Snorre in-depth water diversion using silicate

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FORCE
Water based EOR diversion techniques
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IRIS

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Introduction

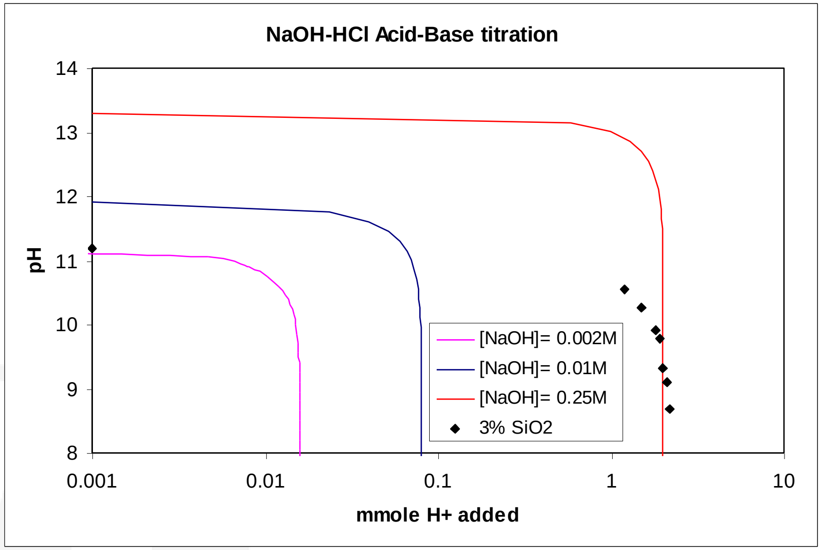
- Sodium silicate is an alkaline liquid
- Diluted, the viscosity is water like
- Upon reaction, triggered by temperature, or concentrations, silicate gel is formed
- Can be used for water shut-off or as diversion agent
- Sodium silicate is on the PLONOR list

Dissolution of ions

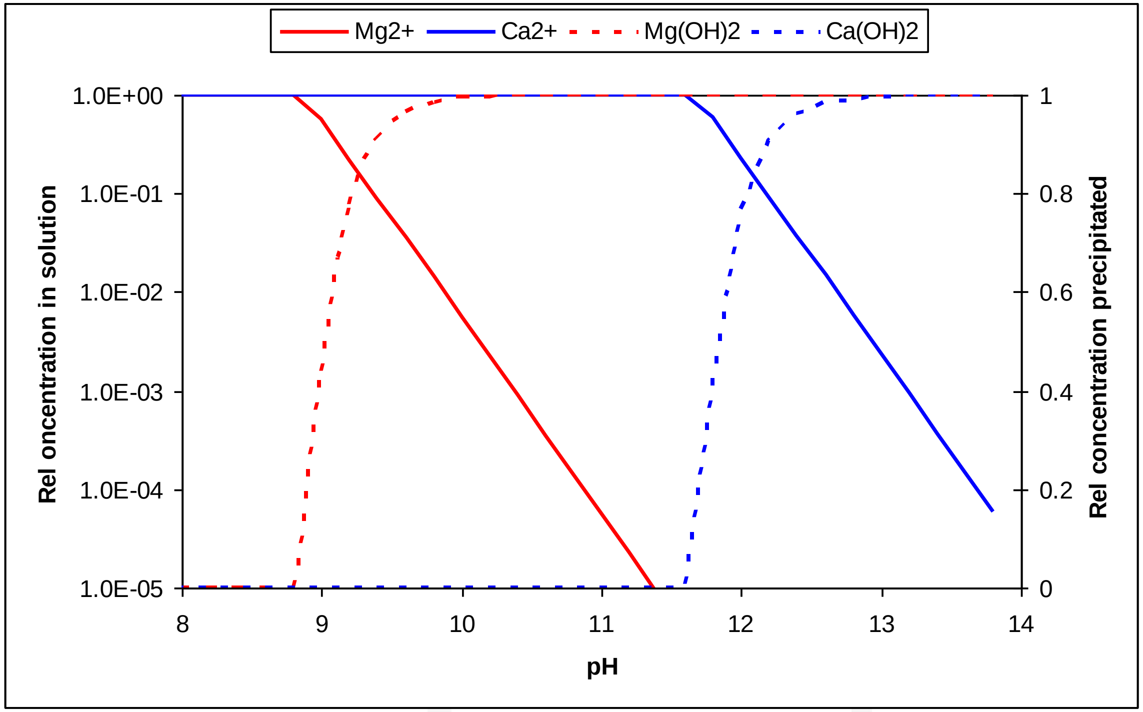
Reservoir minerals mixed with silicate or NaOH

- NaOH dissolves Al^{3+} while silicate did not
- Both NaOH and silicate dissolved Ca^{2+} (5-28 mg/l)
- No Mg^{2+} was dissolved. Precipitation of $Mg(OH)_2$ at high pH
- For NaOH the final pH was lowered while remained constant in silicate samples

$$K = 0.02 = \frac{[Al(OH)_4^-]\cdot[Si(OH)_3O^-]}{[OH^-]^2}$$



Silicate and divalent cations



Precipitation of $Mg(OH)_2$, while Ca^{2+} and Ba^{2+} will be soluble in alkaline brine
Core floods demonstrated higher mobility reduction when silicate displaced SSW.
When mixed in SSW, front plugging was observed.

Gelation kinetic

- As for most chemical gel system, the gelation kinetics

$$k = 1/t = f(T, C, salinity, pH, ...)$$

- By assuming independent variables, the following model is suggested

$$t_g = A \cdot e^{\alpha [Si]} e^{\beta [HCl]} e^{\gamma \sqrt{[Ca^{2+}]}} e^{Ea/RT}$$

- Need to define
  - The constant A and the exponents, α, β, γ and Ea

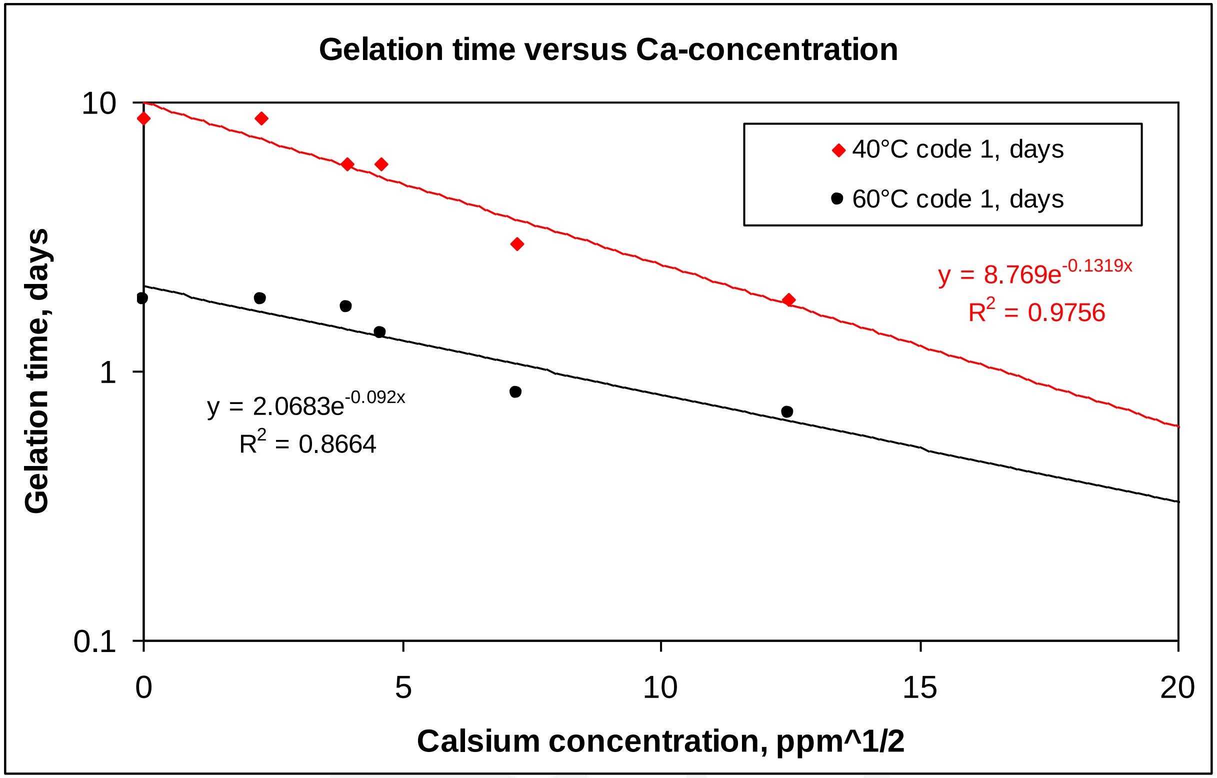
Bulk gelation time

- Define gel codes ranging from 0-3

Code	Bulk studies	Flood experiments
0	Blank	Good injectivity
1	Cloudy	Filtration and pressure increase
2	Cloudy, increased viscosity	Filtration and pressure increase
3	Rigid Gel	Complete blocking after shut in

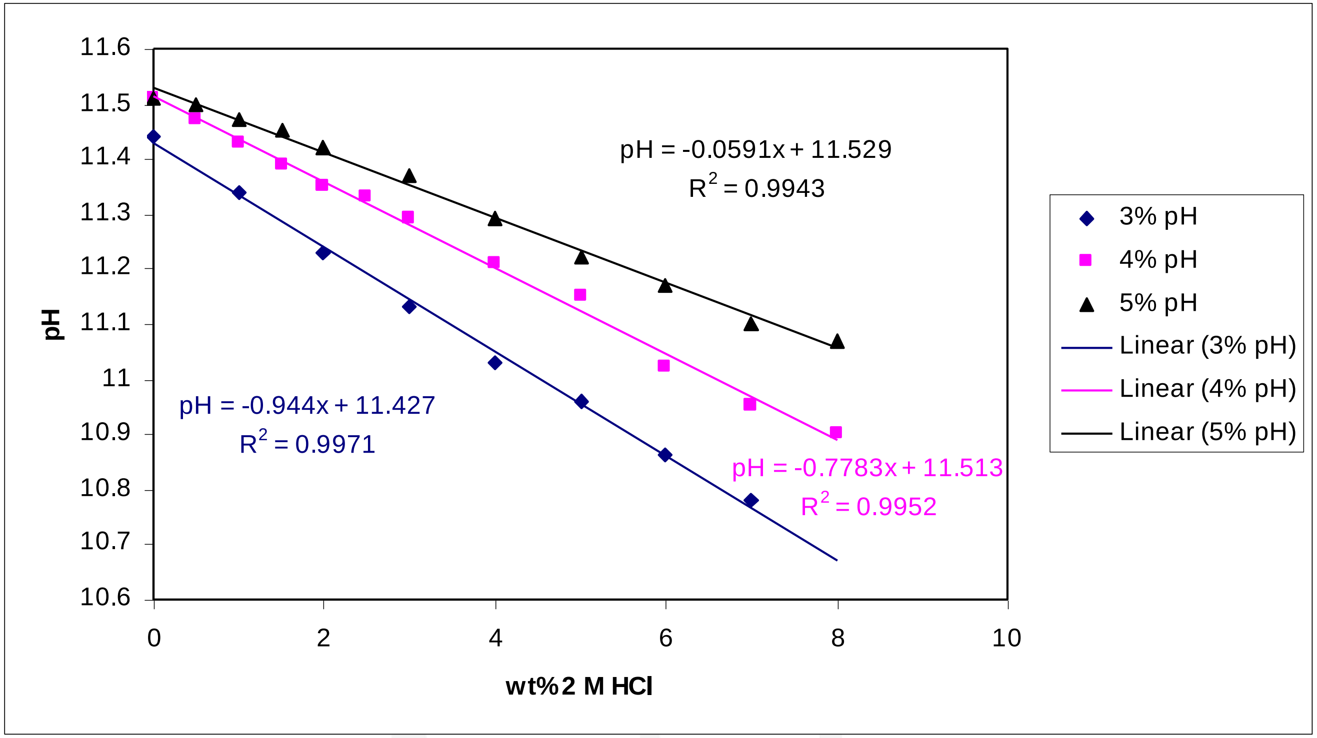
- Variables:
  - Silicate concentration, 3-5 wt%, K40 from BIM
  - Make-up water, distilled water, tap water, SSW
  - Temperature, 20-80°C
  - Acid, HCl, pH ~10.5-11.5
- Visual inspection of samples versus time
  - Gel code and syneresis

Gelation time versus Ca^{2+}



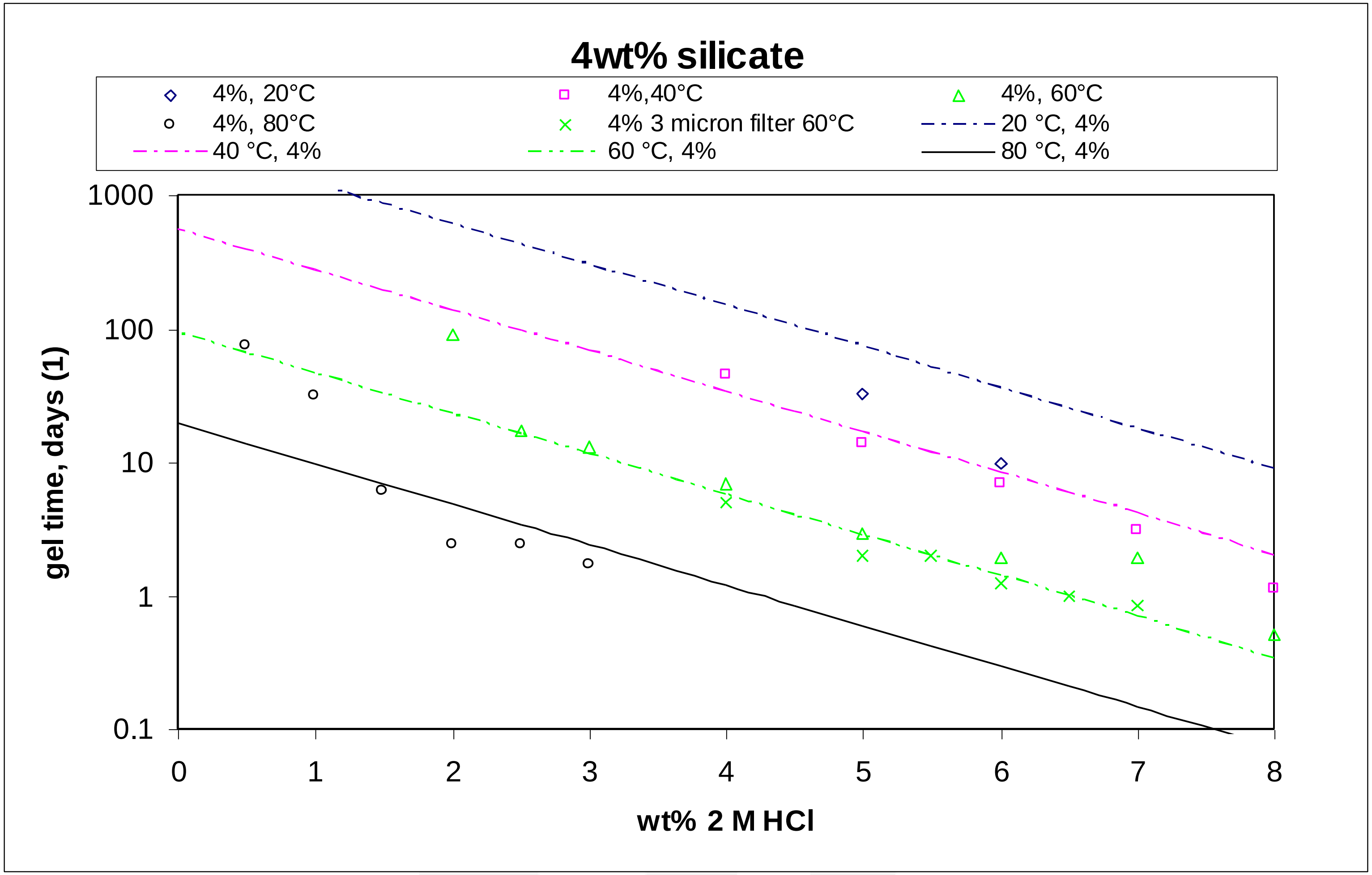
- Gelation time decreases by increasing calcium concentration
- Tap water with 20 ppm Ca^{2+} has gelation time 1.6 times lower than in distilled water

pH versus HCl concentration

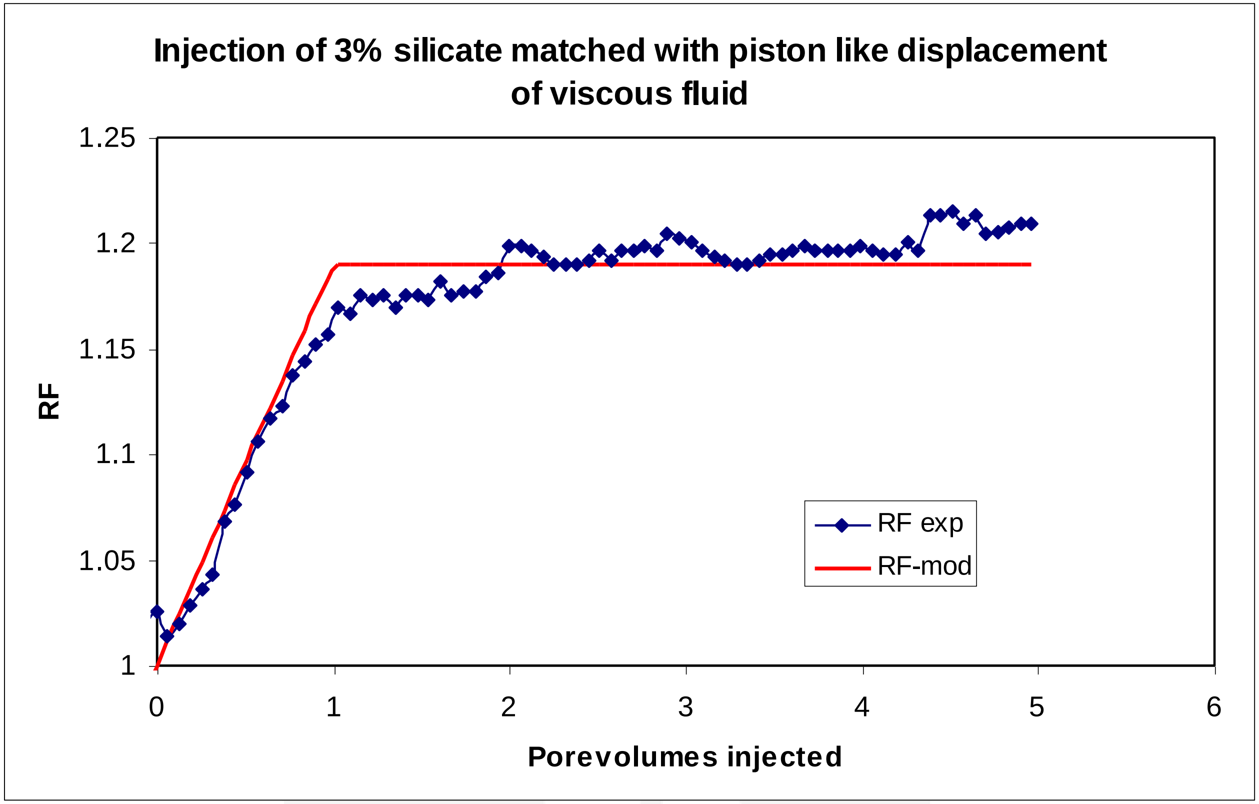


- Linear relationship between HCl added and pH
- Can design silicate system by controlling HCl added

Gelation time, experiment versus prediction

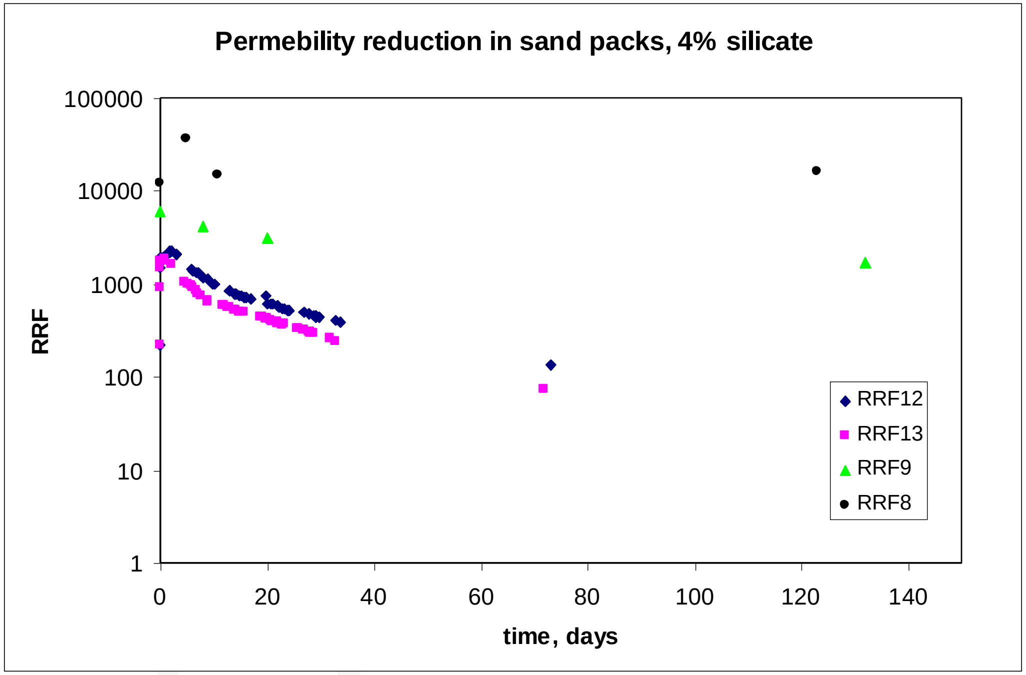


Mobility reduction during silicate injection



Permeability reduction 4 wt% silicate

- After shut-in permeability was measured by water injection
- Low silicate concentration (3 wt %) could not withstand high pressure gradients
- Higher silicate concentrations show proper stability, RRF in 9 Darcy sand of ~10^2-10^3



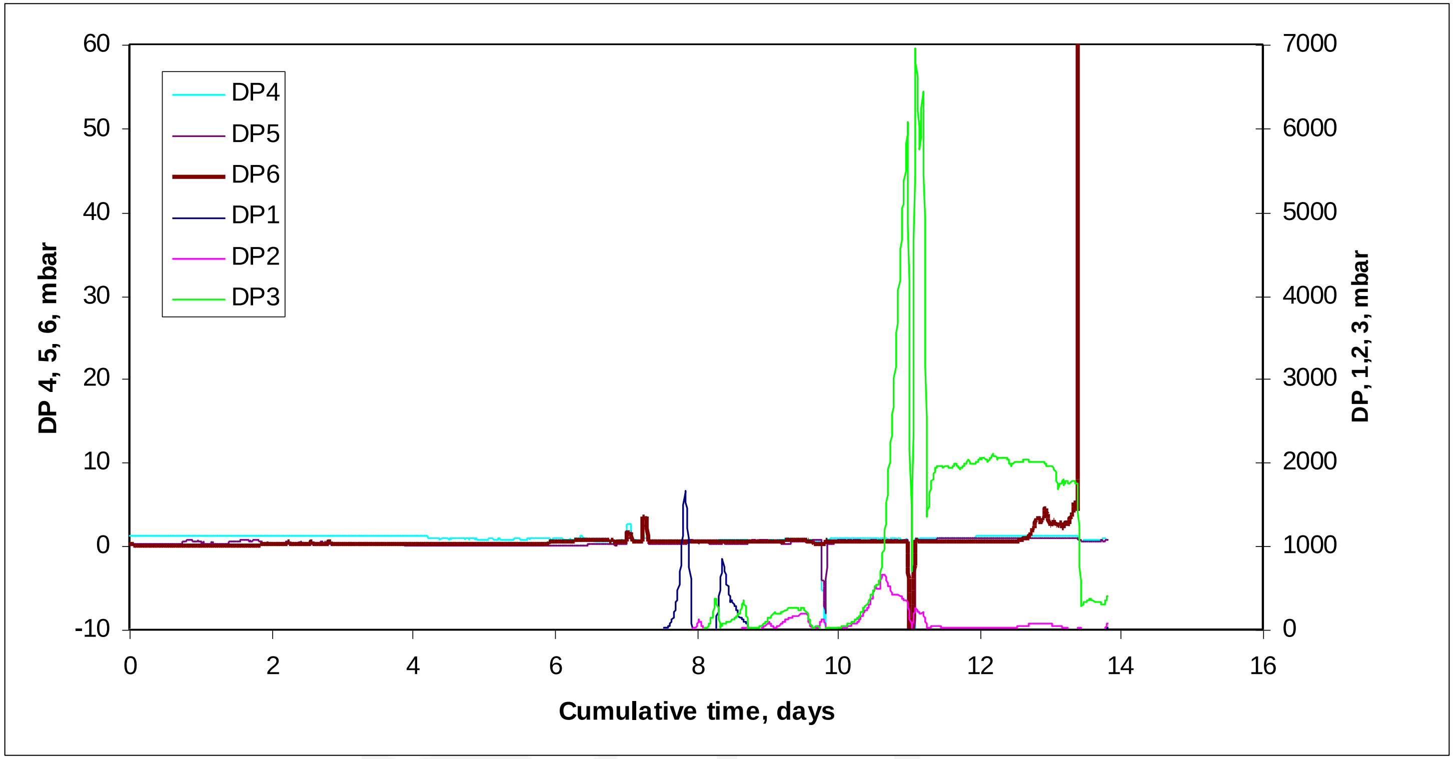
Dynamic flood experiments

- 3 x 75 cm columns, pv = 2100 ml, high permeability quartz sand
- 6 ΔP sections
- Temperature = 55°C
- 4 wt% silicate + acid + tap water, injected from piston cell
- Flow rate
  - D1-D2: 0.24 ml/min, residence time of 6 days
  - D3: decreasing from 12 – 0.03 ml/min, residence time varies from 0.04 – 17.1 days
- Objectives
  - Compare dynamic plugging time with bulk gelation time
  - Demonstrate that plugging time and location can be controlled
  - Silicate retention in porous media
  - Contribute to design field pilot

Experiment D1

- From gelation model define a system which has bulk gelation time = 3.2 days – 4.76 wt% HCl
  - Did not form gel after 7 days at 55°C
  - Increased temperature to 64 °C, gel formed after total injection time of 13.5 days
  - In terms of residence time (at 55°C) gelation at 11.6 days, which is 3.6 time longer than predicted
    - It was observed that effluent silicate concentration was ~70% of injected, (corresponds to a factor of 2)
    - High perm sand assumed to show longer plugging time than low perm sand (factor of ~1.3)

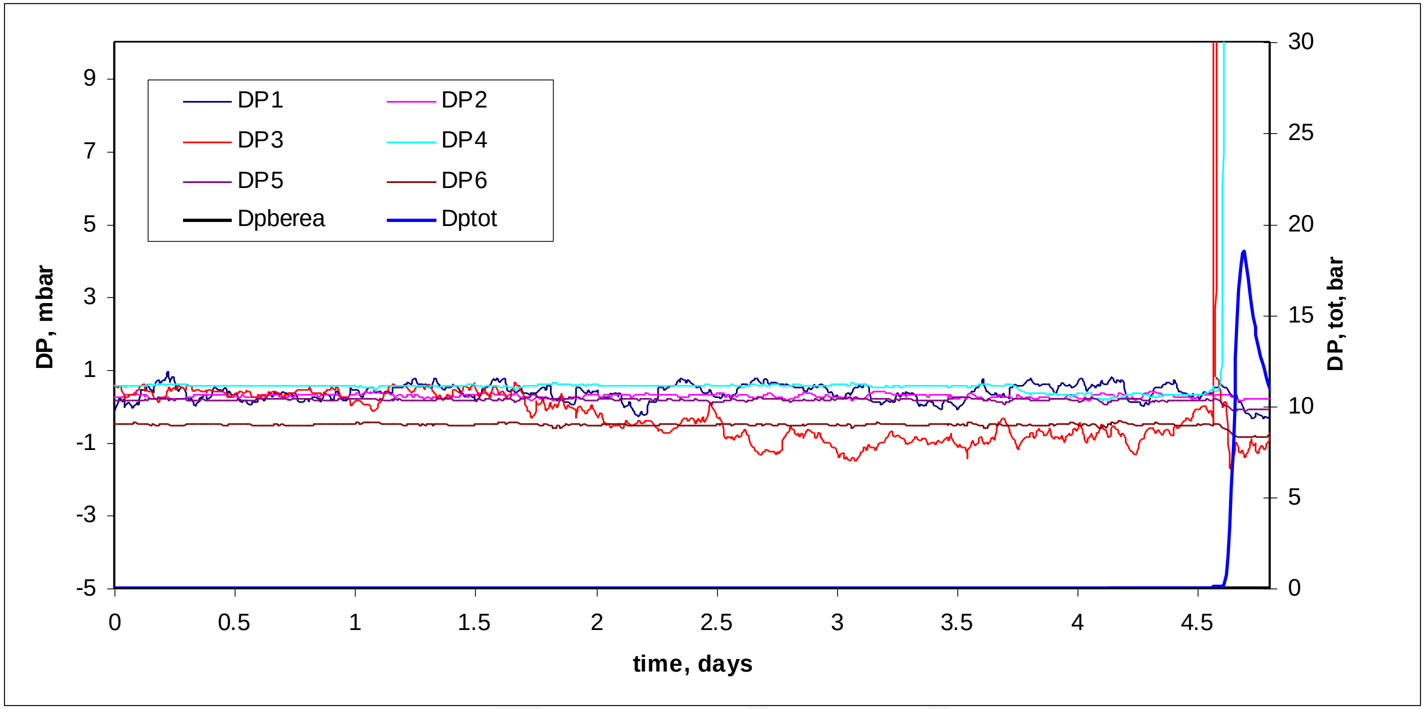
D1, Pressure profile



Experiment D2

- Adjust gel model with a factor of 3.6 to produce plugging at 3.4 days – 6.5 wt% HCl
- Plugging was observed at 4.6 days, sections 3 and 4, strongest in section 4 (residence time = 3-4 days)
  - Silicate front has reached section 5 but no gel, probably because of diluted silicate in the front
  - Good agreement with prediction
- Post water injection show stable permeability reduction for more than 2 months
- No permeability reduction in sections 1 and 2

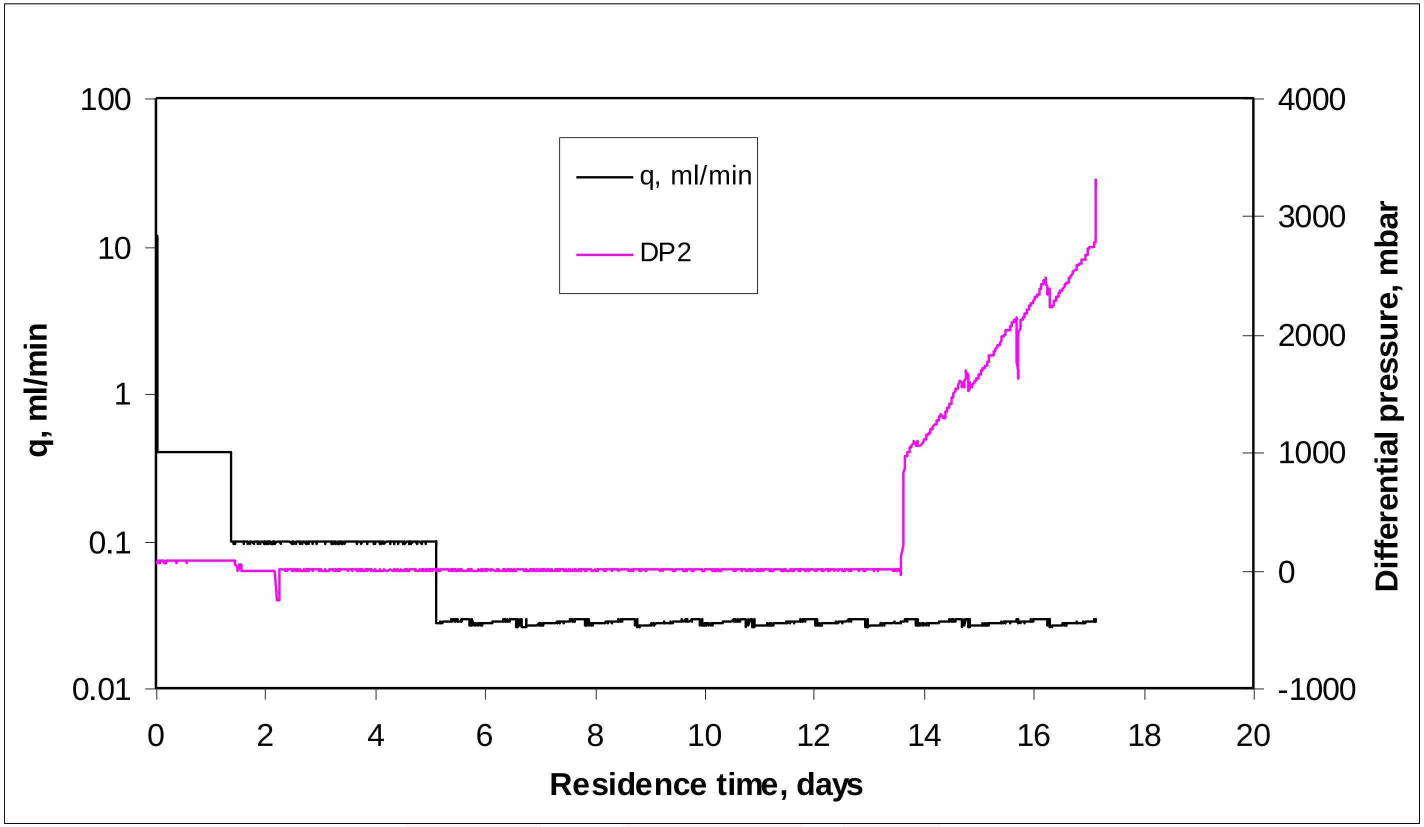
D2, Pressure profile



Experiment D3

- Rerun D1 – 4.76 wt% HCl
- Initially the flow rate was 12 ml/min, step wise decreased to 0.03 ml/min
- According to adjusted model, plugging at residence time of 11.6 days
  - Observed plugging in section 2 at total residence time of 13.6 days
  - No plugging in section 1, residence time > 6.8 days
- Effluent concentrations depend on residence time

D3, pressure profile



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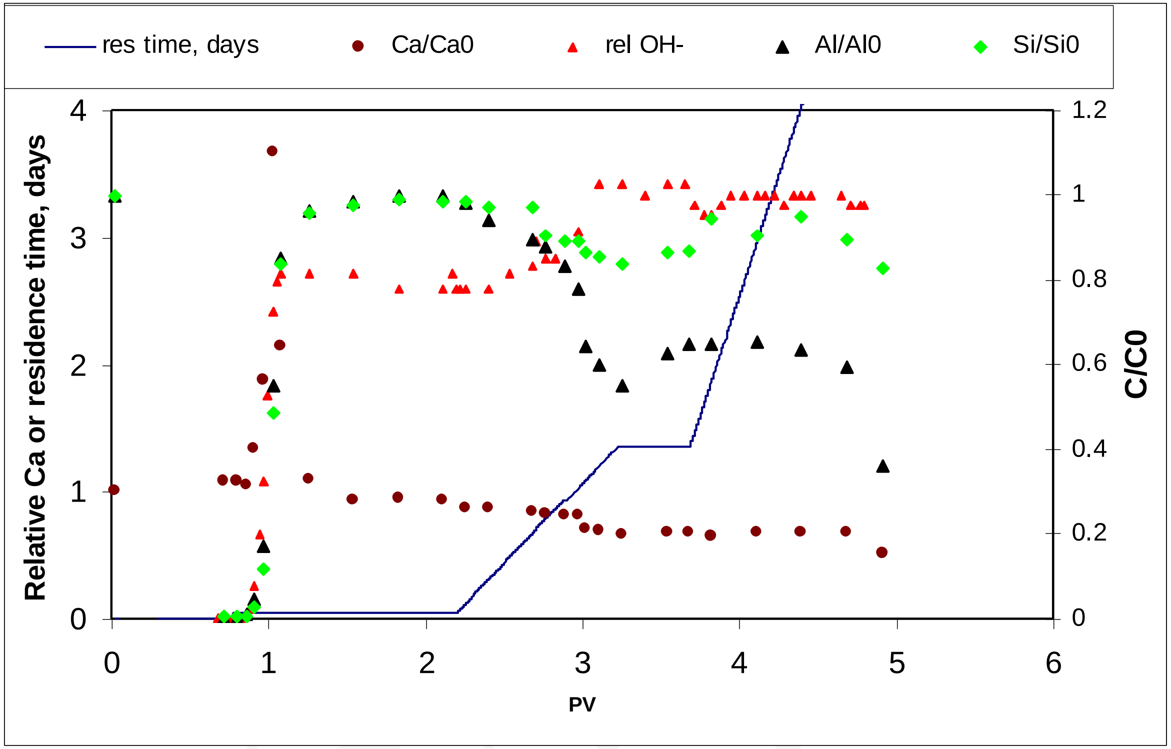
D3, Effluent concentrations



Al and Si concentration decreases as residence time increases

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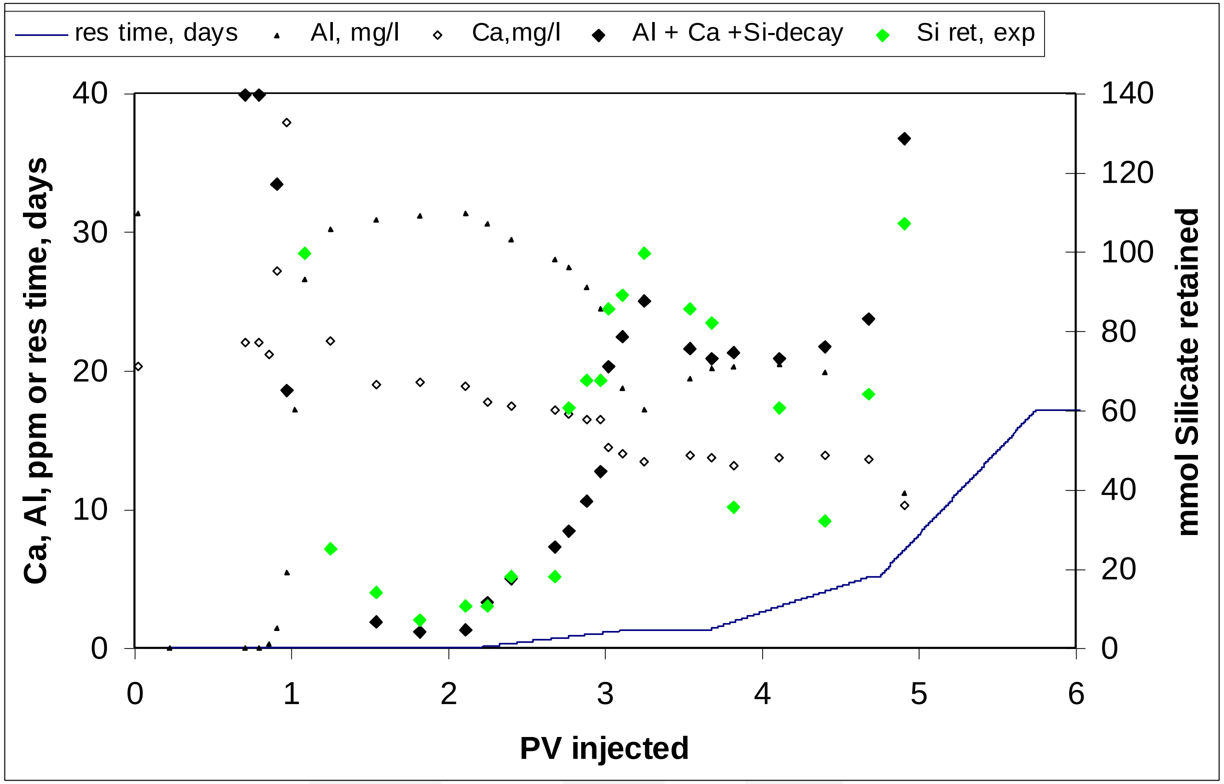
D3, Silicate retention vs residence time

$$Si_{retained} = Si_0 \cdot (1 - e^{-\lambda t}) + nAl_{retained} + mCa_{retained}$$



Dynamic experiments - summary

	D1	D2	D3
Silicate conc, wt%	4	4	4
HCl, wt%	4.76	6.5	4.76
Temp, °C	55 and 64	55	55
Residence time	6.13	6.07	0.04-17.1
Flow rate, ml/min	0.24	0.24	12-0.03
Planned plugging time, days	3.2	3.4	11.6
Observed plugging time, days	11.6	4.6 (3 – 4)	13.6 (6.8 – 13.6)

Conclusions

- Sodium silicate is a good buffer and show good injectivity prior to gelation
- A gelation model controlled by pH, temperature, concentrations and salinity matches bulk gelation experiments
- The gelation model, accounted for silicate retention and high permeability, predicts plugging time observed in dynamic flood experiments
- It is possible to design a silicate system with given gelation time by controlling the concentration of HCl
- In dynamic flood experiments RRF was in the order of 10^3-10^4 and somewhat lower in static experiments
- Silicate gel can be dissolved by high pH

Snorre in-depth water diversion using Silicate

2009 Work completed

- DG0 – Large scale implementation
- Laboratory program - phase 1

2010 Operator's plan

- Laboratory program - phase 2
- P07 single well Silicate injection pilot 2q2010
  - Operational experience from preparing and injecting Sodium Silicate
  - Confirm placement of an in-depth permeability reduction approx. 30-50 m from the wellbore

2011+ Operator's preliminary plan

- Two well pilot
- Requirements
  - Successful single well silicate injection pilot in P07
  - Positive results from laboratory program phase 2
  - Suitable area/well pair – IOR potential, response measurement and cost

Acknowledgements

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  - Statoil AS (Operator)
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