DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2007/52

Geochemistry of the Upper Jurassic Heno Formation in the Karl-1 well, Danish North Sea

Rikke Weibel

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MINISTRY OF THE ENVIRONMENT

G E U S

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Abstract

This report is a continuation of a previous investigation on the chemostratigraphy and mineral-chemical fingerprinting in the Upper Jurassic Heno Formation from the Danish North Sea. Geochemical analysis of cuttings samples from the Karl-1 well are compared with results from core and cuttings samples from the Hejre-2 well, and with results from core samples in all other investigated wells from the Danish Central Graben: Diamant-1, Gert-1, Gert-2, Gert-4, Hejre-1, Jeppe-1 and Rita-1. In all 45 cuttings samples from the Karl-1 well have been geochemically analysed for major elements by XRF (X-ray fluorescence) and for trace elements by ICP-MS (inductively coupled plasma - mass spectrometry).

The cuttings samples from the Ravn and Gert Members of the Heno Formation in the Karl-1 well can generally be distinguished from each other by the same parameters as core samples from the other previously investigated wells. The distinction, though, is less clear for the cuttings samples in the Karl-1 well than for the core samples in the other investigated wells. Furthermore, the Cr content cannot be used, as it is high for all cuttings samples probably due to steel chip impurities rather than sediment differences. The Gert Member in the Karl-1 well generally has lower Th / TiO_2 (and REE / TiO_2), Nb / TiO_2, P_2O_5 / Al_2O_3, Na_2O / Al_2O_3 and higher V / P_2O_5 ratios than the Ravn Member. Several possible explanations can account for the observed differences between the Ravn and Gert Members. Less altered material could have been brought into the system during deposition of the Gert Member, whereas intensively altered material dominated during deposition of the Ravn Member. Different source areas could have been exposed during deposition of the Gert Member than when the Ravn Member was deposited. The Mid North Sea High seems a likely source for the high Th, REE and P_2O_5 content characteristic of the Ravn Member. The Gert Member in the Karl-1 and Hejre-2 wells is not characterised by as high peak amounts of TiO_2 as Gert Member in other wells. The local source that supplied high Cr and TiO_2 during deposition of the Gert Member seems to be less important or more distal in the areas of the Karl-1 and Hejre-2 wells. The depositional environment may also have played a major role in the variation of Mg, as the Ravn Member, in the more distally placed wells, generally has a much higher MgO content than the Ravn Member from the wells characterised by shoreface conglomerate.

The Karl-1 well, as well as the Hejre-2 well, have volcanic material underlying the Upper Jurassic sediments. The volcanic material in the Karl-1 well is Permian and consists of alternating horizons of dominating sodic and potassic compositions. The volcanic material in the Hejre-2 well is characterised by high amounts of K-feldspar, which also has influenced the overlying Upper Jurassic sediments. A volcanic sediment source may also have played an important role in the Karl-1 well, but would have been dominated by alternating sodic and potassic composition rather than the dominating potassic composition found in the Hejre-2 and Jeppe-1 wells. Future petrographic investigations could verify if sodium incorporation in feldspars and clays are correct; and explain whether potassium is related to detrital K-feldspar or clays in the Karl-1 well.

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Introduction

The purpose of the study is to make a geochemical fingerprinting of the Upper Jurassic Heno Formation sandstones in the Karl-1 well for correlation and comparison with the chemostratigraphy of the Hejre-wells as investigated in a previous study on chemostratigraphy and mineral-chemical fingerprinting, Heno Formation, Danish North Sea (Weibel & Knudsen 2007).

Geological setting

The geological setting presented here is a brief summary from the previous report (Weibel & Knudsen 2007) and more details can be found in, e.g. Damtoft et al. (1992), Michelsen et al. (1992), Johannessen & Andsbjerg (1993), Rasmussen (1995), Johannessen et al. (1996), Andsbjerg (2003), Andsbjerg & Dybkjær (2003), Johannessen (2003) and Michelsen et al. (2003).

The tectonic stationary conditions of the Early Jurassic with deposition of offshore uniform mudstones changed in the earliest Middle Jurassic with the regional uplift related to the doming of the central North Sea and the Ringkøbing–Fyn High (Andsbjerg et al. 2001). Due to extensive and continued uplift a highly erosive unconformity formed in the North Sea, on the Ringkøbing–Fyn High and in the Fennoscandian Border Zone (Andsbjerg et al. 2001; Nielsen 2003). Older sandstones were exposed and eroded and re-deposited in accommodation space generated by incipient rift-related subsidence in the Danish Central Graben (Andsbjerg et al. 2001). The rift-related subsidence ceased or slowed down in the late Kimmeridgian resulting in a decrease in accommodation space generation, which, combined with a possible increase in sediment supply, caused the progradation of shallow marine sands of the Heno Formation in the north-western parts of the Danish Central Graben (Andsbjerg et al. 2001). Sands with their source in the Mid North Sea High, prograded towards the east on to the Heno Plateau, while sands from the Mandal High prograded towards the west on to the Gertrud Plateau (Gertrud Graben on Fig. 1), in the easternmost part of which the Karl-1 well is located, and in the Feda Graben (Johannessen & Andsbjerg 1993; Johannessen et al. 1996; Andsbjerg et al. 2001; Johannessen 2003). The Heno Formation has been redefined by Michelsen et al. (2003). The classical shoreface sandstone previously defined as the Heno Formation or Heno Sand is now referred to the Ravn Member (Michelsen et al. 2003) and the back-barrier and shoreface sediments previously described as the 'basal sandstone unit' (Johannessen et al. 1996) or Basal Sand are now referred to the Gert Member (Fig. 2; Michelsen et al. 2003). According to Johannessen (2003) the Heno Formation is roughly equivalent to the Fulmar Formation in the UK sector and has many similarities with the 'Heno equivalent' and the Ula Formation of the Norwegian sector. The Lola Formation, an offshore mudstone, underlies the Gert Member and wedges in between the Gert and Ravn Members. The Farsund Formation, another offshore mudstone overlies the Ravn Member.

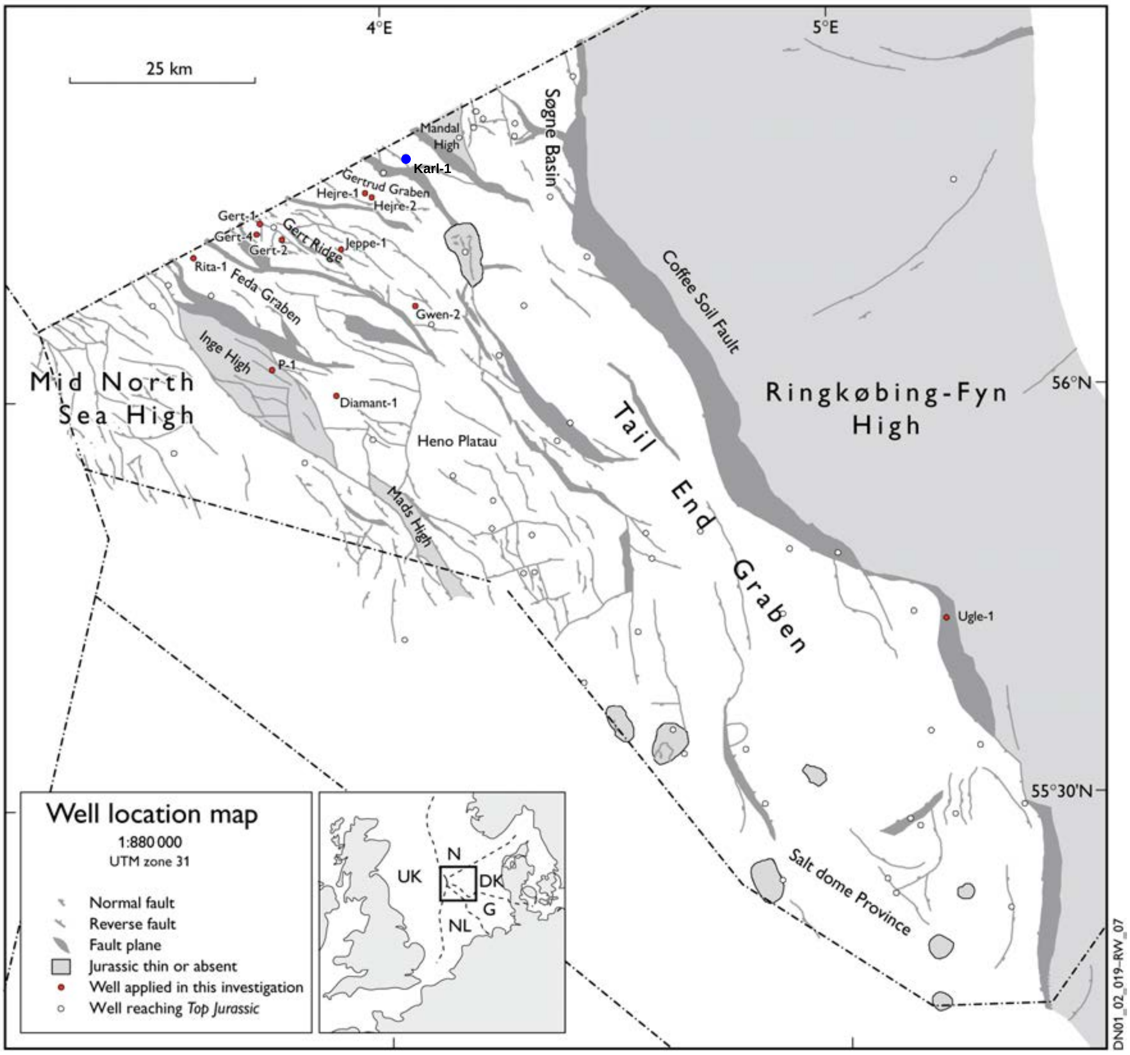

Fig. 1. *Wells reaching the Jurassic in the Danish sector of the North Sea are indicated with white dots. Wells geochemically investigated are marked with red dots. The Karl-1 well is marked by a blue dot. Modified after Japsen et al. 2003.*

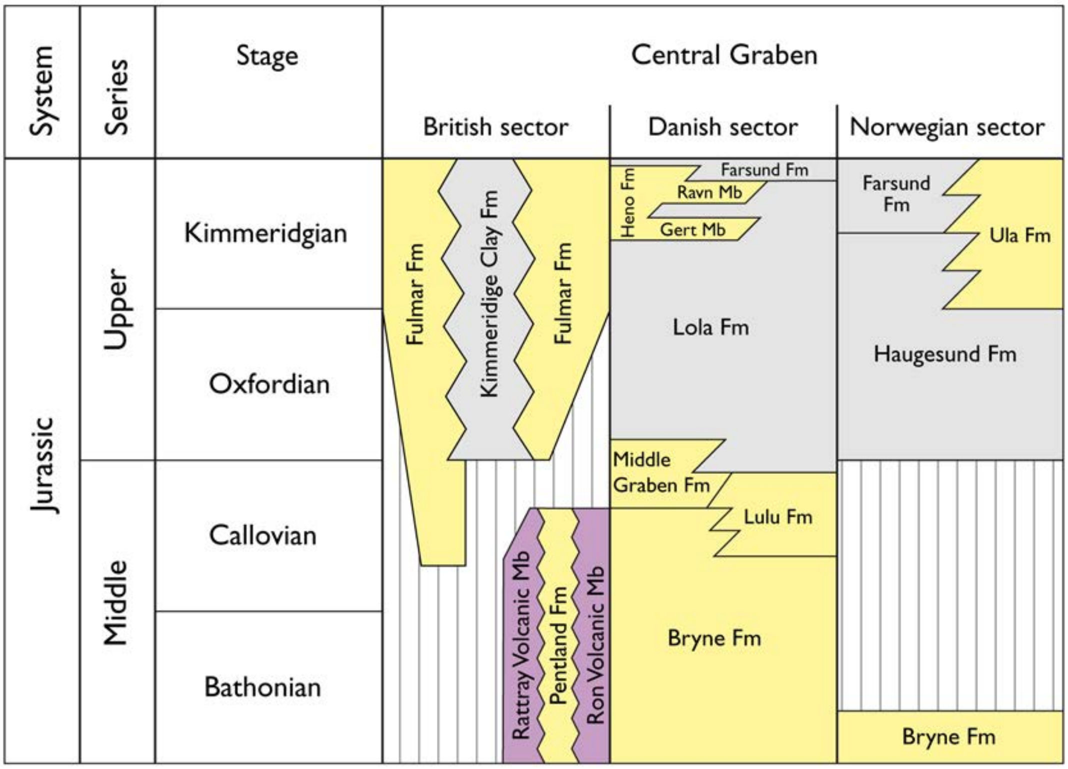

Fig. 2. *Stratigraphic scheme showing the Middle and Upper Jurassic formations in different sectors of the North Sea. Note that the Lola Formation may intersect the two members (Ravn Member and Gert Member) of the Heno Formation. Sandstones are yellow, mudstones are grey and volcanic units are purple. Hiatus is marked by vertical lines. Modified after Michelsen et al. 2003.*

Samples

Table 1. *Cuttings samples taken from the Karl-1 well.*

Well	No	ID	Depth (ft) top interval	Depth (ft) bottom interval	Depth (m)	Formation / Member
Karl-1	1	KA1-4378cu	14360	14370	4378	Farsund Fm
	2	KA1-4388cu	14390	14400	4388	Farsund Fm
	3	KA1-4394cu	14410	14420	4394	Farsund Fm
	4	KA1-4400cu	14430	14440	4400	Farsund Fm
	5	KA1-4406cu	14450	14460	4406	Farsund Fm
	6	KA1-4412cu	14470	14480	4412	Farsund Fm
	7	KA1-4415cu	14480	14490	4415	Farsund Fm
	8	KA1-4418cu	14490	14500	4418	**Ravn Mb**
	9	KA1-4421cu	14500	14510	4421	**Ravn Mb**
	10	KA1-4424cu	14510	14520	4424	**Ravn Mb**
	11	KA1-4427cu	14520	14530	4427	**Ravn Mb**
	12	KA1-4430cu	14530	14540	4430	**Ravn Mb**
	13	KA1-4433cu	14540	14550	4433	**Ravn Mb**
	14	KA1-4436cu	14550	14560	4436	**Ravn Mb**
	15	KA1-4439cu	14560	14570	4439	**Ravn Mb?**
	16	KA1-4442cu	14570	14580	4442	**Ravn Mb?**
	17	KA1-4446cu	14580	14590	4446	**Ravn Mb?**
	18	KA1-4449cu	14590	14600	4449	**Ravn Mb?**
	19	KA1-4452cu	14600	14610	4452	**Ravn Mb?**
	20	KA1-4455cu	14610	14620	4455	Gert Mb
	21	KA1-4458cu	14620	14630	4458	Gert Mb
	22	KA1-4461cu	14630	14640	4461	Gert Mb
	23	KA1-4464cu	14640	14650	4464	Gert Mb
	24	KA1-4467cu	14650	14660	4467	Gert Mb
	25	KA1-4470cu	14660	14670	4470	Gert Mb
	26	KA1-4473cu	14670	14680	4473	Gert Mb
	27	KA1-4476cu	14680	14690	4476	Gert Mb
	28	KA1-4479cu	14690	14700	4479	Gert Mb
	29	KA1-4482cu	14700	14710	4482	Gert Mb
	30	KA1-4485cu	14710	14720	4485	Gert Mb
	31	KA1-4488cu	14720	14730	4488	Gert Mb
	32	KA1-4491cu	14730	14740	4491	Gert Mb
	33	KA1-4494cu	14740	14750	4494	Gert Mb
	34	KA1-4497cu	14750	14760	4497	Gert Mb
	35	KA1-4500cu	14760	14770	4500	Gert Mb
	36	KA1-4503cu	14770	14780	4503	Gert Mb
	37	KA1-4506cu	14780	14790	4506	Permian
	38	KA1-4510cu	14790	14800	4510	Permian
	39	KA1-4516cu	14810	14820	4516	Permian
	40	KA1-4522cu	14830	14840	4522	Permian
	41	KA1-4528cu	14850	14860	4528	Permian
	42	KA1-4534cu	14870	14880	4534	Permian
	43	KA1-4540cu	14890	14900	4540	Permian
	44	KA1-4546cu	14910	14920	4546	Permian
	45	KA1-4552cu	14930	14940	4552	Permian

The cuttings samples taken in the Karl-1 wells are presented in Table 1.

Methods

Geochemical samples were taken from washed and dried cuttings samples. Magnetic or electrostatic removal of foreign material was avoided as it leads to preferential removal of certain minerals (i.e. rock fragments and mica).

The sample preparation and measurements were performed in exactly the same way as the previous investigation (Weibel & Knudsen 2007) with which the results are compared. The main elements were measured by X-ray fluorescence (XRF) or atomic absorption spectrometry (AAS) whereas most trace elements and REEs were measured by inductively coupled plasma - mass spectrometry (ICP-MS). For detailed information see Table 2.

Table 2. *Methods used for analysing the different elements.*

Method	Elements
XRF	Si, Ti, Al, Fe, Mn, Mg, Ca, K, P Ba, Ce, Cr, La, Nb, Ni, Rb, Sr, V, Y, Zn, Zr
ICP-MS	Ba, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Ga, Gd, Hf, Ho, La, Lu, Mn, Nb, Nd, Ni, Pb, Pr, Rb, Sc, Sm, Sr ,Ta, Tb, Th, Ti, Tm, U, V, Y, Yb, Zn, Zr
AAS	Na, Cu
Loss on ignition	volatiles

XRF

Samples were machine crushed in a tungsten carbide mortar. Contents of organic matter and volatiles were analysed by ignition (1 hour at 1000°C) of the powdered samples. Glass discs were prepared by fusing 0.75 g of dried powder with 5.25 g sodium tetraborate for 1–1½ hours in Pt/Au crucibles over gas burners before it was poured into a Pt/Au mould (Kystol & Larsen 1999). The fusion method was chosen to ensure that refractive minerals, such as zircon and chrome spinel, were brought into solution when the glass disc was dissolved for the subsequent ICP-MS analysis. The glass discs were analysed with a Phillips PW 1606 wavelength dispersive multichannel XRF spectrometer equipped with a Rh-anode X-ray tube operating at 50 kV and 50 mA. Recommended detection limits for the main elements were in general twice the precision (= trueness), which was one standard deviation based on experimentally repeated analysis over time of a set of international standards (Kystol & Larsen 1999). The recommended detection limits for the main elements (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K and P) varied from 0.01 wt% for P_2O_5 to 0.3 wt% for SiO_2 (Kystol & Larsen 1999 for more detailed information). Trace elements (V, Cr, Ni, Zn, Rb, Sr and Nb with the exception of Ba and Y) were determined on reconnaissance basis at the > 50 ppm level (Kystol & Larsen 1999). Values for Mo and Sn were only informative.

ICP-MS

A piece of the glass disc was dissolved in a mixture of HCl and HNO_3 (in the ratio 3:1). The solutions were dried and re-dissolved in HNO_3 three times. Finally the solutions were diluted and sprayed, with a Meinhard nebuliser, into the argon carrier gas and analysed by the Perkin Elmer 6100 DRC quadrupole inductively coupled plasma – mass spectrometer (ICP-MS). Detection limits vary with sample type and elements analysed, from < 100 ppb to < 1 ppt (Frei & Kystol 2004). Routine analyses of international standards and in-house standards have demonstrated that the analytical precision and the accuracy are better than 5 % for the majority of elements analysed (Dirk Frei, personal communication 2006).

Europium results in the cuttings are obscured by interference from Ba, due to BaO generated in the ICP-MS instrument, which has a mass equivalent to the main Eu isotope analysed. Due to extremely high amounts of barite in cuttings samples correction of BaO interference on Eu was not possible. Zn has interference from Ba^{2+} and usually this can be corrected. However, the extremely high sulphate content from the barite in the drilling mud change the ionisation of the plasma so the usual correction factor is incorrect for the cuttings samples with high barite contents. Consequently, XRF results for Zn have been applied instead.

XRF of Ba and Sr at extremely high concentrations are better than the ICP-MS data and consequently XRF data for these elements have been applied for correction for barite in the drilling mud.

AAS

Crushed samples (0.25–0.5 g) were dissolved in hydrofluoric acid, evaporated to dryness and re-dissolved in a hydrochloric-potassium chloride solution (Kystol & Larsen 1999). These solutions were analysed for Na and Cu on a Perkin Elmer PE2280 atomic absorption spectrometer (AAS). Recommended detection limits are 0.08 wt% for Na_2O and 5 ppm for Cu (Kystol & Larsen 1999).

Geochemical results and discussion

In the Karl-1 well where only cuttings samples are available the cuttings samples are, fortunately, of relatively high quality and suitable for geochemical comparison. Therefore the geochemical composition of cuttings for the Karl-1 well has been compared with core samples from all formerly investigated wells: Diamant-1, Gert-1, Gert-2, Gert-4, Jeppe-1 and Rita-1 (Weibel & Knudsen 2007) and both cuttings and core samples from the Hejre wells, which also have cuttings samples of high quality.

Problems with artefacts and general relations between major and trace elements have been discussed earlier (Weibel & Knudsen 2007).

Geochemical variations with depth

Selected oxides, trace elements and element ratios that show large variation between the Ravn and Gert Member have been chosen for illustration of the geochemical variation with burial depth for the Karl-1 and the Hejre-2 wells (Figs. 3 and 4).

In the Hejre-2 and Karl-1 wells the SiO_2 content is at its highest in the Gert Member and is at a lower level in the Lola Formation and the Ravn Member. A similar observation is apparent in the Gert-4 and Gert-2 wells (Weibel & Knudsen 2007). The Al_2O_3 content (Fig. 3) in the Karl-1 and Hejre-2 wells show the opposite trends to the SiO_2 content. A high SiO_2 content reflects the sand-dominated intervals, whereas a relatively high Al_2O_3 content reflects more clayey intervals. The Zr content follows the SiO_2 content, whereas many other elements follow the Al_2O_3 content. The zirconium content is also associated with the SiO_2 content in most of the previously investigated wells (Rita-1, Gert-4, Gert-2, Diamant-1 and possibly Gert-1) (Weibel & Knudsen 2007).

The Cr and TiO_2 content is highest in the lower part of the Gert Member and decreases upwards in the Hejre-2 well (Fig. 4) as in the Gert-1, Gert-2 and Gert-4 wells (Weibel & Knudsen 2007). However in the Karl-1 well the TiO_2 content seems to be similar in the Ravn and Gert Members (Fig. 3). The chromium content cannot be applied for cuttings samples and therefore the information on Cr for the Karl-1 well is not reliable. Assuming the high TiO_2 and Cr came from a local source the effect would be less in a more distal area, where the Karl-1 well might be located.

The Gert Member (in the Hejre-2, Jeppe-1, Gert-4 and Rita-1 wells) has a relatively low MgO content compared with the Ravn Member, and the Lola and Farsund Formations (Fig. 4; Weibel & Knudsen 2007). This relation is also clearly seen in the Karl-1 well, where the increased MgO content also begins at the boundary between the Gert Member and the Lola Formation and continues at the higher level throughout the Ravn Member and Farsund Formation (Fig. 3).

The Gert Member in the Karl-1 well has lower Na_2O and P_2O_5 contents when compared with those in the Ravn Member, and the Lola and Farsund Formations (see next chapter:

Geochemical variations between Gert and Ravn Members). The lowermost part of the Gert Member in the Karl-1 well, though, has a very high Na_2O content, which exceeds that of the Ravn Member and the Lola Formation. In a similar way there is a high Na_2O level in the lower part of the Gert Member in the Hejre-2 well. In the previously investigated wells (Gert-1, Gert-2, Gert-4, Jeppe-1 and Rita-1) the Ravn Member is also typical in having increased Na_2O and P_2O_5 contents compared with the Gert Member (Weibel & Knudsen 2007). The amounts of REE, Y, V, Th and U increase in the Ravn Member compared with the Gert Member in the Karl-1 and Hejre-2 wells (Figs. 3 and 4) similar to the previously investigated wells (Weibel & Knudsen 2007).

A decrease in K / Rb and Ti / Nb ratios can be observed from the Gert Member through the Ravn Member and ending with the lowest level in the Farsund Formation in both the Hejre-2 and Karl-1 wells (Figs. 3 and 4). The Jeppe-1 well also shows an upward decreasing K / Rb ratio, though most other previously investigated wells have a stable K / Rb ratio (Weibel & Knudsen 2007). Several other previously investigated wells also show an upward decreasing Ti / Nb ratio in the Gert Member and stable or less decreasing ratio in the Ravn Member (Weibel & Knudsen 2007). The P / Y ratio increases upwards through the Gert Member and remains at this level in the Lola Formation and the Ravn Member in the Karl-1 well (Fig. 3). In the Hejre-2 well the P / Y ratio also increases through the Gert Member. However in the Ravn Member it drops to a lower level (Fig. 4).

The Ti / Mg, Zr / Y and Zr / Th ratios are higher in the Gert Member than in the Ravn Member in the Karl-1 and Hejre-2 wells. The change in the Ti / Mg ratio is mainly related to a relatively higher MgO content in the Ravn Member. The higher Zr / Y and Zr / Th ratios are related to higher contents of Y, Th and REE in the Ravn Member than in the Gert Member, as the Zr content shows smaller variations (Figs. 3 and 4).

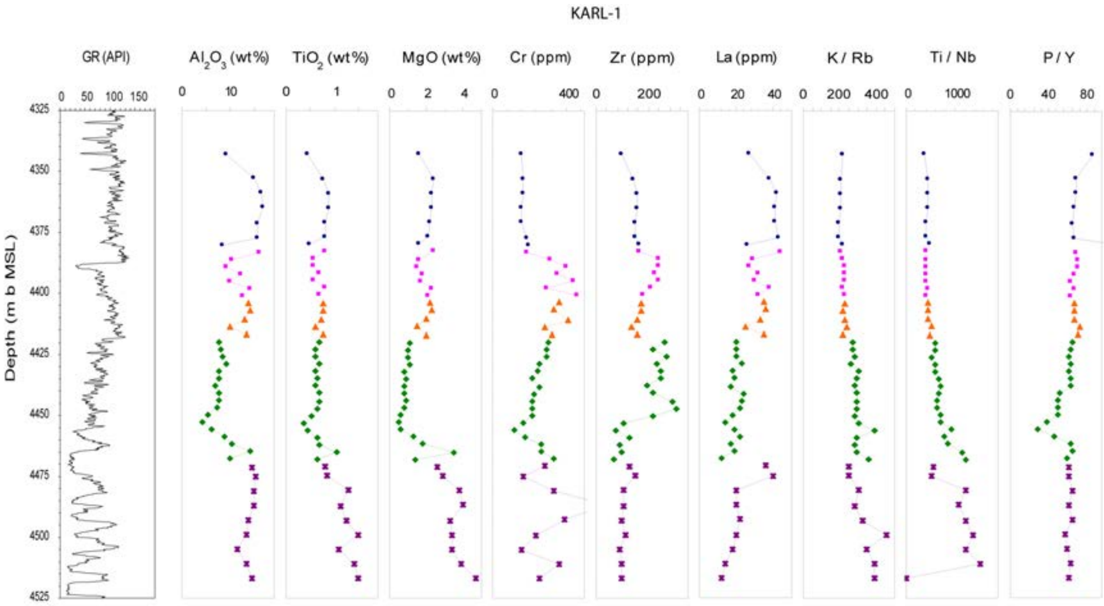

Fig. 3. *Gamma ray log (GR) and selected geochemical logs for the Karl-1 well. Cuttings samples are blue circles for the Farsund Formation, pink squares fort the Ravn Member, orange triangles for the Lola Formation, green diamonds for the Gert Member and purple crosses for the Permian interval.*

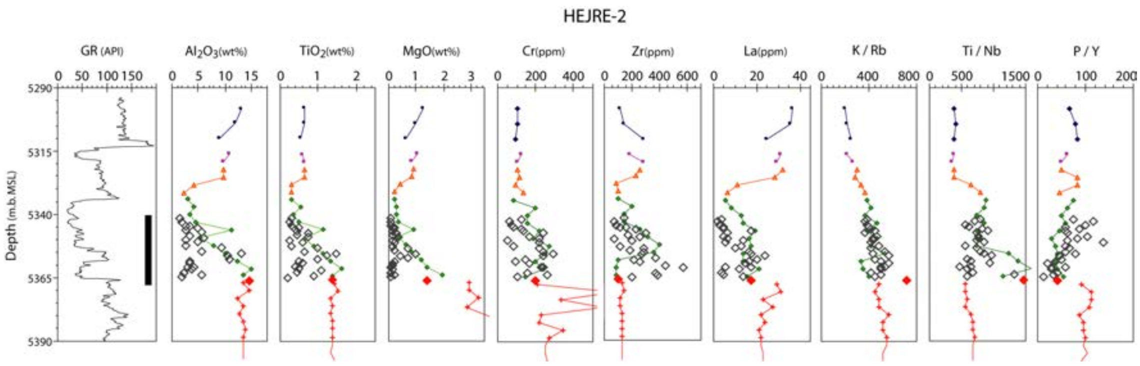

Fig. 4. *Gamma ray log (GR) and selected geochemical logs for the Hejre-2 well. Cuttings samples are blue circles for the Farsund Formation, pink squares for the Ravn Member, orange triangles for the Lola Formation, green diamonds for the Gert Member and red crosses for the pre-Upper Jurassic sediments. Core samples are open black diamonds for the Gert Member and filled red diamonds for the pre-Upper Jurassic sediments. Cored intervals marked by a black box.*

Geochemical variation between the Gert and Ravn Members

Gert Member in the Karl-1 well

Core samples from the Gert Member in most wells have lower Nb / TiO_2 and Th / TiO_2 ratios than the Ravn Member (Figs. 5 and 6). This relation, though less distinct, can also be seen in the Karl-1 and Hejre-2 wells. The TiO_2 content is typically lower in cuttings samples from the Karl-1 well and the cuttings and core samples from the Hejre-2 well than in core samples from the Gert Member in other wells. A local source possibly of exposed Carboniferous sediments has been suggested as source for the high TiO_2 and Cr content in the lower part of Gert Member in the Gert-1, Gert-2, Gert-4 and Diamant-1 wells (Weibel & Knudsen 2007). This source might have been located in the Gert Ridge area (Weibel et al. unpublished data) and it therefore seems plausible that the effect would be less in the areas of the Karl-1 well and the Hejre wells, which are located more distal to this source.

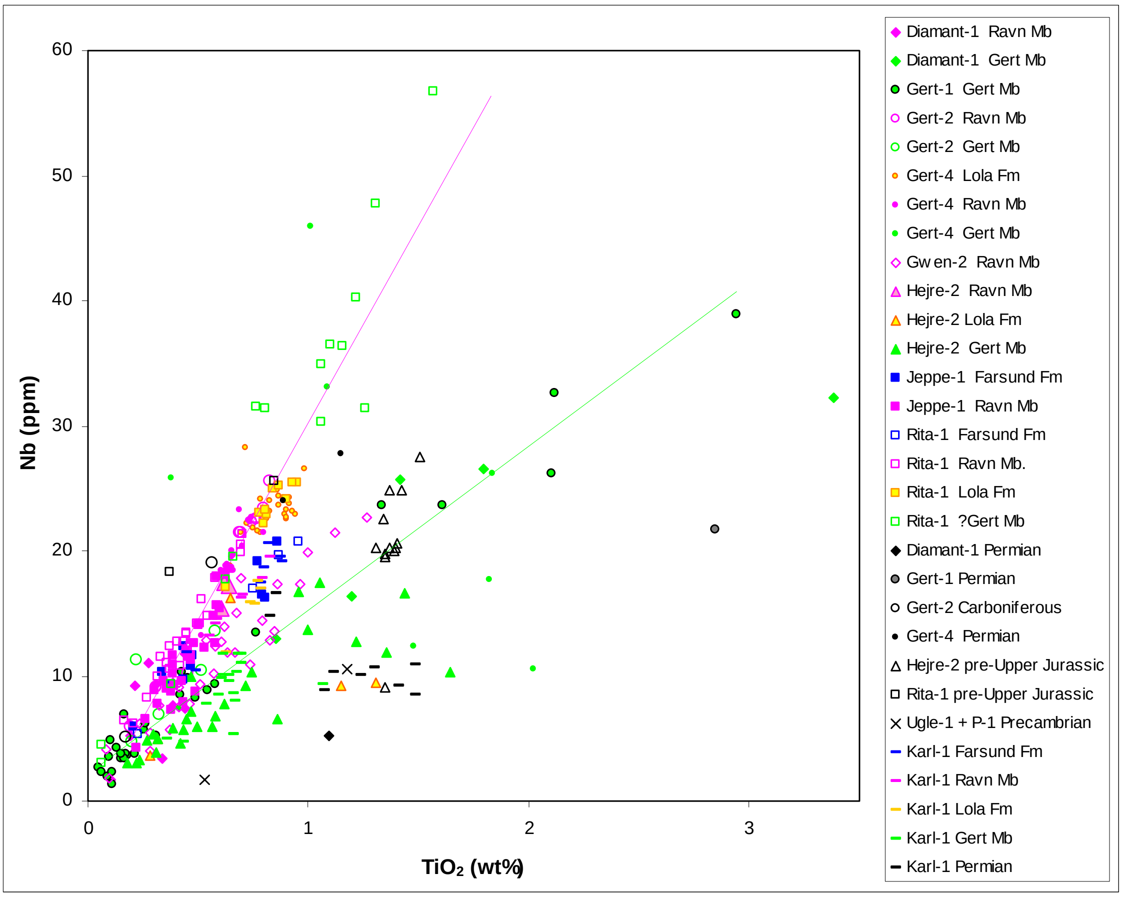

Fig. 5. *Graph showing positive correlation between Nb (ppm) and TiO_2 (wt%) in core samples with different ratios for the Gert and the Ravn Members. This differentiation is also valid for the Karl-1 well, though with more scattering as the results are from cuttings samples only. The Hejre-2 well is represented by both core samples and cuttings samples, whereas results from other wells are from core samples only.*

Th typically occurs in stable heavy minerals (Friis et al. 2007) such as monazite and will therefore generally behave similar to the REE. Nb typically occurs together with TiO_2 in rutile and other Ti-minerals; however, TiO_2 can also be present in other minerals, for example mafic silicates and clay minerals. The relatively low Nb / TiO_2 ratio of the Gert Member suggests that much of the titanium is present in other Ti-bearing minerals than rutile, thus less stable minerals. The less altered material characterising the Gert Member could reflect its trangressive depositional system (Johannessen et al. 1996; Johannessen 2003) during which unaltered or less altered material occasionally might have been brought into the system, possibly during storm episodes.

In general core samples from the Gert Member in many of the wells (Diamant-1, Gert-1, Gert-2, Gert-4) show higher peak amounts of Cr besides TiO_2 (Fig. 7; Weibel & Knudsen 2007). As cuttings samples typically contain chromium-rich steel chips, the Cr content does not necessary reflect the sedimentary rock, but rather the amount of impurities in the cuttings samples and therefore cannot be applied for geochemical comparison.

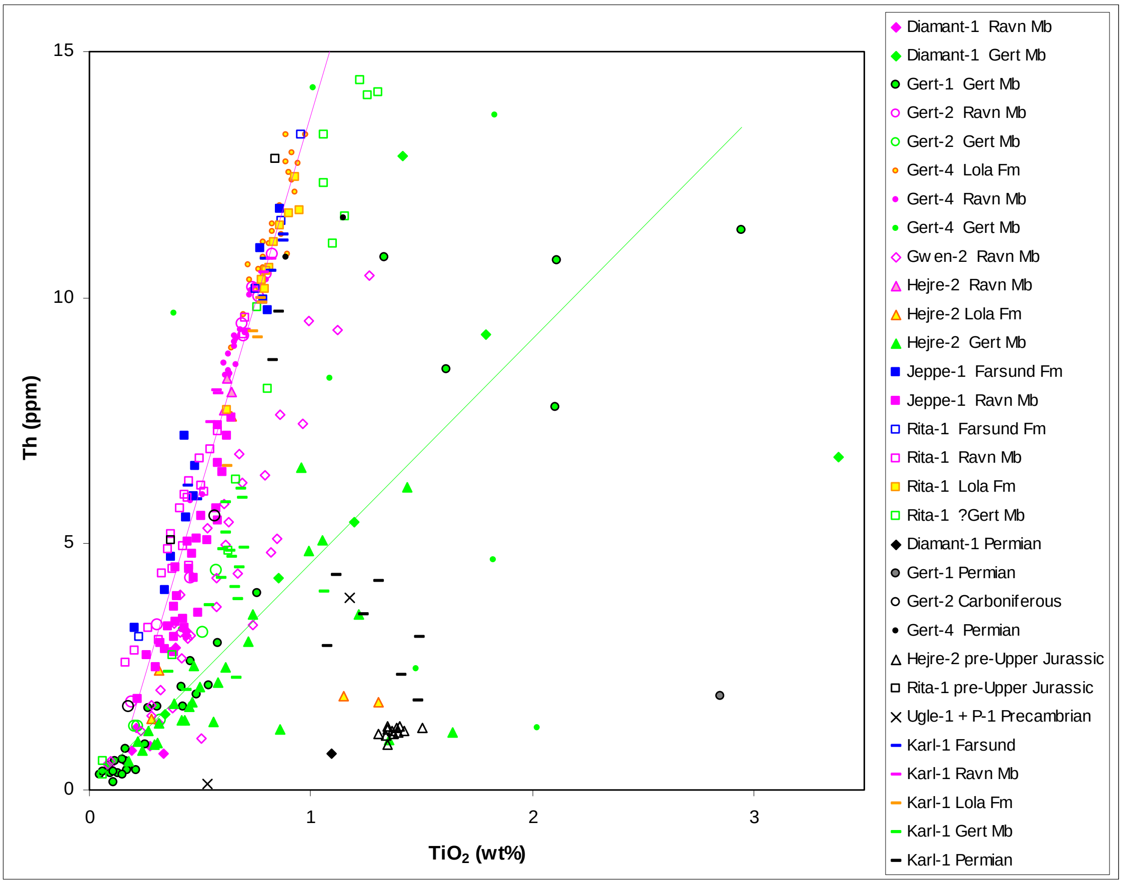

Fig. 6. *Graph showing positive correlations between Th (ppm) and TiO_2 (wt%) in core samples with different ratios for the Gert and Ravn Members. The samples from the Karl-1 wells show a less distinct differentiation, but still the Ravn Member seems to have a higher Th / TiO_2 ratio than the Gert Member.*

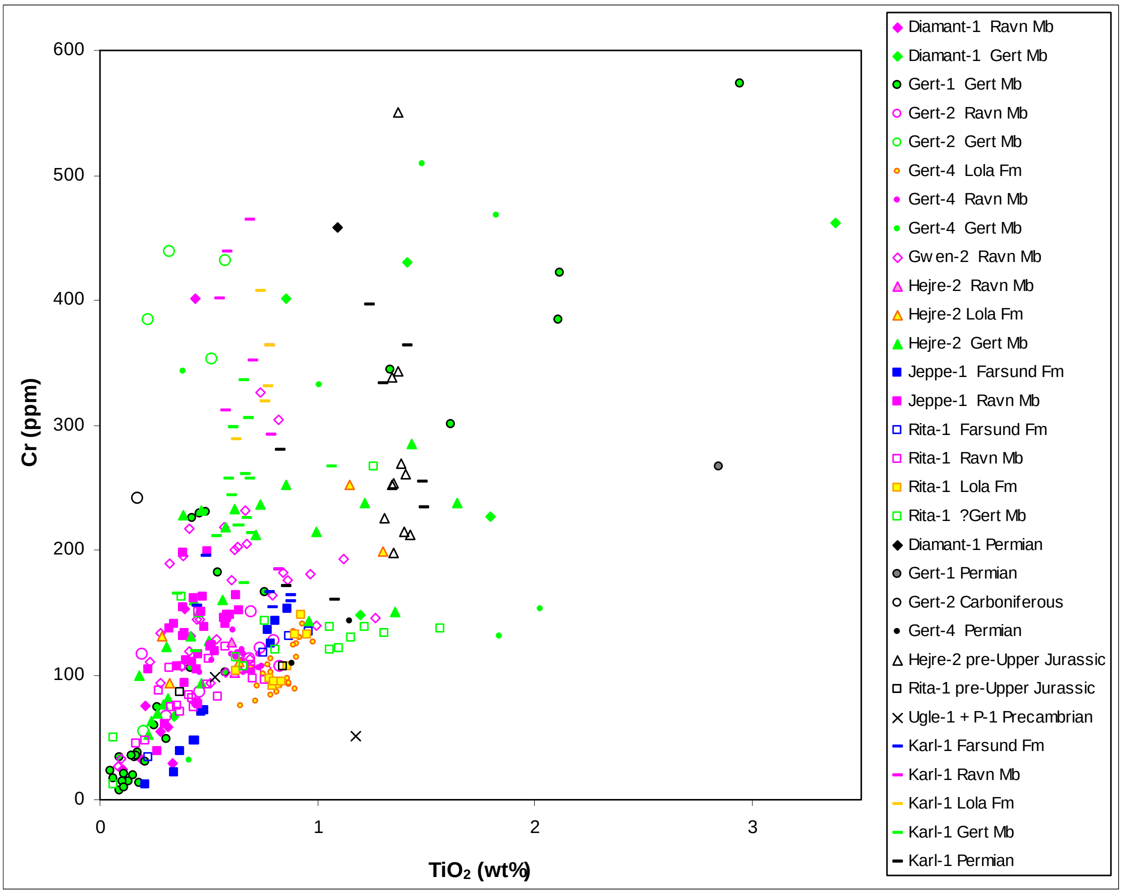

Fig. 7. *Graph showing that the highest amounts of TiO_2 (wt%) and Cr (ppm) generally appear in the Gert Member core samples, whereas lower amounts are found in the Ravn Member. The high Cr values in the Karl-1 well cuttings samples can be due to steel chip impurities.*

Ravn Member in the Karl-1 well

Core samples from the Ravn Member generally have higher Th / TiO_2, Nb / TiO_2, P_2O_5 / Al_2O_3 and Na_2O / Al_2O_3 ratios and lower V / P_2O_5 ratio than the Gert Member (Figs. 5, 6, 8, 9 and 10). The Ravn Member in the Karl-1 and Hejre-2 wells has a little higher P_2O_5 / Al_2O_3 ratio than the Gert Member, though this is not as clear as for the core samples in other wells (Fig. 8). P_2O_5 may be present in detrital heavy minerals, as apatite or monazite, but could also be part of authigenic marine phosphate minerals or may even occur in organic matter. The highest P_2O_5 values found in the offshore claystones, the Farsund and Lola Formations, may in particular originate from organic matter or marine authigenic phosphate minerals. The P / Y ratio is also a little higher for the Ravn Member than for the Gert Member in both the Karl-1 and Hejre-2 wells (Figs. 3 and 4) and the V / P_2O_5 ratio is lower for the Ravn Member than the Gert Member (Fig. 9). Vanadium may be present in detrital heavy minerals (Friis et al. 2007; Weibel & Friis 2004). When this is combined with the higher Nb / TiO_2 and Th / TiO_2 ratios in the Ravn Member relative to the Gert Member it could indicate that the heavy mineral assemblage is different. The different heavy mineral assemblage suggests that another source area, which was more dominated by stable heavy minerals as monazite, apatite and others, was more active during the deposition of the Ravn Member than during the deposition of the Gert Member. The source might be similar to the monazite-rich source on the Mid North Sea High described by Spathopoulos et al. (2000).

The Ravn Member in the Karl-1 well has a little higher Na_2O content than most of the Gert Member samples (Fig. 10). The most obvious origins of sodium are halite, clay minerals and plagioclase. Halite seems less likely as sodium generally occurs in similar amounts in core samples and in washed and dried cuttings samples (Weibel & Knudsen 2007). The clay-rich Lola Formation shows a negative correlation between Na_2O and Al_2O_3, which is different to the positive correlation of the Ravn Member (Fig. 10). This could indicate that in the Lola Formation sodium is located in other minerals than in the Ravn Member, possibly mainly in clay minerals in the Lola Formation and mainly plagioclase in the Ravn Member. Therefore sodium might reflect a combination of clay minerals and plagioclase. The main ions incorporated in the clay minerals may reflect the salinity of the depositional environment and as such the Ravn Member is expected to have been more saline than the

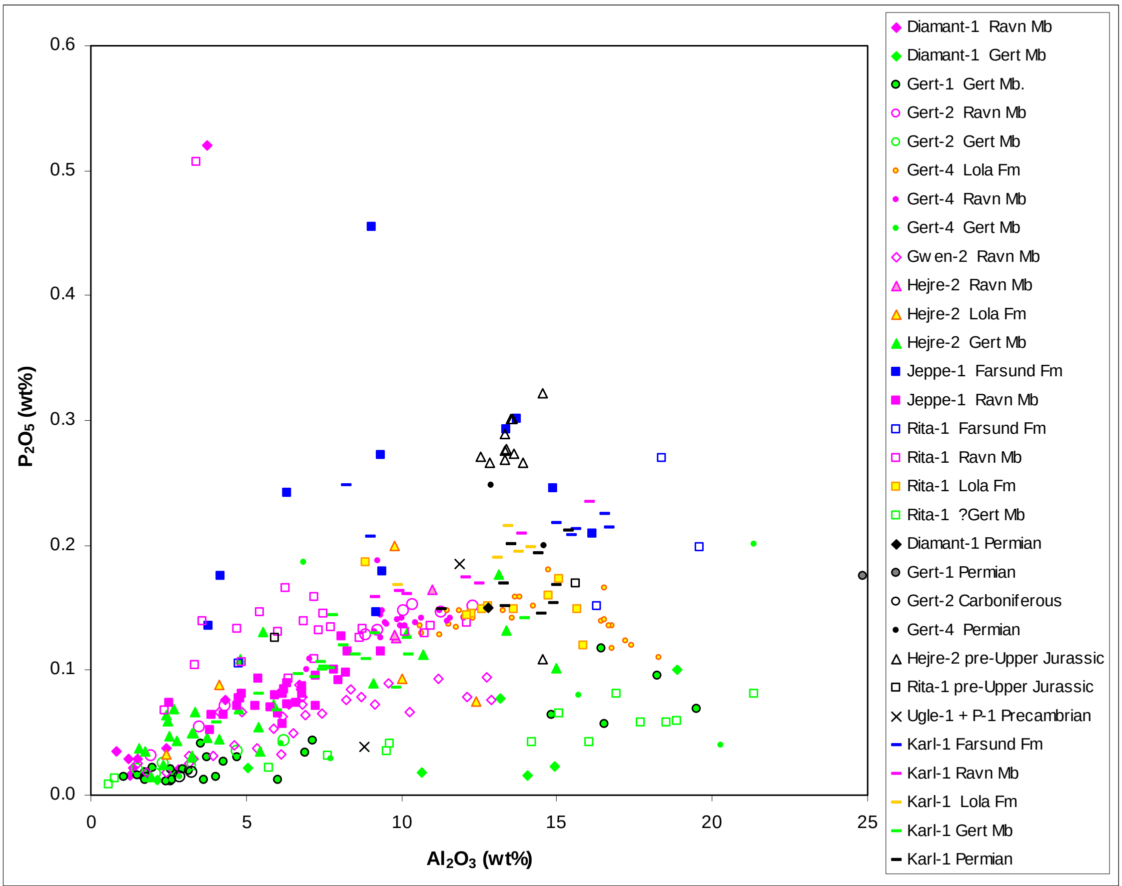

Fig. 8. *Graph showing positive correlation between P_2O_5 (wt%) and Al_2O_3 (wt%) in core samples with different ratios for the Gert and Ravn Members (the Ravn Member from the Gwen-2 well seems to be an exception). The Ravn Member in the Karl-1 well has a little higher P_2O_5 / Al_2O_3 ratio than the Gert Member, but this is not nearly as clearly as for the core samples in other wells.*

Gert Member, as the Ravn Member was deposited in a marine shoreface environment, whereas the Gert Member was deposited in a back-barrier and marine shoreface environment (cf. Johannessen et al., 1996, Johannessen, 2003). During deposition of the lower part of the Lola Formation the amount of MgO increases in several wells and continues at an increased level throughout deposition of the Ravn Member (Weibel & Knudsen 2007). Also in the Karl-1 well it is evident that the Gert Member has the lowest magnesium content and that it increases in the Ravn Member (Fig. 3). The Ravn Member seems to de divided into two groups with different MgO / Al_2O_3 ratios (Fig. 11), one group close to the Gert Member (Ravn Member in the Hejre-2, Jeppe-1, Diamant-1, Gwen-2 wells and partly the Gert-2 well) and another group following the trend of the Lola Formation (Ravn Member in the Karl-1, Rita-1, Gert-4 and partly Gert-2 wells). The subdivision of the Ravn Member into two groups is possibly related to the depositional environment and grain-size differences, as the sediment in the Gwen-2, Diamant-1 and Jeppe-1 wells are dominated by oversized clasts and were deposited in a beach / shoreface environment. The Ravn Member in the other group was deposited farther out in the basin in the middle–upper shoreface environment, which explains their stronger affinity to the Lola Formation. Magnesium occurs in the sediments as clays, glauconite and heavy minerals, some of which are stable and others very unstable. The increased Mg content could reflect more magnesium brought into the depositional system, i.e. more Mg-rich material reached the final area of deposition or the depositional environment favoured incorporation of Mg in glauconite and chlorite, or a combination of both.

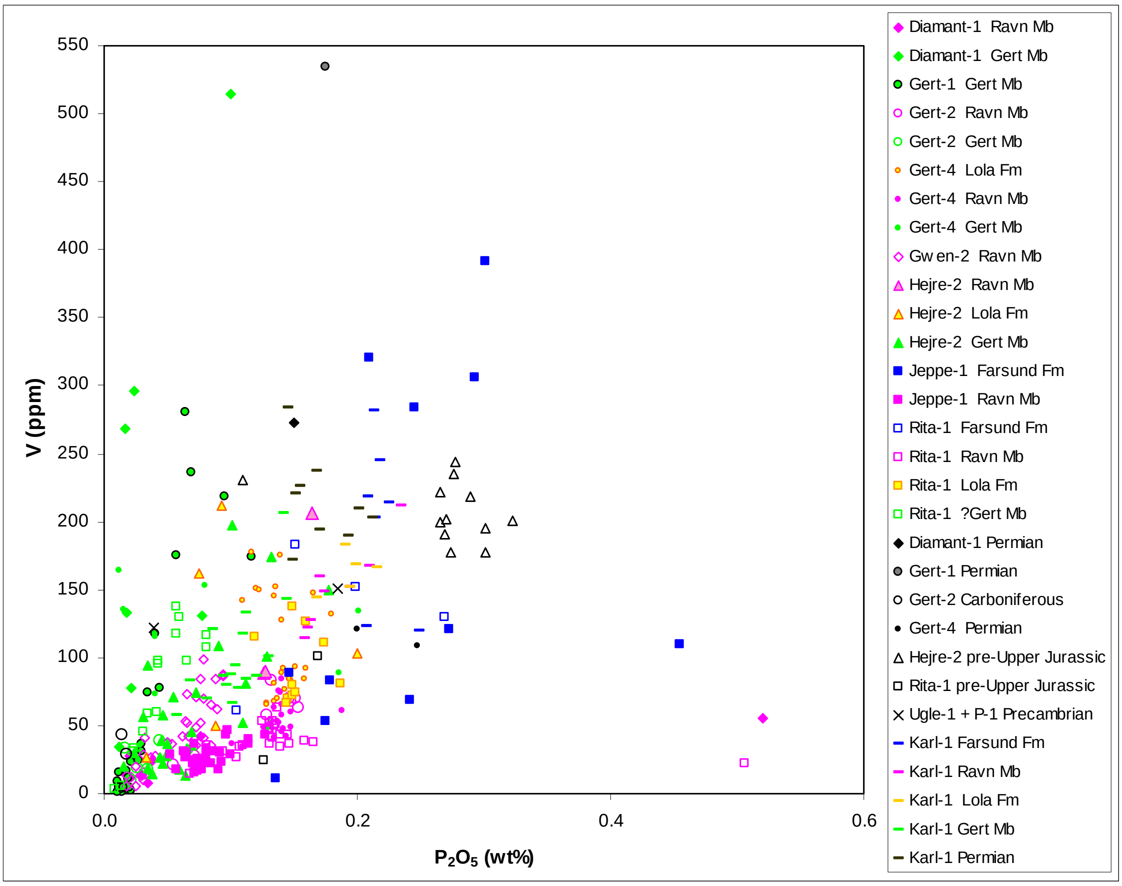

Fig. 9. *Graph showing positive correlations between V (ppm) and P_2O_5 (wt%) with different ratios for the Gert and Ravn Members. Also the Gert Member in the Karl-1 and Hejre-2 wells has a higher V / P_2O_5 ratio than the Ravn Member.*

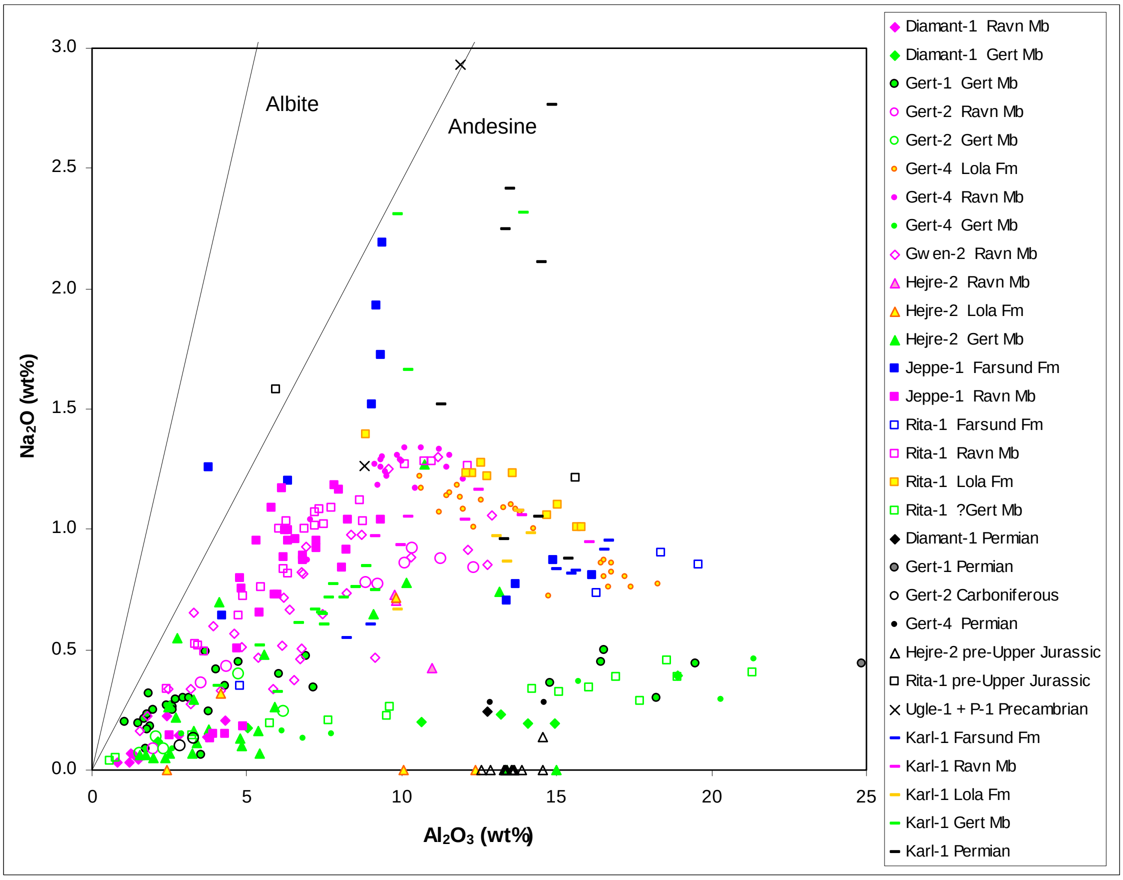

Fig. 10. *Graph showing positive correlation between Na_2O (wt%) and Al_2O_3 (wt%) in core samples of the Heno Formation and negative correlation in the Lola Formation. The negative correlation of the Lola Formation suggests that sodium is located in other minerals than for the Heno Formation, possibly clay minerals. The Ravn Member generally has higher sodium content than the Gert Member; this is also true for cuttings samples from the Karl-1 well.*

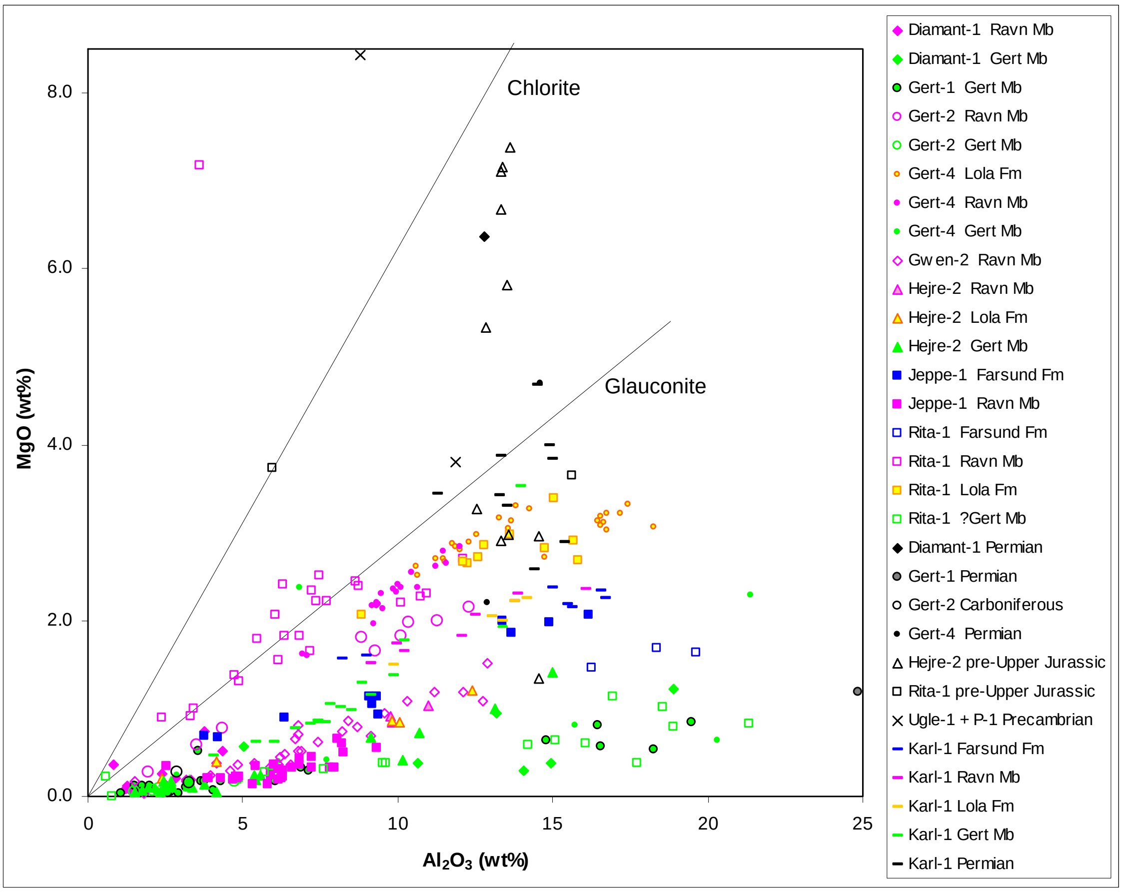

Fig. 11. *Graph showing positive correlation between MgO (wt%) and Al_2O_3 (wt%) in core samples. Note the subdivision of the Ravn Member into two groups with different ratios. The Ravn Member in the Jeppe-1, Diamant-1 and Gwen-2 wells have a low ratio MgO / Al_2O_3. The sediment in these wells was deposited in a beach / shoreface environment. The cuttings samples from the Ravn Member in the Hejre-2 well seem to group together with samples from this environment. The Ravn Member in the Rita-1, Gert-2 and Gert-4 wells has a higher MgO / Al_2O_3 ratio. The sediments in these wells were deposited farther out in the middle to upper shoreface which explains their stronger affinity to the Lola Formation. The cuttings samples from the Ravn Member from the Karl-1 well show affinities towards this middle to upper shoreface environment. Consequently, the subdivision of the Ravn Member seems to be related to depositional environment. The lines marked 'chlorite' and 'glauconite', respectively, are examples of the chemical composition of these minerals, which may vary more than indicated by the lines in the graph.*

Geochemical variation between wells - volcanic influence?

In the Karl-1 well the Upper Jurassic sediments were deposited upon Permian volcanic material, which has been radiometric K-Ar dated (on plagioclase) as 261-269 Ma (Stemmerik et al. 2000; Aghabawa 1993). In the Norwegian sector directly north of the Karl-1 well several wells occur with Permian volcanic material (Norwegian Petroleum Directorate 2007). In the Hejre-2 well the volcanic material has not been dated and is therefore referred to as: 'Pre-Upper Jurassic'. The Permian volcanic rocks in the Central Graben area are commonly alkaline, and can be divided into a sodic series (alkali basalt, hawaiite, mugearite) and a potassic series of alkali basalt - trachybasalt (Aghabawa 1993). In the Hejre-2 well the Gert Member is strongly influenced by K_2O and appears with the highest K_2O / Al_2O_3 ratio (Fig. 12). The high K_2O / Al_2O_3 ratio has earlier been related to K-feldspars from an abundant volcanic source (Weibel & Knudsen 2007). The Ravn Member in the Jeppe-1 well also appears with a relatively high K_2O / Al_2O_3 ratio suggesting that the supply of K-feldspar rich material continued during the deposition of the Ravn Member (Fig. 12). The Gert Member in the Karl-1 well and the Ravn Member in the Gwen-2 well occur on a level close to the illite composition (Fig. 12). A supply of potassic volcanic material to the Karl-1 and the Gwen-2 wells is possible but cannot be concluded.

The K_2O and Na_2O trends are opposite for the Permian interval and the lower part of the Gert member in the Karl-1 well (Fig. 13). This could be an indication of dominance of either Na-rich or K-rich feldspars. Sodium is not identified in some of the cuttings samples in the Hejre-2 well but is present in all the core samples, which could suggest under-representation of certain minerals in the cuttings samples or the presence of halite (from dried formation water) in the core samples (Fig. 13).

A few Gert Member samples from the Karl-1 well have extremely high sodium values (Fig. 10), which could suggest that pollution of some cuttings samples may have occurred, even though they have been washed. But these samples actually originate from a specific level - at the boundary between the Permian level and the Upper Jurassic Gert Member in the Karl-1 well, which is characterised by a very high sodium content (Fig. 13). In the Hejre-2 well the maximum sodium content occurs at the boundary between the lower part of the Gert Member and the upper part of the Gert Member (Fig. 13).

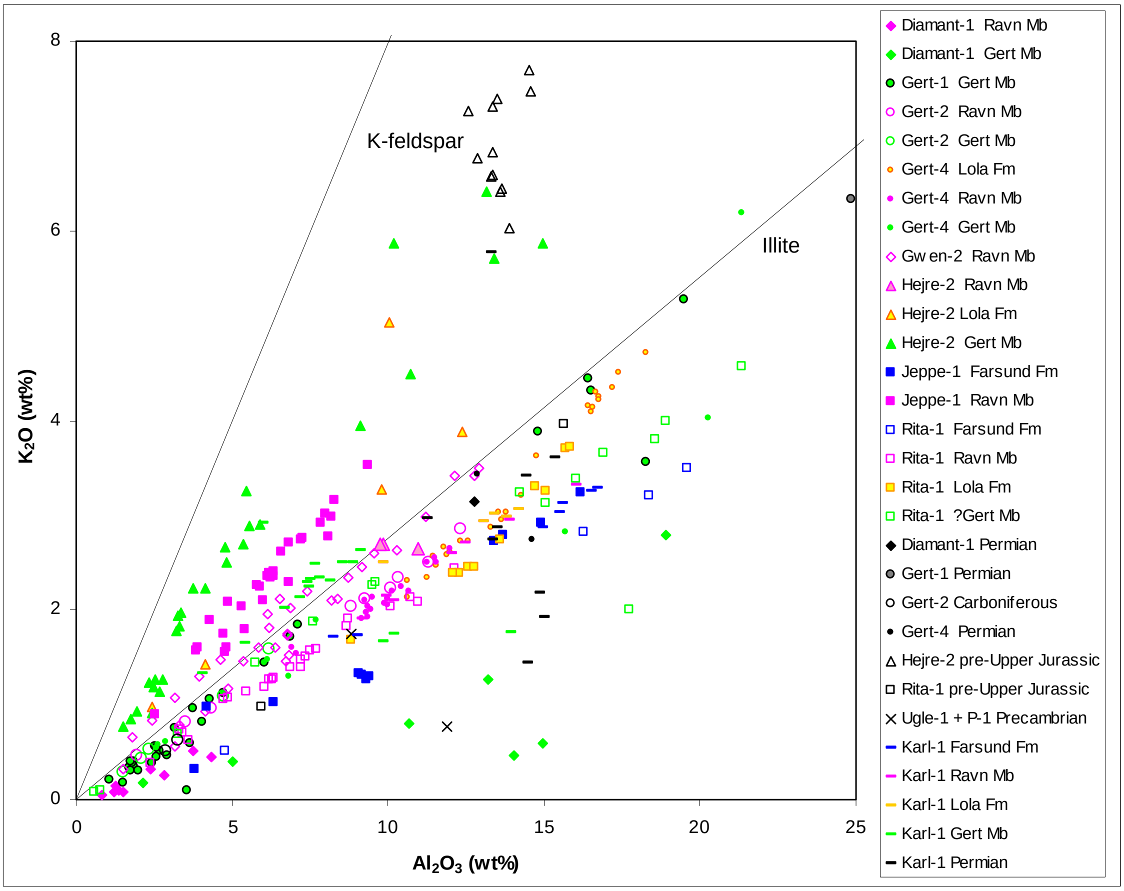

Fig. 12. *Graph showing positive correlation between K_2O (wt%) and Al_2O_3 (wt%) in core samples. The black lines show examples of the composition of orthoclase and illite. Note that certain wells occur with specific K_2O / Al_2O_3 ratios. The Gert Member in the Herjre-2 well has the highest K_2O / Al_2O_3 ratio indicating the largest supply of K-feldspar. The Ravn Member in the Jeppe-1 well also has a relatively high K_2O / Al_2O_3 ratio suggesting that the supply of K-feldspar rich material continued during the deposition of the Ravn Member. The Gert Member in the Karl-1 well and the Ravn Member in the Gwen-2 well occur on a level close to the illite composition.*

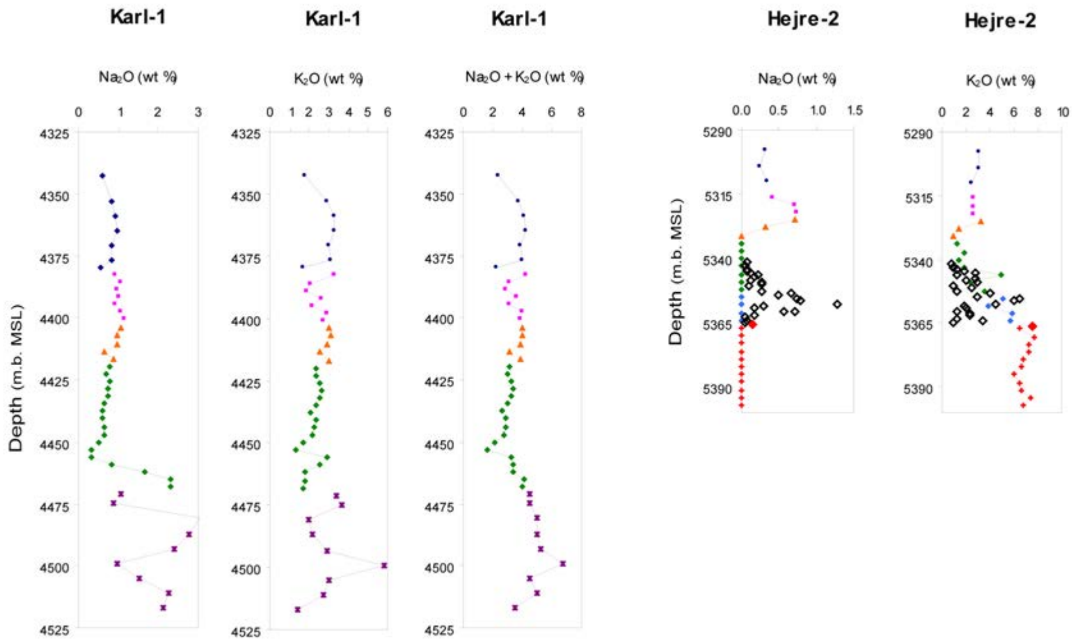

Fig. 13. *Selected geochemical logs for the Karl-1 and Hejre-2 wells. Cuttings samples are blue circles for the Farsund Formation, pink squares for the Ravn Member, orange triangles for the Lola Formation, green diamonds for the Gert Member, purple crosses for Permian intervals and red crosses for the pre-Upper Jurassic sediments. Note the opposite K_2O and Na_2O trends and the more stable K_2O + Na_2O curve characteristic of the Permian interval, but also seen in the Gert Member, in the Karl-1 well possibly indicating that either Na-rich or K-rich feldspar dominated the interval. In the Hejre-2 well sodium is not identified in some of the cuttings samples but is present in the core samples, which could suggest under-representation of certain minerals in the cuttings samples.*

Conclusion

The cuttings samples from the Karl-1 well are fortunately of high quality and can therefore be compared with the previous geochemical results from other wells in the Central Graben area. As cuttings samples typically have a high content of impurities there are limits to their applications. For example the high amount of Cr in all cuttings samples from the Karl-1 well is most likely due to the presence of steel chips.

The geochemical investigation of the Karl-1 well supports the previous findings (Weibel & Knudsen 2007) that the dominating sediment source was different during deposition of the Gert Member compared to the Ravn Member. The Gert Member in the Karl-1 well is characterised by lower Nb / TiO_2, Th / TiO_2, P_2O_5 / Al_2O_3 and Na_2O / Al_2O_3 ratios and higher V / P_2O_5 ratio than the Ravn Member. A similar difference between the Gert and Ravn Member has been observed for the previously investigated wells (Diamant-1, Gert-1, Gert-2, Gert-4, Hejre-2, Jeppe-1, Gwen-2, Rita-1). This distinction must be related to different silicate minerals and especially heavy mineral assemblages. Consequently, other source rocks or probably another source area may have dominated the supply to the sedimentary basin during the deposition of the Gert Member than during the Ravn Member. The Mid North Sea High has previously been suggested as a possible source especially for the Ravn Member, as this area is known to be relatively enriched by monazite and consequently expected to supply materials with high amounts of Th, Nb, REE and P_2O_5.

Previous investigations have shown that the Gert Member is characterised by having high peak amounts of Cr and TiO_2. However, in the Karl-1 well and Hejre-2 well the peak TiO_2 content is typically lower than for the Gert Member in other wells. The high Cr content cannot be confirmed nor disproved for the cuttings samples from the Karl-1 well, as these are all characterised by high Cr contents probably due to steel chip impurities. A local source, possibly of exposed Carboniferous sediments, may have supplied high Cr and relatively Ti-rich materials during the deposition of the Gert Member. The effect of this local source is less in the areas of the Karl-1 well and the Hejre-2 well, which are probably located more distal to this source.

A volcanic sediment source is obvious for the Hejre-2 well and the Jeppe-1 well and may also have played an important role in the Karl-1 well. In the Karl-1 well, though, a possible volcanic source could have been dominated by alternating sodic and potassic composition rather than the dominating potassic composition found in the Hejre-2 and Jeppe-1 wells.

Several future investigations could contribute to an improved understanding of the differences between the Gert Member and the Ravn Member. The most essential are K-Ar dating of the volcanic material in the Hejre-2 well, and petrographic investigations of the core samples form the Hejre-2 and Jeppe-1 wells and of sidewall cores from the Karl-1 well, if possible. The petrographic investigations could verify if the assumptions of magnesium incorporation in clays (glauconite) and sodium incorporation in feldspars and clays are correct; and explain whether potassium is related to detrital K-feldspar or clays in the Karl-1 well.

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