

Formation waters of the Norwegian Continental Shelf

R. A. McCartney¹ and E. Rein²

¹*GeoScience Limited, Falmouth Business Park, Bickland Water Road, Falmouth, TR11 4SZ, United Kingdom (mccartney@geoscience.co.uk).*

²*Hydro Oil and Energy, Operations, Technology, P.O. Box 7190, N-5020, Bergen, Norway (Elin.Rein@hydro.com).*

ABSTRACT

New and previously published analyses of formation waters for the Norwegian Continental Shelf (NCS) have been evaluated and interpreted to determine the compositional distribution of formation waters in the region and factors controlling their compositions, and also to obtain information on subsurface fluid flow. Formation waters in the region are Na-Cl and Na-Ca-Cl-type waters that display a wide range of salinity (2500-212000 mg/kg Cl). Generally, the concentrations of most dissolved constituents are positively correlated with Cl so that their distribution in formation waters largely reflects the variations shown by salinity. Exceptions are SO₄ which is generally low (<40 mg/l) regardless of Cl, and HCO₃ and in-situ pH which are negatively correlated with Cl. The main factors determining the compositions of the formation waters are mixing of meteoric water (probably late-Jurassic to Eocene), ancient seawater and primary brine together with diagenetic reactions that have affected each of these components individually as well as mixtures of them. Evaluation of the distribution of salinity has helped us identify where vertical and/or lateral migration of brine from the evaporites has occurred. This has in turn provided us with information on the presence of leak-points and vertical mixing, although further investigation of the location of evaporites and basin palaeohydrogeology are required to determine whether regional lateral advection has occurred in the past. The results of this study may benefit oil exploration and production activities in the NCS including constraint of hydrocarbon migration models, economic evaluation of undrilled prospects, scale management and compartmentalisation studies.

INTRODUCTION

Interpretation of regional formation water analyses can be very beneficial to oilfield operations providing information which can be used to (a) constrain hydrocarbon migration models, (b) understand the controls on the distribution of species that can affect oilfield development costs (eg H₂S, Ba, etc), (c) help understand diagenetic processes in the basin, and (d) understand the causes of variation in formation water compositions within individual fields. In the latter case this can, for example, aid scale management. Regional data can also be used to help assess the quality of formation water samples and analyses obtained from new wells in the area.

A number of studies have been undertaken on formation water analyses from the Norwegian Continental Shelf (NCS). The earliest, by Egeberg and Aagaard (1989), suggested that the compositions of formation waters in this area are determined by mixing between primary brine (ie evaporated seawater) and pre-Oligocene meteoric water with diagenetic reactions overprinting the composition of the original primary brine and the brine-meteoric water mixture. Subsequent studies identified spatial variations in formation water compositions

across the North Sea (Bjørlykke and Gran, 1994; Moss et al., 2003; Warren and Smalley, 1994) and helped understand the relationship between diagenetic reactions and the compositions of formation waters in the region (Aagaard and Egeberg, 1998; Aagaard et al., 1990; Aagaard et al., 1992; Aplin et al., 1993; Bjørlykke et al., 1995). They also identified the factors controlling the compositions of formation waters in individual fields (Ziegler et al., 2001), and helped constrain regional fluid flow (Bjørlykke and Gran, 1994; Moss et al., 2003).

In this paper we present the results of interpretation of both new and previously published formation water analyses for the region. We have determined the compositional distribution of formation waters in the region, factors controlling their compositions, and also obtained information on subsurface fluid flow.

FORMATION WATER ANALYSES

We have used 68 published (Eggenkamp, 1994; Kleven et al., 1997; Warren and Smalley, 1994; Ziegler et al., 2001) and 29 previously unpublished formation water analyses in our study. The locations of the wells and fields from which these analyses were obtained are shown in Figure 1. These data were derived from formations of Triassic to Miocene age. The analyses included data for Na, K, Mg, Ca, Sr, Ba, Cl, HCO₃, SO₄, Br, $\delta^2\text{H}$, $\delta^{18}\text{O}$, $\delta^{37}\text{Cl}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ and generally the data are believed to be of good quality. In-situ (reservoir) compositions were calculated using MultiScale[©] (Petrotech, 2003), surface water analyses, PVT analyses, and reservoir pressure and temperature. To simplify data presentation, in the following sections the data are plotted by area and by the stratigraphic age of the formation from which they were obtained (see Table 1).

RESULTS AND DISCUSSION

Variation of formation water compositions

Previous studies (Bjørlykke and Gran, 1994; Moss et al., 2003) have shown that formation water salinity is highest at depth in the grabens and decreases with decreasing depth and toward the graben flanks. The highest salinity formation waters occur in the Jurassic strata of the Central Graben (up to 212000 mg/kg Cl equivalent). Smaller areas of high salinity formation waters also occur in the Jurassic strata of the Central Viking Graben (CVG), and Cretaceous/Cenozoic strata of the Central Graben, South Viking Graben (SVG) and CVG. Moderate salinity waters (19350-52200 mg/kg Cl equivalent) occur in the Jurassic strata of the North Viking Graben (NVG) and its eastern flanks and the Haltenbanken. The Triassic/Jurassic strata of the Tampen Spur and East Shetland Basin are notable for their lower salinity formation water (< seawater; <19350 mg/kg Cl equivalent).

Our new data are consistent with these results but very low salinity formation waters have been identified in the Fram and Ormen Lange Fields (<3640 mg/l Cl). Cl increases with depth along a regional trend in most areas (Figure 2). Only in the Lower and Middle Jurassic formations of the Tampen Spur area is there no significant change in salinity with depth (2507-4116 mBSL). The waters in this area have anomalously low salinity relative to the regional depth trend, as do waters from Edda, Fram, Ormen Lange and Veslefrikk.

Anomalously high salinity formation waters are present in Ekofisk, Gyda, Sleipner West, Tor, Tambar, Ula and Varg.

At a local scale, variations in salinity with depth are more complex. In some localities salinity increases with depth within individual formations and between formations. In others, salinity does not always change significantly with depth. Also, salinity can be fairly constant in the same formation at a given depth whereas in other cases, significant variations in formation water salinity can occur within a formation at the same depth.

Formation waters from the region are generally Na-Cl type waters except where Cl is in excess of 90,000 mg/l (Na-Ca-Cl type). Ormen Lange formation waters are Na-Cl-HCO₃ type. The concentrations of all dissolved constituents vary significantly but most very broadly increase with increasing Cl concentration (eg Figures 3-6). Warren and Smalley (1994) have noted the particularly large variability of K, Sr and Ba relative to Cl in formation waters from the North Sea and we also see this in the NCS area (eg Figures 5-6). SO₄ is generally low (<40 mg/l) regardless of Cl content (Figure 9), and pH and HCO₃ decline with increasing Cl (eg Figures 7). The general trends with Cl displayed by all constituents are typical of sedimentary formation waters (Hanor, 1994).

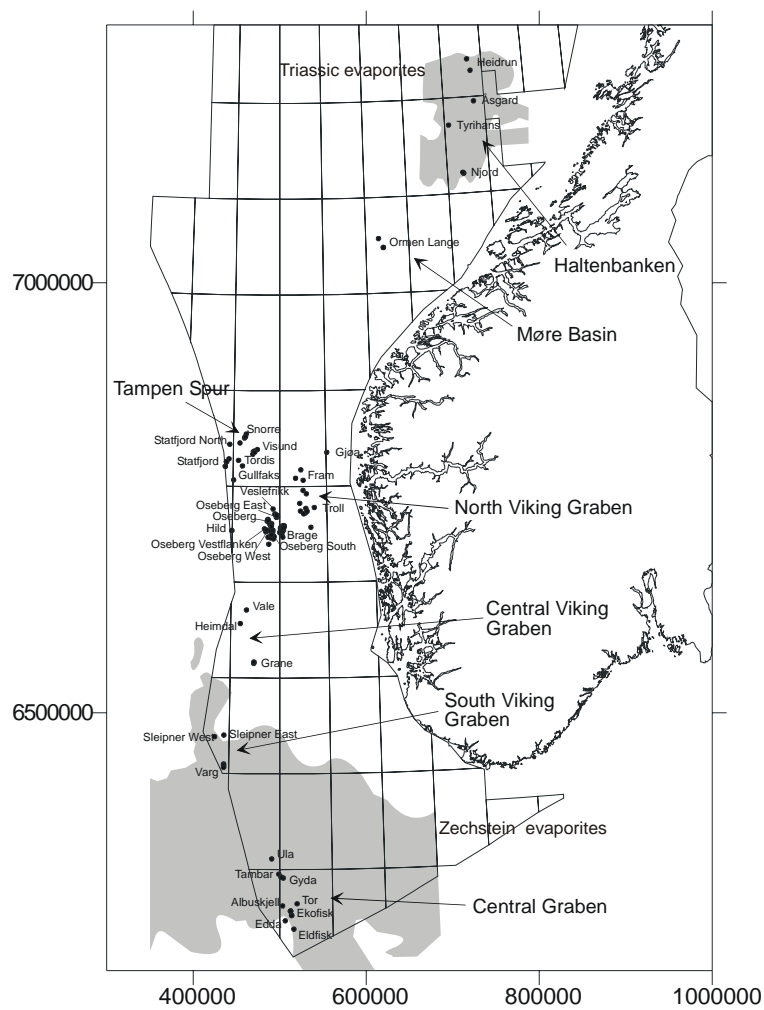


Figure 1 : Sample locations and locations of evaporites (grey).

Table 1 Source of formation water analyses used in the study

Legend symbol	Area	Stratigraphic age	Fields
A	Central Graben	U. Jurassic	Gyda, Tambar, Ula
B	Central Graben	U. Cretaceous	Albuskjell, Edda, Ekofisk, Eldfisk, Tor
□	South Viking Graben	M. Jurassic	Sleipner West, Varg
○	South Viking Graben	Palaeocene	Sleipner East
△	Central Viking Graben	Palaeocene	Grane, Heimdal
▽	Central Viking Graben	M. Miocene	Grane
1	North Viking Graben	L. Jurassic	Brage, Gullfaks, Oseberg South, Oseberg Vestflanken, Oseberg West, Tordis, Visund
2	North Viking Graben	M. Jurassic	Brage, Fram, Gullfaks, Hild, Oseberg, Oseberg East, Oseberg South, Oseberg West, Veslefrikk, Visund
3	North Viking Graben	U. Jurassic	Brage, Fram, Gjøa, Troll
4	North Viking Graben	M. Miocene	Brage, Oseberg East
▲	Tampen Spur	Triassic	Snorre
▼	Tampen Spur	L. Jurassic	Snorre, Statfjord
■	Tampen Spur	M. Jurassic	Statfjord, Statfjord North
×	Møre Basin	U. Cretaceous	Ormen Lange
+	Møre Basin	Palaeocene	Ormen Lange
⊞	Haltenbanken	L. Jurassic	Njord
⊠	Haltenbanken	M. Jurassic	Åsgard, Heidrun, Tyrihans
●	Seawater		

Factors determining the compositions of formation waters

The compositions of oilfield formation waters are determined by both chemical and physical factors including the original composition of the waters at the time of sediment deposition, diagenetic reactions, advection, dispersion and mixing. Our interpretation of the compositions of NCS formation waters has resulted in the generation of a general model to explain the variability of their compositions (Figure 8). In the following sections we present the evidence to support this model which consists of the mixing of ancient seawater, ancient meteoric water and primary brine. Each of these components appears to have been affected by diagenetic reactions both before and after they have mixed.

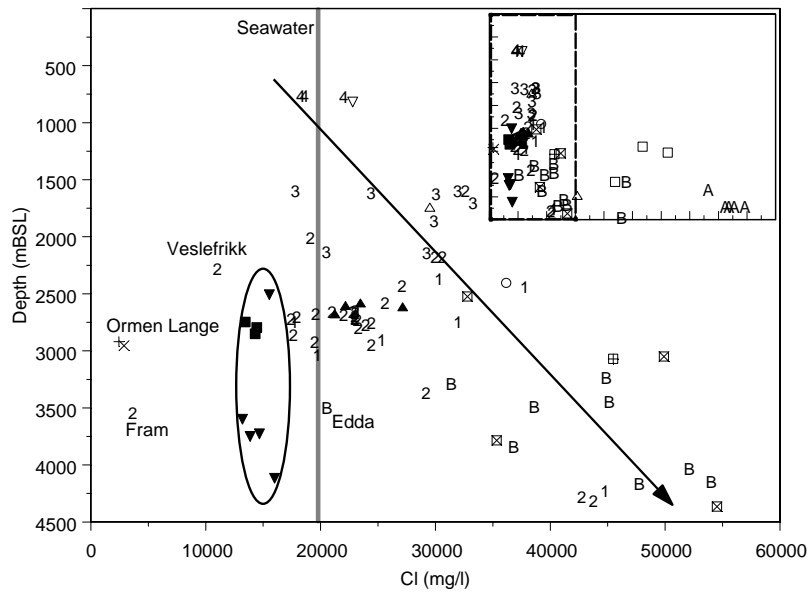


Figure 2 : Variation of formation Cl content with depth. The inclined arrow depicts the broad regional trend. Lower and Middle Jurassic analyses, Tampen Spur area, are circled

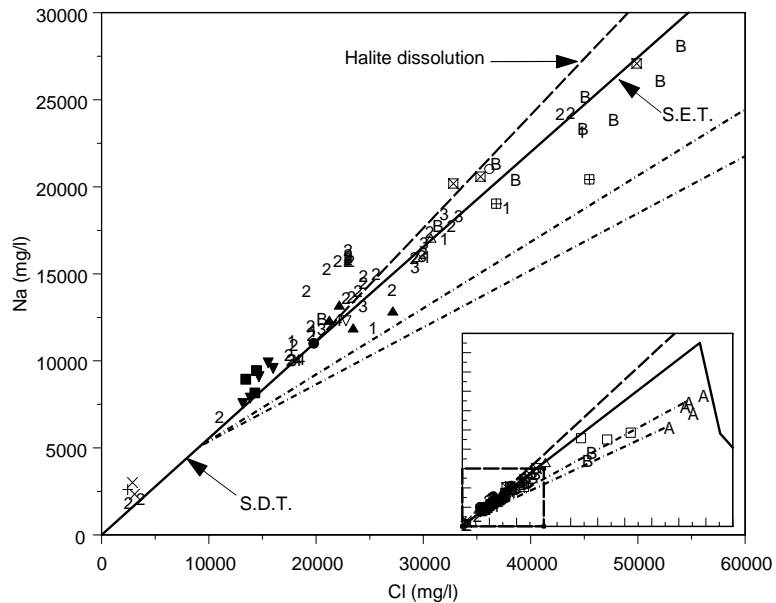


Figure 3 : Variation of Na with Cl. Inlaid graph shows all data and main graph shows moderate to lower salinity data. See Table 1 for legend. SDT = Seawater Dilution Trend. SET = Seawater Evaporation Trend. The data trend expected for halite dissolution is shown for reference. Dotted lines represent hypothetical mixing lines between reacted seawater/meteoric water mixture (50:50) and reacted primary brine.

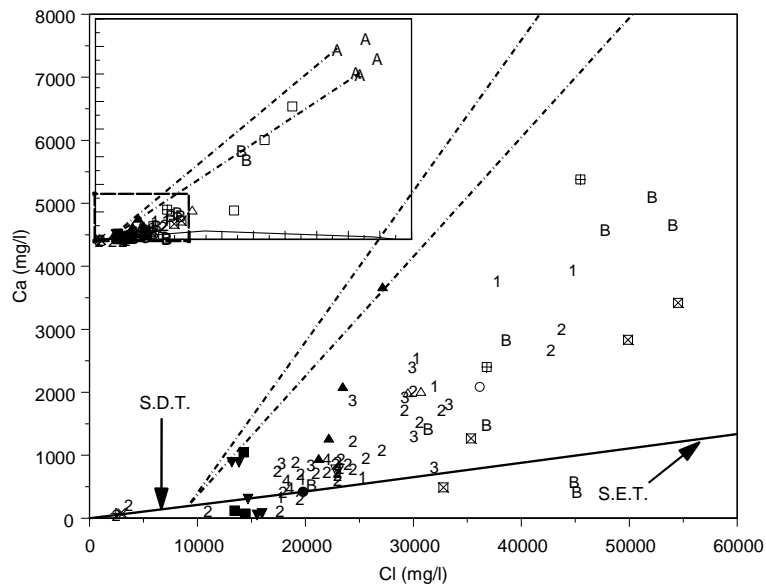


Figure 4 : Variation of Ca with Cl. Inlaid graph shows all data and main graph shows moderate to lower salinity data. See Table 1 for legend. SDT = Seawater Dilution Trend. SET = Seawater Evaporation Trend. Dotted lines represent hypothetical mixing lines between reacted seawater/meteoric water mixture (50:50) and reacted primary brine.

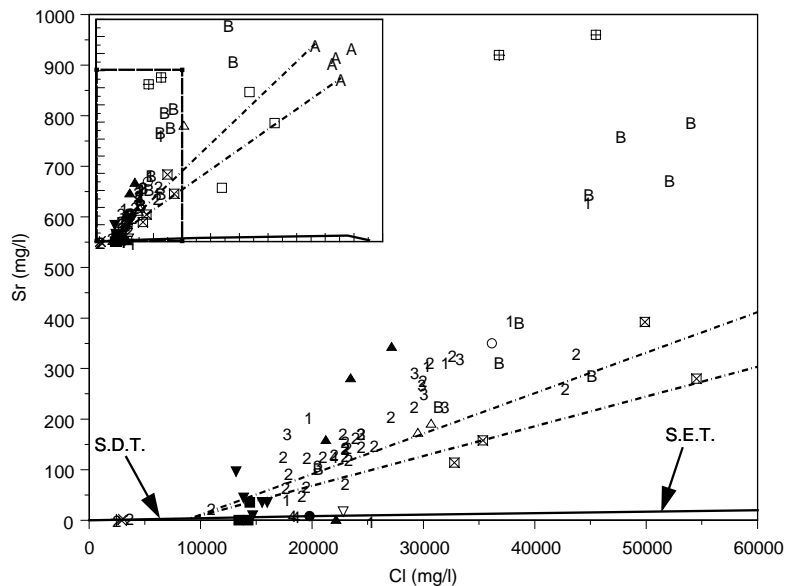


Figure 5 : Variation of Sr with Cl. Inlaid graph shows all data and main graph shows moderate to lower salinity data. See Table 1 for legend. SDT = Seawater Dilution Trend. SET = Seawater Evaporation Trend. Dotted lines represent hypothetical mixing lines between reacted seawater/meteoric water mixture (50:50) and reacted primary brine.

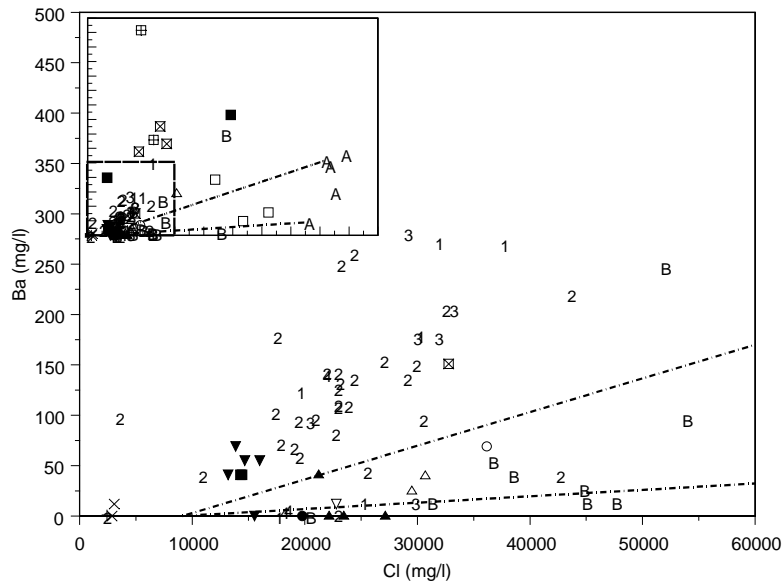


Figure 6 : Variation of Ba with Cl. Inlaid graph shows all data and main graph shows moderate to lower salinity data. See Table 1 for legend. SDT = Seawater Dilution Trend. SET = Seawater Evaporation Trend. Dotted lines represent hypothetical mixing lines between reacted seawater/meteoric water mixture (50:50) and reacted primary brine

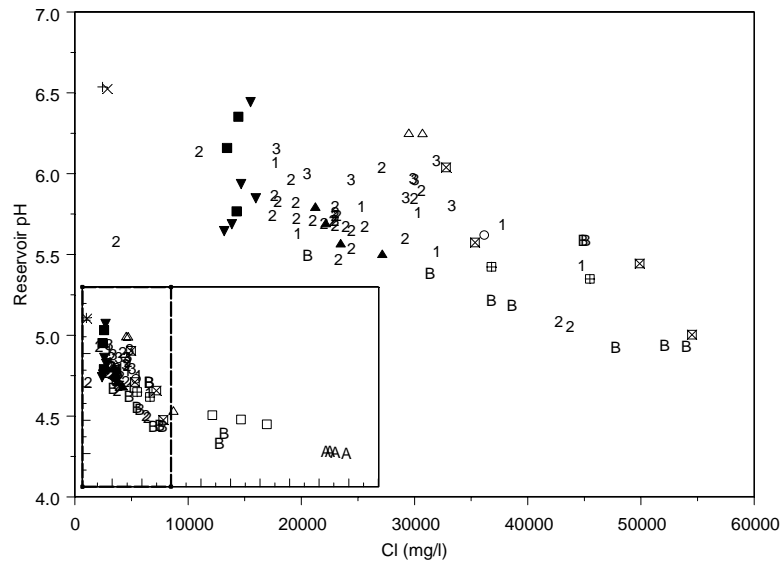


Figure 7 : Variation of reservoir pH with Cl. Inlaid graph shows all data and main graph shows moderate to lower salinity data. See Table 1 for legend.

Evidence for the presence of meteoric waters and ancient seawater

Figure 9 shows formation water $\delta^2\text{H}$ and $\delta^{18}\text{O}$ analyses for the NCS and the North Sea generally. The Utsira Formation (Middle Miocene) was deposited under marine conditions and has since been maintained below sea level. This, coupled with its low temperature (25°C), suggests that Utsira formation water is connate seawater. Agreement between its composition and our estimate for pre-Pliocene seawater (Figure 9) supports the validity of the latter. Meteoric water during the Jurassic-Tertiary periods is believed to have had a fairly constant $\delta^2\text{H}$ composition (Figure 9). All but one sample from Hild have $\delta^2\text{H}$ compositions between the ancient seawater and meteoric water compositions. $\delta^2\text{H}$ data can be affected by reactions in sedimentary basins and exchange with clays is the most important process (Kharaka and Carothers, 1986). However, we do not see the decrease in $\delta^2\text{H}$ with increasing temperature and depth expected if this process were significant in the NCS. Therefore, we believe the NCS formation waters contain components of both ancient seawater and ancient meteoric water. Previous interpretations of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ compositions of North Sea formation waters and diagenetic minerals have argued for the presence of a significant meteoric water component within the basin (eg Aplin et al., 1993; Egeberg and Aagaard, 1989; Glasmann et al., 1989) and based on geological evidence meteoric water ingress to the basin could have occurred between Middle Jurassic to Middle Eocene depending on locality. $\delta^{18}\text{O}$ compositions are affected by reactions in the NCS and are discussed further below.

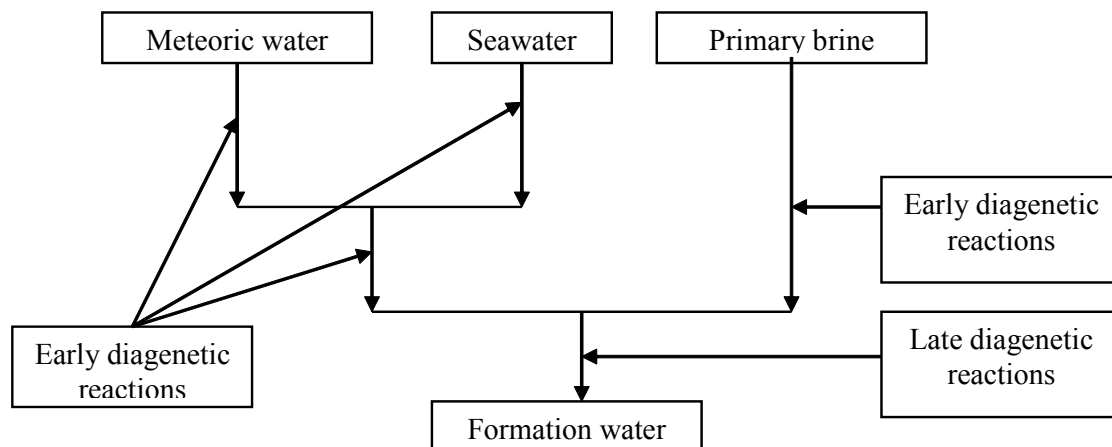


Figure 8 : Conceptual model to explain variation in formation water composition in the NCS

Evidence for the presence of primary brines

The majority of samples are enriched in Cl relative to what would be expected for meteoric water-seawater mixtures. This implies that there is another source of Cl. Largely on the basis of Br/Cl enrichment above the seawater dilution and seawater evaporation trends (SDT, SET) (Figure 10) Egeberg and Aagaard (1989) and Ziegler et al. (2001) both concluded that the additional Cl is mainly derived from the presence of primary brine (evaporated seawater

deposited with evaporites) in NCS formation waters. Although they did not consider all possible explanations for Br/Cl enrichment (eg dissolution of sylvite and/or carnallite, degradation of organic matter, etc) after further evaluation of these data we agree with their conclusions. The Br/Cl data can be explained by mixing between meteoric water, seawater and primary brine where the latter has evaporated between halite and epsomite saturation (Figure 10). $\delta^2\text{H}$ and $\delta^{18}\text{O}$ data are also consistent with this conclusion (Figure 9).

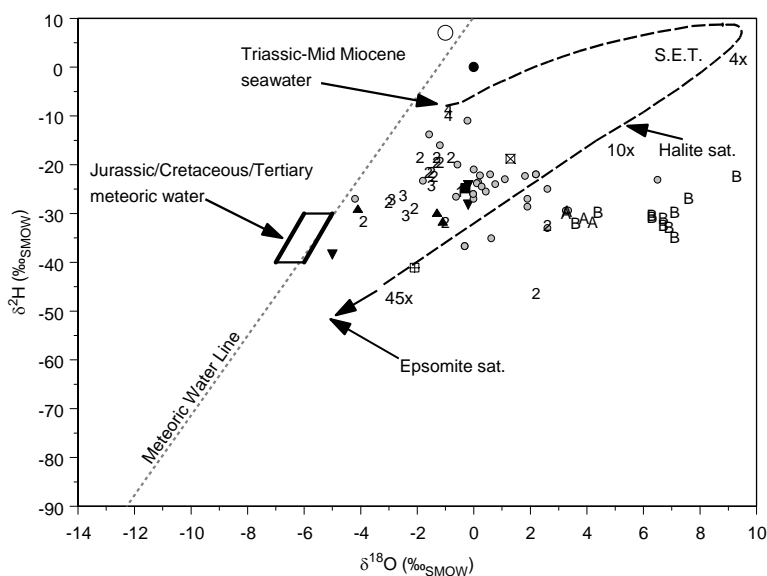


Figure 9 : Variation of $\delta^2\text{H}$ and $\delta^{18}\text{O}$. Grey circles are data for other areas of the central and northern North Sea. The SET is shown for reference with evaporation factors (eg 10x) and estimated points where halite and epsomite saturation occurs. Also included are ranges for Triassic-Middle Miocene seawater and Jurassic-Tertiary meteoric water. See Table 1 for legend.

Permian Zechstein evaporites are present in the southern NCS and Triassic evaporites exist in the Haltenbanken area (Figure 1). Compaction of these evaporites during burial would result in the upward release of primary brines into shallower formations in these areas. The presence of primary brine in the Tampen Spur and NVG areas is more problematic, as discussed later. Also, it is worth noting that Br data are not available in the SVG, CVG, Møre Basin and Haltenbanken areas, so the presence of primary brines in these areas is more speculative.

Chemical composition of the primary brines

Primary brines should dominate the compositions of the more saline formation waters. However, the Upper Jurassic waters from the Central Graben do not reflect the Na-Mg-SO₄-Cl-type composition expected of primary brines. Relative to the SET they are enriched in Ca, Sr and Ba, and depleted in Na, Mg and SO₄ (Figures 3-6). Gyda samples have K contents expected of the primary brine while those for Ula and Tambar are depleted in K. These

discrepancies have been explained by water-rock reactions occurring between the primary brines and formations during their burial, migration, and within the formations from which they were sampled (Egeberg and Aagaard, 1989; Ziegler et al., 2001). They suggested the primary brines have been affected by dolomitisation, anhydrite and K-feldspar deposition, celestite (and possibly biotite and plagioclase) dissolution, albitisation of K-feldspar and illitisation of smectite. Bacterial sulphate reduction may also have contributed to loss of SO_4 (Carpenter, 1978). Our best estimates of the composition of the primary brine are the range of compositions displayed by the Upper Jurassic Central Graben samples which are believed to comprise close to 100% reacted primary brine.

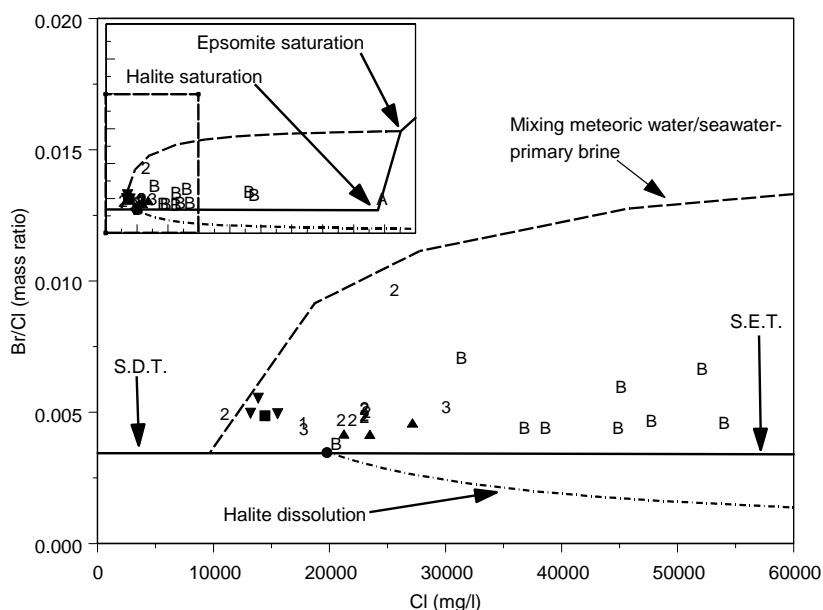


Figure 10: Variation of Br/Cl with Cl. Inlaid graph shows all data and main graph shows moderate to lower salinity data. See Table 1 for legend. SDT = Seawater Dilution Trend. SET = Seawater Evaporation Trend. Trends due to halite dissolution and mixing between epsomite saturated primary brine and meteoric water/seawater mixture (50:50) are shown for reference.

Chemical composition of connate ancient seawater/meteoric water mixtures

The Middle Miocene Utsira Formation sample from Brage well N31/4-A-24 has an isotopic composition expected for ancient seawater but is ~10% less saline than current seawater. This is probably representative of Middle Miocene seawater because the lack of ice caps at this time would result in lower seawater Cl. Utsira formation water with similar salinity is also present in Oseberg East. Samples from Grane and Brage well N31/4-A-29 are ~15% more saline and probably reflect ingress of more saline water into the formation. The low Cl Utsira samples lie close to the Seawater Dilution Trend (SDT) for Na. They are also enriched in Ca and Sr and depleted in K, Mg and SO_4 relative to the SDT and enriched in Ba and alkalinity relative to seawater (Figures 3-6). These deviations may, in part, be explained by differences between current and Middle Miocene seawater compositions (eg Horita et al., 2002) but

diagenetic reactions must also be involved. The Utsira Formation comprises mainly quartz with subordinate feldspar, is rich in glauconite and bioclastic debris, and contains minor lignite (Fyfe et al., 2003). Possible reactions explaining these deviations include glauconite precipitation, bacterial sulphate reduction, and feldspar dissolution.

Those NCS formation waters with Cl contents just less than ancient seawater are likely to be dominated by seawater/meteoric water mixtures and contain little primary brine. Although there are some exceptions, these samples generally display similar enrichments/depletions relative to the SDT that are shown by the Utsira samples suggesting that both seawater and seawater/meteoric water mixtures are undergoing similar reactions following sediment deposition (Figures 3-6).

Effects of reaction on seawater-meteoric water-primary brine mixtures

To assess the degree to which mixing can explain the chemical compositions of formation waters in the NCS we have generated mixing lines through (a) our estimate of the composition of a 50:50 mixture of 'reacted' seawater/meteoric water and (b) our best estimates of the composition of the primary brine (Figures 3-6). In most cases formation water analyses lie outside these mixing lines suggesting that post-mixing diagenetic reactions have affected the formation waters. Na, Sr, Ba and $\delta^{18}\text{O}$ are generally enriched above the mixing lines indicating a net gain via reaction whilst K, Mg and Ca are generally depleted indicating a net loss. The reactions responsible for these gains and losses have been assessed by considering the mineralogical composition of rocks in the region and their stability in contact with NCS formation waters (eg Figures 11 and 12). Insufficient data was available to assess the effects of reaction on SO_4 and HCO_3 .

The net gain in Na may reflect the importance of albite and plagioclase dissolution. Both are common in sandstones throughout the NCS and are unstable in the presence of these formation waters (Figure 11). Similarly, where shales or mudstones are present locally, illitisation of smectite within them followed by transport of Na into the reservoirs might also explain the enrichment (Aagaard et al., 1990). This reaction starts at 60-70°C in the North Sea and I/S component ordering develops between 80-110°C. It is also possible that halite dissolution may have caused Na-enrichment in some samples although as indicated above, in most cases Cl enrichment of samples generally reflects the addition of primary brine. Albitisation of K-feldspar has been reported between 2 and 3.5km depth in the NCS (eg Bjørlykke et al., 1992; Saigal et al., 1988) which is inconsistent with the observed Na gain and albite instability. However, the gain in Na is a net effect and does not preclude Na loss at some stage in the past. For example, albitisation may have occurred at a time when the $a_{\text{Na}^+}/a_{\text{H}^+}$ ratio of the formation waters was higher than currently observed (lower P_{CO_2} ?).

K-feldspar is unstable in contact with NCS formation waters and should be dissolving. K released from this reaction and K within the formation water can be consumed by illitisation of kaolinite above 130-140°C. This reaction is extensive in the NCS in the presence of kaolinite (eg Bjørlykke et al., 1992; Saigal et al., 1988). At temperatures below approximately 130°C kinetic barriers prevent significant illitisation of kaolinite (Bjørlykke et al., 1995) but K can be removed by diffusion into adjacent shales/mudstones where illitisation of smectite can occur (Aagaard et al., 1990). This reaction process can also proceed above 130°C.

Formation waters lie close to the equilibrium line for disordered dolomite and calcite (Figure 12) suggesting that these minerals buffer Ca and Mg in formation waters in the region. This relationship has been observed in other sedimentary basins (eg Hyeong and Capuano, 2001). Both dolomite and calcite are authigenic minerals in the NCS. Mg may also be buffered by chlorite. Authigenic chlorite has been observed in reservoirs on the NCS at temperatures as low as 70°C. Mg loss may therefore be due to precipitation of dolomite or chlorite prior to equilibrium being achieved. Similarly, Ca may be lost through calcite deposition or dedolomitisation. Any Ca released via other reactions (eg illitisation of smectite, plagioclase dissolution) must also be removed by these reactions. Loss via anhydrite precipitation is unlikely from current formation waters because they are all undersaturated with respect to this mineral.

NCS formation waters are undersaturated with respect to celestite (SrSO_4) so this could be a source of Sr. This mineral normally only occurs in evaporite deposits and some of the Sr-enrichment could have coincided with halite dissolution. Sr in formation waters commonly appears to be buffered by strontianite in sedimentary basins (Kharaka et al., 1985) and this may be the case for NCS formation waters although there is uncertainty in the thermodynamic data for this mineral. If so, it may have been a source of Sr but now may be limiting the amount of Sr in some samples. Although we are not aware this mineral has been recorded in the NCS, this does not mean that the mineral is not present. Sr may also be derived from plagioclase dissolution and recrystallisation of Ca-carbonates. $^{87}\text{Sr}/^{86}\text{Sr}$ data suggest that at least some Sr must be derived from authigenic carbonates and for some Chalk group formation waters a marine carbonate Sr source is also likely.

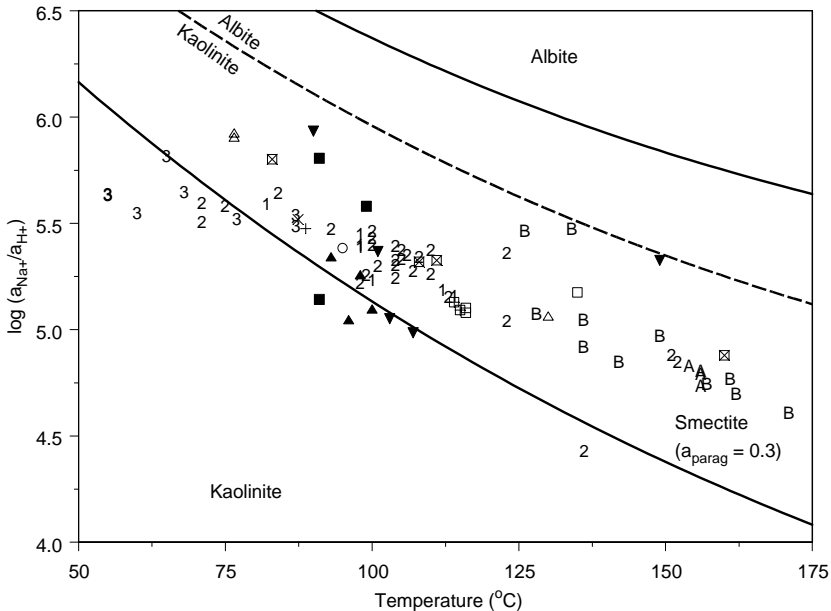


Figure 11 : Stability diagram describing the equilibrium between albite, smectite and kaolinite at quartz saturation (Johnson et al., 1991). Typical North Sea formation pressures assumed. $\log a_{\text{Na}^+}$ and a_{H^+} for formation waters obtained from calculated in-situ compositions. See Table 1 for legend.

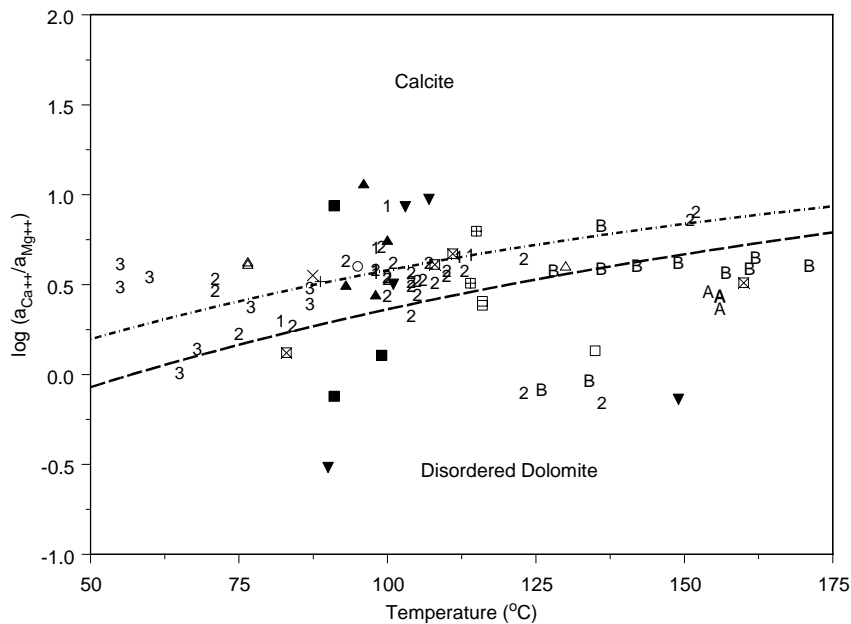


Figure 12 : Stability diagram describing the equilibrium between calcite and disordered dolomite. Dashed line (Johnson et al., 1991). Dash-dot line (Hyeong and Capuano, 2001). Typical North Sea formation pressures assumed. $a_{Ca^{++}}$ and $a_{Mg^{++}}$ for formation waters obtained from calculated in-situ compositions. See Table 1 for legend.

Ba substitutes for K in K-feldspar. Given the widespread occurrence of this mineral and its instability in the presence of NCS formation waters (see above), this is likely to be a primary source of Ba in the NCS. NCS formation waters are close to equilibrium with barite and this is typical for formation waters in sedimentary basins (Hanor, 1994). Samples that are significantly oversaturated with respect to barite tend to have elevated SO_4 which in most cases is likely to be a sampling or analytical artefact. Barite is often reported as an authigenic mineral in the NCS although whether it is widely distributed is not known. Clearly, it can act as a sink for Ba and where present it can act as a source. Witherite ($BaCO_3$) is another possible source but we do not have thermodynamic data to determine its role and nor are we aware that its presence has been reported in the NCS.

Enrichment in $\delta^{18}O$ increases with depth and is particularly noticeable in Chalk Group samples. The high carbonate content of these limestones may explain the greater shift observed in these samples. Carbonates are a large reservoir of O atoms easily exchangeable with waters (Kharaka and Carothers, 1986). For samples from the sandstones, the $\delta^{18}O$ shift may be the result of illitisation and chloritisation of kaolinite and smectites (Egeberg and Aagaard, 1989). This is consistent with reactions discussed above.

One uncertainty in our analysis results from our assumption that the composition of the primary brine is similar for the whole region. Deviations from this composition might explain some of the observed deviations from the mixing lines. Collection and analysis of more high salinity samples from the region may help us determine the importance of this uncertainty. Based on the above results, however, and comparing the compositions of the reacted meteoric

water/seawater, primary brine, and deviations from the mixing lines we can conclude that other than for Na and Cl in lower salinity samples (<20000 mg/l Cl), the dissolved load is primarily determined by mixing with the primary brine and post-mixing reactions. In most cases, as salinity increases, the contribution of primary brine to the dissolved load becomes dominant. At lower salinities, the influence of reaction is generally more important although the salinity at which this dominance occurs varies from element to element. For Sr and Ba, the contribution from a reaction source is important/dominant compared with the primary brine source for most samples regardless of salinity.

Distribution of primary brine

Based on $\delta^2\text{H}$ and Cl data for NCS formation waters and assuming that halite dissolution is not significant we estimate that the proportion of primary brine in the anomalously high salinity samples of the Central Graben and SVG probably varies between ~45% and approaching close to 100%. In the other areas the proportion of primary brine is probably less than ~25% at 4km and ~6% at 1.5-3km (see Figure 2 for Cl versus depth). In the Fram and Ormen Lange areas where salinity is very low the primary brine content must be less than 2%, if it is present at all (we have no Br data for these fields). Where halite dissolution has occurred, the above percentages will overestimate the amount of primary brine present but as halite dissolution is not thought to be a dominant process in the region, the general trends in distribution are likely to be valid.

Migration of brine

Other than in the Central Graben area, the fields in this study are located away from salt diapirs so salinity in excess of that expected for seawater/meteoric water mixtures can be used to show where brine (whether primary or secondary in origin) has migrated to from the Permian/Triassic evaporites. This has revealed a number of results relevant to fluid flow in the basin including:

- a) High salinity formation waters, high in the stratigraphic column above evaporites are indicative of vertical 'leak points' and have been identified near Ekofisk N2/4-B12 and Tor. Higher salinity waters in Varg and Sleipner West are also close to what is believed to be a leak point in the southern SVG (Gaarenstrom et al., 1993; Wilkinson et al., 1997).
- b) In the Haltenbanken, there is a general increase in salinity with depth consistent with brine flowing from the Triassic evaporites below but the amount of brine entering these Jurassic formations is not as great as that seen in the Jurassic formations in the SVG and Central Graben. This may be due to the Triassic evaporites being thinner than the Zechstein (Gran et al., 1992). Alternatively, it may reflect the relatively lower vertical permeability in this area compared with the Central Graben.
- c) For areas where brine occurs away from known locations of evaporites there are two possible explanations. Egeberg and Aagaard (1989) proposed that the Permian Zechstein evaporites extend underneath the Central and North Viking Graben areas because in the early Permian, the Viking Graben constituted the connection between the northern Permian Basin and the early Permian Ocean. Alternatively, extensive pressure generated

lateral flow may have occurred in this area prior to development of compartmentalisation in the Jurassic sandstones. Both explanations are currently unsubstantiated.

- d) Regardless of the brine migration route to the NVG, the salinity increase with depth in the Oseberg and Brage areas is consistent with brine penetrating from below. However, the salinity increase with depth is greater at Brage. This might be explained by the Brage area have relatively higher vertical permeability.
- e) In the Tampen Spur area salinity is fairly constant with depth. The small amount of brine that may have reached these fields appears to have been well mixed vertically.
- f) In the Ormen Lange and Fram N35/11-2 and N35/11-3 areas, low salinity water is present at significant depth. In these areas little or no brine appears to have entered the formations. In the case of Ormen Lange, this may reflect lack of lateral flow in the past, lack of underlying evaporites, lower vertical permeability or greater flushing by meteoric water in this area. In the case of Fram, formation waters with elevated salinities are present in nearby Troll and Gjøa and recent information suggests they are present in just to the south-east of the wells considered in this study. Therefore, brine may have been prevented from entering the N35/11-2 and N35/11-3 area or the area may have been particularly well flushed by meteoric water in the past. In either case, the implication is that peripheral barriers to lateral±vertical flow may be present.
- g) The presence of leak-points and vertical mixing suggest that locally advection must be important although diffusion must also occur. Previously, Bjørlykke and Gran (1994) have suggested diffusion of Cl from depth is a dominant vertical migration process in the NCS. Further investigation of the location of evaporites in the basin and palaeohydrogeology are required to determine whether regional lateral advection has occurred in the past.

CONCLUSIONS

Formation waters from the NCS have a wide range of compositions. The variations in composition reflect mixing between at least three different fluid components: meteoric water (probably late-Jurassic to Eocene), ancient seawater and primary brine. These components have each undergone diagenetic reactions prior to mixing and following mixing. For most constituents, the dominant contributors to the dissolved load of the formation waters are (a) the fraction of primary brine present and (b) the influence of reactions that have occurred after mixing. The contribution of seawater and meteoric water to the dissolved load is generally minor except for Na and Cl in formation waters with lower salinity (<20000 mg/l Cl). The contribution of the primary brine is generally highest at higher formation water salinities. Post-mixing reactions are more important at lower salinities although they are generally the main source of Ba and Sr regardless of salinity.

The primary brine has migrated from Permian/Triassic evaporites and is more abundant at depth, close to known evaporite occurrences and close to leak points that channel brines from depth. The meteoric and seawater components were probably partly deposited with the sediments of the host formation but a contribution from other formations is also likely (via their compaction and migration of the expelled water). Evaluation of the distribution of salinity has helped us identify where vertical and/or lateral migration of the brine from the

evaporites has occurred. This has in turn provided us with information on the presence of leak-points and vertical mixing, although further investigation of the location of evaporites and basin palaeohydrogeology are required to determine whether regional lateral advection has occurred in the past.

The results of this study can benefit both oil exploration and production activities in the NCS. For example, information on brine migration directions could be used to help constrain hydrocarbon migration models. Also, possible sources and controls on the concentrations of scaling ions (eg Ca, Ba, Sr) have been identified. This information can be used to help determine possible development costs before prospects are drilled and help understand scaling risks within operating fields. Finally, an improved understanding of the regional controls on formation water compositions can reduce the uncertainties on the interpretation of formation water analyses from individual fields (eg for compartmentalisation studies).

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