from pipeline permitting and construction, but is extremely limited across the US. (Source: Orennia)

4&5. Community Engagement and Environmental Impact

> **There is a certain familiarity in Louisiana with oil and gas wells that I think we thought would carry over into people's understanding.**
>
> — ***Andrew Connolly,*** *vice president of large low-carbon hydrogen projects, Air Products and Chemicals*

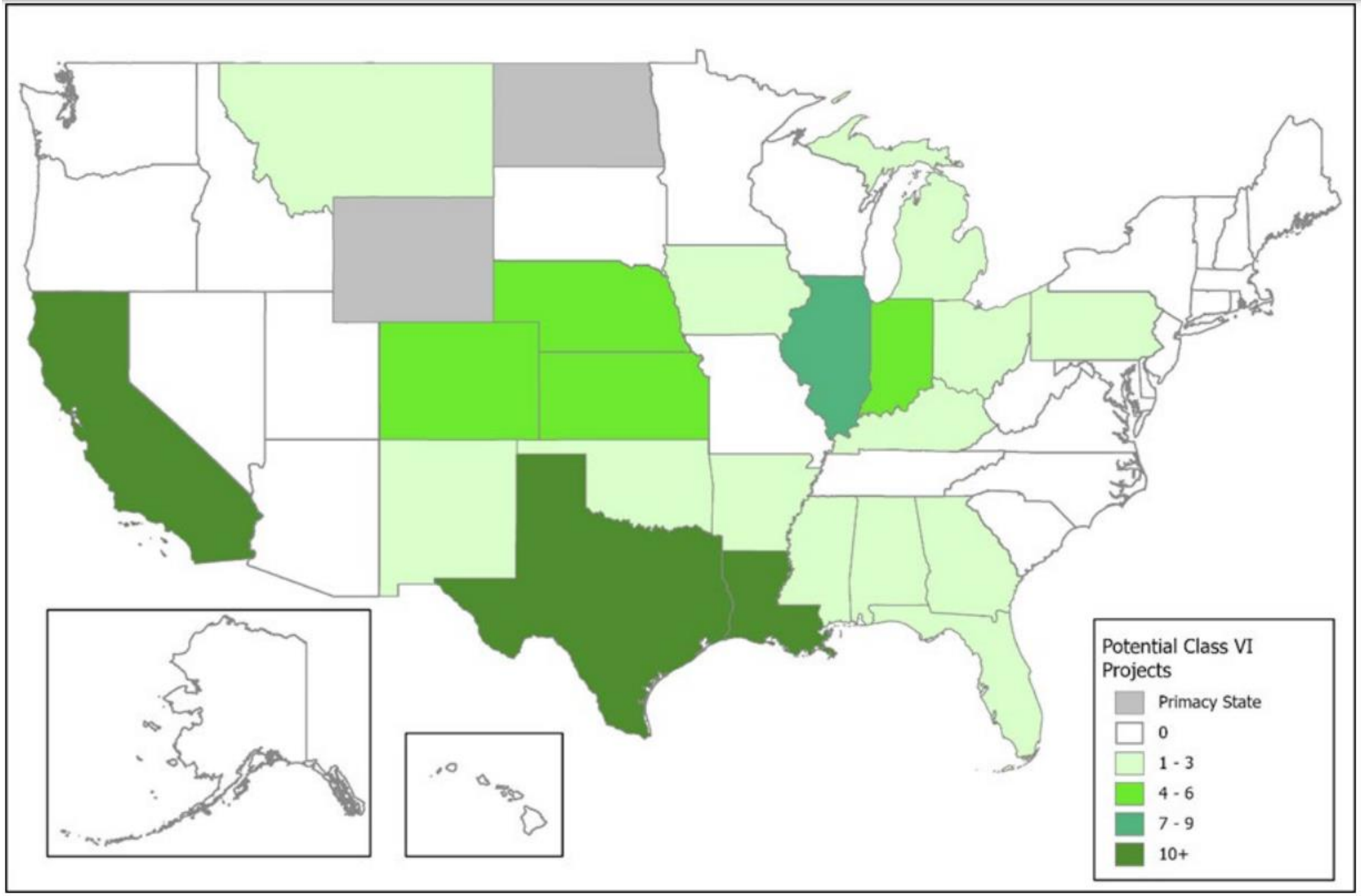
Source: Chemical & Engineering News

- Regulators are under increased scrutiny to protect vulnerable communities.
- Increasing effectiveness of opposition groups who see carbon sequestration as a means for continued fossil fuel use.
- General public uneasiness surrounding new technologies and health and safety.
- Environmental impact studies required for surface access.
- Recent opponents have also recommended storage site exclusion zones surrounding populated regions, schools, hospitals, parks, critical electric grid infrastructure, drinking water storage, and water treatment facilities.

Community engagement is critical in maintaining project schedules as permitting and local legislation is frequently being used to stall new construction. (Source: State Journal-Register)

6a. Well Permitting

- Most CO_2 sequestration sites require an Underground Injection Control (UIC) Class VI well permit.
- The Safe Drinking Water Act (SDWA) enables the US EPA to manage Class VI well permits.
- The EPA has previously taken 3-6 years to approve Class VI well permits.
- States are encouraged by the EPA to apply for primacy to allow state regulators to control well permitting.
  - However, North Dakota and Wyoming remain only states to have Class VI well Primacy.
- States with primacy have shortened the process for well permitting to as quick as 5 months.
- Louisiana appears to be approaching primacy with Texas following.
- Some investors are viewing well permitting as a binary decision gate hindering project development.



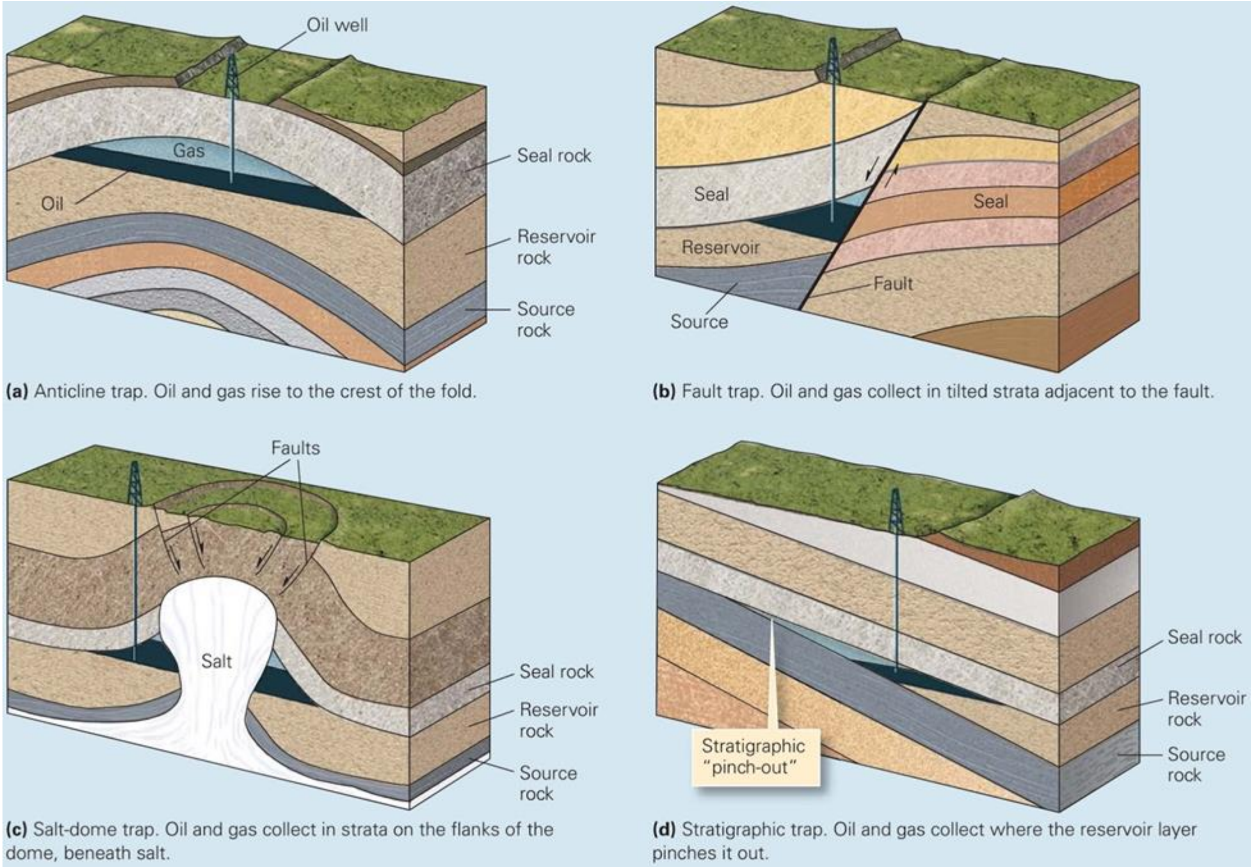
Companies across the US have begun to file multiple Class VI well permits with the EPA focused in areas with prior oil and gas exploration and high emission source concentrations. California continues to lead decarbonization efforts from substantial economic incentives for low carbon intensity energy sources. (Source: EPA, 2022)

6b. Permit Requirements

- The purpose of the Class VI well requirements is primarily to protect Underground Sources of Drinking Water (USDWs).
- These permits require substantial subsurface characterization using:
  - 2D/3D Seismic
  - Adequate coring/sampling of reservoir seal, often avoided during oil and gas exploration.
  - Well Logs
- Identification of Area of Review
  - Anticipated surface footprint of subsurface region affected by CO_2 migration and pressure disturbance.
  - Class II Well: ¼ mile radius from well (Texas)
  - Class VI Well: maximum extent of injection pressure or CO_2 front; ~1.5 mile radius for Decatur project. 3D seismic required in cases of lateral discontinuity to determine extent and location of faults.
- Survey of Existing Wells
  - P&A legacy wells of particular interest.
- Injection Well Design
- Well Plugging Plan
- Subsurface and Surface Monitoring
- Emergency Response Plan
- Assessment of Financial Liabilities

7. Structural Traps are Needed

- CO_2 sequestration projects target formations with similar subsurface structures as oil and gas reservoirs.
- Fluids are prevented from continuing to migrate to the surface by impermeable rocks layers called reservoir seals or cap rock.
- In oil and gas exploration these structures are used to determine target well locations.
- For carbon sequestration, these traps can have high uncertainty except in cases of depleted hydrocarbon reservoir utilization.
- Different structures, such as anticline traps, fault traps, salt domes, and stratigraphic traps, can be exploited for CO_2 sequestration sites.
- Anticline traps and stratigraphic traps rely on an intact, impermeable reservoir seal that can be easily determined from surface imaging, well logs, and subsurface samples.
- Fault traps and salt dome traps rely not only on the reservoir seal but also the blockage of fluid flow along discontinuities, which is much harder to determine.
- Therefore, anticline and stratigraphic traps are preferred from the ease in which reliable sealing can be assured.



Different subsurface formation that are capable of trapping fluids in the subsurface. (Source: S. Marchak, Essentials of Geology)

8. Drilling in Unfamiliar Regions

- Drilling technologies have continued to advanced, but drilling in unexplored or underdeveloped areas can still pose issues.

- Drilling mud lubricates the drill string and helps to clear drilled solids from the wellbore while keeping lighter fluids (oil and gas) from rushing to the surface in exposed formations.

- Maintaining a careful balance between drilling mud weight and exposed rock formations is crucial to prevent mud from entering weaker formations.

- Potential drilling loss of circulation issues for a well is shown (right).

- If significant damage to the wellbore has occurred during drilling, additional delays can be expected during well completions.

- The damaged formations will need additional repair work in order to guarantee a proper seal has been created between the well cement and casing before a permit to operate is granted.

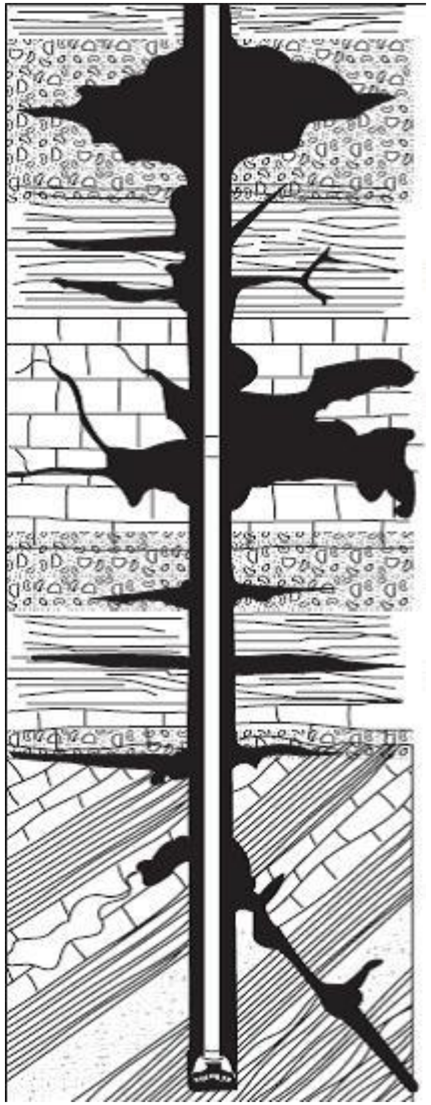
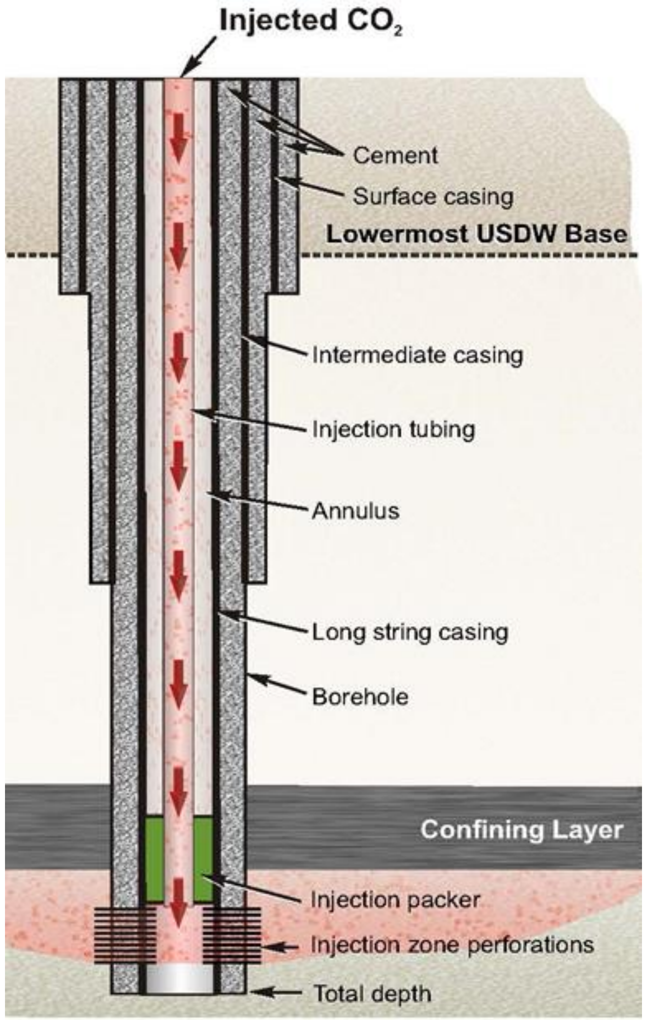


Diagram showing various events during well drilling that can lead to loss of drilling fluids and may pose other problems during well cementing and assuring leakage of sequestered CO_2 will not occur along the length of the wellbore. (Source: Drilling Manual)

9. Enhanced Well Completion Requirements

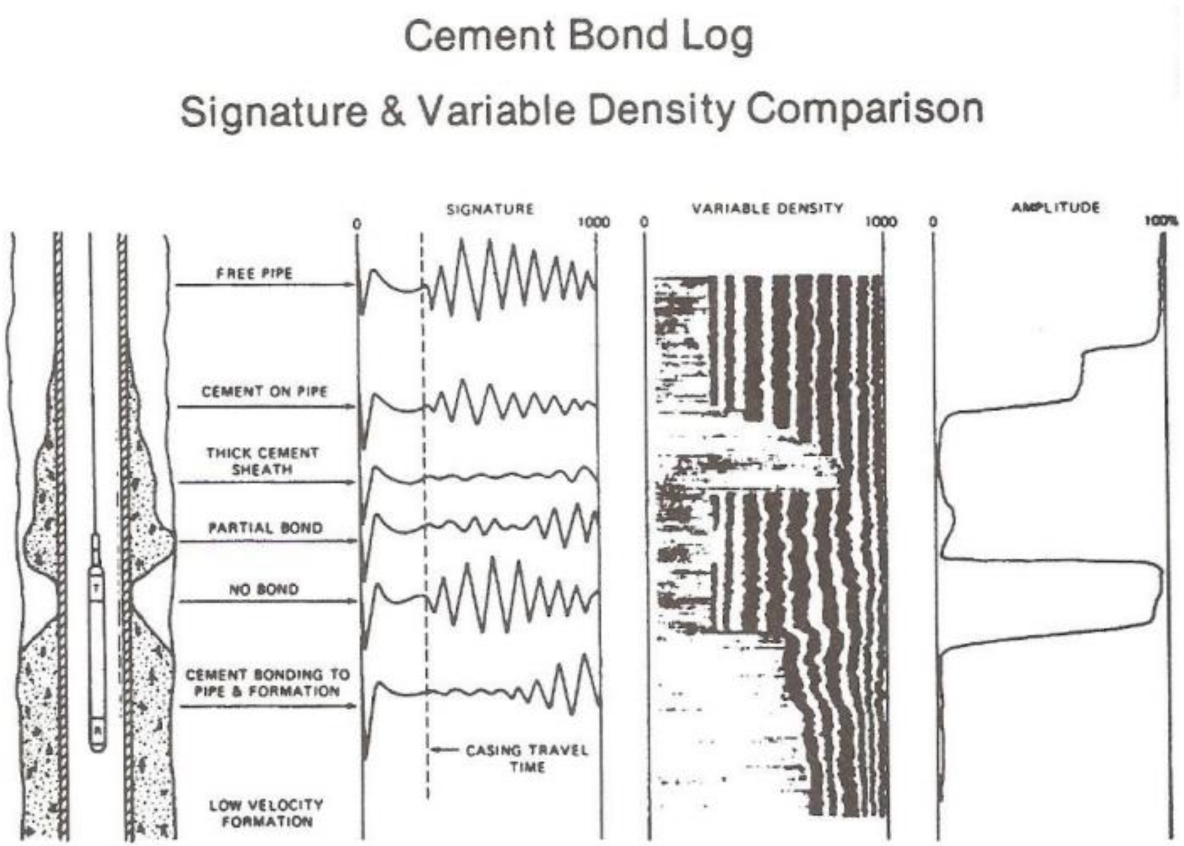
- Wells for carbon sequestration projects have a similar construction to oil and gas wells, but with additional requirements that can add to the cost.
- The additional cementing and casing design for a CO_2 injection well is shown here.
- Well cement is crucial for preventing CO_2 leakage and must be pumped from the bottom of each interval to the surface.
- To prevent corrosion from CO_2, lower portions of cement and tubing/inner casing strings may need to be made of higher-cost corrosion-resistant materials.
- Careful consideration and selection of materials are critical for the safe and effective deployment of carbon sequestration wells.



An example Class VI well completion showing the complete cementing of each casing string to the surface. (Source: EPA)

10. Well Cement

- Injection wells for carbon disposal pose one of the highest risks of leakage for projects.
- Cement is used to seal the annulus between the well casing or liner, but residual drilling mud, gas bubbles, and cracks can prevent a complete seal.
- Carbon dioxide mixed with water can dissolve cement and corrode metal used in traditional wells.
- Proper well design and numerous techniques can address material issues and fix leakage problems.
- Ensuring the integrity of the cement and preventing leakage is critical for the safe and effective disposal of carbon dioxide.
- Cement bond logs (right) are used currently in industry to verify proper isolation in hydrocarbon wells.
- CBLs will also likely be required in sequestration projects to confirm proper cementing around injection wells and in areas of concern with legacy wells.



Cement bond logs (CBLs) are one of the tools that can be used in determining the quality well cement. CBLs can show regions of poor- and high-quality cementing. (Source: Western Atlas)

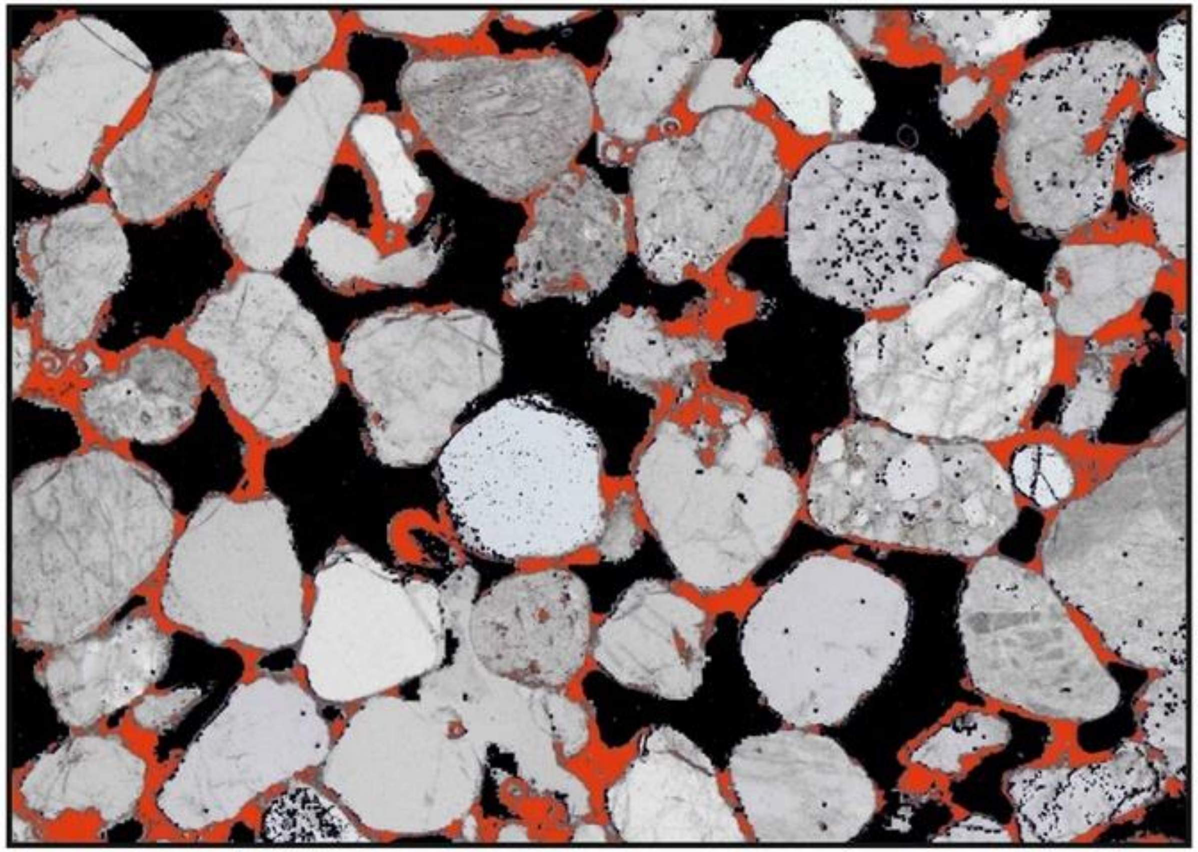
11. Formation Injectivity

- Storage reservoirs that have not been thoroughly investigated for storage potential may suffer from unexpected injectivity limitations that limit the rate or total amount of carbon dioxide that can be stored.

- Reservoir permeability needs to be high enough to allow for the movement of water away from the injection well displaced by the invading carbon dioxide.

- The thickness of the target formation needs to be sufficient to support both the well injection rate and the total final storage volume of injected carbon dioxide.

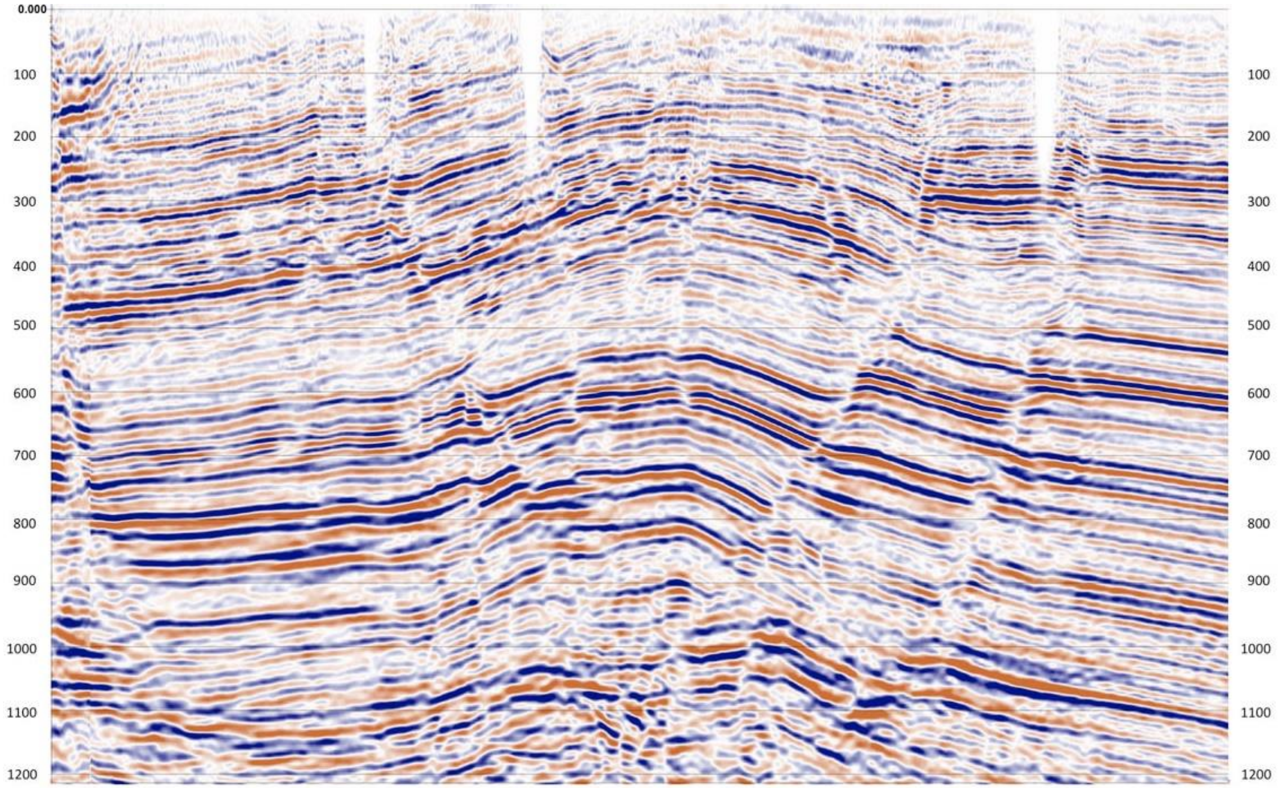
- Hydraulic stimulation of a disposal well is feasible to improve injection rate and access to the storage formation, however, caution is warranted to prevent the exacerbation of other potential leakage pathways.



Changes in water chemistry from the injection of CO_2 can cause the formation of salts (shown in red) and mineral deposits in the pores of a target storage formation. (Falcon-Suarez et al. Sci Rep. 2020.)

12. Unidentified Fractures and Faults

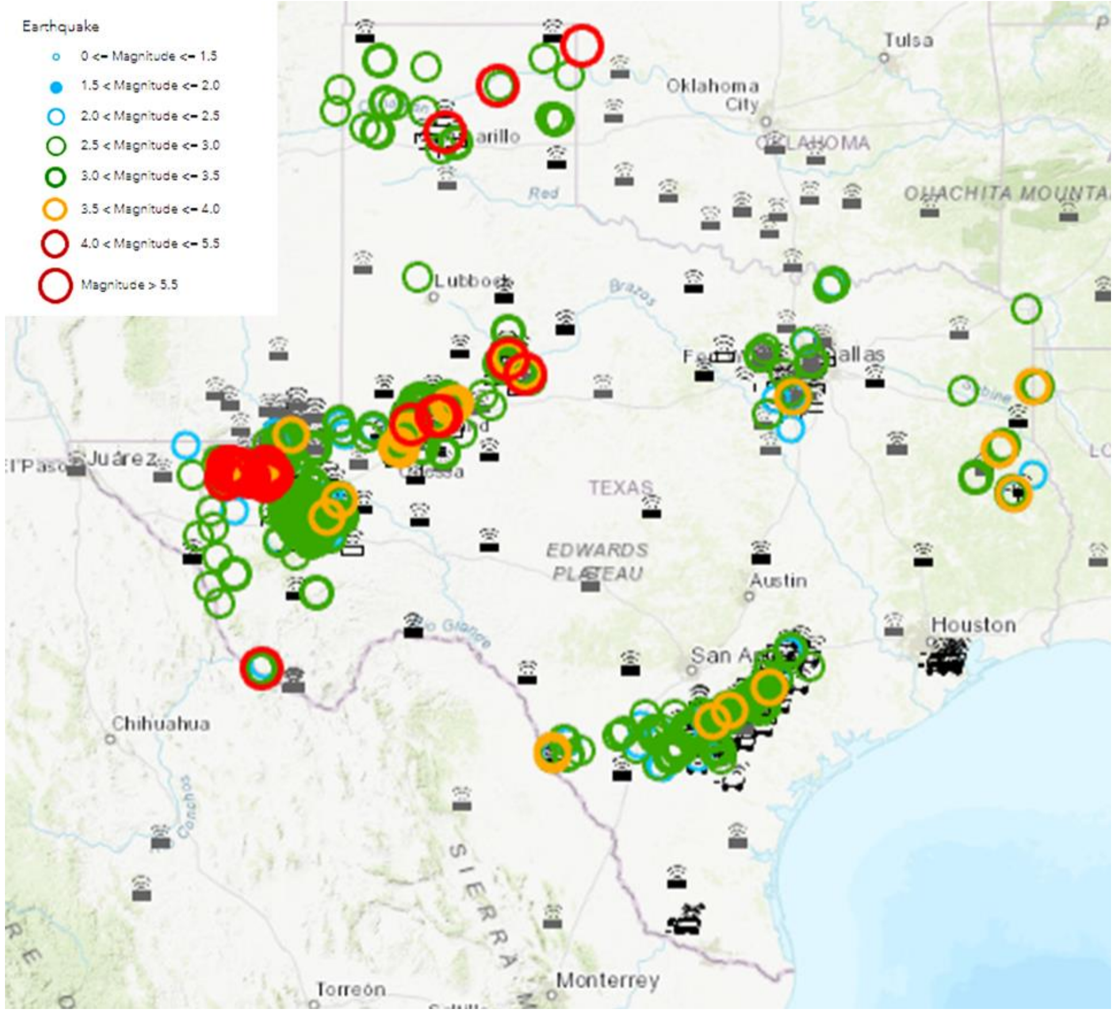
- Subsurface fractures and faults can be high permeability shortcuts that pose risks to disposal projects.
- Faults and fractures are common in the subsurface, but some can be sealed through geologic processes.
- Sealing faults can restrict fluid flow across fault planes, which can improve the containment of injected CO_2.
- Large faults can typically be seen in subsurface imaging from the vertical displacement of sedimentary layers.
- Strike-slip faults however are more difficult to image from the lack of vertical offset.
- Overall, understanding the nature and distribution of subsurface faults and fractures is critical for safe and effective carbon dioxide disposal.



Subsurface seismic of significantly faulted region. Experienced subsurface engineers and geologists are skilled in identifying subsurface structures, but uncertainty can persist around missed features. (Source: Yilmaz, O. Seismic data analysis 2001.)

13. Induced Seismicity

- Sites with no previous seismic activity or identified fractures and faults that may slip from stress changes should be targeted.
- Injection of CO_2 or produced water can cause faults to shift, potentially leading to felt earthquakes.
- The bigger the shift, the more energy is released, increasing the probability of local populations reporting tremors.
- Changes in subsurface stress leading to fractures and faults shifting is referred to as induced seismicity or triggered seismicity.
- These shifts can allow a CO_2 plume to move unexpectedly along fault planes.
- CO_2 sequestration projects require active seismic monitoring and avoidance of exceeding permit injection thresholds.
- Understanding and mitigating seismic risks is critical for the safe and effective deployment of CO_2 sequestration projects.



Recorded earthquakes across Texas highlight regions of increased seismic activity usually corresponding with increased subsurface wastewater injection. (Source: TexNet Seismic Monitoring)

14. Legacy Wells

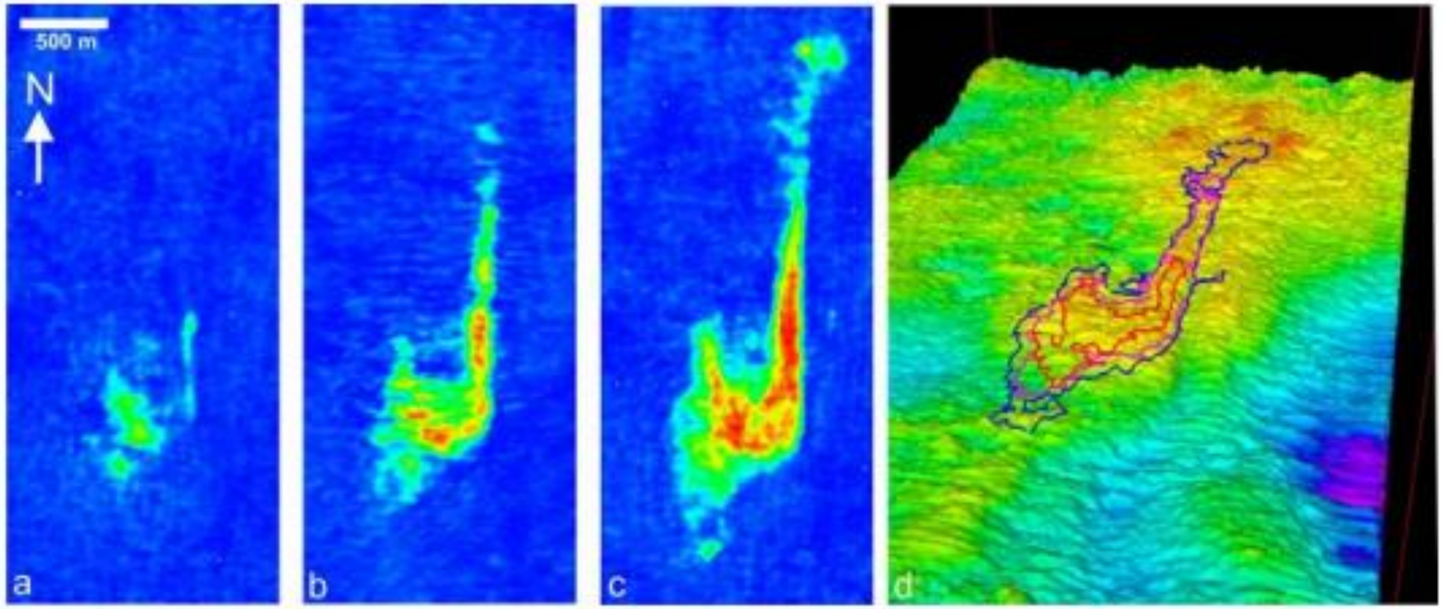
- Previous oil and gas exploration can improve the success of geologic disposal projects by providing reservoir performance data and understanding of fluid injection.
- The presence of an oil and gas accumulation can indicate viability of fluid immobilization and low risk of leakage.
- Old wells, however, can pose a significant liability as potential leakage pathways.
- Industry standards for well cementing have improved, but older wells may have been incorrectly completed, improperly abandoned, or degraded with age.
- Remediation may be necessary prior to CO_2 disposal in a previously produced storage reservoir.

Leaking abandoned wells from previous oil and gas drilling are a likely leakage pathway for sequestered CO_2. Wells that were drilled without permitting or other documentation can raise costly remediation costs when no information regarding well plugging, abandonment, or completion can be found. (Source: PA Dept. of Env. Protection)

Sidewall plugs extracted from a 30 year old well located in the SACROC CO_2-EOR field showed that even neat Portland cement is capable of withstanding exposure to CO_2-brine. The dissolution of the cement leads to the formation of leak slowing minerals in well annulus. (Source: Carey et al., 2007.)

15. Fluid Migration

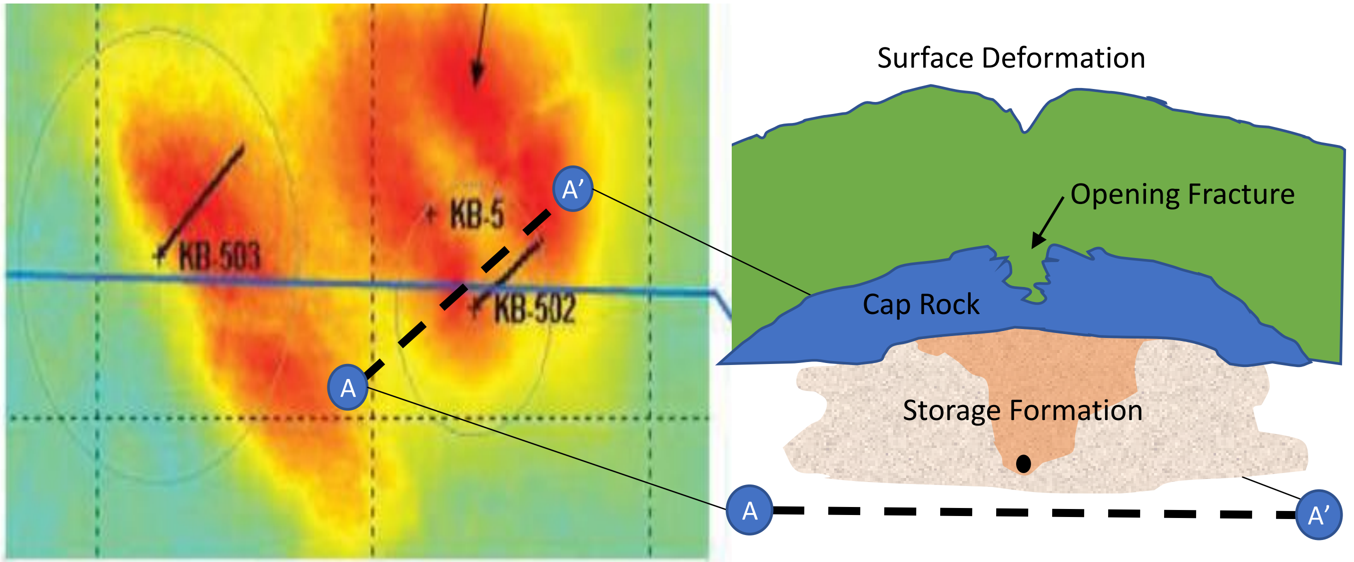
- Sequestered CO_2 is designed to remain in the subsurface for thousands of years, moving through the target formation and settling along the impermeable reservoir seal.
- Supercritical CO_2 rises naturally due to its lower density compared to other fluids in the subsurface.
- Tracking the migration of the CO_2 plume is possible using modern tools in oil and gas subsurface characterization.
- Unintended migration of the disposed CO_2 can be disastrous if other subsurface features are not considered in reservoir models or have been missed in the initial screening.
- High permeability highways, such as fractures and faults, can facilitate the spread of the CO_2 plume beyond anticipated boundaries, potentially violating pore space ownership rights.
- In a worst-case scenario, CO_2 plume migration may extend beyond secured sealing regions and leak into higher formations, posing risks to drinking water and potential surface leaks.



Subsurface monitoring of the CO_2 plume migrating at the Sleipner storage site over several years from left to right. The plume migration observed off the coast of Norway followed the predicted migration pathway to the higher elevation reservoir seal locations. (Source: Chadwick and Noy, GSL, 2010.)

16. Reservoir Seal Failure

- Reservoir seal integrity is crucial for successful CO_2 sequestration projects.
- The cap rock is an impermeable layer that isolates injected CO_2 from unintended formations.
- The finite strength of the cap rock presents the risk of fractures that can allow CO_2 to migrate into overlaying formations.
- A thick sealing formation is necessary to minimize the risk of unintended migration and provide additional security for sequestered CO_2.



Satellite imaging recorded during the operation of a CO_2 sequestration site in Algeria identified the potential fracture opening of the reservoir seal during CO_2 injection. No CO_2 was determined to have escaped from the intended storage formation, but the project was suspended for several years and finally shutdown after seismic activity increased following reactivation. (Modified from Ringrose et al., Energy Procedia, 2013.)

17. Active Monitoring to Minimize Risk

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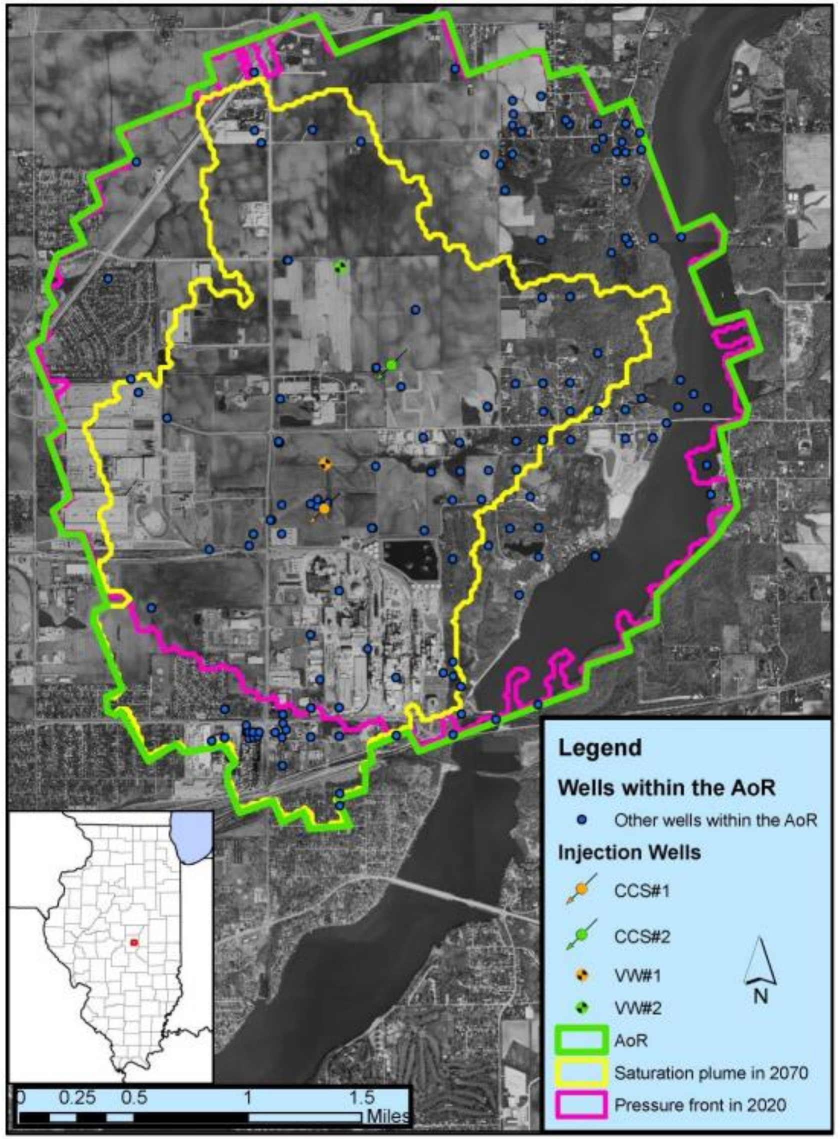
- A variety of monitoring stations are necessary for CO_2 sequestration projects, including air and water quality monitoring and seismic activity monitoring.
- The area of review and the additional subsurface monitoring wells drilled for the Decatur sequestration project are shown.
- Air monitoring stations are used to detect changes in CO_2 concentration near well site operations and populated areas, providing advanced warning of potential air issues.
- CO_2 sequestration operations may force hazardous substances into existing water supplies, necessitating water quality monitoring.
- Existing water wells are monitored for changes in water quality and potential contamination.
- While necessary for public safety, monitoring wells only safeguard projects after a significant amount of investment in project development.



Predicted pressure front and plume migration of CO_2 at the Decatur, Illinois CO_2 sequestration site. The injection wells CCS#1 & #2 along with deep vertical observation wells VW#1 & 2 are shown along with multiple other wells that overlay the storage formation. Multiple other surface locations were developed for air and water quality monitoring. (Source: ADM - EPA Class VI Permit)

18. Final Destination of Sequestered CO_2

- CO_2 sequestered in the subsurface is designed to remain there for millennia.
- Supercritical CO_2 will eventually mix with aquifer brine and convert into solid carbonate minerals, sinking to the bottom of the target formation.
- Our confidence in the security of carbon sequestration is bolstered by the long-term stability of fossil fuel reservoirs, which have remained in place for millions of years.
- The principles that have kept oil and gas reservoirs securely in the subsurface for millions of years will also prevent CO_2 from migrating out of the sequestration site.
- Similarly, natural leakage pathways presenting as CO_2 geysers and natural oil seeps help in determining the maximum leakage rates and potential remediation techniques that could be used in fixing problematic sequestration reservoirs.
- A more detailed note on the assurance of the safe, long-term disposal of CO_2 in the subsurface is available on request from PEP.

Crystal Geyser in Utah is driven by subsurface charging of an aquifer with carbon dioxide. (Source: Utah GS)

Disclosures

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