Experimental Insights on the Impact of Injection Strategies on CO_2 Storage in Aquifers

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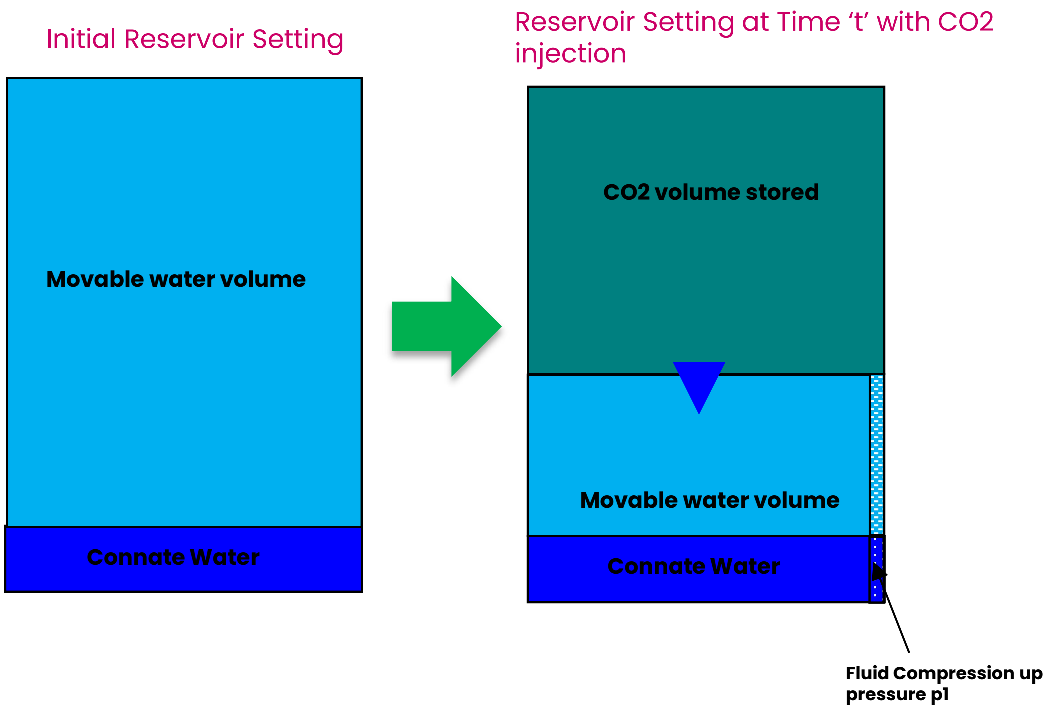
(Geoenergy, Unconventional Resources, Numerical Simulation)

Storage Capacity and Efficiency



- Storage capacity is a pore volume within the structure or alternatively, the volume of mobile water within the structure (Total Storage, total pore volume, effective pore volume, bulk volume, or storable quantity for a specific project)
- Storage efficiency is the ratio of estimated ultimate storage to the storage capacity

$$E_{saline} = E_{A_n/A_t} \times E_{h_n/h_g} \times E_{\emptyset_e/\emptyset_{tot}} \times E_v \times E_d$$

Storage Capacity= $Ah\emptyset\,(1 - S_{wirr})$

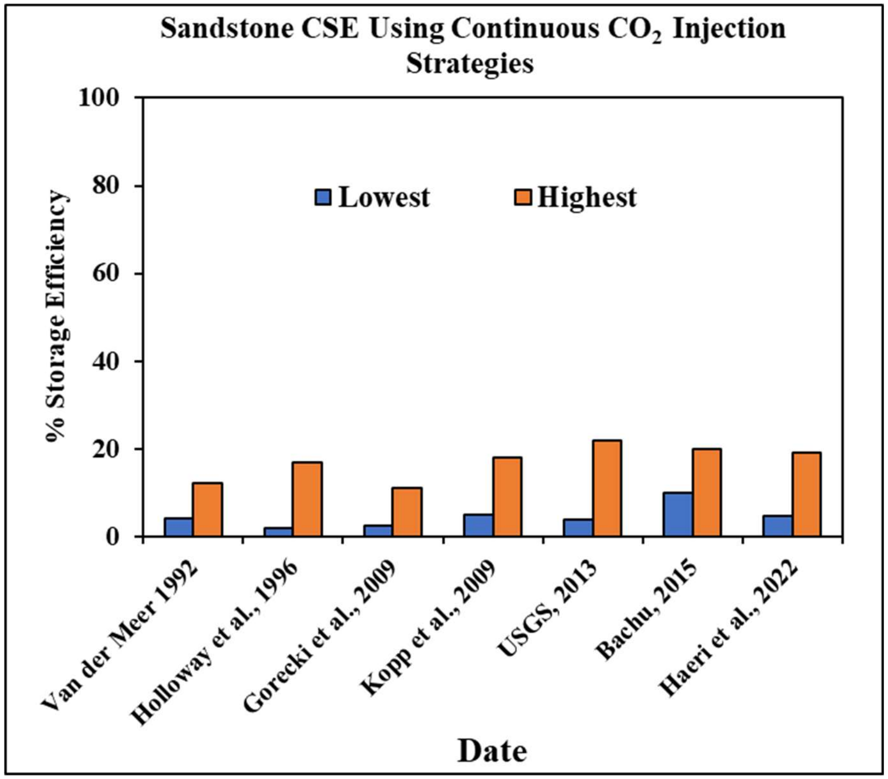
$$G_{CO_2} = Ah\emptyset\rho E_{saline}$$

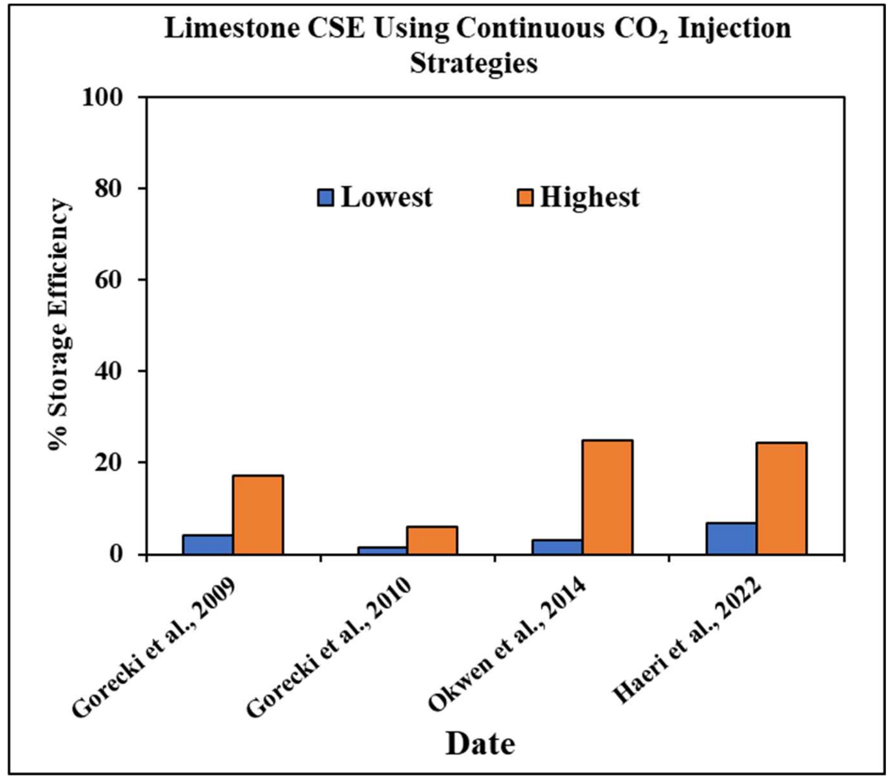
Storage volume (G_{CO_2})

Storage Efficiency (E_{saline})

$E_{An/At}$ -Net-to-total area
$E_{hn/hg}$ - Net-to-gross thickness
$E_{\phi e/\phi tot}$ - Effective-to-total porosity
E_d- Microscopic displacement efficiency=1-Swirr
E_v-Volumetric displacement efficiency=$E_A E_v E_g$

Subsurface CO_2 storage gaps





- There is a need to optimize or enhance all the storage trapping mechanisms, limiting rock alterations in the formation.
- There are limited storage efficiency (partly may be due to method of estimation) due to constraint such as Overpressure, capillary breakthrough, and injectivity impairment limit CO2 storage efficiency

Optimize Storage Efficiency

Accurate Site Characterization

- Identify key geological properties, such as porosity, permeability
- Evaluate caprock integrity or seal performance
- Detect the presence of faults or fractures, which influence storage capacity and efficiency

Reservoir Monitoring and Surveillance

- Continuous monitoring and modeling to assess storage performance
- Track changes in pressure temperature and the spatial distribution of CO_2
- Detect potential leakage pathways
- Information used to adapt injection strategies and improve storage efficiency

Maintaining CO_2 storage Supercritical Condition

- $scCO_2$, rather than gas, occupies less volume, allowing for greater storage efficiency.
- $scCO_2$ has a higher density than gaseous CO_2 and occupies less volume, allowing for more efficient use of available pore space and better storage capacity
- CO_2-interaction with reservoir fluid

Injection Strategy

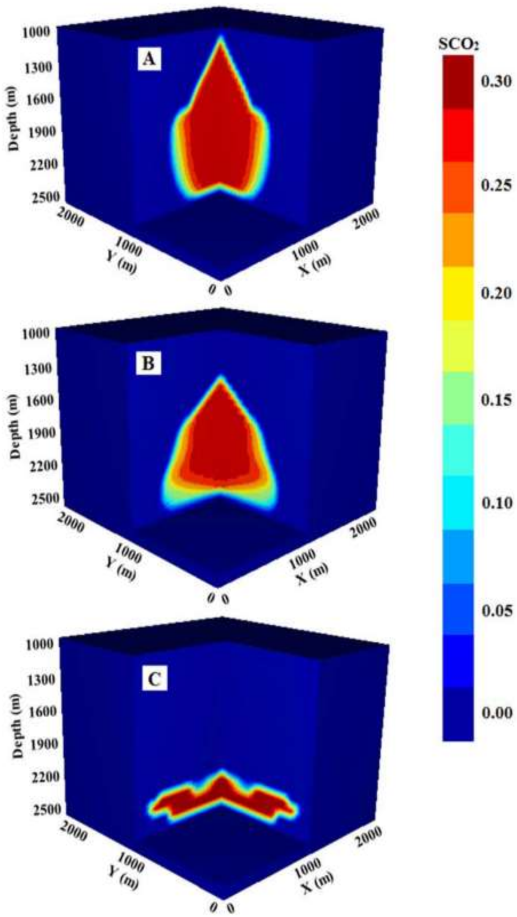
- Injection Scheme-Rate, pressure, etc.
- Duration of injection, CO_2 plume distribution, CO_2 trapping mechanism
- Well type/Orientation, pattern, spacing, and number
- Monitoring and adaptive management

Reference: https://doi.org/10.1080/15567036.2024.2347417

Optimizing Injection through Injection schemes

Injection Strategy	Description	Reservoir Type	Type of Study
Continuous CO_2 Injection	CO_2 is injected at a constant rate over time.	Deep Saline Aquifers, CO_2-EOR	Field/Pilot
Cyclic CO_2 Injection	Alternating periods of CO_2 injection and shut-in to allow pressure equilibration and enhance trapping.	CO_2-EOR	Numerical Simulation, Field
Water Alternating Gas (WAG)	CO_2 injections are alternated with water injections to enhance sweep efficiency	CO_2-EOR	Field/Pilot, Numerical Simulation
Simultaneous CO_2 and Brine Aquifer Injection (SAI)	Simultaneous injection of CO_2 and brine to enhance sweep efficiency	CO_2-EOR	Numerical Simulation
Pulsed CO_2 Injection	Short, repeated bursts of CO_2 injection to optimize plume distribution and prevent pressure build-up.	Deep Saline Aquifers, CO_2-EOR	Numerical Simulation
Push-Pull Injection	CO_2 (push) is injected, followed by water or CO_2-saturated water, and subsequent fluid withdrawal (pull).	Deep Saline Aquifers	Experiment, Field/Pilot
Dissolved CO_2 Injection	Injection of CO_2 dissolved in brine at the surface to minimize free-phase CO_2 migration.	Deep Saline Aquifers	Numerical Simulation, Experiment
Continuous Injection with Pressure Management	CO_2 injection combined with water production from adjacent wells to control reservoir pressure.	Deep Saline Aquifers	Numerical Simulation, Field
Acid-Gas Injection	Injection of a CO_2-H_2S mixture, sometimes dissolved in brine, for storage or disposal.	Depleted Oil and Gas Reservoirs, Deep Saline Aquifers	Field/Pilot

Numerical Insight



WAG- Reduces vertical plum migration

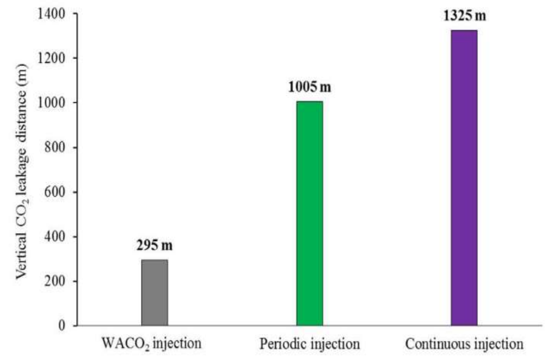


Figure 5—The total vertical CO_2 leakage distance for the three injection scenarios investigated after after 200 years CO_2 storage period.

WAG- Increases Capillary Trapping of CO_2

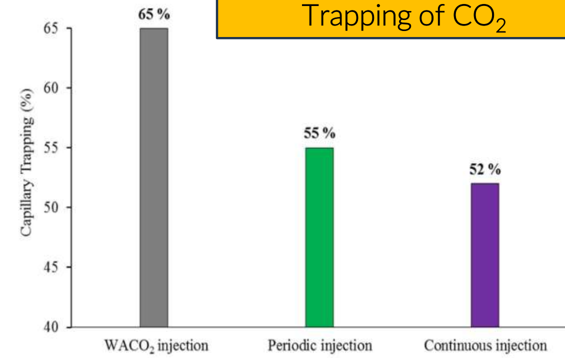


Figure 6—The percentage of the capillary trapping capacity to the total amount of CO_2 injected (20 Mton) for the three injection scenarios investigated after after 200 years CO_2 storage period.

WAG- Increases Solubility Trapping of CO_2

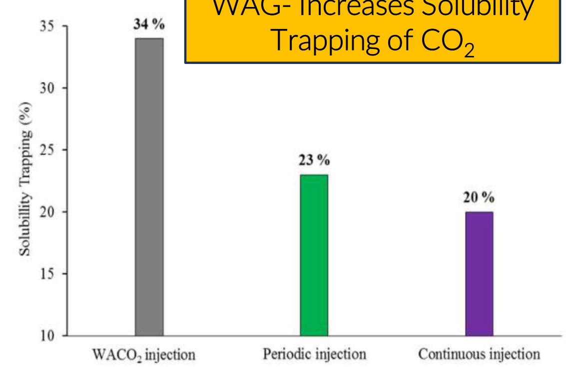


Figure 7—The percentage of the solubility trapping capacity to the total amount of CO_2 injected (20 Mton) for the three injection scenarios investigated after 200 years CO_2 storage period.

WAG- CO_2 becomes Less mobile

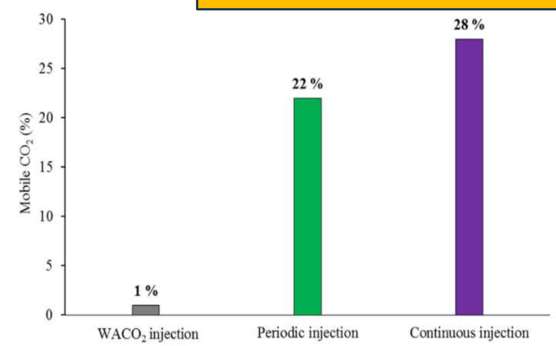


Figure 8—The percentage of the free CO_2 to the total amount of CO_2 injected (20 Mton) for the three injection scenarios investigated after 200 years CO_2 storage period

Al-Khdheeawi, Emad A. et al (2018)

What if low-salinity or freshwater is replaced by high-salinity water? What is the effect?

Requirements

Provide experimental data to calibrate and validate the concept of using WAG/ SAI injection strategy to improve storage efficiencies of DSAs.

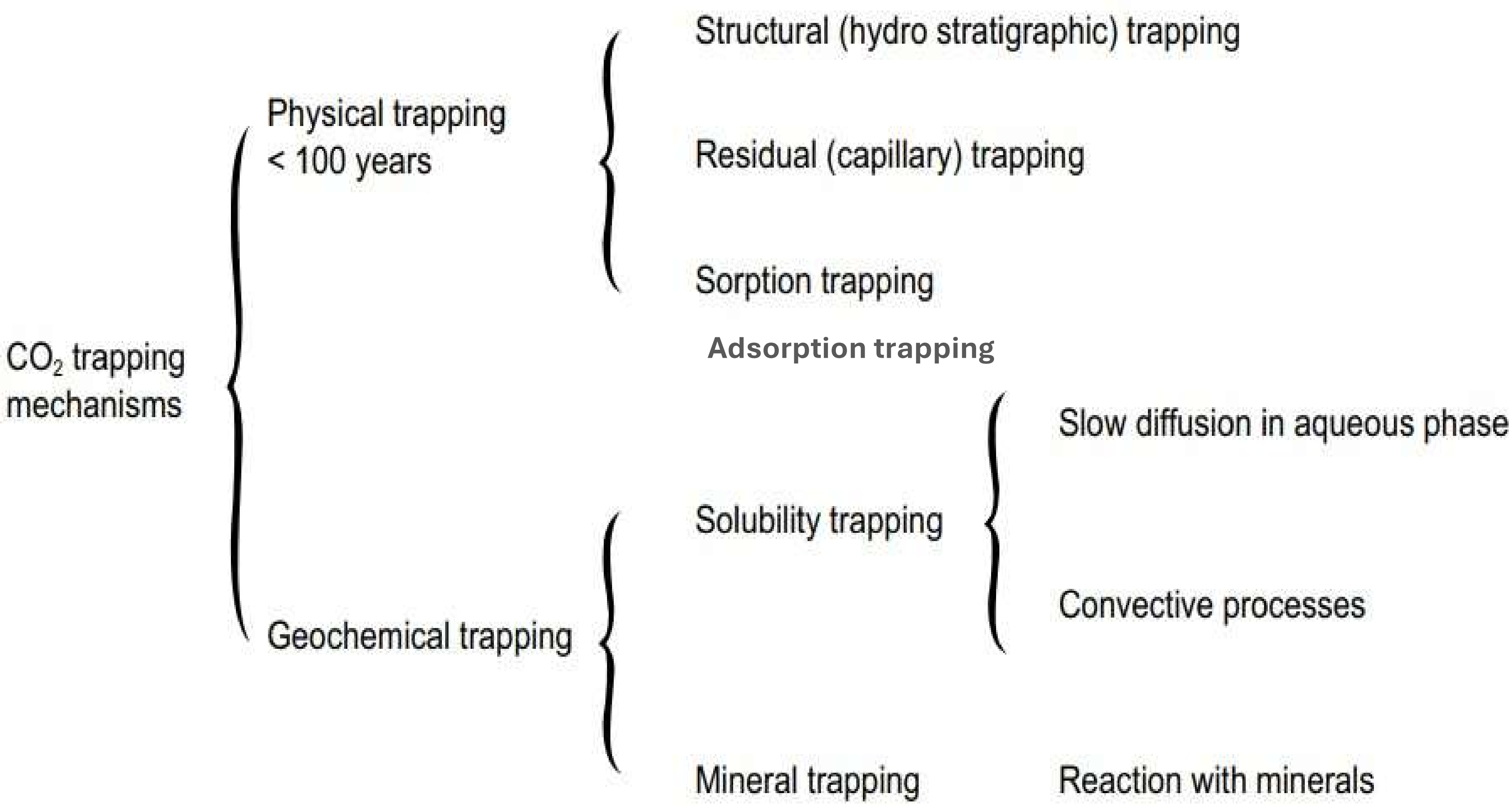
This includes the microstructural, mineralogical, petrophysical, and geomechanical changes in sandstone and carbonate.

This also includes substituting the injected water with high salinity water to mimic the PW scenario for water conservation

Numerical simulation to quantify the life cycle storage efficiency and also identify risks and uncertainties that could occur.

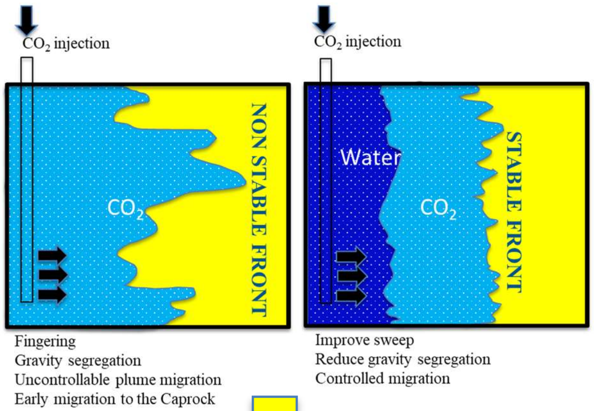
Experimental Investigation

Storage Trapping Mechanism



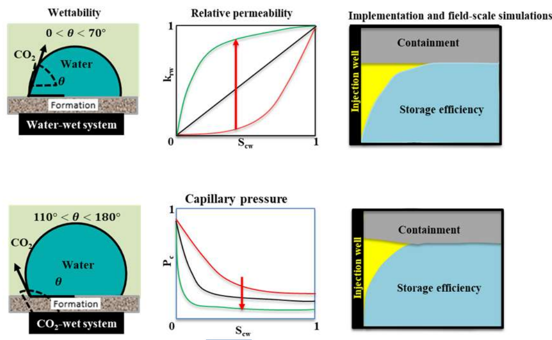
Properties Indicative of Storage Mechanism

Structural/Stratigraphy



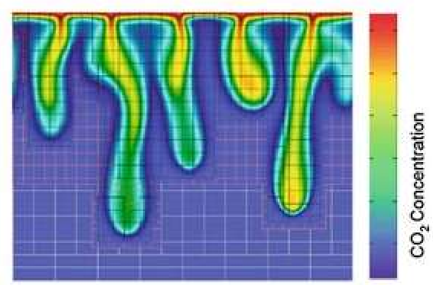
- Rock properties-ϕ, k

Residual Trapping



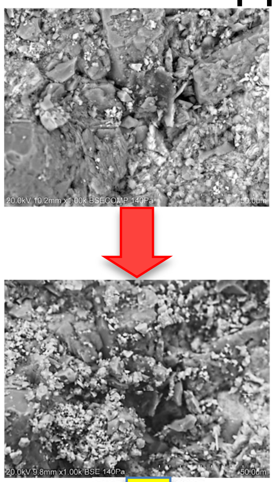
- Contact angle
- Wettability

Solubility Trapping



- Fluid properties
- Aquifer properties and volume

Mineral Trapping



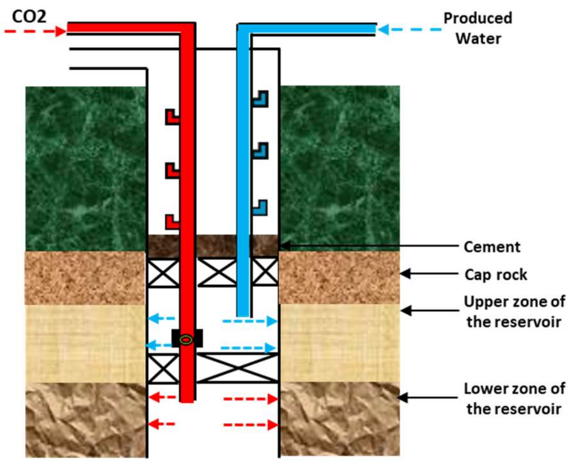
- Rock Mineralogy
- Geochemical reaction
- $scCO_2$ conditions

Reservoir Integrity

- Rock Geomechanical properties

Parameters considered in the experimental study

Injection Strategies

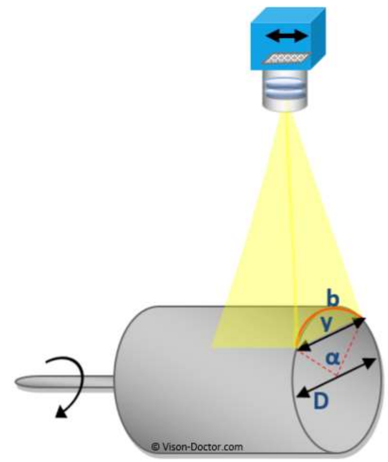


- $scCO_2$ Continuous Injection(base case)-CCI
- $scCO_2$ and water/brine alternating injection-WAG
- $scCO_2$ and water/brine simultaneous injection-SAI

Salinity Effect

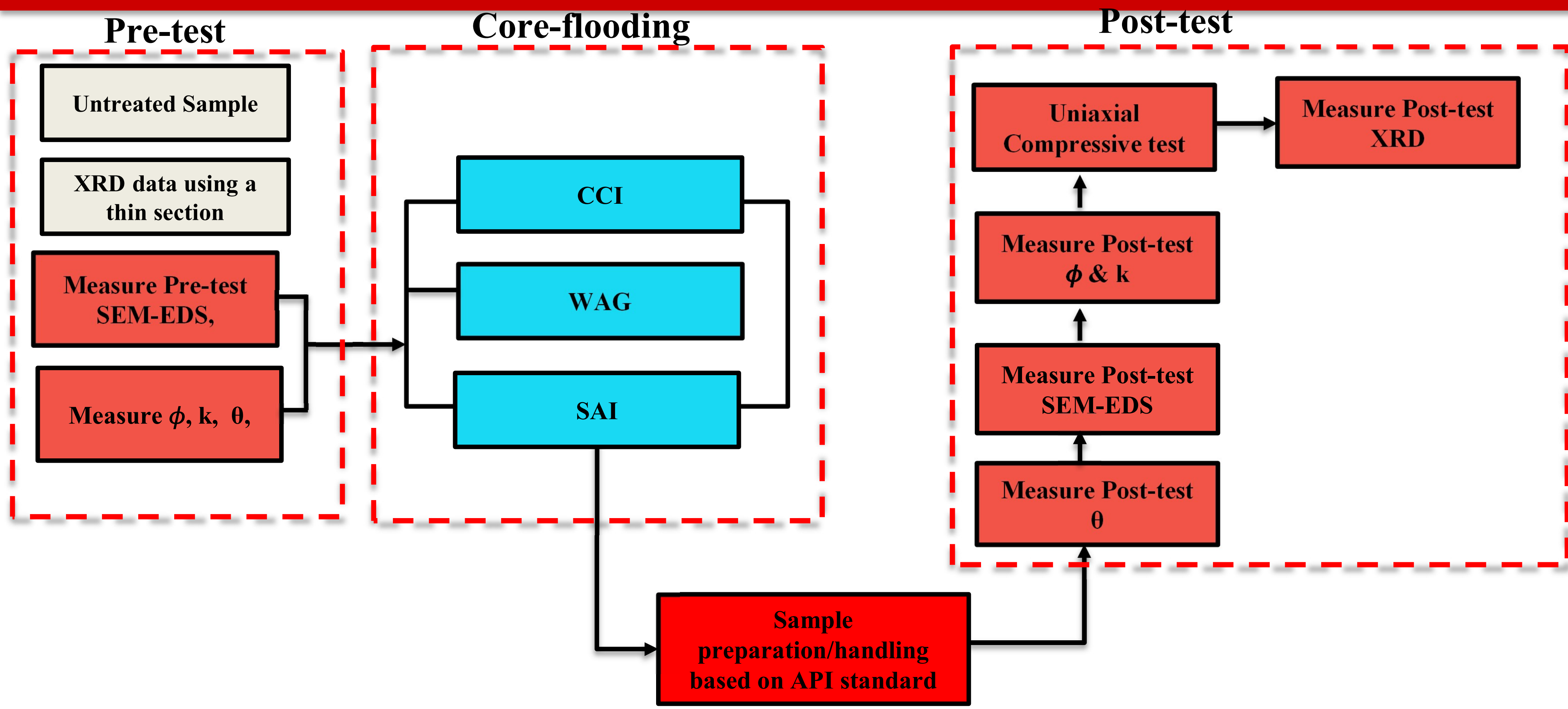
- 0g/l, (0ppm)
- 20g/l (20,000ppm)
- 50g/l (50,000ppm)
- 100g/l (100,000ppm)
- 200g/l (200,000ppm)

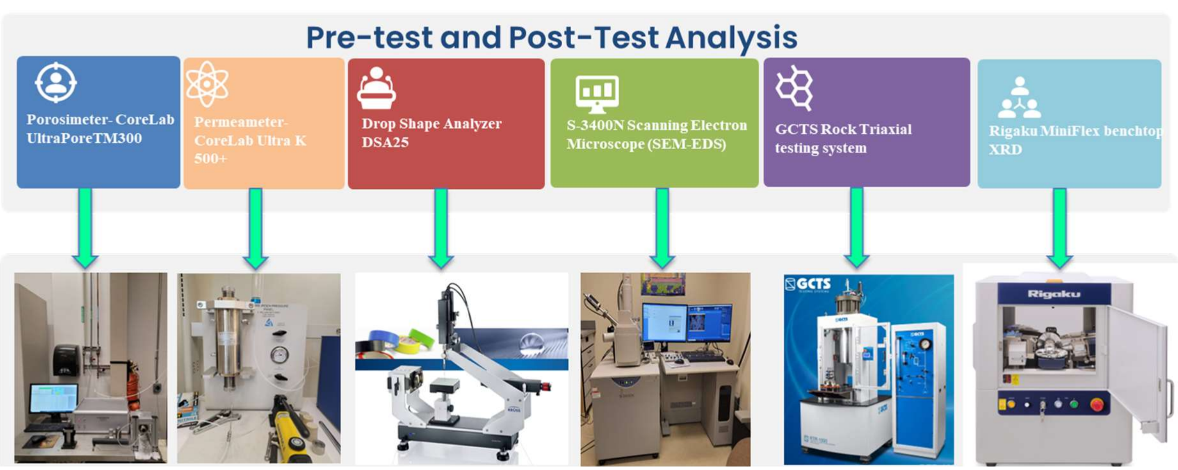
Different Exposure times

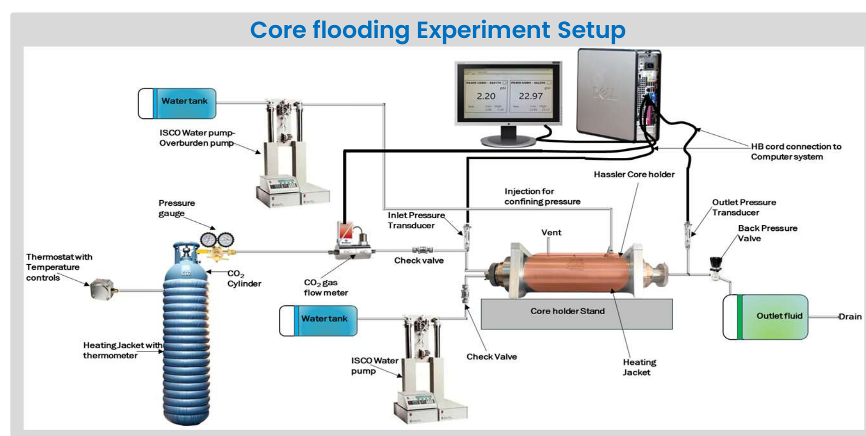


- 75PV injection (24hours CO_2 injection)
- 225PV injection (72 hours CO_2 injection)
- 525PV injection (168hrs of $scCO_2$ injection)

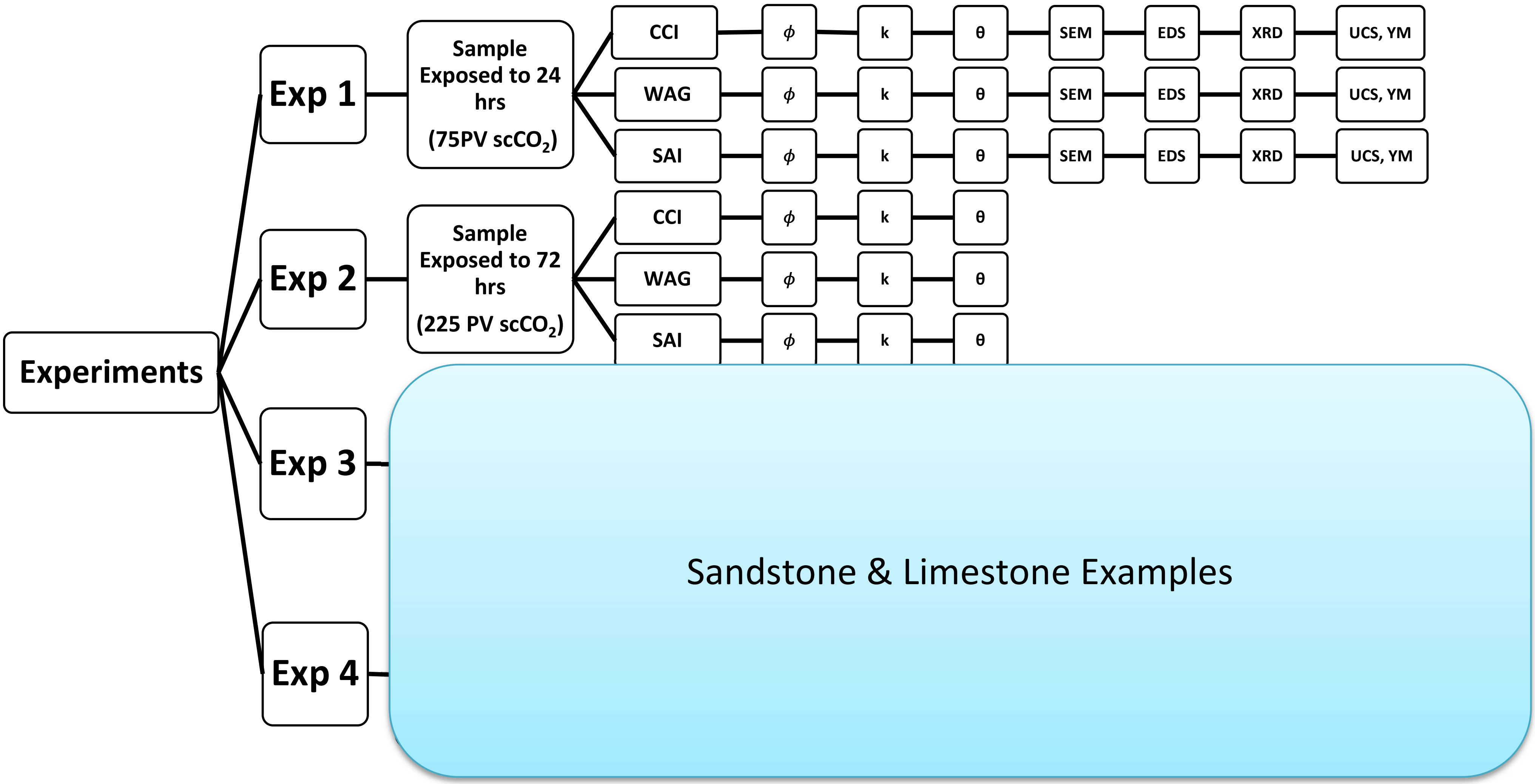
Comprehensive Experimental Workflow





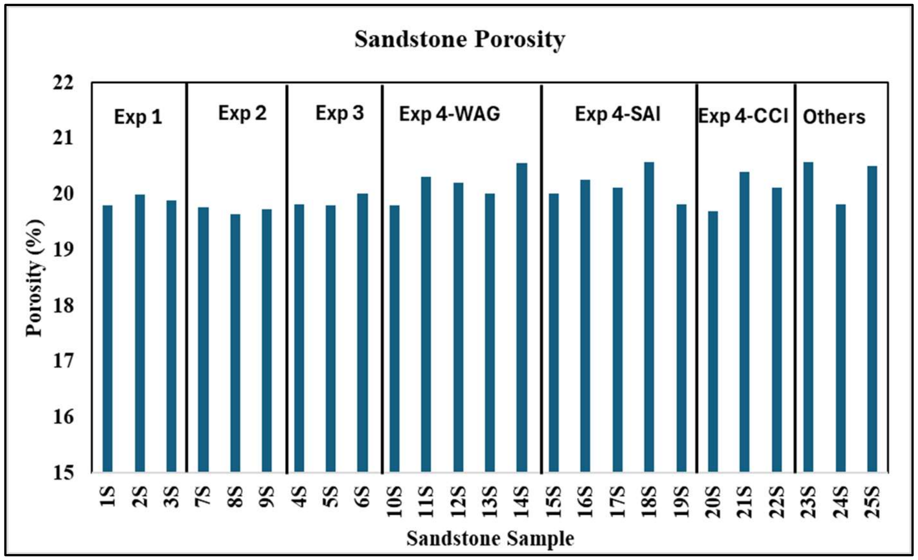


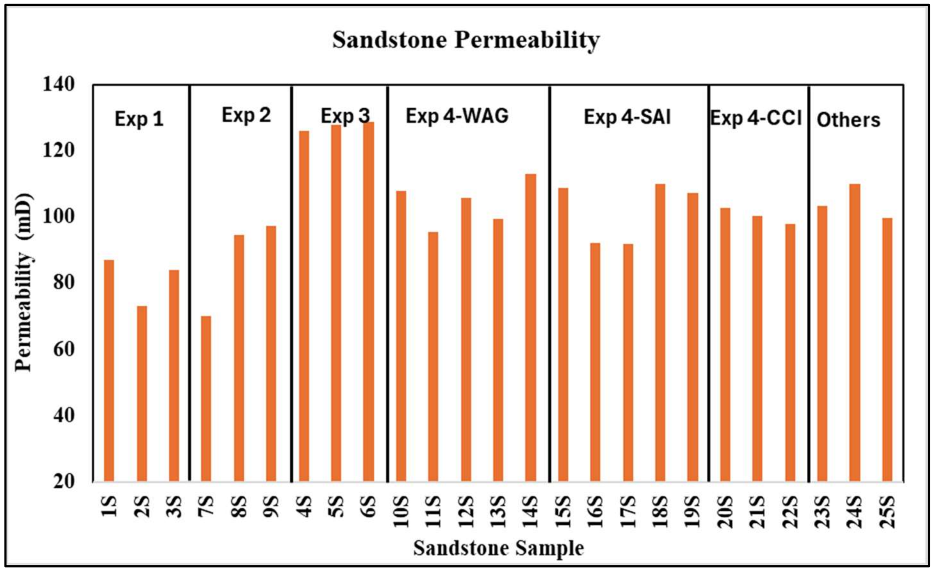
Experimental Design (Cont'd)

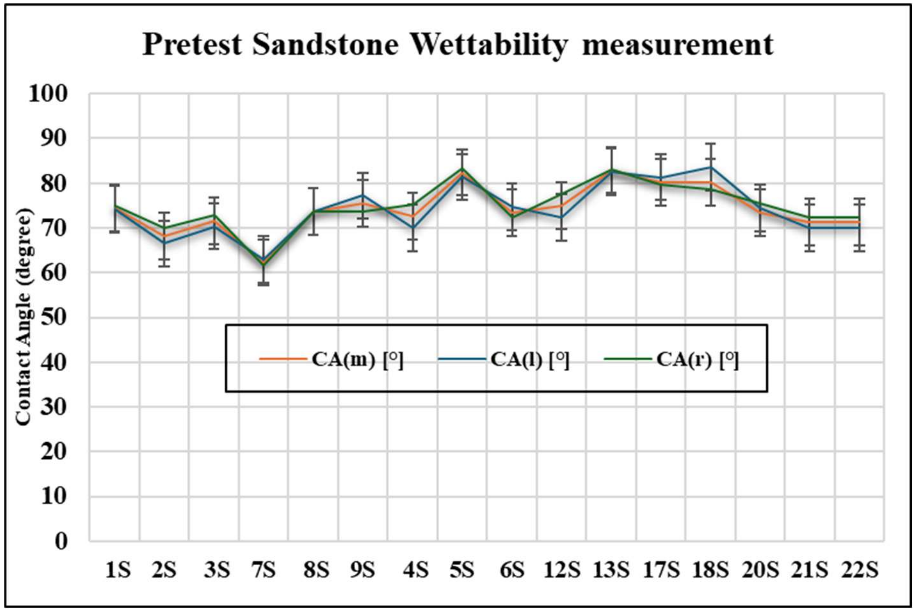


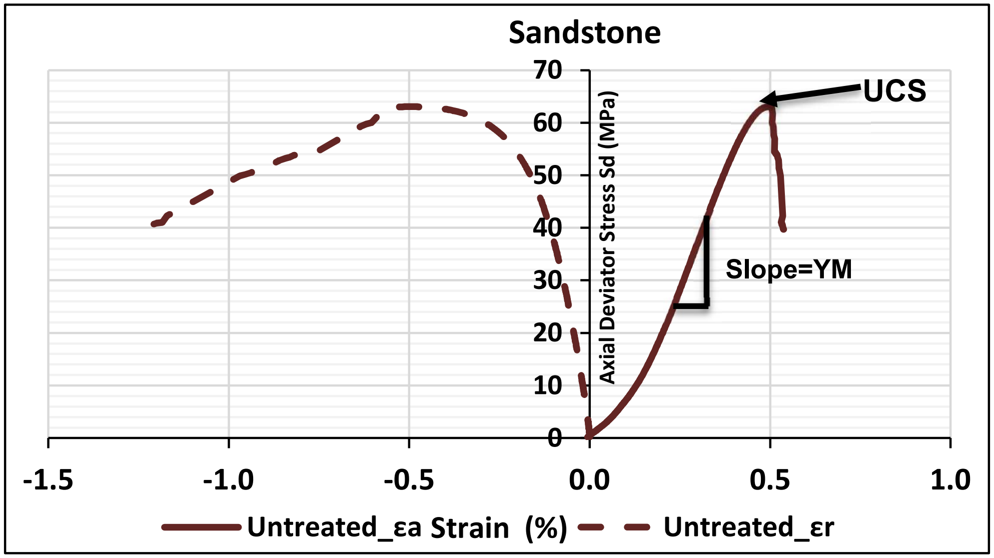
over 500 experiments (24 core flooding exposures, 110 pretests, and 120 post-tests each for Sandstone & Carbonate samples)

Pretest
(Sandstone Examples)



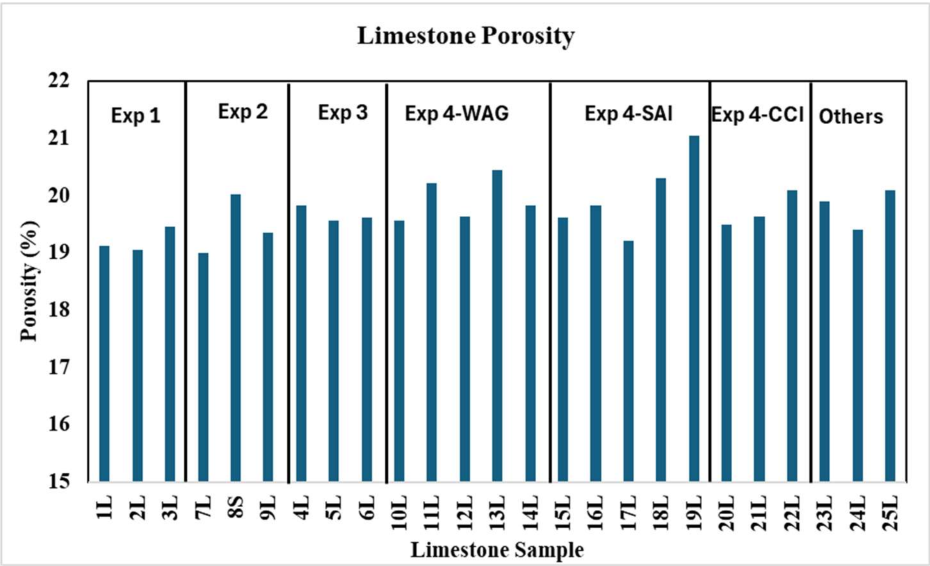


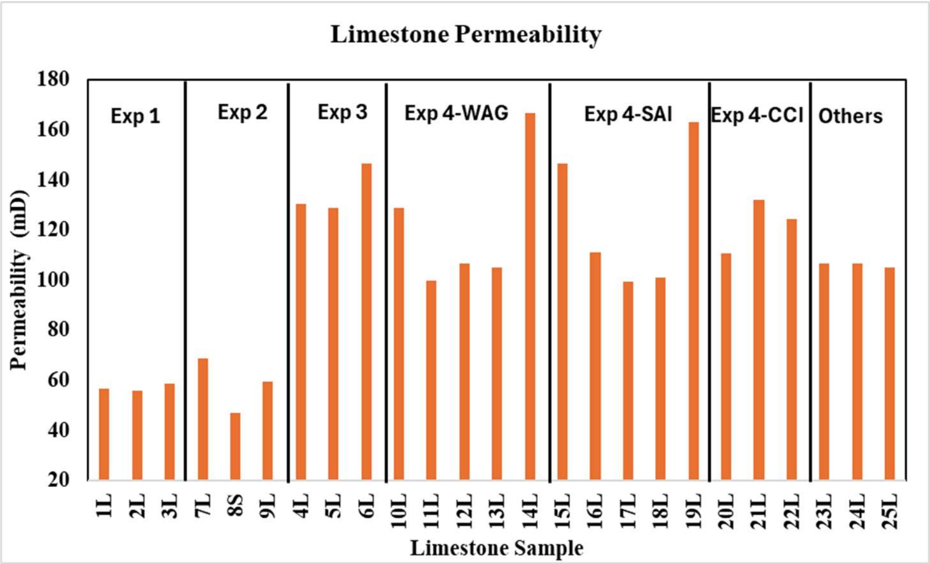


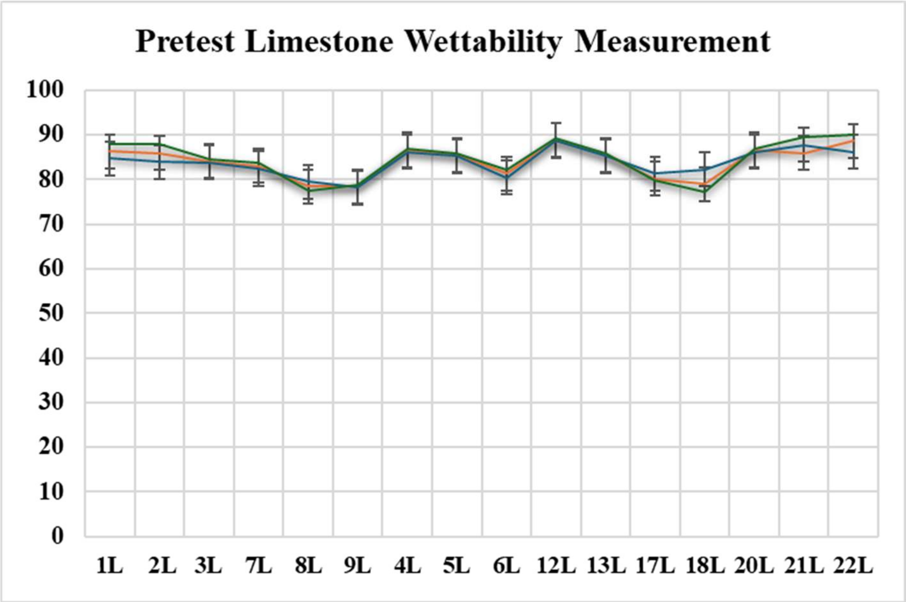


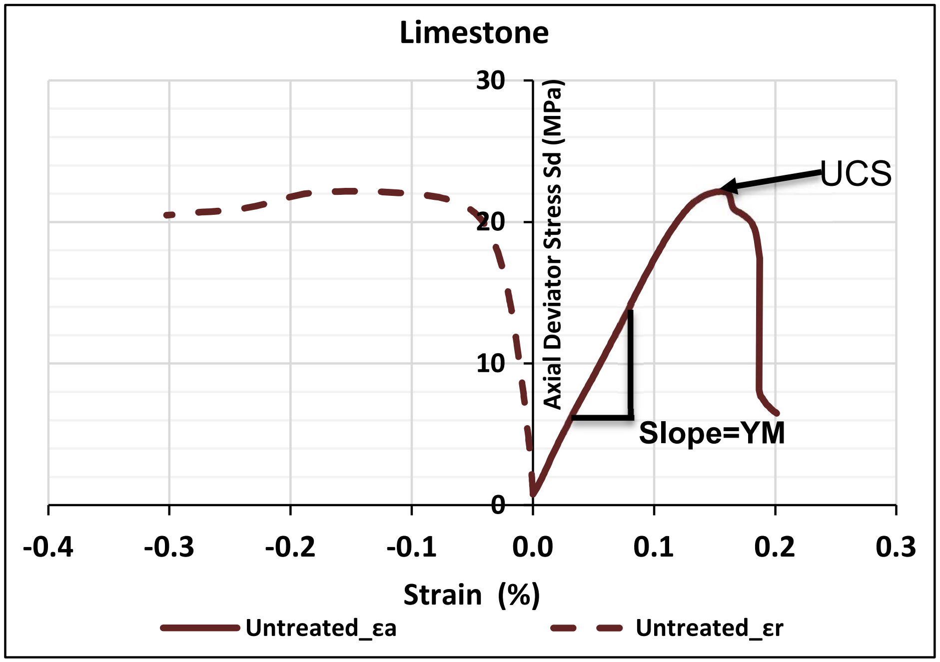
"Similar samples are used for the same type of experiments regarding exposure time or pore volume"

Pretest
(Limestone Examples)



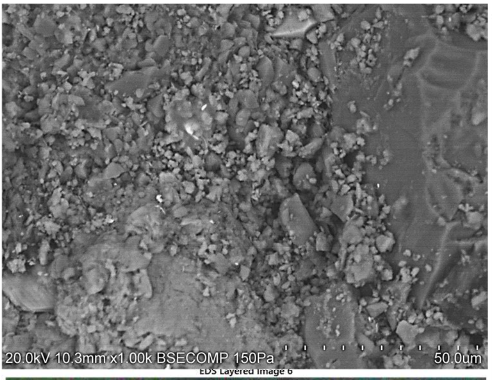


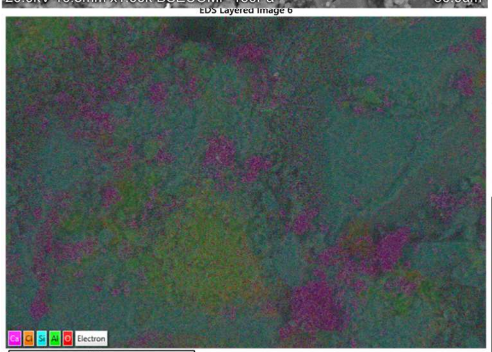


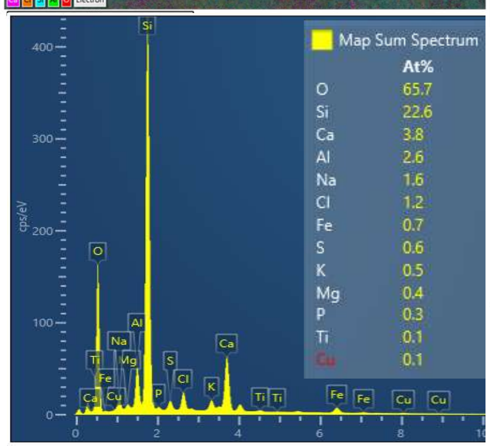


Pretest
(Microstructural, Elemental mapping & Mineralogy)

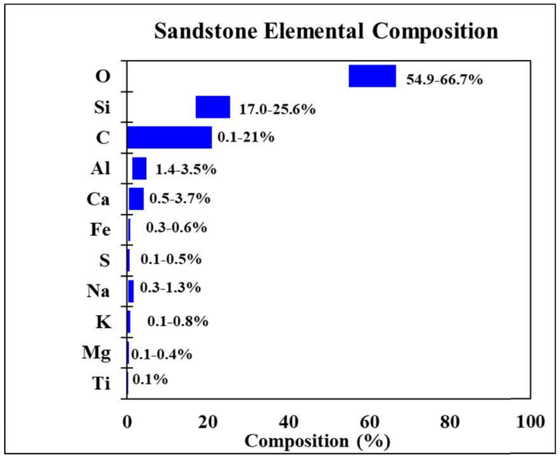
SEM, SS



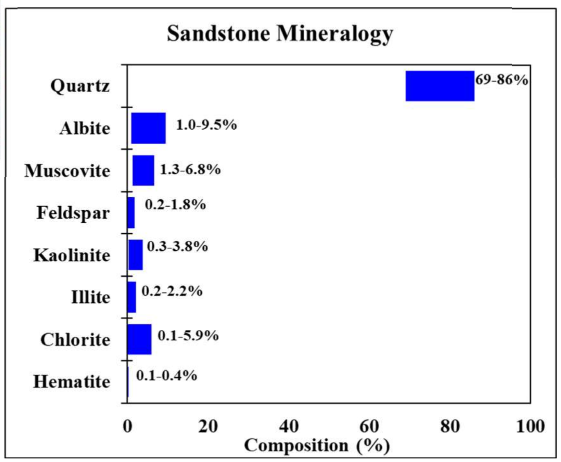




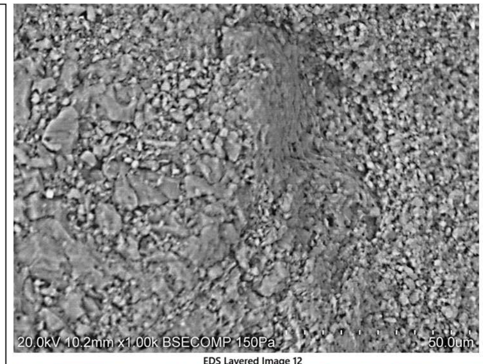
EDS

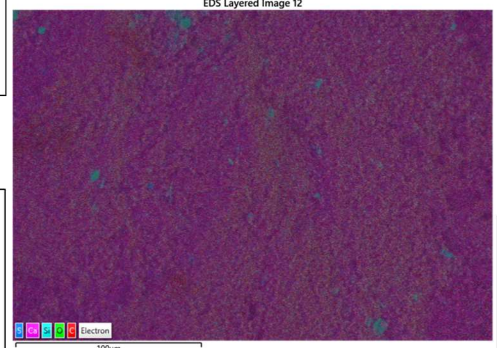


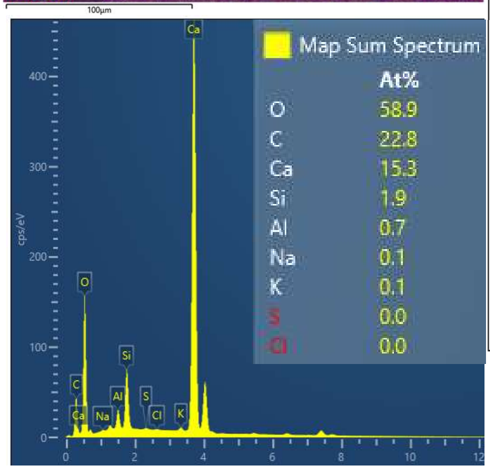
XRD



SEM, LM







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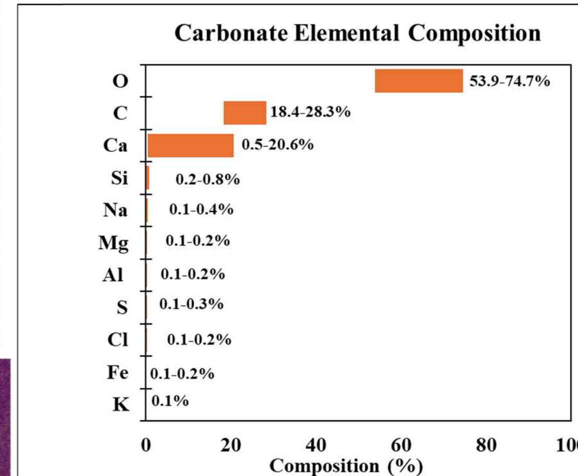
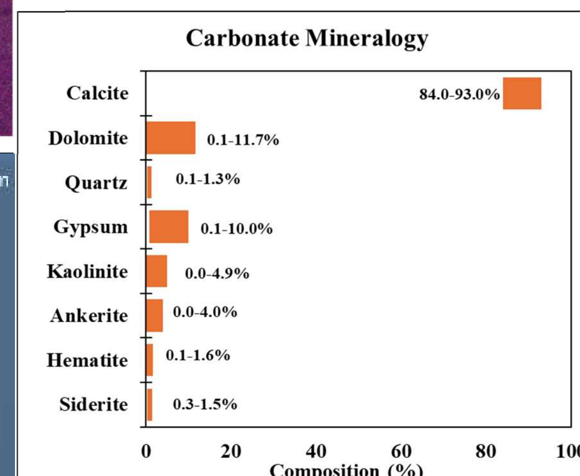
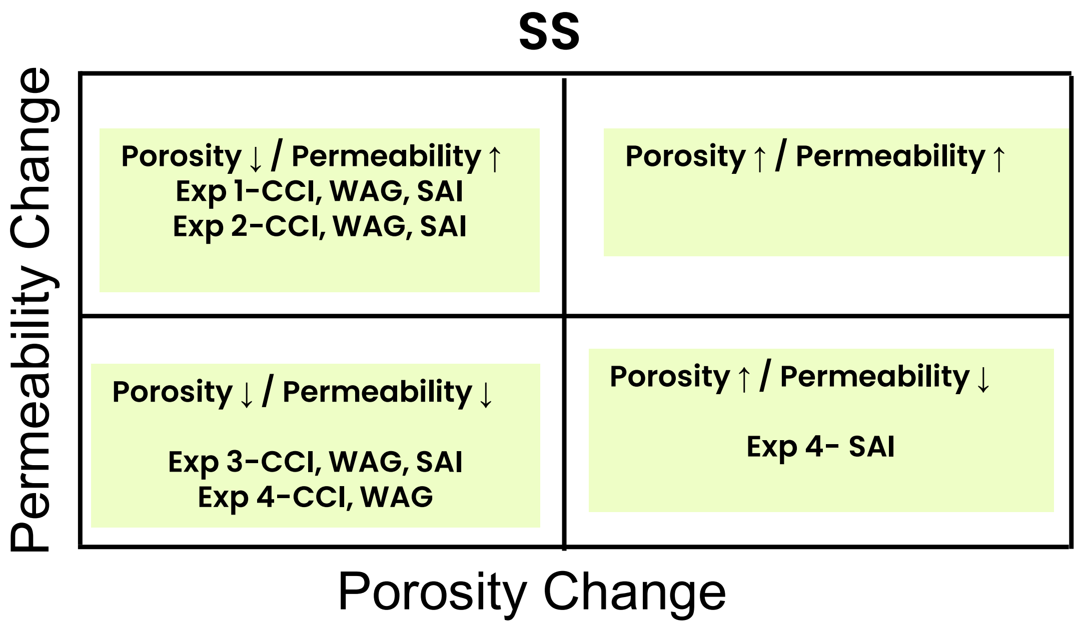


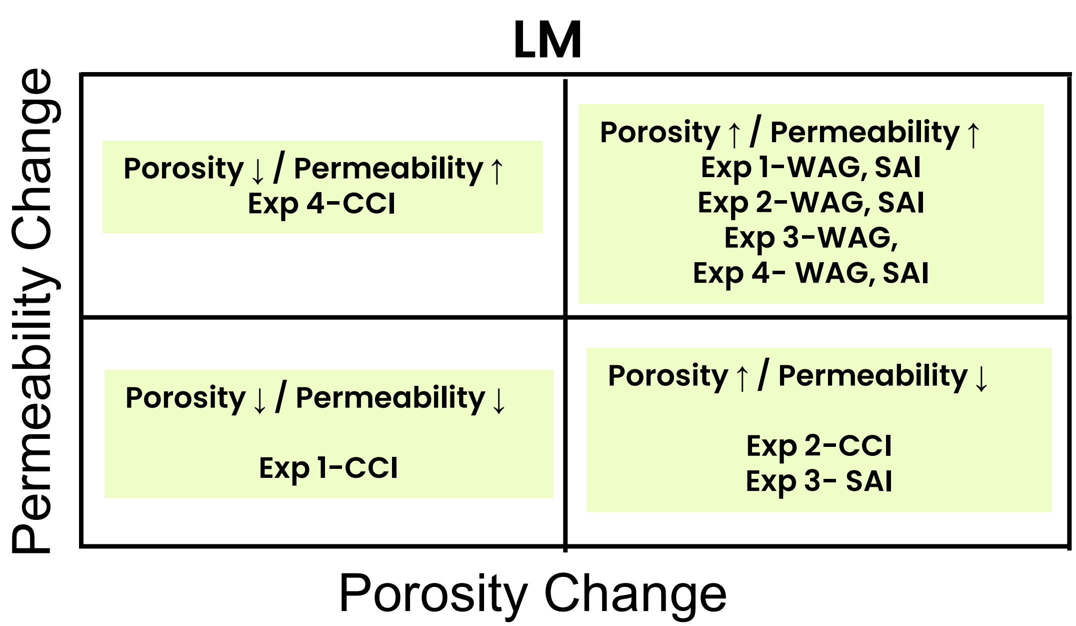
XRD



Post-test
(Petrophysical Changes)



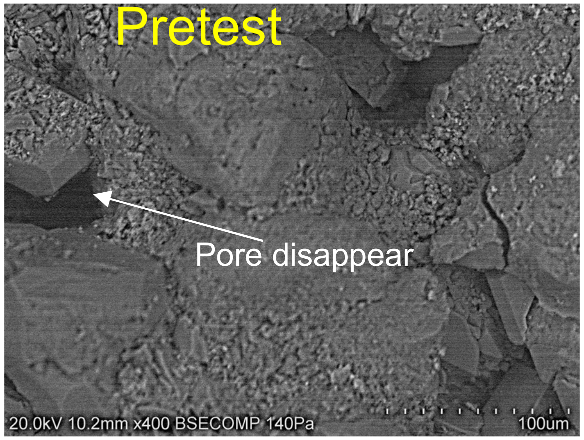
- CCI has more reduction in porosity than other injection methods at salinity <20g/L
- WAG preserves the porosity when salinity is <50g/L, equivalent to the changes observed in CCI.
- >50g/L, there is a considerable reduction in porosity when using WAG.
- However, SAI offers the highest porosity increase at higher salinity

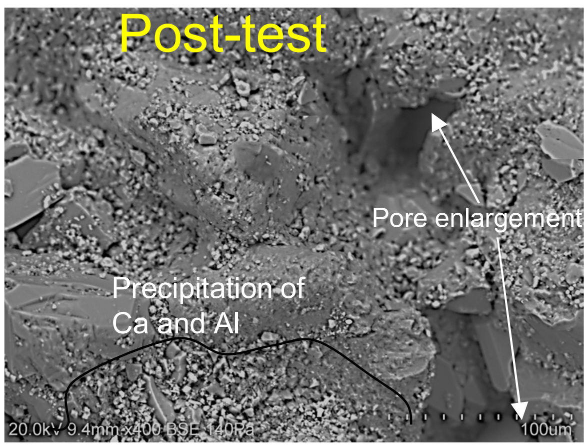


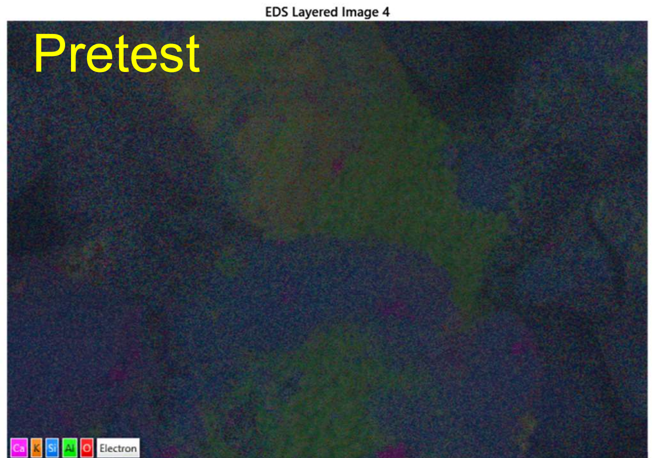
- WAG and SAI offer a high potential for increasing storage capacity in limestone, even at high salinity levels.
- WAG exhibits a significant increase in permeability as salinity increases, whereas SAI displays moderate changes in permeability.
- Increased porosity enhances stratigraphic trapping, which is crucial for CO_2 storage ($G_{CO2} = A^d h^s \emptyset^s \rho^s E_{saline}{}^s$).

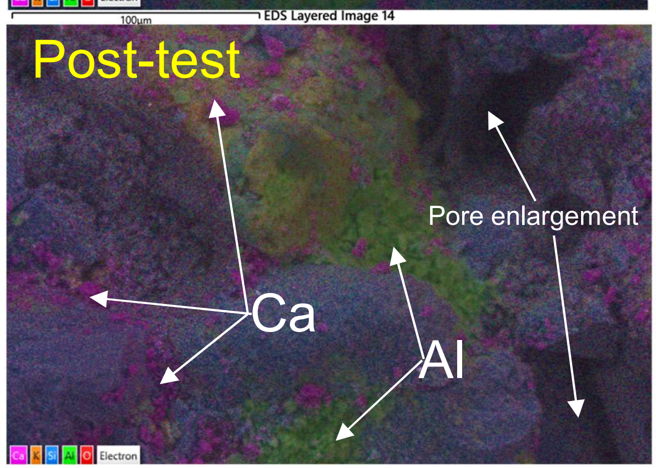
Post-test

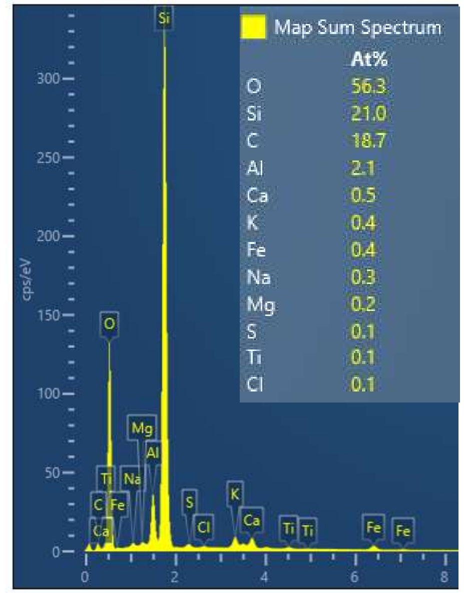
(Microstructural changes and Elemental mapping, SS)

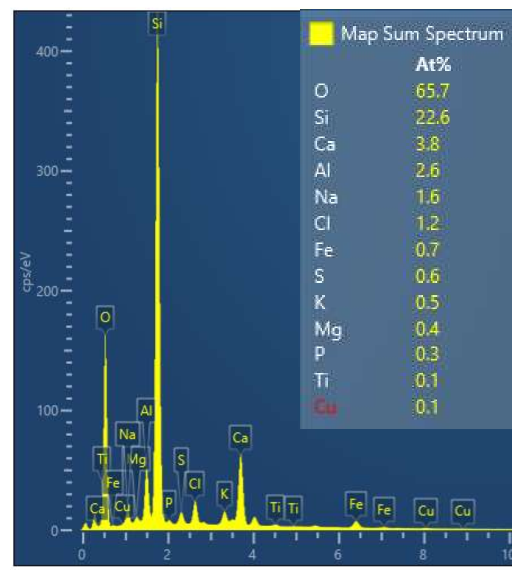






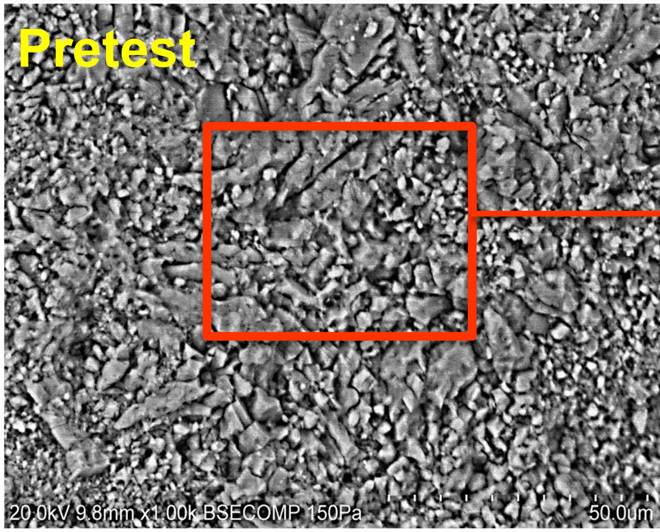


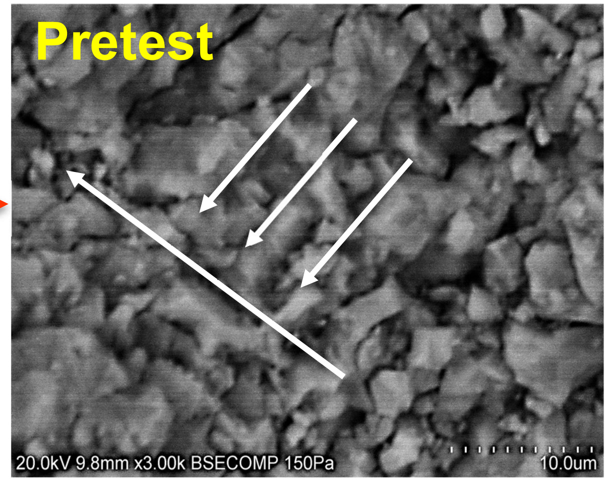


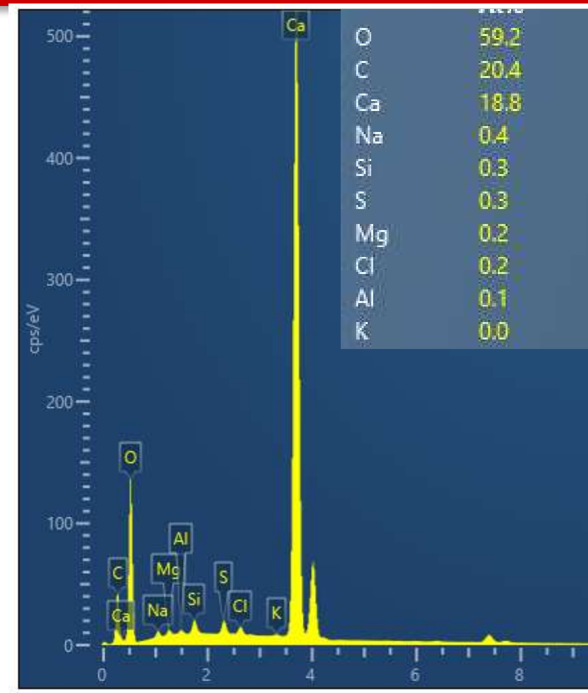


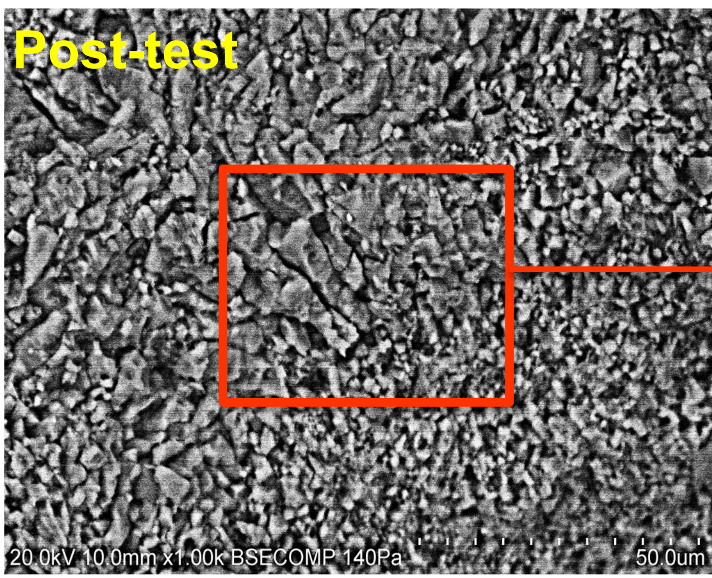
“Stables carbonates & Bicarbonates to study mineralization, i.e., changes in Ca, Fe, Mg, Si, and Al (quartz, feldspar, hematite, and chlorite)

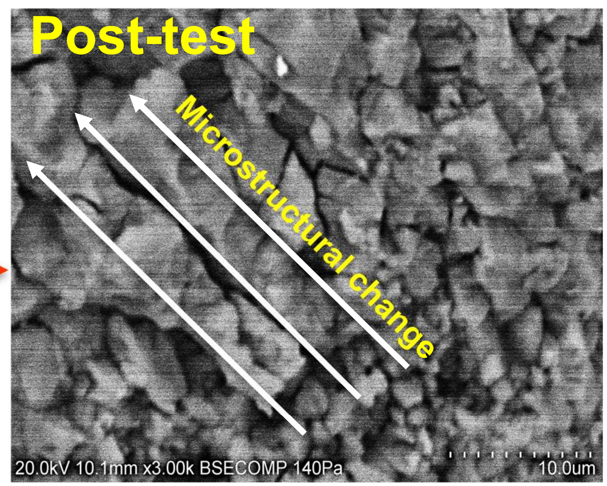
Post-test
(Microstructural changes and Elemental mapping, LM)

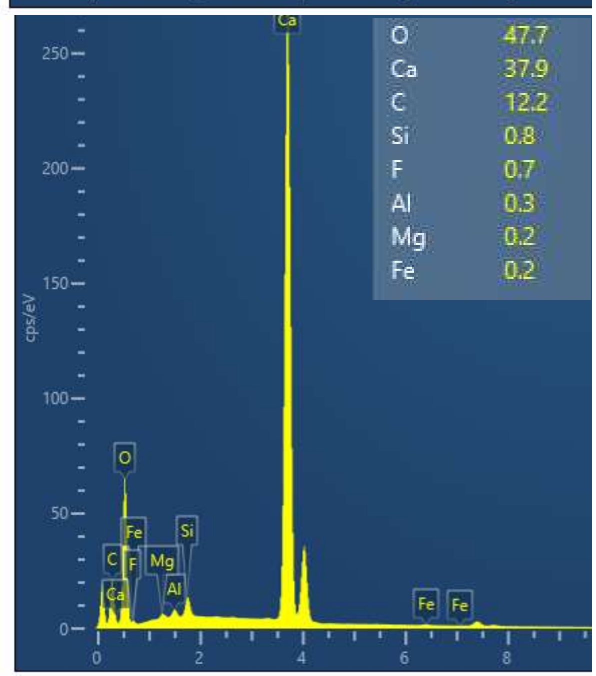












CO_2 Geochemistry (Mineralization)

$SiO_2+2CO_2+2H_2O\rightarrow H_4SiO_4+2HCO_3^-$

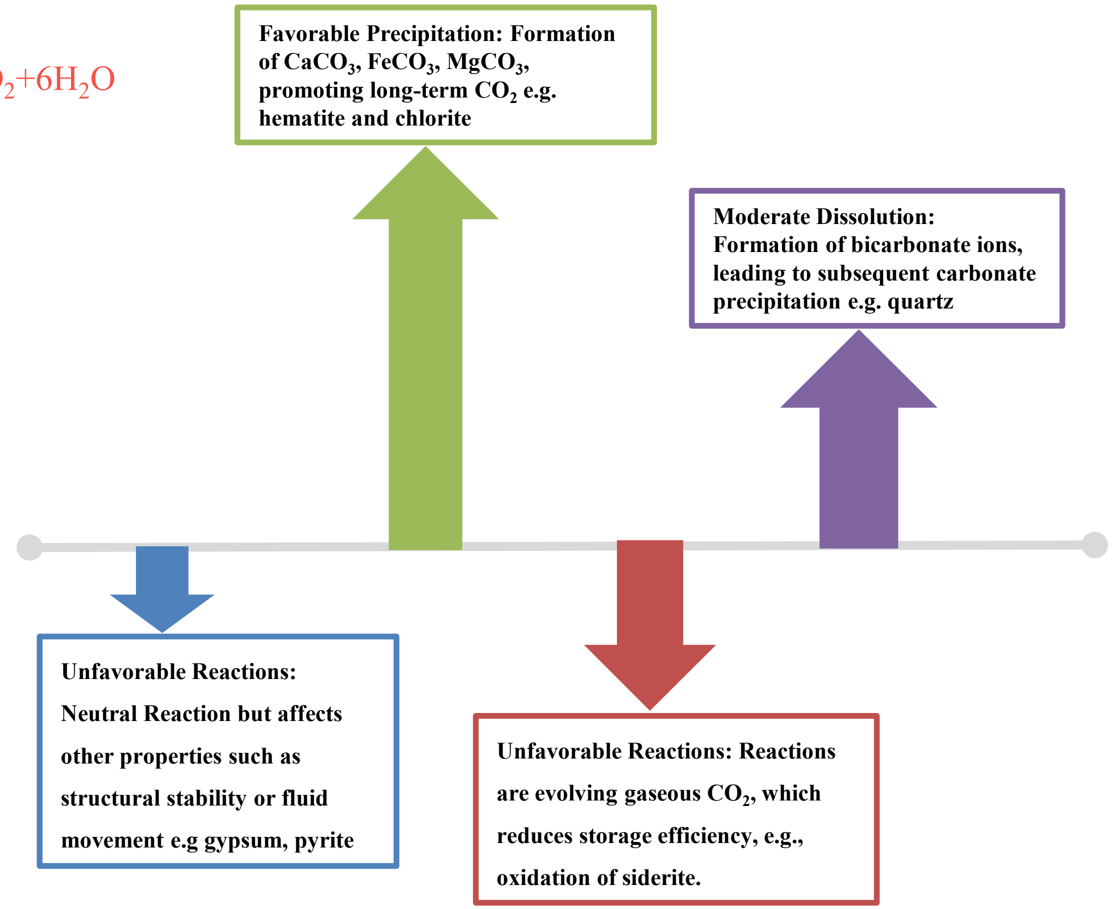
$Fe_2O_3+3CO_2+3H_2O\rightarrow 2FeCO_3+3HCO_3^-$

$(Mg,Fe)_5Al_2Si_3O_{10}(OH)_8+CO_2+H_2O\rightarrow MgCO_3+FeCO_3+Al_2Si_2O_5(OH)_4$

$Ca^{2+}+2HCO_3^-\rightarrow CaCO_3+H_2O$

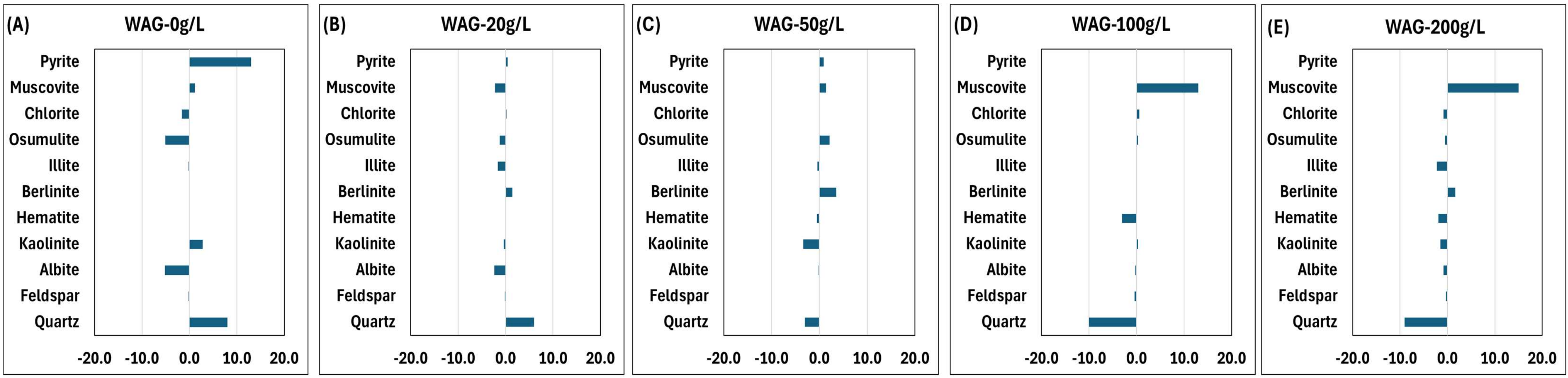
$CaSO_4\cdot 2H_2O\rightarrow Ca^{2+}+SO_4^{2-}+2H_2O$

$4FeCO_3+O_2+6H_2O\rightarrow 2Fe_2O_3+4CO_2+6H_2O$



Precipitation and Dissolution Dynamics

Post-test
(Mineralogy Changes in SS)



$$SiO_2+2CO_2+2H_2O \rightarrow H_4SiO_4+2HCO_3^-$$

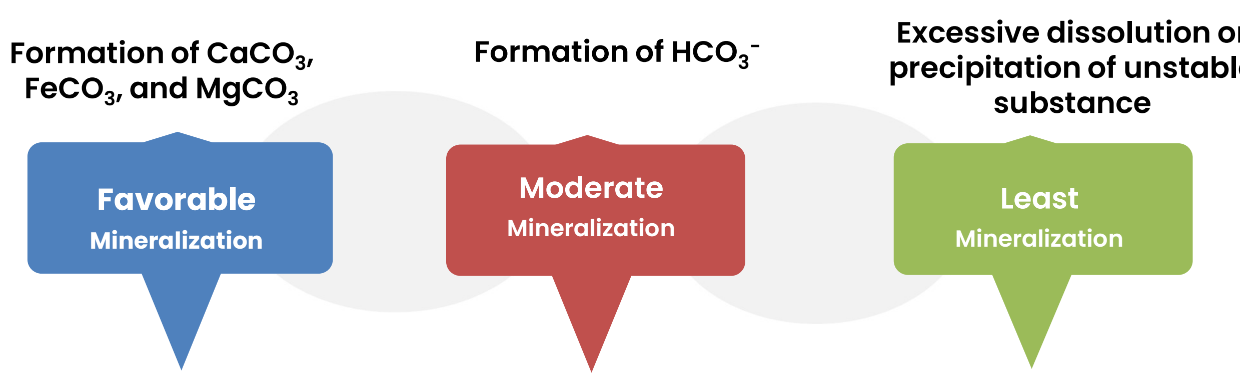
$$Fe_2O_3+3CO_2+3H_2O \rightarrow 2FeCO_3+3HCO_3^-$$

$$(Mg,Fe)_5Al_2Si_3O_{10}(OH)_8+CO_2+H_2O \rightarrow MgCO_3+FeCO_3+Al_2Si_2O_5(OH)_4$$

$$Ca^{2+}+2HCO_3^- \rightarrow CaCO_3+H_2O$$

$$CaSO_4 \cdot 2H_2O \rightarrow Ca^{2+}+SO_4^{2-}+2H_2O$$

$$4FeCO_3+O_2+6H_2O \rightarrow 2Fe_2O_3+4CO_2+6H_2O$$



Exp 3 CCI | WAG, SAI

Exp 4 CCI, WAG, SAI

Post-test
(Combined interpretation for SS)

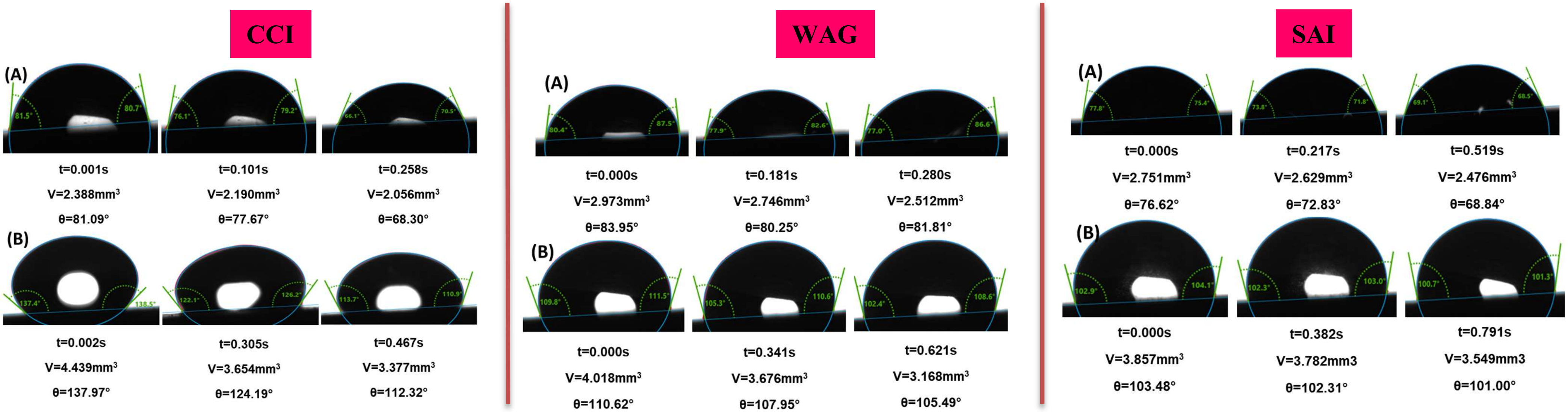
Rock type	Injection Strategy	Pore volume Injected	XRD (mineral)		EDS (element)		Porosity	Permeability	SEM	Mineralization ($CaCO_3$, $FeCO_3$, $MgCO_3$)
			Precipitation	**Dissolution**	**Precipitation**	**Dissolution**				
Sandstone	**CCI**	**75**	Feldspar, Albite, Kaolinite, Hematite, illite, osumulite, Chlorite,	Quartz, Berlinite, illite, muscovite, pyrite	C, Ca	O, Na, K, Fe, Mg, Al, Si	Decrease	Increase (least)	Microstructural changes observed- Mineral dissolution, pore enlargement, and new pore spaces.	$CaCO_3$ precipitation
	WAG	**75**	Feldspar,Hematite, Berlinite, osumulite, Chlorite, pyrite	Quartz, Albite, Kaolinite, Berlinite, illite, muscovite,	C, Al, Si, K, Fe	Ca*, Na, Mg, O	Decrease (most)	Increase	Minimal microstructural changes, pore sizes reduction	$CaCO_3$ and $FeCO_3$ precipitation
	SAI	**75**	Feldspar, Albite, Kaolinite, Hematite, Berlinite, illite	Quartz, osumulite, muscovite, pyrite	Ca, C, Fe	Al, Si, Na, K, Mg, O	Decrease (least)	Increase (most)	Overall pore enlargement, significant formation of new minerals, and minor dissolution hence moderate microstructural changes	$CaCO_3$ and $FeCO_3$ precipitation
	CCI	**525**	Kaolinite, Hematite, illite, muscovite,	Quartz, Feldspar, Albite, Berlinite, osumulite, Chlorite,	C, Ca,K	O, Na, Si, Fe, Mg, Al	Decrease (most)	Decrease (least)	Higher change in the microstructure features due to excessive precipitation reducing pore sizes and distribution	$CaCO_3$ precipitation
	WAG	**525**	Quartz, Berlinite, Chlorite, pyrite	Feldspar, Albite, Kaolinite, Hematite, illite, osumulite, muscovite,	Ca, C, Si, Na, Fe, O	Al, K, Mg	Decrease	Decrease (most)	Minimal microstrural changes with minor visible mineral dissolution, and precipitation effect. Pore enlargement visible on the x3000 magnification digital image.	$CaCO_3$ and $FeCO_3$ precipitation
	SAI	**525**	Quartz, Feldspar, Hematite, Berlinite,	Kaolinite, Albite, illite, osumulite, Chlorite, muscovite, pyrite	Si, O, C, Fe	Al, Ca*, K, Mg	Decrease (least)	Decrease	Severe microstructural changes due to precipitation with minimal alterations in pore sizes and notable changes in pore distribution	$FeCO_3$ precipitation

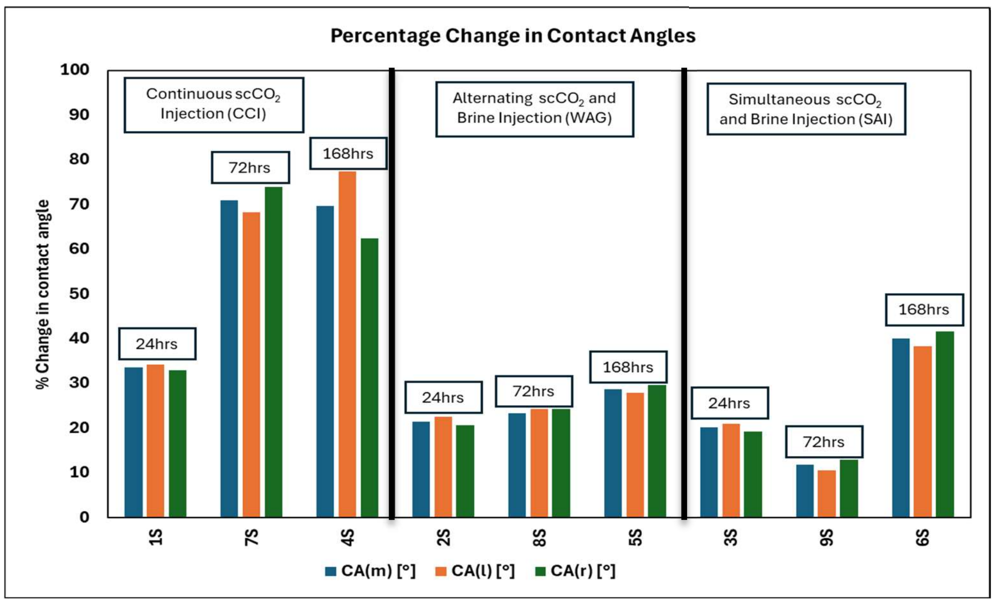
Post-test

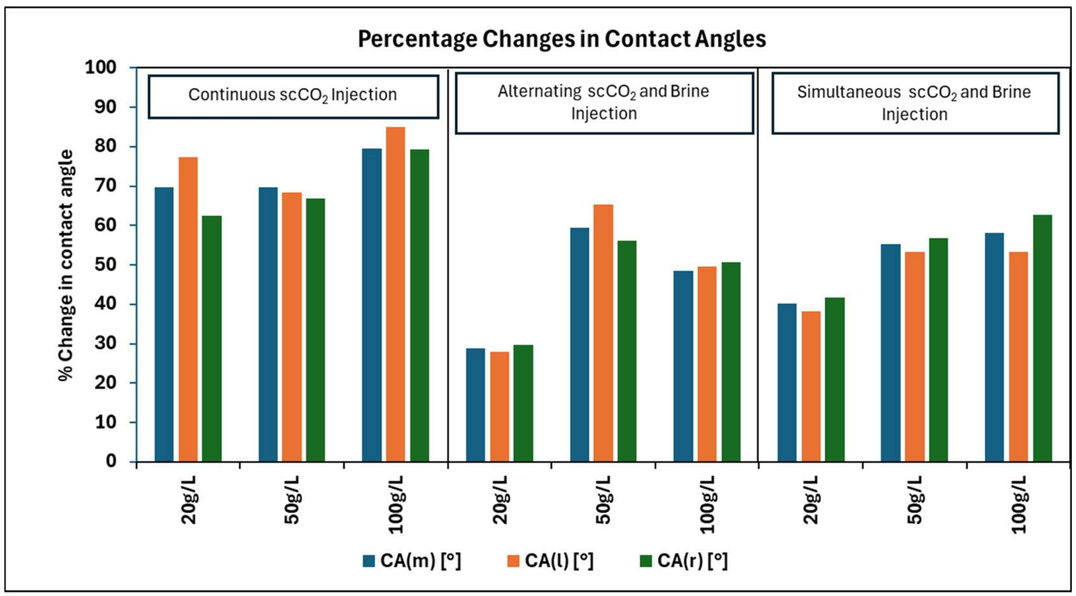
(Combined interpretation for LM)

Rock type	Injection Strategy	Pore volume Injected	XRD (mineral)		EDS (element)		Porosity	Permeability	SEM	Mineralization ($CaCO_3$, $FeCO_3$, $MgCO_3$)
			Precipitation	Dissolution	Precipitation	Dissolution				
Limestone	CCI	75	Gypsum, siderite,hematite, ankerite	Calcite, dolomite, kaolinite,	Ca, C, O,Fe,	Al, Si, Mg	Decrease (most)	Decrease (most)	Visible microstructural changes at a x3000 magnifcation due to precipitation (Ankerite and siderite) outweighing calcite, dolomite	Dissolution of any of the carbonate minerals constitutes unfavorable dissolution reactions; however, $FeCO_3$ precipitation leads to mineralization
	WAG	75	Gypsum, dolomite, kaolinite, hematite, ankerite	Calcite, Quartz, kaolinite, siderite,	Ca, Al, Si,	O, C	Increase (same)	Increase (most)	Minor mineral dissolution and precipitation, accompanied by slight pore size and microstructural changes	$CaCO_3$ precipitation
	SAI	75	Calcite, Quartz, Gypsum, dolomite, kaolinite, siderite,	hematite, ankerite	Al, Si, C, Mg	Ca, O, Fe	Increase (same)	Increase	Severe microstructural changes, including significant rearrangement and grain orientation. At ×3000 magnification, pore enlargement with minimal precipitation is observed.	Moderate to limited mineralization ($MgCO_3$). Moderate mineralization due to precipitation of carbonate minerals.
	CCI	525	Calcite, Quartz, dolomite, kaolinite,	Gypsum, siderite, ankerite	Ca, Mg, C	Si,O	Decrease (most)	Increase (most)	Visible microstructural rearrangements however both dissolution, and precipitation.	Unfavorable dissolution Reactions
	WAG	525	Gypsum, dolomite, kaolinite, siderite,hematite, ankerite	Calcite, Quartz,	Al, Si, Mg, C,Fe	Ca, O	Increase (most)	Increase	Visible microstructural changes with pore reductions (x400 magnification). Minimal dissolution but higher precipitation. Mineral build-up from precipitation and some pore enlargements are visible in the digital images (x3000 magnification)	$FeCO_3$ and $MgCO_3$ precipitation, moderate mineralization due to precipitation of carbonate minerals.
	SAI	525	Quartz, Gypsum, dolomite, kaolinite, siderite,hematite,	Calcite, ankerite	Al, Si, Fe, Cl,C,Mg, O	Ca, Na	Increase	Decrease	Minimal or no microstructural changes, little pore rearrangement, minimal pore size alterations, and no changes in pore distribution	$FeCO_3$ and $MgCO_3$ precipitation

Post-test
(Wettability Alteration in Sandstone)







Post-test
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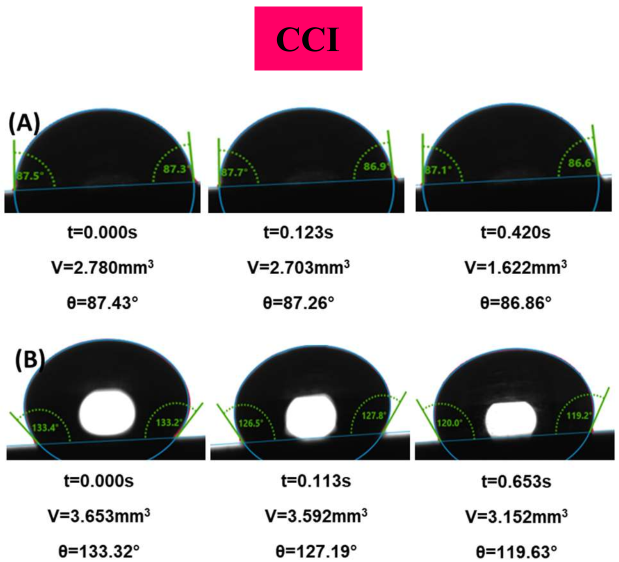
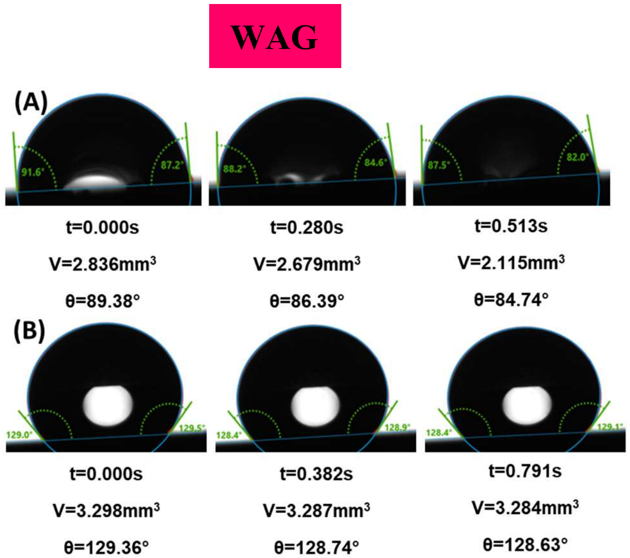
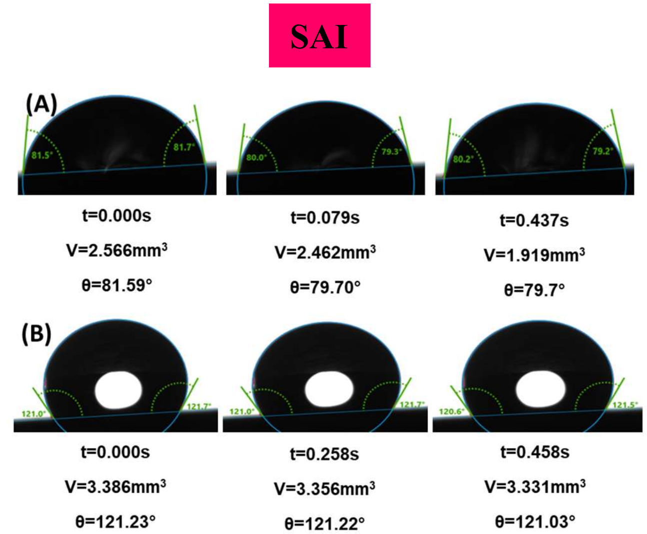
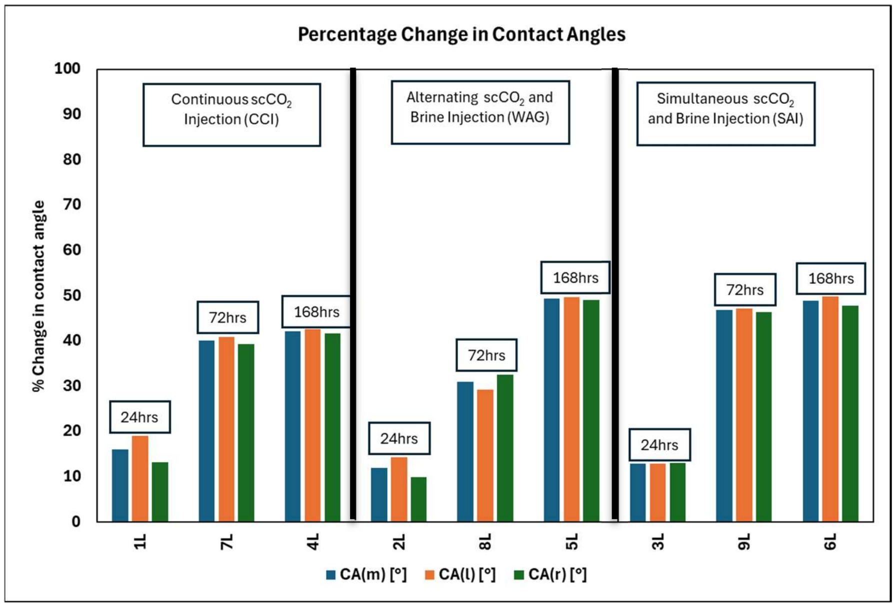
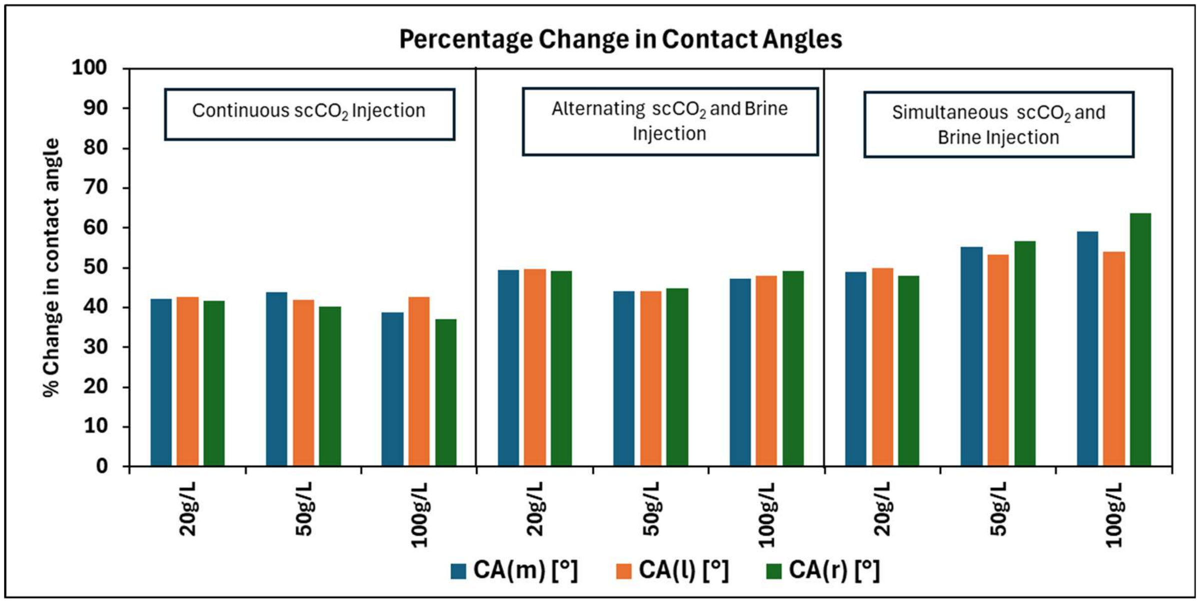


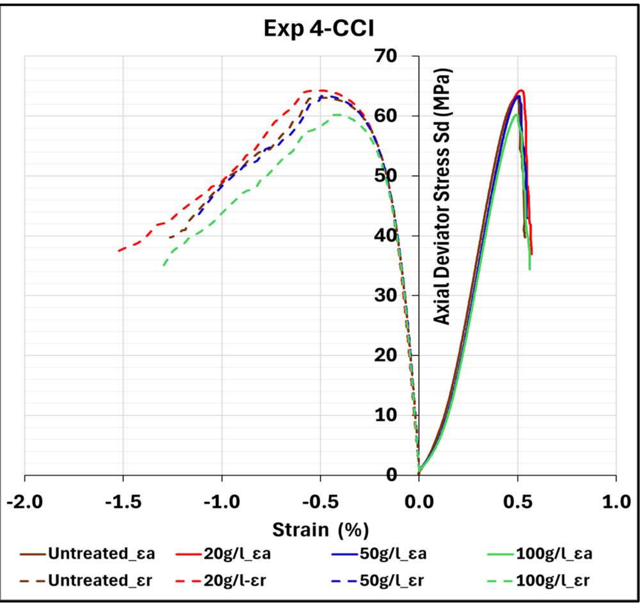


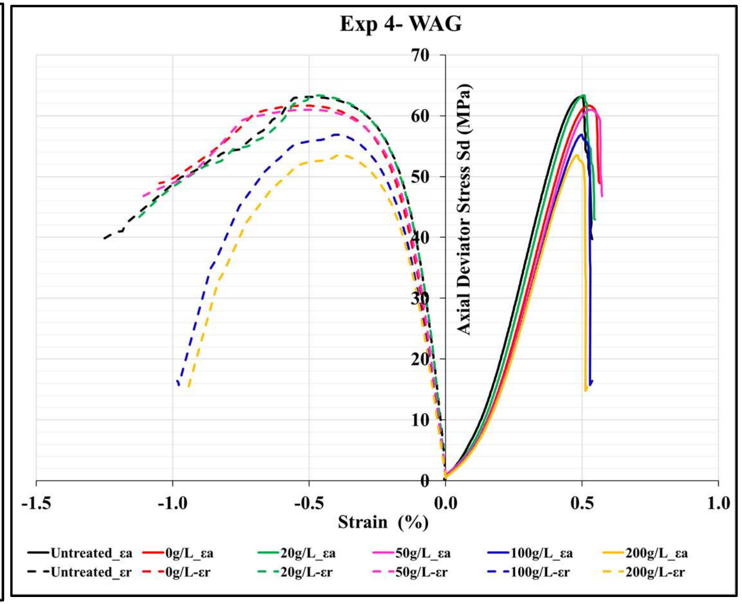


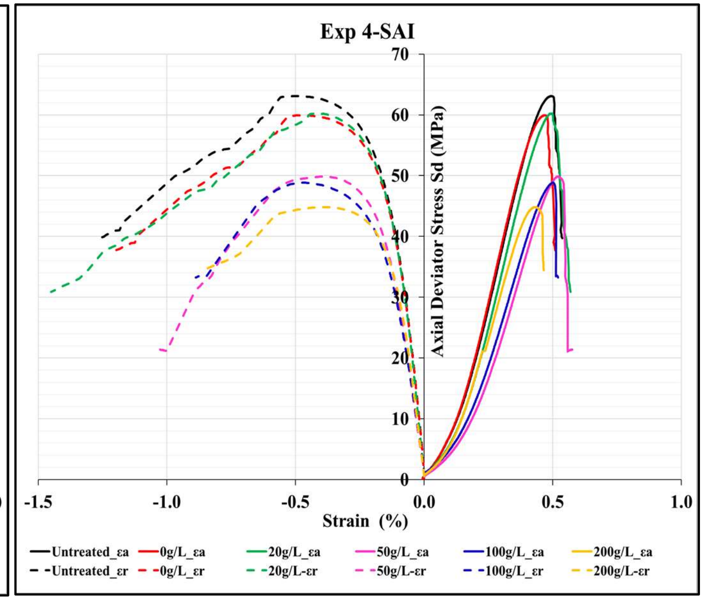


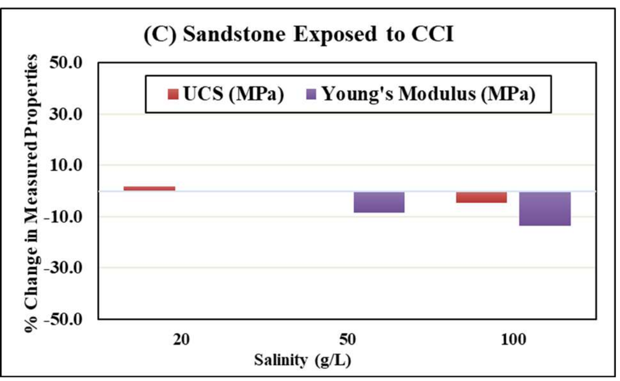


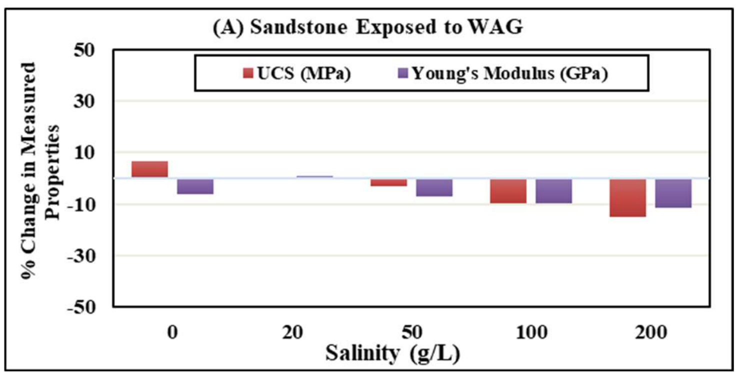
Post-test
(Geomechanical Changes in SS)

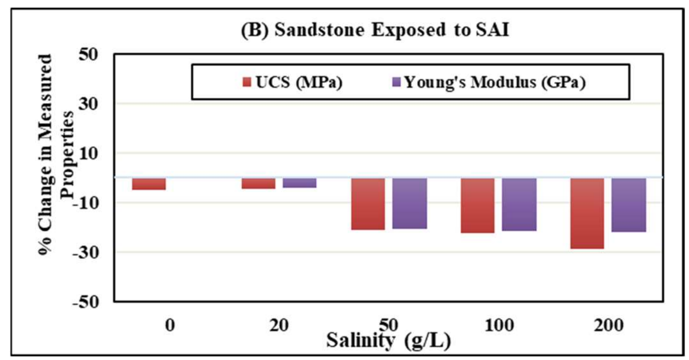




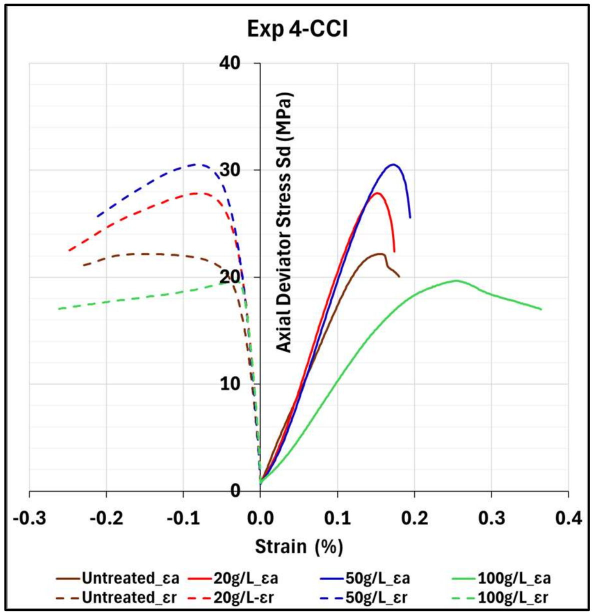


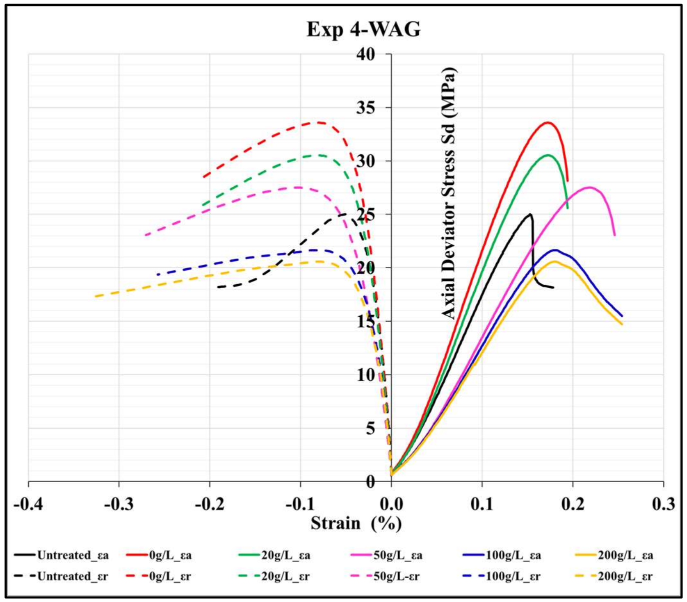


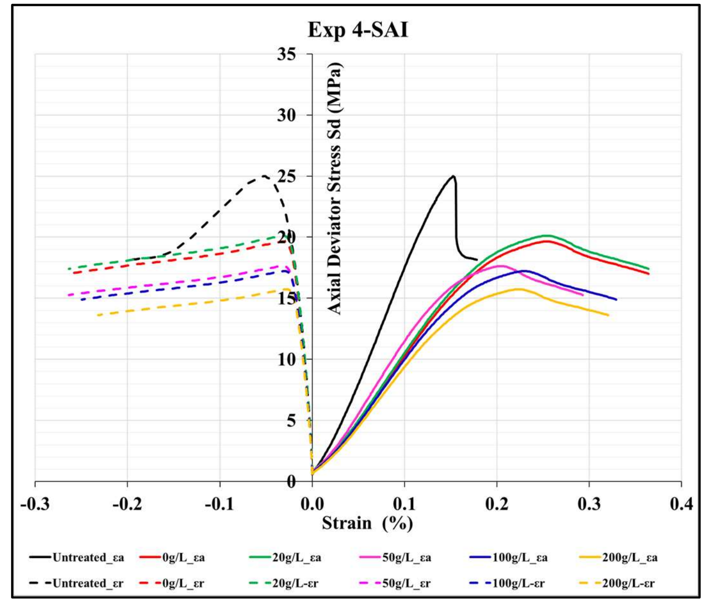


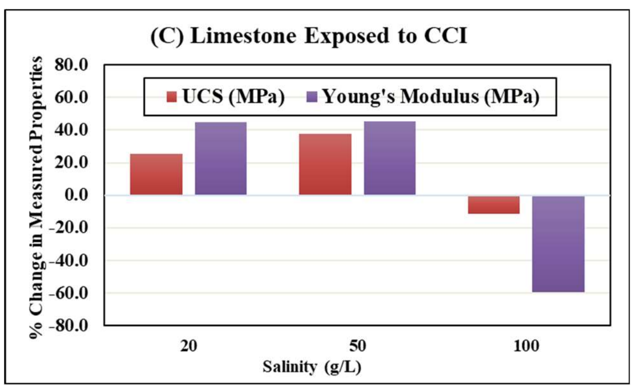


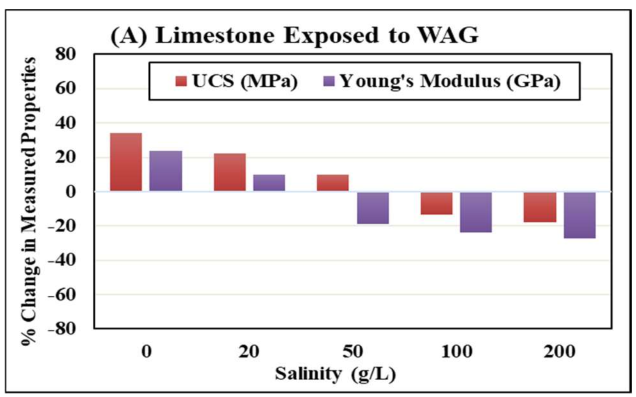
Post-test
(Geomechanical Changes in LM)

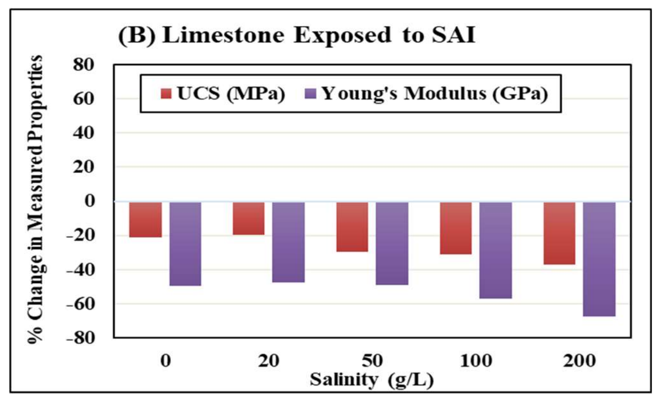








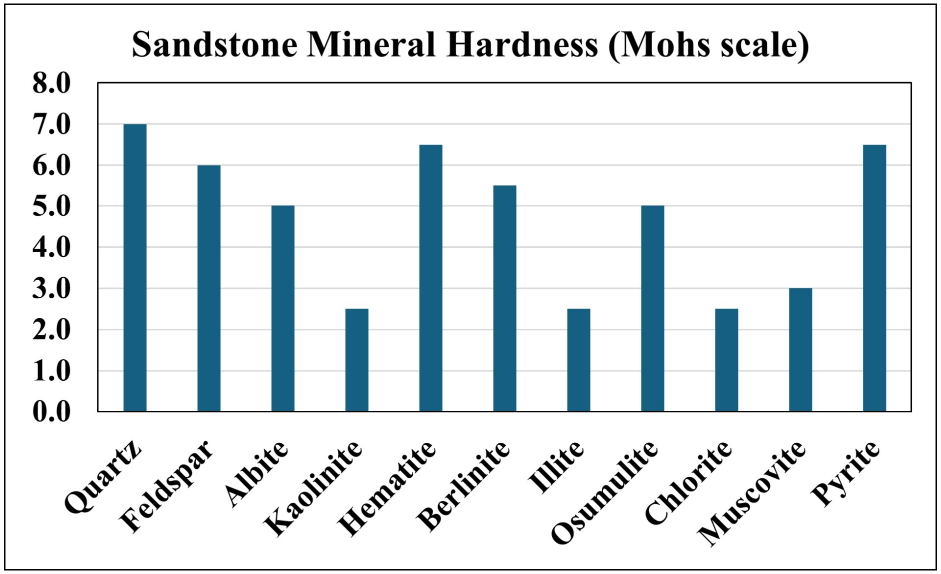


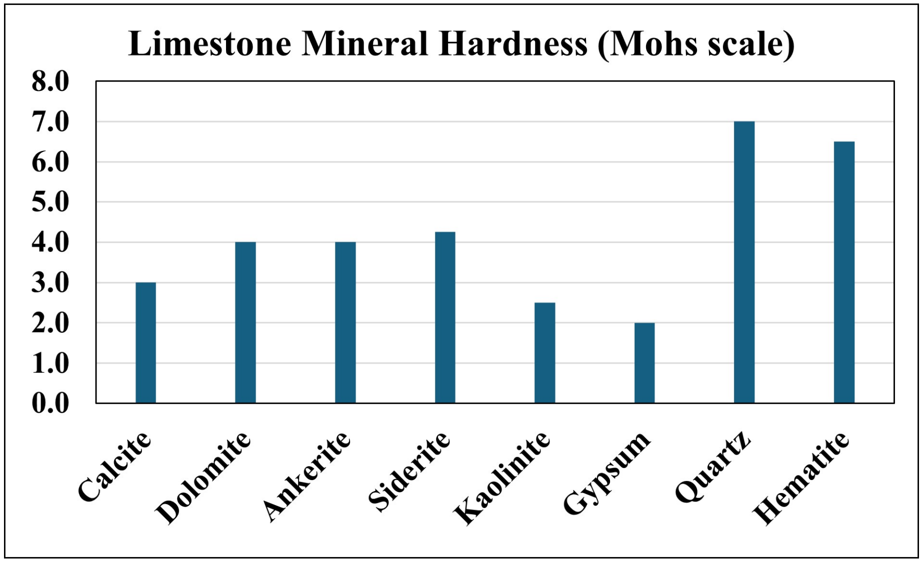


Post-test
(Geomechanical Changes)

Factors responsible for mechanical integrity or mineral stability loss are:

- Geochemical reaction,
- Sequences of the dissolution and precipitation processes,
- Cyclic effect, and
- Mineral hardness.
- Acidification





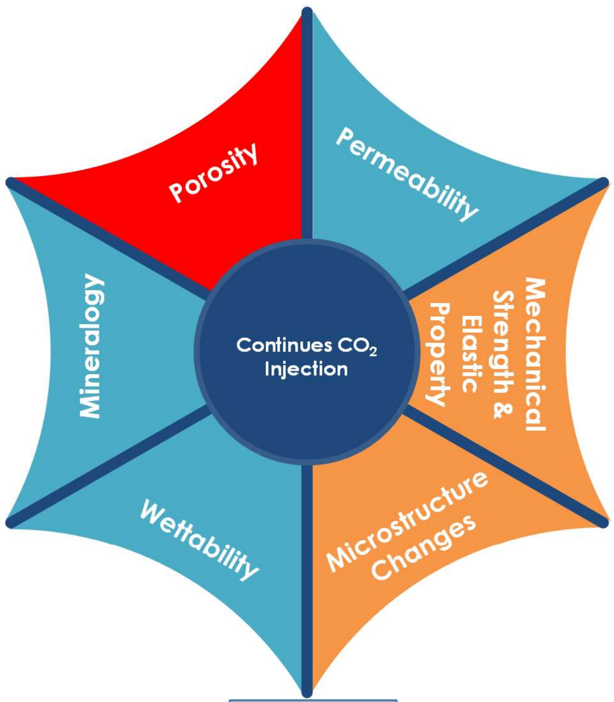
Comparative Analysis of Results
(Sandstone)

Minor changes or beneficial result

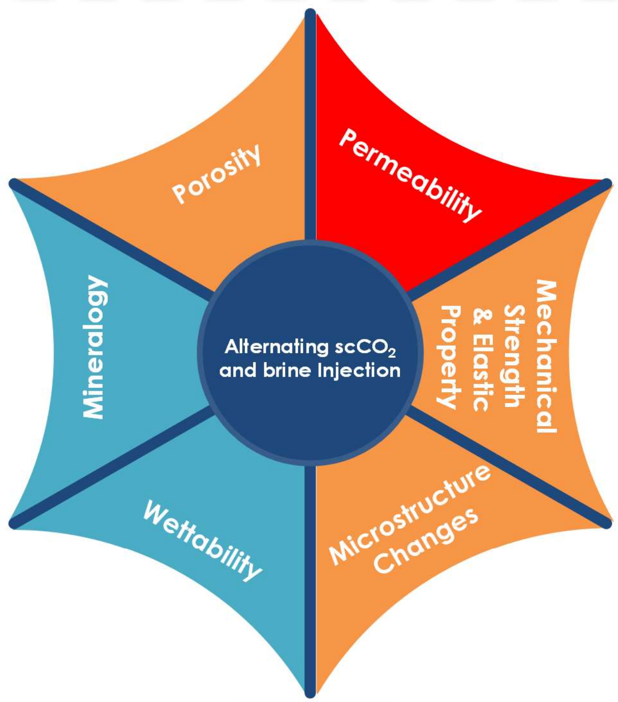
Moderate changes but not detrimental

Significant changes that are detrimental result

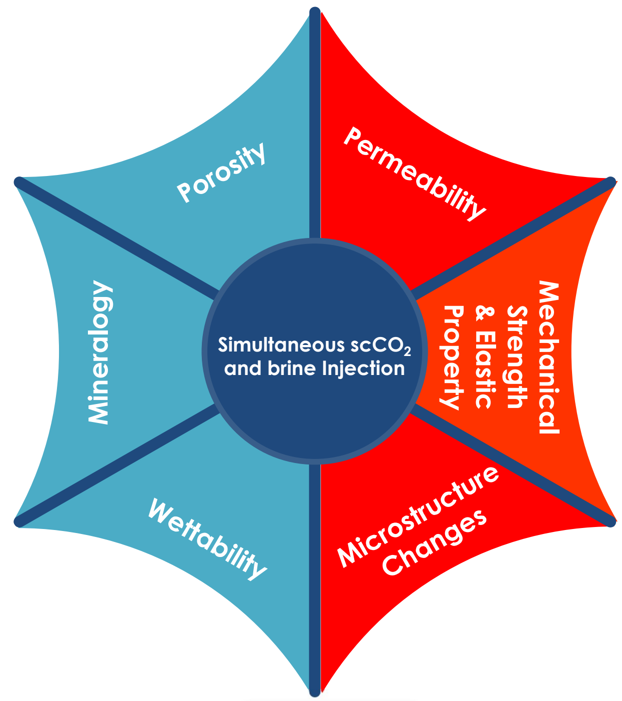
Salinity (<100g/L)



CCI



WAG

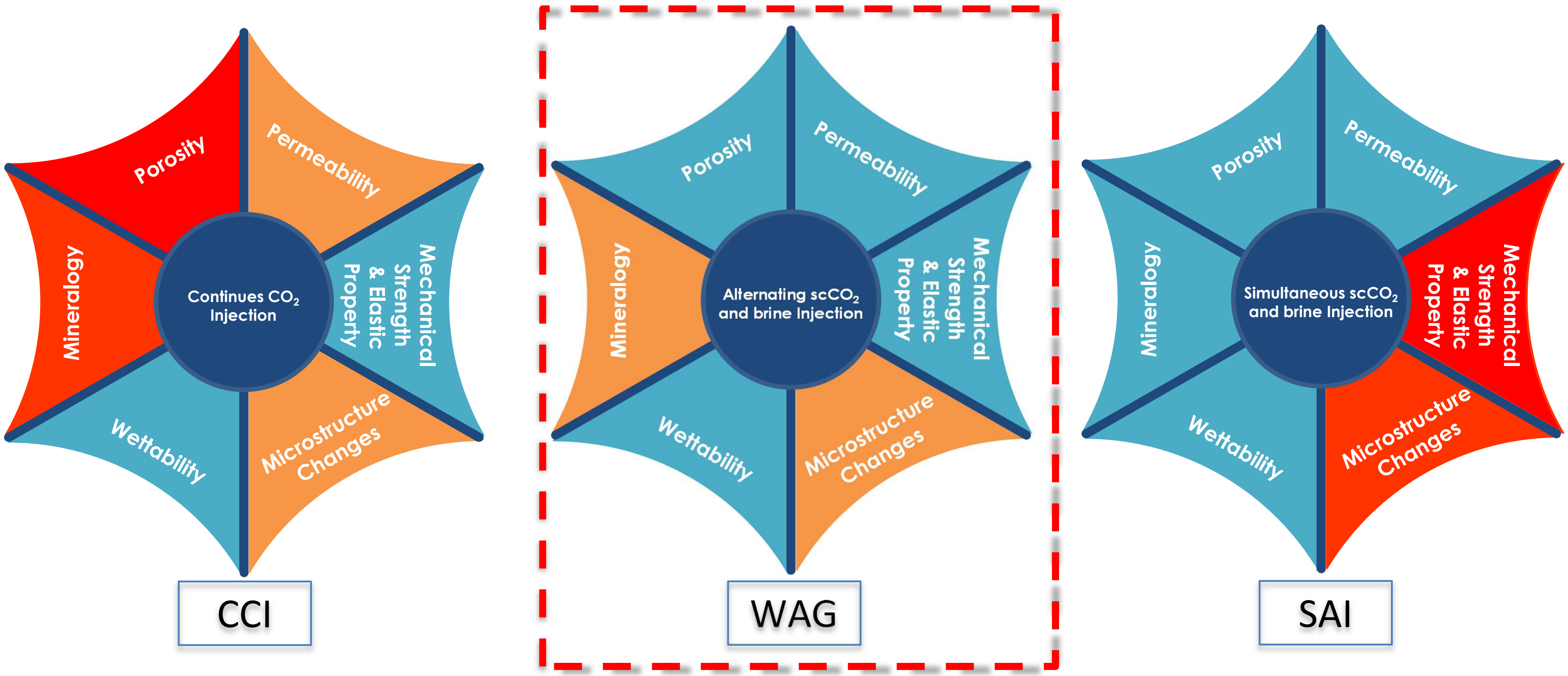


SAI

Comparative Analysis of Results
(Limestone)

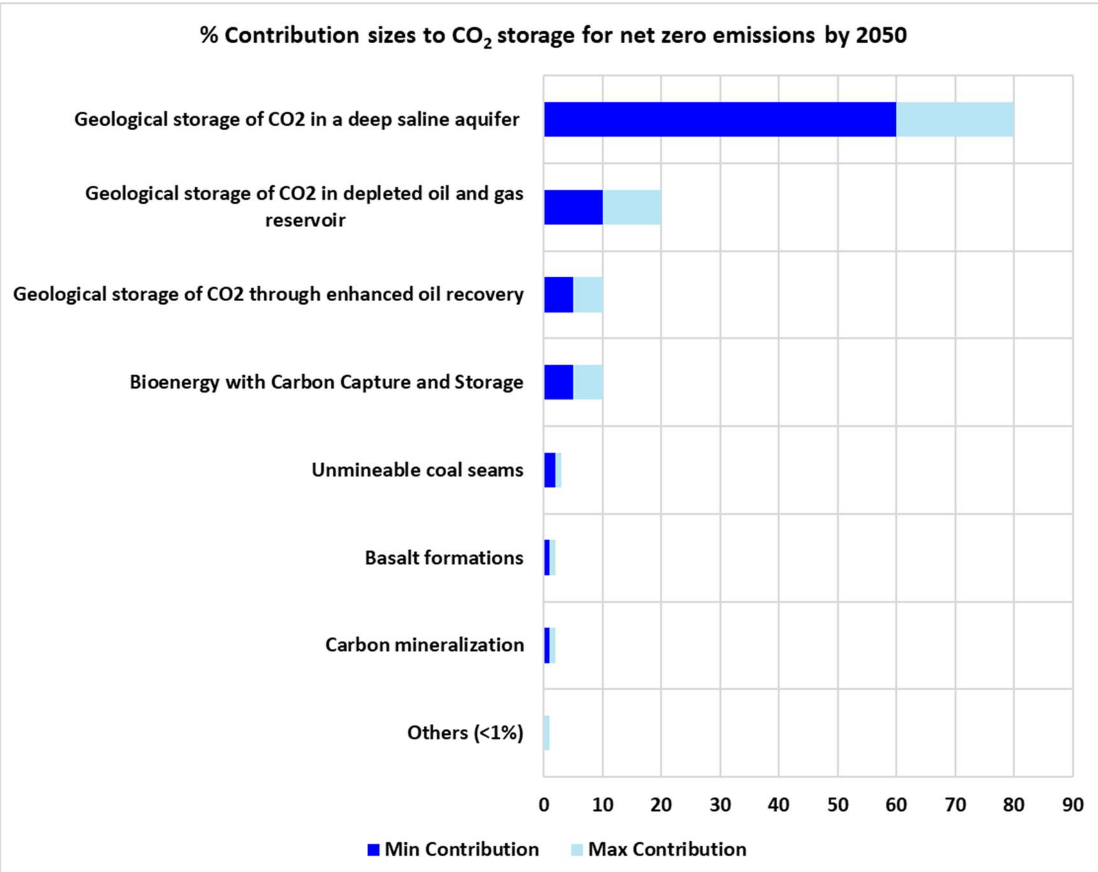
Minor changes or beneficial result | Moderate changes but not detrimental | Significant changes that are detrimental result

Salinity (<100g/L)

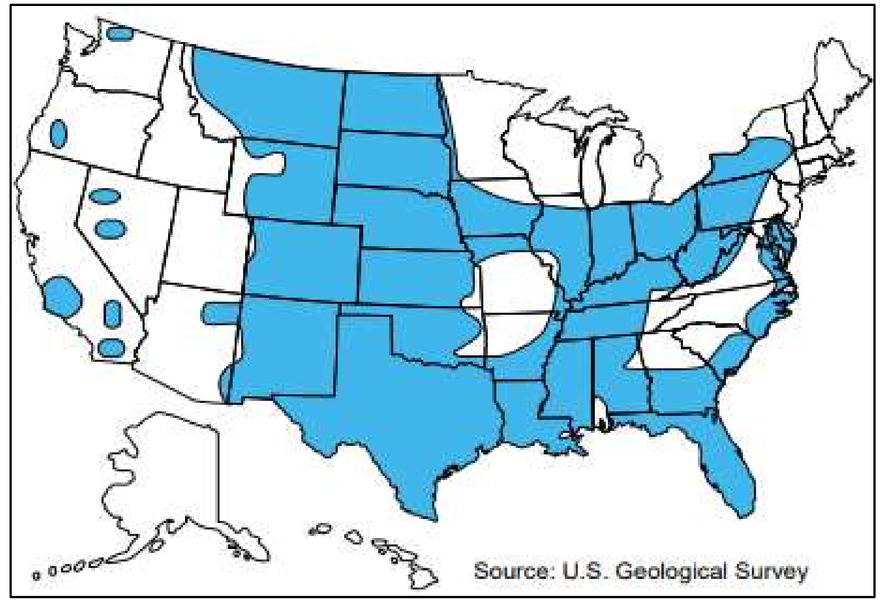


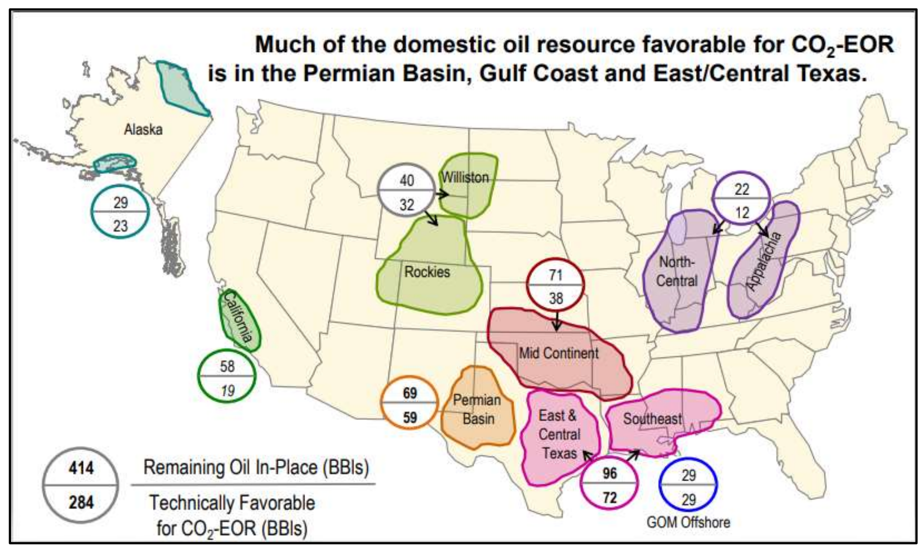
Opportunity

How is CO_2 currently stored?



Location of deep saline aquifer in the United States





DSA offers a significant opportunity for CO_2 storage due to their large capacity (US DOE NETL, 2015).

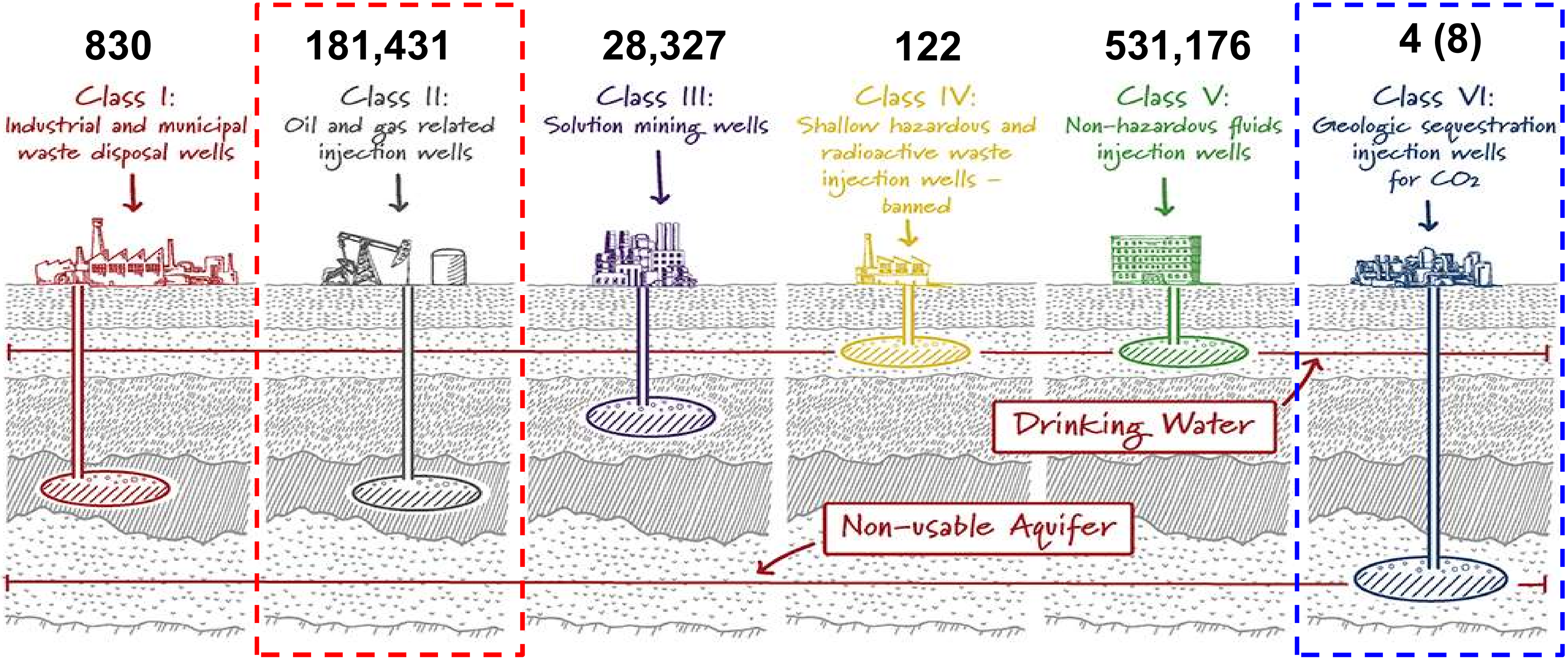
Economics Support Storage in Aquifers

	2018 Amount (First Proposed)	Updated 45Q Credits in IRA (Industry & Power)	Updated 45Q Credits in IRA (Direct Air Capture)
Dedicated Secure Geologic Storage In saline or other geologic formations	$50 per ton	$85 per ton	$180 per ton
Carbon Utilization Projects Conversion of CO or CO_2 into useful products (e.g., fuels, chemicals)	$35 per ton	$60 per ton	$130 per ton
Secure Geologic Storage (Enhanced Oil Recovery) In oil and gas fields through enhanced oil recovery	$35 per ton	$60 per ton	$130 per ton

If the deep saline aquifer is the largest, why is deployment not as fast as in CO_2-EOR in the oil and gas industry?

UIC Injection Well Numbers As of 2024….

1. Saltwater disposal wells
2. EOR wells, and
3. Hydrocarbon storage wells.

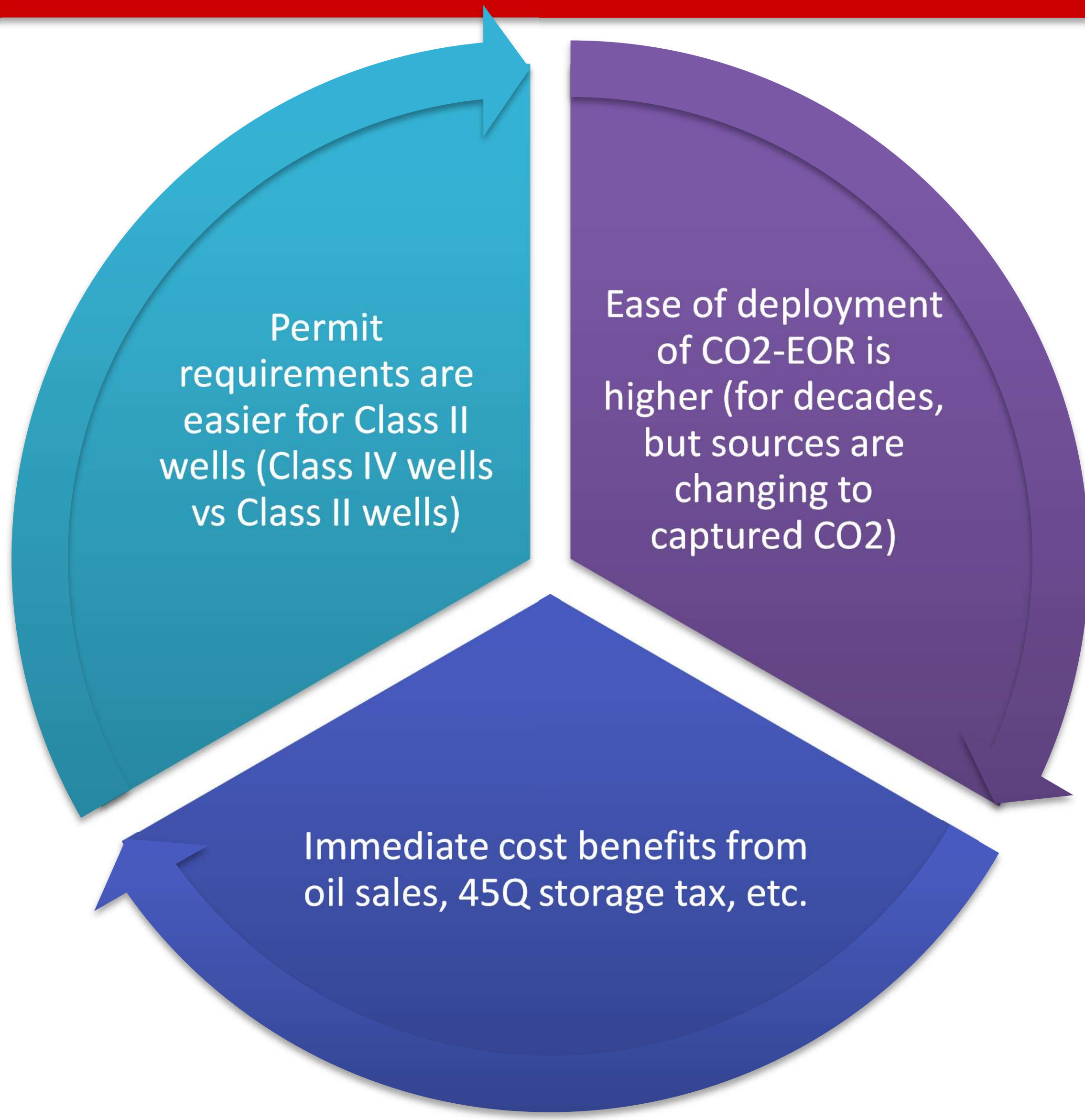


https://www.epa.gov/uic/class-ii-oil-and-gas-related-injection-wells

https://www.congress.gov/crs-product/R48033

https://www.clearpath.org

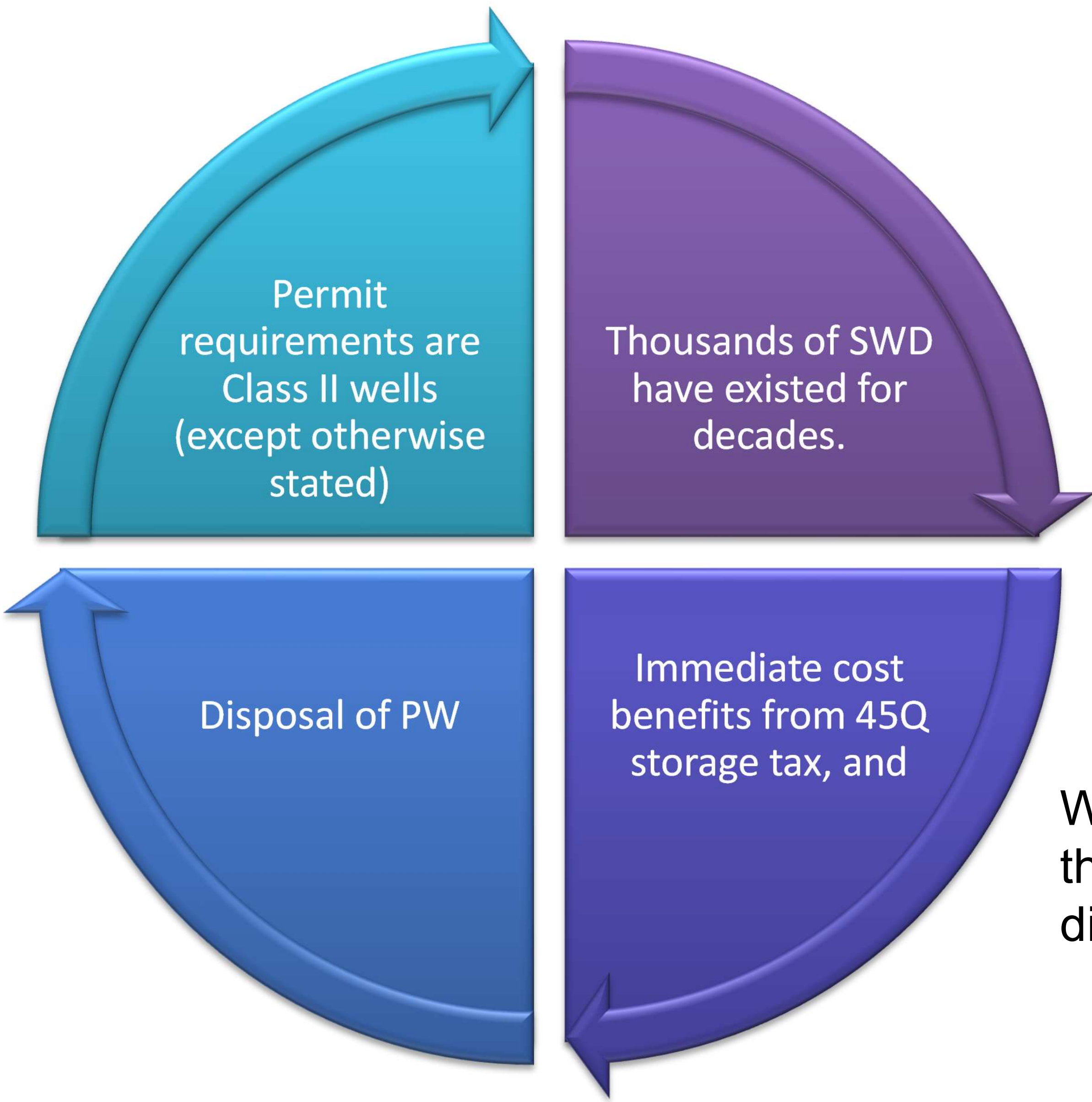
CO_2- EOR Drivers



Is there any other methods that has all this benefit aside CO_2-EOR but injection in deep saline aquifer?

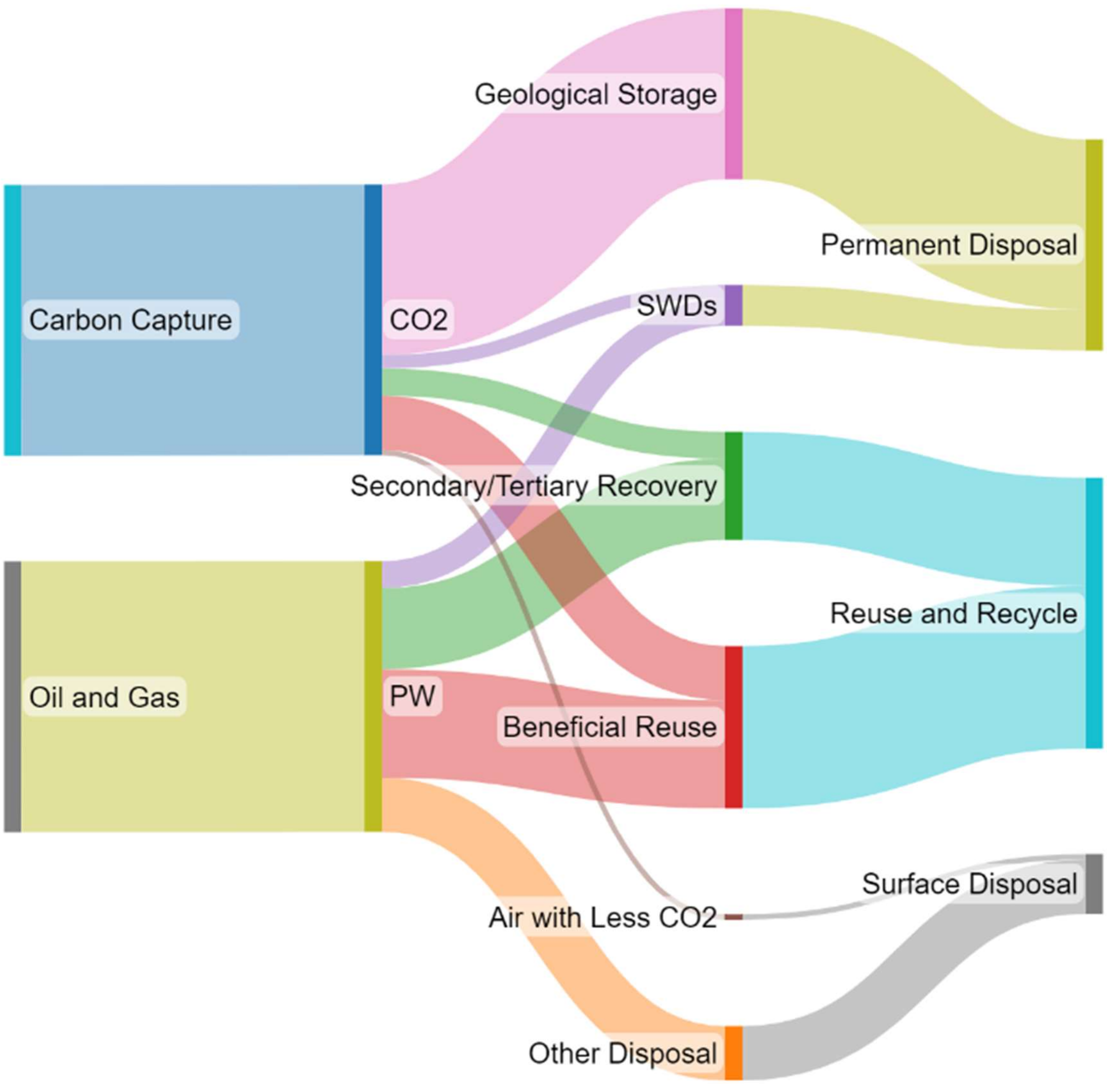
Deep Saline Aquifer using SWD

Can SWD a potential conduit for DSA storage?



What would this mean is that CO2 and PW are disposed using one well?

CO_2 Storage and PW- Lots in common

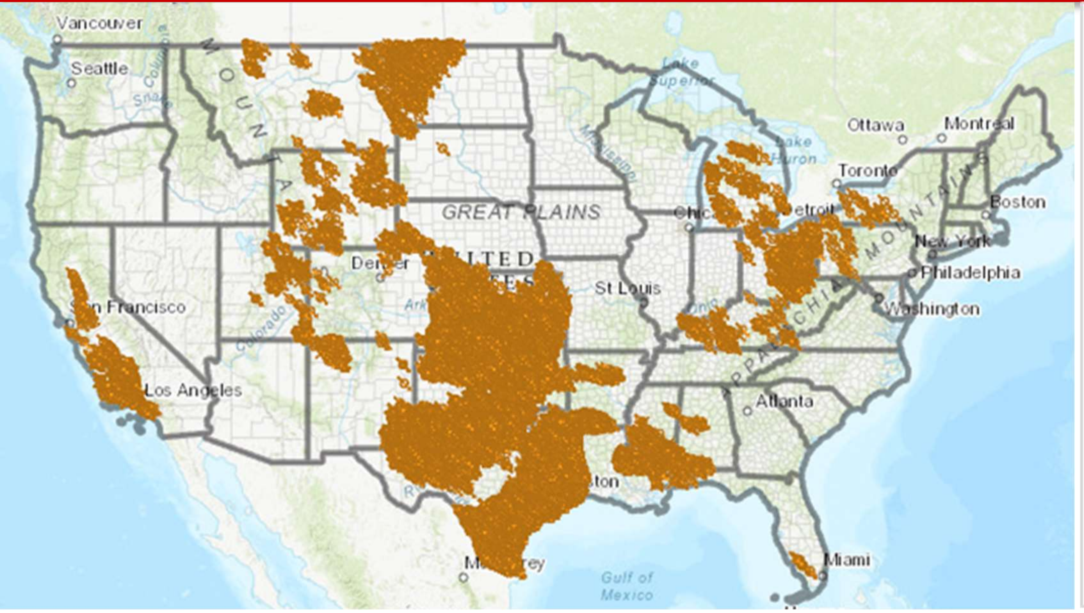


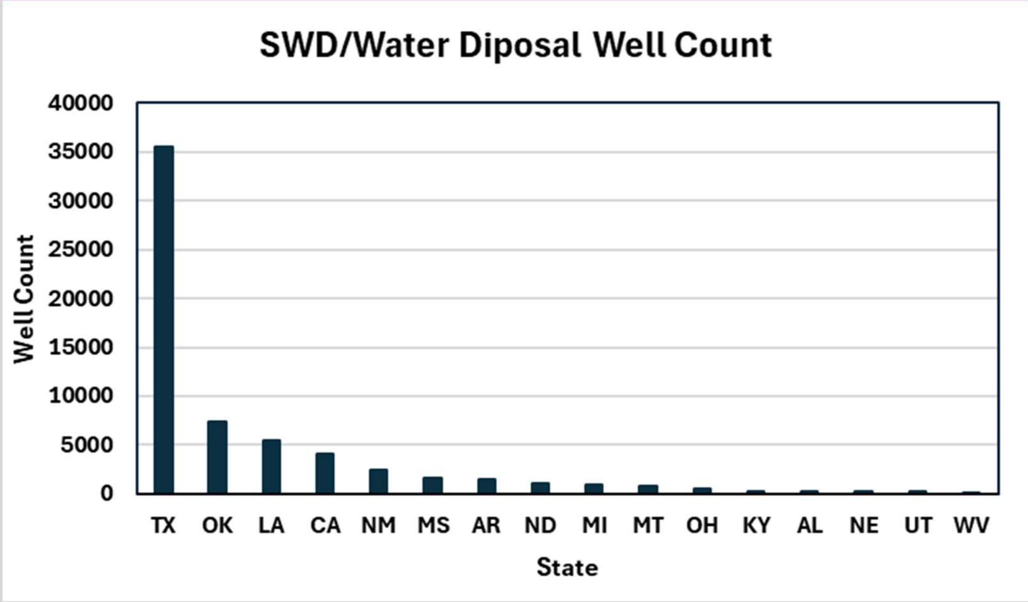
- CO_2 storage and produced water share significant operational and geochemical commonalities.

- Both use deep subsurface formations for their fluid injection.

- However, both involve complex fluid-rock interactions, reservoir pressure management, and long-term containment considerations,

Integrating SWD in CCS Projects





- SWDs are pre-existing wells used for oil and gas PW disposal (62,567) with a 4,000 to 10,000 ft (≈1,200 to 3,000 m).
- As more production wells are drilled, more SWD wells are also drilled
- SWD wells are the cheapest means for PW Disposal ($0.50–$2.50 per bbl according to the US EPA- this includes transportation to the SWD site (via truck or pipeline), injection costs, and regulatory compliance and monitoring)

Research Impact

Opportunity

Technical

- Validating the concept
- Calibrating models
- Improved storage capacity and efficiencies

Environmental

Potential to enhance CO_2 trapping and reduce the environmental impact of produced water disposal.

Economic

Potential for higher tax credits ($85-180 per ton vs $60-130 per ton) via integration with SWD

Deployment

Supports CCUS deployment in DSAs

Conclusion

Sandstone	Carbonate
•WAG balances reactivity and stability in clastic systems •WAG/SAI increases Mineralization enhancing mineral trapping •WAG enhanced storage, minimal degradation, ideal for integration with produced water.	•SAI increases capacity up to 30% in carbonates, •Severe rock degradation •Excessive reductive in fluid mobility due to permeability reduction, •SAI is recommended for end-of-life for permeability reduction & sealing effects

Injection strategies impact the reaction kinetics, sequence, types and severity of the geochemical reactions in all cases.

These control the petrophysical changes, wettability alteration, and geomechanical degradation.

WAG and SAI have a lower wettability alteration effect than aiding the capillary trapping of CO_2 in sandstone reservoir, but CCI is better in carbonates

PW at a salinity of 20–50 g/L, offered a balanced performance while using WAG, but rock weakens at salinity >100 g/L (especially in SAI)

Reservoir Simulation Model

These results are used to calibrate reservoir models for:

- CO2 plume migration
- Geomechanical stability
- Trapping efficiency under WAG/SAI

Acknowledgements

Publications

1. **Eyitayo, S. I.,** Gamadi, T., Kolawole, O. and Watson, M. C. (2025). Experimental study of $scCO_2$ injection strategies: Effects on geochemical reactions and reservoir properties in sandstone and carbonate formations, *Gas Science and Engineering*, Vol 140, https://doi.org/10.1016/j.jgsce.2025.205660

2. **Eyitayo, S. I.,** Watson, M. C., Ispas, I., and Kolawole, O. (2025). Geochemical Interactions of Supercritical CO_2-Brine-Rock under Varying Injection Strategies: Implications for Mechanical Integrity in Aquifers. *Rock Mechanics and Rock Engineering.* https://doi.org/10.1007/s00603-025-04496-7

3. **Eyitayo, S. I.,** Gamadi, T., Ispas, I., Kolawole, O., Watson, M. C. (2024). Produced Water Integration in CO_2 Storage Using Different Injection Strategies: The Effect of Salinity on Rock Petrophysical, Mineralogy, Wettability and Geomechanical Properties. *Journal of Environmental Management*, 372, 123307, 2600. https://doi.org/10.1016/j.jenvman.2024.123307

4. **Eyitayo, S. I.,** Gamadi, T., Kolawole, O., Okere, C. J., Ispas, I., Arbad, N., Emadibaladehi, H., Watson, M. C. (2024). Experimental Investigation of the Impact of CO_2 Injection Strategies on Rock Wettability Alteration for CCS Applications. *Energies*, 17(11), 2600. DOI: 10.3390/en17112600

5. **Eyitayo, S. I.,** Arbad, N., Kolawole, O., Watson, M. C. (2024). Optimizing CO_2 storage in deep saline formations: A comprehensive review of enhancing pore space utilization through simultaneous or alternate aquifer injection. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, Volume 46, Issue 1. DOI: 10.1080/15567036.2024.2347417

6. **Eyitayo, S.,** Arbad, N., Okere, C. et al. Advancing geological storage of carbon dioxide (CO2) with emerging technologies for climate change mitigation. Int. J. Environ. Sci. Technol. 22(6):1-34. 10.1007/s13762-024-06074-w.

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