Definition of AoR Onshore and its Equivalent Offshore

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Offshore

- GoM is highly prospective for CO2 storage
  - Large point-source emissions
  - Abundant subsurface data
  - Proven reservoirs and seals
  - Potentially re-usable infrastructure
- Attraction of offshore
  - Single landowner
  - Relatively few wells
  - Relatively few competing uses
  - Relatively modern infrastructure

Data: US EPA FLIGHT database and IHS Enerdeq (2022)
North American Experience is Onshore

Rapidly growing interest in offshore, lots of new players entering CCS and a range of views

Global CCS Institute, 2020: https://www.globalccsinstitute.com/resources/publications-reports-research/
Onshore and Offshore Storage
Temperatures and Salinities are Highly Variable

Figure 8. Map of interpreted below-mudline depths to 300°F (BMLD300), areas in the Gulf of Mexico. See Table 1 for summary of data and key to protraction area abbreviations. Forrest et al, 2007
Questions

• How do you explain AoR to new audiences?
• What is the range of critical pressure increases?
  • Onshore vs offshore
  • Different injection zone salinities
  • Different USDW/injection zone depths
• How does rock strength vary?
  • How much pressure increase is allowable?
• How do you translate critical pressure change into AoR?
  • Quick-look methods?
  • How much area does a typical CCS project need?
Finding $\Delta P_{\text{crit}}$

Water density varies with temperature and salinity

$\Delta Z = \text{depth difference between base USDW and top injection zone}$

$\Delta \rho = \text{midpoint difference between initial and final density profiles}$

$\Delta P_{\text{crit}} \propto \Delta Z \cdot \Delta \rho$

After Nicot et al, 2009

www.creativefabrica.com
Finding $\Delta P_{\text{max}}$

- Hydrostatic pressure
  - Density of water column
  - Calculate for a given salinity and geothermal gradient

- Lithostatic pressure
  - Compaction curves for sand and shale
  - Known grain densities
  - Pore water density
  - Calculate for a given sand/shale mix

- Frac pressure
  - Function of lithostatic pressure and pore pressure
  - Calculate via Eaton’s method or Zhang’s method

$\Delta P_{\text{max}}$ (pressure space for injection)
Variations in $\Delta P_{\text{crit}}$ and $\Delta P_{\text{max}}$

All cases: Injection at 2500m depth into brine with 60Kppm TDS; USDW = 6Kppm TDS; Seawater = 35Kppm TDS
Onshore, Base USDW at 2km

USDW:
6K ppm TDS
Base at 700m

Injection zone:
Brine salinity 60K ppm TDS
Top at 2500m

Rock:
50/50 sand/shale mix

Temperature:
20°C at surface
30°C/km gradient

Pressure:
$\Delta P_{\text{crit}} : 0.12 \text{ MPa}$
$\Delta P_{\text{max}} : 11.9 \text{ MPa}$
Onshore, Base USDW at 700m

USDW:
- 6K ppm TDS
- Base at 700m

Injection zone:
- Brine salinity 60K ppm TDS
- Top at 2500m

Rock:
- 50/50 sand/shale mix

Temperature:
- 20°C at surface
- 30°C/km gradient

Pressure:
- $\Delta P_{\text{crit}} = 0.81 \text{ MPa}$
- $\Delta P_{\text{max}} = 11.8 \text{ MPa}$
**Offshore, 10m Water Depth**

Seawater:
- 35K ppm TDS
- Base at 10m

Injection zone:
- Brine salinity 60K ppm TDS
- Top at 2500m

Rock:
- 50/50 sand/shale mix

Temperature:
- Surface: 20°C
- Gradient: 30°C/km

Pressure:
- \( \Delta P_{\text{crit}} \): 0.89 MPa
- \( \Delta P_{\text{max}} \): 11.6 MPa

\( \Delta P = 11.6 \text{MPa} \) ~ Over-pressured

![Diagram](Image)
Offshore, 100m Water Depth (Shelf Edge)

Seawater:
35K ppm TDS
Base at 100m

Injection zone:
Brine salinity 60K ppm TDS
Top at 2500m

Rock
50/50 sand/shale mix

Temperature
Surface: 21C
Gradient: 30C/km

Pressure:
$\Delta P_{\text{crit}} : 0.80 \text{ MPa}$
$\Delta P_{\text{max}} : 11.6 \text{ MPa}$

Note that this depth is over-pressured and not injectable at the shelf edge
Offshore, 1000m Water Depth

**Seawater:**
- 35K ppm TDS
- Base at 1000m

**Injection zone:**
- Brine salinity 60K ppm TDS
- Top at 2500m

**Rock**
- 50/50 sand/shale mix

**Temperature**
- Surface: 5C
- Gradient: 30C/km

**Pressure:**
- $\Delta P_{\text{crit}}: 0.26$ MPa
- $\Delta P_{\text{max}}: 6.4$ MPa

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**Graphs:**
- **Strength (MPa) vs. Depth (m):**
  - Seawater
  - Supercritical CO$_2$
  - $\Delta P = 11.6$ MPa
  - ~Over-pressured

- **Water Density (kg/L) vs. Depth below Sea Level (m):**
  - Seawater
  - $\Delta = 0.0165$ kg/L

- **Pressure Diagram:**
  - TDS = 35,000 mg/L
  - TDS = 40,000 mg/L
Injection at 2500m Depth

$\Delta P_{\text{max}} = 11.9 \text{ MPa} \text{ (Based on San Antonio line)}$

$\Delta P_{\text{crit}} = 0.81 \text{ MPa}$

$\Delta P_{\text{max}} = 11.8 \text{ MPa}$

$\Delta P_{\text{crit}} = 0.89 \text{ MPa}$

$\Delta P_{\text{max}} = 11.6 \text{ MPa}$

$\Delta P_{\text{crit}} = 0.80 \text{ MPa (OP)}$

$\Delta P_{\text{max}} = 11.3 \text{ Mpa (OP)}$

$\Delta P_{\text{crit}} = 0.26 \text{ MPa}$

$\Delta P_{\text{max}} = 6.4 \text{ MPa}$

All cases: Injection at 2500m depth into brine with 60Kppm TDS; USDW = 6Kppm TDS; Seawater = 35Kppm TDS
Injection at Base of Storage Window

**Inj. Depth**
- 4000m
- 3000m
- 1500m
- 3700m

**ΔP<sub>max</sub>**
- 20.8 MPa (Based on San Antonio line)
- 20.7 MPa
- 14.4 MPa
- 6.0 Mpa

**ΔP<sub>crit</sub>**
- 1.1 MPa
- 2.67 MPa
- 2.10 MPa
- 0.55 Mpa

**ΔP**
- Based on San Antonio line
- 13.0 Mpa

All cases: Injection into brine with 120K ppm TDS; USDW = 6K ppm TDS; Seawater = 35K ppm TDS

The key variables are depths to base of protected zone and OP.
Pressure Build-up: Open Boundaries

- 1Mtpa for 20 years
- 2.5km depth
- Reservoir
  - 10x10km area
  - 100m thick
  - 25% porosity
  - 500mD
  - Initially hydrostatic pressure
- Open boundaries
- ~0.5MPa of pressure build-up over 20 years
- Under most $\Delta P_{\text{crit}}$
- Way under all $\Delta P_{\text{max}}$
Pressure Build-up: Closed Boundaries

- 1Mtpa for 20 years
- 2.5km depth
- Reservoir
  - 10x10km area
  - 100m thick
  - 25% porosity
  - 500mD
  - Initially hydrostatic pressure
  - Closed boundaries
- ~13MPa of pressure build-up across entire area
- Way over all $\Delta P_{crit}$
- Close to typical $\Delta P_{max}$
Closed Boundaries, Large Area

- 1Mtpa for 20 years
- 2.5km depth
- Reservoir
  - 40x40km area
  - 100m thick
  - 25% porosity
  - 500mD
  - Initially hydrostatic pressure
  - Closed boundaries
- >1MPa of pressure build-up near well
- Red circle shows AOR for typical $\Delta P_{\text{crit}}$
- With closed boundaries, we need large area to avoid reviewing all of it
Summary

• We can estimate $\Delta P_{\text{crit}}$ fairly easily
  • For hydrostatic reservoirs, typical values ~1-2MPa (145-290psi)

• We can estimate $\Delta P_{\text{max}}$
  • For hydrostatic reservoirs, typical values are ~10-20MPa (1450-2900psi)

• Translating $\Delta P_{\text{crit}}$ values to AoR depends on the geology
  • How much connected pore volume is available to dissipate pressure?
  • Reservoir thickness and boundary conditions are critical!
  • Unless you have very large pore volume or open boundaries, the entire connected area is likely within the AoR

• There are important differences between onshore and offshore but critical pressure thresholds are not among them

• The key variables are
  • Depth below ground surface (or mudline)
  • Depth below protected zone
  • Salinity contrast between injection zone and protected zone
Backup
Onshore, Water Table 1km Deep

**USDW:**
- 6K ppm TDS
- Base at 700m

**Injection zone:**
- Brine salinity 60K ppm TDS
- Top at 2500m

**Rock**
- 50/50 sand/shale mix

**Temperature**
- Surface: 20°C
- Gradient: 30°C/km

**Pressure:**
- $\Delta P_{\text{crit}} = 0.37 \text{ MPa}$
- $\Delta P_{\text{max}} = 16.1 \text{ MPa}$

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**Graphs:**
- Depth vs. Strength (MPa)
- Water Density (kg/L)
- Depth below Sea Level (m)
Geothermal Gradient and CO2 Density

CO2 Phase Diagram

- Geothermal gradient:
  - 15C/km
  - 30C/km
  - 45C/km

- Mean annual surface temp: 20C
- Pressure gradient: 10MPa/km

CO2 density vs depth:

<table>
<thead>
<tr>
<th>Depth</th>
<th>15C/km</th>
<th>30C/km</th>
<th>45C/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>1km</td>
<td>650 kg/m³</td>
<td>400 kg/m³</td>
<td>300 kg/m³</td>
</tr>
<tr>
<td>2km</td>
<td>720 kg/m³</td>
<td>575 kg/m³</td>
<td>440 kg/m³</td>
</tr>
</tbody>
</table>
Onshore (20°C at surface)

Onshore, 2km deep water table

100m water (23°C at seabed)

1km water (5°C at seabed)

Geothermal gradient: 30°C/km

Hydrothermal gradient: GoM observations (Forrest et al, 2007)

Pressure gradient: 10MPa/km

Water Depth and CO2 Density

CO2 Phase Diagram

- Liquid
- Supercritical fluid
- Gas

Deepwater storage creates much denser CO2—higher storage efficiency and less buoyancy

A deep water table (e.g., California central valley) has the opposite effect
EPA Well Review Requirements

40 CFR 146.84(c)(2): Using methods approved by the UIC Program Director, identify all penetrations, including active and abandoned wells and underground mines, in the AoR that may penetrate the confining zone(s). Provide a description of each well’s type, construction, date drilled, location, depth, record of plugging and/or completion, and any additional information the UIC Program Director may require;

• 40 CFR 146.84(c)(3): Determine which abandoned wells in the AoR have been plugged in a manner that prevents the movement of carbon dioxide or other fluids that may endanger USDWs, including use of materials compatible with the carbon dioxide stream;
• 40 CFR 146.84(d): Perform corrective action on all wells in the AoR that are determined to need corrective action, using methods designed to prevent the movement of fluid into or between USDWs, including use of materials compatible with the carbon dioxide stream, where appropriate

Area of Review

Area of possible CO$_2$ leakage

Footprint of area of elevated pressure = Area of Review

Injection well

wells

Plume of injected CO$_2$

Courtesy of Sue Hovorka