

# **Detection and quantification of Utsira formation water in production wells of the Oseberg Sør Field and impact on scale management**

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## **ABSTRACT**

Detection of injection water breakthrough (IWB) and quantification of the injection water fraction (IWF) in the produced water using artificial and natural tracers are commonly used to aid scale management decisions, but at the Oseberg Sør field it has not been possible to obtain reliable information of this type. In this paper, we use reactive transport modelling results, water analyses and artificial tracer results from a typical production well to demonstrate why this is the case. With respect to artificial tracers, the challenge has been their lack of use in some areas of the field, their delayed injection relative to the start of water injection and infrequent monitoring of the tracers in produced water. For natural tracers, the challenges are the effects of reservoir reactions, small differences between formation water and injection water compositions relative to the sampling/analytical uncertainties on ion analyses, lack of formation water compositions for some wells, mixing of formation waters of different compositions in some wells, and re-injection of produced water where the formation water compositions vary across the field.

For this reason, a scale management approach has been successfully developed that does not utilise IWB and IWF information. This involves identifying scaling conditions in the production wells soon after water breakthrough occurs, implementing scale mitigation procedures, and then monitoring produced water compositions and production conditions to identify significant changes over time. When these occur, scaling conditions are re-evaluated and mitigation procedures modified accordingly. With this approach the scale management effort and costs are similar to those required using IWB and IWF information.

The study also has implications for new developments. For example, before production starts it may be possible to predict whether or not useful IWB and IWF information is likely to be available during production. This will require (a) collection of multiple formation water samples during appraisal and (b) prediction of produced water compositions via reactive transport modelling. Appropriate scale management plans can then be developed.

## **INTRODUCTION**

For fields under waterflood, the composition of produced water is normally monitored for evidence of injection water breakthrough (IWB) because this event is often accompanied by a change in downhole scaling potential and signals the

need for scale mitigation to either start or change (e.g. by undertaking a squeeze treatment). Similarly, following injection water breakthrough, monitoring of the produced water composition continues so that changes in the fraction of injection water in the produced flow (injection water fraction, IWF) can be detected. Such changes also usually result in changes in downhole scaling potential and often lead to changes in the minimum inhibitor concentration (MIC). Where IWB and IWF results have been obtained, they can also be used to help constrain the reservoir model.

Although IWB can be identified by monitoring produced water for artificial tracers where the latter have been injected with the injection water, such tracers are not always used or are not always injected at the start of water injection. In these cases, IWB can be identified and IWF quantified using naturally-occurring tracers present in the injection water (e.g. Cl, SO<sub>4</sub>). Natural tracer techniques rely on differences in the composition of the injection water and formation water. Changes in the produced water composition from the formation water toward that of the injection water are used to signify IWB. Similarly, the amount of change can be equated to the IWF. For example, the ion track and cumulative sums methods (Schmidt and Thingvoll, 1990) rely on monitoring of changes to individual ions or ion ratios in the produced water, although in reality the results for several different ions are often considered collectively. Multivariate statistical methods (Partial Least Squares, PLS; Principal Components Analysis, PCA) make use of the analyses of several ions simultaneously and can reduce the influence of sampling/analytical uncertainties on IWB and IWF results (Scheck and Ross, 2008; Schmidt and Thingvoll, 1990; Webb and Kuhn, 2004). Matrix methods that also use analyses for several ions simultaneously are also available (e.g. McCaffrey et al., 1996). To provide reliable results, these methods should make use of the analyses for those ions that are either not affected, or are insignificantly affected, by reservoir reactions which can occur as a result of water injection. A recent alternative is to use the reacting ions method (Ishkov et al., 2009) which corrects for the effects of some reservoir reactions when IWB and IWF are determined.

At the Oseberg Sør field where Utsira formation water (UFW) is injected, the principal production well scaling risk is from CaCO<sub>3</sub> deposition (which decreases with increasing UFW fraction in the produced water). However, identification of IWB and quantification of IWF have been a challenge. Although artificial tracers have been injected, they could not always be reliably used to identify IWB in production wells because they have not been injected in all areas. Also, the tracers were injected 1-9 months after the start of water injection, and production wells were not sampled regularly for these tracers. Therefore, IWB has usually occurred before tracer breakthrough was identified. With respect to IWB and IWF results from natural tracer techniques, these have been too variable or insensitive to be useful for a variety of reasons:

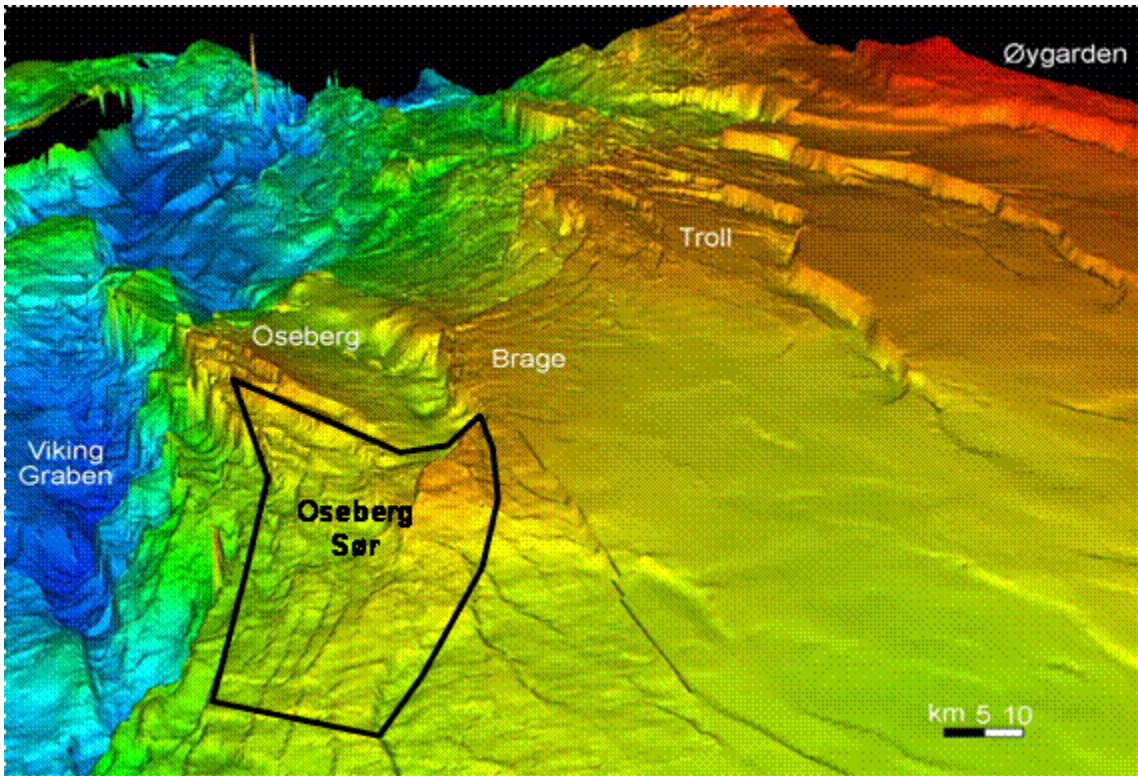
1. The reservoir formation water (RFW) compositions are variable and not sufficiently well characterised.
2. Reservoir reactions resulting from UFW injection have modified produced water compositions.
3. The difference between the compositions of UFW and RFW is small relative to the sampling/analytical uncertainty associated with the water analyses.
4. Variations in water compositions associated with UFW breakthrough are very similar to those occurring as a result of mixing of different reservoir formation waters.
5. Produced water has been re-injected.

In the absence of reliable IWB and IWF results, a scale management approach has been developed that does not rely on these data. In this paper, the influence of these factors on IWB and IWF determinations at Oseberg Sør are discussed using the results for a typical well (F-28AT2) as an example and we describe how this has affected the scale management approach for the field. This study is relevant to new developments where the above factors are likely to occur because challenges similar to those found at Oseberg Sør can be expected and scale management approaches that do not rely on IWB and IWF results will need to be considered.

## **BACKGROUND**

The Oseberg Sør Field is located at the eastern margin of the Viking Graben approximately 115km west of the Norwegian Coast just south of the Oseberg Field and south-west of the Brage Field (Figure 1). It consists of several structures step-wise down-faulted from east to west, separated mainly by north-south trending faults. Most of the field lies in Block 30/9 although the some structures extend into Blocks 30/6 and 30/12. Current daily oil production is approximately 8,000m<sup>3</sup> and daily water production is approximately 6,000m<sup>3</sup>. Pressure support is achieved by injection of UFW, and re-injection of produced water and gas.

Well F-28AT2 is completed in the shallow and marginal marine sandstones of the Tarbert Formation (initial reservoir pressure and temperature are 295 bar and 108°C respectively). Typical XRD analyses for these sandstones are shown in Table 1. These are notable for their variable mixed-clay content. The estimated CEC (Cation Exchange Capacity) varies between 0.56 and 4.28 meq/100g (see Table 1, allowing for uncertainty). Although not present in these analyses, calcite also occurs in the reservoir sandstones.



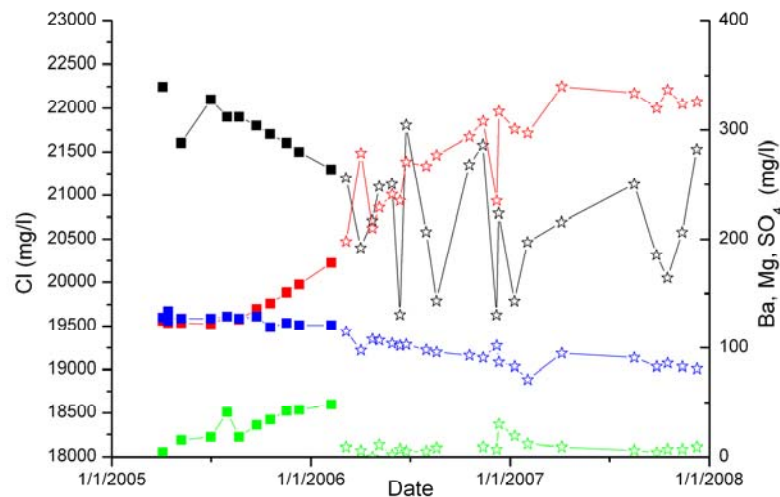
**Figure 1** Location of the Oseberg Sør Field.

Well	F-18 (vol%)	F-26 (vol%)
Quartz	74.5	87.6
K-Feldspar	5.7	3.9
Plagioclase	2.1	1.5
Illite/mica	4.6	2.1
Kaolinite	10	3.4
Chlorite	1.2	0.4
Dolomite	1	0.5
Pyrite	0.8	0.6
Total	99.9	100
CEC (meq/100g)	2.81±1.47	1.14±0.58

**Table 1** Typical XRD analyses for the Tarbert Formation. CEC estimated from typical CEC for minerals and model compositions.

Production from this well started in June 2004 and water breakthrough occurred in December 2004. The first good quality sample obtained from the well was collected in April 2005 (30% water cut, see Figure 2). Artificial tracer results

show that UFW breakthrough probably occurred between December 2004 and February 2005 (i.e. before the sample was collected). Between April 2005 and February 2006 (75% water cut), produced water Cl declined from ~22,300 to ~21,300 mg/l. This small decrease was accompanied by decreases in Na, Ca, Sr, and alkalinity. K remained approximately constant while Ba and Mg remained constant until August/September 2005 before decreasing and increasing respectively. SO<sub>4</sub> increased from 0ppm to approximately 50ppm between April 2005 and February 2006 (see Figure 2). After February 2006, these trends generally continue although produced water compositions are more variable. The exception is SO<sub>4</sub> which decreased abruptly and remained low thereafter. The earlier increasing trend is believed to be an analytical artifact because the abrupt decrease is seen in produced water SO<sub>4</sub> in several wells at this time. The variable composition observed after February 2006 appears to be associated with significant breakthrough of re-injected produced water (see below). The data before and after this date are discussed separately in this paper.



**Figure 2** Well F-28AT2 produced water analyses. Black=Cl, red=Mg, blue=Ba, green = SO<sub>4</sub>. Solid squares and open stars = pre and post-significant breakthrough of re-injected produced water respectively.

## IDENTIFICATION OF INJECTION WATER BREAKTHROUGH

Where artificial tracers are used, their appearance in produced water can confirm IWB. But, for tracer appearance and IWB to coincide, the tracers need to be injected at the start of water injection and the produced water needs to be monitored frequently for the tracer over time. At Oseberg Sør, neither of these criteria has been achieved. So, although artificial tracer data have been used to

retrospectively confirm IWB, it has not been possible to identify IWB from them in 'real time'.

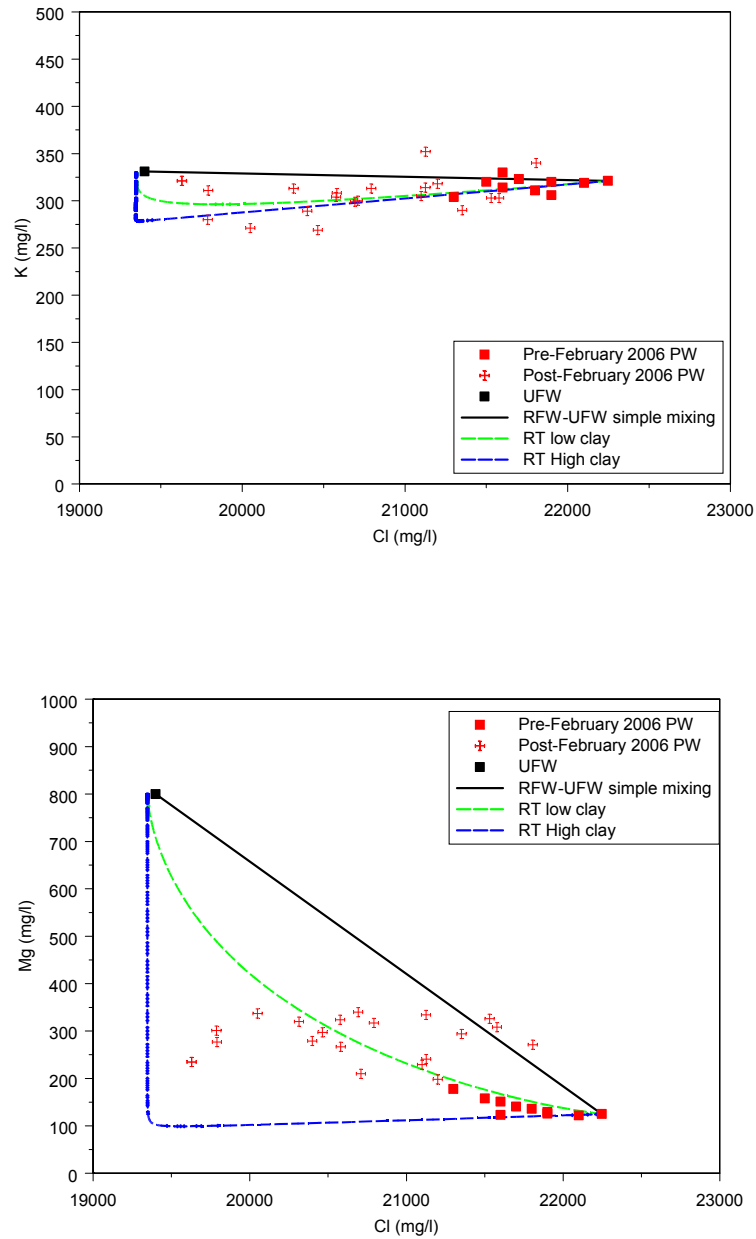
As produced water samples are collected regularly from most wells, the use of natural tracers provides an alternative method of identifying the approximate date of IWB (e.g. via ion tracking, cumulative sums method, etc). However, it is necessary to demonstrate that changes in produced water composition are a result of injection water breakthrough and not mixing of different formation waters, which can sometimes be the case.

### **Evidence for injection water breakthrough and associated reservoir reactions**

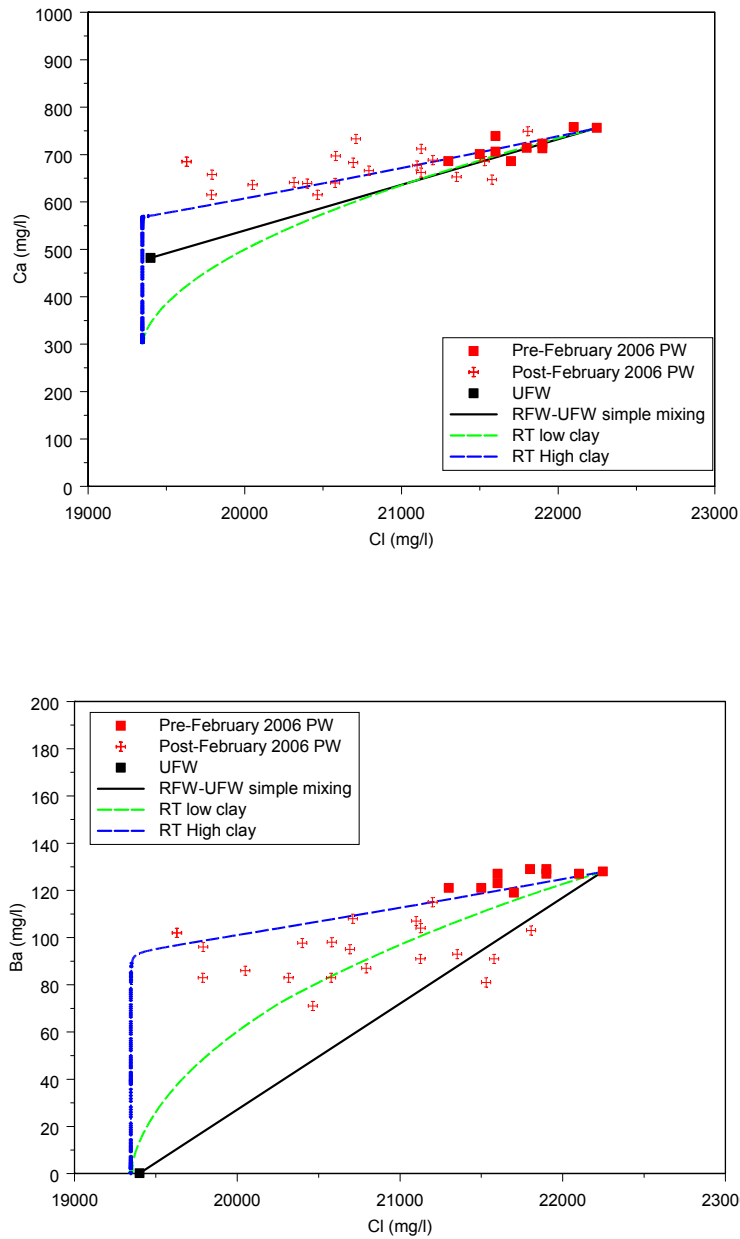
Where the RFW composition is known and produced water analyses display a deviation in composition from this toward the injection water composition on Cl versus X scatter plots (where X is another ion) this would support simple mixing between these two waters. But, for well F-28AT2 and most wells at Oseberg Sør, the formation water composition is not known (see below). Also, pre-February 2006 produced water analyses on these plots do not deviate toward the composition of UFW (see Figures 3a-3g). Therefore, simple mixing can be discounted.

**Reactive transport modelling.** Geochemist's Workbench (GWB) (Bethke, 2007) was used to investigate whether the pre-February 2006 produced water compositions can be explained by the combined effects of reservoir reactions and UFW breakthrough. A thermodynamic database for GWB was developed for the study. This was based on that utilised by MultiScale 6.1 (Petrotech, 2003). MultiScale 6.1 incorporates pressure corrections on activity coefficients but these cannot be applied in GWB. To compensate for this difference, those equilibrium constants for reactions relevant to this study, and used by GWB, were modified. This meant that for flash calculations simulating the mixing of UFW and RFW, the results (i.e. saturation ratios, SR, and scale masses for  $\text{CaCO}_3$ ,  $\text{BaSO}_4$ ,  $\text{CaSO}_4$  and  $\text{SrSO}_4$ ) from the use of GWB were almost the same as those obtained using MultiScale 6.1.

X1t, a 1-D reactive transport model which is part of GWB, was used to simulate injection of UFW into a single flow path where it mixed with and displaced RFW. Reactions between (a) RFW and UFW, (b) formation minerals and UFW, and (c) formation minerals and mixtures of UFW and RFW, were allowed. To simulate oil-leg conditions exchange of  $\text{CO}_2$  between water and petroleum was included in the model whilst exchange was prevented for the simulation of water-leg conditions.

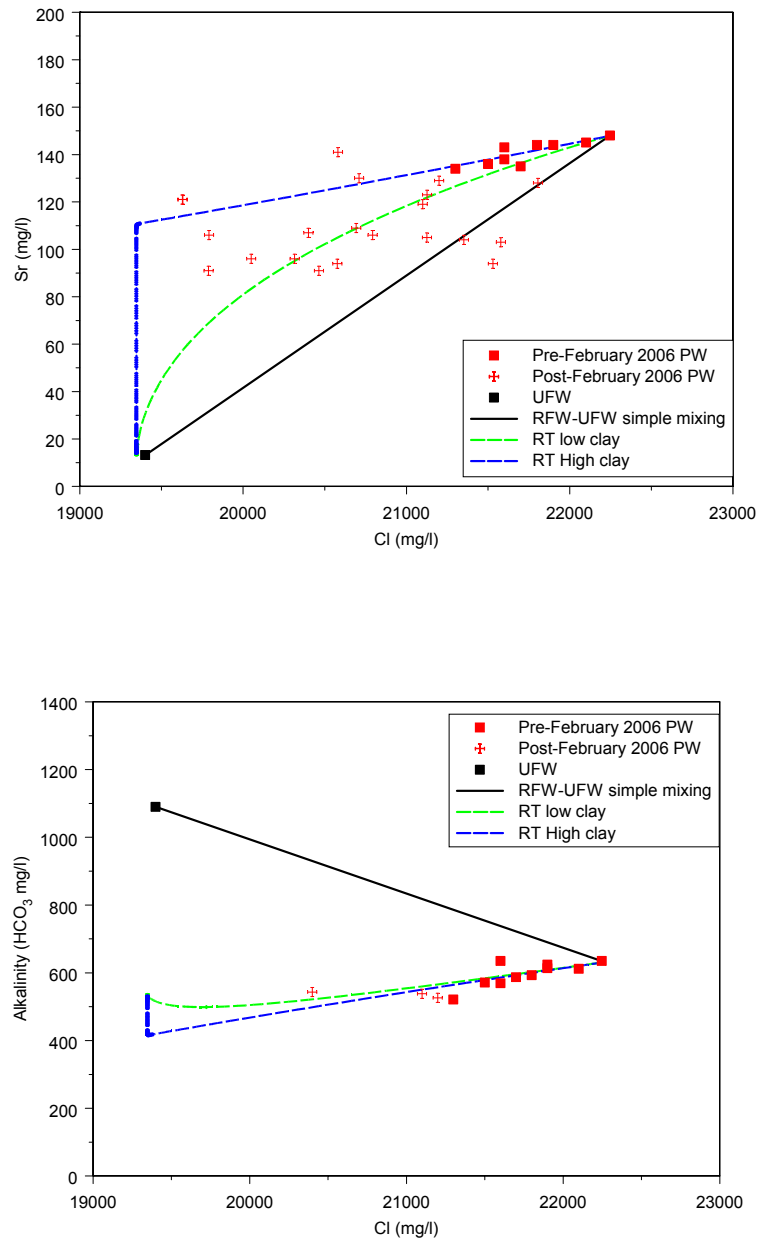


**Figure 3 Comparison of produced water analyses for well F-28AT2 with predicted compositions for (i) simple mixtures of UFW and RFW, (ii) reactive transport low clay simulation and (iii) reactive transport high clay simulation. (a) Cl v K, (b) Cl v Mg.**

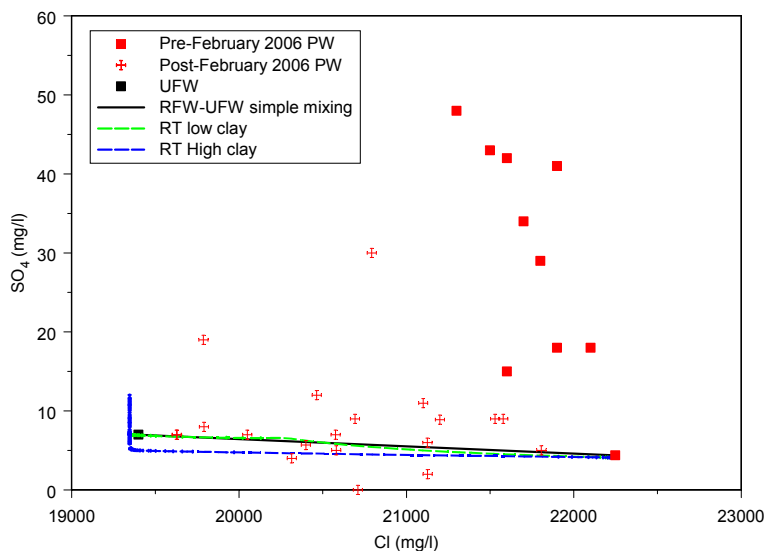


**Figure 3 Comparison of produced water analyses for well F-28AT2 with predicted compositions for (i) simple mixtures of UFW and RFW, (ii) reactive transport low clay simulation and (iii) reactive transport high clay simulation. (c) Cl v Ca, (d) Cl v Ba.**





**Figure 3** Comparison of produced water analyses for well F-28AT2 with predicted compositions for (i) simple mixtures of UFW and RFW, (ii) reactive transport low clay simulation and (iii) reactive transport high clay simulation. (e) Cl v Sr, (f) Cl v total alkalinity.



**Figure 3 Comparison of produced water analyses for well F-28AT2 with predicted compositions for (i) simple mixtures of UFW and RFW, (ii) reactive transport low clay simulation and (iii) reactive transport high clay simulation. (g) Cl v SO<sub>4</sub>.**

The estimated composition of RFW at the location of Well F-28AT2 is shown in Table 2. This was used in the simulations and has the composition of the first good quality sample obtained from this well. An erroneous SO<sub>4</sub> analysis for this sample was adjusted so the RFW is saturated with respect to BaSO<sub>4</sub> at reservoir pressure and temperature. Given the presence of calcite in the reservoir, *in situ* pH and carbonate alkalinity were estimated by assuming equilibrium between the formation water, this mineral and petroleum CO<sub>2</sub> (0.92 mol %) in the reservoir. Dolomite is also present in the reservoir, and although it is predicted to be the stable carbonate phase in contact with the RFW under these conditions, it is only slightly more stable than calcite (SR = 1 for CaCO<sub>3</sub> and 1.26 for disordered dolomite). There are significant uncertainties in the solubility of dolomite so it is likely that both it and calcite are in equilibrium with the RFW and petroleum CO<sub>2</sub> in the reservoir. A total alkalinity measurement was not available for this sample so it was assumed to be the same as observed on samples obtained a month later (635 mg/l as HCO<sub>3</sub>). For the simulations, it was also assumed that organic acids were present (173 mg/l) so that the simulated total alkalinity was consistent with that of the RFW sample. Table 2 shows the composition of UFW used in the calculations. Only two UFW analyses are available for the field but they are in reasonable agreement except for their SO<sub>4</sub> content (39 and 92 mg/l). Both of these analyses are much higher than recorded for UFW on the Brage Field (~7

mg/l). Again, due to concerns regarding SO<sub>4</sub> analyses at Oseberg Sør it was assumed that UFW contains 7 mg/l SO<sub>4</sub>.

Constituent	Utsira FW (F-15)	Reservoir FW (F-28AT2)
Na (mg/l)	10,728	13,256
K (mg/l)	331	321
Mg (mg/l)	800	125
Ca (mg/l)	482	756
Sr (mg/l)	13.2	148
Ba (mg/l)	0.2	128
Cl (mg/l)	19,400	22,247
Alkalinity (mg/l as HCO <sub>3</sub> )	1,090	635
SO <sub>4</sub> (mg/l)	7	4.4
Organic acids (mg/l)	0	173
pH	6.64	5.75

**Table 2 UFW and RFW compositions used in simulations. Na estimated by charge balance. UFW pH calculated after heating to reservoir temperature and pressure (no reaction).**

Several published (e.g. McCartney et al., 2007; Østvold et al., 2010; Tjomsland et al., 2010) and unpublished studies have indicated that reservoir reaction effects on produced water compositions can largely be explained by ion exchange reactions and dissolution/precipitation of carbonates and sulphates. Typically, these reactions reach equilibrium within days suggesting that although other ‘slower’ reactions might occur (e.g. dissolution of feldspar, precipitation of clays), it is the faster reactions that dominate reaction effects on produced water compositions. Therefore, dolomite, calcite, barite, celestite and anhydrite dissolution/precipitation were allowed in the simulations, along with multi-component ion exchange (involving Na, K, Ca, Mg, Ba and Sr). Because the time for these reactions to reach equilibrium is very short compared to the minimum reservoir residence time for water produced from Well F-28AT2 (8-11 months), it has been assumed that all reactions achieve instantaneous equilibrium. As a result, produced water compositions are at equilibrium with respect to these reactions on reaching the end of the flow path. The reactive phases in the reservoir rock were limited to ion exchange surfaces (clays) and calcite. The CEC was set to 0.56 and 4.28 meq/100g (lowest and highest values from Table 1, allowing for uncertainty) and the ion exchange selectivity coefficients were taken as the averages given in Appelo and Postma (1999).

Figures 3a-3g show two sets of simulated produced water compositions from the model assuming the lowest (‘RT low clay’) and highest (‘RT high clay’) CEC (see above) for the field respectively. Also shown are actual produced water analyses for well F-28AT2 and produced water compositions expected if no reactions were

to occur (i.e. simple mixtures of UFW and RFW). The low clay and high clay models were run under water-leg conditions. The reactions in the simulations cause  $\text{SO}_4$  and Ba to be gained and Ca and alkalinity to be lost from UFW. For the mixtures of UFW and RFW, reactions result in the gain of Ca (high clay only), Na, Ba and Sr, and loss of Mg, K,  $\text{SO}_4$  and alkalinity. For the low clay case, minor Ca is gained at lower UFW fractions in the produced water and lost at higher UFW fractions.

Allowing for some sampling/analytical uncertainty of the produced water analyses, it can be seen that the simulated results generally reproduce the trends seen in the pre-February 2006 analyses indicating that these trends may reflect increasing breakthrough of UFW over time. The trends in Mg, Ba and Sr analyses are most sensitive to changes in reservoir rock clay content. Although the low clay predictions lie close to many of the observed Mg analyses, they slightly underestimate most losses in Mg and show a poorer fit with the Ba and Sr analyses. In contrast, the high clay predictions are a better 'fit' to the Sr and Ba analyses whilst the general fit to the Mg analyses is not so good, except with those samples that show a decline in both Mg and Cl with increasing UFW fraction. Therefore, the clay content of flow paths intersecting F-28AT2 appears to be moderate to high. Interestingly, the trend of declining Mg and Cl is observed in the produced water analyses for several wells in the field suggesting water being produced from these wells may come from flow paths with higher clay content. The results for water-leg and oil-leg conditions were very similar with both being consistent with the produced water analyses. The oil-leg predictions contained slightly higher Ca and alkalinity.

The reactions responsible for the predicted produced water compositions are listed in Table 3 and by inference it is possible that these reactions are also occurring in the reservoir. It can be seen that only multi-component ion exchange,  $\text{CaCO}_3$  precipitation and  $\text{BaSO}_4$  precipitation/dissolution are required to generate the reaction effects observed in the F-28AT2 produced water analyses. UFW precipitates  $\text{CaCO}_3$  on entering the reservoir (due to heating) and dissolves  $\text{BaSO}_4$  which was previously precipitated from mixtures of UFW and RFW before the mixing zone was displaced away from the injection well. Within the UFW-RFW mixing zone, trends in produced water analyses reflect both mixing of reacted UFW and RFW and reservoir reactions. Minor  $\text{CaCO}_3$  precipitation is induced by release of Ca from ion exchange surfaces. At lower UFW fractions the net effect on Ca is small but at high UFW fractions mixing with low Ca UFW causes a net loss in produced water Ca. The latter effect is delayed when clay content is high. The amount of  $\text{CaCO}_3$  deposition is lowered in the oil-leg resulting in marginally higher Ca and alkalinity in the produced water. For Ba, release of Ba from clays causes  $\text{BaSO}_4$  precipitation but the net effect is a gain in Ba.

Location	Reactions
Injection well zone	CaCO <sub>3</sub> precipitation BaSO <sub>4</sub> dissolution (previously deposited in RFW-UFW mixing zone)
Behind the RFW-UFW mixing zone	Ba, Sr, Ca, Na released from clay until equilibrium reached Mg, K taken up on clays until equilibrium reached
RFW-UFW mixing zone	CaCO <sub>3</sub> precipitation BaSO <sub>4</sub> precipitation at lower UFW (induced by Ba release from clay) fraction and then dissolution at high UFW fraction K, Mg, taken up on clay Ba, Sr, Ca, Na released from clay

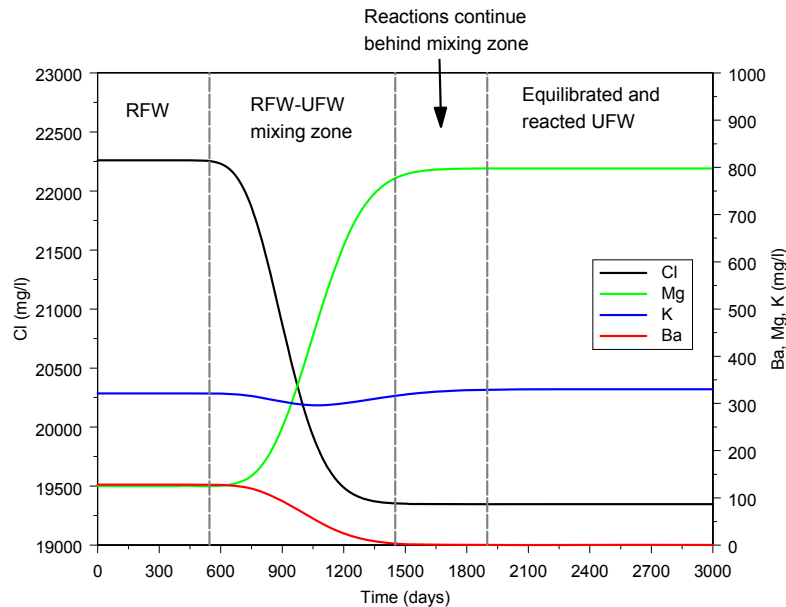
**Table 3 Summary of reservoir reactions occurring in the reservoir.**

When the clay content is low, SO<sub>4</sub> increases slightly due to the net effect of increasing UFW fraction combined with minor BaSO<sub>4</sub> deposition. However, where the clay content is high, SO<sub>4</sub> is maintained at low levels by greater BaSO<sub>4</sub> deposition induced by greater release of Ba from clays. The gains and losses in Na, K, Mg and Sr are solely accounted for by ion exchange reactions. These ion exchange reactions continue to affect UFW behind the mixing zone until the ion exchange surfaces have equilibrated with the UFW. Figure 4 shows the trends of some ions over time for a hypothetical production well from the low clay model. Early produced water is RFW, then UFW breakthrough occurs and finally only UFW is produced. Note that the composition of the UFW is still changing after 100% UFW breakthrough due to gradual equilibration of ion exchange reactions behind the mixing zone.

### **Evidence for production of mixed formation waters**

Formation water samples have been obtained via formation testing (MDT) and drill stem tests at Oseberg Sør. In addition, based on artificial tracer results, additional formation water samples have been obtained during production (i.e. produced water samples) although from few wells because often UFW breakthrough occurs before samples can be collected. Formation water analyses show that the RFW composition varies across the field (e.g. Figures 5a and 5b). Additional produced water analyses that may or may not be formation water, indicate that the formation water salinity can be  $\geq 26,300$  mg/l Cl in some areas. Of particular interest to this study are the formation water analyses for well F-19A. These vary over time indicating mixing of formation waters. On Cl versus X scatter plots, these mixed formation water compositions display very similar trends to those seen for well F-28AT2 produced water analyses. Reactive transport modelling indicates that the formation water compositions observed across the field may have been generated in the past by mixing of lower and

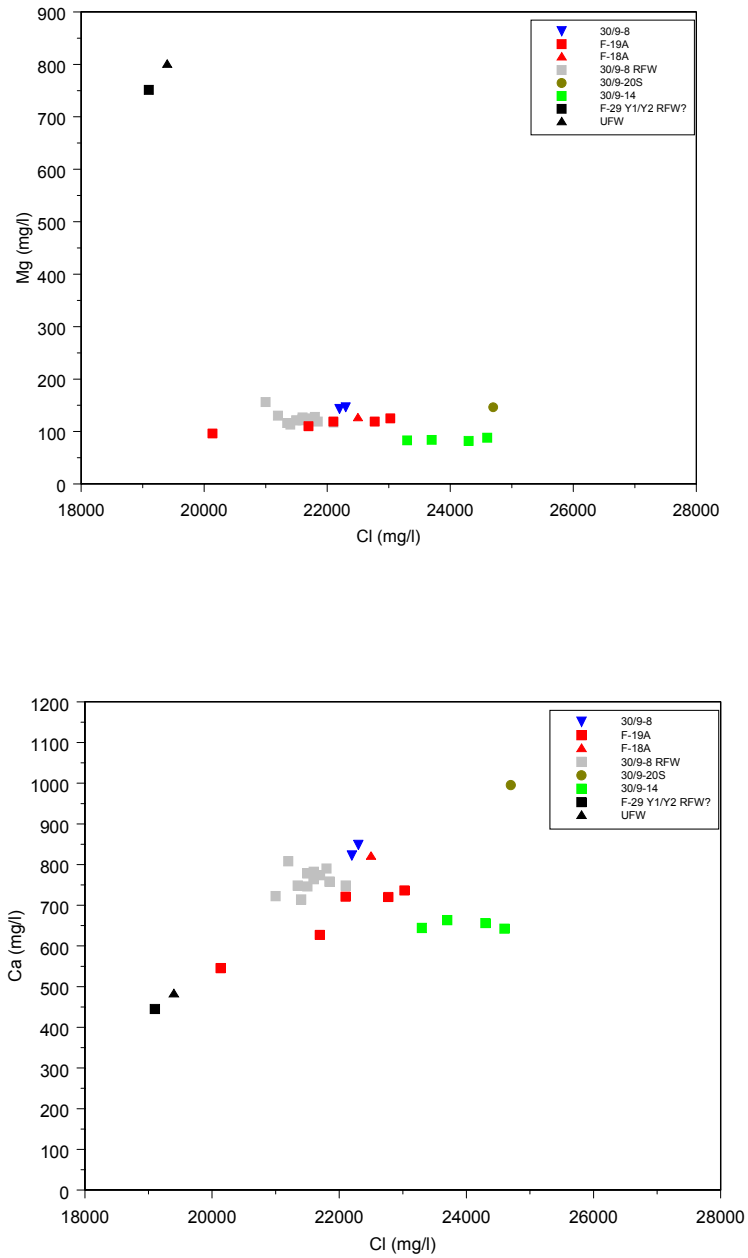
higher salinity formation water, accompanied by multi-component ion exchange reactions. These are similar conditions to those used in the UFW injection model and may explain why mixing of formation waters might produce compositions similar to those occurring as a result of UFW injection. Therefore, the possibility that production of mixed formation waters might contribute to the variation in well F-28AT2 produced water compositions cannot be discounted.



**Figure 4** Variation in produced water compositions for Cl, Ba, Mg and K over time.

### Summary

Using artificial tracer and reactive transport modelling results, it has been possible to show that variations in pre-February 2006 produced water analyses from well F-28AT2 are consistent with injection water breakthrough. However, it is also plausible that production of mixed formation waters might contribute to production from this well. These conclusions are also valid for other Oseberg Sør wells, but where artificial tracer data are not available there is a risk that variations in produced water composition might be incorrectly interpreted as IWB when mixed formation waters are being produced (and vice-versa). Finally, in this study identification of UFW breakthrough for well F-28AT2 has been retrospective when, for scale management decisions, identification should ideally occur at the time when breakthrough occurs. This is discussed in the following section.



**Figure 5** Variation in formation water (a) Cl and Mg and (b) Cl and Ca concentrations at Oseberg Sør. Note the variation in formation water composition from well F-19A due to mixing of formation waters of different composition.

## DETERMINING THE TIME OF INJECTION WATER BREAKTHROUGH

### Natural tracer results from well F-28AT2

A retrospective attempt was made to determine the time of injection water breakthrough from well F-28AT2 produced water analyses assuming the change in produced water composition was the result of UFW breakthrough. Although retrospective, the methods used could also have been used in near real time as each produced water analysis became available. The methods used included the ion track, cumulative sums, matrix and PLS methods.

The ion track method (Schmidt and Thingvoll, 1990) requires that the formation water composition, and the uncertainty on this (95% confidence limits), be known. The IWB time is recorded when two successive samples have compositions lying outside these confidence limits. For this study the formation water composition was taken as that of the first sample collected whilst the uncertainty was estimated from the variability of the first five samples collected. A range of IWB dates were obtained between 22 September 2005 and 2 February 2006 depending on which ion was used. The following order from earliest to latest IWB date was obtained from the ions and ion ratios: Na > Mg > Ca, Sr > Ba. IWB was not positively identified using Cl or K with this method. Use of carefully selected ion ratios can improve the sensitivity of the ion track method where the numerator and denominator of the ratio to IWB are opposite. For example, in this case, use of Sr/Mg ratios gives an IWB date of 21 August 2005. This is the earliest date derived from any ratios.

The cumulative sums method (Schmidt and Thingvoll, 1990) requires a baseline formation water composition to be established. For this study this was taken as the mean of all samples collected prior to 31 July 2005. The CUSUM values are then calculated for the chosen ions or ion ratios using Equation 1 and the results plotted versus time. The injection water breakthrough date is estimated from the graph as the time when the trend in CUSUM values consistently deviates from the formation water composition. The strength of this method over the ion track method is that it incorporates information and trends available from previous samples thereby making trends more obvious. The weakness for this study is that by generating the baseline formation water composition from the mean of the samples collected prior to 31 July 2005 the calculated breakthrough date cannot be earlier than this.

$$C = \sum_{j=1}^n (X_j - \bar{X}) \quad \text{Eq.1}$$

Where:  $C$  = CUSUM value.  
 $X_j$  = Measured value at a given date.  
 $\bar{X}$  = Average formation water composition.



With the cumulative sums method, breakthrough dates were between 31 July 2005 and 17 October 2005 with the order of ions from which they came being Ca > Na, Mg, Sr, Cl > Ba (earliest to latest dates). Breakthrough was not positively identified using K by this method. Again, carefully selected ion ratios can be sensitive to IWB but in this case, no more so that Ca alone.

With the matrix method (e.g. McCaffrey et al., 1996) the fractions of different waters present in a mixture (produced water sample) can be calculated given the compositions of the different waters (i.e. RFW and UFW in this study) and the composition of the produced water sample. This is achieved by solving for matrix M in Equation 2

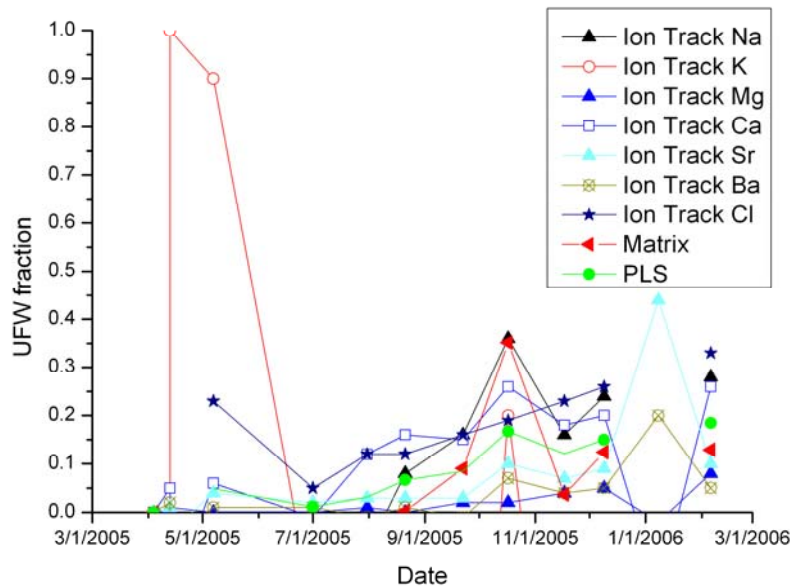
$$M = [G^T G]^{-1} G^T d \quad \text{Eq. 2}$$

Where,  $G^T$  = Transpose of matrix G

The only requirement is that the number of constituents analysed in the samples exceeds the number of waters being mixed (i.e. 2 in this study). Once the IWFs for the samples have been calculated, the date where IWB has occurred is estimated from these results.

A similar approach is taken using the PLS method (Schmidt and Thingvoll, 1990) which is also used to calculate IWFs. In PLS, multiple regression is first applied to selected ions in calculated mixtures of RFW and UFW (IWF = 0 to 1; the 'calibration data set'). The regression coefficients are then applied to the same ion analyses for the produced water samples to estimate the IWF of each sample. Figure 6 shows the results of the calculation of IWF in produced water using the matrix method and the PLS method with Na, K, Ca, Mg, Ba, Sr, SO<sub>4</sub> and Cl analyses. In each case a breakthrough date of 22 September 2005 was obtained. Breakthrough dates could not be obtained with the reactive ions method (Ishkov et al., 2009) due to the poor SO<sub>4</sub> analyses. In addition, this method does not account for Ba release from clays via ion exchange.

Using these methods IWB is detected at a later date than indicated by artificial tracers (between December 2004 and February 2005) and the dates obtained show a wide variation depending on the method or constituents used to determine them. These results are typical of Oseberg Sør production wells. For this well, the later breakthrough dates may be partly due to the formation water composition not being accurately known. However, even when formation water compositions are known, sampling/analytical errors and effects of reaction conspire to make it difficult to determine the time of IWB using natural tracers.



**Figure 6** Calculated IWF results for pre-February 2006 produced water analyses from well F-28AT2.

**Influence of sampling/analytical uncertainty and effects of reservoir reactions**

As an example of this, assuming that the natural tracer is not affected by reactions in the reservoir, to detect IWB by the ion track method requires that the produced water composition changes from the RFW composition by an amount greater than the sampling/analytical uncertainty ( $2\sigma$ ). The point at which this occurs will depend on:

1. The uncertainty on the RFW composition.
2. The difference between the RFW and UFW compositions (expressed as the ‘formation water multiple’,  $M_{FW}$ , see below).

The UFW fraction required in the produced water before breakthrough is detected can be calculated from:

$$F_{UFW} = \frac{E_F \cdot M_{FW}}{(1 - M_{FW})} \tag{Eq. 3}$$

$$F_{UFW} = - \frac{E_F \cdot M_{FW}}{(1 - M_{FW})} \tag{Eq. 4}$$

Where:

$F_{UFW}$  = Fraction of UFW required before injection water breakthrough identified.

$E_F$  = Fractional sampling/analytical uncertainty associated with mean RFW composition ( $2\sigma$ ).

$M_{FW}$  = Formation water multiple (concentration of ion in RFW/concentration of ion in UFW).

Equation 3 is valid for the case where the concentration in the RFW is less than that in the UFW and vice-versa for Equation 4. In the absence of reservoir reactions, the most sensitive constituents for detecting injection water breakthrough are those with low fractional uncertainty on the RFW composition and that are significantly lower in the RFW than in the UFW ( $M_{FW} \ll 1$ ). In this case, detection of UFW breakthrough is increasingly sensitive as sampling/analytical uncertainty and/or the  $M_{FW}$  is reduced. Above  $M_{FW} = 0.5$ , the UFW fraction required for breakthrough detection is greater than the fractional sampling/analytical uncertainty and below, it is less. In contrast, where  $M_{FW} > 1$ , the UFW fraction at which breakthrough can be detected improves with lower fractional sampling/analytical uncertainty and increasing MFW but is eventually limited as MFW increases to a UFW fraction that equals the fractional sampling/analytical uncertainty. This occurs when  $M_{FW} \sim 10$ .

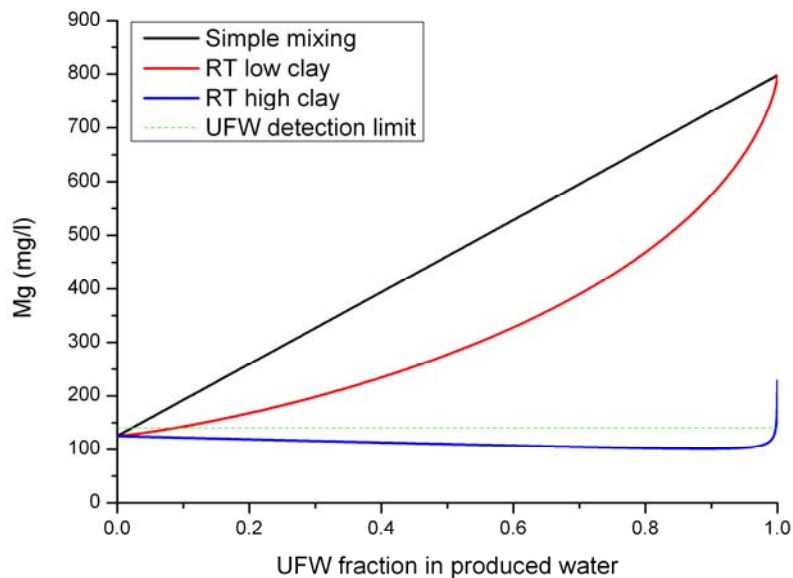
Had no reactions occurred in the reservoir, and given the estimate of F-28AT2 RFW composition and typical sampling/analytical uncertainties for this field, Equations 3 and 4 can be used to calculate the UFW fraction in produced water required before UFW breakthrough can be confirmed using the ion track method. The order of detection is  $Mg \gg Sr > Ba > Cl > Ca > Na > K$  with Mg being by far the most sensitive allowing UFW breakthrough to be identified once  $\sim 0.02$  UFW fraction is present (see Table 4). Under these conditions Mg would provide the earliest breakthrough date. K is insensitive to breakthrough because the K concentrations in RFW and UFW are similar and uncertainty on the analyses is large.

However, other than Cl, all these constituents participate in reactions in the reservoir. For these reactive constituents, their sensitivity to identification of UFW breakthrough is reduced and gets worse as the clay content increases. For example, when the reservoir clay content is high, the order of sensitivity to UFW detection is  $Cl > Sr > Ba > Ca > Na > Mg$  (see Table 4). Where the clay content is low, Mg is still the most sensitive constituent to use to identify UFW breakthrough (at 0.08 UFW fraction) but where clay content is high, the UFW fraction needs to be greater than 0.998 for UFW breakthrough to be detected. This is because of significant uptake of Mg on ion exchange sites until very high

UFW fractions are achieved (see Figure 7). In the high clay case, and using the ion track method, the earliest that UFW breakthrough can be detected is when ~30% UFW is present. This lack of sensitivity reflects the small difference in Cl concentration between RFW and UFW and high sampling/analytical uncertainty on the Cl analyses relative to this difference. Due to the effects of reservoir reactions, using other ions and the ion track method would be even less sensitive.

	Ba	Ca	Cl	K	Mg	Na	Sr
RFW composition (mg/l)	128	756	22260	321	125	13268	148
UFW composition (mg/l)	0.20	481	19347	330	798	10702	13
M <sub>F<sub>W</sub></sub>	642.10	1.57	1.15	0.97	0.16	1.24	11.25
Uncertainty on RFW composition (mg/l)	15.37	90.77	890.40	64.24	15.00	1061.43	11.85
<b>UFW fraction required for detection</b>							
No reaction	0.120	0.200	0.306	>1	0.022	0.414	0.088
Low clay case	0.224	0.325	0.306	>1	0.087	0.509	0.185
High clay case	0.435	0.469	0.306	>1	0.998	0.652	0.307

**Table 4** Detection of UFW breakthrough via the ion track method.



**Figure 7** Detection of UFW breakthrough using simulation Mg data.

## Summary

Despite the delay in their injection, in areas of the field where artificial tracers have been used and monitored, these have detected IWB before detection has been achieved using natural tracers. In those areas of the Oseberg Sør field where artificial tracers have not been used, identification of IWB is reliant on the use of natural tracers. But, they give IWB times that are very variable and delayed relative to those obtained by artificial tracers. This reflects reservoir reaction effects, small differences between RFW and UFW compositions, large sampling/analytical uncertainty on some ions relative to this difference, and for some wells the lack a known RFW composition.

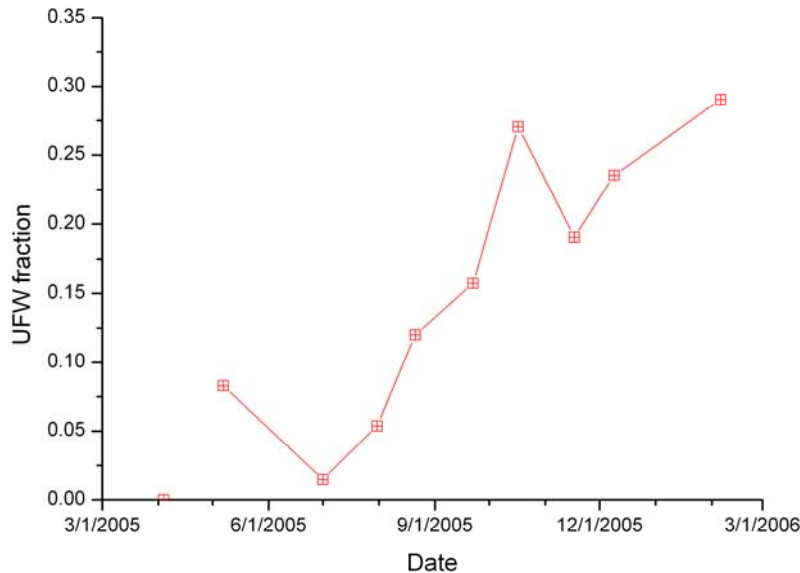
Reactive transport reservoir simulations can be used to help identify which natural tracers and methods are likely to be most sensitive to detection of UFW breakthrough. For example, given conditions at Oseberg Sør, if the ion track method were to be used with single ion analyses (as opposed to ratios), detection of IWB would be best achieved by monitoring Mg and Cl analyses. But, to aid rapid decision-making additional favourable conditions are required. Firstly, the RFW needs to be known and secondly the increase in UFW fraction needs to be fast to ensure rapid detection. That is, it needs to quickly increase above 0.08 if UFW breakthrough occurs along low clay flow paths and Mg is used in the ion track method or above 0.3 if breakthrough is along high clay flow paths and Cl is used (see Table 4). Unfortunately, these conditions are not met in any Oseberg Sør wells.

## QUANTIFICATION OF INJECTION WATER BREAKTHROUGH

### Comparison of well F-28AT2 and reactive transport modelling results

Because the RFW composition is unknown for well F-28AT2, it is not possible to calculate reliable IWF data. This is the case with several other wells too. However, to illustrate the uncertainties associated with IWF results at Oseberg Sør, Figure 6 shows them for pre-February 2006 produced water analyses from well F-28AT2 assuming the first sample collected is RFW and using the ion track, matrix and PLS methods. It can be seen that all methods show a gradual increase in UFW but there are significant discrepancies between them. For example, by February 2006, calculated IWFs vary between 0.05 and 0.33. The UFW fractions for K were generally negative. It is noticeable that the three ion track constituents that display least reaction effects are reasonably consistent during this period (0.26-0.33). In contrast, those ion track constituents that display reaction effects produce lower UFW fractions. The matrix and PLS methods also produce lower UFW fractions and these use a combination of both reactive and less reactive constituents. When the PLS method uses only Na, Ca, and Cl analyses, it produces results consistent with the ion track results for these constituents (0.29; see Figure 8). Using the low clay reactive transport simulation results there is a good correlation between these and the observed

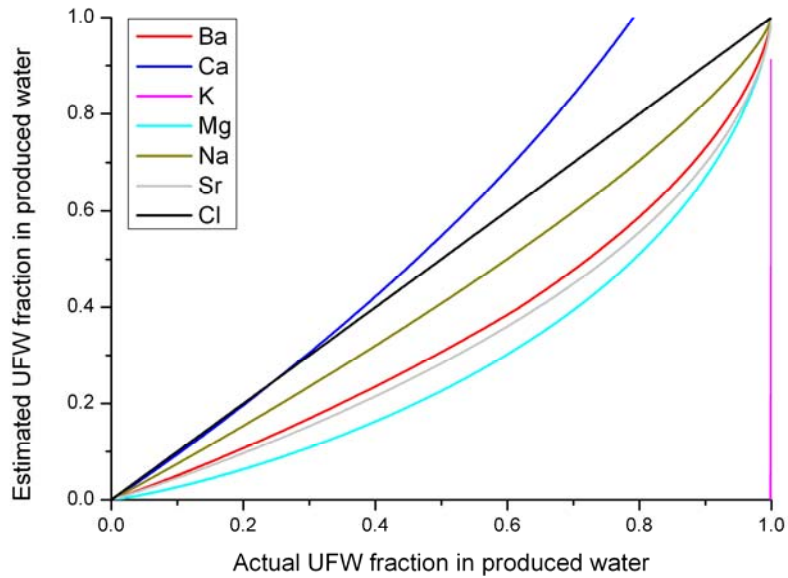
produced water analyses in February 2006 which equates to a simulated UFW fraction of ~0.32.



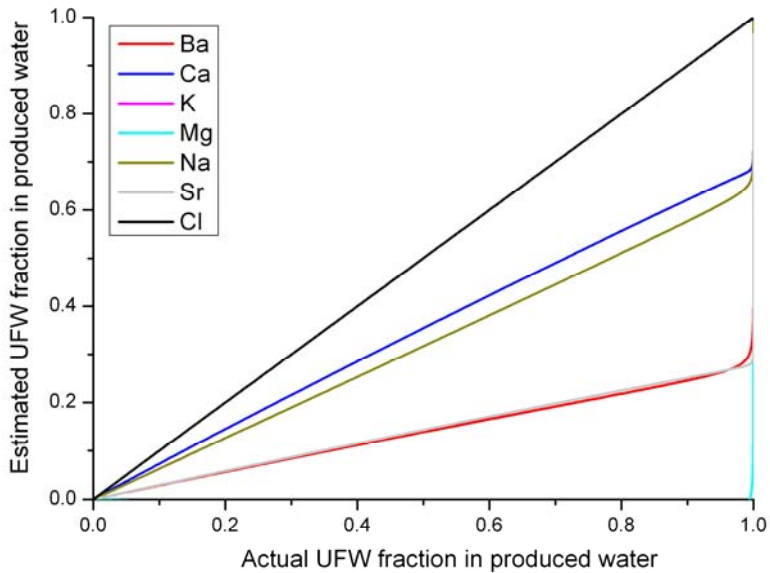
**Figure 8 UFW fraction in produced water using PLS method (Cl, Na, Ca).**

Figures 9 and 10 compare actual UFW fractions in produced water against those calculated from the low clay and high clay case simulation results respectively. It can be seen that within the UFW fraction range of the F-28AT2 analyses (up to ~0.3), only Cl and Ca are predicted to provide reliable results and in the latter case, only when the clay content in the reservoir is low. At approximately 0.3 UFW fraction from Ca and Cl data in the low clay case, the UFW fraction estimated from Na data is ~0.24. These results are similar to those above obtained using the actual produced water analyses. The modelling results show that whilst Ca provides reasonable estimates of the UFW fraction under low clay conditions up to UFW fractions of 0.3, these estimates start to increasingly overestimate actual values as the UFW fraction increases. This is due to loss of Ca from UFW via  $\text{CaCO}_3$  precipitation. When the clay content is high, UFW fractions obtained from Na and Ca data underestimate the UFW fraction in produced water (estimated UFW fraction = ~0.20 and 0.22 respectively when actual fraction = 0.3). Estimates of the UFW fraction obtained from all other ions in the low and high clay cases underestimate the UFW fraction with the degree of underestimation increasing with reservoir clay content. Again, this is consistent with what has been found from the produced water analyses. The underestimation occurs where ions are either (a) gained by the produced water in the reservoir via reaction when their concentrations are lower in the UFW than in

the RFW or (b) lost from the produced water via reaction when the opposite condition applies.



**Figure 9** Comparison of actual UFW fraction in produced water with that estimated from low clay simulation results.



**Figure 10** Comparison of actual UFW fraction in produced water with that estimated from high clay simulation results.

Based on the above results, only CI analyses can provide reliable UFW fractions in the produced water given that the actual UFW fraction relevant to a well will be unknown. For well F-28AT2, the UFW fraction in February 2006 is likely to be approximately 0.3 (or more, considering that the formation water CI content could be higher than that assumed for the above calculations). However, although a trend of increasing UFW fractions for F-28AT2 implies reasonable precision on the CI analyses, from duplicate samples obtained from Oseberg Sør typical sampling/analytical uncertainties ( $2\sigma$ ) on CI analyses equate to an uncertainty of  $\pm 0.3$  on the calculated UFW fraction. This is due to the small difference between RFW and UFW CI concentrations. This significant uncertainty on the calculated UFW fraction means that the results are less useful for operational decisions. In addition, UFW fractions might also be inaccurate in some wells as a result of the effects of mixing of formation water in the well (see above).

### **Effects of production of re-injected produced water**

When significant breakthrough of re-injected produced water (RIPW) occurs, this can also affect the results. For example, based on artificial tracer results and injected and produced water volumes for the field, it is estimated that the earliest produced injection water from well F-28AT2 was a mixture of 95:5 UFW:RIPW. This mixture changed to approximately 85:15 UFW:RIPW by February 2006. The CI content of the RIPW is not known but if it is the same as that of the RFW (i.e. if the RFW were to be constant across the field), the calculated fraction of UFW in the produced water will still be valid. But, if the CI content of the RIPW is higher or lower than that of the RFW, as is possible at Oseberg Sør, the calculated fraction of UFW will be erroneously lower or higher respectively. The actual injection water composition was not monitored at Oseberg Sør. When significant variability in produced water compositions starts after February 2006, it is likely to reflect the increasingly variable injection water composition as more wells across the field started to produce formation water of differing compositions. This would explain, for example, the elevated Ca content of post-February 2006 analyses for well F-28AT2 (i.e. above model predictions) and the wide spread in Cl relative to Mg (see Figures 3b and 3c). By mid-2007 the injection water ratio had increased further to 73:27 UFW:RIPW. The possibility of variable injection water composition further increases uncertainty on the reliability of UFW fractions calculated.

### **Summary**

The calculated IWF for Oseberg Sør wells varies with the method and ions used for the calculation. Reactive transport modelling has provided explanations for the variations observed and demonstrated that the ion track method applied to CI analyses should provide the most reliable IWF results, regardless of calculated UFW fraction. However, this requires the RFW composition to be known and this is not the case for many wells. Also, there is high uncertainty associated with these IWF results due to the high sampling/analytical uncertainty on CI analyses



relative to the difference in RFW and UFW Cl concentrations. These results can also be biased where formation waters of differing compositions mix in the well and, due to the variable RFW across the field, where RIPW is produced.

## **IMPLICATIONS**

### **Scale management**

At the Oseberg Sør field where Utsira formation water (UFW) is injected, the principal production well scaling risk is from CaCO<sub>3</sub> deposition (which decreases with increasing UFW fraction in the produced water). Because it has not proved feasible to use either artificial or natural tracers to (a) determine whether UFW is being produced from Oseberg Sør wells, (b) accurately detect the onset of IWB and (c) accurately quantify the UFW fraction in produced water, in 'real-time', it has been necessary to develop scale management strategies that do not use this information for day-to-day operational decisions.

The approach adopted (Fleming et al., 2006) involves similar effort and costs to those required using IWB and IWF information. First, the 'baseline' downhole scaling potential is determined from observed production conditions (including produced water compositions) soon after water breakthrough occurs. Produced water compositions and production conditions are then monitored to identify when significant changes in these parameters occur. For example, increased differential pressure over a perforated interval could result in CaCO<sub>3</sub> precipitation with consequent reduction in productivity index (PI). A decrease in wellhead pressure (WHP) and/or increase in wellhead temperature (WHT) could result in the precipitation of CaCO<sub>3</sub> scale in the upper tubing and, in particular, around the downhole safety valve (DHSV). On Oseberg Sør, the major factors influencing CaCO<sub>3</sub> scaling are downhole production parameters while of secondary importance is variation in produced water composition. The reasons for this are, as has already been stated, there is not a significant ion compositional difference between RFW and UFW. Of significance for downhole scale management decisions, is that the UFW contains approximately 500 mg/l Ca while the RFW has a corresponding value of between approximately 600 and 900 mg/l Ca. Therefore, increasing proportions of UFW will help to reduce the scaling potential.

### **New developments**

Based on the results of this study, there are a number of actions that could be taken during the planning stages of new developments to determine to what extent scale management will be able to rely on IWB and IWF results during production. For example, collection of multiple water samples from appraisal wells would help determine whether formation water compositions vary across the field and to what extent. Where compositions do vary, there may be an increased risk of production of mixed formation waters which could make

identification of IWB more difficult. Also, it may highlight the need to try to obtain produced formation water samples from each well following water breakthrough. Similarly, by undertaking reactive transport modelling, predictions of produced water compositions could be generated showing the changes in composition expected when IWB occurs and subsequently as IWF increases. These results could then be used to determine what ion analyses and methods are likely to be useful for detecting IWB and calculating reliable IWF data. It may be that there will be a case for reducing sampling/analytical uncertainty or monitoring alternative natural tracers during production (e.g. Br,  $\delta^2\text{H}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$ ). For example, as part of an effort to investigate the use of other natural tracers to identify and quantify UFW breakthrough at Oseberg Sør,  $^{87}\text{Sr}/^{86}\text{Sr}$  data is now being acquired. Core material has been sampled and analysed for  $^{87}\text{Sr}/^{86}\text{Sr}$  to generate baseline rock values in an area of the field where water production has not yet occurred and injection and produced water will be monitored over time for their  $^{87}\text{Sr}/^{86}\text{Sr}$  content. In other new developments, there may also be an argument for the use of artificial tracers from the start of water injection. Equally, it may become evident that IWB and IWF data and information may not be of sufficient quality to be useful for scale management during production, and alternative approaches will be required, as at Oseberg Sør.

For fields where IWB information is likely to be obtained, it may be beneficial to use a scale management approach that is a hybrid of those discussed above. This is because MICs are often determined in the laboratory by mixing seawater and formation water whilst ignoring reservoir reaction effects. However, reservoir reaction effects are usually beneficial in that they reduce the production well scaling risks. The hybrid approach would be to monitor produced water compositions to detect IWB but also to place less emphasis of the use of IWF data and more on calculating actual scaling potentials for wells over time (from monitored produced water compositions and production conditions) to determine the MIC required. With this approach it may be possible to reduce the MIC (and hence reduce costs) in cases where the scaling potential is lowered by the effects of reservoir reactions.

## CONCLUSIONS

Detection of IWB and quantification of IWF in the produced water are commonly used to aid scale management decisions. This is particularly relevant in fields with SW injection where IWB is frequently followed by the precipitation of  $\text{BaSO}_4$ . However, in fields such as Oseberg Sør where the compositional differences between RFW and UFW are relatively small, the potential benefits of accurate detection of IWB and IWF are less.

Using artificial tracer and reactive transport modelling results, and interpreting variations in produced water analyses for Oseberg Sør, it has been possible to show that IWB has occurred in several wells, but real-time detection of

breakthrough and quantification of the IWF in produced water has proved impossible due to:

1. Lack of use of artificial tracers in some areas of the field.
2. Delayed injection of artificial tracers relative to the start of water injection.
3. Infrequent monitoring of tracers in produced water.
4. Effects of reservoir reactions on natural tracers.
5. Small differences between RFW and UFW compositions relative to the sampling/analytical uncertainties on ion analyses.
6. Lack of RFW compositions for some wells.
7. Mixing of formation waters of different compositions in some wells.
8. Re-injection of produced water where the RFW varies across the field.

For this reason, a scale management approach has been successfully developed that does not utilise IWB and IWF information. The well production parameters such as increasing WHT, decreasing BHP and increased drawdown combined with scale predictions are the main controls on downhole scale management on Oseberg Sør.

For new developments, it is recommended that multiple water samples are obtained prior to the start of production and reactive transport modelling be used to predict changes in produced water compositions as a result of IWB and subsequent increases in IWF. This information will help determine whether or not IWB and IWF data is likely to be useful for scale management during production. Scale management plans can then be developed accordingly.

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## **NOMENCLATURE**

Ba	Barium
BaSO <sub>4</sub>	Barium sulphate
Br	Bromide

°C	Degrees Celcius
Ca	Calcium
CaCO <sub>3</sub>	Calcium carbonate
CaSO <sub>4</sub>	Calcium sulphate (anhydrite)
Cl	Chloride
CEC	Cation exchange capacity
CO <sub>2</sub>	Carbon dioxide
DHSV	Downhole safety valve
E <sub>F</sub>	Fractional uncertainty associated with mean RFW composition (2σ)
F <sub>UFW</sub>	Fraction UFW required before injection water breakthrough identified.
g	Gram
GWB	Geochemist's Workbench
H <sup>+</sup>	Hydrogen ion
δ <sup>2</sup> H	Stable hydrogen isotopes
HCO <sub>3</sub>	Bicarbonate
IWB	Injection water breakthrough
IWF	Injection water fraction
K	Potassium
Km	Kilometre
M <sub>FW</sub>	Formation water multiple.
m	Metre
Mg	Magnesium
meq	Milliequivalents
mg/l	Milligrams per litre
Na	Sodium
pH	-log activity a <sub>H+</sub>
PI	Productivity index
PLS	Partial Least Squares
PCA	Principal Components Analysis
RIPW	Re-injected produced water
RSD	Relative standard deviation
SO <sub>4</sub>	Sulphate
Sr	Strontium
SR	Saturation ratio
SrSO <sub>4</sub>	Strontium sulphate
<sup>87</sup> Sr/ <sup>86</sup> Sr	Strontium isotopes
TDS	Total dissolved solids
TVDSS	True vertical depth relative to mean sea level (sub sea)
UFW	Utsira formation water
WHP	Wellhead pressure
WHT	Wellhead temperature
XRD	X-ray diffraction

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