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Petrographic Aspects of the Rotliegend of the Groningen field

Inventory and quick-look analysis of petrographic data from the Groningen field

Clemens Visser

Date November 2016

Editors Jan van Elk & Dirk Doornhof

General Introduction

Petrography focusses on the mineral content and the textural relationships within rocks. These are described in detail in this report, where an inventory is presented of the petrographic data from wells in the Groningen field and neighboring areas. The data has been acquired since the early days of appraisal and development of the Rotliegend play in the northern Netherlands. It was published in a widely scattered fashion in reports compiled by NAM, KSEPL, universities and service companies.

Many of the important properties of the reservoir rock depend on the detailed mineral content and the textural relationships within the rock. An important example is rock permeability that impacts on the flow and pressure changes within the reservoir. This report is therefore important for geology studies and reservoir engineering studies (Ref. 1, 2 and 3).

Concurrent to this study, a number of experimental studies are performed using the core recovered from the Zeerijp-3A well. These studies cover rock compaction and rupture. The current report will be useful in interpreting the results on a field scale.

References

1. Supplementary Information to the Technical Addendum of the Winningsplan 2013, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), December 2013.
2. Groningen Field Review 2015 Subsurface Dynamic Modelling Report, Burkitov, Ulan, Van Oeveren, Henk, Valvatne, Per, May 2016.
3. Technical Addendum to the Winningsplan Groningen 2016 - Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field, PART I – Summary and Production,

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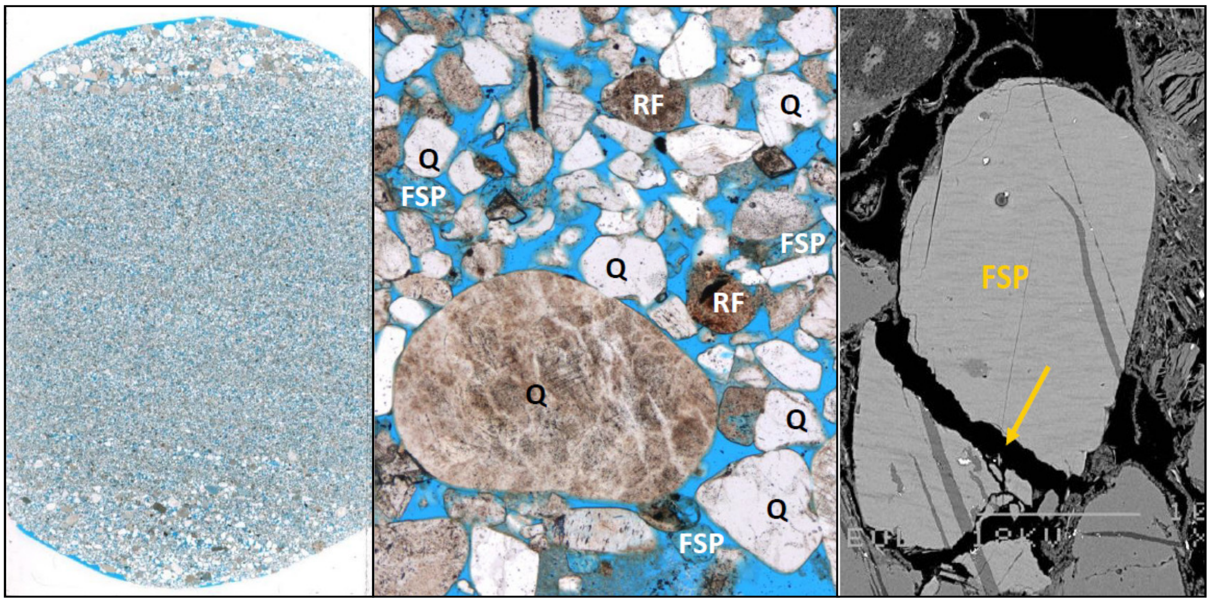
Organisation	NAM	**Organisation**	NAM
Place in the Study and Data Acquisition Plan	<u>Study Theme:</u> Groningen Reservoir Model <u>Comment:</u> Petrography focusses on the mineral content and the textural relationships within the rock. These are described in detail in this report, where an inventory is presented of the petrographic data from wells in the Groningen field and neighboring areas. The data has been acquired since the early days of appraisal and development of the Rotliegend play in the northern Netherlands. It was published in a widely scattered fashion in reports compiled by NAM, KSEPL, universities and service companies. Many of the important properties of the reservoir rock depend on the detailed mineral content and the textural relationships within the rock. An important example is rock permeability that impacts on the flow and pressure changes within the reservoir. This report is therefore important for geology studies and reservoir engineering studies (Ref. 1, 2 and 3). Concurrent to this study a number of studies are performed using the core recovered from the Zeerijp-3A well. These studies cover rock compaction and rupture. The current report will be useful in interpreting the results on a field scale.		
Directliy linked research	(1) Reservoir engineering studies in the pressure depletion for different production scenarios. (2) Subsidence and compaction studies.		
Used data			
Associated organisation	NAM, KSEPL, universities and service companies		
Assurance	Internal NAM		

Petrographic Aspects of the Rotliegend of the Groningen field



Inventory and quick-look analysis of petrographic data from the Groningen field

Clemens Visser, August 2016

Doc. No. EP201609201573

Summary

An inventory has been made of petrographic data from wells in the Groningen field and neighboring areas. The data has been acquired since the early days of appraisal and development of the Rotliegend play in the northern Netherlands. It was published in a widely scattered fashion in reports compiled by NAM, KSEPL, universities and service companies.

The data has been derived from a number of standard petrographical methods: whole_rock and clay_fraction X-ray diffraction, optical microscopy, point count modal analysis and scanning electron microscopy. All (semi-)quantitative XRD results and the point count results of wells with higher sampling density have been compiled in an Excel spreadsheet. A list of reference reports containing qualitative thin section and SEM descriptions is included in the present document.

After compilation of the spreadsheet, a quick-look data analysis was carried out to check for field-wide petrographic trends. Such trends have been identified with good confidence for the abundance of feldspar and for the abundance and habitat of authigenic clays. Particularly the distribution of authigenic chlorite clay rims around framework grains could be a factor affecting reservoir quality and geomechanical behavior. A more thorough analysis of the data is required to quantify the observed trends and possibly identify additional ones.

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1. Introduction

One of the options for improving the static model of the Groningen field is to obtain a better understanding of the relation between mineral composition, diagenesis and reservoir quality. The recently drilled and cored well Zeerijp-3A offered an excellent opportunity to kick off a petrographic study on a series of fresh rock samples from the gas-saturated zone and the aquifer. The analyses have been carried by PanTerra Geoconsultants. Pending the results it was decided to make an inventory of all available petrographic data for the field. This would allow placing the newly derived information in the larger context of the Groningen field, and could yield additional clues for incorporating geological information in the property models.

The first step was to review internal Shell and NAM reports on the subject, and to compile a database of available quantitative data. It turned out that the subject had gained only limited attention in the past. In the early days of discovery and development of the Rotliegend play in the northern Netherlands, extensive petrographic work was done but on a limited number of wells. In consecutive years only small projects were carried out on a limited number of wells and a limited number of samples per well. This work was mainly descriptive and, at best, presented suggestions for field-wide trends. However, there has been no integrated study to systematically test such trends, or to establish relations between petrography and reservoir quality. This is because reservoir quality has never been an issue in the development of the Groningen field. This situation has changed in recent years. More and more detailed knowledge is required to better understand the reservoir, not only in terms of flow behavior but also of induced seismicity and geomechanical behavior.

However, the subject of petrographic characterization is very complex. Mineral composition and diagenesis are highly variable and controlled by a large number of factors: composition of the sediment source area, depositional environment, lithofacies, burial history, pore fluid composition, and so on. It is important to have a dataset that samples the full vertical and lateral variability. Comparing results from separate studies requires that analyses and reporting of results must have been done in a consistent way. This has not been the case for Groningen. Consequently, the objectives of the present study have to be modest. An attempt is made to compile the available information in such a way that comparison between datasets is possible. Quick-look methods are applied to investigate trends in mineral composition and diagenetic impairment, and the relation with reservoir quality. Ideally, clues can be established for refining property models and for improved understanding of geomechanical behavior at a microscale.

The general approach for the present study has been as follows:

- Review of existing petrographic databases
- Review of internal reports and documents
- Compilation of a working dataset
- Quick-look investigation of petrographic trends and relations
- Incorporate results from the Zeerijp-3A study

2. Petrographic database

Petrographic information can be obtained from different methods. Qualitative information is derived from the description of thin sections and scanning electron microscopy (SEM). Typical features include the textural and mineralogical composition of constituent grains and pore-filling material, and the habitat of authigenic clays. Quantitative information is obtained from point count model analysis of thin sections and from X-ray diffraction (XRD) of whole-rock and clay-fraction samples.

In the nineteen eighties, first attempts were made in NAM to set up databases for capturing geological en petrophysical information. One such database was Petdb (or Petrographic Database) where point count and XRD data was stored. It turned out that this database is not accessible anymore because the underlying Oracle software is no longer supported in NAM. The current plan is to migrate Petdb to the Recall environment but that is a low-priority activity for which a number of compatibility issues need to be resolved first. However, the data itself can still be retrieved from an extensive collection of Excel spreadsheets, with separate documents per well and per analytical method.

Scrolling the list of Excel spreadsheets learns that the Groningen dataset is incomplete and, in cases, there are discrepancies between the contents of a spreadsheet and the data as originally reported. Therefore, it was decided to do an extensive check of Shell and NAM internal documents concerning with Groningen petrography, to make sure that as large a dataset as possible could be evaluated. Tabulated data contained in these pdf documents have been converted to data files and also loaded in Excel. Table 2.1 is an inventory of all samples loaded in the compilation datasheet. Red-coloured cells indicate thin section point count data that is yet to be converted and loaded. This may be done in a later phase when the need arises. The current study is mainly based on results from XRD analysis, and on thin section analysis of a limited number of wells.

well	THS	XRD_whole	XRD_clay		data source
ANN-1		8	8		Petdb folder "CORELAB_with_capitals"
BHM-3	4	4	4		in McAfee et al, 2003
BHM-5B	4	4	4		in McAfee et al, 2003
BIR-13B		71	71		Petdb folder "CORELAB_with_capitals"
BRW-2	7	7	7		in McAfee et al, 2003
DZL-1	30		6		in Clelland, 1987
EKR-1	20	20	20		in Burfoot & Wood, 2003
FRM-1C			74		Petdb folder "CORELAB_with_capitals"
GLH-1	9	9	9		in McAfee et al, 2003
HND-1	15	15	15		in Burfoot & Wood, 2003
KWR-1A		19	6		Petdb folder "CORELAB_with_capitals"
MWD-1	5	4	4		in Burfoot & Wood, 2003
NSS-1A			34		Petdb folder "Corelab"
NWS-1	37	20	37		in Rahdon, 1969
ODP-1	15	15	15		in Burfoot & Wood, 2003
OPK-2A			2		Petdb folder "CORELAB_with_capitals"
PPS-Z1			74		Petdb folder "CORELAB_with_capitals"
RDW-1		16	16		Petdb folder "CORELABS"
ROT-1A	7	6	6		in Burfoot & Wood, 2003
RYSM-Z1B			46		Petdb folder "Corelab"
SAP-1	25	24	24		in Burfoot & Wood, 2003
SCB-1	6	6	6		in McAfee et al, 2003
SDM-1	42	8	10		in Clelland, 1987
SLO-2	5	5	5		in Burfoot & Wood, 2003
SMR-1	4	5	5		in Burfoot & Wood, 2003
SMR-1	16				in Okkerman & Amthor, 1994
SSM-1	38	95	38		SSM-1 core description report
SSM-2		30	30		Petdb folder "CORELAB_with_capitals"
TBR-4	4	4	4		in Burfoot & Wood, 2003
UHM-1	105	54	8		in Rahdon, 1970
UHM-1	18		5		in Clelland, 1988
ZPD-12A	17	17	17		in McAfee et al, 2003
ZRP-3A	25	25	25		PanTerra, 2016
ZWD-1	3	3	3		in McAfee et al, 2003
total	461	494	638		

Table 2.1 : Inventory of petrographic datasets for wells from the Groningen field and immediate surroundings. Data source refers to internal Shell/NAM documents which are listed and summarized in Section 3 of the present report.

3. Relevant petrographic documents

The following documents, listed in chronological order, have been searched for Groningen petrographic data.

- Porrenga, 1964-1965: various reports on mineralogy of Rotliegend sediments, referenced in Sluijk, 1965
- Sluijk, 1965: Rotliegend in The Netherlands and the Dutch North Sea Shelf, NAM-OP 708
- Rahdon, 1969: Diagenesis of the Rotliegend in Northwest Europe, EP38439 vol 7.
- Rossel, 1975: Investigation of core from well 't Zandt, Groningen, The Netherlands, RKTR.0084.75
- Nicholls et al., 1987: Sedimentological description and facies definition of cores from the Rotliegend Group, Groningen/Annerveen area, RKTR.87.009
- Clelland et al., 1987: Pilot Study into the Diagenesis of the northern Groningen wells SDM-1, UHM-1 and DZL-1, RKTR.87.282
- Speksnijder et al., 1988: Pilot study into mechanical and diagenetic fault sealing in the groningen and Annerveen gas fields, onshore The Netherlands, RKTR.88.004
- Nicholls, 1991: Permeability mapping in the Groningen field, NAM Report No. 19658
- Cohen, 1991: Reservoir geological study of the Ten Boer in the Groningen area with special emphasis on the Eemsmonding area, NAM Report No. 19.403
- Okkerman & Amthor (1992): Diagenesis of Rotliegend sandstones in the northern Netherlands and in offshore blocks K, L and M, NAM Rep. Nr. 23413.
- Walzebuck, 1993: Advances in the Prediction of Porosity, Permeability and Well Productivity of the Dutch Rotliegend. NAM Report No. 24.308.
- McAfee *et al*. (1993): Geological investigation of Rotliegend Core from well Saaksum-1, NAM Report No. 25.413-1
- Huis in 't Veld & Ladipo (1994): Rotliegend High Porosity Streaks in the northern part of the Lauwerszee Trough area, NAM Rep. Nr. 26585
- Fulljames & Filbrandt, 1995: Fault sealing in the Groningen field, The Netherlands, RKGR.94.178
- Kelly & Greenwood (1996): Patterns of Clay Mineral Diagenesis in the Rotliegend of the NE Netherlands, NAM Rep. Nr. 28765.
- Greenwood, Ladipo & Segers (1996): Quantification of sedimentological, depositional and diagenetic data of Upper Rotliegend reservoirs in the Munnekezijl Field, NE Netherlands, NAM Rep. Nr. 30.297
- Gluyas, J., Jolley, L. & Primmer T. (1997) Element mobility during diagenesis: sulphate cementation of Rotliegend sandstones, Southern North Sea. Marine and Petroleum Geology, 14, pp. 1001-1011.
- Wood, Rushton & Phillips, 2001: Petrography of the MWD-1, ROT-1A, SAP-1, SLO-2, SMR-1 and TBR-4 wells, Groningen Field, The Netherlands, Core Laboratories REG 010303
- Forbes et al., 2003: Integrated Geological and geophysical Evaluation of the Rotliegend in the Groningen East Area, NAM200308002107

- Pipping & Kraft, 2003: Groningen Field Review 2003 report, Volume3, Reservoir Geological Modelling and Static GIIP Estimates, NAM200308000867
- McAfee *et al*., 2003: East groningen Rotliegend sedimentological study, NAM200309000154
- Burfoot & Wood, 2003: Regional field review of Permian Rotliegend – Volume IV – Petrographic review – Phase II, EP200908312263
- Richardson, 2005: Bleaching and Diagenesis affecting reservoir quality in the Upper Slochteren (ROSLU), Lauwerszee trough, The Netherlands, NAM/Univ. Durham student internship report
- Gaupp and Okkerman, 2011: Diagenesis and reservoir quality of Rotliegend sandstones in the northern Netherlands – a review. SEPM Special Publication No. 98: the Permian Rotliegend of the Netherlands (eds Grötsch & Gaupp)
- Veeningen & Könitzer, 2016: Petrographic study of well Zeerijp-3A, Panterra draft report

A selection of the above documents contains information and clues that are particularly relevant for the current study. These are briefly summarized below.

Sluijk, 1965:
Sluijk summarizes a petrographic study by T. de Booy (University of Amsterdam) on 900 samples from NAM wells in the northern Netherlands, including data from Groningen wells BIR-1, SMR-1 and SLO-4 (note that a search for the report from de Booy has not been successful yet).
Two main petrographic assemblages are recognized:

1. Is characterized by a certain amount of sedimentary and epimetamorphic rock fragments, some acid volcanic fragments, no potassium feldspar. Generally poorly sorted, including all conglomerates and pebbly sandstones.
2. Is characterized by plutonic and higher-grade metamorphic rock fragments or minerals, plutonic fragments and a variety of feldspars (potassium feldspar and microcline)

A general observation is that assemblage 1 occurs in the lower part of the Slochteren Fm, and assemblage 2 in the upper part. Where coarser grained to pebbly, the upper part can show a mixture of assemblages, but this does not seem to happen in Groningen, at least not in BIR-01 and SMR-1. However, there is a gradual transition between the two assemblages, which makes it difficult to assign an assemblage on the basis of a limited number of samples. The two assemblages point to two different source areas. Assemblage 1 is derived from Carboniferous and Devonian rocks from the close-by Rhenish mountains. Assemblage 2 may come from a more distant eastern source, introduced by wind and spreading over the entire Southern Permian Basin.
Interesting observation includes feldspar trends, which are also observed in WR_XRD data from other Groningen wells (see later section). Is it possible to link the two different petrographic assemblages to a subdivision into ROSLU and ROSLL?

Rahdon, 1969:
37 samples analyzed from NWS-1, 106 samples analyzed from UHM-1A, contains point count data, and whole-rock and clay fraction XRD data. The XRD data is rounded off at five percent-point values.

Rahdon mentions a transition from NWS-1 to UHM-1A from kaolinite to chlorite as the dominant "matrix" mineral (matrix is used in a broad sense to combine both detrital and authigenic clays). Reported XRD data for UHM is very different from data mentioned in Clelland, 1987. Also the XRD data for NWS-1 looks suspicious. Maybe better to treat the Rahdon data as low-confidence.

Rossel, 1975:
SEM study of 18 samples from well ZND-1, 5 samples also subjected to microscopic analysis and XRD Mainly includes descriptions of habitat of pore-filling cements, including authigenic clays.

Nicholls, 1987:
Very general observations are made on diagenesis from visual inspection of cores. Remarks are made on iron staining, visible cements (carbonates), leaching, grain dissolution and bitumen.

Clelland *et al*., 1987
Petrography and diagenesis of wells SDM-1, UHM-1 and DZL-1, see tables for analytical program including thin sections, SEM and XRD; 42, 18 and 29 samples respectively.
Special attention is paid to mineralogical differences between gas and water zones. These relate to relative abundances of some authigenic minerals. This is particularly true for grain-coating clay, but differences are found to be quite subtle. They do seem to be correlated to some decrease in permeability in the water zone, but this may also represent a depth trend. Additional remarks:

- Grain-coating is usually a mixed-layer illite-smectite type, intergranular clay is more illitic
- Early diagenesis: grain-coating clay and non-ferroan dolomite, beginning of grain-dissolution processes,
- Burial diagenesis: continuation of grain dissolution and alteration processes, pore fluids change from alkaline to acidic and reducing. Precipitation of kaolinite, formation of chlorite from conversion of haematite and illite-smectite, minor illitisation
- Presence of grain-coating clays may lead to too high log-derived water saturations.

Nicholls, 1991:
Extensive documentation on geological controls on permeability distribution, including remarks on the relation with gas or water pore fill. It is suggested that the amount of grain-coating clay has a larger effect. This is controlled by lithofacies.

- Relates lower plug permeability to larger content of grain-coating clay. Particularly in the reservoir unit directly below the Ameland Claystone.
- Note that the above remarks are mainly derived from wells in the Eems area. It is questionable if these wells are representative for the entire field.
- Pore fluid content is considered less important compared to the stratigraphic (read clay-coating) control.
- The Groningen charge period is thought to be very long (38 my?). This speaks for gradational vertical diagenetic changes rather than a sharp transition along a gas-water contact.

Cohen, 1991:
Contains petrographical data (THS, XRD, SEM, Mineralog) on multiple samples from wells (BIR-13B, FRM-1A, FRM-1C, PPS-Z1A and RYS-Z1B. This study concerns with the reservoir quality of the Ten Boer Claystone, so may not be directly relevant for the present study.

Okkerman and Amthor, 1994:
Present an extensive study on the diagenesis of the northern Netherlands and JDA area Rotliegend deposits. Unfortunately, only one well from the Groningen field was included: SMR-1 with only point count data. Also presented is a diagenetic summary graph for various “reservoir provinces”. SMR-1 is grouped with several Lauwerszee Trough wells. A selection of reported conclusions:

- Groundwater table is the main control on sedimentation and early diagenesis
- Proximal alluvial and distal wet sandflat deposits show highest abundance of grain-coating clays.
- Patterns of authigenic grain-coating clay follow that of detrital grain coatings

Kelly & Greenwood, 1996:
Describe patterns in the distribution of diagenetic clay minerals: 7 geographical provinces and also vertical trends. One of the provinces PG concerns with the Groningen area. It is based on data from wells UHM-1A, DZL-1 and SDM-1 (Sub-province PG1), and from BIR-13B, FRM-1C, RYS-Z1B and PPS-Z1 (Sub-province PG2). Kaolinite is most abundant, but also important are illite and chlorite. Habitat and subtle trends are described: downward decrease in kaolinite accompanied by an increase in illite (and concomitant increase in feldspar content?). More study wells are mentioned, hence should have petrographic data. These are USQ-1, ZND-12, SMR-1, EKL-1, KPD-1, TUS-1, NWS-1 and ZPD-12A.

- Not documented how the mineral percentages quoted in this study were derived, other than reference to an earlier study
- Wells from PG1 have only very few samples analyzed, so conclusions are a bit thin
- Wells used to define PG2 are all situated in the northeast periphery of Groningen and are not representative for the entire field.

Wood, Rushton & Phillips, 2001:
Contains tabulated data from several wells MWD-1 (5 samples), ROT-1A (8 samples), SAP-1 (5 samples), SLO-2 (5 samples, SMR-1 (5 samples) and TBR-4 (4 samples). Descriptive only, no interpretations/trends described. Thin section descriptions provide details on grain-coating clays: small percentages only, mainly illitic.

Forbes et al., 2003:
Focusses on the East of Groningen area, but is not so relevant. Widespread illitization is considered a major factor reducing reservoir quality.

McAfee *et al*., 2003
Contains petrographycal analyses of samples from well BHM-3 (4 samples), BHM-5B (4 samples), BRW-2 (7 samples), GLH-1 (9 samples), SCB-1 (6 samples), ZPD-12A (17 samples) and ZWD-1 (3 samples). Thin section descriptions provide details on grain-coating clays.

Burfoot & Wood, 2003:
Report on petrographic analysis (THS, XRD, SEM) of samples from wells ODP-1 (15 samples), HND-1 (15 samples), SMR-1 (4/5 samples), TBR-4 (4 samples), EKR-1 (20 samples), MWD-1 (5/4 samples), ROT-1A (7/6 samples), SAP-1 (25/24 samples) and SLO-2 (5/4 samples). Mainly descriptive, with few lateral and vertical trends suggested, but evidence is very limited due to paucity of data, i.e. small number of samples analyzed.

Gaupp & Okkerman, 2011:
Overview article on Rotliegend diagenesis, with proposed mechanisms for the formation of authigenic clay phases such as chlorite rims.

Veeningen & Könitzer, 2016
Analyzed 25 samples and reported strong variation in the amount, type and thickness of clay coatings. A relation is suggested between degree of compaction and the content of clay coatings.

4. Petrographic data analysis

A database containing all available quantitative petrographic data as described in Section 2 allows searching for trends and relationships. The three data sources – whole-rock XRD, clay-fraction XRD and point count modal analysis – each provide a different type of information. They are presented separately in the following.

One point of caution has to be mentioned here. The database combines data from different contractors and laboratories, each with their own sample preparation standards, analytical techniques and interpretation methods. Consequently, there will be quite some variation in the reliability of the data. This is not accounted for in the following, which is meant as a quick-look investigation only. Only when data is clearly out of range it is excluded from the analyses.

4.1 Whole-rock XRD results

Whole-rock XRD results are available for 494 samples from 24 wells. The data can be grouped in four main categories as follows:

- Silicates quartz and feldspar: quartz, plagioclase and alkali-feldspar
- Phyllosilicates: chlorite, illite, mixed-layer illite-smectite and kaolinite
- Carbonates and evaporites: dolomite, siderite, halite and anhydrite
- Various other minerals have been reported in very low quantities: hematite, opaque minerals

Whole-rock XRD gives the bulk mineralogical composition of a rock sample. It does not provide information on the habitat of the component minerals. For example, quartz can occur as detrital sediment framework grains, as a diagenetic phase, as constituent mineral in a lithic fragment, and so on. Detrital quartz grains can be monocrystalline, polycrystalline or cryptocrystalline. These different habitats cannot be resolved with whole-rock XRD. The method can identify different clay minerals, but is less accurate than clay-fraction XRD and cannot distinguish between detrital and authigenic clays.

However, the whole-rock data is very useful for identifying bulk trends in mineralogical composition, particularly for the silicates. The approach followed here is to focus on the silicates only and calculate their relative percentages. This is to remove a certain facies effect: finer-grained or fluvial-dominated intervals tend to have higher clay content and more extensive dolomite cementation, leading to a relatively low percentage of silicates. It is assumed that the relative abundance of quartz and feldspars is not affected by facies. This is not necessarily correct, but serves the purpose of this quick-look analysis.

The first attempt was to plot the relative abundances of plagioclase and alkali-feldspar against depth. This is done for all the wells that have at least 10 samples analyzed. The results are shown in Figure 4.1. The blue curves represent the relative abundance of alkali-feldspar and the red curve represents the total feldspar abundance (for alkali-feldspar plus plagioclase). For some wells, the sample density is low and leads to spikey patterns (e.g. ZPD-12A and NWS-1). Well UHM-1A looks suspicious: it has many data points but the results are very spikey and out of range compared to the other wells. However, two general observations can be made. First, plagioclase is always more abundant than alkali-feldspar. Second, both the relative abundance of alkali-feldspar and of total feldspar is decreasing with depth. Note that this trend was recognized already long time ago. It is used in petrophysics to explain the trend of upward-increasing gamma ray response that is generally observed in wells in the Groningen area.

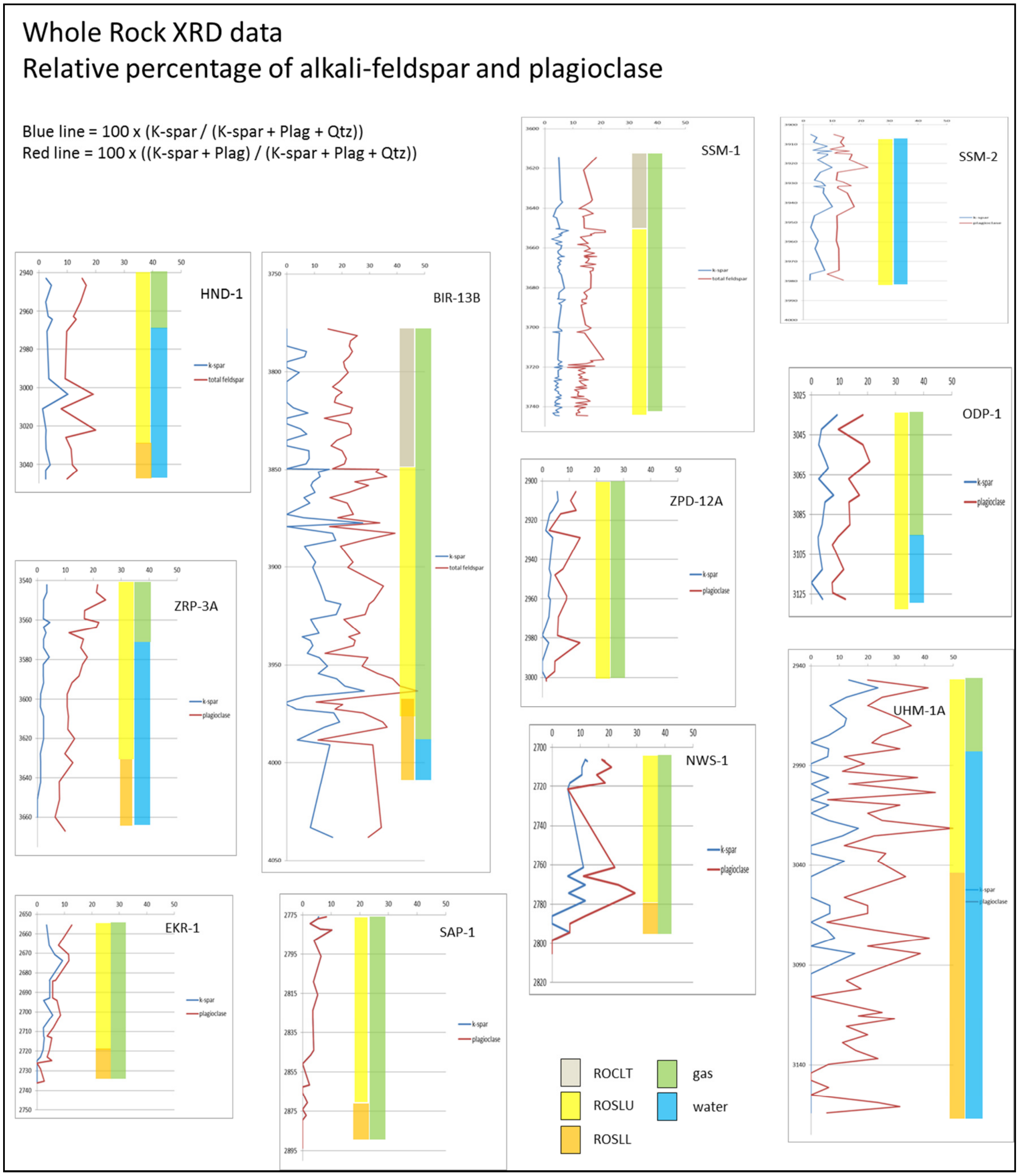
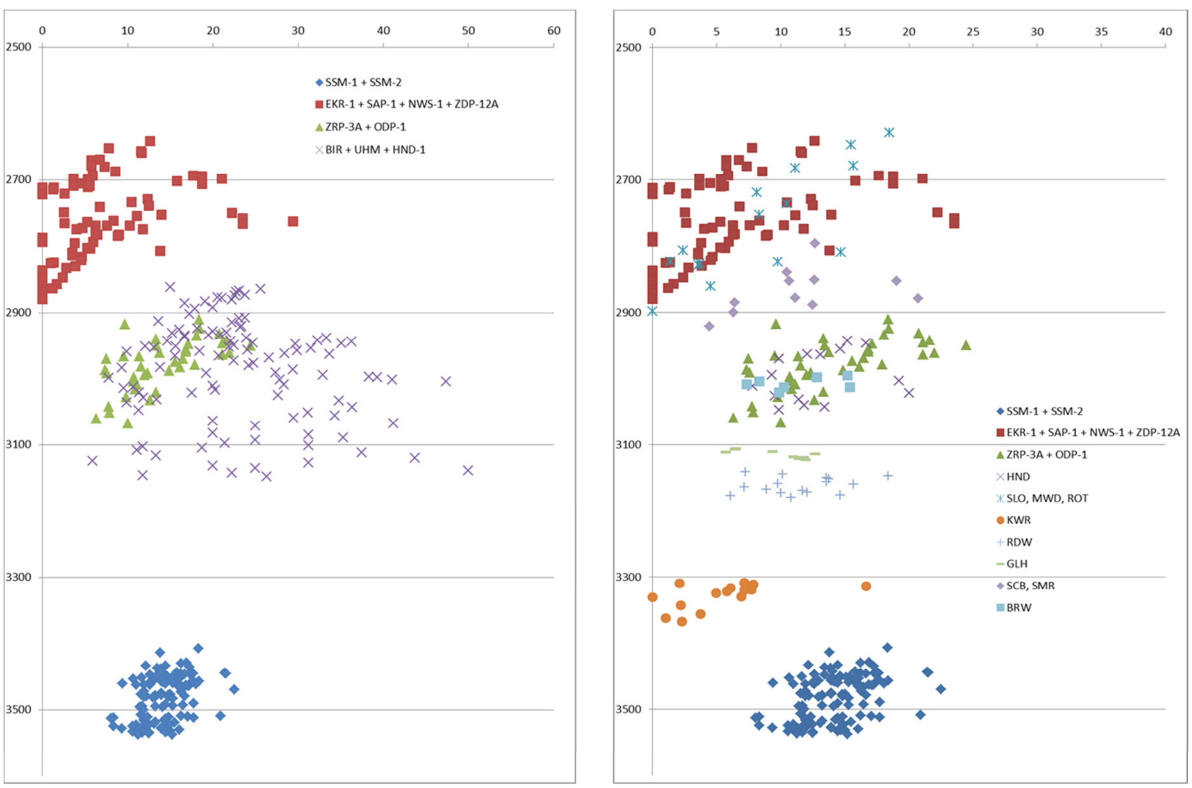


Fig. 4.1 Relative percentage of alkali-feldspar and plagioclase from whole_rock XRD analysis. Only wells with at least 10 samples are shown. Colored bars indicate stratigraphic interval and pore fluid content, see key to colors.

The graphs in Figure 4.1 also show colored bars to indicate the main reservoir intervals Ten Boer Claystone, Upper Slochteren Sandstone and Lower Slochteren Sandstone. Pore fluid content is indicated by green and blue bars for gas and water, respectively. There is a clear sampling bias for gas-bearing Upper Slochteren Sandstone intervals. The data suggest that feldspar content in the ROSLU is higher than in the ROSLL, but this may also be related to the general depth trend mentioned above. Similarly, the feldspar content in the water leg seems to be consistently lower than in the gas leg, but also there the general depth trend may play a role.

The same relative total feldspar abundance data is plotted together for a selection of wells in Figure 4.2a. The wells are tentatively grouped into geographical areas. The depth trends are clearly visible again, but the northeastern wells BIR, UHM and HND show a different distribution. Wells BIR and UHM have been excluded in Figure 4.2b and replaced by a number of other wells. Again, depth trends are obvious for most of the (groups of) wells. Less obvious trends or no trends at all can be observed for SSM, KWR, RDW and GLH. Interestingly, these are all located outside the closure of the Groningen field. Data from wells GLH and BRW only represent very limited depth intervals. This could offer an alternative explanation for the absence of a depth trend.



A. Wells with larger sample depth range

B. Small datasets added, UHM and BIR removed

Fig. 4.2 Relative percentage of alkali-feldspar and plagioclase from whole_rock XRD analysis.Wells are grouped per geographical area.

Figure 4.2b also shows that the southern wells have lower feldspar content compared to the northern wells. This seems to be in conflict with the general depth trend described above. Southern wells are located at shallower depths so would be expected to contain more feldspar. This suggests that there is an additional (strong) south-to-north trend of decreasing feldspar. This is supported by the data from KWR, which is geographically close to the southern Groningen wells, but at a downthrown position in terms of depth.

4.2 Clay-fraction XRD results

Clay-fraction XRD results are available for 638 samples from 32 wells. Clay fractions are prepared from whole-rock samples by disintegrating them with ultrasonic techniques and repeated centrifuging of suspensions. This yields a filtrate residue that consists of clay minerals only. The XRD results provide the relative abundance of clay minerals in the sample. The method cannot distinguish between detrital and authigenic clay or between different habitats such as grain-coating or grain-replacive clay. Another point of caution is the fact that rosette-shaped crystals of chlorite or kaolinite may exceed the size of 2 microns and are filtered out. The clay minerals identified by XRD are illite, mixed layer illite-smectite, kaolinite and chlorite. Small amounts of mixed layer chlorite-smectite have been reported for very few samples. This clay type is not considered in the following.

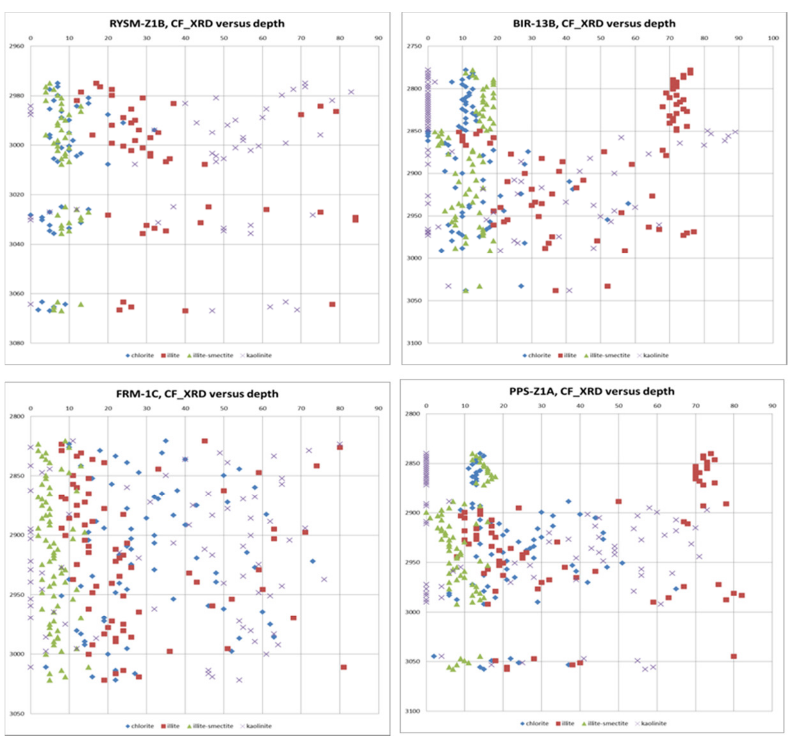


Fig. 4.3 Relative percentage of clay minerals from clay_fraction XRD analysis for four wells in the northeast of the Groningen field.

The first step was to check for depth trends. This was done for two groups of wells. One group consists of four wells in the north-east of the Groningen field: BIR-13B, FRM-1C, RYSM-Z1B and PPS-Z1A (Figure 4.3). Wells BIR-13B and PPS-Z1A have high illite percentages at shallower depths. These samples were taken from the ROCLT. This suggests that most of the illite was deposited as matrix clay. Alternatively but less likely, the illite represents a diagenetic replacement of a precursor detrital clay mineral. High illite in the ROSL below the ROCLT is probably associated with finer-grained facies. High illite correlates with low or zero kaolinite. Within the ROSL no depth trends are apparent for chlorite or kaolinite.

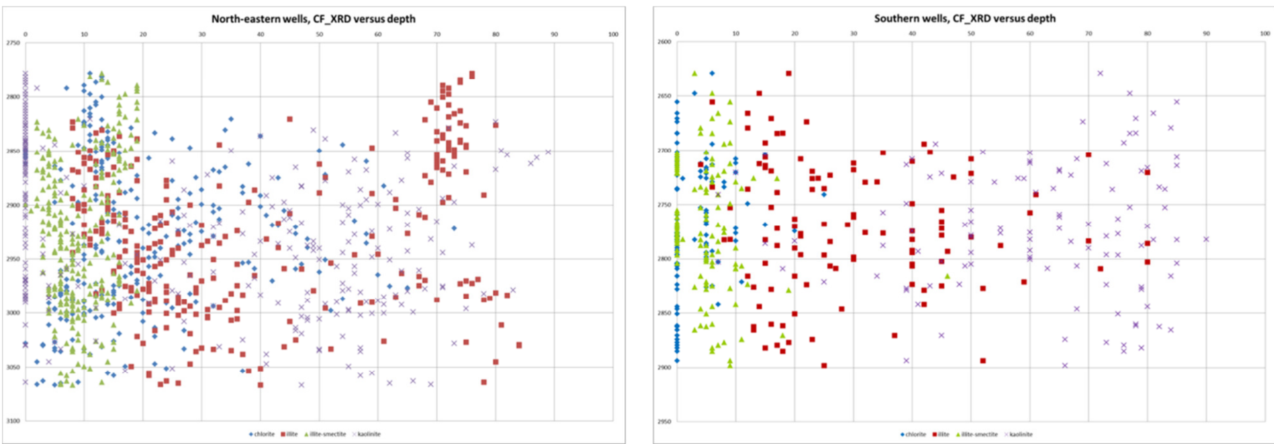


Fig. 4.4 Clay mineral composition from clay_fraction XRD analysis for four wells in the northeast of the Groningen field (left-hand graph) and for seven wells in the south (right-hand graph).

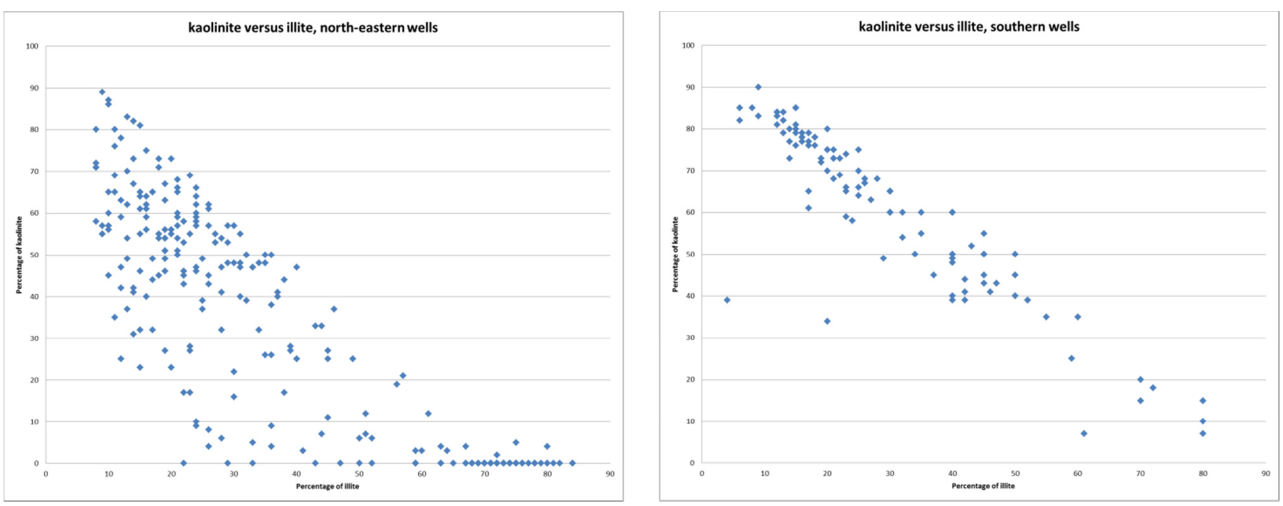


Fig. 4.5 Kaolinite percentage versus illite percentage from clay_fraction XRD analysis for four wells in the northeast of the Groningen field (left-hand graph) and for seven wells in the south (right-hand graph).

The second group of data points is taken from seven wells in the southern part of the field: NWS-1, ZPD-12A, EKR-1, SAP-1, ROT-1A, SLO-2 and MWD-1. Figure 4.4 shows the grouped results for the northeastern wells on the left, and for the southern wells on the right. The content of mixed layer illite-smectite is low throughout, chlorite only occurs in very small amounts. No obvious depth trends are observed for illite and kaolinite. High illite correlates with low kaolinite and vice versa, similar to the observation for the northeastern wells. This is illustrated in Figure 4.5 where percentage of kaolinite is plotted against percentage of illite.

Comparing the two groups of data in Figure 4.4 reveals a major difference in clay mineralogy. Southern wells only contain small amounts of chlorite whilst northern wells show a much higher abundance. At the same time, top_reservoir in the southern wells is some 100 – 150 m shallower than in the northern wells. Therefore, the observed variation in chlorite abundance may represent a depth trend, a south-north trend, or even a combination of the two.

An alternative way of analyzing the clay fraction XRD data is presented in Figures 4.6 to 4.8. Average clay composition has been calculated for all wells, with samples grouped per reservoir interval and per pore fluid content. The results are plotted as pie charts on a map view with the number of samples indicated as well. Wells with less than 6 samples are excluded here.

Figure 4.6 presents all ROSLU samples in the gas leg. A top_reservoir fault map with an outline of the gas-bearing part of the Groningen area is used as a back-drop. Wells within the Groningen closure do show high kaolinite abundance in the south and higher chlorite in the north. Wells outside the Groningen closure show different compositions, particularly NSS-1A and SSM-1. The kaolinite-chlorite trend becomes more obvious when illite is excluded from the calculation of well averages. This is building on the observation mentioned above that illite represents a detrital rather than a diagenetic phase. The result is shown in Figure 4.7. Again, the composition in wells NSS-1A and SSM-1 is diverging from the Groningen wells. Groningen appears to be divided into a kaolinite-rich southern half and a more chloritic northern half.

Less data is available for the water-bearing interval of the ROSLU, see Figure 4.8. The green polygon indicates the boundary between gas-bearing and water-bearing ROSLU. All wells in the southern half of the field are well above the contact. Across the south-eastern boundary and, from there, going to the northwest, the transition from kaolinite to chlorite is again visible. ZRP-3A and ODP-1 in the northwest do not show consistent results. This may be due to the limited size of the available dataset.

A comparison of gas-bearing samples with water-bearing samples from the same well (Figure 4.9a) generally shows lower chlorite and higher kaolinite abundance above the contact. The difference is large for HND-1, but subtle and reverse for ODP-1. Again, the limited size of the dataset makes it difficult to define strong trends.

Only four southern wells have at least 6 samples from gas-bearing ROSLL, and only two north-eastern wells from water-bearing ROSLL. This is obviously not sufficient to identify any trends. Gas-bearing ROSLL is compared with gas-bearing ROSLU in Figure 4.9b, indicating similar clay mineral distributions for both intervals in three out of four wells. Water-bearing ROSLU is compared with water-bearing ROSLL in Figure4.9c. No trends can be derived from this small dataset.

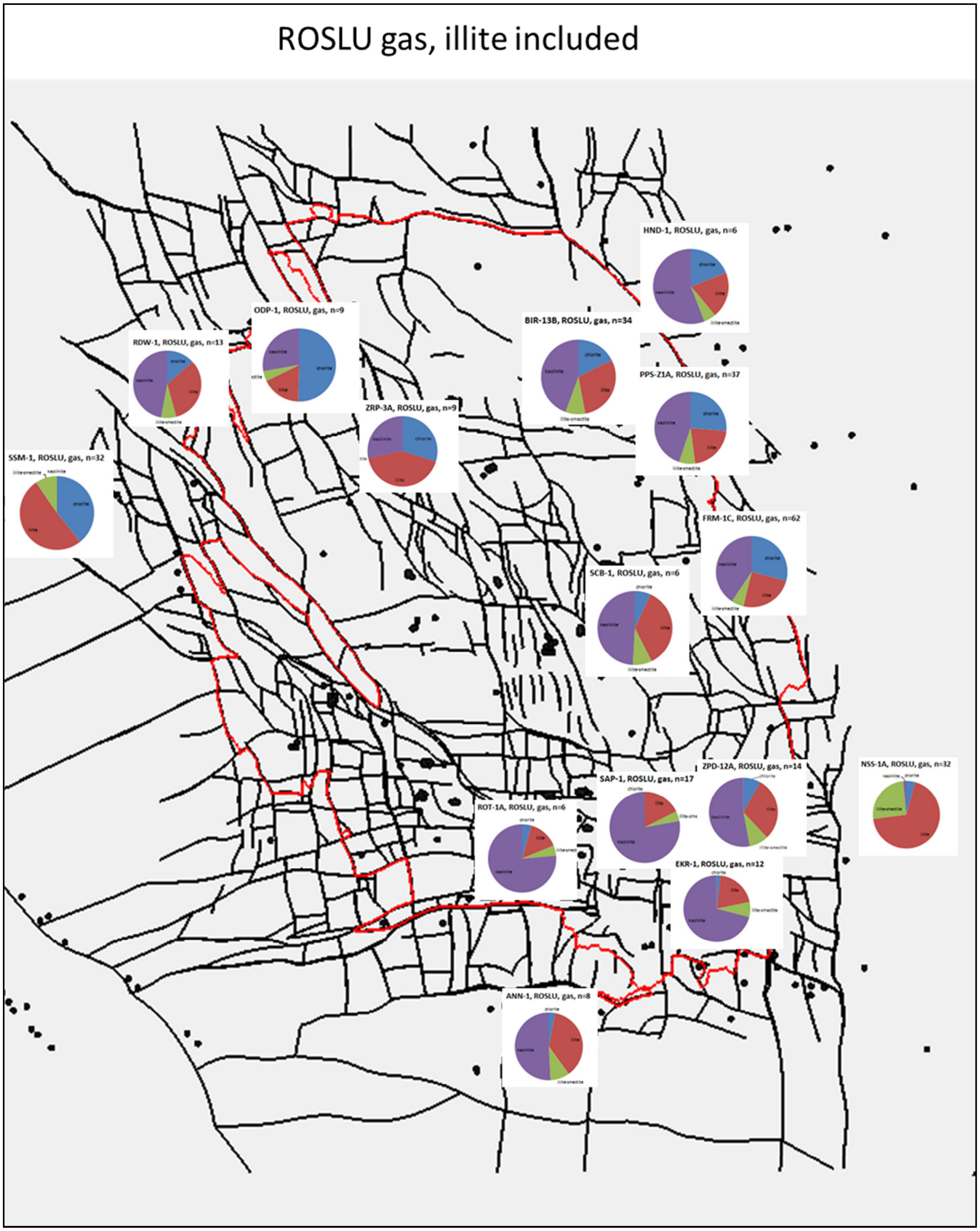


Fig. 4.6 Clay mineral distribution from clay_fraction XRD, averaged per well for gas-bearing Upper Slochteren Sandstone intervals only.

Fig. 4.7 As in Figure 4.6, but now excluding illite (see text for explanation)

Fig. 4.8 Clay mineral distribution from clay_fraction XRD, averaged per well for water-beringUpper Slochteren Sandstone intervals only, illite excluded.

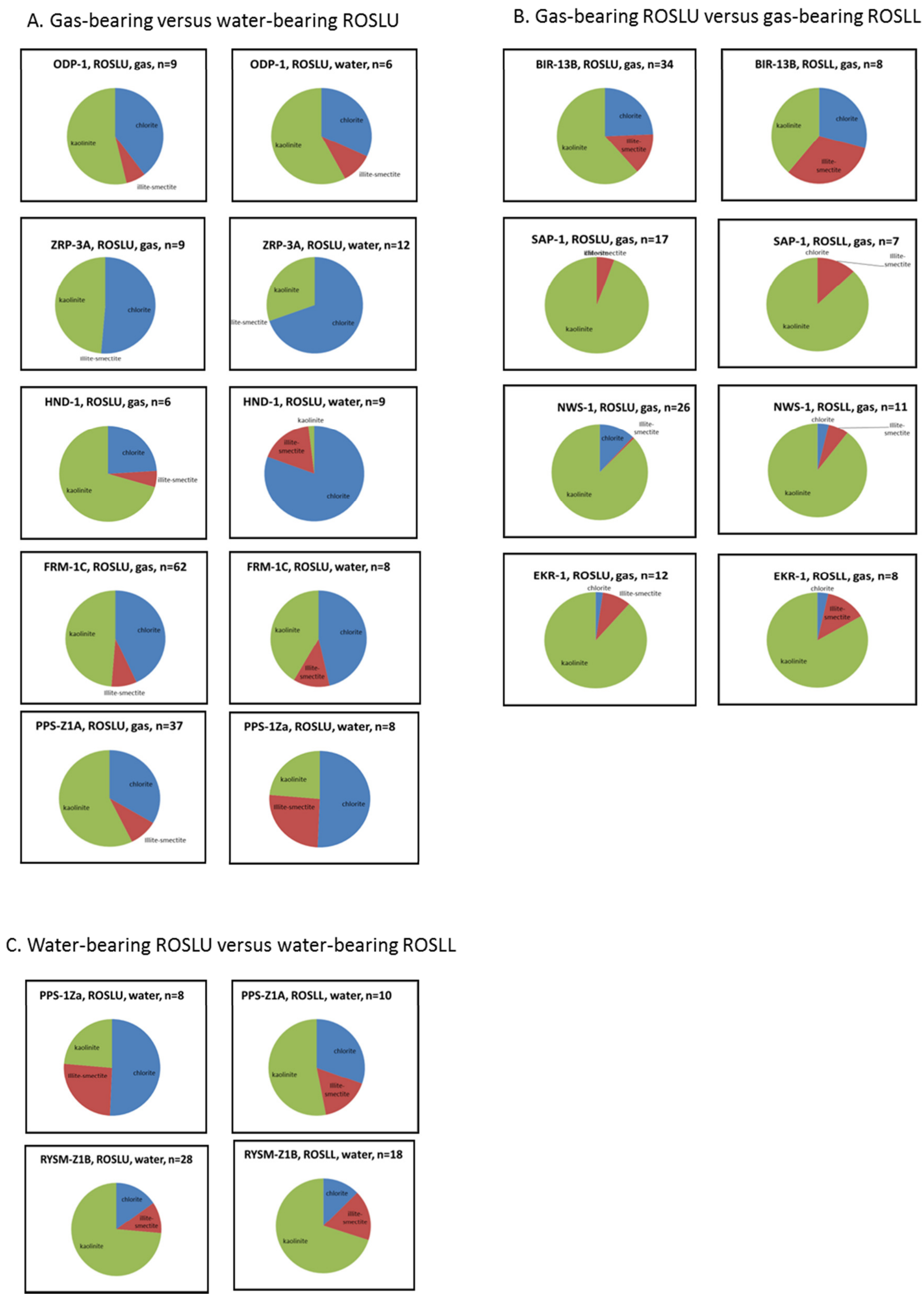


Fig. 4.9 Clay mineral distribution from clay_fraction XRD, averaged per well for water-bearingUpper Slochteren Sandstone intervals only, illite excluded.

4.3 Thin section description and modal analysis results

Thin sections are 30 microns thick slices of rock sample mounted on a glass plate. The samples are impregnated with a blue-dye epoxy to aid in the identification of pore spaces, and can be stained to aid in the identification of certain mineral types. Thin sections are studied with an optical microscope using transmitted polarized light. Qualitative description includes the mineralogical composition of rock components, textural parameters, porosity, compaction, and so on. The distribution of clay minerals in a sample can be studied in some detail to distinguish between grain-coating, grain-replacive and pore-filling clay types. Point count modal analysis allows for a quantitative assessment of the composition of the sample. Standard procedure is to count 300 points per thin section, in a regular grid.

Point count results are available for 461 samples from 24 wells. At this stage, 263 samples from 12 wells have been loaded in the project data spreadsheet, but 6 of these wells have 7 or less samples only. The rest of the data is available in pdf format from scanned report documents. These data are yet to be digitized and added to the spreadsheet for quantitative analysis. The reports contain a wealth of qualitative information and have been consulted for the present study.

SEM analysis shows occasional illite fibers extending from other clay types. Amounts are so small that they are not likely to affect reservoir quality, as has been the case in many other Rotliegend gas fields.

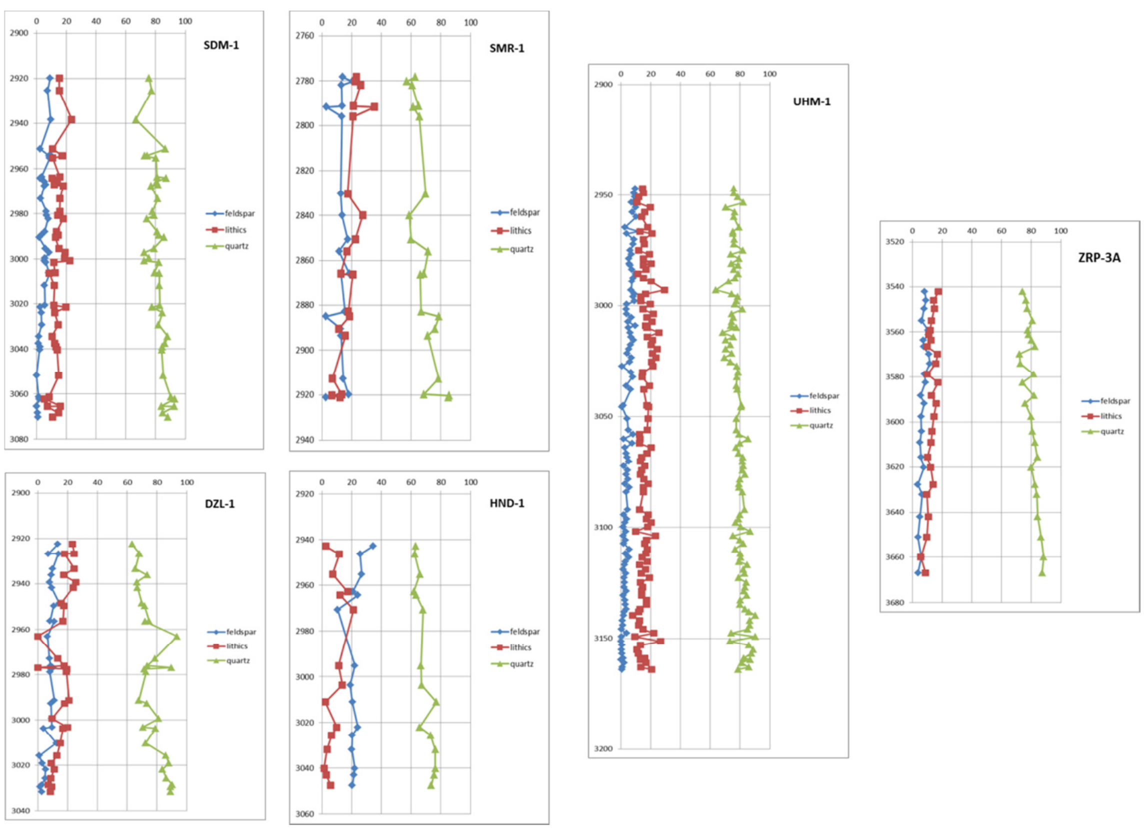


Fig. 4.10 Relative percentage of total feldspar, lithic fragments and detrital quartz plotted with depth for six wells, data from point count modal analysis.

Figure 4.10 shows the relative percentages of feldspar, lithic fragments and quartz plotted with depth for the 6 wells with more than 7 samples available. A trend of reducing feldspar content with depth is observed, similar to the trend in the whole-rock XRD results shown in Figure 4.1. The percentage of lithic fragments also seems to decrease with depth. Unfortunately, there is no consistent description of the composition of the lithic fragments, be they sedimentary, metamorphic or igneous.

The distribution of clay-size material in the thin sections is included in the point count results in different ways in each well:

- Non-specified detrital clay
- Non-specified grain-coating clay
- Non-specified pore-filling or grain-replacive authigenic clay
- Authigenic clay with specified mineralogy (mainly kaolinite and chlorite) and habitat (grain-coating, replacive, pore-filling).

The identification of clay mineral types is based on their optical properties in combination with XRD and SEM data. The combination of different techniques makes it possible to extract the (volume) percentage of grain-coating clay, as well as their mineralogy. Clay rims around sand grains can have a significant impact on reservoir and geomechanical properties (see Section 5), so it is important to study their occurrence in more detail. Plotting the point-counted percentage of clay rims against depth in Figure 4.11 reveals a poorly defined downward increasing trend for individual wells followed by a decrease, but with another increase at the basal parts of the sampled depth intervals. A potential relation with the depth of the gas-water contact, or with the proximity of the Ameland Claystone is difficult to assess with the limited number of samples.

There is quite some variation in the abundance of clay coatings between the wells. For example, wells SDM-1 and DZL-1 show values mainly ranging between 0 and 5 %, but have peak values between 8 and 10 %. Samples from ZRP-3A range between 5 and 10 %, but HND-1 has a few samples that consist for some 20% of grain-coating clay. Note that all the wells in Figure 4.11 are located in the northern half of the field. Checking thin section descriptions from a number of southern wells (Wood et al., 2001; Burfoot & Wood, 2003; wells EKR-1, SLO-2, SAP-1, MWD-1, ROT-1A, ZWD-1, ZPD-12A) yields very low percentages that only rarely exceed 1%. Percentages in SCB-1 and BRW-2 are comparable to DZL-1. Well SSM-1 located west of the Groningen field again shows very high percentages. Altogether, these data show a clear south-to-north trend of increasing grain-coating clay content within the Groningen field. Thin section and SEM analysis indicates that chlorite is an important grain-coating clay mineral, but this will be further evaluated in the next section.

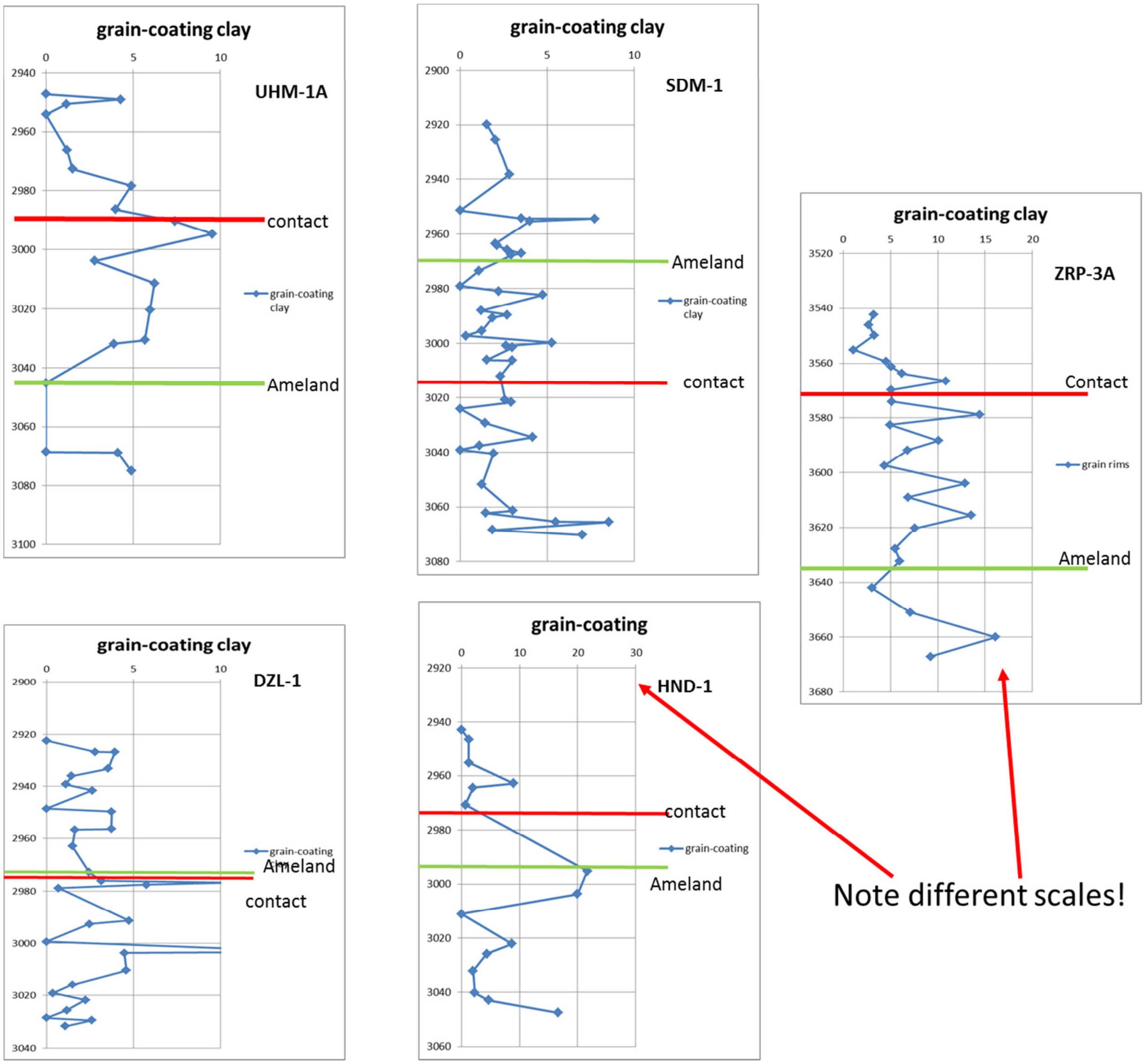


Fig. 4.11 Percentage of grain-coating clay plotted with depth for five wells, data from point count modal analysis. Red lines indicate the depth of the gas-water contact in each well, green lines indicate the approximate position of the Ameland Claystone.

4.4 Discussion of trends

Summary of main observations from the various analytical methods

Whole-rock XRD:

- Plagioclase is always more abundant than alkali-feldspar
- Both the relative abundance of alkali-feldspar and of total feldspar is decreasing with depth, alkali-feldspar decreasing to almost absent
- Feldspar content in the ROSLU is higher than in the ROSLL, but this may also be related to the general depth trend mentioned above
- Feldspar content in the water leg seems to be consistently lower than in the gas leg, but also here the general depth trend may play a role
- Less obvious trends or no trends at all can be observed for SSM, KWR, RDW and GLH, all located outside the closure of the Groningen field
- Strong south-to-north trend of decreasing feldspar.

Clay-fraction XRD results:

- Illite was deposited as matrix clay or represents a diagenetic replacement of a precursor detrital clay mineral
- High illite is probably associated with finer-grained facies and correlates with low or zero kaolinite.
- Within the ROSL no depth trends are apparent for chlorite or kaolinite
- Wells within the Groningen closure do show high kaolinite abundance in the south and higher chlorite in the north
- The kaolinite-chlorite trend becomes more obvious when illite is excluded from the calculation of well averages
- Wells outside the Groningen closure show different compositions, particularly NSS-1A and SSM-1.
- The south-north transition from kaolinite to chlorite is also visible in the water leg, but is poorly defined because of limited data
- There are indications for lower chlorite and higher kaolinite abundance above the contact, but limited size of the dataset makes it difficult to define strong trends. This may also be a depth trend
- Specific trends for the ROSLL cannot be established due to limited data.

Thin section description and modal analysis results:

- Trend of reducing feldspar content with depth is confirmed by thin section analysis
- Lithic fragments also decrease with depth
- Clear south-to-north trend of increasing grain-coating clay content within the Groningen field
- Chlorite is an important grain-coating clay mineral

- Poorly defined downward increasing chlorite trend for individual wells, but with another increase at the basal parts of the sampled depth intervals
- No obvious relation of chlorite abundance and proximity of the gas-water contact, or with the proximity of the Ameland Claystone
- Illite is not a major authigenic clay phase.

Framework grain mineralogy trends

Quartz grains, feldspar grains and lithic fragments are the three main framework constituents of Rotliegend sandstones in the Groningen area. Together, they comprise 65 – 90% of the analyzed samples. Smaller percentages also occur but are associated with silt- to clay-rich lithofacies. The feldspar proportion of the framework grains shows well-defined trends that are revealed by whole_rock XRD and thin section analysis. There is a clear decrease in feldspar going from south to north, in combination with decreasing feldspar percentages with depth (Figure 4.2). This trend is also picked up by gamma ray logs. The upward increase in percentage of potassium feldspar leads to higher gamma ray readings from base to top of the Slochteren Sandstone.

Feldspar trends have been observed in early work on Groningen petrography. In Sluijk, 1965, an explanation is given by interpreting two different source areas for the Rotliegend sediments, based on two different mineral assemblages. One is situated south to south-east of Groningen in the Rhenish Mountains, Germany, and is characterized by sedimentary and epimetamorphic rock fragments, low feldspar and no potassium feldspar. This material is introduced in the Groningen area by fluvial systems in a dominantly south-to-north transport direction. The other source area is located east of Groningen at much larger distance. It is characterized by higher-grade metamorphic rock fragments or minerals, plutonic fragments and a variety of feldspars, including alkali feldspars. This sediment is introduced in the Groningen area by easterly winds. The interplay of the two source areas results in a northward decrease in importance of the southern source which is concomitant with increased intermixing of sediment from the eastern source. This is supported by lithofacies observations in the Groningen area. Fluvial sediments decrease in importance towards the north whilst aeolian processes have an increasingly large influence on the preserved sediments.

Similar trends to the feldspar content may be found in the composition of lithic fragments and different types of quartz grains, *i.e.* monocrystalline versus polycrystalline. This was not pursued in the present study.

Trends in clay mineralogy and habitat

The four clay minerals identified by XRD are illite, illite-smectite, chlorite and kaolinite. Few samples show small amounts of other clay types such as chlorite-smectite, but these are not considered here. Illite and illite-smectite are thought to be mainly detrital components. The depositional processes are both settling from suspension in a low-energy aqueous environment, or infiltration of wind-blown dust in porous sands close to the surface. Clay-rich intervals such as the Ten Boer Claystone and Ameland Claystone contain high percentages of both minerals, together with small amounts of chlorite and no kaolinite at all. Small quantities of authigenic illite have been identified from SEM as small fibres, and from thin section analysis as radial illite coating framework grains. Altogether, the abundance of illitic clay types follows general lithofacies trends, i.e. higher quantities are associated with finer-grained deposits.

Chlorite and kaolinite are not detrital components, but are formed in situ during diagenesis. Kaolinite mainly occurs in relatively coarse-crystalline clusters. Thin section analysis suggests that kaolinite replaces unstable framework grains such as feldspar. This is supported by the fact that higher kaolinite content correlates with lower feldspar content (Figure 4.12a). Note that replacement of feldspar by kaolinite cannot fully account for the depth trend observed in feldspar abundance: plotting kaolinite versus depth also shows a decrease in kaolinite content with depth (Figure 4.12b).

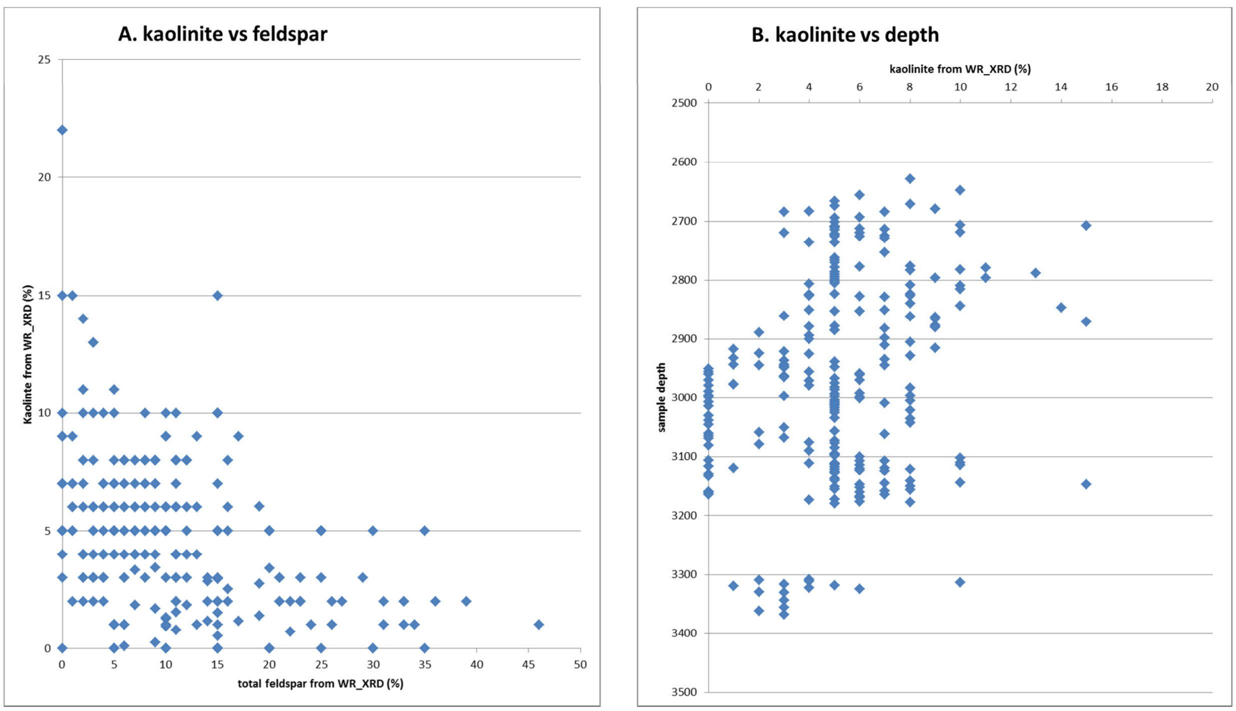


Fig. 4.12 A. Kaolinite versus feldspar content, and B. Kaolinite content versus depth (mineral percentages from whole_rock XRD)

The main occurrence of chlorite is associated with clay rims around framework grains (Figure 4.13). Clay rims can only be observed in thin section and SEM. This makes identification of the constituent clay minerals a bit difficult. Part of the grain-coating clay is platy tangential or fine-crystalline radial, but is intermixed with extensive chlorite. This is evidenced by the optical properties of the rims and by the fact that high percentages of clay rims are associated with higher chlorite readings from whole_rock and clay_fraction XRD.

Small amounts of clustered chlorite crystals are associated with the replacement of unstable framework grains.

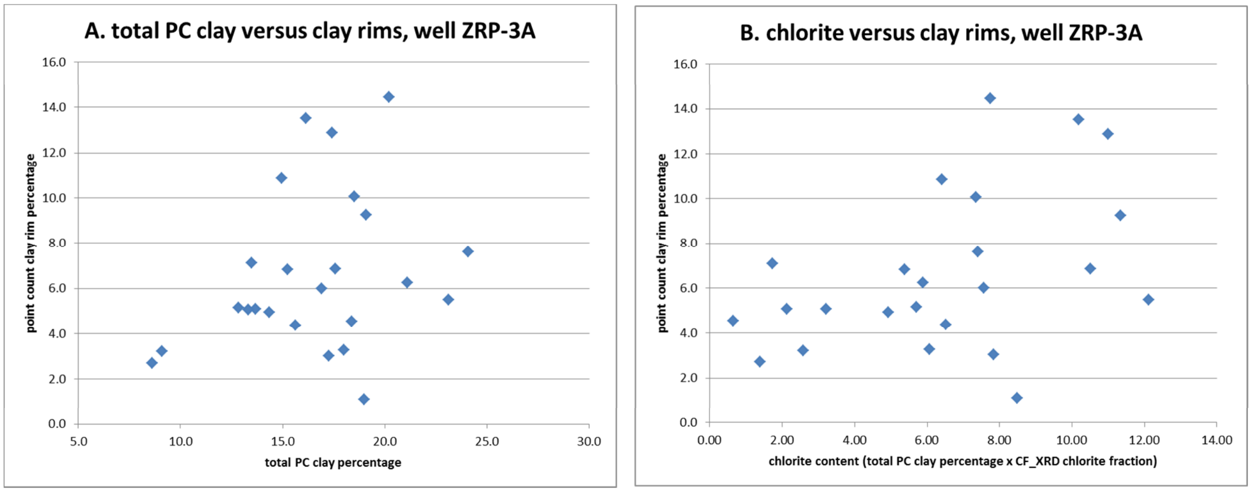


Fig. 4.13 A. Relation between total clay content and percentage of clay rims, and B. Relation between chlorite content and percentage of clay rims (data from point count modal analysis and clay_fraction XRD for well ZRP-3A)

South-to-north trends in the relative abundance of kaolinite and chlorite are very clear from the clay_fraction XRD data (Figure 4.7). This is in line with a northward trend of increasing clay rims observed in thin section analysis, and the fact that chlorite is an important constituent of the clay rims. A depth dependence for the occurrence of chlorite could not be established because of the limited thin section dataset available. It has been suggested elsewhere that a relation may exist with the proximity of the gas-water contact or with stratigraphic position. This may be a subject for further study.

5. Petrographic trends and rock properties

5.1 Impact on reservoir quality

One of the objectives of the present study was to identify potential relations between mineral composition, diagenetic effects and reservoir quality. Two trends could be defined with some confidence. The feldspar trend is not likely to impact reservoir quality to a large extent. Lower feldspar content is associated with higher quartz content and not with higher porosities. Also, dissolution of feldspar may create additional pore space but is also associated with formation of kaolinite so the net result is limited. The development of clay rims during diagenesis, be they newly formed or growing or extending from “detrital” grain coatings, will certainly affect reservoir quality. They will be considered more extensively in the following.

Several reports describe a positive effect of chloritic clay rims on reservoir quality. Precipitation of early clay rims prevents the formation of more extensive diagenetic phases such as quartz cement. Clay rims can also prevent compaction to a certain extent. Thus, they can help preserve pore space upon burial and diagenesis. But there can also be a negative effect. Extensive development of grain-coating clay leads to reduction of porosity and increased blockage of pore throats, hence a reduction of permeability. Which one of the two effects will prevail is depending on primary textural parameters (grain size, sorting) and on pore water chemistry.

A model for the development of chlorite clay rims has been described in Gaupp & Okkerman, 2011. Precursor minerals such as mixed-layer illite-smectite and chlorite-smectite can precipitate directly from playa groundwater that evolved into highly concentrated brines. This particularly happens in distal areas in sandstones that are in contact with playa shales. The compacting shales release hypersaline brines which migrate into adjacent sandstones and mix with fresher water. Such a situation may well have existed in the northern part of the Groningen field where clay-rich distal (lacustrine) facies is interfingering with fluvial-aeolian sandstones.

A common observation from thin sections and SEM is that clay rims around framework grains consist of two layers. The inner layer directly adjacent to the grains consists of tangential plates of detrital illite or mixed-layer clay. An outer layer consists of newly formed authigenic clay growing from the inner layer. This suggests that the presence of detrital clay rims is favorable for the development of thicker coatings during diagenesis. However, such clay rims have also been described for wells in the south of the field. Their presence alone cannot explain the observed difference in abundance between the south and the north. But clay rims in the south are thin and illitic, while rims in the north are thicker and chloritic.

Previous reports concerning with the Groningen field have suggested a relationship between reservoir quality and pore fluid content. This is confirmed by poroperm cross-plots of plug measurements, where samples from the aquifer are generally plotting in the lower permeability ranges compared to samples from the gas leg. Other studies have suggested that the presence of clay rims tends to decrease reservoir quality, whilst the present study shows that chlorite is an important constituent of these rims. All these factors seem to come together in the north of the Groningen field. There, the Slochteren Sandstone is dipping into the water leg, the amount of clay-coating clay is increasing, and so is the chlorite content.

It is also possible that illite plays a role. Groningen samples do not show extensive illitisation or formation of a fibrous illite network in the pores, but illite is an important constituent of the clay rims. There is indeed a northward trend of increasing illite content. This trend is difficult to interpret because illite occurs both as detrital and as authigenic component of the Rotliegend sediments. At least part of the northward increase should be attributed to the depositional trend of increasing finer-grained facies towards the north.

It should in principle be possible to test the relation between chlorite or illite clay rims and reservoir quality. This requires a large number of samples and a full petrographic analysis of each sample, preferably on freshly drilled material. The currently available historical dataset is probably not large enough to derive at conclusive results, but may be indicative of certain trends.

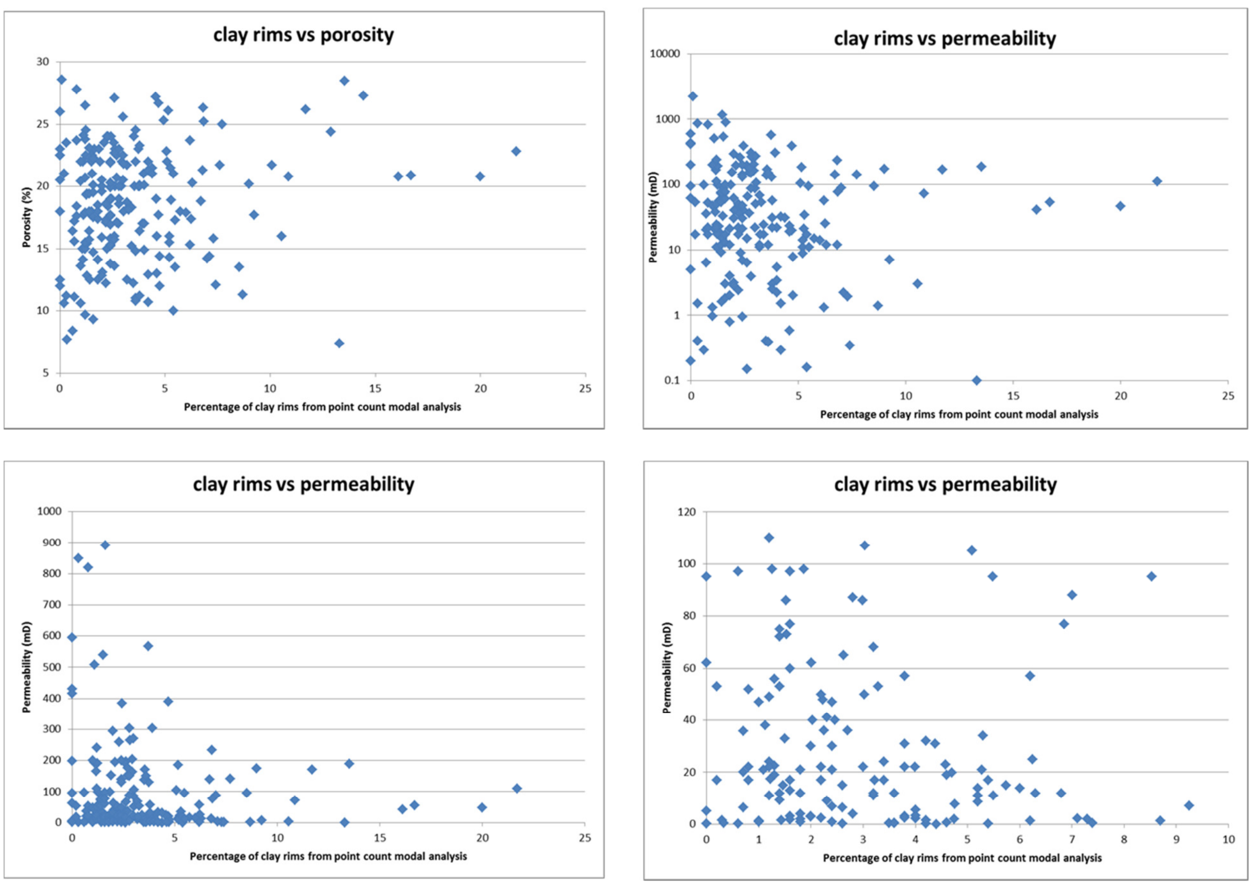


Fig. 4.14 Percentage of clay rims versus porosity (upper left) and versus permeability at three different scales. Data from wells HND-1, ODP-1, ZRP-3A, SDM-1, DZL-1 and UHM-1, all in the northern half of the field.

Figure 4.14 shows data from 6 wells in the northern half of the Groningen field. A small subset of the samples has more than 10% clay rims, but still reasonably good reservoir quality. The bulk of the samples have less than 10% clay rims. The correlation with porosity is not clear, but there is a trend of decreasing permeability with increasing clay rim content. This becomes more obvious when permeability is plotted on a linear scale or when a subset of the data is considered (Figure 4.14, lower left and lower right, respectively).

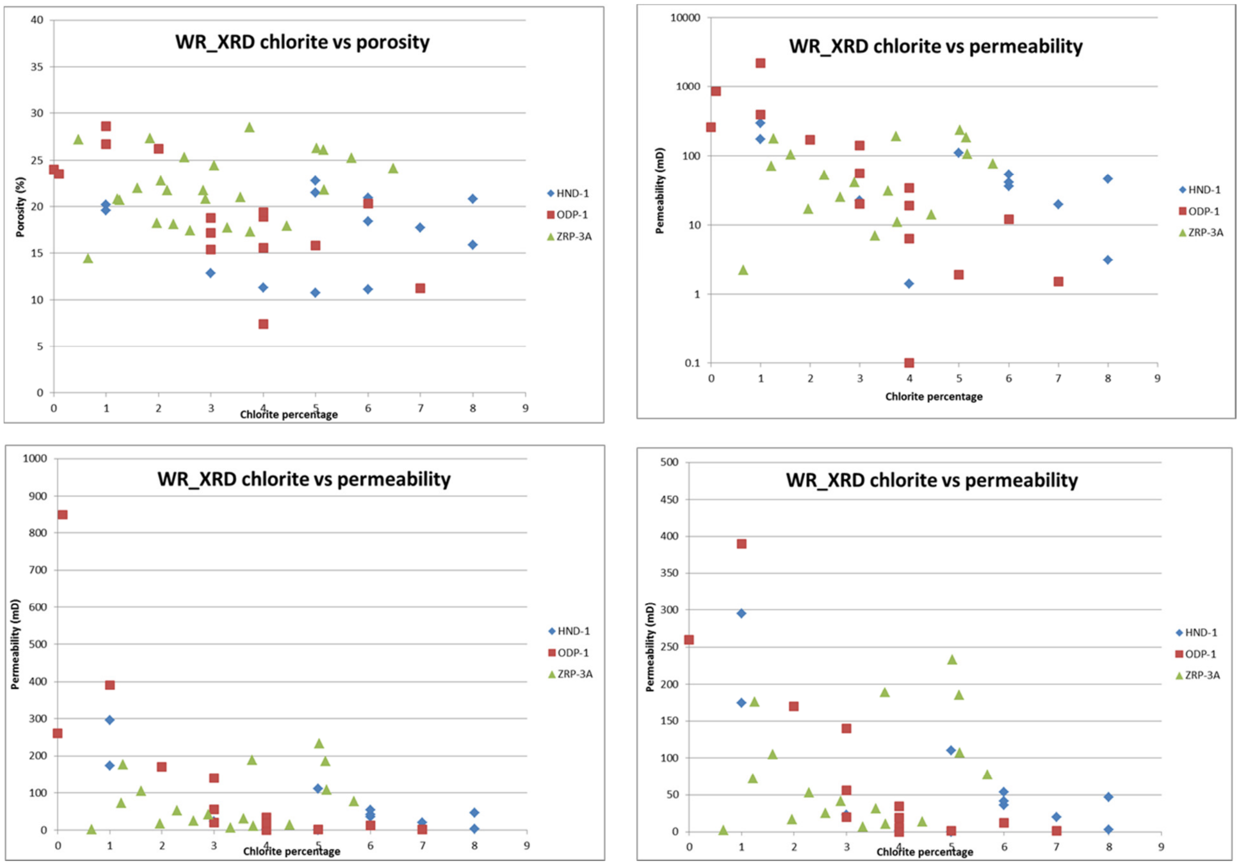


Fig. 4.15 Chlorite percentage from hole_rock XRD analysis versus porosity (upper left) and versus permeability at three different vertical scales).

Three wells have point-counted clay rim percentages and chlorite percentages from whole_rock XRD analysis, see Figure 4.15. Both porosity and permeability seem to decrease with increasing chlorite content. As in Figure 4.14, plotting permeability at a linear scale makes the trends more apparent.

In conclusion, the available data show a correlation between the abundance of clay rims, the abundance of chlorite and reservoir quality. The observed correlations do not necessarily prove a possible causal relationship between these factors.

5.2 Impact on compaction

The observed trends in feldspar content and in abundance and mineral composition of authigenic clay could well have an impact on compaction. Associated research questions include:

- Does the dissolution of feldspar framework grains lead to weak spots in the reservoir that are prone to collapse?
- Are feldspar grains more susceptible to compaction-induced micro-fracturing than other framework grains
- What is the timing of feldspar dissolution relative to gas charge?
- Does the presence of clay rims have an effect on compaction behavior at the micro-scale, e.g. by lubricating the movement of framework grains?
- Do clay rims promote or prohibit the formation of micro-fractures?
- …………………

These questions are, or possibly will be, addressed in ongoing work by research partners in Rijswijk and at Utrecht University.