Storage 1- Reservoirs, Traps, Seals and Storage Capacity for CO₂ Storage

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Carbon capture & storage (CCS) value chain

Geological storage of CO₂

What do we need?
RESERVOIR ROCK – porous, e.g. sandstone
SEAL ROCK – non-porous, e.g. claystone
Occurring at appropriate depth

Geological Structures

“Ductile” deformation results in FOLDS.
Convex upwards folds are called ANTICLINES.
Concave upwards folds are called SYNCLINES.
Geological Structures: Anticlines & Synclines

Anticline – syncline; Calico, Mojave, CA

Anticline, road cut, near Oak Ridge, Tennessee

Structural trap for CO₂: Anticline Trap

- Injection into reservoir rock
- Buoyancy drives CO₂ upwards
- Top seal prevents escape
- Such features have safely held oil, gas & natural accumulations of CO₂ for millions of years

Geological Structures: Faults

“Brittle” deformation results in Faults and/or Fractures

Faults and fractures are breaks (cracks) in the rocks that make up the Earth’s crust that have formed as a response to natural or induced stresses

A fault is where rocks on either side of the crack have moved past each other; a fracture is where there has been no motion.

Faults form due to earth stresses

Extension results in NORMAL faults.

Compression results in REVERSE or THRUST faults.

Horizontal shearing results in STRIKE SLIP or WRENCH faults.

What sort of fault is this?

Normal Fault, near Moab, Utah

What sort of fault is this?

Reverse (thrust) fault, Ketobe Knob, Utah
What sort of fault is seen on this air photo?

- Strike-slip fault, San Andreas, California
- Small offset fault on hwy 18, North Park, CA

Structural trap for CO₂: Fault Trap

- Injection into reservoir rock
- Buoyancy drives CO₂ upwards
- CO₂ retained by:
  - Fault juxtaposed seal-on-reservoir
  - Shale gouge / cement on fault plane
- Risks: fault reactivation
  - ΔP (from injection)
  - Natural seismic events

Stratigraphic trapping

- Unconformity
- Pinch out

Stratigraphic traps are created by changes in rock type. These traps have historically been regarded as high risk, because identification of rock type is much less certain on seismic data than delineation of structure.

Examples are: UNCONFORMITY traps. PINCHOUT traps.

Unconformity, near Moab, Utah

What sort of feature is this?

CO₂ Storage Trapping Mechanisms

- Structural / Stratigraphic Trapping (SST)
  - Most familiar; best understood; lowest risk

Storage in Deep Saline Formations
**CO₂ Storage Trapping Mechanisms**

- Migration Associated Trapping (MAT)
  - Least familiar
  - Modelled, but poorly understood
  - Highest uncertainty
  - Focus of many storage demo projects

**CO₂ Storage Effectiveness Increases with Time**

*Modelling the dissolution of injected CO₂*

- Homogeneous Reservoir
- Flat-lying Seal
- Cross-sectional view

**Mineral Trapping: Also Increases with Time**

- Calcite cement (red)
- CaCO₃ (Calcite) precipitation occurs at all scales at different rates

**Residual CO₂ Saturation by Plume Migration**

- "Snap-off"
Residual CO₂ saturation during plume migration (CAPILLARY TRAPPING)

CO₂ storage effectiveness increases with depth

“Dense-phase”

Residual (trapped) CO₂

Water filled pore

CO₂ enters pore

Containment of CO₂

Caprock properties controlling containment

Fault properties controlling containment

Rate controls on containment

Caprock Properties: “Seal potential”

Capacity:
- maximum CO₂ column that can be retained by caprock

Geometry:
- thickness and lateral extent of the caprock

Integrity:
- geomechanical properties of caprock

Evaluating seal capacity of caprocks for CO₂ containment

Relative densities: Oil > CO₂ > CH₄
Relative buoyancy: Oil < CO₂ < CH₄

Evaluating seal capacity of caprocks for CO₂ containment

• If the seal capacity is calculated as being too low to hold the required column, the cap rock may still be OK, because low permeabilities may inhibit migration = “rate” seal

• If upward migration through the seal does occur, it would be at very slow rates

• Calculated migration rates of CO₂ through Muderong Shale (NW Shelf, Australia) >0.3Ma / 100m for migration
  - Muderong Shale = 1500 metres thick; Break-through in 4.5 million years
**Seal geometry**

Refers to thickness and areal extent of caprocks
Estimated by integrating seismic, core & well log data, with geological/depositional models

**Intraformational seals (baffles)**

Increase length of CO₂ migration pathways & potential for Sgr and dissolution

**The role of faults in CO₂ containment**

Faults and fractures are breaks (cracks) in the rocks that make up the Earth’s crust that have formed as a response to natural or induced stresses

A fault is where rocks on either side of the crack have moved past each other.

Faults do not necessarily act as fluid conduits; empirical evidence that many thousands of hydrocarbon accumulations are trapped by sealing faults

In such cases, either the fault itself acts as a seal or the juxtaposition of rocks across the fault results in sealing

**Shale-sand juxtaposition traps CO₂**

Tectonic forces “juxtapose” sealing rocks against reservoir rocks, on either side of a fault, resulting in trapping of buoyant fluids (oil, gas, CO₂)

**Clay Smear (Shale Gouge)**

Yielding et al 1997
Faults and fractures are breaks (cracks) in the rocks that make up the Earth's crust that have formed as a response to natural or induced stresses. A fault is where rocks on either side of the crack have moved past each other. Faults do not necessarily act as fluid conduits; empirical evidence that many thousands of hydrocarbon accumulations are trapped by sealing faults. In such cases, either the fault itself is acting as a seal or the juxtaposition of rocks across the fault results in sealing. Fault movement (reactivation) could result in fluid migration along the fault & potential unintended migration.

Juxtaposition + Reactivation

Seal Integrity: Geomechanics

The Stress Tensor:
- Key to understanding risk of induced seismicity
- By understanding the orientation of the in-situ stress field, and any induced stress, relative to the orientation of existing faults, we can predict the likelihood of reactivation of those faults

Storage Capacity

What do people want to know about storage capacity?
- Volumetric approach – current state of art
Injectivity

\[ \frac{I}{t} = A \cdot P \cdot k \]

- \( I \) = Injection rate
- \( A \) = Area of wellbore in contact with formation
- \( P \) = Injection pressure (below frac pressure)
- \( k \) = Permeability

(K, P, are constant; A is proportional to number and orientation of wells)

Injectivity / Pressure Considerations:

- Pore space in storage formations already full…injection of fluids (eg CO2) causes reservoir pressure build up
- In depleted fields, pressure build-up may be beneficial or neutral
- In both depleted fields and saline aquifers, must maintain pressure below fracture pressure
- In low permeability reservoirs this may limit economic storage capacity due to decreased injection rate, requiring more wells
- Injection in saline formations may displace saline fluids & increase risk of possible mixing with freshwater system
- Drilling pressure relief (water production) wells is a possible solution

Storage capacity estimation

Techno-Economic Resource-Reserve Pyramid for CO2 Storage Capacity

- Total Pore Volume
  - Total physical limit of what the storage system can accept. Assumes entire volume is accessible to store CO2 in the pore space or dissolved in formation fluids or adsorbed at 100% onto total coal volume. This represents the maximum upper limit to a capacity estimate.
  - However, this is an unrealistic number as there will always be physical, technical, regulatory and economic limitations.
Prospective Capacity
Subset of Total Pore Volume and obtained by applying technical (geological & engineering) limits. This estimate usually changes with acquisition of new data or knowledge.

Contingent Capacity
Subset of prospective capacity obtained by considering technical, legal and regulatory, infrastructure and general economic barriers. Value changes as technology, policy, regulations and/or economics change. Corresponds to “Reserves” as used in energy and mining industries.

Operational Capacity
Subset of contingent capacity obtained by detailed matching of large, stationary sources with geological storage sites that are adequate in terms of capacity, injectivity and supply rate. Corresponds to “Proved, marketable reserves” used by mining industry.

Volumetric equation for storage capacity calculation:

\[ G_{\text{CO}_2} = A h_g \phi \rho E \]

- \( G_{\text{CO}_2} \) = Volumetric storage capacity
- \( A \) = Area (Basin, Region, Site) being assessed
- \( h_g \) = Gross thickness of target saline formation defined by \( A \)
- \( \phi \) = Avg. porosity over thickness \( h_g \) in area \( A \)
- \( \rho \) = Density of \( \text{CO}_2 \) at Pressure & Temperature of target saline formation
- \( E \) = Storage "efficiency factor" (fraction of total pore volume filled by \( \text{CO}_2 \))

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