Fundamentals of CO$_2$ Storage in Geological Media
CO₂ Capture and Storage Chain

Capture → Compression → Pipeline Transport → Underground Injection & Storage
Process Scales for CO$_2$ Geological Storage
Carbon Sequestration leadership Forum
www.cslforum.org

Relevant CO₂ Properties, CO₂ Trapping Mechanisms, Means and Media for CO₂ Geological Storage
Phase Diagram for Carbon Dioxide

- Solid CO₂
- Liquid CO₂
- Gaseous CO₂
- Sublimation Line
- Vaporization Line
- Melting Line
- Critical Point (31.1°C, 7.38 MPa)
- Triple Point (-56.6°C, 0.51 MPa)
CO₂ Density for Pressure and Temperature Conditions in the Earth Crust
Variation of CO$_2$ Density with Depth and Geothermal Regime
Trapping of CO\textsubscript{2} in the Pore Space at Irreducible Saturation
Carbon Dioxide Solubility in Water

In pure water

![CO2 solubility in pure water graph](graph)

In brine

![CO2 solubility in brine graph](graph)
Sequence of Geochemical Reactions between CO$_2$ and Formation Water and Rocks

1. Solubility Trapping

$$\text{CO}_2(g) \rightleftharpoons \text{CO}_2(aq)$$

$$\text{CO}_2(aq) + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3(aq)$$

2. Ionic Trapping

$$\text{H}_2\text{CO}_3(aq) \rightleftharpoons \text{HCO}_3^-(aq) + \text{H}^+$$

$$\text{HCO}_3^-(aq) \rightleftharpoons \text{CO}_2^-(aq) + \text{H}^+$$

3. Mineral Trapping

$$\text{CO}_2^-_3(aq) + \text{Ca}^{2+} \rightarrow \text{CaCO}_3(s)$$

$$\text{HCO}_3^-(aq) + \text{Ca}^{2+} \rightarrow \text{CaCO}_3(s) + \text{H}^+$$
Aqueous Species Dominance Diagram

- **Mineral Trapping**
  - (Calcite)
  - (Magnesite)
  - (Siderite)

- **Solubility Trapping**
  - $\text{H}_2\text{CO}_3$

- **Ionic Trapping**
  - $\text{HCO}_3^-$
  - $\text{CO}_3^{2-}$

- pH

- Concentration
  - $\log (\text{Ca}^{++} \text{ or Mg}^{++} \text{ or Fe}^{++})$
Adsorption of Various Gases on Coal

![Graph showing the adsorption of various gases on coal.](graph.png)
**CO₂ Trapping Mechanisms**

- **Physical Trapping (in free phase)**
  - In Static Systems (no flow)
    - In large man-made cavities
    - In the pore space in stratigraphic and structural traps
      - Mobile (continuous phase able to flow)
      - At irreducible saturation (immobile residual gas)
  - In Dynamic Systems (flow in long-range regional-scale systems)

- **Chemical Trapping**
  - Adsorbed onto organic material in coals and shales
  - Dissolved in formation fluids (oil or water)
  - Precipitated as a carbonate mineral (irreversible process)
Temporal Scales of CO$_2$ Injection and Geological Storage Processes

From IPCC SRCCS, 2005
Relation between Time, Trapping Mechanisms and CO$_2$ Storage Security

From IPCC SRCCS, 2005
Required Characteristics of Geological Media Suitable for Storage of Fluids

- **Capacity**, to store the intended CO$_2$ volume
- **Injectivity**, to receive the CO$_2$ at the supply rate
- **Containment**, to avoid or minimize CO$_2$ leakage
Igneous rocks
- Rocks formed from cooling magma
  - Granite
  - Basalt

Metamorphic Rocks
- Rocks that have been subjected to high pressures and temperatures after they are formed
  - Schist
  - Gneiss

Sedimentary rocks
- Rocks formed from compaction and consolidation of rock fragments
  - Sandstone
  - Shale
- Rocks formed from precipitation from solution
  - Limestone

Rocks Suitable for CO$_2$ Storage

Granite
- Crystalline
- Low porosity
- Low permeability
- Fractures

Schist
- Crystalline
- Low porosity
- Low permeability
- Fractures

Sandstone
- High porosity
- High permeability
- Few fractures
Geological Media Suitable for CO$_2$ Storage

- Porous and permeable rocks (sandstone and carbonate) overlain by tight rocks (shales and evaporitic beds):
  - Oil and gas reservoirs
  - Deep saline aquifers
- Coal beds
- Salt caverns

All are geological media found ONLY in sedimentary basins
Types and World Distribution of Sedimentary Basins

(based on St. John et al., 1984)
Means for CO$_2$ Geological Storage

As a byproduct in energy production operations

- In oil reservoirs in enhanced hydrocarbon recovery
- In coal beds in enhanced coalbed methane recovery

In disposal operations

- In depleted oil and gas reservoirs
- In deep saline aquifers
- In salt caverns (mainly as a buffer in CO$_2$ collection and distribution systems)
Means of CO₂ Geological Storage
Example of Subsurface Temperature and Pressure for CO$_2$ Storage

Temperature ($^\circ$C) vs Depth (m):

- $T_s = 10^\circ$C
- $T = 10^\circ$C + $25^\circ$C/1,000 m x 1,250 m
  - $= 41.25^\circ$C

Pressure (bar) vs Depth (m):
- Watertable = 0 m
- $p = 10^5$ Pa + 1,000 kg/m$^3$ x 9.81 m/s$^2$ x 1,250 m
  - $= 12.36$ MPa (123.6 bar)
CO₂ Phases in a Transportation and Storage System

Carbon dioxide: Temperature - pressure diagram

- **CO₂ Solid**
- **CO₂ Liquid**
- **CO₂ Vapour**
- **Pipeline Transportation**
- **Supercritical Fluid**

- **Critical Point**
  - (31.1°C, 7.38 MPa)
- **Leak in the atmosphere**
- **Sublimation line**
- **Saturation line**
- **Melting line**

Temperatures:
- 1,600 m
- 1,250 m
- 900 m
- 500 m
- 200 m
Storage Depth is Defined by CO₂ Density

- Storage below 800 m
  - Supercritical CO₂
  - Dense phase CO₂ (500 to 800 kg/m³); Water is 1.3 to 2 times denser (heavier)
  - Low viscosity (0.04 to 0.06 MPa·s); Water is 10-20 times more viscous

- Rule-of-thumb
  - Depends on P and T profile
  - Will vary from site to site
    - Watertable depth
    - Mean annual surface temperature and geothermal gradient
Three primary conditions:
- Sedimentary rocks with storage reservoirs and seals
- Pressure and temperature greater than critical values (31°C, 78.3 bars)
- Not a source of drinking water

Prospectivity of Sedimentary Basins for CO$_2$ Storage

From IPCC, 2005
Controversial Storage Media

Among the media proposed for CO₂ storage:

1. Storage in coal beds:
   - Has never been successfully demonstrated
   - Uneconomic coals have not been defined

2. Storage in shales rich in organic material:
   - Based on the same principles as storage in coal beds
   - Has not been attempted and demonstrated
   - Will require fracturing the shale, which constitute the caprock for hydrocarbon reservoirs and deep saline aquifers

3. Storage in basalts (based on rapid geochemical reactions)
   - Very controversial because of basalts’ high porosity and permeability
   - A test is attempted in western Washington state
Concluding Remarks

- **CO₂** can be trapped in free phase, mobile and/or immobile, in solution in formation water or oil, adsorbed onto coal or organic-rich shales, and as a mineral precipitate in the pore space or in basalts.

- **CO₂** can be stored in oil and gas reservoirs, deep saline aquifers, uneconomic/unmineable coal beds, salt caverns, and possibly in organic-rich shale beds and basalt flows.

- Various trapping mechanisms operate on different temporal time scales that need to be taken into account.
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