Geochemical Reactions upon Injection of Heated Formation Water in a Danish Geothermal Reservoir

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DATE: 2025/01/03
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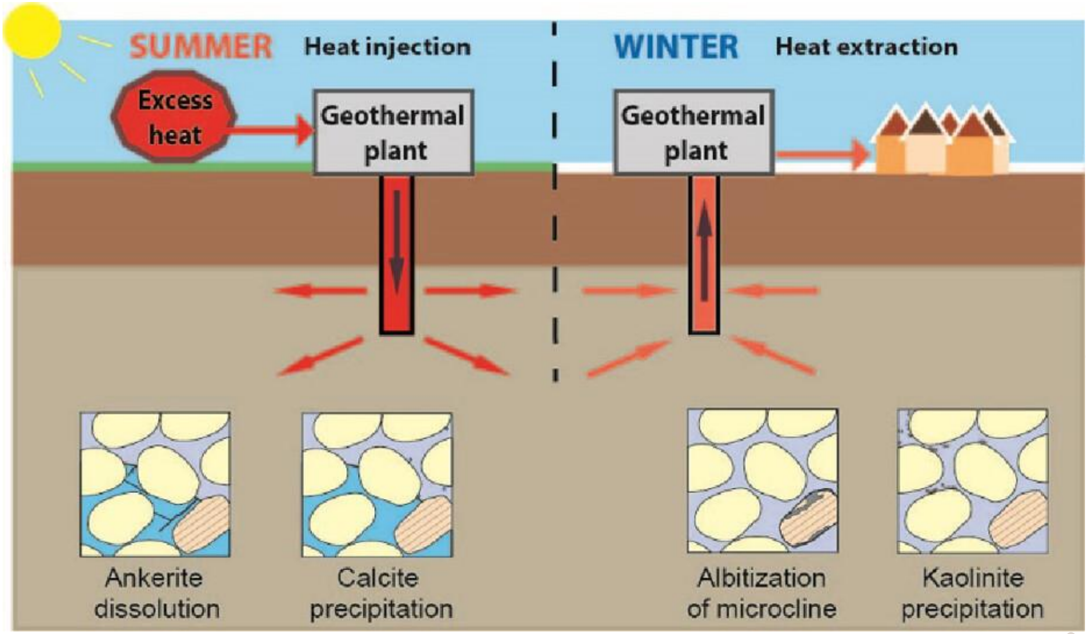
OUTLINE

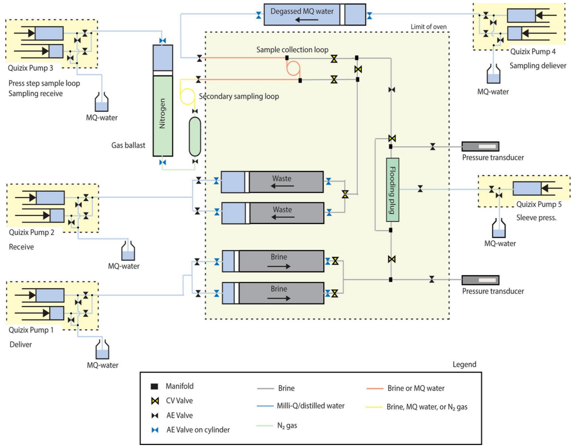
- INTRODUCTION
- MATERIALS AND METHODS
- RESULTS AND DISCUSSION
- CONCLUSIONS

- Renewable energies, such as geothermal energy, solar radiation, or wind, are playing a major role in this transition toward sustainable energy supply.
- The supplement of solar and wind energy is unstable, leading to a seasonal gap between the supply and the demand for energy.
- Aquifer thermal energy storage (ATES) is one means to manage this seasonal gap between the energy demand and supply.



Objective

- Investigating the heat-induced dissolution and precipitation processes in the Upper Triassic–Lower Jurassic Gassum Formation.
- Using **core flooding experiment** at reservoir conditions and elevated temperatures up to 120 °C to conducted simulation of injection of heated formation water.
- Combine with **PHREEQC Version3** with core flooding experiment to constrains and supports the interpretation of the results from the laboratory experiments.



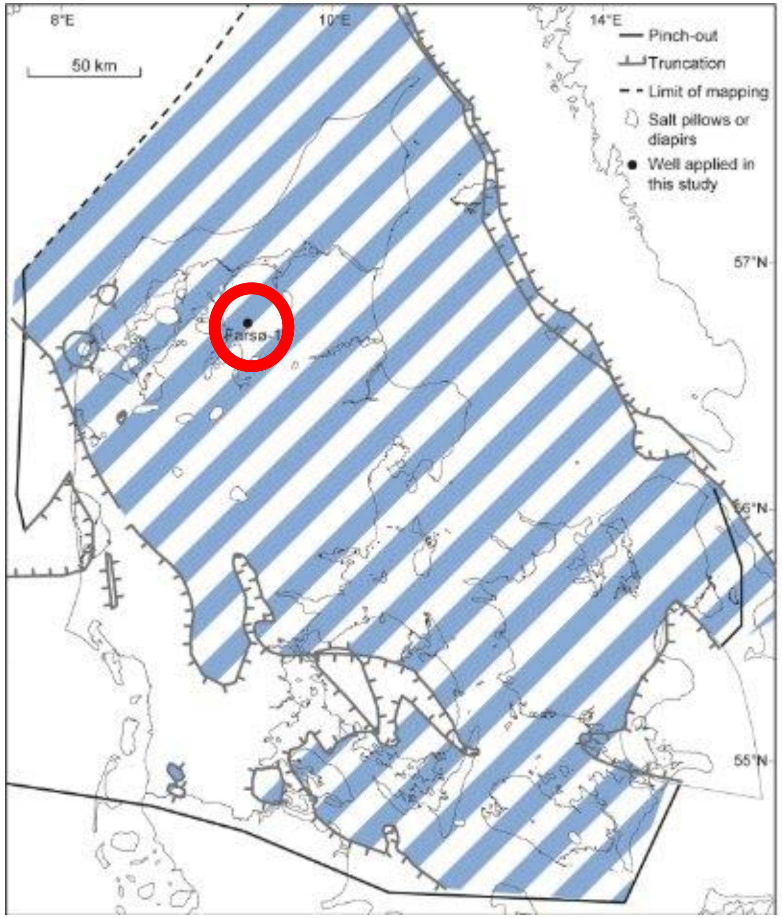
2.1. Sample Description and Fluid

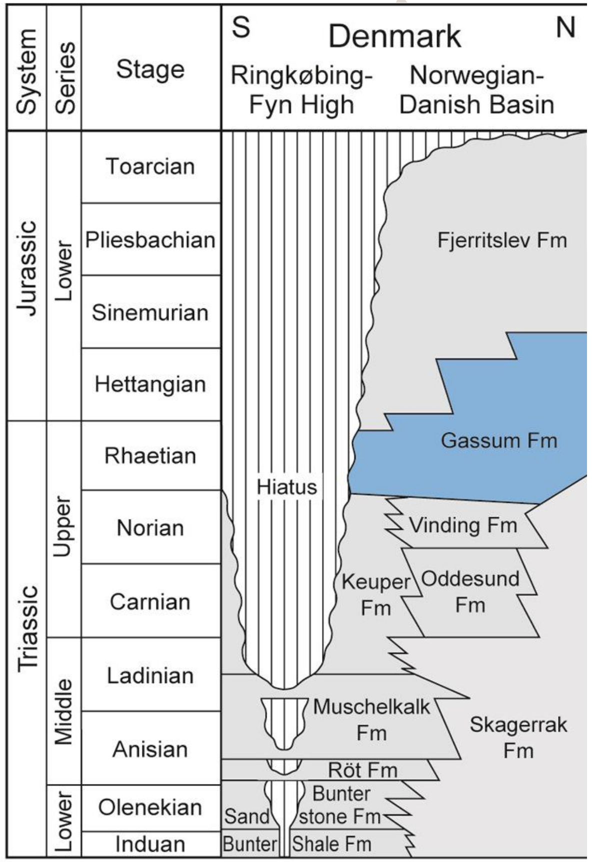
- Core material from the Upper Triassic–Lower Jurassic Gassum Formation was selected for the laboratory experiment.
- The Gassum Formation is characterized by a mature mineralogical composition with quartz.

Rock Core Sample

- Location: Farsø-1
- Burial depth: 2875m
- Length: 56.6mm
- Diameter: 24.85 mm
- Porosity: 15.7%
- Gas permeability: 86 millidarcy
- Temperatures: approximately 80 °C

Denmark Gassum Formation





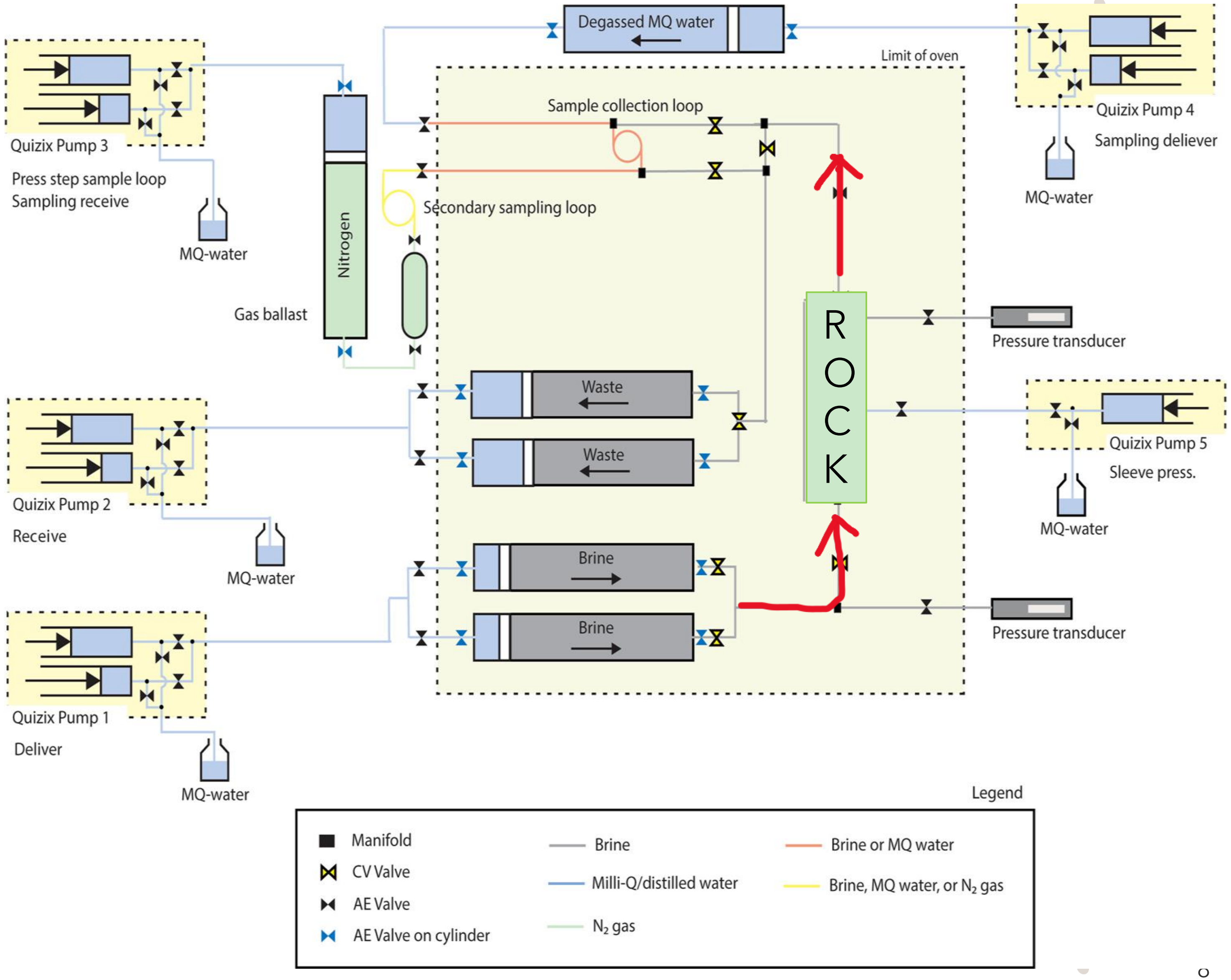
Fluid Composition

- Salinity: 23.4 wt %
- Dissolved gas content: 0.2% (vol/vol) at 25 °C and 1 atm of which 24% is CO_2.
- HCO_3^-: reduced from 128 to 50 mg/L to avoid carbonate scaling.

Element	**Concentration(mg/L)**
Na	73000
Ca	28000
Mg	2000
K	1600
Sr	920
Cl	169000
HCO_3^-	50
SO_4^{2-}	250

2.2. Experimental Procedure

- Flow rate: 0.25 PV/h (1.4 cm/h when the cross-sectional area)
- Confining pressure: 300 bar
- Pore pressure: 145 bar
- Temperature: 23 (room temperature), 60, 80, 100, and 120 °C.
- Time: 1 month with 2 days at 23 °C and 1 week with each of the other temperatures.



2.3. Mineralogical Characterization

- Three samples of the experimental core were investigated.

(1) An end trim taken prior to the experiment

(2) A trim taken after the experiment, close to the inlet

(3) A trim taken after the experiment, from the outlet

- The samples were impregnated with blue epoxy for easy identification of porosity and prepared as polished thin sections prior to analysis with transmitted and reflected light microscopy.

2.4. Numerical Modeling

- Injection of heated formation water into the Gassum Formation core specimen was modeled using the numerical code PHREEQC version 3.0.
- The Thermoddem database was used for the calculations.
- The model included the thermokinetic processes of mineral dissolution/precipitation reactions using the kinetic rate law.

$$R = k \cdot \frac{A_0}{V} \cdot \left(\frac{m}{m_0}\right)^{0.67} \cdot (1 - \Theta)$$

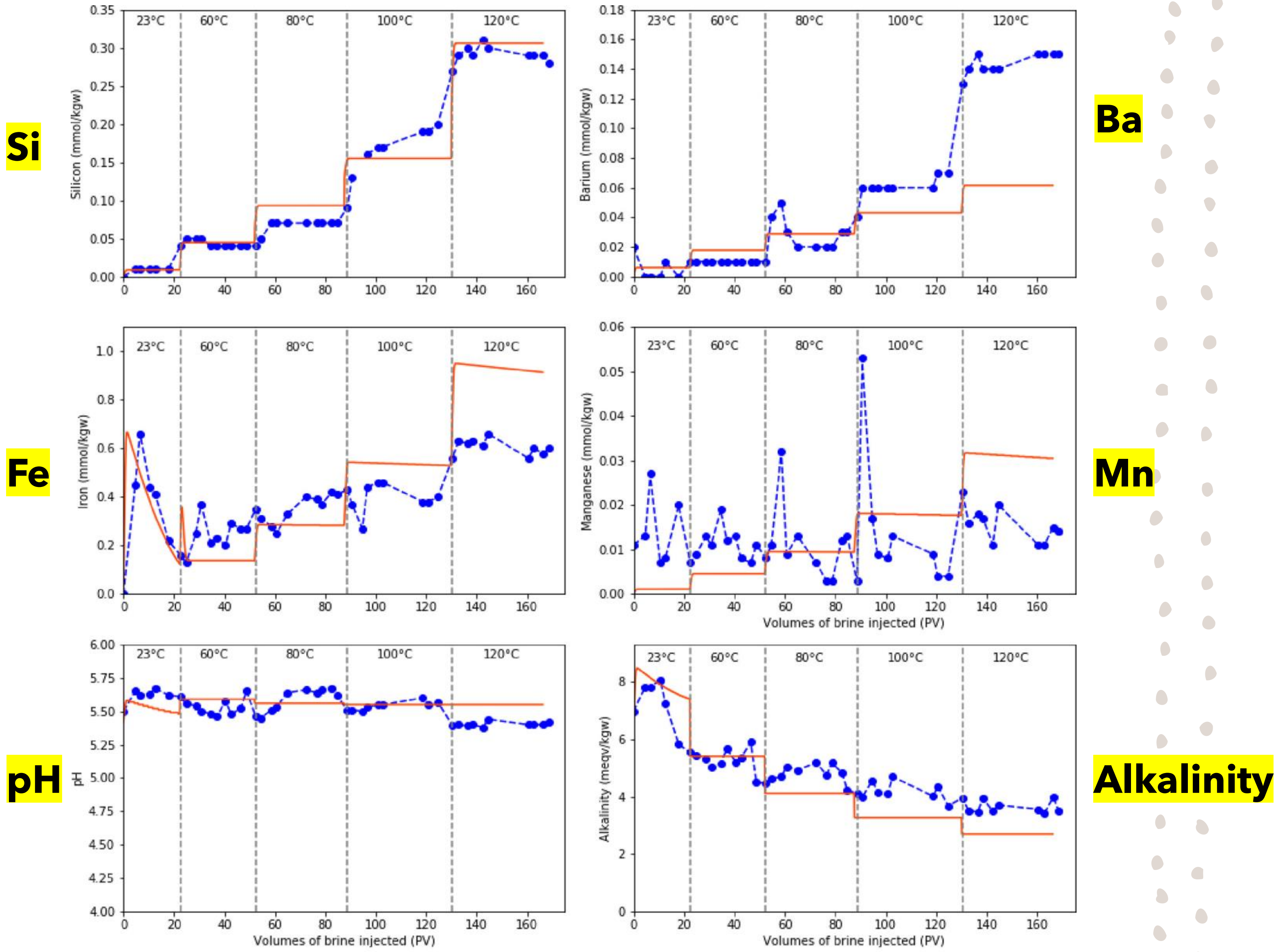
Others

$$R = A_0 \cdot A \cdot \exp\left(\frac{-E_a}{RT}\right) \cdot \gamma_H \cdot 10^{n_I \sqrt{I}} \cdot (1 - \Theta)$$

Barite

3.1. Water Chemistry

- Chemical analysis of the effluent from the core flooding experiment
- Ca、Mg、K、SO_4^{2-}、Na、Cl^-, their concentration were too high to see the variation.
- Al is below the detection limit.

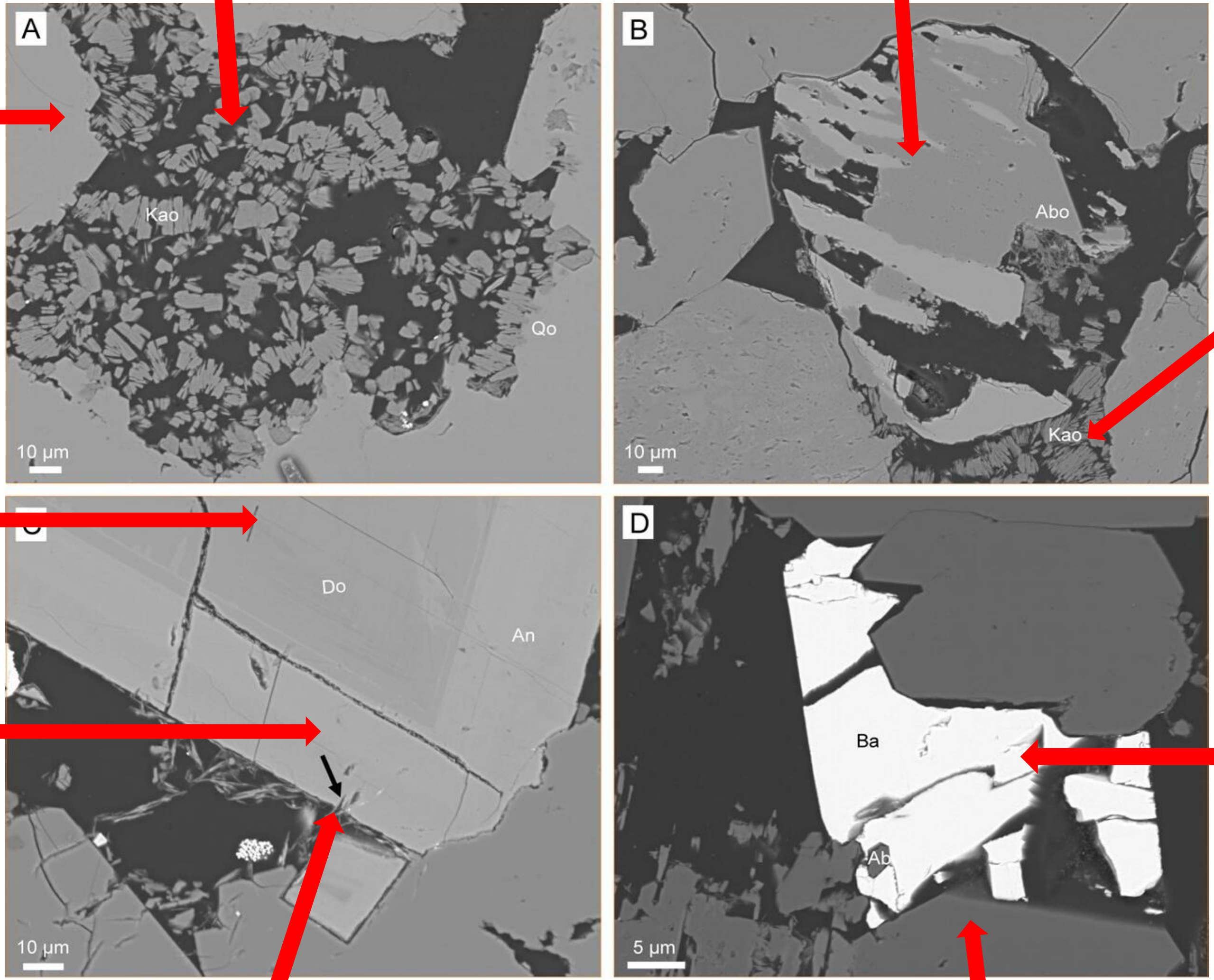


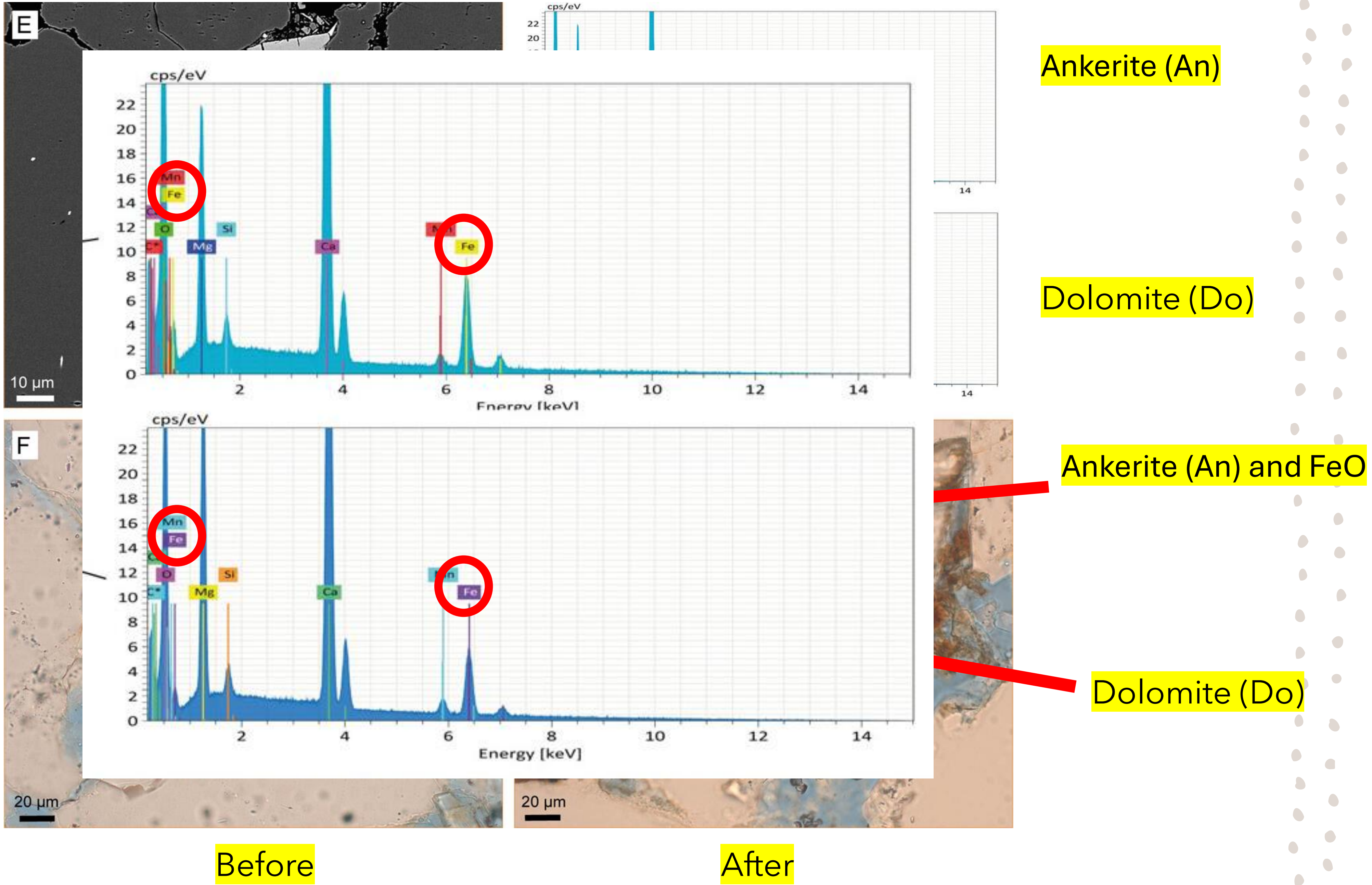
experiment modeling

3.2. Mineralogical Composition and Petrophysical Investigations

- The sandstone is medium-grained and quartz-dominated with common microcline and albite grains.
- K-feldspar shows common dissolution features and albitization.
- Mainly metamorphic
- Cementing phases are mainly quartz overgrowths, feldspar overgrowths, kaolinite, illite clays, ferroan dolomite/ankerite, and pyrite.

sandstone composition (vol %)	average	standard deviation
Detrital grains		
quartz	59.1	1.2
K-feldspar (microcline)	8.0	0.5
plagioclase (albite)	6.2	4.5
mica	0.3	0.2
sedimentary rock fragments	0.4	0.3
metamorphic rock fragments	0.6	0.9
plutonic rock fragments	0.9	0.1
mud clasts	0.1	0.1
opaque minerals	0.1	0.1
transparent heavy minerals	0.2	0.0
Cement phase		
quartz overgrowths	7.8	2.6
feldspar overgrowths	0.8	0.3
anatase	0.1	0.1
pyrite	-	-
carbonate (sparry/rhombs)	0.1	0.1
barite cement	0.1	0.1
kaolinite	3.0	1.7
illite	0.2	0.3
red coatings	0.1	0.1
porosity (primary)	8.9	1.3
porosity (secondary)	3.0	1.1
total	100.0	


Kaolinite (Kao)
Albite overgrowths (Abo)
Quartz overgrowths(Qo)
Kaolinite (Ka)
Dolomite (Do)
Ankerite cement (An)
Barite cement (Ba)
Illite
Albite crystal (Ab)
A
Kao
Qo
10 μm
B
Abo
Kao
10 μm
Do
An
10 μm
D
Ba
5 μm


E
F
10 µm
20 µm
20 µm
cps/eV
Energy [keV]
Mn
Fe
O
Si
Mg
Ca
C*
Ankerite (An)
Dolomite (Do)
Ankerite (An) and FeO
Dolomite (Do)
Before
After

3.3. Potential Geochemical Reactions

- **Silicate Minerals**

Temperatures ≤80 °C:

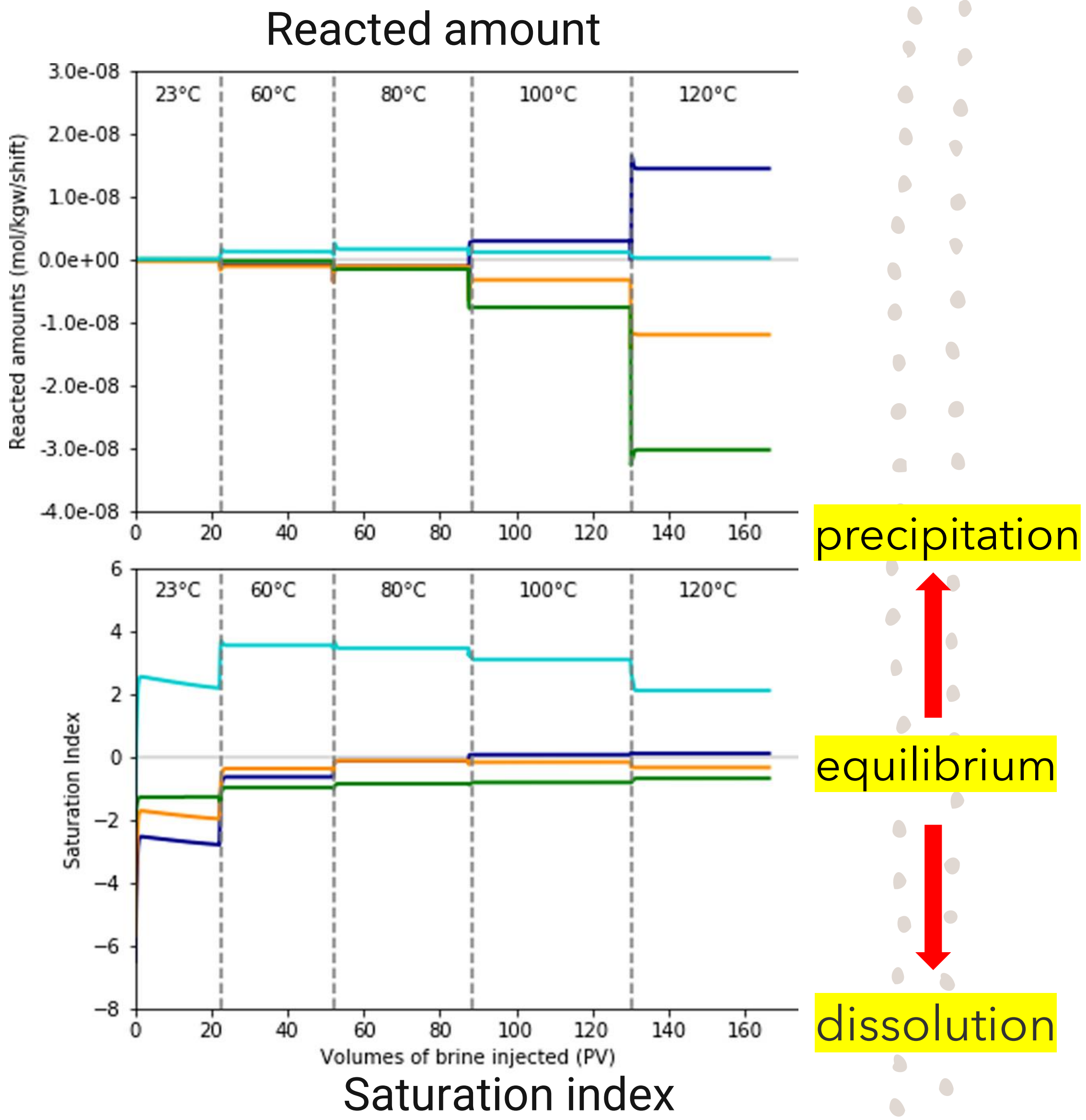
Microcline Kaolinite

$KAlSi_3O_8 + H^+ + 0.5H_2O \rightarrow 0.5Al_2Si_2O_5(OH)_4 + K^+ + 2SiO_{2(aq)}$

Temperature > 80 °C:

Microcline Albite

$KAlSi_3O_8 + Na^+ \rightarrow NaAlSi_3O_8 + K^+$ (Albitization)



Kaolinite Albite Microcline Quartz

- **Carbonates**

At temperatures ≥60 °C:

Ankerite

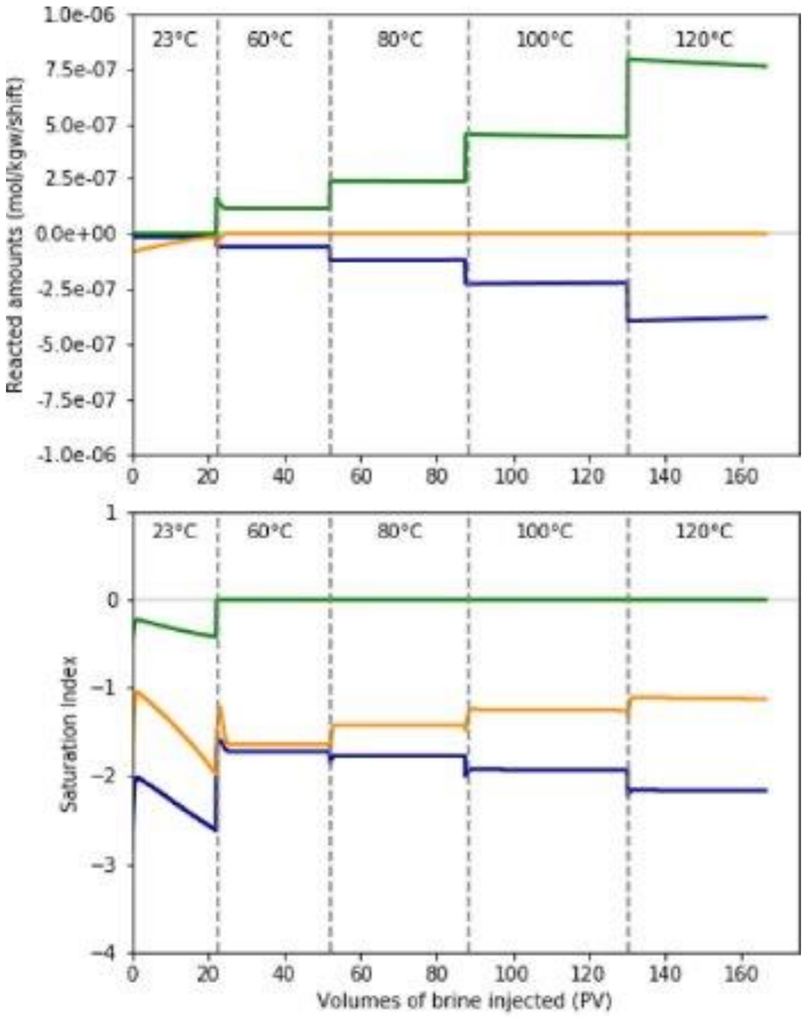
$CaFe_{0.3}Mg_{0.69}Mn_{0.01}(CO_3)_2 + Ca^{2+}$

$\rightarrow 2CaCO_3 + 0.3Fe^{2+} + 0.69Mg^{2+} + 0.01Mn$

Calcite

Calcite　Siderite　Ankerite

Reacted amount



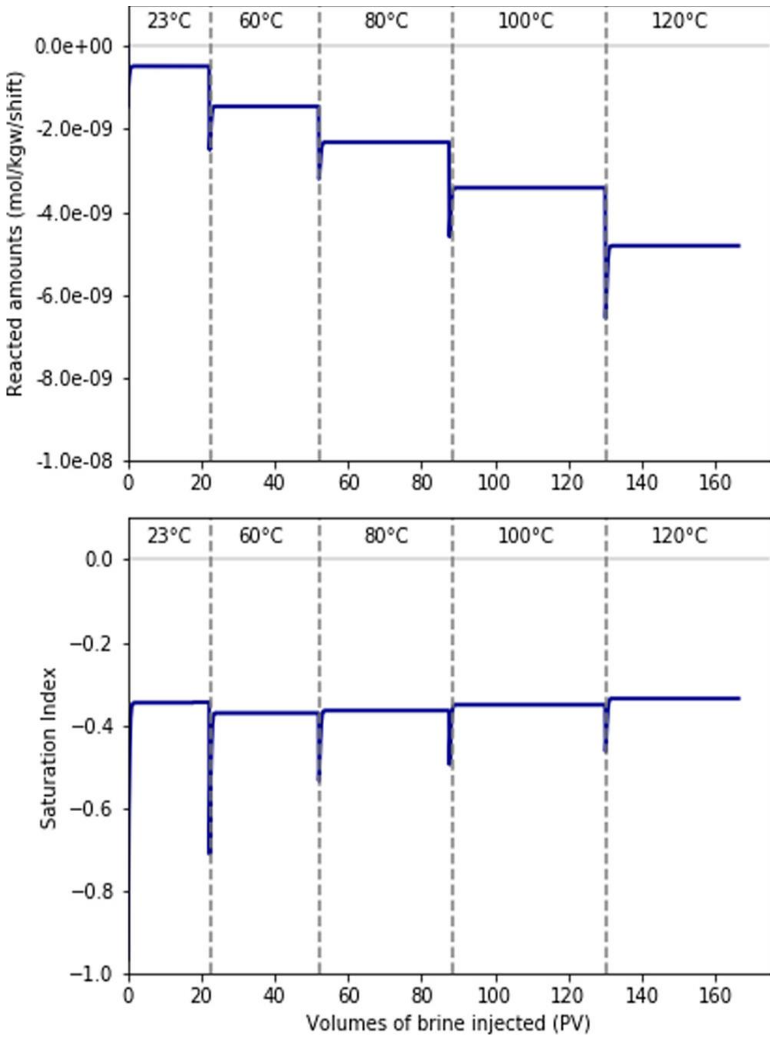
Saturation index

equilibrium

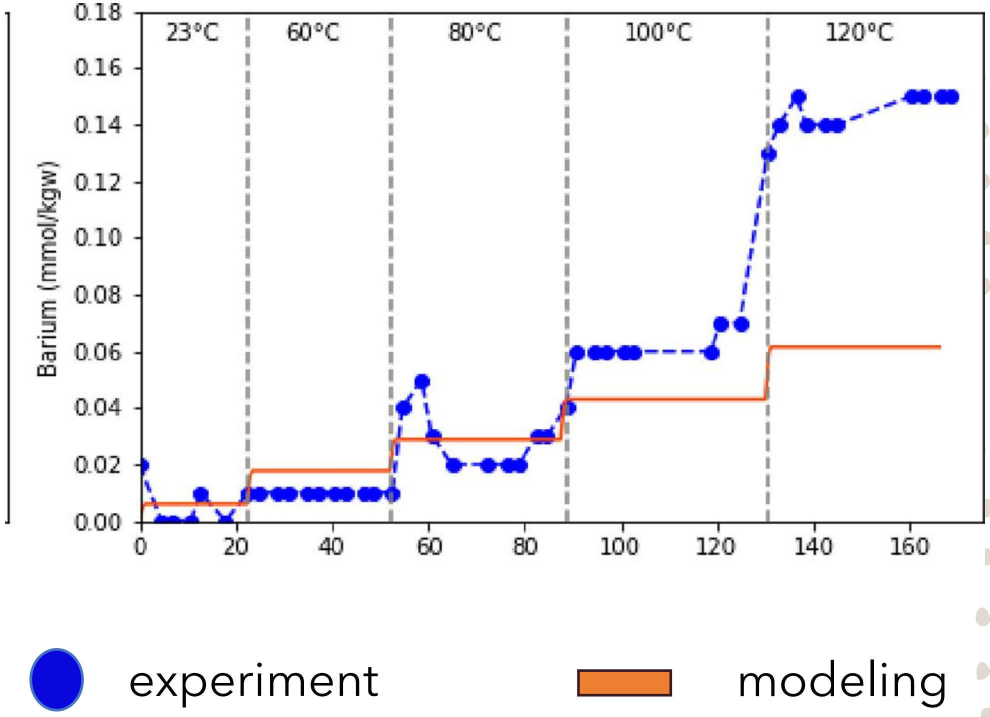
dissolution

- **Barite**

Reacted amount



Saturation index



- Changes in the formation water and the sandstone mineral composition were examined geochemically and petrographically, respectively, and supported by geochemical modeling.
- Reinjection of heated formation water into the reservoir may induce or enhance the albitization of microcline; dissolution of quartz, dolomite/ankerite, and barite; and precipitation of kaolinite and calcite.
- Except for the calcite precipitation at higher temperatures as this may cause injectivity problems, the effects of other minerals on the reservoir properties are expected to be of minor importance.
- Scaling of calcium carbonates at higher temperatures should be considered as part of any thermal energy storage project, even for reservoirs with a low calcium carbonate content.

Thanks for your listening!

- The deep subsurface of Denmark contains large siliciclastic saline geothermal reservoirs with high porosity and permeability and temperatures between 50 and 75 °C suitable for geothermal exploitation.
- Injecting heated water back to reservoir increase affects both the mineral solubility and the extent and rate of chemical reactions between the reservoir minerals and the formation water.
- A major concern regarding heat storage in geothermal reservoirs is injection of heated water may permanently damage the reservoir.

3.4. Evaluation of the Impact on Reservoir Quality.

- Calcite-free and a partly calcite-cemented reservoir and found that in neither sandstone reservoir types was the dissolution/precipitation of silicates considered problematic for the stability of the reservoir.
- Highly unlikely the injection of heated formation water into the Gassum Formation at Farsø will induce reactions with the silicate minerals that may deteriorate the reservoir.
- Althought the formation of kaolinite will increase the damaging potential of the reservoir, the amount of kaolinite formed is very small during the experiment.
- The precipitation of carbonates at higher temperatures may be a challenge and may necessitate precautions to avoid precipitation of calcite in the heat exchanger or injection well.

MATERIALS AND METHODS

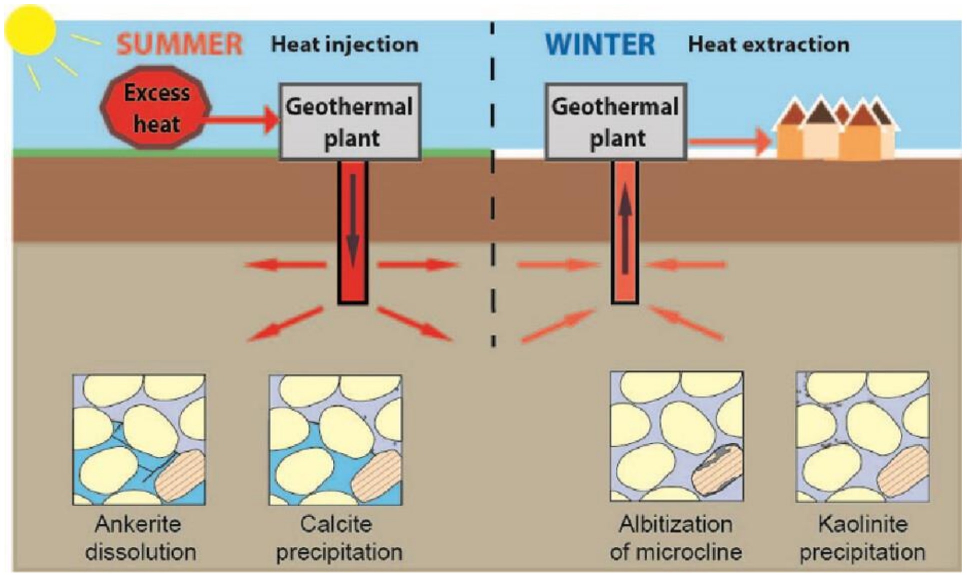
2.2. Experimental Procedure.

- Core flooding experiment was performed to simulate the injection of heated formation water into the reservoir.
- Flushing the cored sample with heated synthetic formation water at reservoir conditions and temperatures up to 120 °C.
- Prior to testing, the sample was cleaned in methanol to remove any salt precipitates, placed in a vacuum overnight.
- Than, the sample was prepared to a formation water saturation of 100% by pressurization to 110 bar for 3 days in degassed formation water.

- PH was determined immediately after extracting the effluent from the secondary sampling loop using a pH electrode.
- Major cations (Na, K, Ca, and Mg) were measured by IC.
- Al, Ba, and other trace elements were measured by ICP-MS.
- Anions were analyzed within 14 days by IC.
- Si were analyzed by spectrophotometric analysis.

Aquifer Thermal Energy Storage (ATES)

- A thermal energy storage technology where excess heat is stored in an aquifer for months until it may be used at the surface.
- High-temperature ATES systems (HT-ATES), storing formation water at temperatures greater than 40 °C typically target porous and permeable deeper reservoirs.



3.3. Geochemical Modeling.

- The geochemical model includes kinetically controlled dissolution/precipitation of albite, kaolinite, microcline, quartz, ferroan dolomite/ankerite, and siderite (applied instead of an Fe-rich ankerite).
- Calcite was assumed absent in accordance with the petrographic analysis.
- The model was calibrated against the observed changes in concentration of aqueous species observed in the effluent from the core flooding experiment by adjusting the specific surface area found in the literature.