CO_2 Foam Mobility Control and Adsorption with Nonionic Surfactant

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Core Flood at Reservoir Conditions

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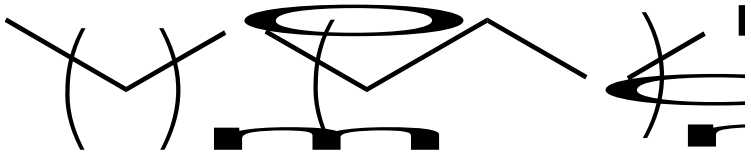
- **Composition of brine of East Seminole reservoir (TDS=34,180 ppm)**

Na_2SO_4 (mg/l)	KCl (mg/l)	$CaCl_2 \cdot 2\ H_2O$ (mg/l)	$MgCl_2 \cdot 6H_2O$ (mg/l)	NaCl (mg/l)
5,236	458	5,825	2,760	22,796

- **Surfactant**

Linear alcohol ethoxylates SURFONIC®L24-22



m=11~13;
n=22

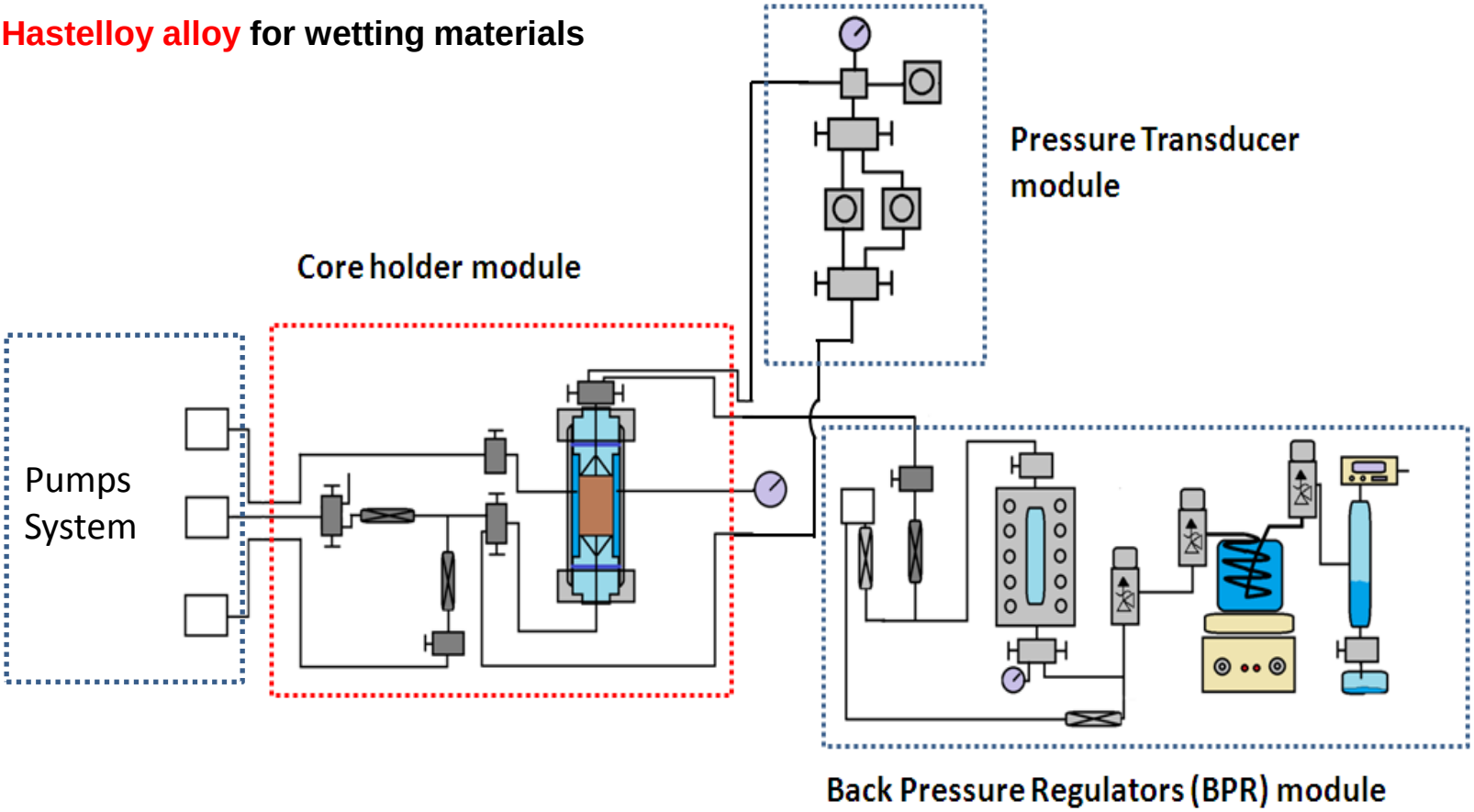
SURFONIC®L24-22, Huntsman Corporation

Core Flood at Reservoir Conditions

- Core
  - Diameter: 1.50 inch
  - Length: 2.97 inch
  - Pore volume: 14.4 cm^3
  - Lithology: Silurian dolomite core from Kocurek Industries
  - Porosity=16.7%
  - Permeability=91 mD

Diagram of the High Temperature and High Pressure Core Flooding Setup

- **Specially designed heating coil, core holder and back pressure regulator system.**
- **Harsh Conditions: 2,600 psi, T=110 °F, moderate salinity and low pH (≈ 4)**
- **Hastelloy alloy for wetting materials**



Core flooding: Apparent Viscosity

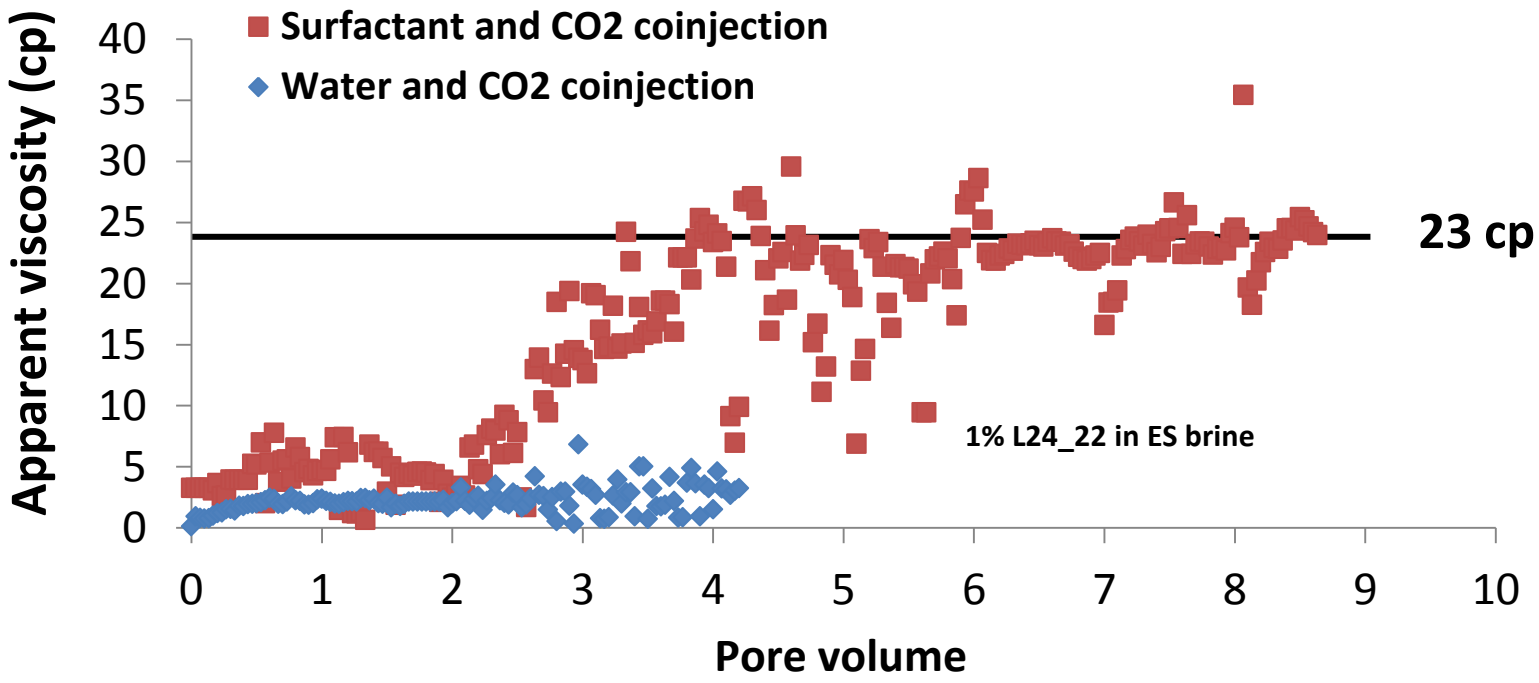
- Apparent viscosity is used to describe the foam strength, which is calculated by **Darcy's law**:

$$\mu_{app} = -\frac{k}{u_t} \cdot \nabla p$$

where μ_{app} is foam apparent viscosity, k is core permeability, u_t is the total superficial velocity and ∇p is the pressure gradient.

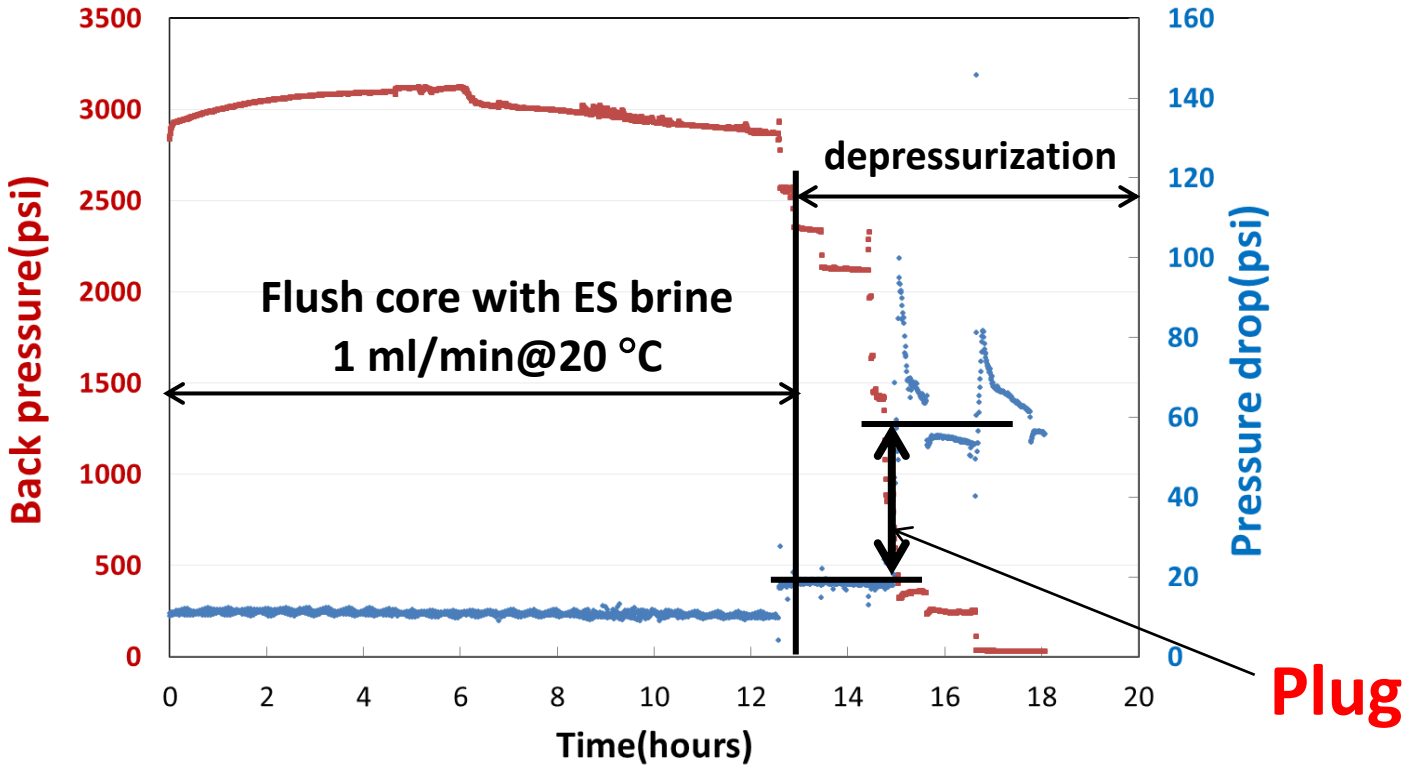
Core flooding

80% foam quality, Injection rate=4 ft/day,
T=110 °F(43.3 °C), Injection pressure=2600 psi.



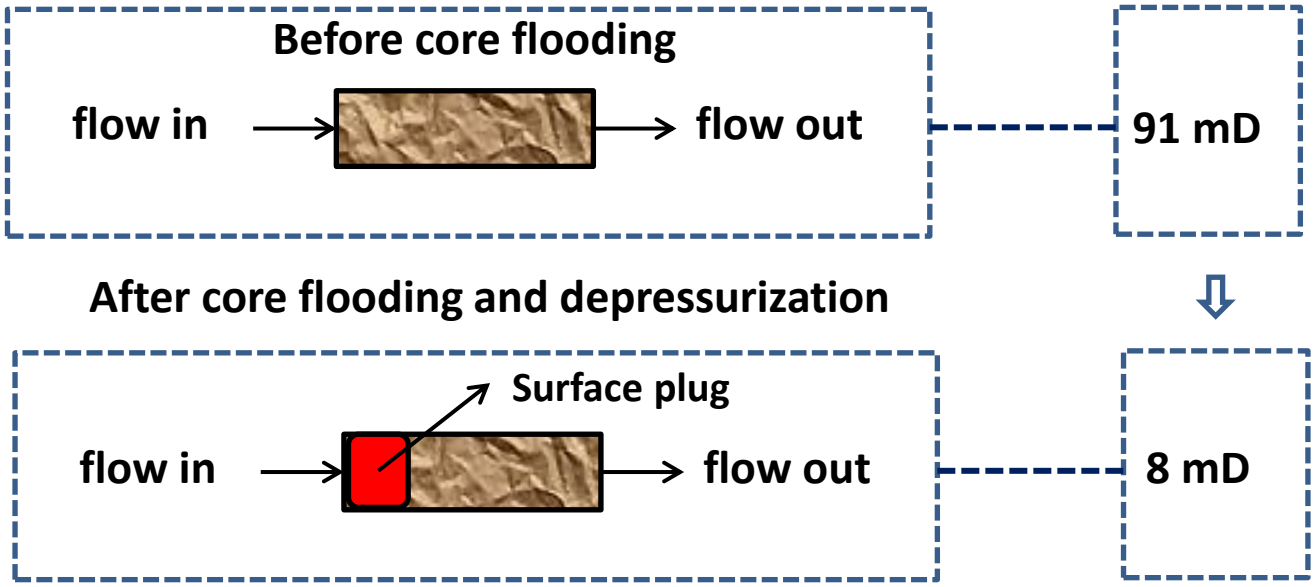
- **Equilibrium average apparent viscosity by co-injection of surfactant and CO_2 is 23 cp**

Depressurization



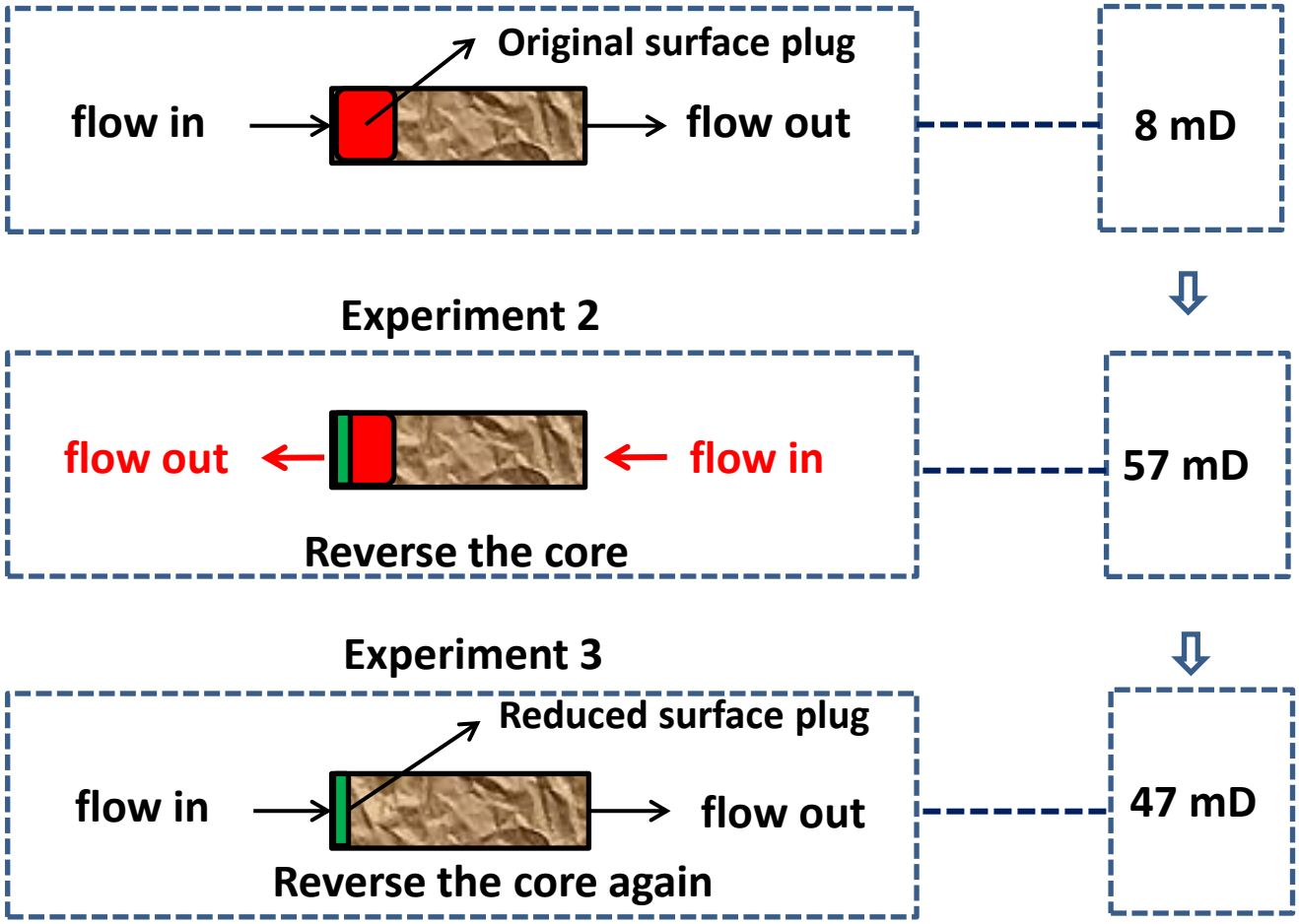
- Depressurization from 1500 psi to 800 psi and then to 200 psi(at 20 °C), we saw a sudden increase of pressure drop(from 20 psi to 60 psi)
- Does the pressure drop indicate core plug?

Assumption: Plug of Core



- Permeability decreased from 91 mD to 8 mD
- Core was plugged

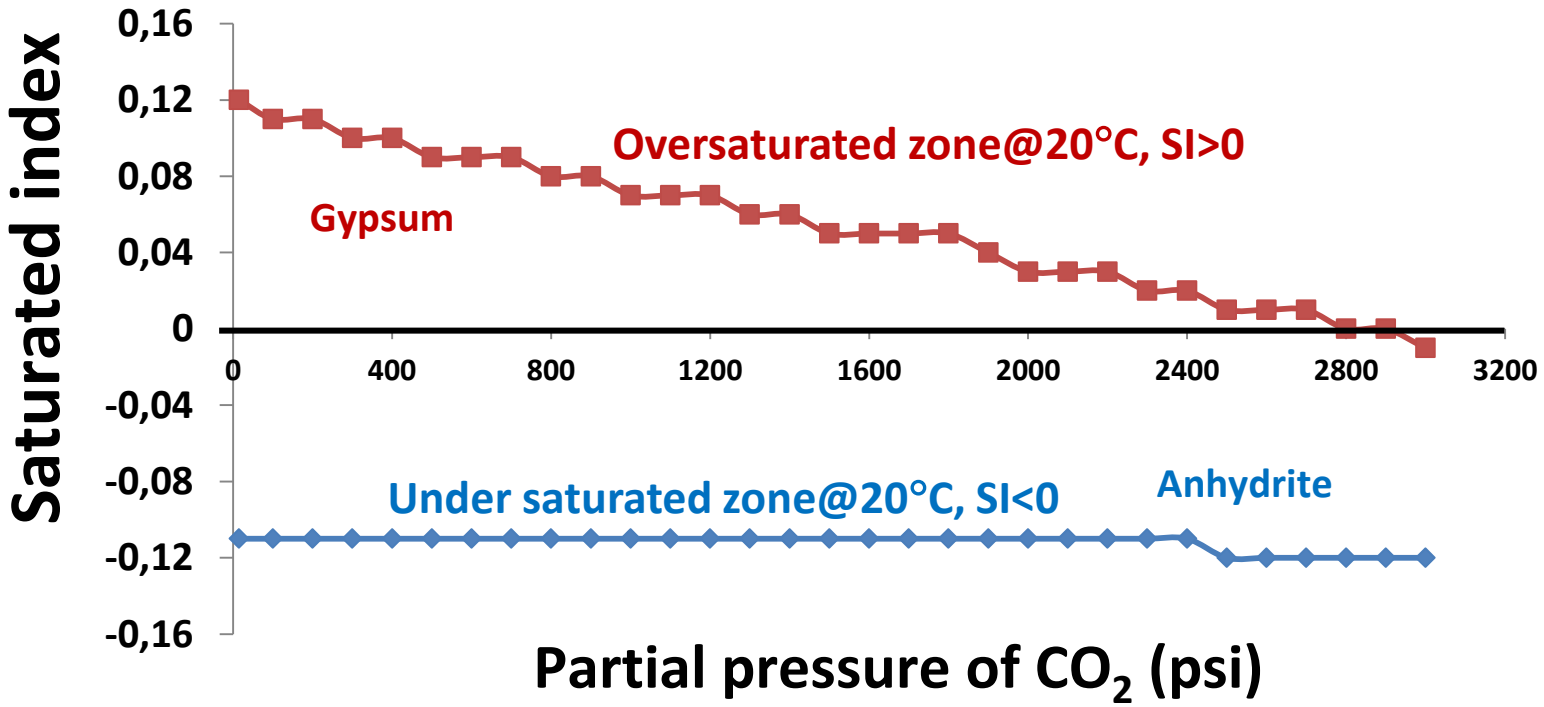
Confirm Plug of Core



- Plug has been partially flushed away which can be reflected from the permeability change

Interpretation of Core Plug

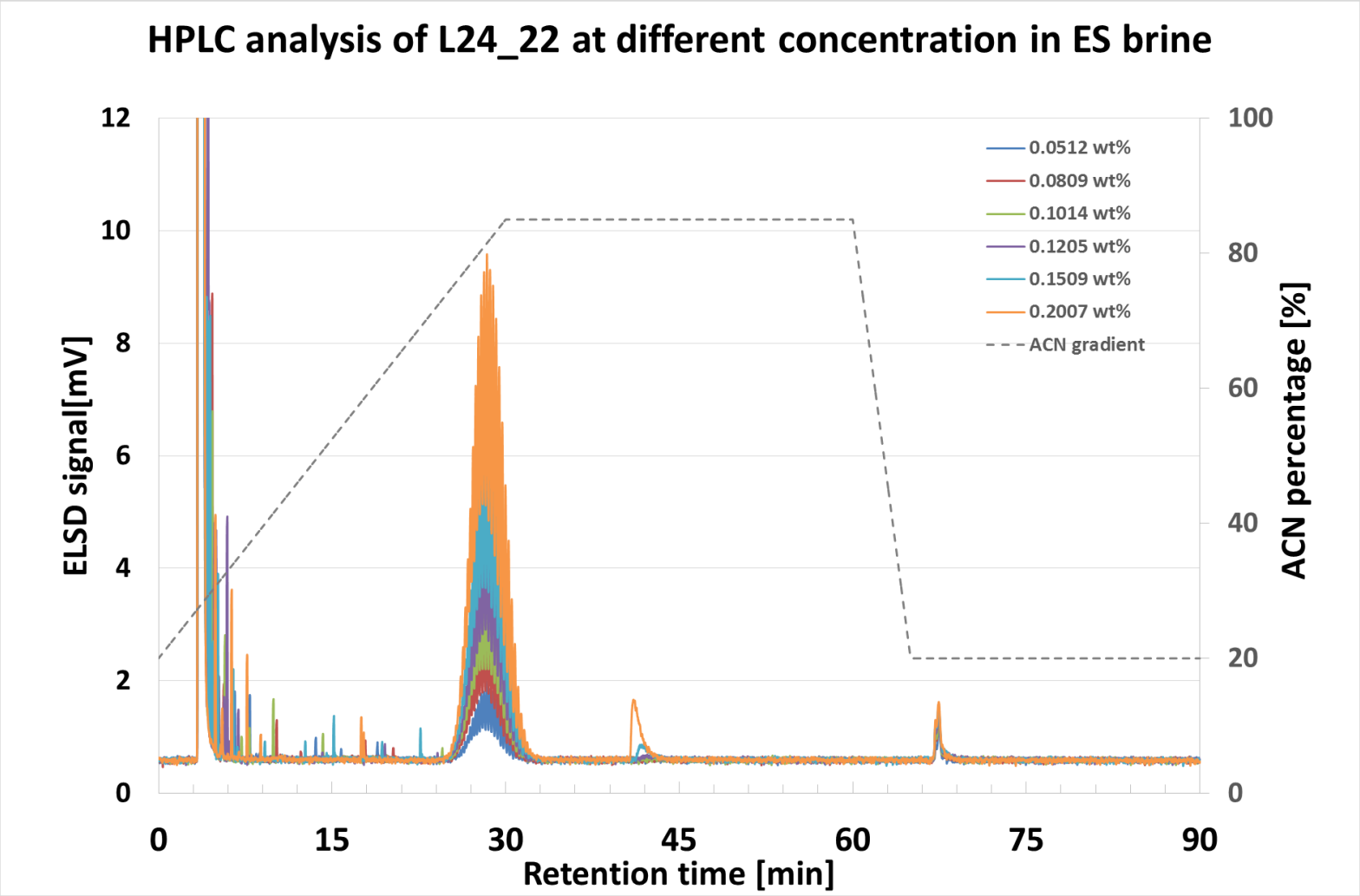
- Saturated Index* of anhydrite and gypsum was simulated by PHREEQC Software
- Negative Saturated index(SI) means under saturated and positive SI means oversaturated



- Anhydrite is under saturated from 14.7 psi to 3000 psi
- Gypsum is over saturated from 14.7 psi to 2800 psi, which indicates that depressurization is favorable for gypsum formation

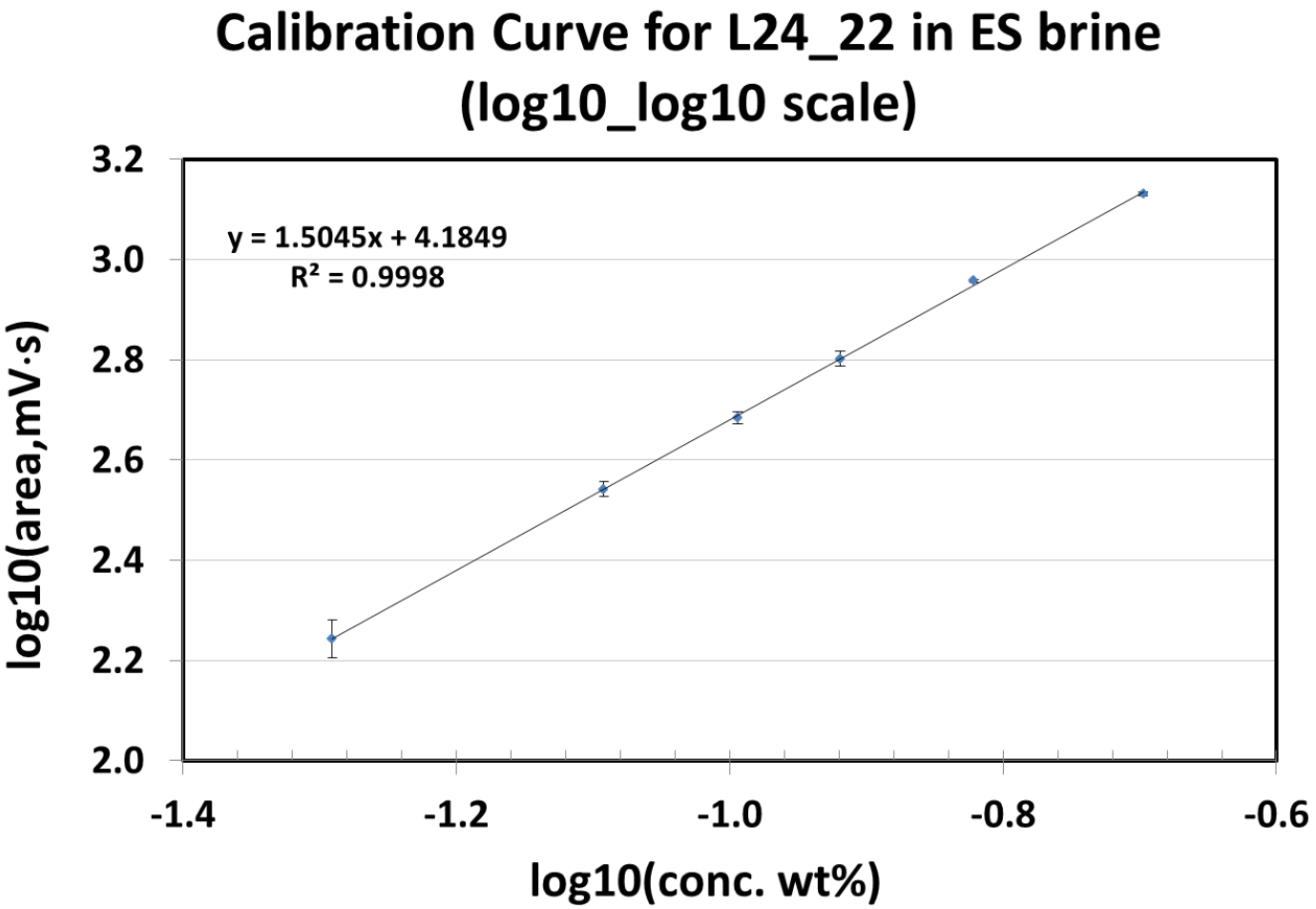
*Lopez-Salinas, Jose Luis, George J. Hirasaki, and Clarence A. Miller. *SPE141420*

HPLC_ELSD Signal of Surfactant



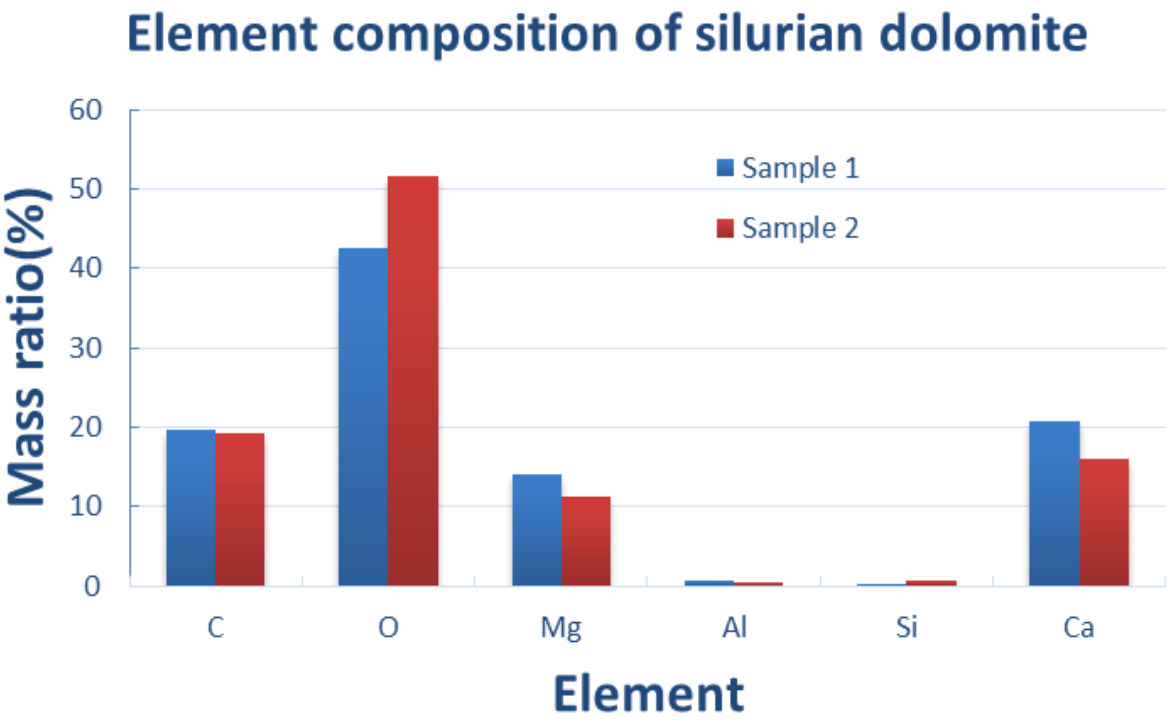
- The peaks with different heights correspond to different surfactant concentrations

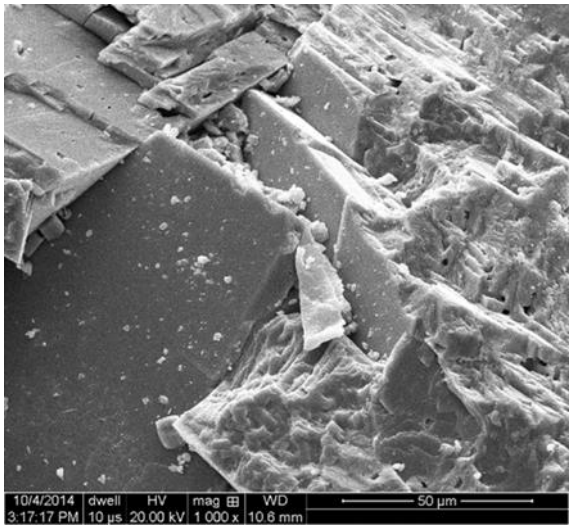
Power Law Calibration Curve



- Calibration curve could be used for determine surfactant concentration in adsorption test

Properties of Adsorbent

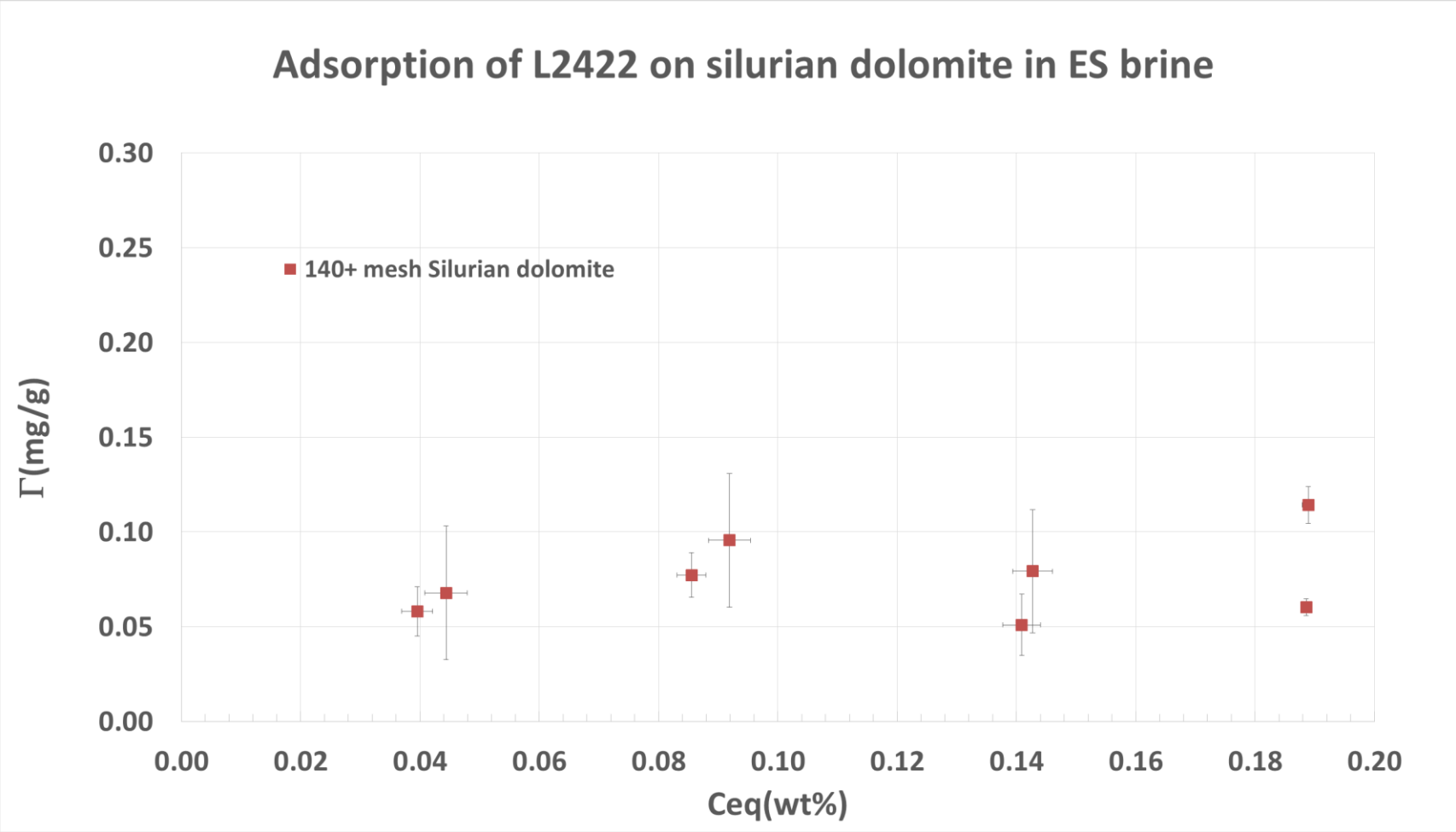




SEM of Silurian dolomite

- **The Silurian dolomite are mainly consist of Ca, Mg; little amount of Al, Si**
- **BET surface area is 0.95 m2/g**

Adsorption on Silurian Dolomite Powder



- **The equilibrium adsorption amount of L2422 on Silurian dolomite is ~0.08 mg/g**

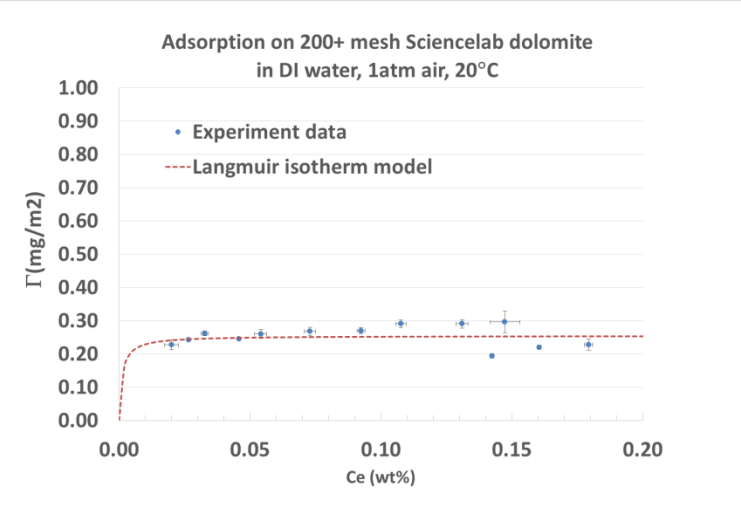
Thermal decomposition

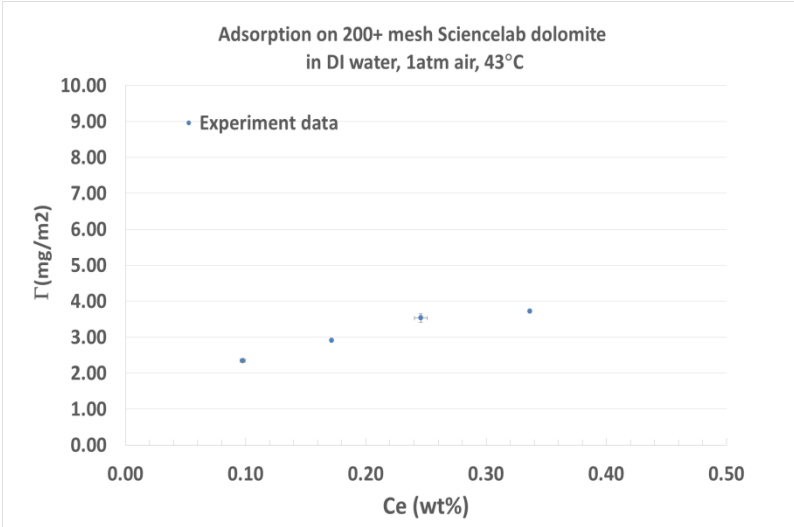
- **Everything seems good till now,**

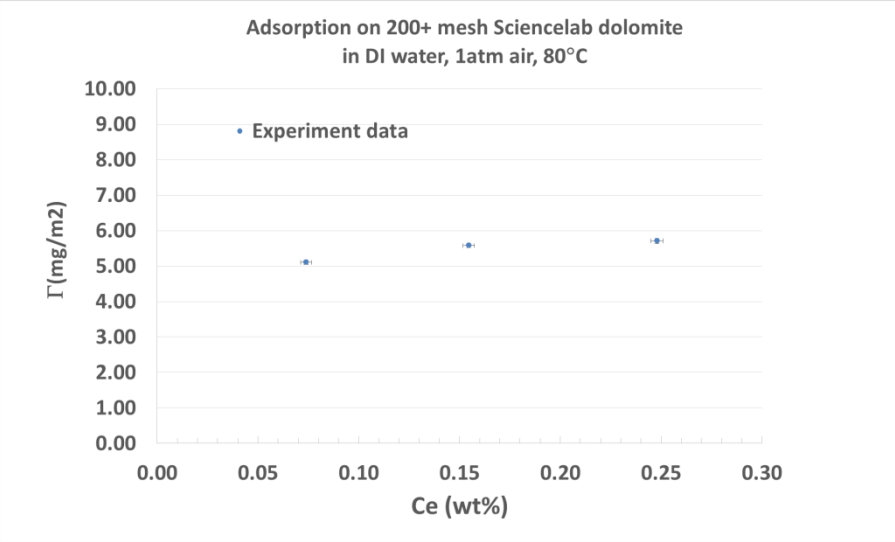
foam could be generated at reservoir conditions with 23 cp apparent viscosity and adsorption on Silurian dolomite is so low which is about 0.08mg/g [0.08mg/m2] rock.

- **How about adsorption at higher temperatures?**

Adsorption without Na2SO3

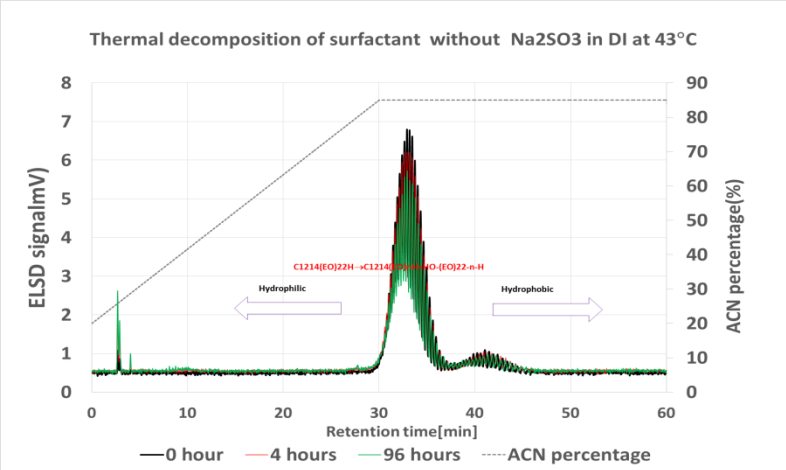


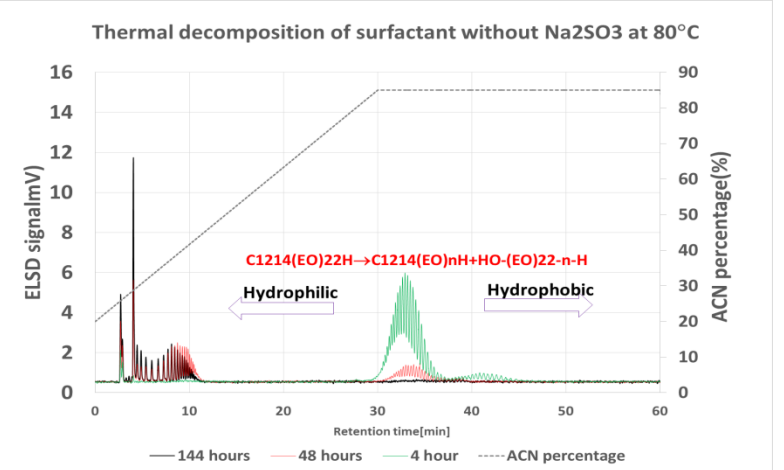


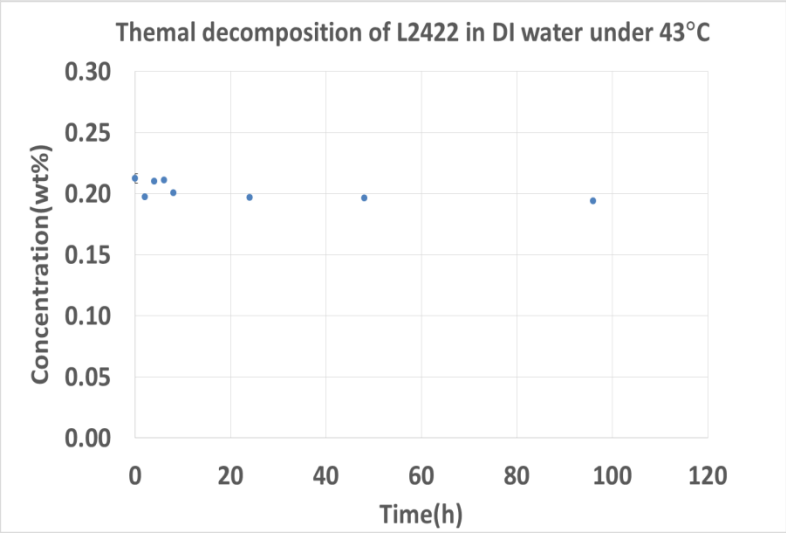


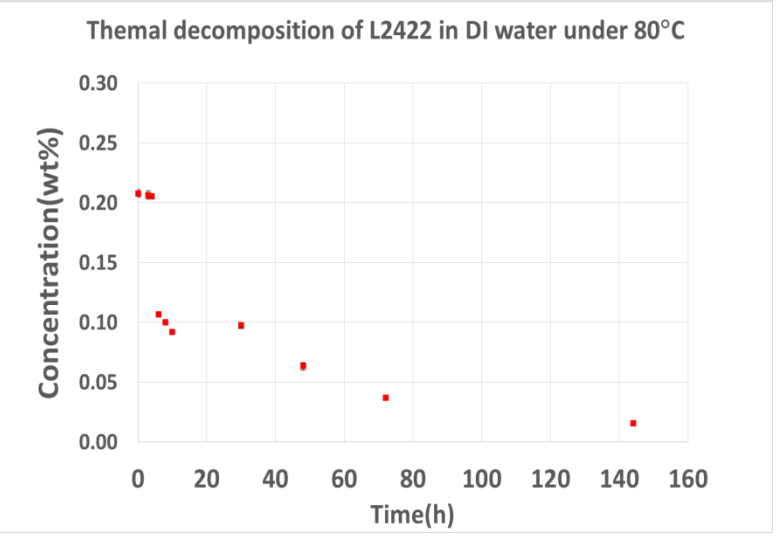
Why is so high adsorption at high Temperature? (on Sciencelab dolomite)

Effect of temperature



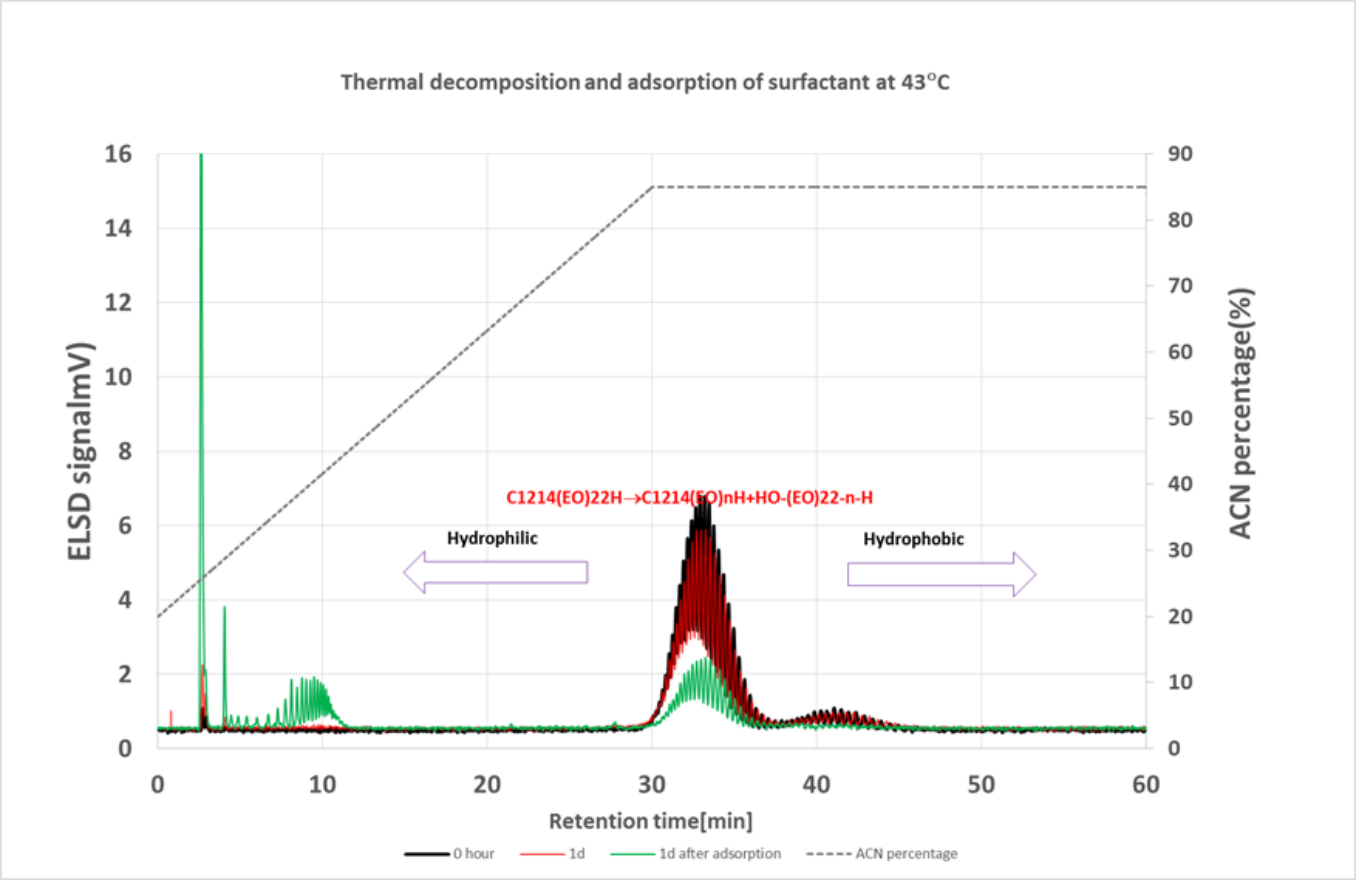






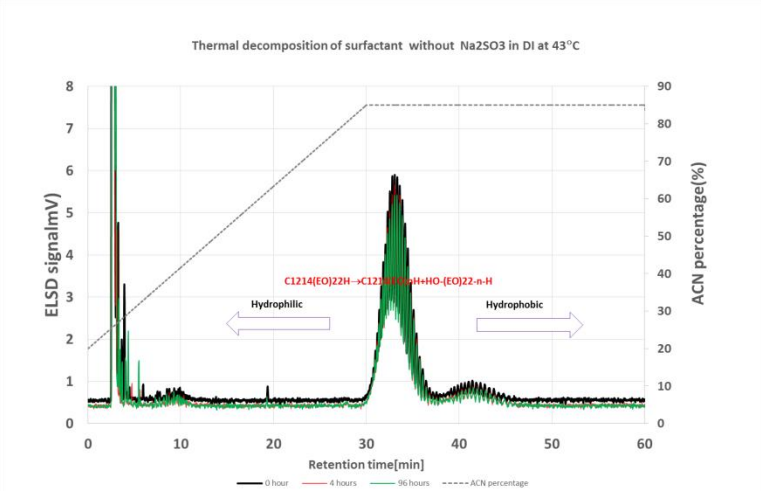
- **Thermal decomposition is severe at 80°C but not at 43°C**

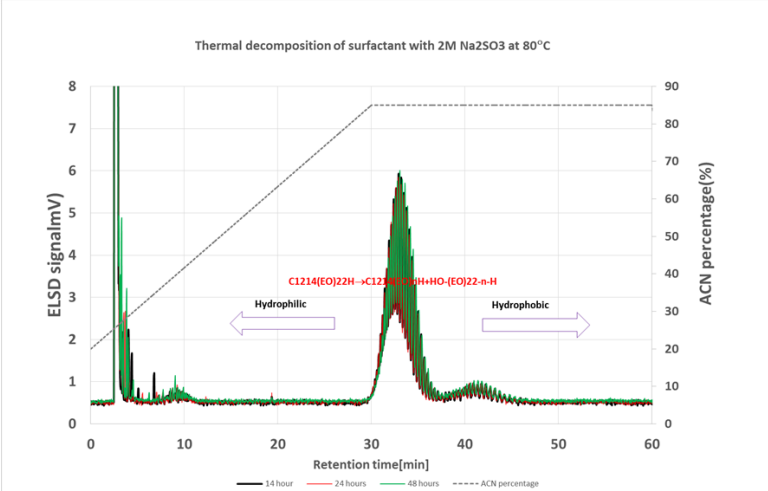
Thermal decomposition

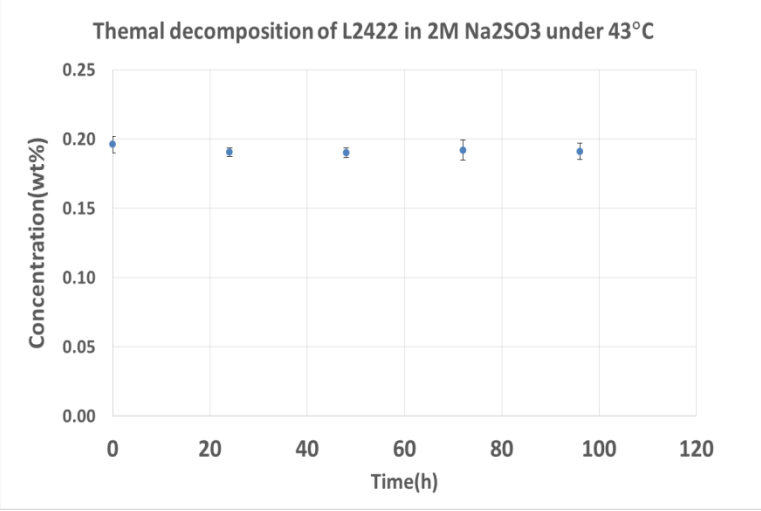


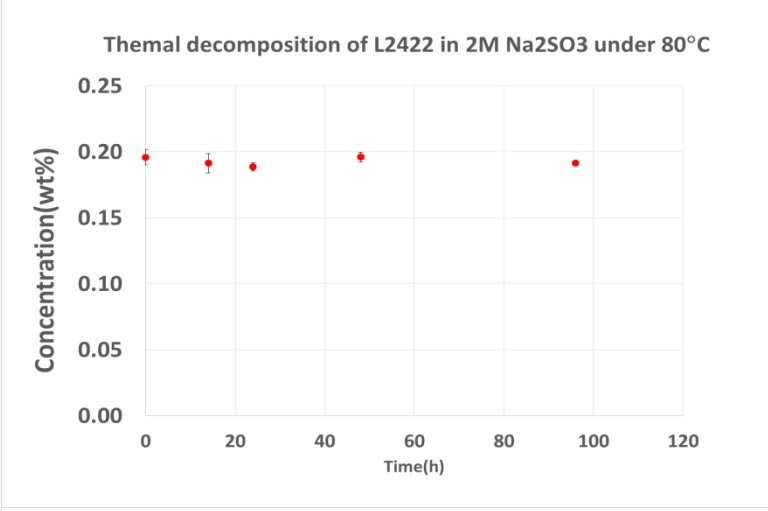
- **Thermal Decomposition is also severe at 43°C, if surfactant contacts with dolomite as pH increase from pH=6.2 to pH~=9.0**

Effect of temperature with 2M Na2SO3



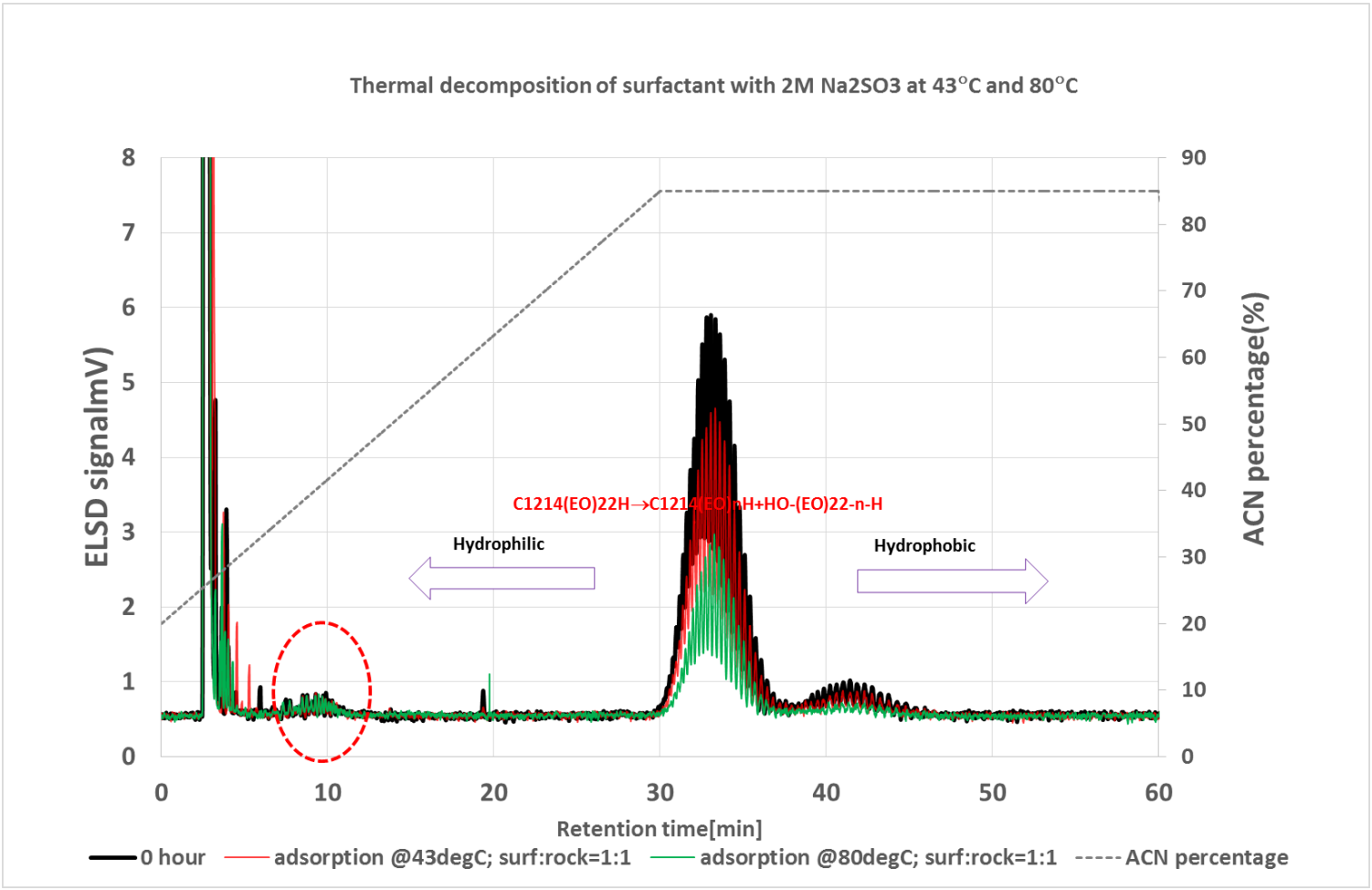






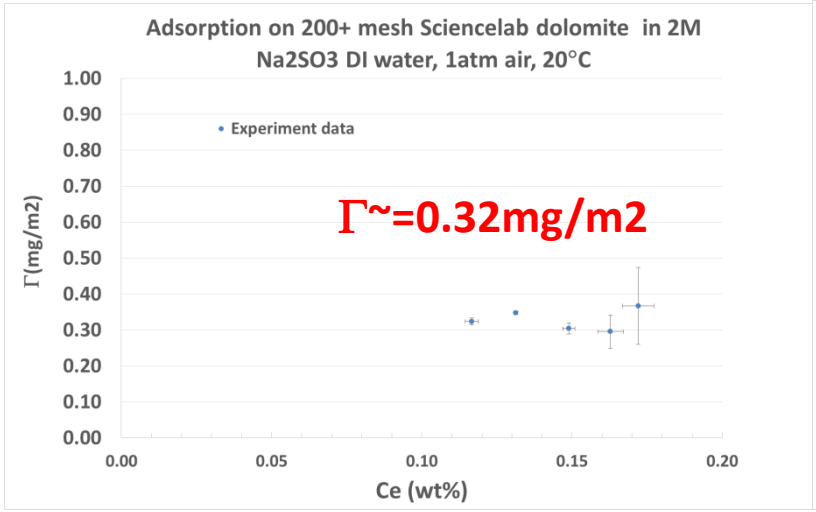
- **No decomposition was found when 2M Na2SO3 was introduced at 43°C and 80°C**

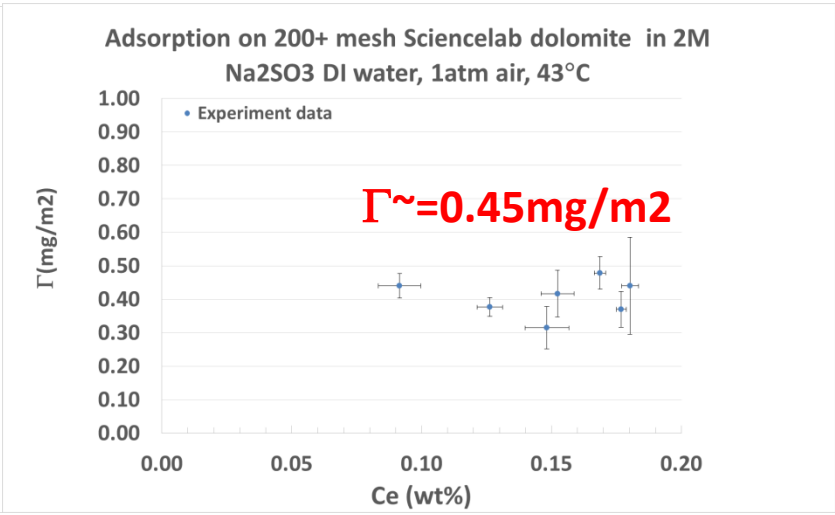
Adsorption (with 2M Na2SO3)

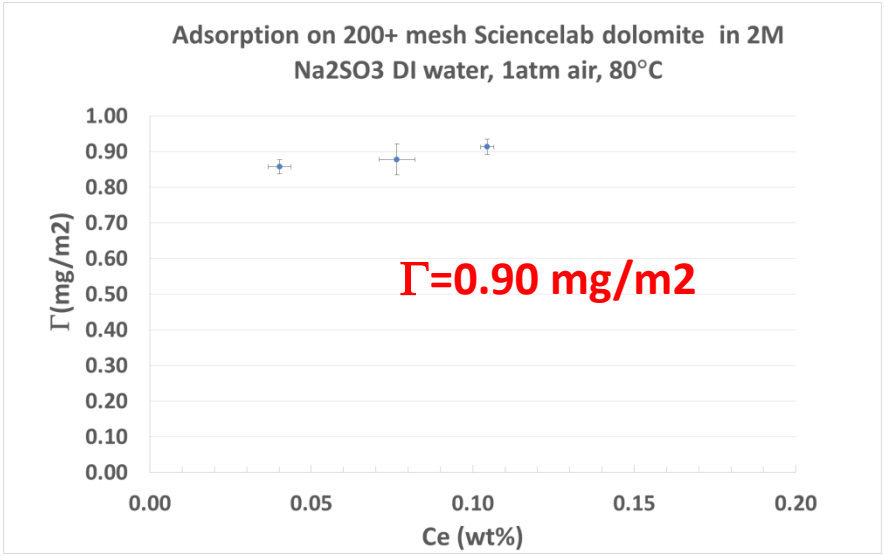


- **For adsorption at 43°C and 80°C, the decomposition product of alcohol was not observed which indicate that decomposition was inhibited with 2M Na2SO3**

Adsorption (with 2M Na2SO3)







Adsorption increases with temperature increase, Γ<1mg/m2

Conclusions

- Using 1wt% L24_22 nonionic surfactant, Foam with apparent viscosity of 23 cp can be generated in Silurian dolomite core(80% foam quality, 4 ft/day injection rate, 110°F(43.3°C), pressure of 2600psi, reservoir brine)
- Gypsum can precipitate during depressurization at 20°C which was observed by experiment and simulation results from PHREEQC
- Adsorption on Silurian dolomite is as low as 0.08 mg/g

Conclusions

- L2422 gets thermal decomposition at high temperature in the presence of oxygen

- Adsorption of L2422 on Sciencelab dolomite increases with temperature at reducing environment(2M Na2SO3), Γ<1mg/m2 for temperature range investigated[20°C~43°C~80°C]

Acknowledgement

This work was financially supported by Department of Energy(DOE) and Rice consortium for processes in porous media

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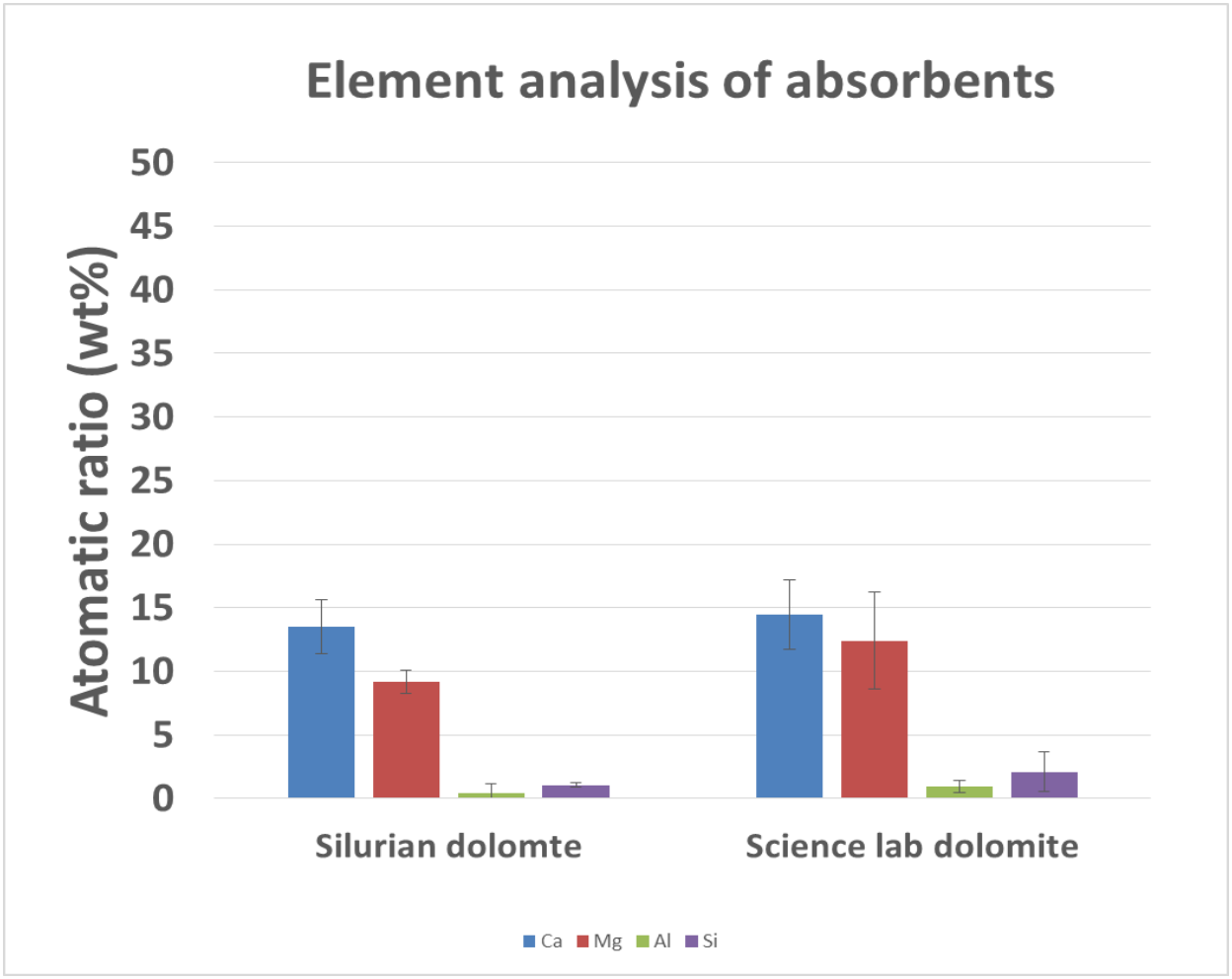
Thank you!
Any questions?

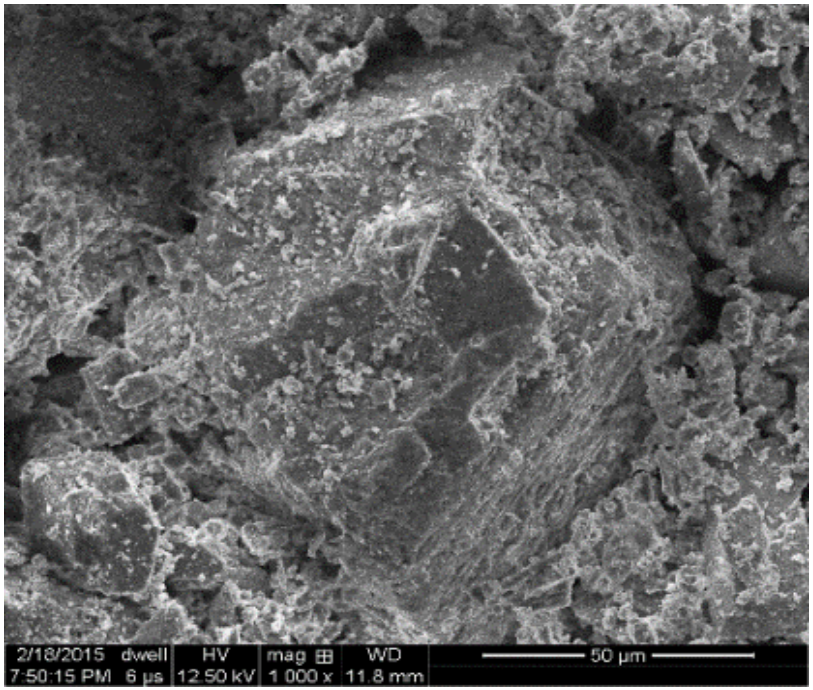
Element analysis of dolomite

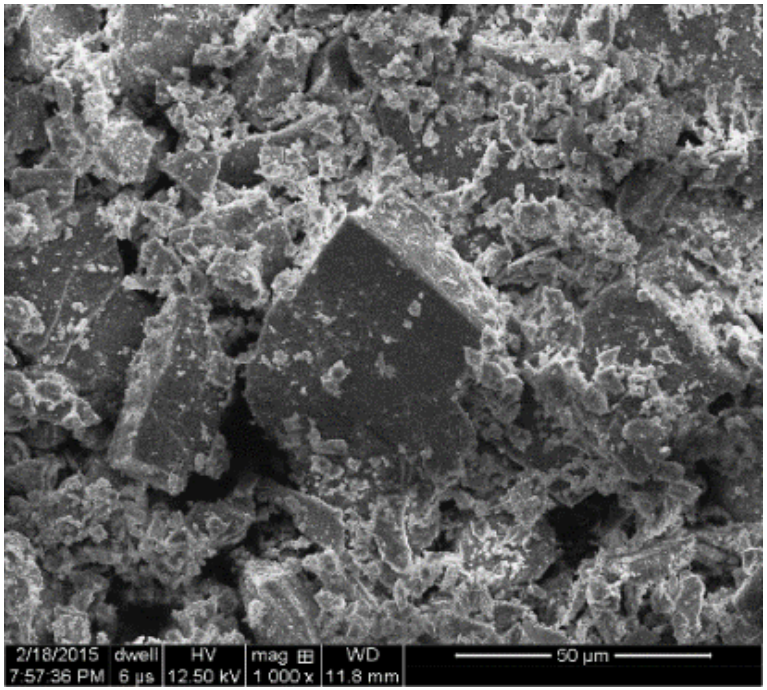


Two dolomite

absorbent	Diameter	BET surface area(m2/g)	Source
Silurian Dolomite	≤105 μm	0.95	Kocurek Industries, silurian dolomite, Ohio, USA
Sciencelab Dolomite	≤74 μm	0.89	Science lab.com, Inc.(Catalog #SLD4477),USA

SEM of two dolomite



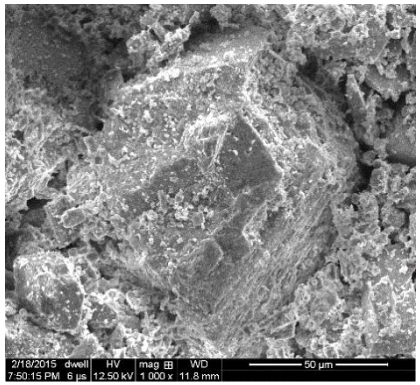


Silurian domomite	Sciencelab dolomite

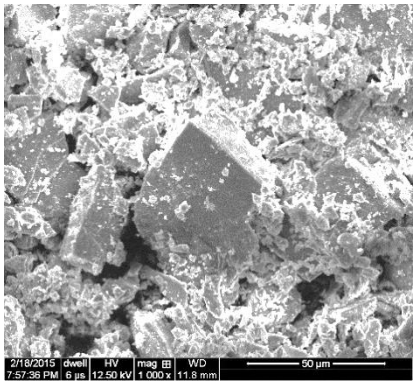
BET surface area of all absorbents

Absorbent	Diameter	BET surface area(m2/g)	Source
Silurian Dolomite	≤105 μm	0.95	Kocurek Industries, silurian dolomite, Ohio, USA
Sciencelab Dolomite	≤74 μm	0.89	Science lab.com, Inc.(Catalog #SLD4477),USA
Calcite	5 μm	1.65	Alfa Aesar(catalog#11403),USA
silica	≤ 10 μm	1.16	U.S.silica Company, Pacific, MO, USA
Kaolin	0.1-4 μm	26.61	Sigma-Aldrich(Catalog#K7375),USA

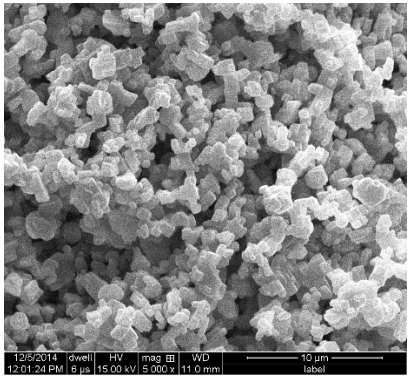
SEM Characterization of Adsorbent



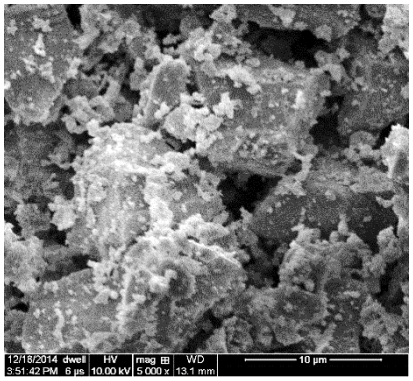
Silurian dolomite



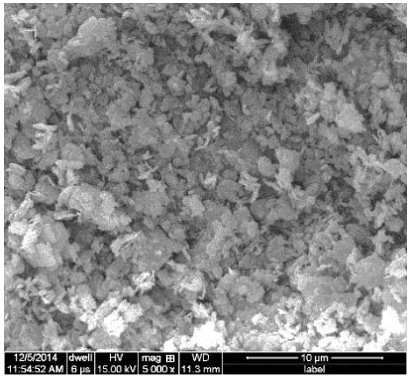
Sciencelab dolomite



Calcite

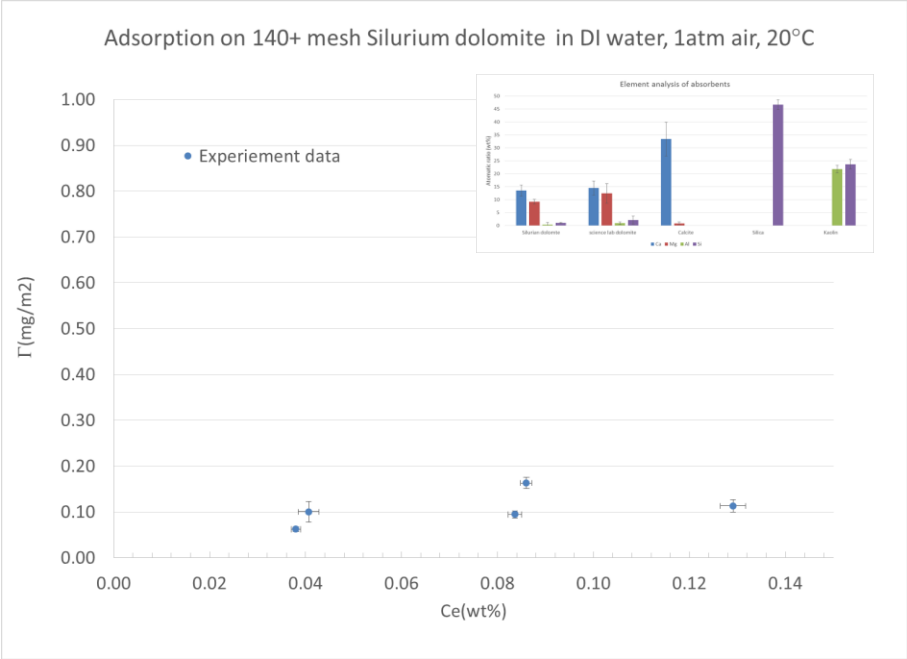


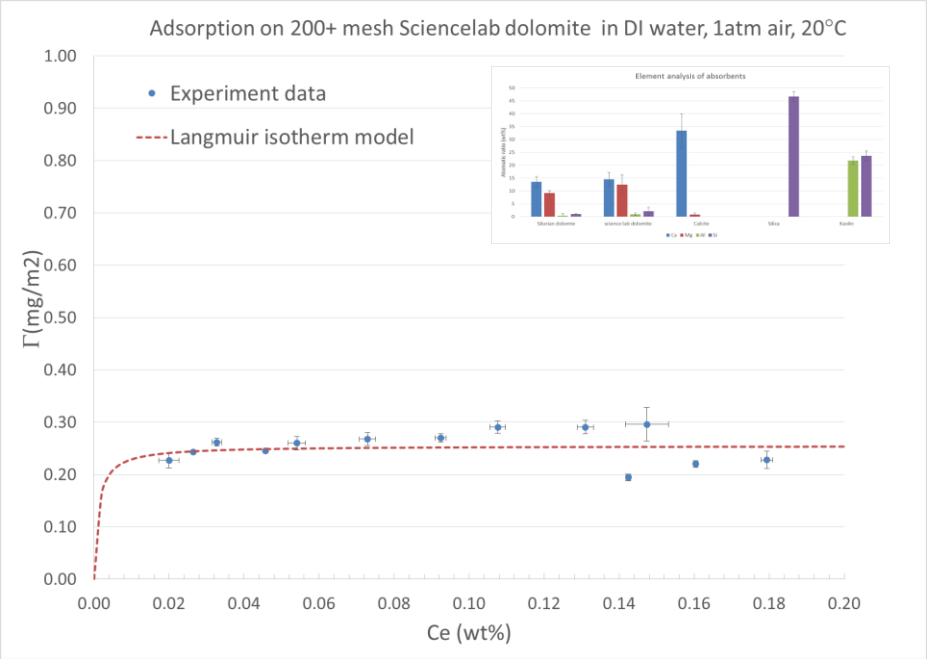
Silica



Kaolin

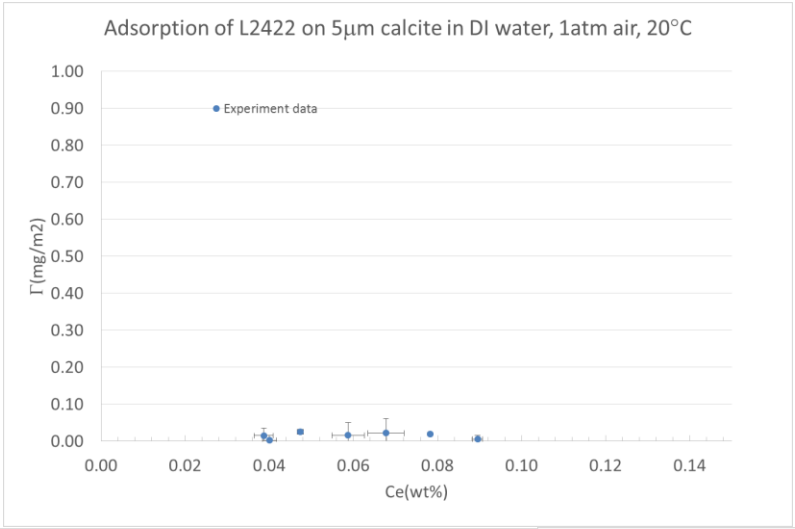
Effect of different dolomite

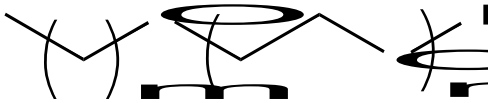




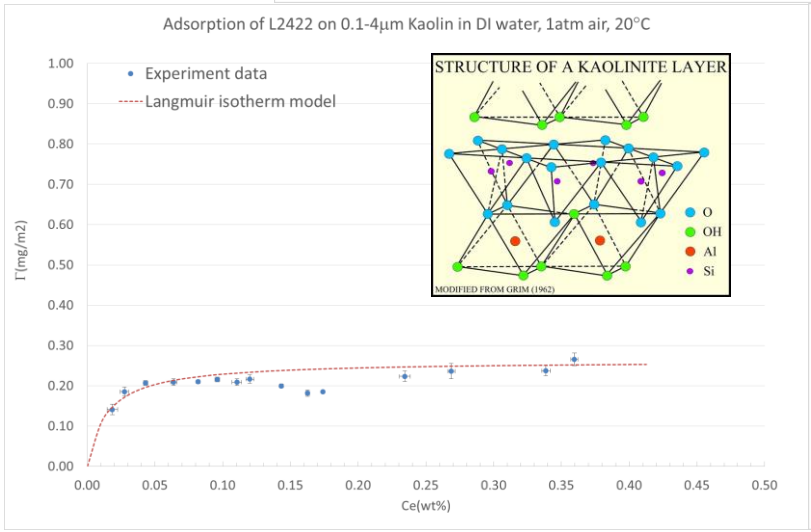
- The equilibrium adsorption amount of L2422 on Silurian dolomite is 0.12 mg/m2 and 0.28 mg/m2 for sciencelab dolomite
- The difference may be caused by the different amount of silica and clay on dolomite surfaces

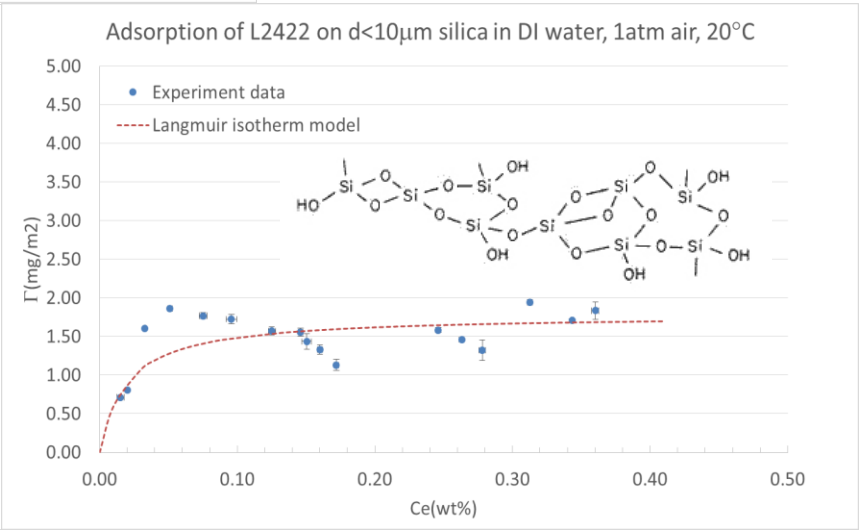
Effect of impurities in Carbonate materials





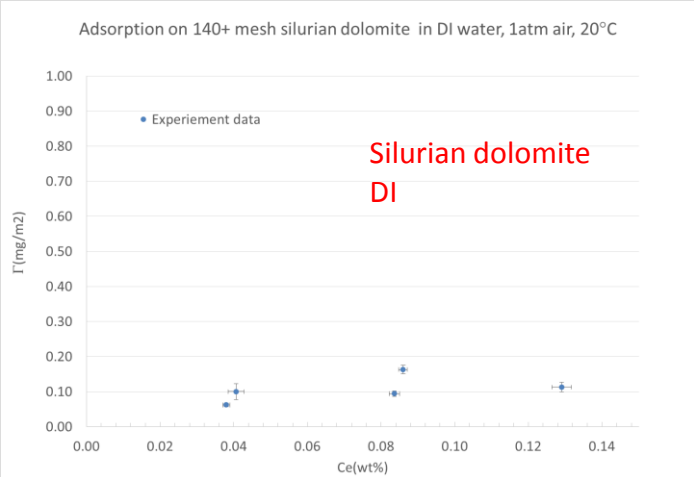
Hydroxyl group

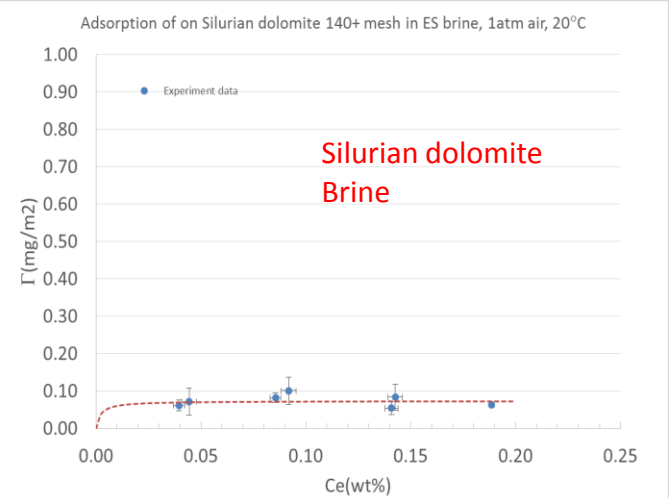


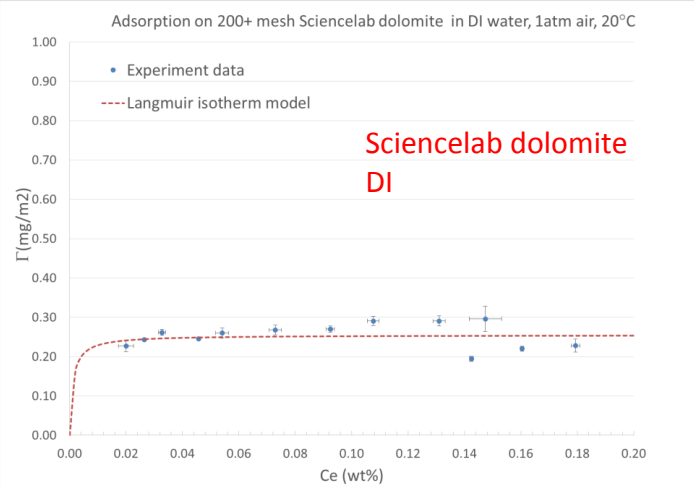


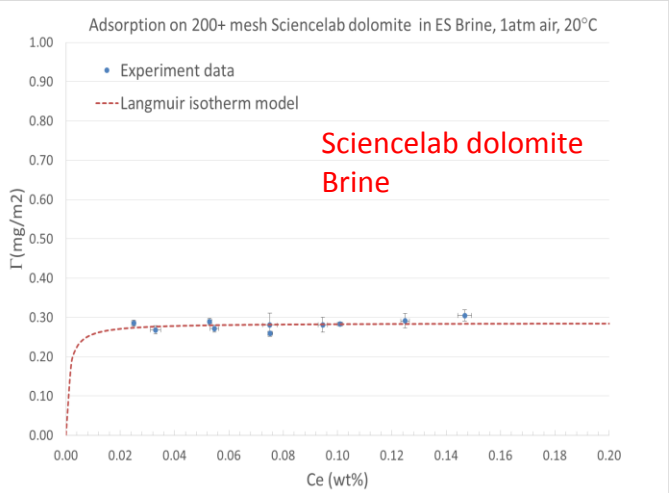
- The equilibrium adsorption amount of L2422 on silica is 1.8 mg/m2 and 0.26mg/2 for Kaolin clay, which was caused by hydrogen bond formed; Below 0.05 mg/m2 for calcite

Effect of brine



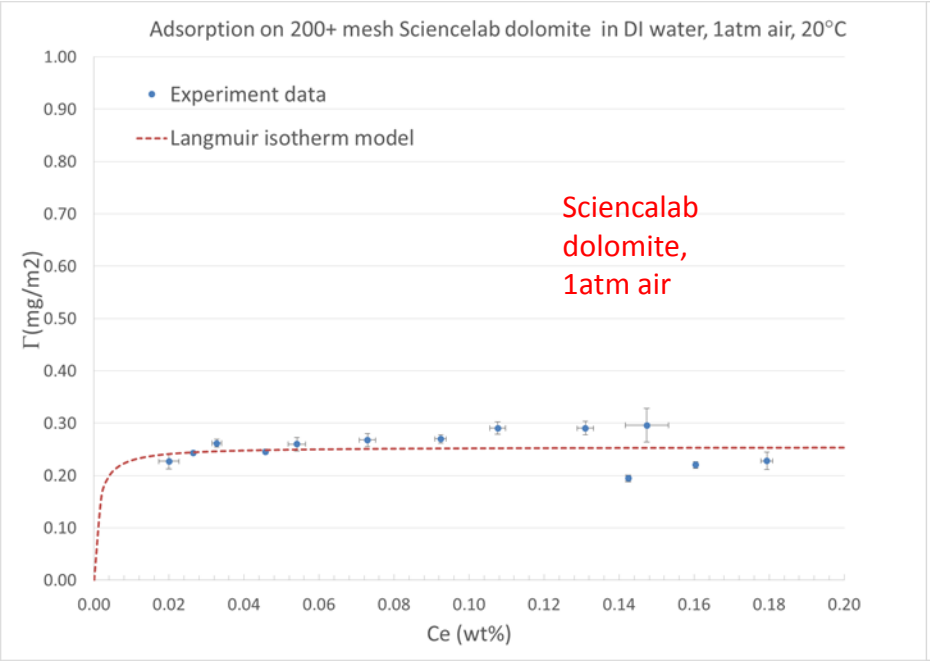


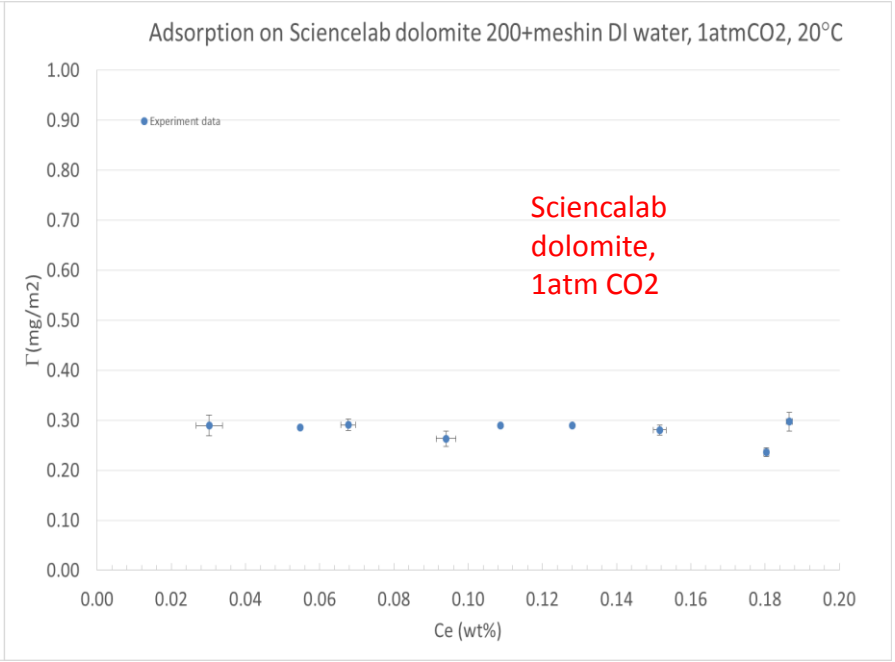




- The adsorption of L2422 decreased from 0.12mg/m2 to 0.09mg/m2 for Silurian dolomite in the presence of ES brine
- The equilibrium plateau of adsorption amount of L2422 on sciencelab dolomite in ES brine is around 0.28mg/m2 which is almost the same as that in DI water environment

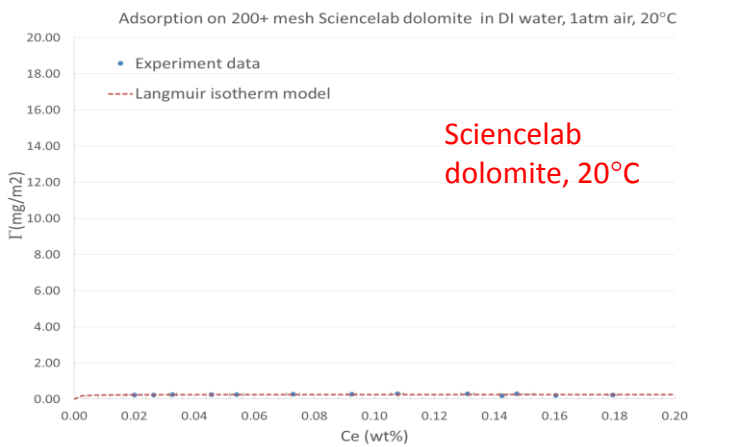
Effect of CO2

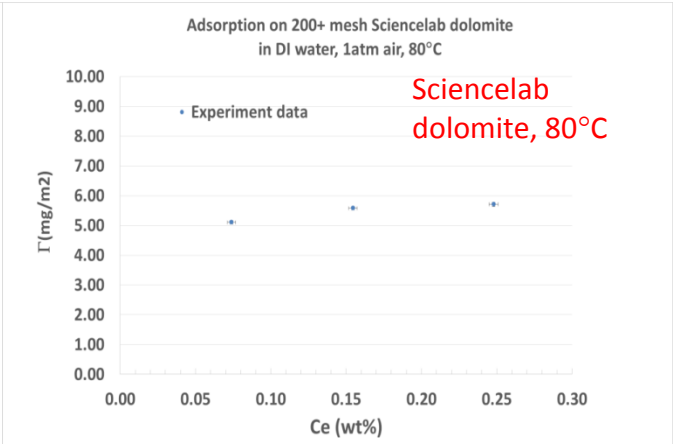


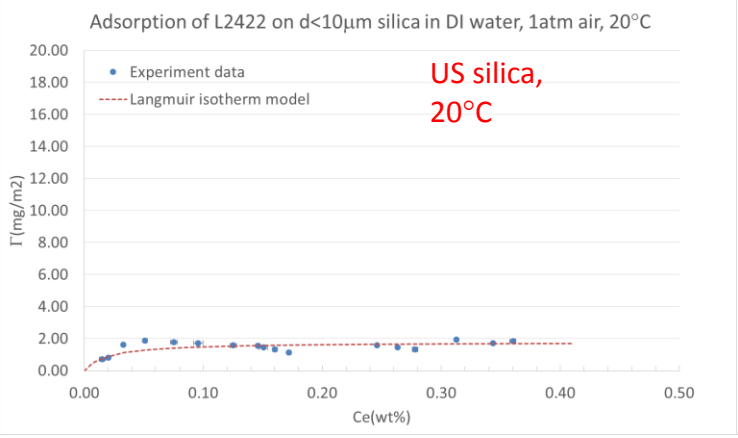


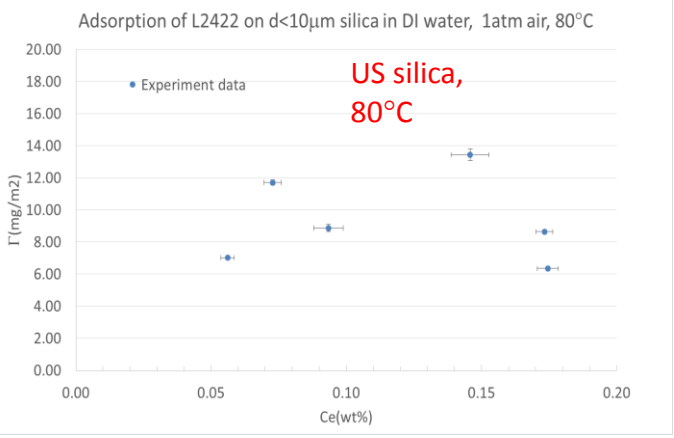
- The adsorption of L2422 was almost the same under the 1atm air and 1atm CO2, both at room temperature

Effect of Temperature



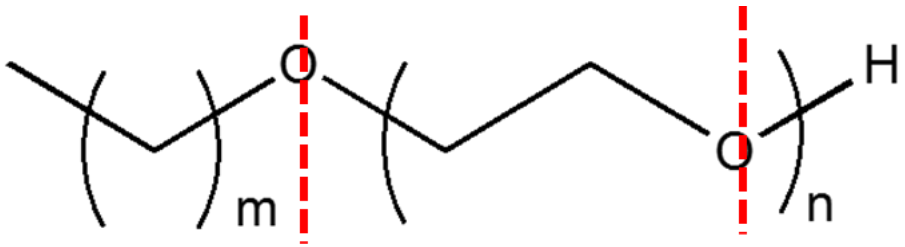






- The adsorption at 80°C are much higher than that under 20°C on calcite and silica
- Degradation beside of adsorption?

Decomposition



m=11~13;
n=22

The thermal decomposition of L2422 under high temperature in oxidization environment