Definition of AoR Onshore and its Equivalent Offshore

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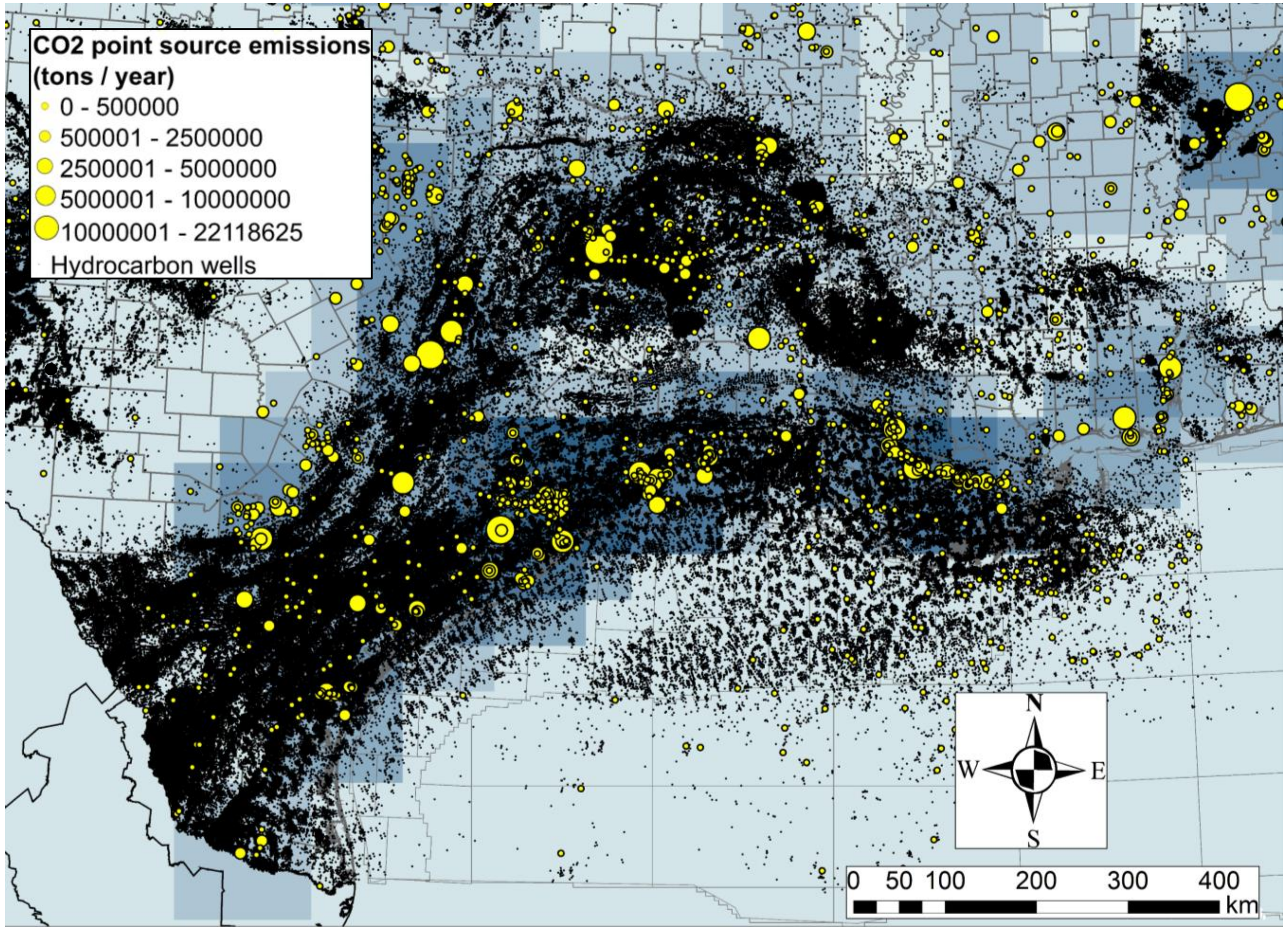
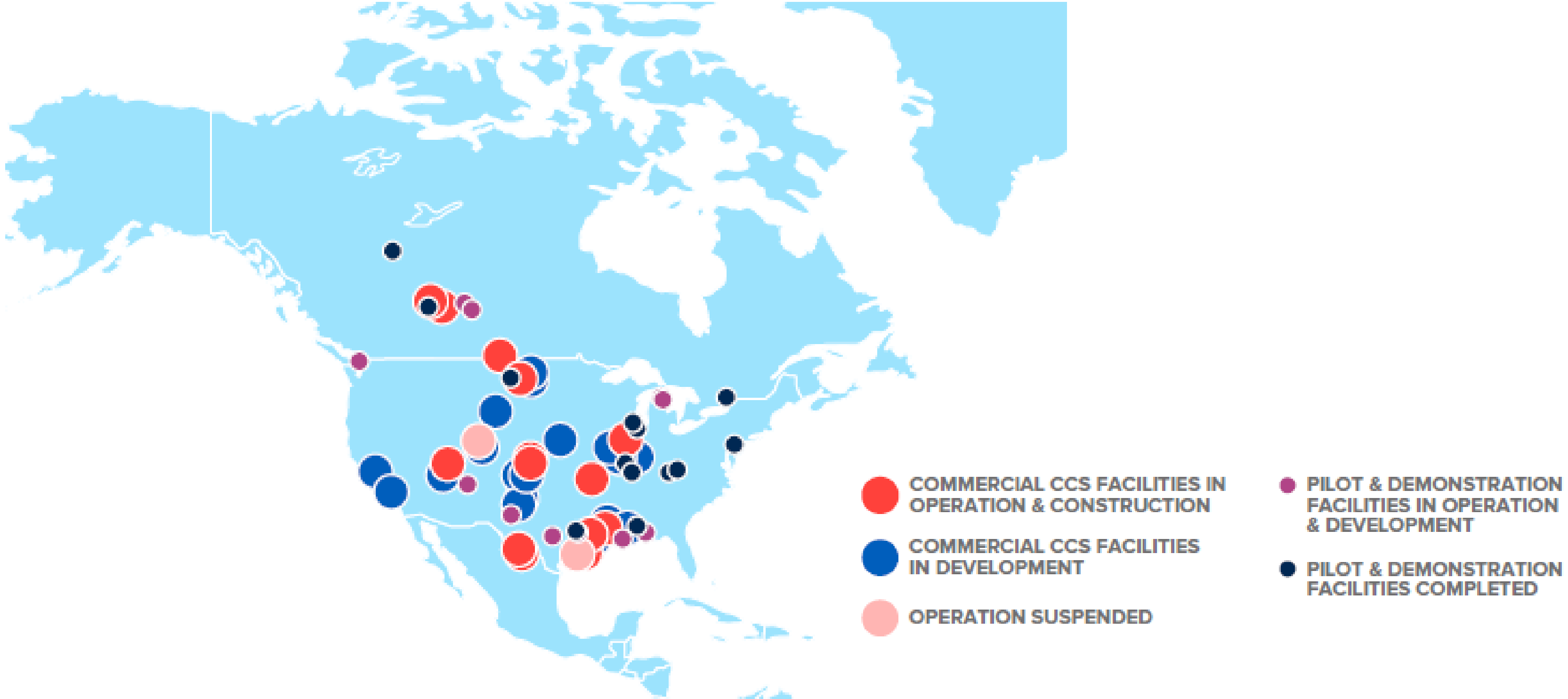
Offshore



Data: US EPA FLIGHT database and IHS Enerdeq (2022)

- GoM is highly prospective for CO_2 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

North American Experience is Onshore



Global CCS Institute, 2020: https://www.globalccsinstitute.com/resources/publications-reports-research/

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

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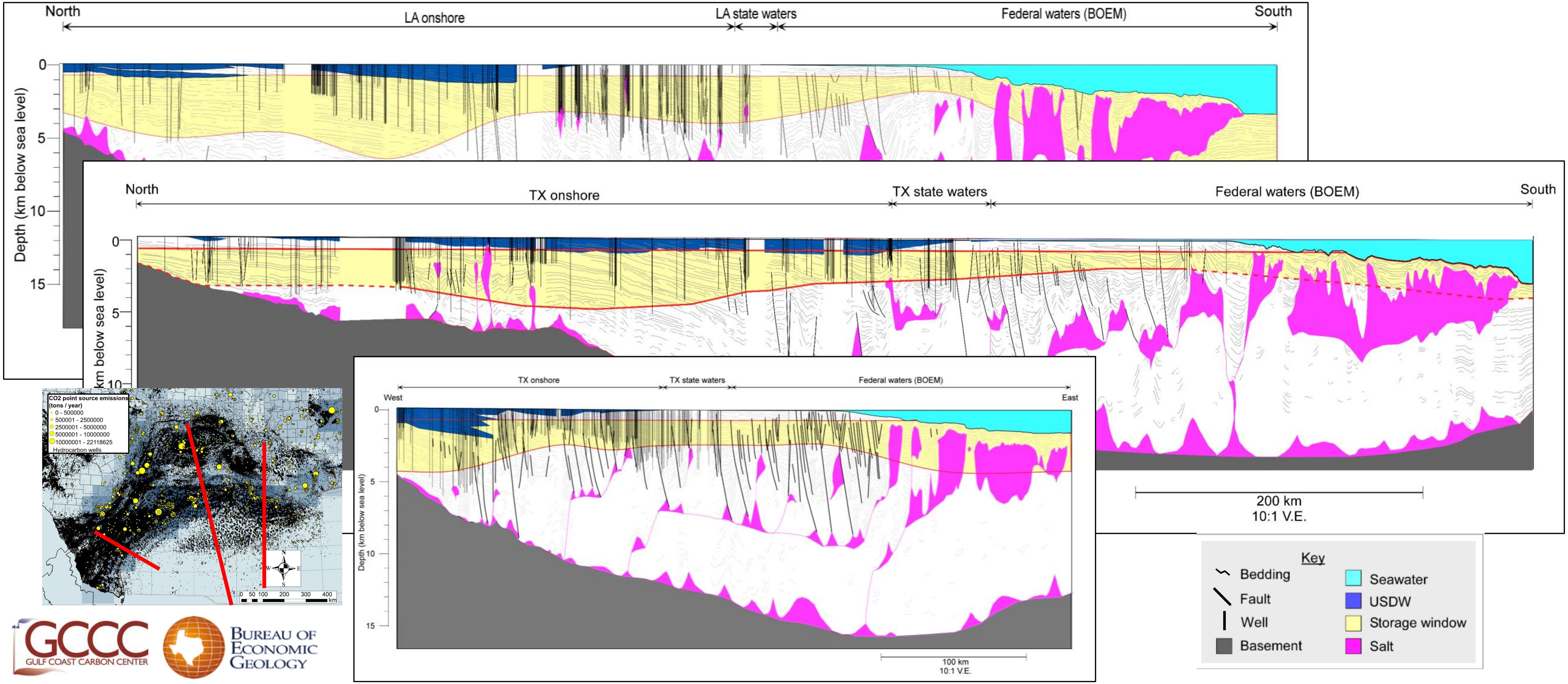
Onshore and Offshore Storage



Temperatures and Salinities are Highly Variable

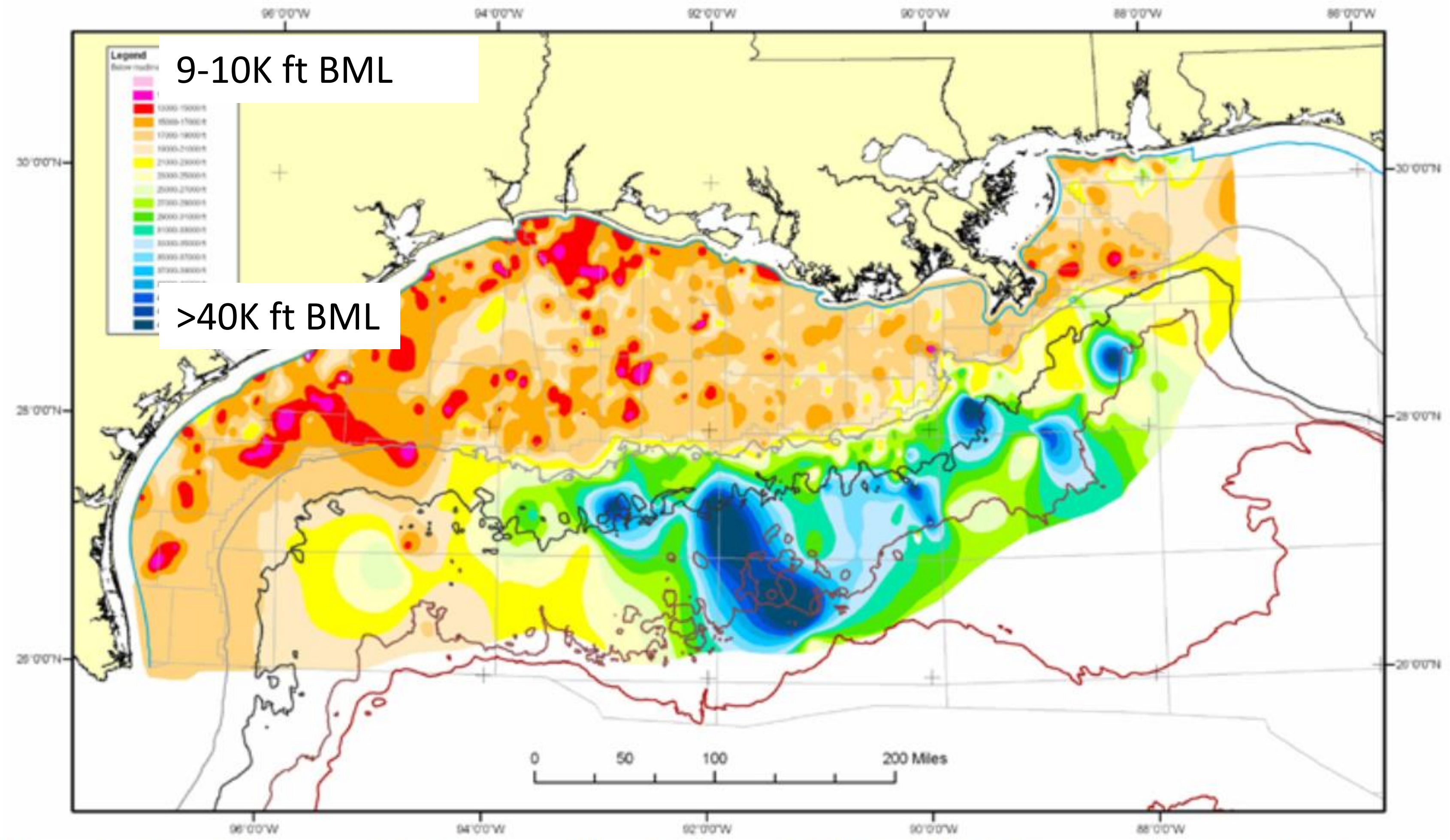


Figure 8. Map of interpreted below-mudline depths to 300°F (BMLD300). areas in the Gulf of Mexico. See Table 1 for summary of data and key to protraction area abbreviations.

Forrest et al, 2007

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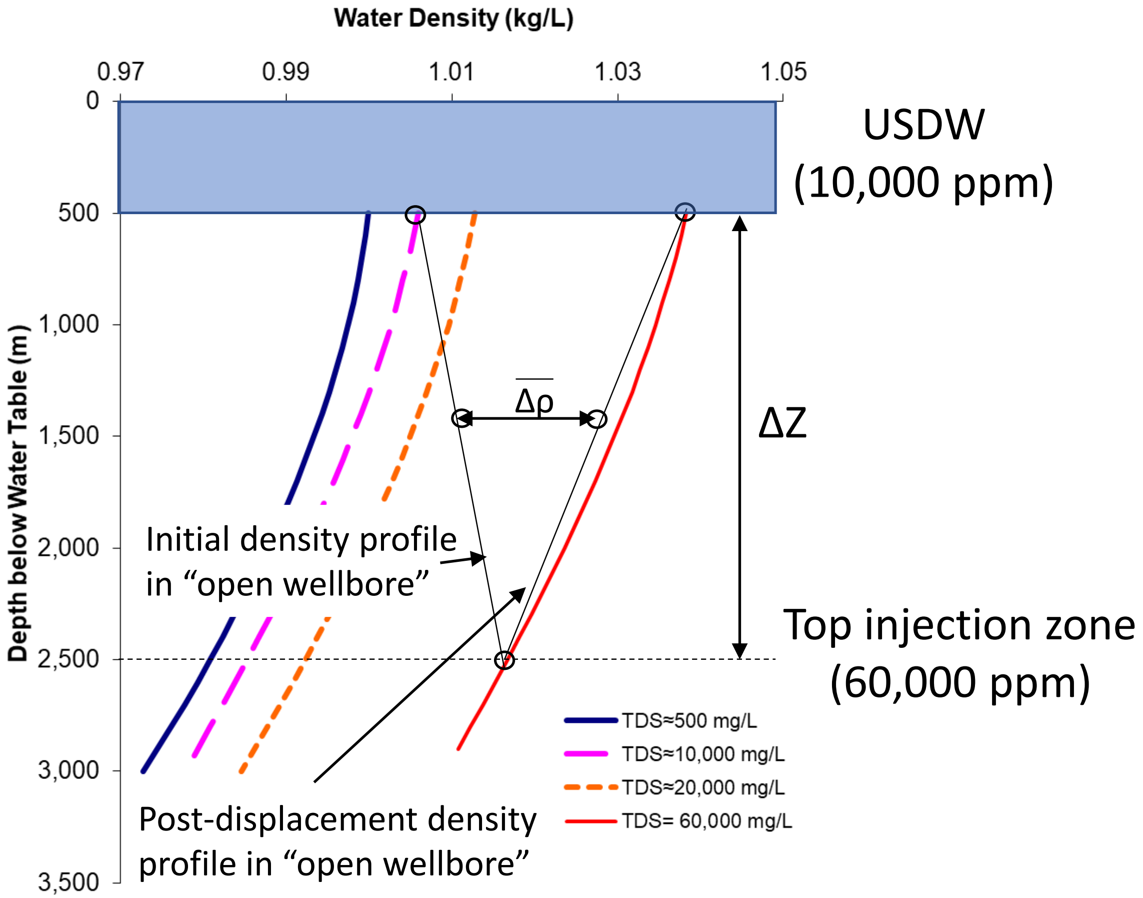
Questions

- 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 ΔP_{crit}



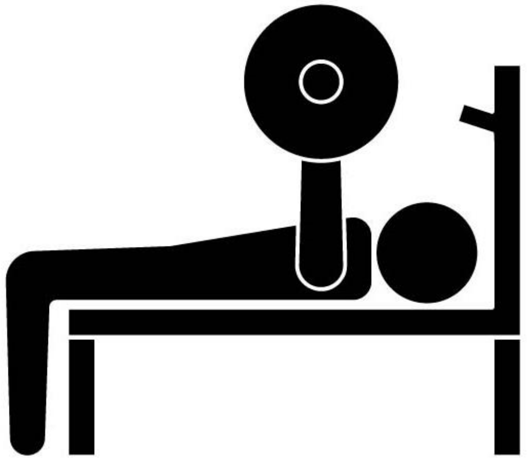
After Nicot et al, 2009

Water density varies with temperature and salinity

ΔZ = depth difference between base USDW and top injection zone

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

$\Delta P_{crit} \propto \Delta Z * \overline{\Delta\rho}$



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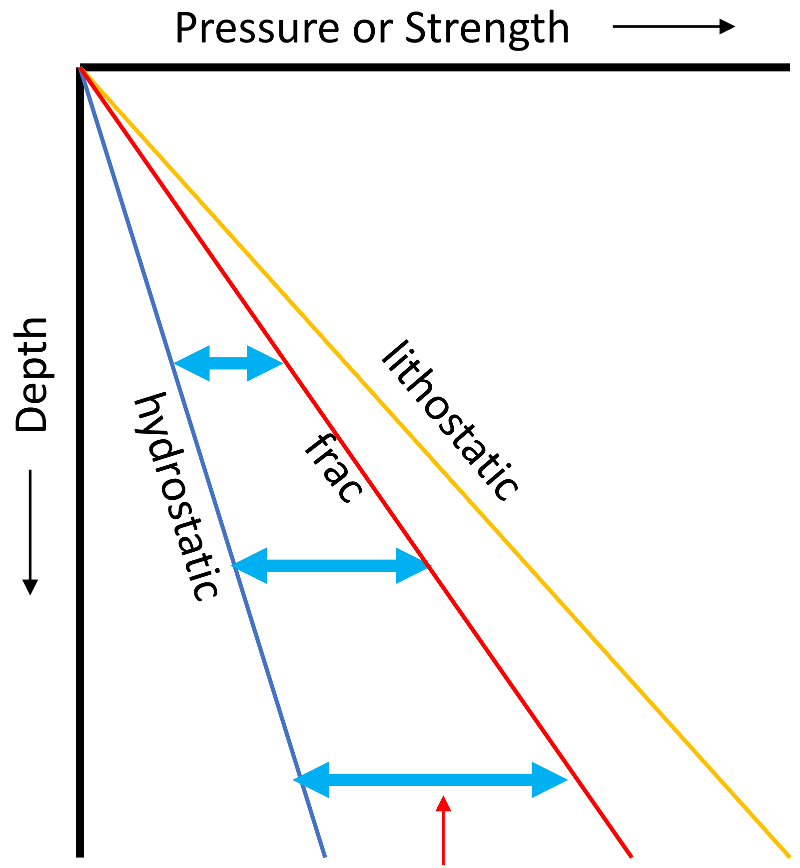
Finding ΔP_{max}



ΔP_{max}
(pressure space for injection)

- 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

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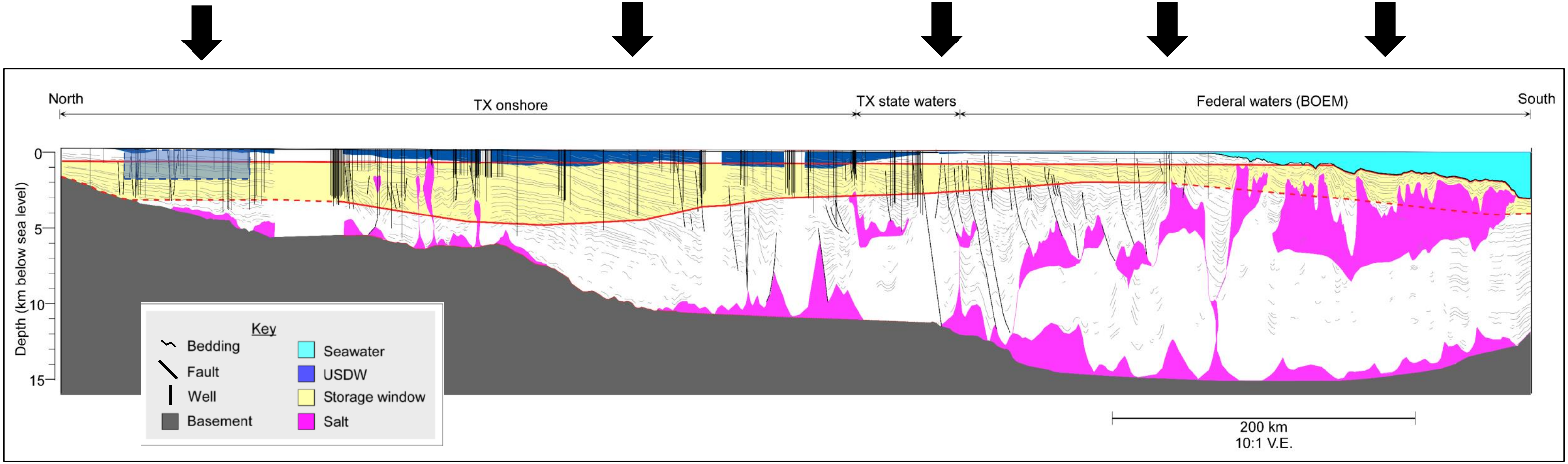
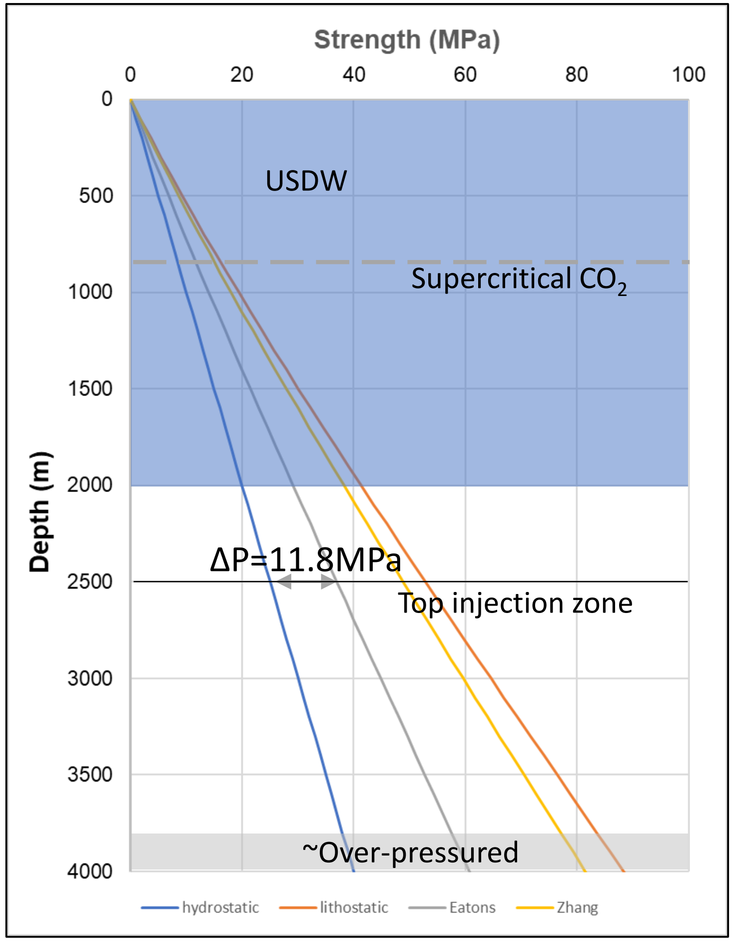
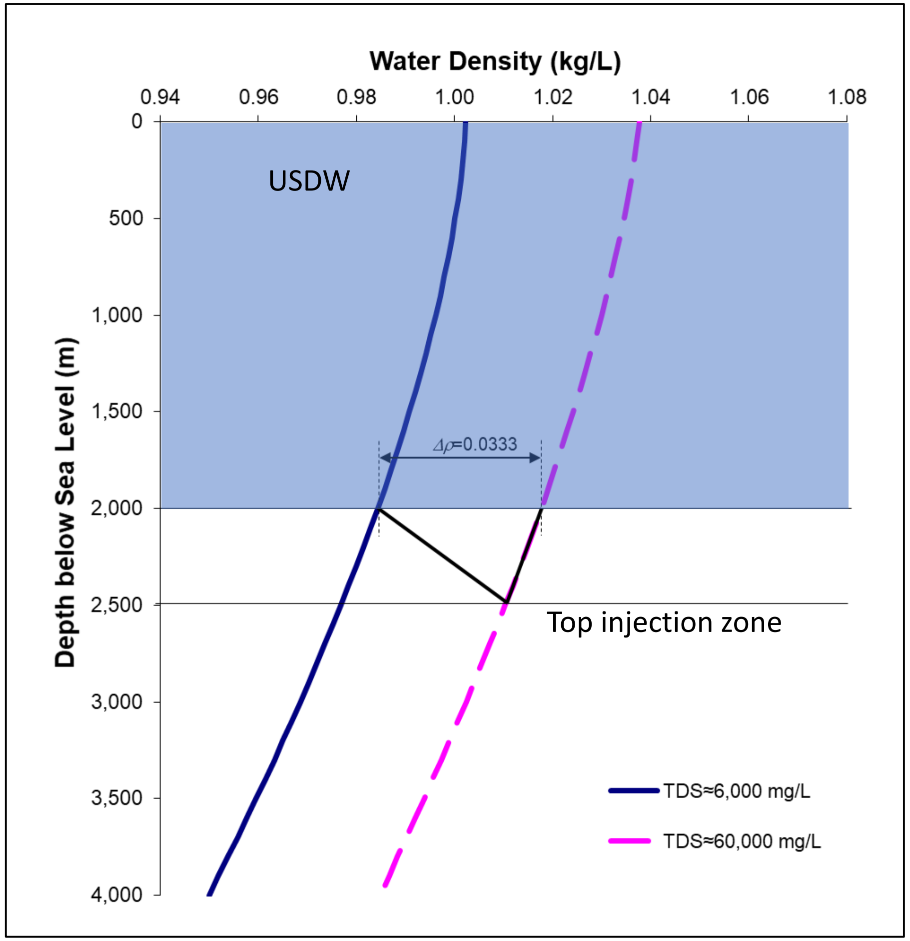
Variations in ΔP_{crit} and ΔP_{max}



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:
ΔP_{crit} : 0.12 MPa
ΔP_{max} : 11.9 MPa

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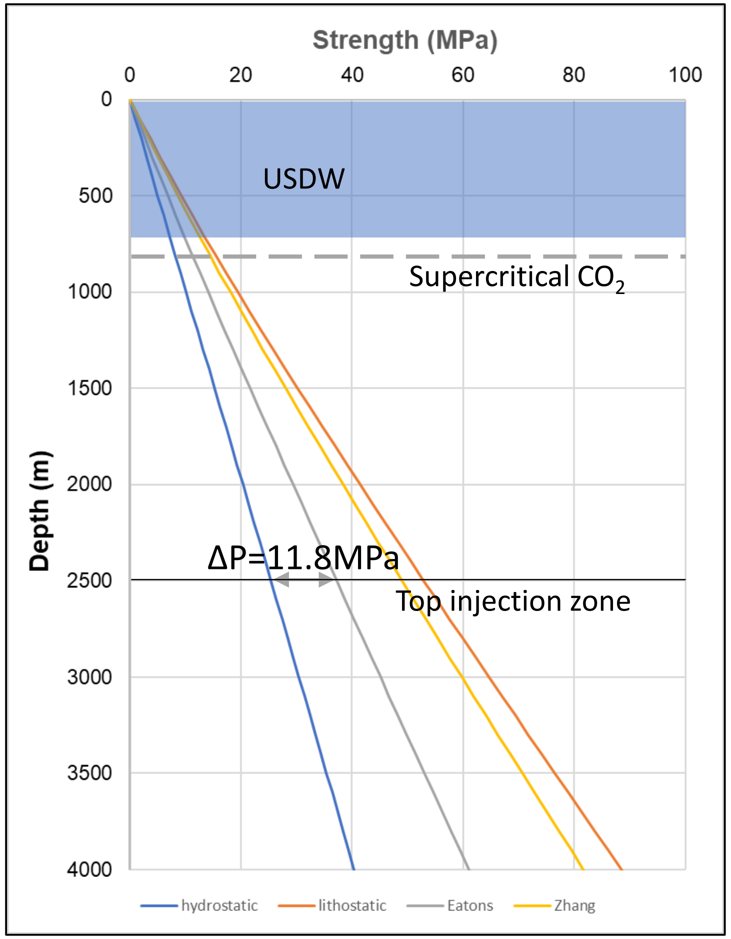
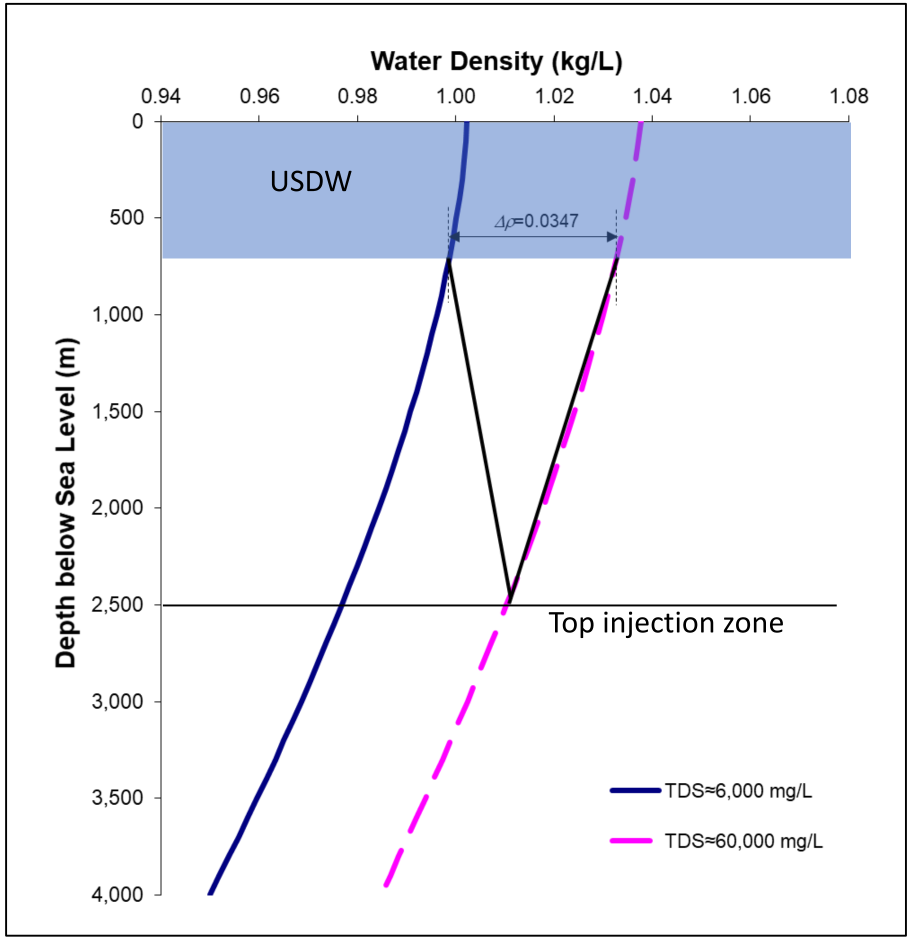
Onshore, Base USDW at 700m





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:
ΔP_{crit} : 0.81 MPa
ΔP_{max} : 11.8 MPa

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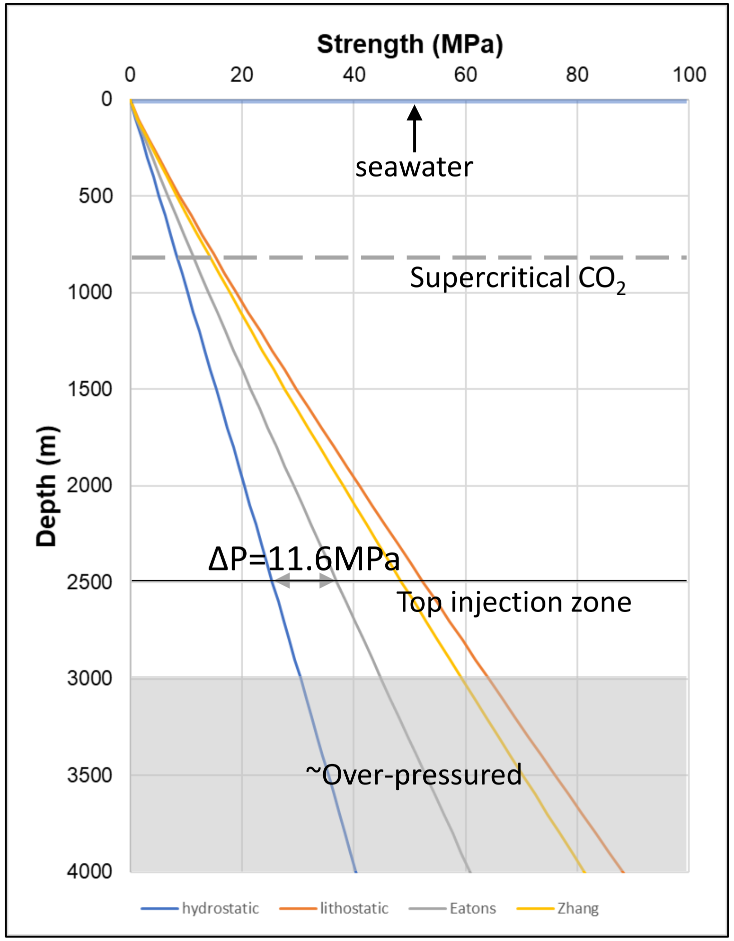
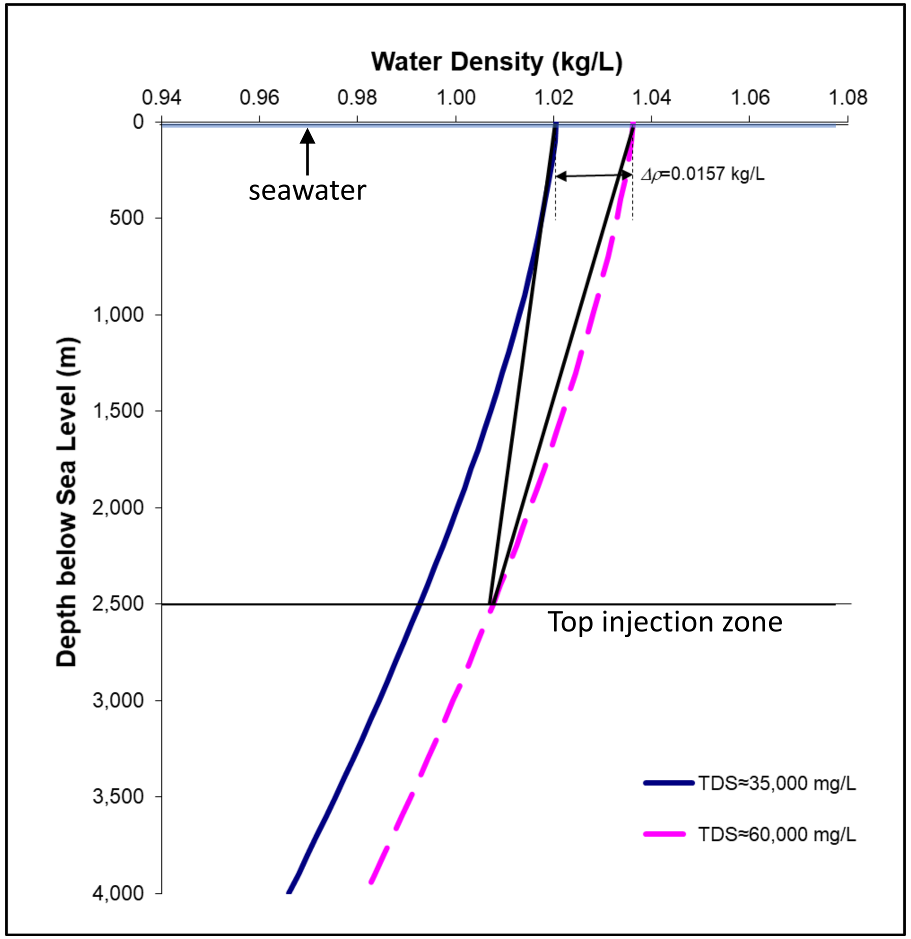
Offshore, 10m Water Depth





Seawater:
35K ppm TDS
Base at 10m

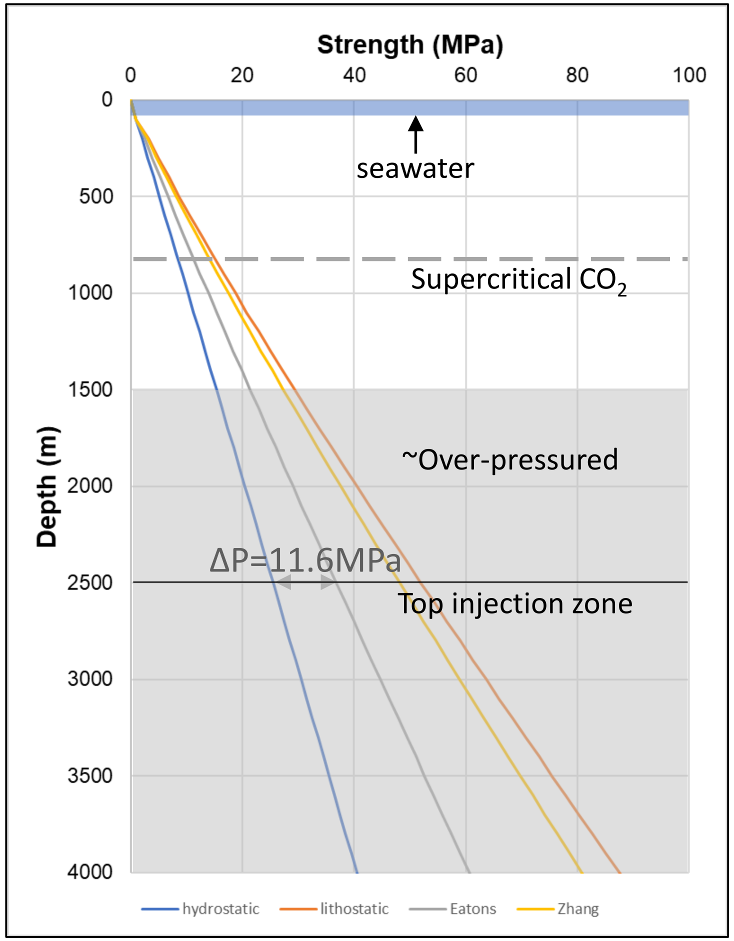
Injection zone:
Brine salinity 60K ppm TDS
Top at 2500m

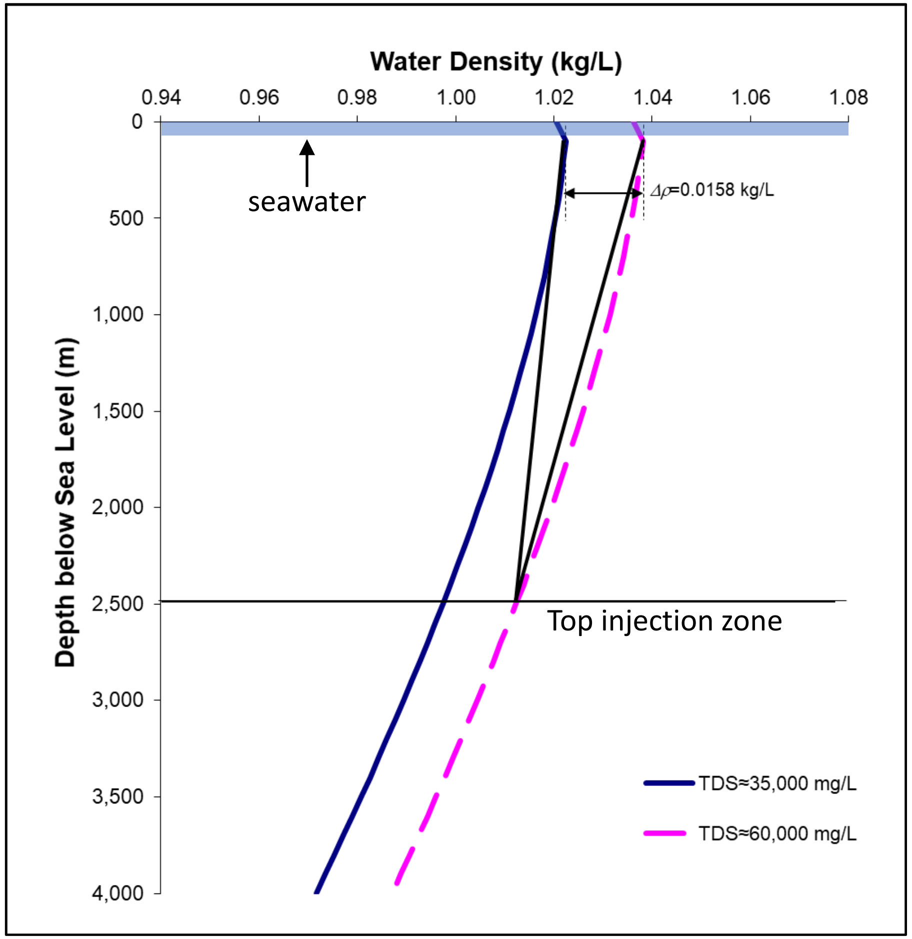
Rock
50/50 sand/shale mix

Temperature
Surface: 20C
Gradient: 30C/km

Pressure:
ΔP_{crit} : 0.89 MPa
ΔP_{max} : 11.6 MPa

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:
ΔP_{crit} : 0.80 MPa
ΔP_{max} : 11.6 MPa

Note that this depth is over-pressured and not injectable at the shelf edge

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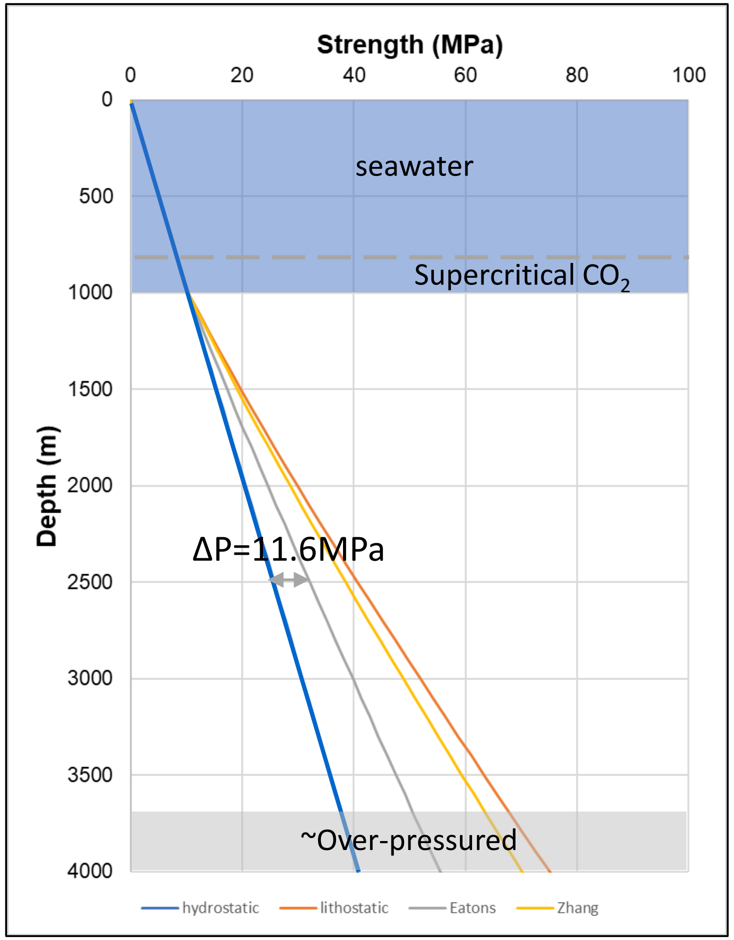
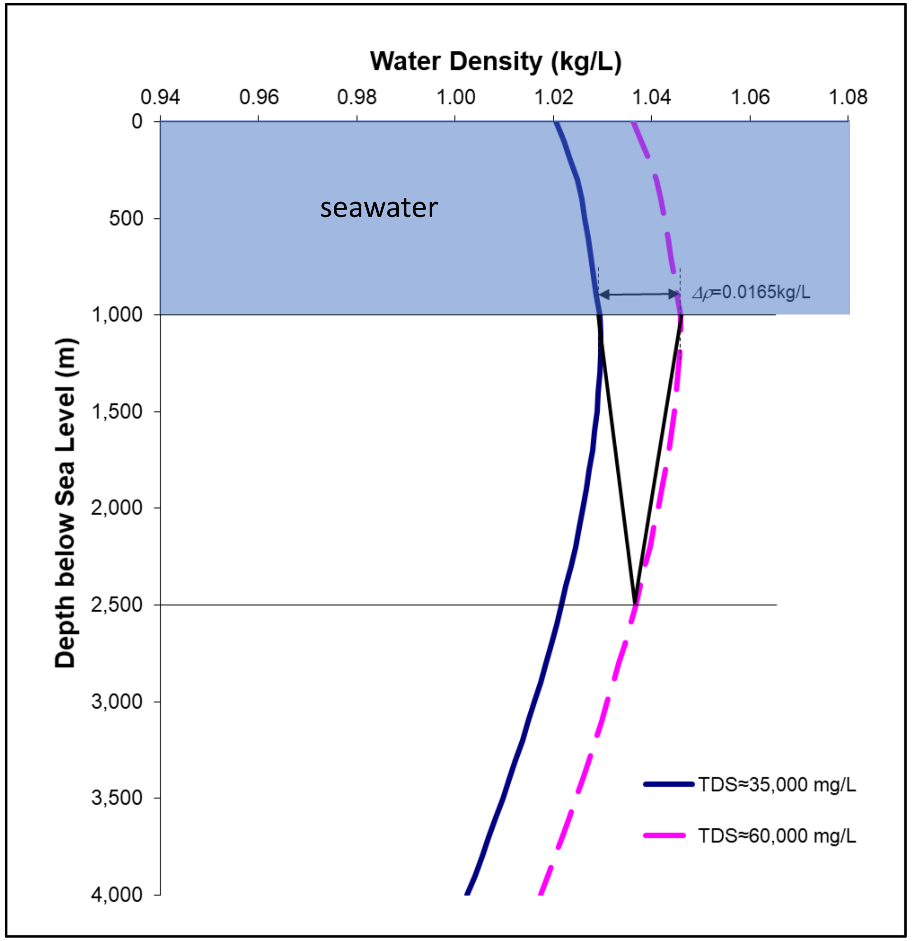
Offshore, 1000m Water Depth





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:
ΔP_{crit} : 0.26 MPa
ΔP_{max} : 6.4 MPa

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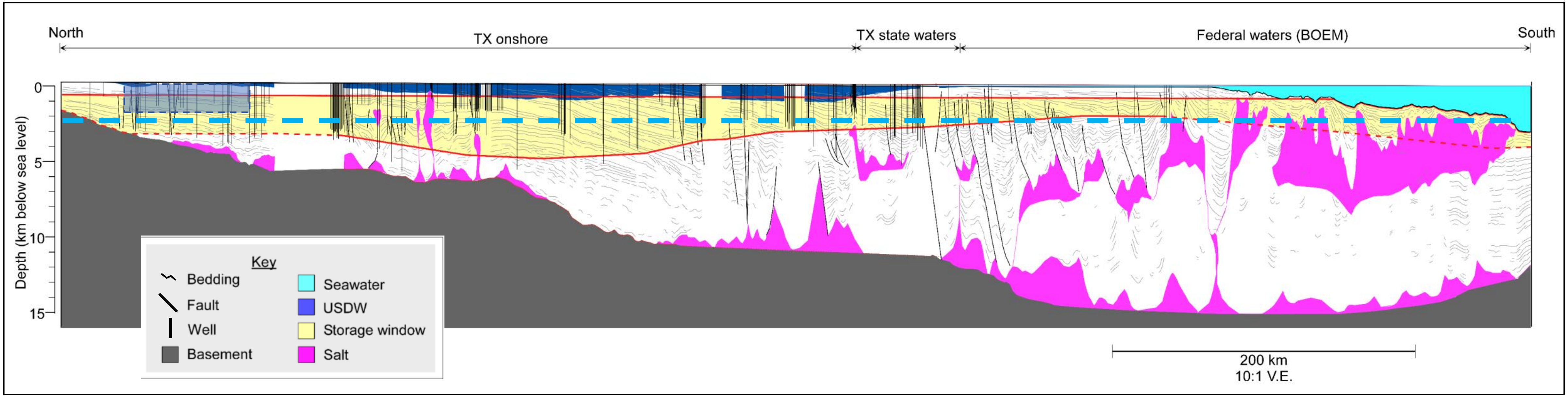
Injection at 2500m Depth

ΔP_{max}	11.9 MPa (Based on San	11.8MPa	11.6 MPa	11.3 Mpa (OP)	6.4 MPa
ΔP_{crit}	0.12 MPa Antonio line)	0.81 MPa	0.89 MPa	0.80 Mpa (OP)	0.26 MPa



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

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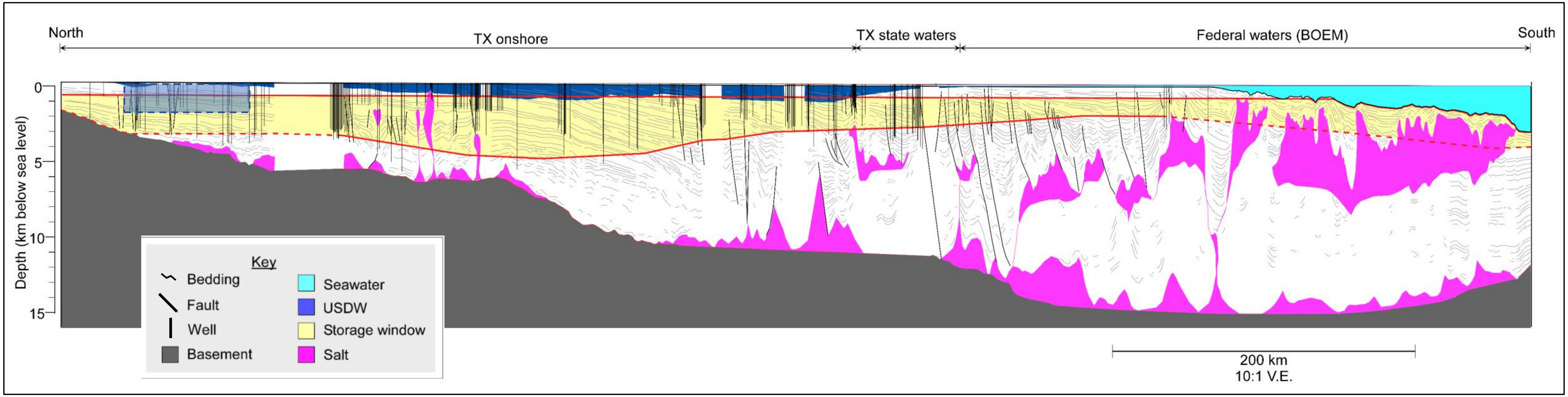
Injection at Base of Storage Window

Inj. Depth	4000m	4000m	3000m	1500m	3700m
ΔP_{max}	20.8 MPa (Based on San	20.7MPa	14.4 MPa	6.0 Mpa	13.0 Mpa
ΔP_{crit}	1.1 MPa Antonio line)	2.67 MPa	2.10 MPa	0.55 Mpa	1.44 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

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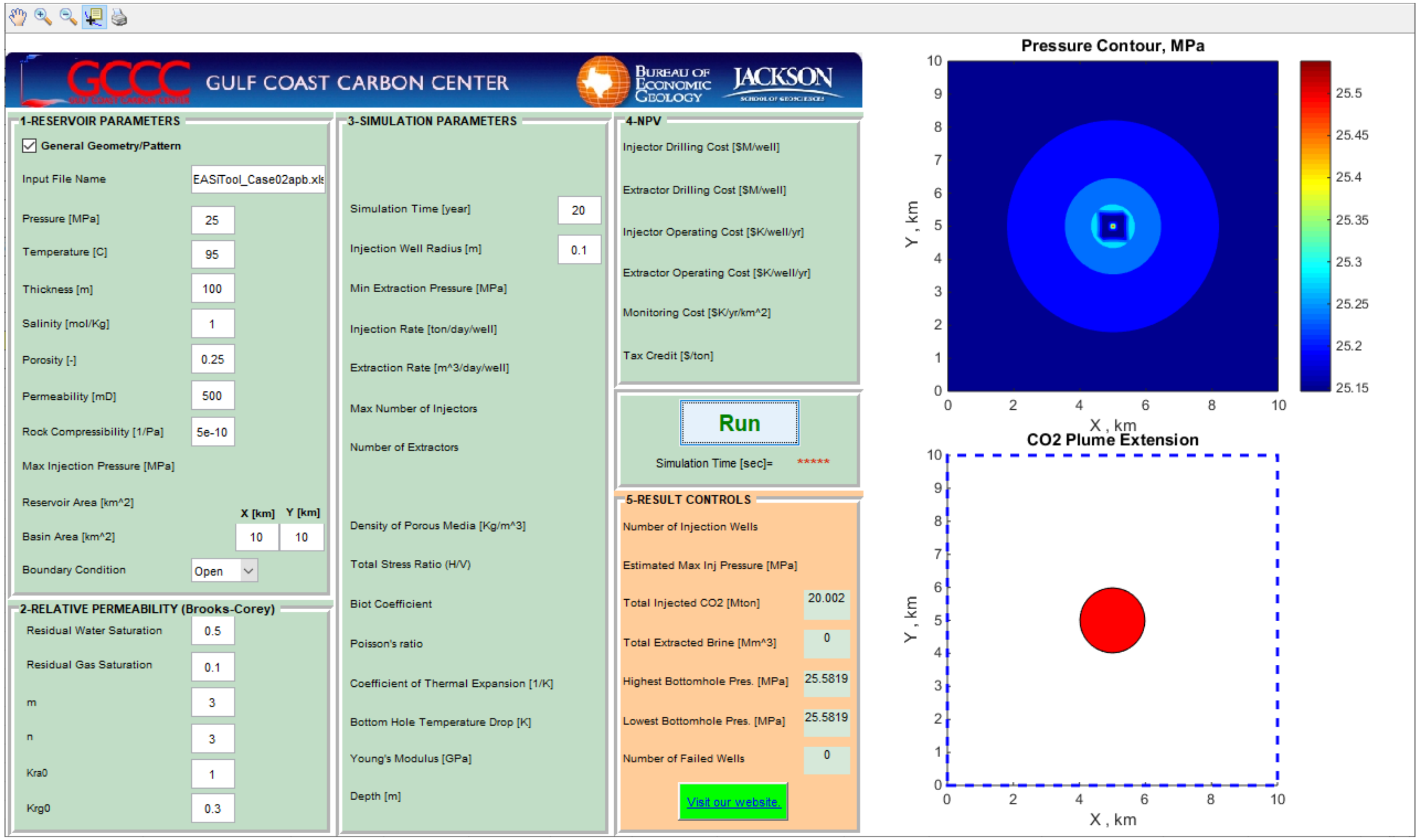
Pressure Build-up: Open Boundaries



- 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 ΔP_{crit}
- Way under all ΔP_{max}

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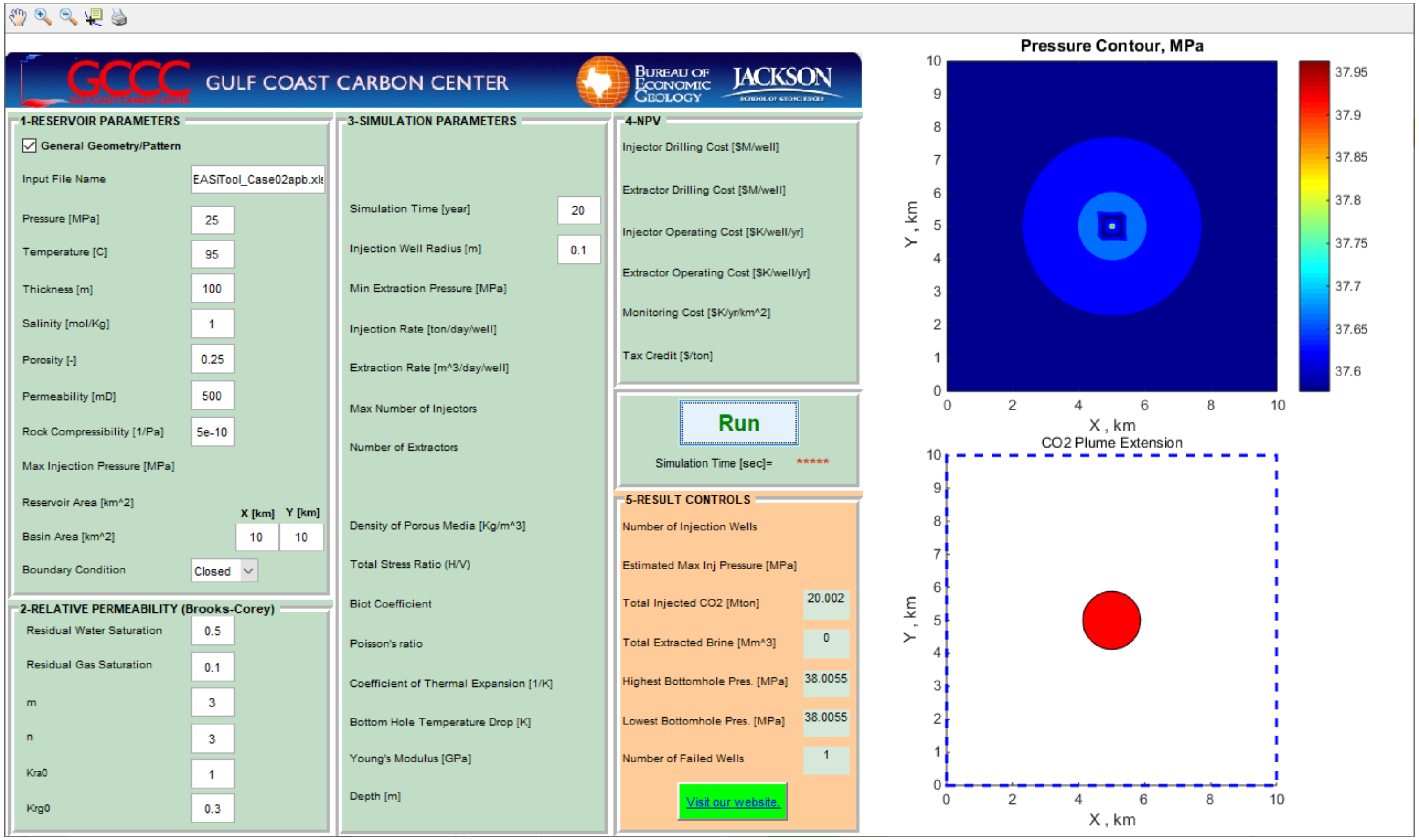
Pressure Build-up: Closed Boundaries



- 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 ΔP_{crit}
- Close to typical ΔP_{max}

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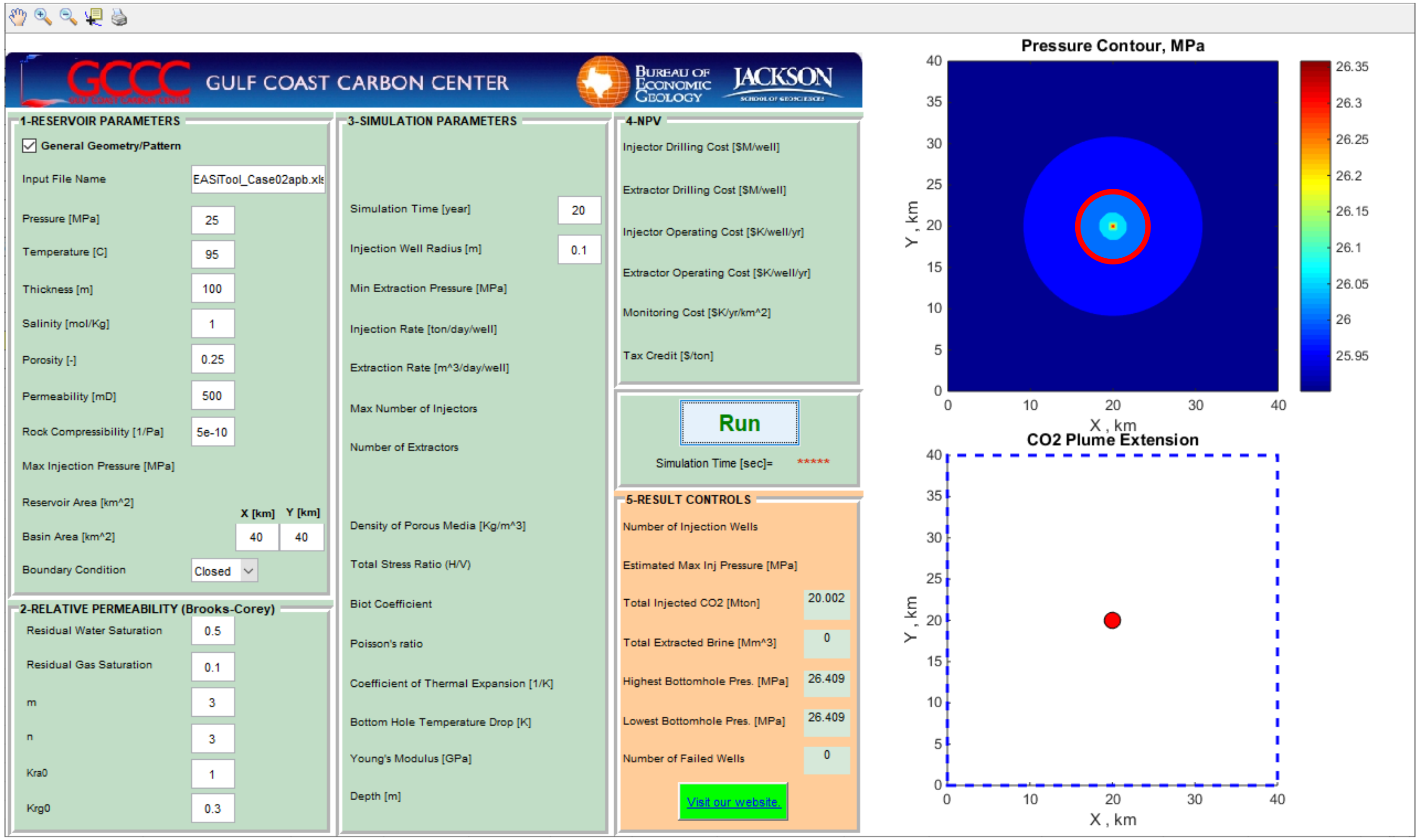
Closed Boundaries, Large Area



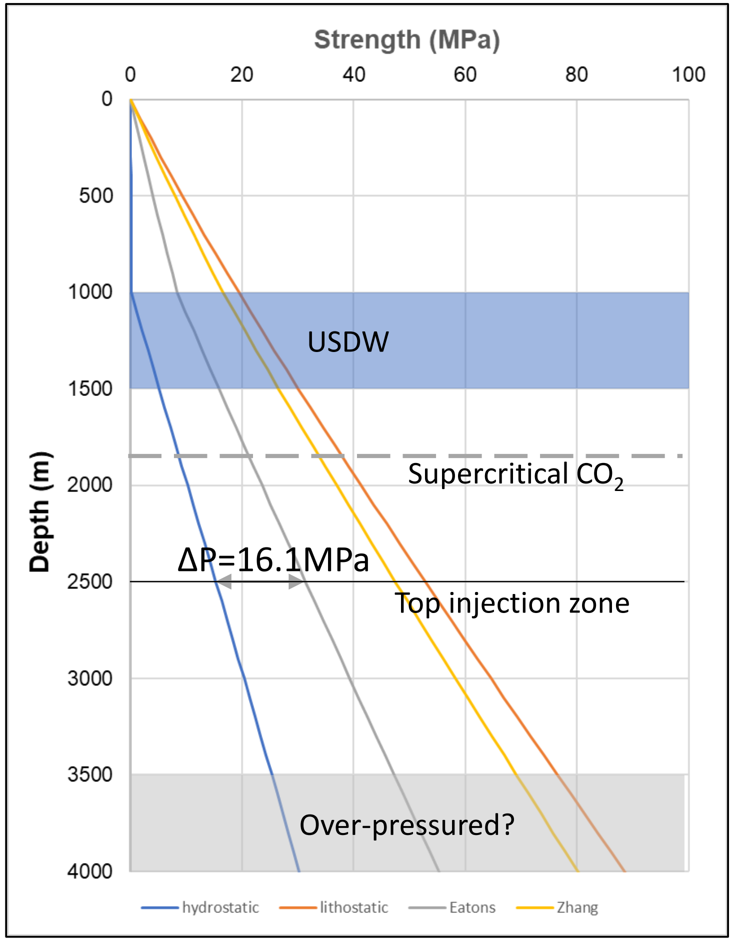
- 1Mtpa for 20 years
- 2.5km depth
- Reservoir
  - **40x40km area**
  - 100m thick
  - 25% porosity
  - 500mD
  - Initially hydrostatic pressure
  - **Closed boundaries**
- >1MPa of pressure build-up near well
- Red circle shows AOR for typical ΔP_{crit}
- **With closed boundaries, we need large area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

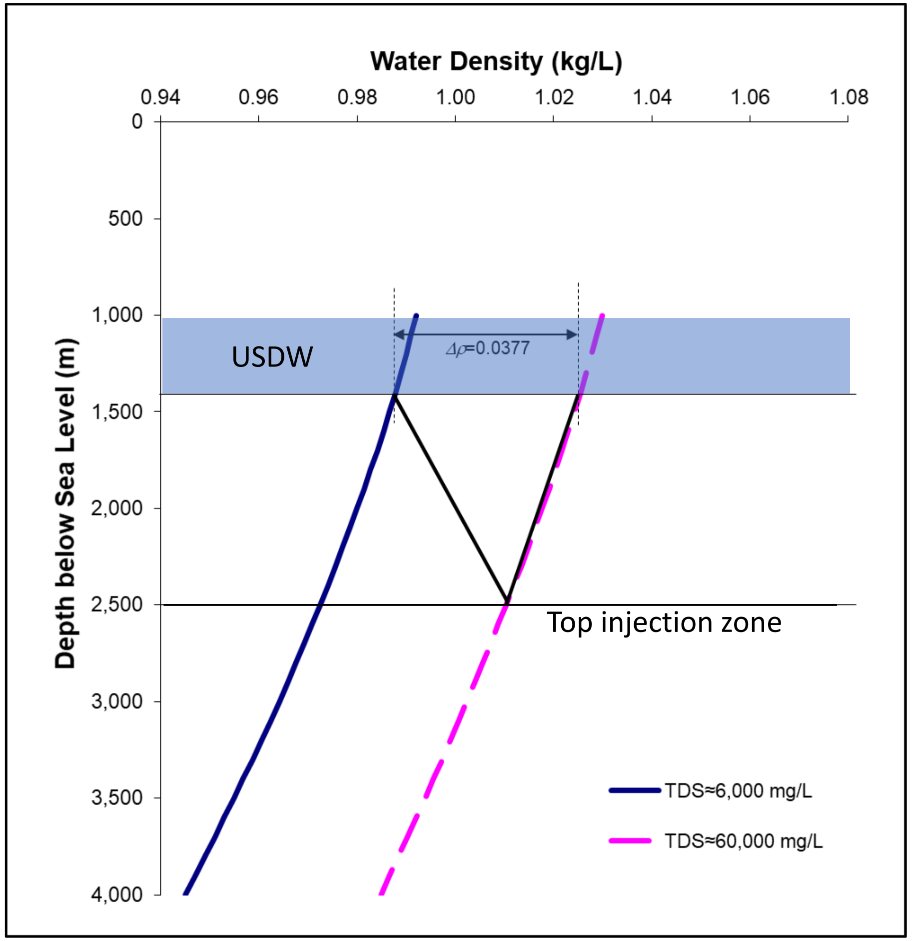
Summary

- We can estimate ΔP_{crit} fairly easily
  - For hydrostatic reservoirs, typical values ~1-2MPa (145-290psi)
- We can estimate ΔP_{max}
  - For hydrostatic reservoirs, typical values are ~10-20MPa (1450-2900psi)
- Translating ΔP_{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: 20C
Gradient: 30C/km

Pressure:
ΔP_{crit} : 0.37 MPa
ΔP_{max} : 16.1 MPa

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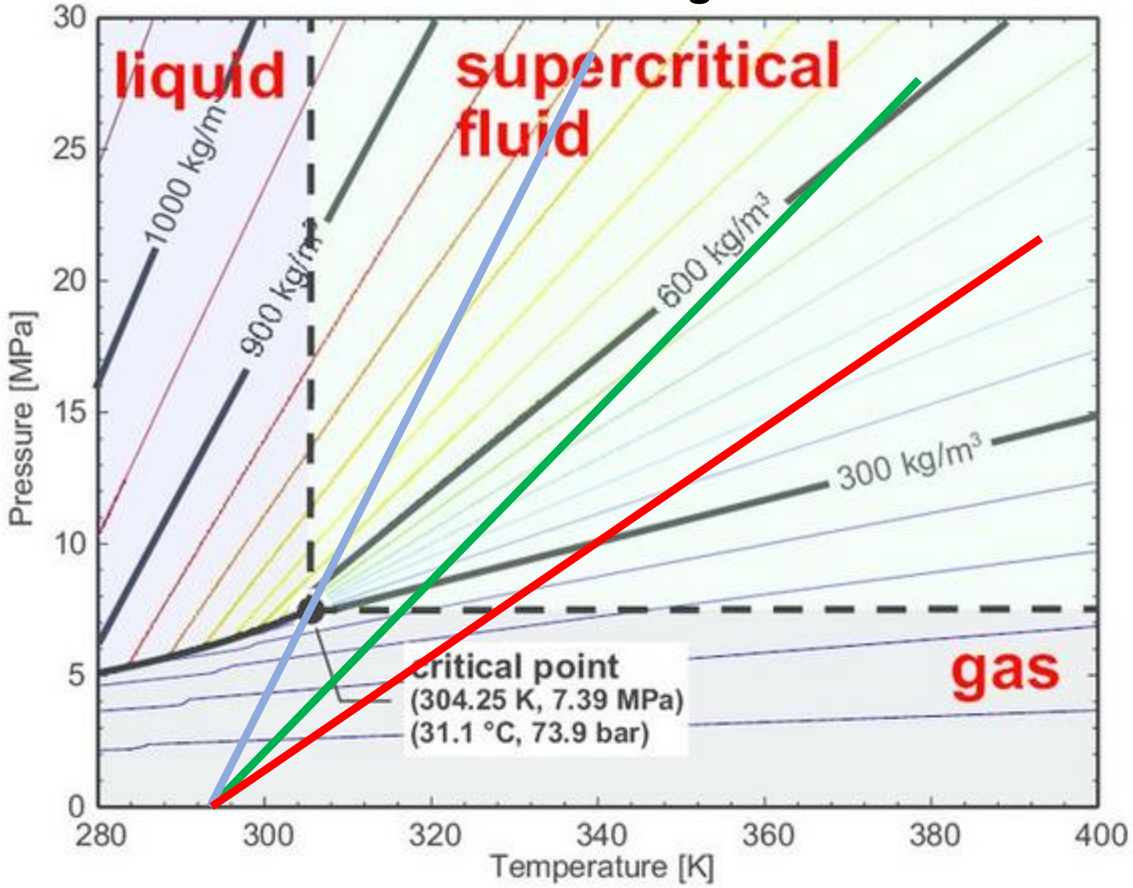
Geothermal Gradient and CO2 Density

CO2 Phase Diagram



<u>Geothermal gradient</u>

- 15C/km
- 30C/km
- 45C/km

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

CO2 density vs depth

Depth	15C/km	30C/km	45C/km
1km	650 kg/m^3	400 kg/m^3	300 kg/m^3
2km	720 kg/m^3	575 kg/m^3	440 kg/m^3

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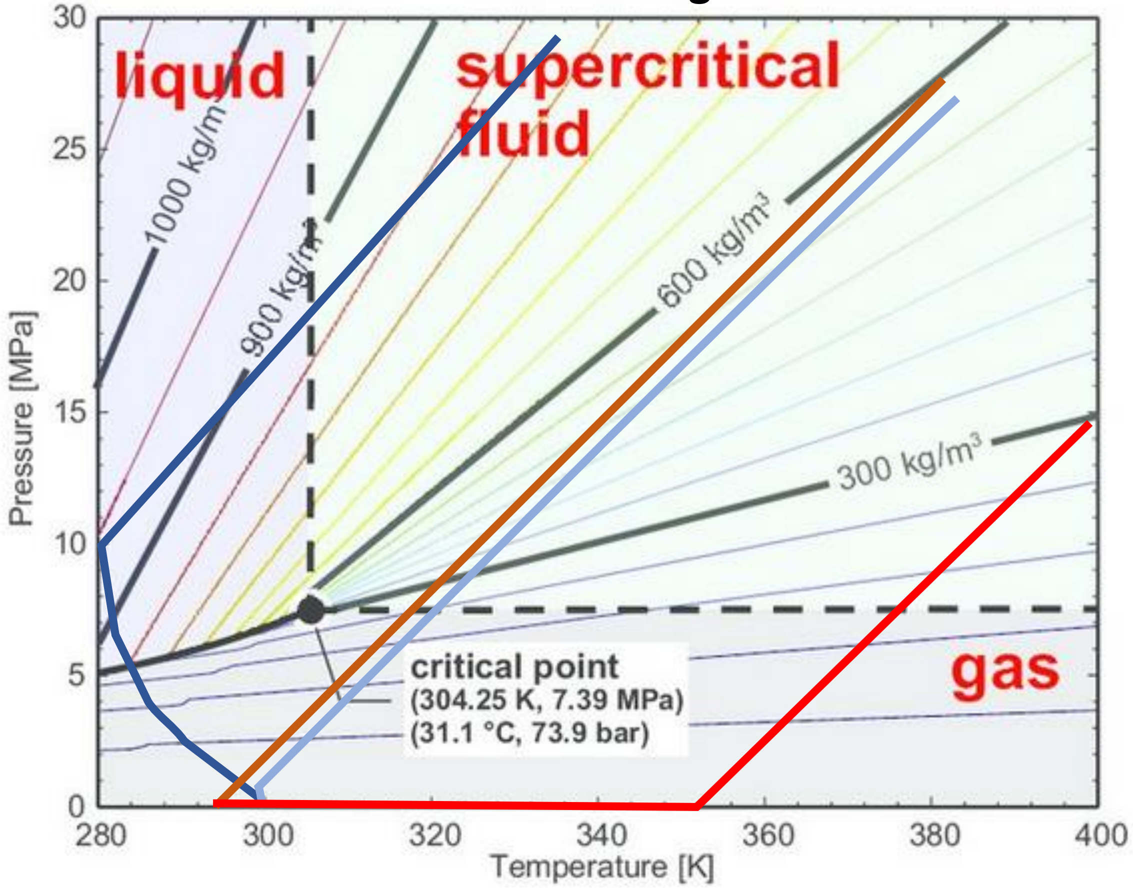
Water Depth and CO2 Density

CO2 Phase Diagram



- Onshore (20C at surface)
- Onshore, 2km deep water table
- 100m water (23C at seabed)
- 1km water (5C at seabed)

Geothermal gradient: 30C/km
Hydrothermal gradient: GoM observations (Forrest et al, 2007)
Pressure gradient: 10MPa/km

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

A deep water table (eg California central valley) has the opposite effect

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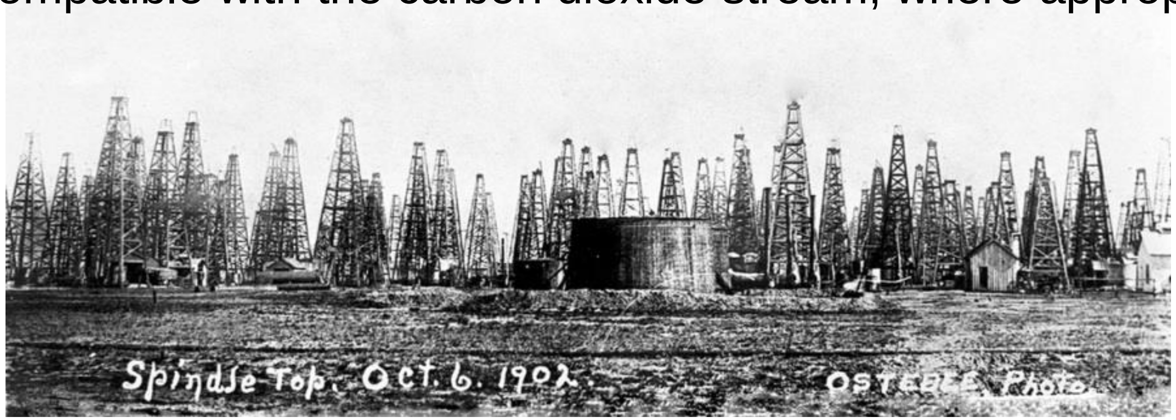
EPA Well Review Requirements

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;

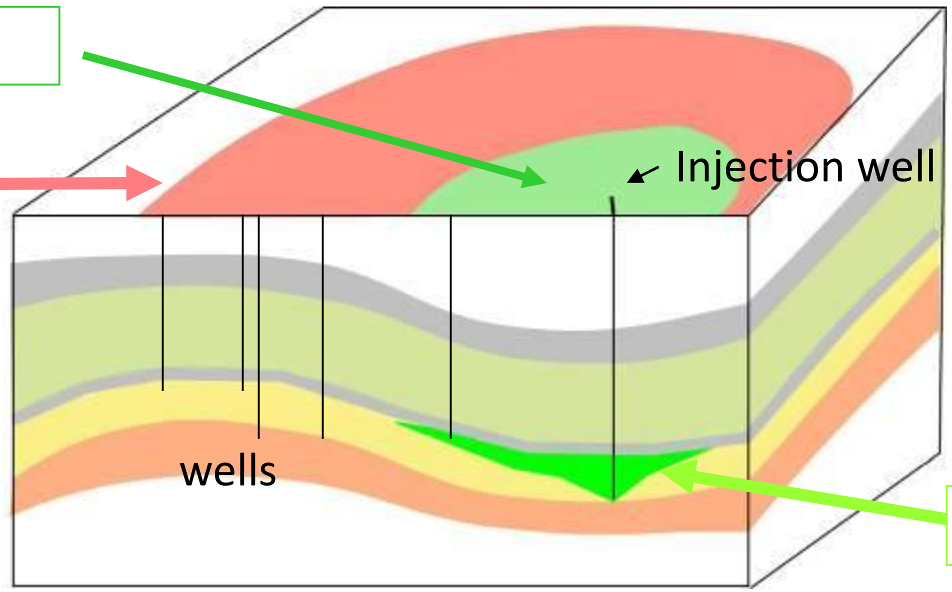
- 40 CFR 146.84(c)(3): Determine which abandoned wells in the AoR have been plugged in a manner that prevents the movement of carbon dioxide or other fluids that may endanger USDWs, including use of materials compatible with the carbon dioxide stream;
- 40 CFR 146.84(d): Perform corrective action on 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

https://www.epa.gov/sites/default/files/2015-07/documents/epa816r13005.pdf



https://www.lamar.edu/spindletop-gladys-city/spindletop-history.html

Area of Review



Courtesy of Sue Hovorka