Formation waters as scale inhibitors: the benefits of scale deposition in the reservoir

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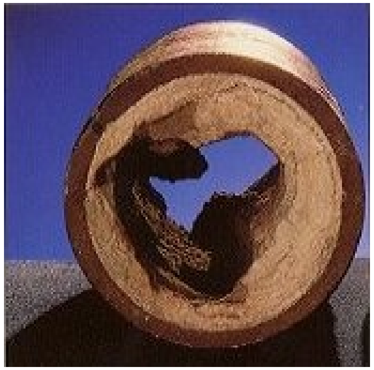
Outline

- Background
  - ➢ Scaling challenges in the North Sea
  - ➢ Current methods of scale risk prediction for waterflood reservoirs
- Evidence for reservoir reactions
- Tools and models
- Key reactions
- Role of formation water
  - ➢ Ca-rich and Ca-depleted formation waters
- Field applications – Frøy Field
- Conclusions

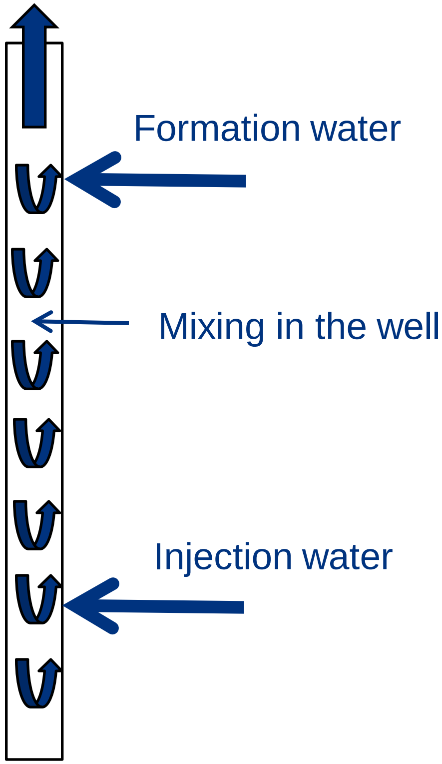
Background

- Prevention and removal of scale deposition is a major production cost in the North Sea.
- Operational costs:
  - Monitoring – frequent sampling/analysis of produced waters, well testing
  - Mitigation – downhole injection, squeeze treatment
  - Removal – scale dissolvers, mechanical
  - Deferred oil costs

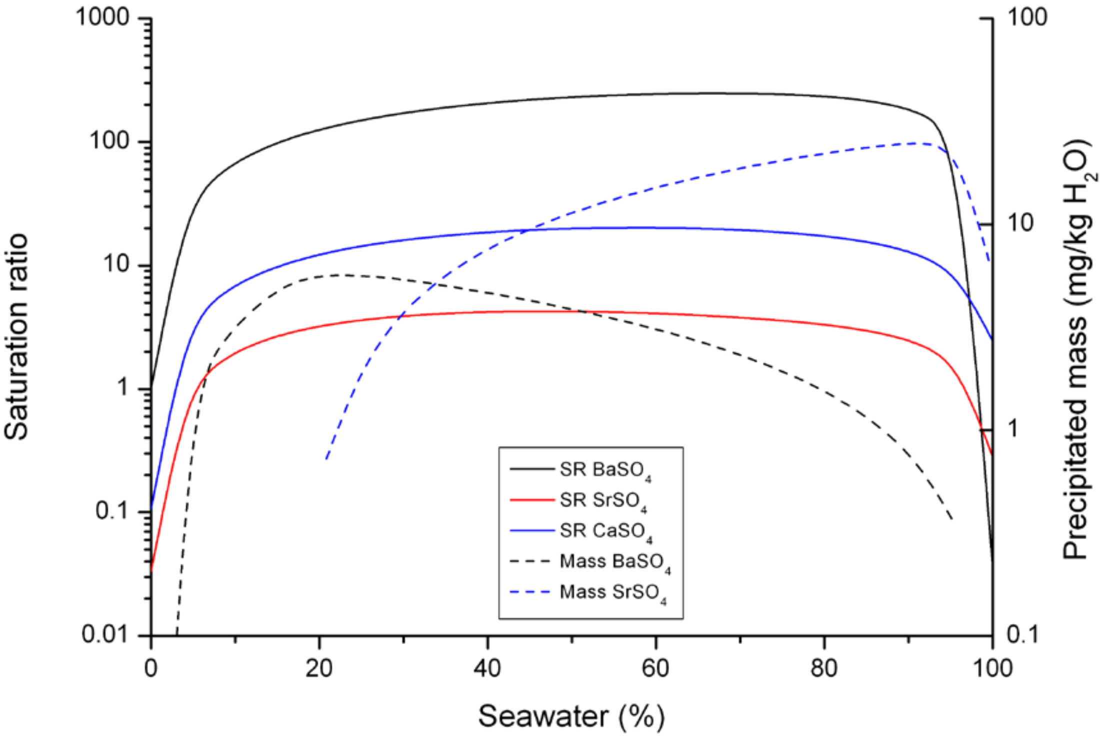


- Types of scale:
  - $CaCO_3$ – self-scaling - formation water pressure reduction
  - $BaSO_4$, $SrSO_4$, $CaSO_4$ – mixing of incompatible brines - commingling of seawater and formation water
  - Brine evaporation – minor formation water production, HP/HT wells, gas wells

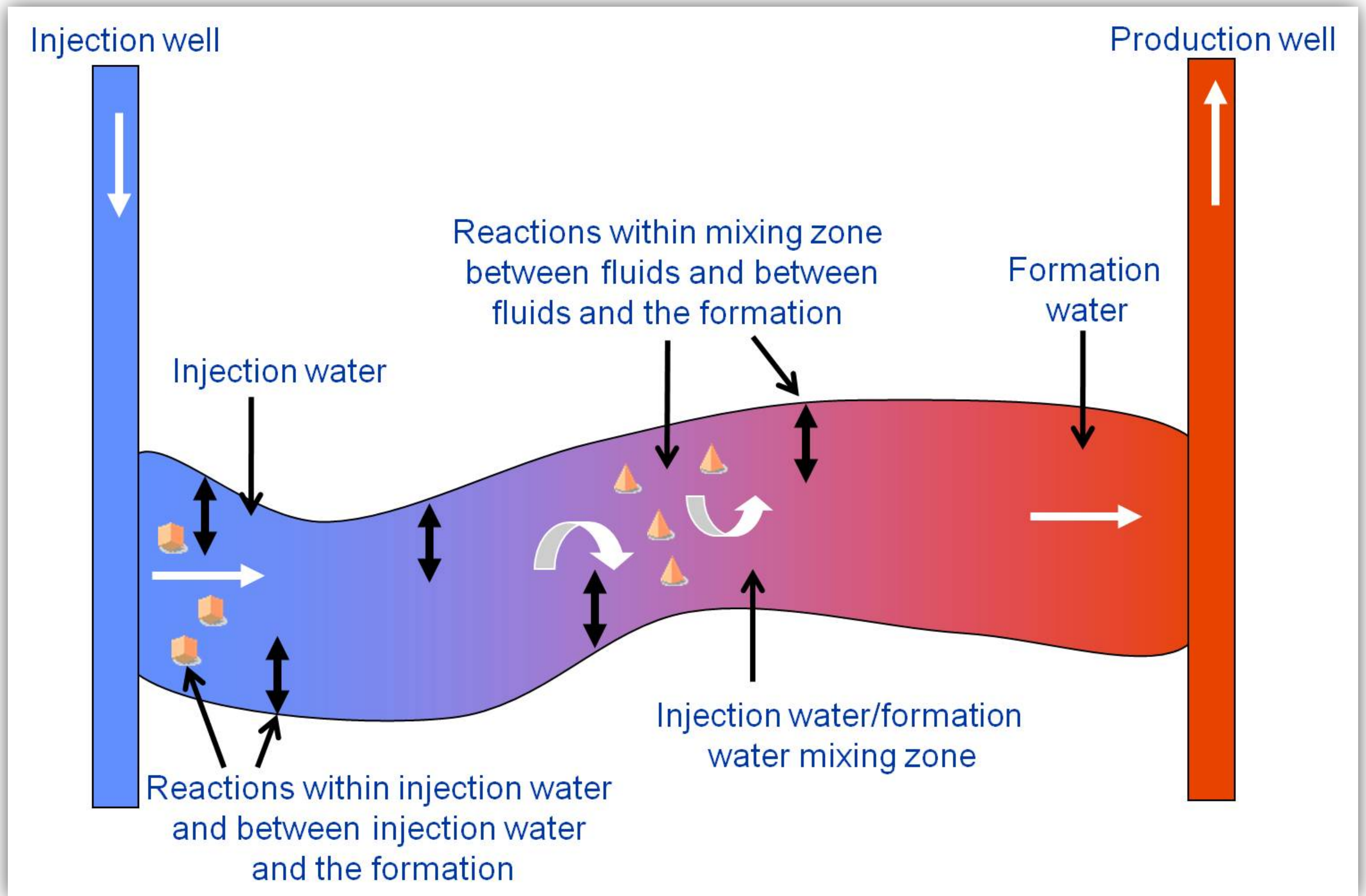
Current methods of prediction



- Flash calculations predict scale risk (saturation ratios and precipitated masses).
- Results used to select scale mitigation chemicals and dosages, and to plan produced water monitoring.
- Predictions are conservative – no account of the effects of reservoir reactions.



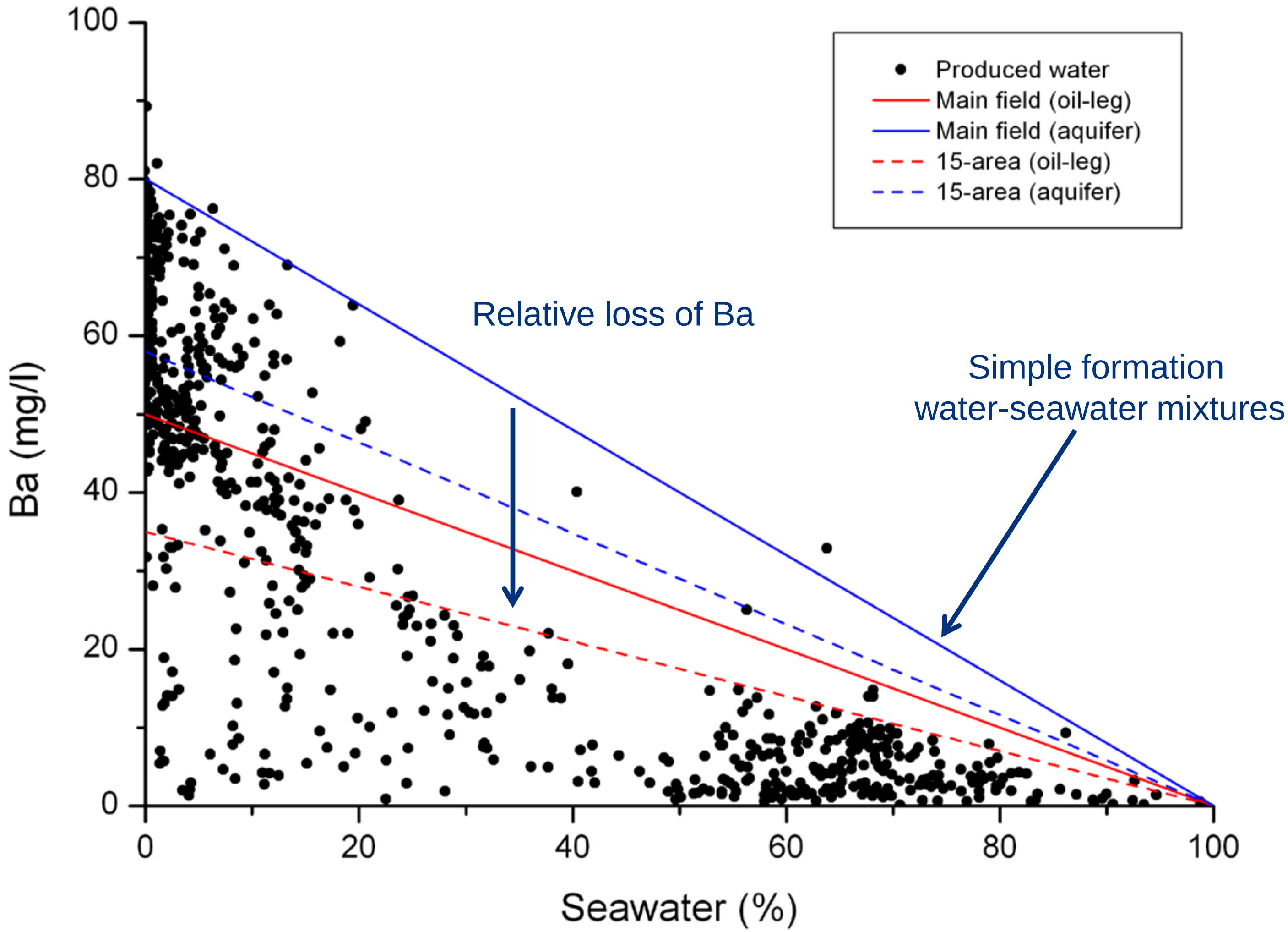
Reservoir reactions



Evidence for reservoir reactions

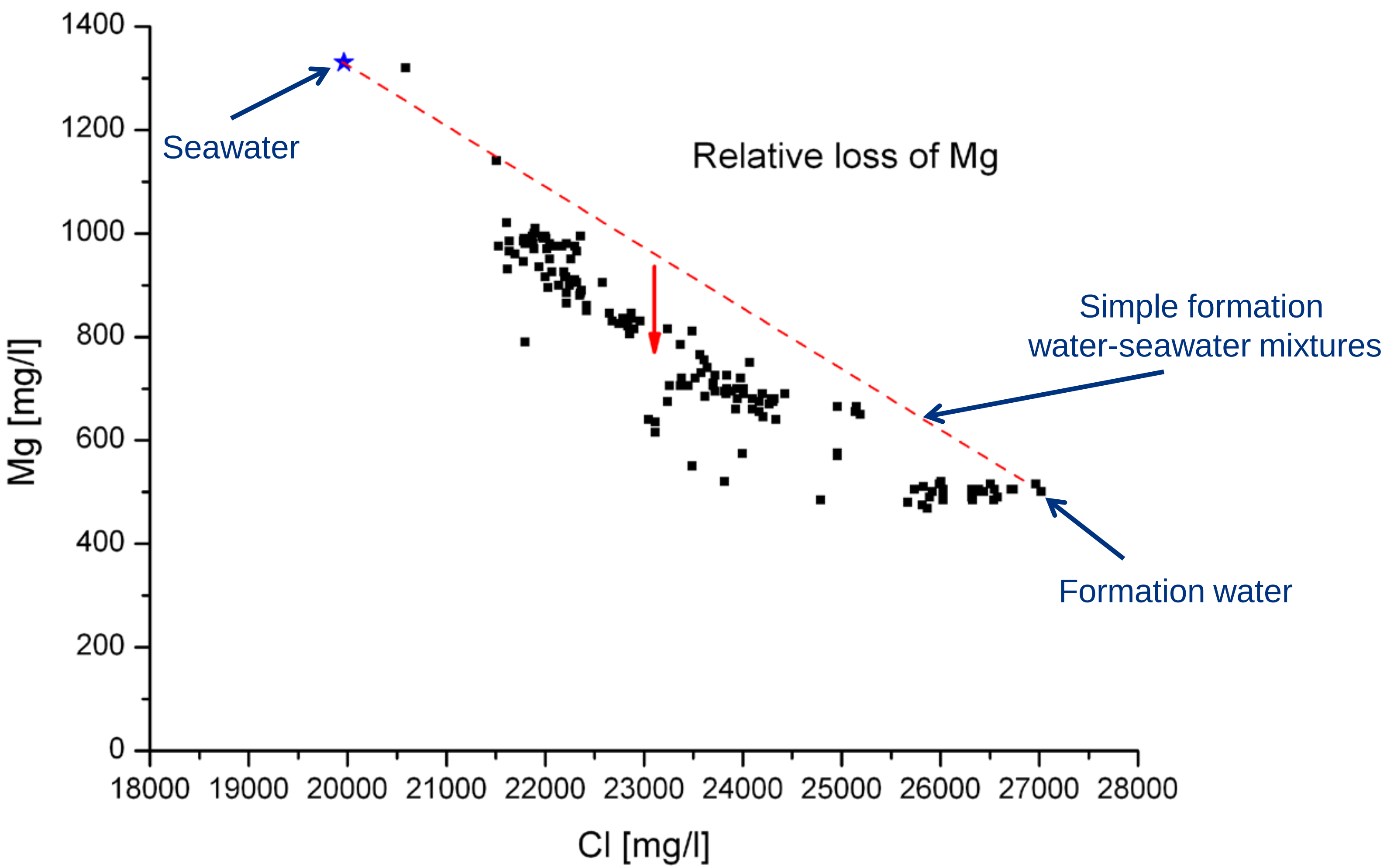
- Alba Field

White et al. (1999)



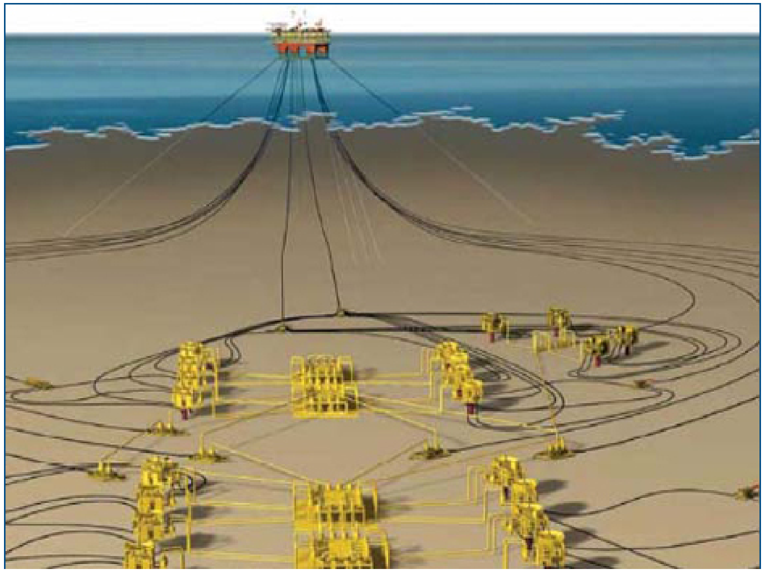
Evidence for reservoir reactions

- Field X, Norwegian North Sea



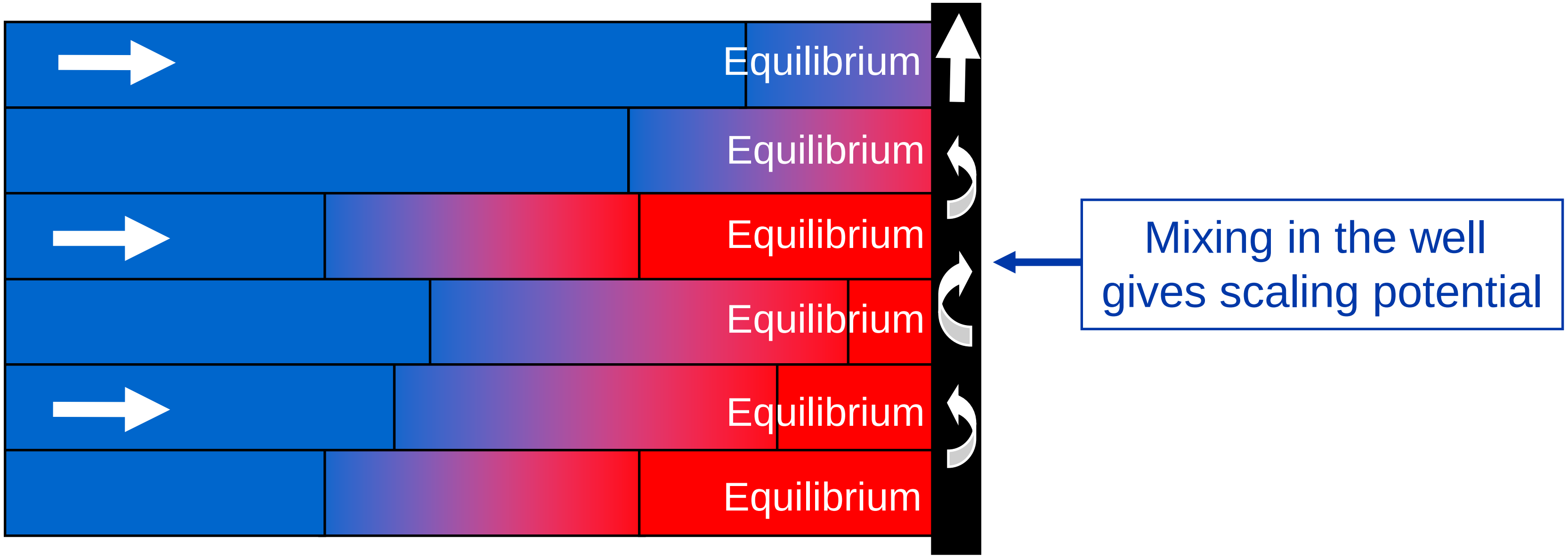
Implications

- Removal of scaling ions in the reservoir reduces the scaling risk to the production wells.
- Standard scale prediction calculations are conservative – no allowance for ‘upside’ – lower scale mitigation chemical requirements, fewer well interventions, etc.
- Caution required when using ion concentrations to monitor downhole scaling, to identify injection water breakthrough and percentage of injection water in produced water.
- With increasing development of deepwater and subsea fields, scale mitigation operations are becoming more complex and costs are high.
- Need to consider effects of reactions in selection of scale mitigation methods (chemicals vs change of injection water) and in estimating scale mitigation costs.
- So, many drivers to gain greater understanding of reactions occurring in the reservoir, and to develop and apply tools to predict their effects on produced water compositions.



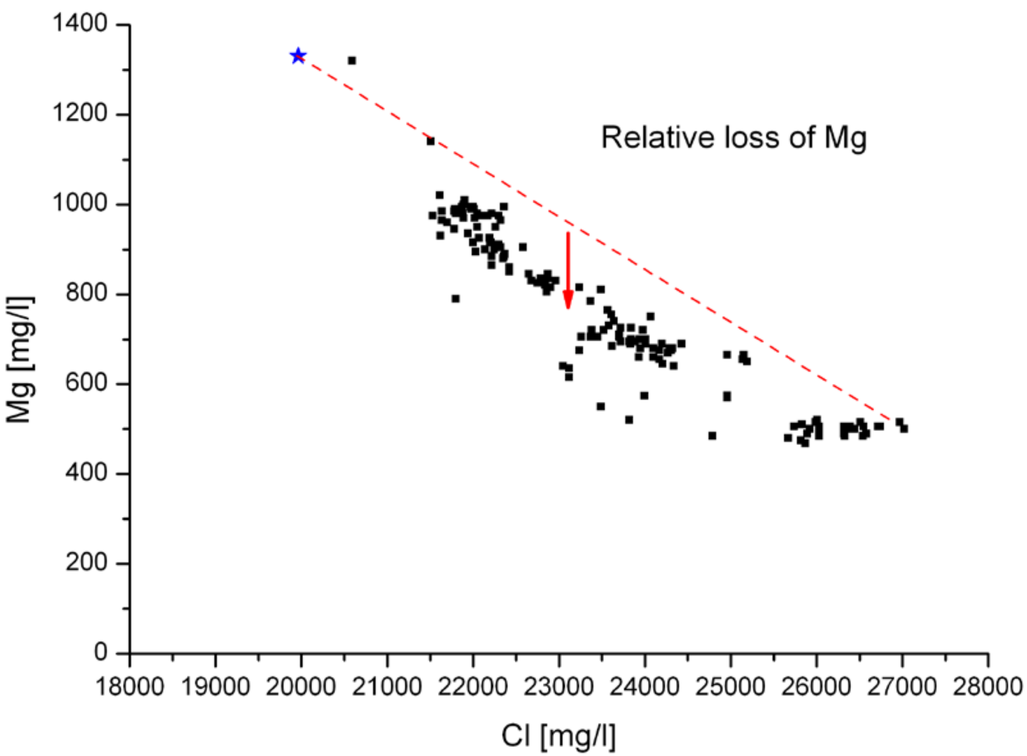
Conceptual model

- Multiple flow paths connect the injection and production wells.
- Along each path, injection waters (IW) and mixtures of waters (IW-FW) react to ~equilibrium with the reservoir rock before they reach production wells.
- At any one time, different waters (IW, IW-FW, FW), with different compositions), enter the well at different locations.
- Scaling risk is the result of these waters mixing in the well.
- For scaling predictions need to know reactions occurring, and types, rates and reacted compositions of these waters.



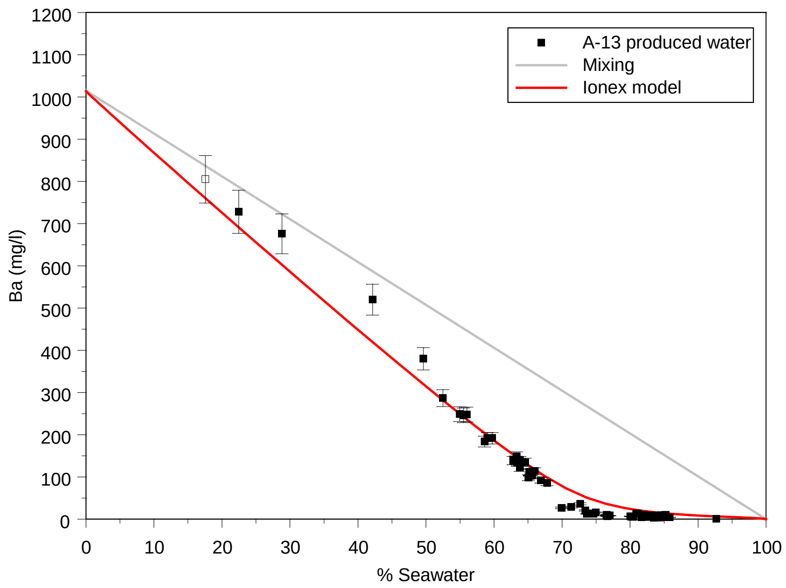
Tools

- Number of studies of reservoir reactions have been undertaken, particularly in the last 5-10 years.
- Tools applied:
  - Comparison of formation water-injection water theoretical mixing compositions with actual produced water compositions – to identify gains/losses of constituents in the reservoir from injection water and formation water/injection water mixtures.



Tools

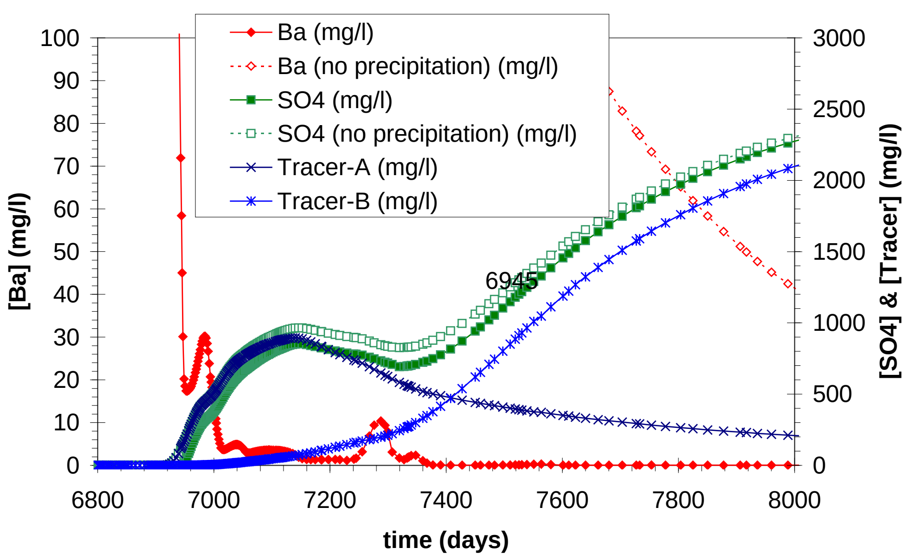
- Geochemical models, 1-D reactive transport models
- 1-D models simulate reservoir reactions along a single path and cannot simulate the effects of mixing in the production well.
- These have been used to:
  - Understand reactions occurring in the reservoir by approximately matching the gains and losses of constituents observed in produced waters (qualitative 'history-matching').
  - Provide qualitative predictions about the effect of changes in injection water composition or increasing injection water fractions in the produced water.

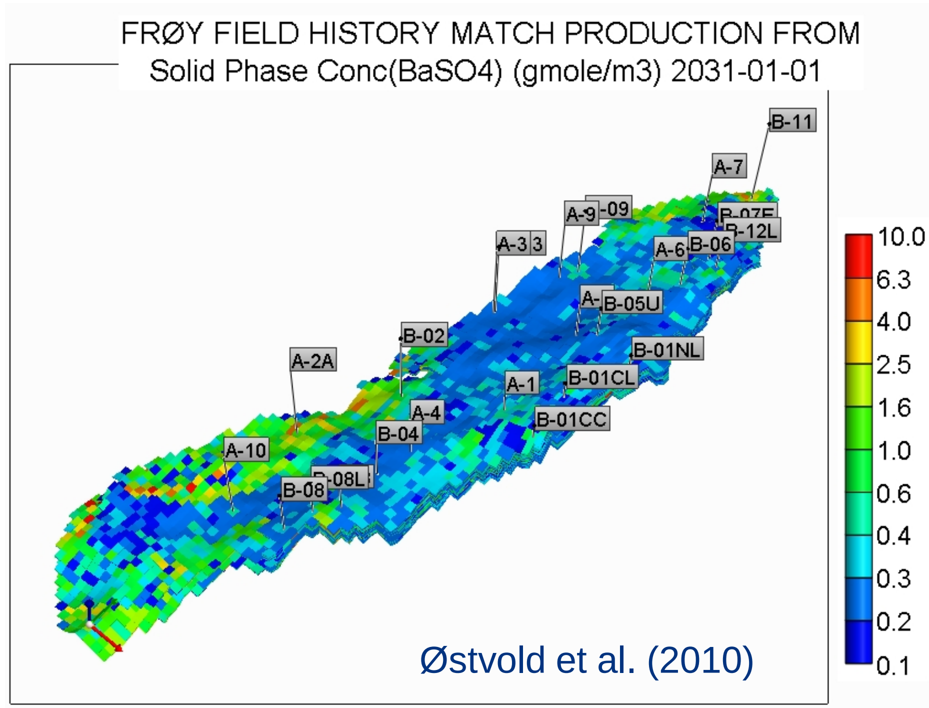


McCartney et al. (2007)

Tools

- Reactive transport reservoir models (e.g. STARS).
- These have been used to:
  - Understand reactions occurring in the reservoir by matching the gains and losses of constituents observed in produced waters (quantitative 'history-matching').
  - Provide quantitative predictions about the effect of changes in injection water composition or increasing injection water fractions in the produced water.





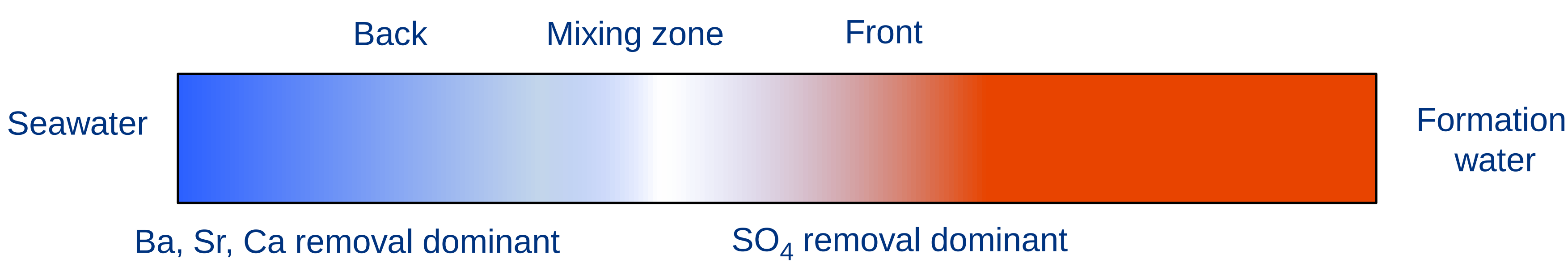
Østvold et al. (2010)

Key reactions

- Reactions occur primarily in the injection well area and in the injection water-formation water mixing zone as it is displaced across the reservoir by water injection.
- Pattern emerging from ‘history-matching’ studies that produced water compositions can be explained using a limited set of ‘rapid’ reservoir reactions:
  - Sulphate mineral dissolution/precipitation :
    - $BaSO_4$, $SrSO_4$ – mainly precipitation within the mixing zone
    - $CaSO_4$ – precipitation in the mixing zone and above ~130^oC from injected seawater in the injection zone
  - Carbonate mineral dissolution/precipitation:
    - Primarily $CaCO_3$, lesser $(Ca,Mg)(CO_3)_2$ in sandstone reservoirs.
    - Both $CaCO_3$ and $(Ca,Mg)(CO_3)_2$ in carbonate reservoirs.
  - Multi-component ion exchange (Na, K, Ca, Mg, Ba, Sr)
  - Souring - <90^oC
- Kinetics appears to be important for dolomite reactions but not for sulphate-mineral, $CaCO_3$ or ion exchange reactions – reactions proceed to equilibrium in less time than typical reservoir transit times (months, years).

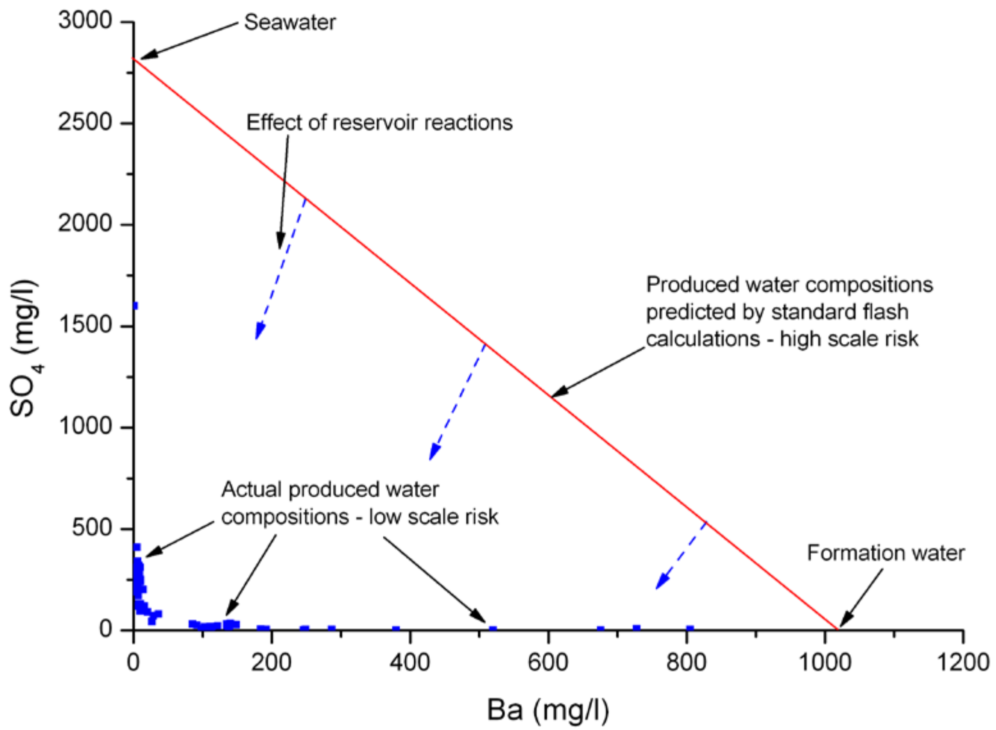
Role of formation water

- Most important where seawater injected.
- Formation water reacts with seawater in the mixing zone.
- $BaSO_4$, $SrSO_4$, $CaSO_4$ can precipitate where solubility exceeded.
- Removal of Ba, Sr, Ca and SO_4 in the mixing zone in the reservoir reduces scaling risk in the production wells – nature's scale inhibitor.
- At lower seawater fractions, front of the mixing zone, high Ba, Sr and Ca in the formation water component causes SO_4 removal from the seawater/formation water mixtures.
- At higher seawater fractions, further back in the mixing zone, high SO_4 in the seawater component causes Ba, Sr and Ca removal from the seawater/formation water mixtures.
- The higher Ba+Sr+Ca in the formation water, the more SO_4 that is removed, the further back into the mixing zone that SO_4 is removed and elevated concentrations of Br, Sr and Ca remain.



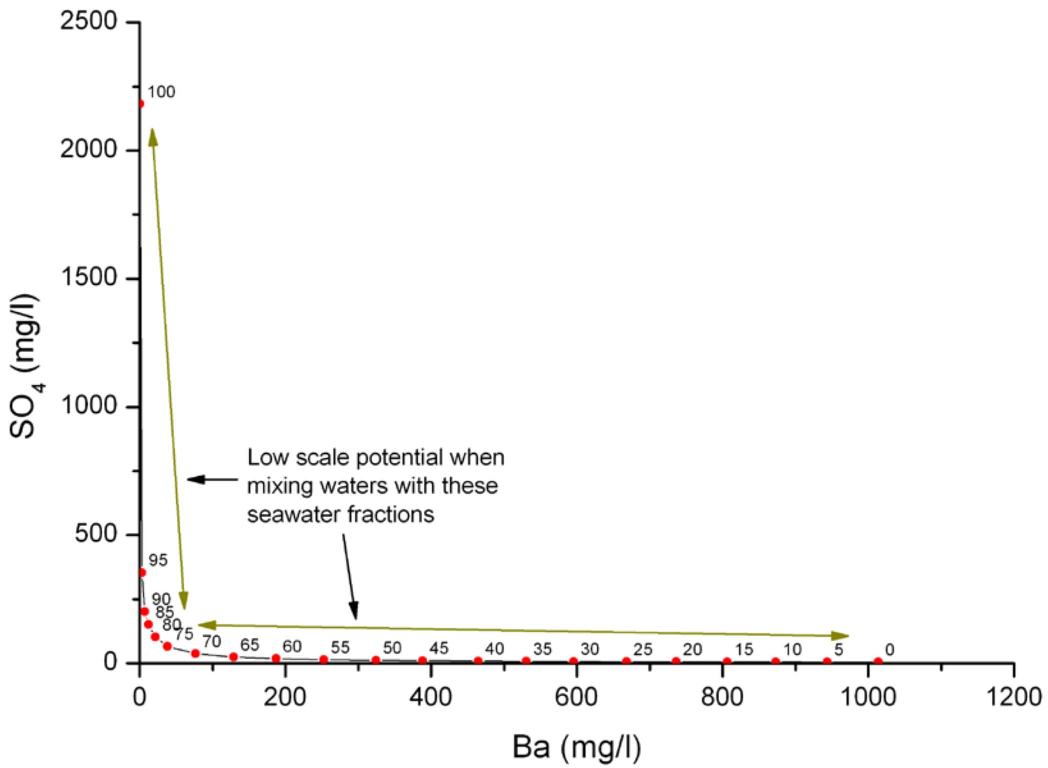
Ca-rich formation water

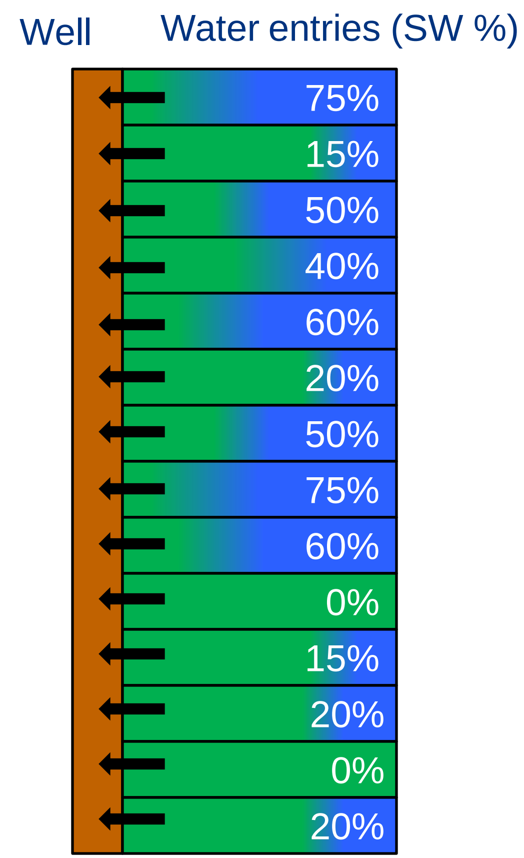
- Ba and Sr are less than 4000 and 2500 mg/l respectively in North Sea formations waters but Ca can be as high as ~60,000 mg/l.
- So the most effective formation waters for removing SO_4 in the reservoir are Ca-rich formation waters (e.g. Skagerrak, Pentland, Ula/Gyda and Fulmar Formations of the Central Graben).
- For example, the Gyda Field (37,000 mg/l Ca) should have a very high SO_4-mineral scaling risk but due to $CaSO_4$ deposition in the reservoir this is not the case.



Ca-rich formation water

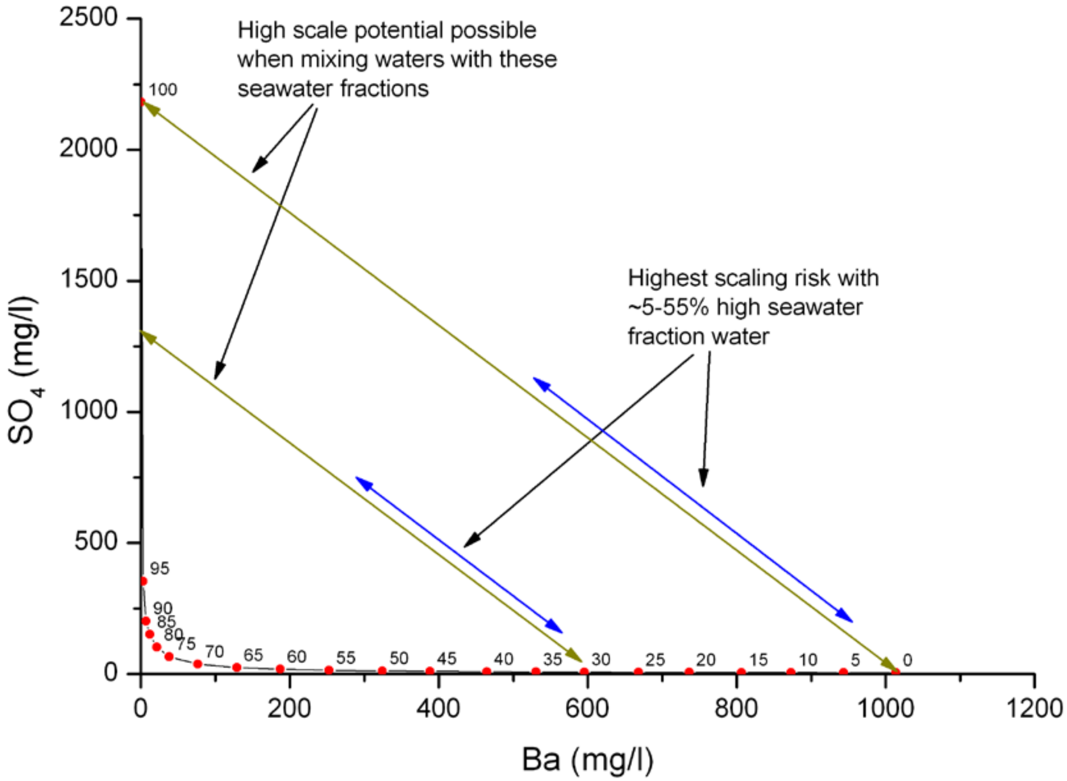
- 1-D reactive transport model for Gyda – good match to actual produced water analyses.
- Model shows that as long as all the fluids entering a well are <75% or >75% seawater the $BaSO_4$ scaling risk is low.
- Reservoirs with Ca-rich formation water are very ‘forgiving’ – even with heterogeneous formations it is likely that the $BaSO_4$ scaling risk will be low.

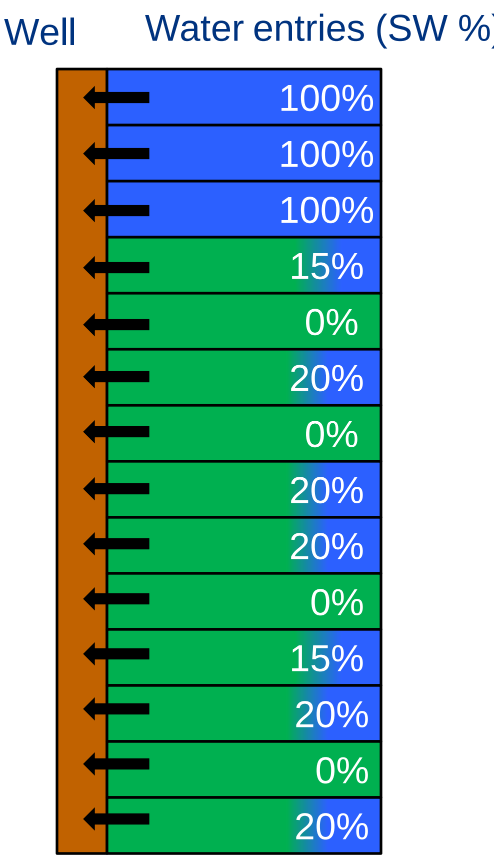




Ca-rich formation water

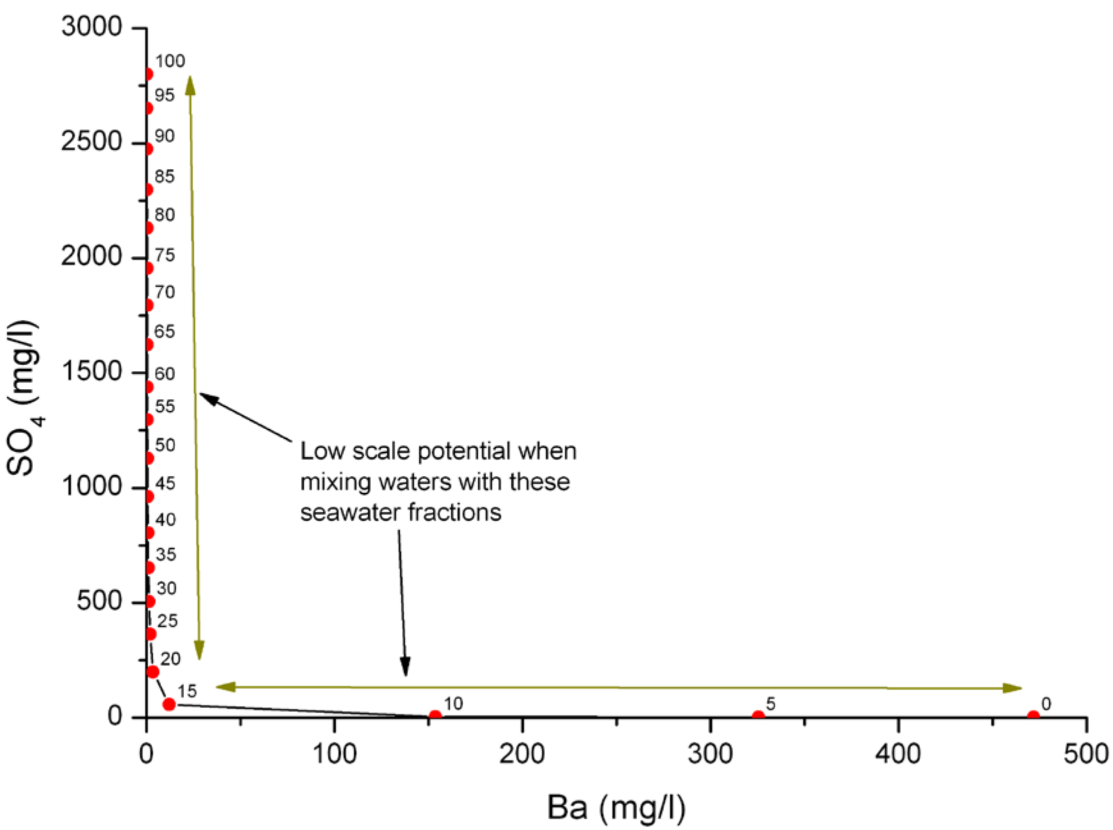
- Principal risk of high $BaSO_4$ scaling risk in reservoirs with Ca-rich formation water is where:
  - A ‘thief’ zone is present so high SW fraction water (95-100%) enters the well with low SW fraction water (e.g. ~<30%). This is more likely to occur earlier in well life.
  - The high seawater fraction is between ~5 and 55% of the total produced flow.
- If the high seawater fraction represents a high (>55%) or very low (<5%) proportion of the total produced flow the scaling risk will still be low.

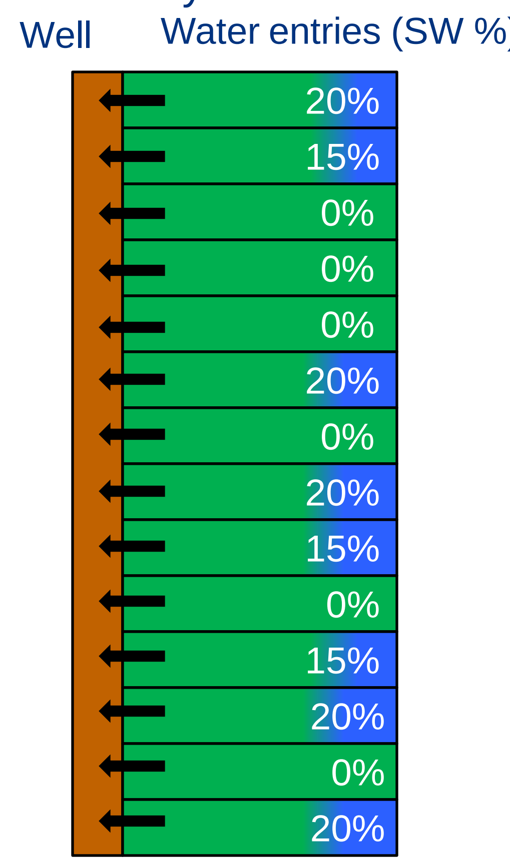




Ca-depleted formation water

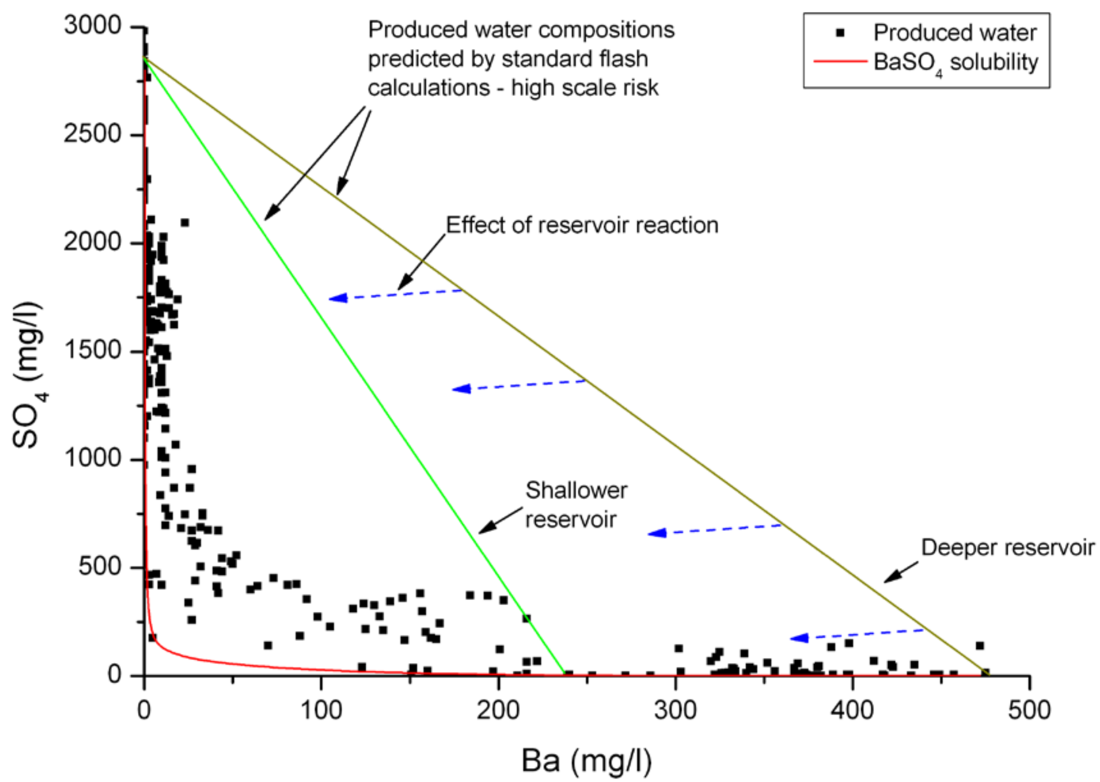
- 1-D reactive transport model results show that as long as all the fluids entering a well are <15% or >15% seawater the $BaSO_4$ scaling risk is low.
- If mixing of moderate-high seawater fraction water (>15%), and low seawater fraction water occurs, the scale risk might still be low if the proportion of high seawater fraction water is high (>55%) or very low (<5%)
- Reservoirs with Ca-depleted formation water are not very ‘forgiving’ – relatively homogeneous reservoirs are required for the $BaSO_4$ scaling risk to be very low.





Ca-depleted formation water

- For example, the X Field, UK North Sea (300-800 mg/l Ca) should have a very high SO_4-mineral scaling risk but due to $BaSO_4$ deposition in the reservoir, and favourable reservoir architecture, this is not the case.
- Note that most of the data does lie above the $BaSO_4$ solubility line indicating production of (a) low seawater fraction water (<15% seawater) or formation water and (b) moderate-high seawater fraction water (>15% seawater).



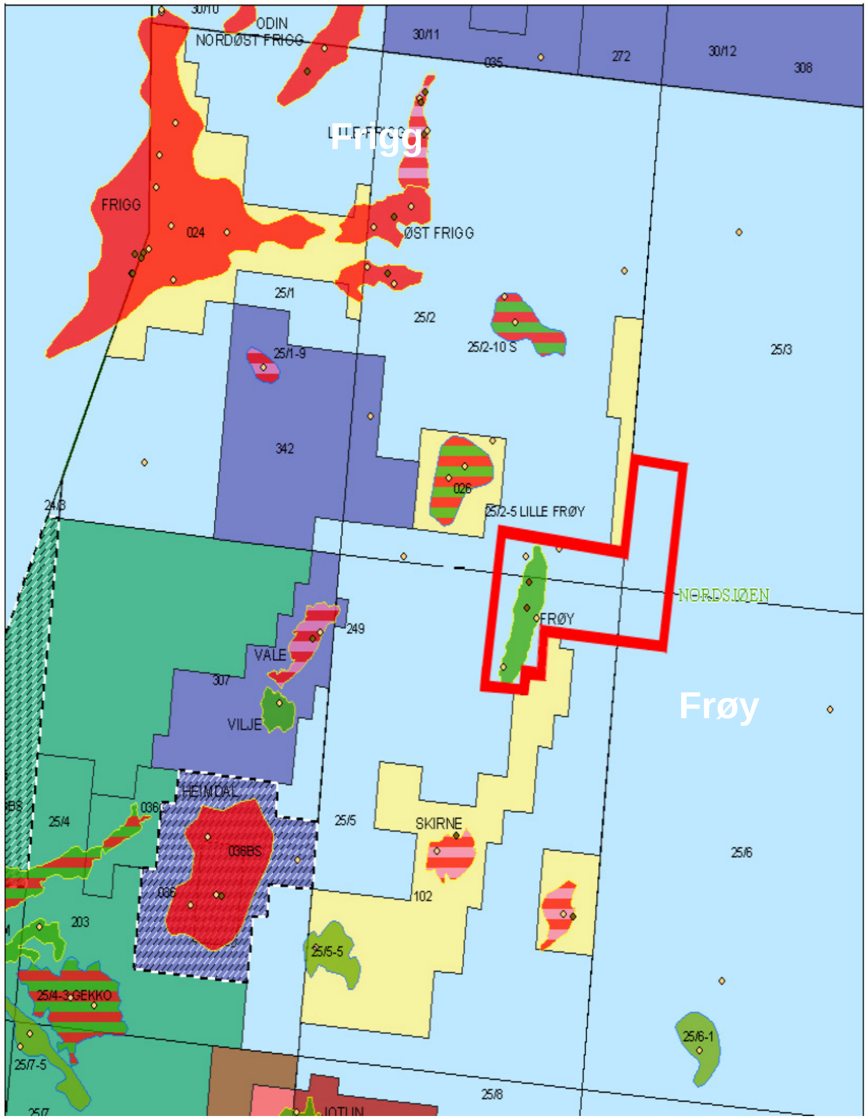
Other key factors affecting reservoir reactions

- Injection water composition.
  - Low sulphate seawater, Utsira formation water – low SO_4, low potential for SO_4, Ca, Ba, and Sr removal but also low SO_4-mineral scaling potential
- Reservoir temperature – higher temperature, greater potential for SO_4 removal from seawater via $CaSO_4$ precipitation near injection well.
- Location of injection zone (oil-leg, water-leg) – more dissolution (less precipitation) of carbonates in oil-leg.
- Lithology – in carbonate reservoirs under seawater flood, release of Ca during dolomitisation results in $CaSO_4$ deposition. Similar effect to having a Ca-rich formation water.
- $SO_4^{2-} + Mg^{2+} + 2CaCO_3 \rightarrow (Ca,Mg)(CO_3)_2 + CaSO_4$

Applications

- An understanding of reservoir reactions has been used in a number of different applications:
  - Understanding the causes of unexpected low scaling risks (Sorbie and Mackay, 2000; Mackay et al. 2006; McCartney et al. 2007; Alba, Gyda Fields).
  - Selection of injection water (Østvold et al. 2010, Frøy Field).
  - Assessment of the effects of changing injection water (McCartney et al. 2010, Blane Field).
  - Obtaining PLT-type data from multi-rate tests and produced water analyses (Tjomsland et al. 2010, Veslefrikk Field).

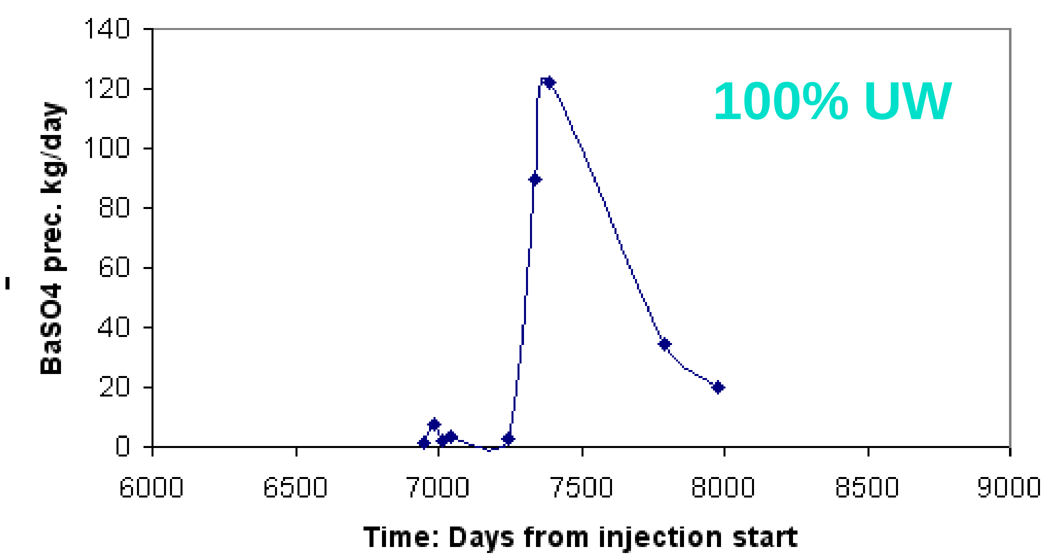
Field application – Frøy Field

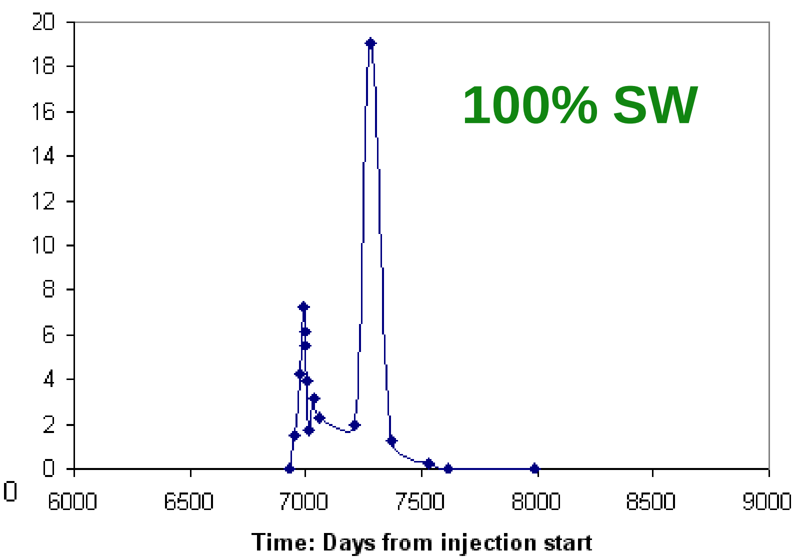


- Due to a combination of low oil prices, low production and $BaSO_4$ scale problems associated with seawater (SW) injection, field ceased production in 2001.
- Det norske oljeselskap and Premier Oil are re-developing the field.
- Choice to be made between SW injection and Utsira FW injection (low SO_4) – latter to avoid scale problems.
- Utsira FW would appear to be the logical choice but high cost – drilling of water supply wells, downhole pumps, Opex costs.
- With seawater injection – potential for high scale mitigation costs.

Field application – Frøy Field

- Produced water analyses were evaluated and these showed that significant $BaSO_4$ deposition occurred in the reservoir.
- A reactive transport reservoir simulation model was run assuming (a) Utsira FW injection and (b) seawater injection.
- Results indicated that in both cases higher scaling risks would occur early in field life due to co-production of pre-existing seawater and Ba-rich formation water.
- Subsequently the scaling risk declines in each case due to the decline in produced water Ba.
- This reflects lower formation water production but with seawater injection, the decline in Ba is greater due to deposition of $BaSO_4$ in the reservoir . This results in a lower scaling risk in the production well (note the smaller axis scale in the SW case).
- Result – there is a strong economic case for continued seawater injection.





Conclusions

- Understanding the effects of reservoir reactions during waterfloods is important for the understanding and prediction of production well scaling conditions.
- In the last 5-10 years, reservoir reactions have been evaluated by interpretation of produced water analyses and various modelling tools.
- A relatively small set of reactions appears to affect produced water compositions under a wide range of reservoir conditions.
- Incompatibility between the injected water and formation water is an important cause of reactions occurring in the reservoir and deposition of sulphate minerals during seawater floods can significantly reduce sulphate mineral scaling risks in the production wells.
- This is most likely to occur in reservoirs with Ca-rich formation water but may also occur in reservoirs with Ca-depleted formation water.
- Our improved understanding of reservoir reactions is now being applied to a variety of challenges during both field development and operation.