PUBLIC

Princetonlaan 6
3584 CB Utrecht
P.O. Box 80015
3508 TA Utrecht
The Netherlands

www.tno.nl

T +31 88 866 42 56
F +31 88 866 44 75

TNO 2015 R10056

Integrated pressure information system for the onshore and offshore Netherlands
Final report

Date	27 January 2015
Copy no	
No. of copies	
Number of pages	83 (incl. appendices)
Number of appendices	2
Sponsor	TKI Gas (TKIG01002), 7 Dutch operators
Project name	Integrated pressure information system for the onshore and offshore Netherlands (TKIG01002, Innovation Program Upstream Gas Project)
Project number	056.01417

Public summary

Knowledge and understanding of the pressure condition in the subsurface is a basic requirement to optimize gas production, to assess the possible impacts of (amongst others) gas production and underground gas storage on surface subsidence and seismicity, and to study and assess possible interaction between different types of subsurface activities. Hence, such knowledge has a high business impact as it is of great importance for optimizing responsible exploration and use of the subsurface, including safe and cost-effective drilling. A project was therefore executed in 2013 and 2014 by TNO for seven Dutch operators with the main objective of improving the quantitative knowledge and understanding of the distribution of pore fluid pressures and fluid dynamic conditions in the Dutch subsurface, both onshore and offshore. For this objective the project activities concentrated on pre-depletion original pressures using public information from exploration and appraisal wells.

The main result of the project is an integrated pressure information system for the onshore and offshore Dutch subsurface, and for this the project departed from the latest (2007) version of the so-called Pressure SNS (Southern North Sea basin) database containing pressure condition data from almost 700 primarily offshore wells. This database has been compiled in the previous decade via two joint-industry projects executed by TNO together with CSIRO, Australia. In the current project this database has been extended with pressure-hydrodynamics condition data for 450 onshore and offshore wells, and additionally the data for the wells in the existing database was slightly enhanced and updated with some new data. The new database resulting from this project consists of pressure-hydrodynamics condition data for 1145 wells, whereby the data has been quality coded. In a subsequent step for the project this database has been the subject of several petroleum-hydrogeological research activities, including analysis and state-of-the-art pressure and fluid dynamic interpretation of the pressure condition data in the updated database, using recent results of lithostratigraphic, structural and reservoir mapping and basin modelling programs executed at TNO.

The project delivered a pressure information system for the onshore and offshore Dutch subsurface to the participating operators together with results from the petroleum-hydrogeological research. These project results concern:

- A quality-controlled database, delivered in MS Access, with measured data on pressures from pressure tests, kicks, mudweights, leak-off pressures, temperatures, salinity/resistivity (also calculated data included), fluid contact/free water level (also calculated data included) and on chemical analyses of formation water, and up-to-date lithostratigraphy. The database includes such data for 1145 (exploration and appraisal) wells, covering the onshore and offshore Dutch subsurface, where the data for almost 700 wells originates from the two previous joint-industry projects executed in the previous decade and which data has been somewhat enhanced and updated in this project. Furthermore, an Excel overview has been delivered on (mainly) all exploration and appraisal wells for which information has become public before July 2014 indicating presence in the MS Access database and availability of any relevant pressure data.
- Two databases in Excel format with derived data and which concern:
  - Pore fluid overpressures and pore water overpressures calculated for those wells in the MS Access database for which appropriate pressure test data is available.
  - Fluid densities, salinities and resistivities determined for the wells in the MS Access database extension for which wireline formation test (WFT) data of sufficient quality is available.

- Digital visualization products of which concern:
  - Overpressure distributions in map view for the main reservoirs units and which displays are accompanied by the ArcGIS projects that have been used to generate these maps.
  - Several cross sections with pressures and overpressure distribution in relation to geologic and fluid geologic framework.
  - Cross plots of pressure and leak-off pressure data in relation to standard stress gradients for the main lithostratigraphic units and structural elements.
- Regional interpretation in final project report as result from coupling pressures, stress field and geological framework via the delivered data products with identification of characteristic regional pressure, leak-off pressure and lithostatic pressure trends.

These project results are expected to have a wide variety of applications, including the exploration and production of conventional oil and gas resources, geothermal and unconventional resources, such as shallow gas and shale gas, and also storage of gas in the Dutch subsurface. During the project several discussions with the participating operators took place which resulted in scope for continuation of several of the project activities. As a result it has been agreed to define a follow-up project for the current operators, with a focus in the coming years on the support, maintenance and extension of the pressure information system. This extension should focus on mainly all wells for which pressure condition data has or will become public between June 2014 and the end of 2017. Furthermore, by participation in such a follow-up project, other organizations not involved yet may get access to the current or near future versions of the pressure information system. Such organizations need to be active in the Dutch on- and offshore subsurface. Further spin-off outside the above foreseen applications are for now not expected.

For further information on this public summary and on any relevant publications, the reader is referred to the contact details as found on the front page of this report.

Maatwerkbeschikkingen 2012: “Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken, voor het TKI Gas uitgevoerd door Rijksdienst voor Ondernemend Nederland.”

Contents

List of tables and figures

Figures

Tables

1 Introduction

Knowledge and understanding of the pressure condition in the subsurface is a basic requirement to optimize gas production, to assess the possible impacts of (amongst others) gas production and underground gas storage on surface subsidence and seismicity, and to study and assess possible interaction between different types of subsurface activities. Such knowledge has therefore a high business impact as it is of great importance for optimizing responsible exploration and use of the Dutch subsurface, including safe and cost-effective drilling.

The objective of the project was to improve the quantitative knowledge and understanding of the distribution of pore fluid pressures and fluid dynamic conditions in the Dutch subsurface, both onshore and offshore. For this objective the activities focused on pre-depletion original pressures using public information from exploration and appraisal wells. Results of all activities became available in an integrated pressure information system for the Dutch subsurface and for this the project departed from the latest (2007) version of the so-called Pressure SNS (Southern North Sea basin) database containing pressure-hydrodynamics condition data from almost 700 mainly offshore wells. This quality-controlled and reliability-coded database has been compiled in the previous decade via two joint-industry projects (Simmelink et al., 2004, 2008) executed by TNO together with CSIRO, Australia. Results of these two projects have been made public according to the specific project agreements. Selected information and knowledge has been published on the website *www.nlog.nl*, presented at national and international conferences and in scientific journals, whereas information from the PSNS database have been used in a wide variety of research projects at TNO projects, and which included PhD projects.

This project has built further upon the knowledge and status obtained in these previous two projects and largely followed the approach developed and applied in these projects. In a first step the PSNS database has been extended with pressure-hydrodynamics condition data for 450 onshore and offshore wells, whereas the data for the wells in the existing PSNS12 database was enhanced and updated with new data. The extension of the database intended to cover mainly onshore wells and wells for which information became public since 2007, whereby information included (amongst others) measured data on pressures from pressure tests, mudweights, leak-off pressures, on temperatures, salinity/resistivity, fluid contact/free water level and on chemical analyses of formation water, and up-to-date lithostratigraphy, quality and reliability coding. The adjustments and additional input for this database are described in chapter 2 of this report.

In a subsequent step for the project, the new database has been the subject of petroleum-hydrogeological research activities, including analysis and state-of-the-art pressure and fluid dynamic visualization and interpretation of the pressure condition data in the updated database, using recent results of lithostratigraphic, structural and reservoir mapping and basin modelling programs executed at TNO. The analyses and visualization performed are described in chapter 3 of this report, whereas the activities, results and conclusions of the characterization and interpretation of the pressure and fluid dynamic conditions in the Dutch subsurface are found in chapter 4. The report concludes with chapters 5 and 6 covering the project’s process, and final conclusions and recommendations, whereas the report is supported by chapters 7-9 which contain the references for the report and two appendices listing the specific deliverables of the project.

The project results as described in this report, and by the specific deliverables of this project, are expected to have a wide variety of applications, including the exploration and production of conventional oil and gas resources, geothermal and unconventional resources, such as shallow gas and shale gas, and also storage of gas in the Dutch subsurface. The project results have been developed from public available information, but the majority of the results and deliverables are marked as confidential and specific deliverables for the project participants as will be described in chapter 5.

1.1 Project details

TKI Gas project number:	TKIG01002
Project name:	Integrated pressure information system for the onshore and offshore Netherlands
Project period:	January 1, 2013 until October 31, 2014
Project participants:	TNO (contractor), Wintershall Noordzee, EBN, Chevron Exploration and Production Netherlands, DANA Petroleum Netherlands, TOTAL E&P Nederland, GDF SUEZ E&P Nederland, Nederlandse Aardolie Maatschappij (NAM).

2 Quality-controlled database and pressure information system

This third project on the Pressure SNS database has followed the existing approach of the previous two projects on this database. The reader is referred to the report of the first project (Simmelink et al., 2004) for the quality control (QC) coding methods, the reliability ranking and abbreviations used. In the second project some enhancements were introduced for the QC coding methods introduced in the first project, whereas an additional code has been introduced to serve as interpretation additional to QC coding applied. The report of the second project (Simmelink et al., 2008) gives a further explanation of these QC code enhancements and introduced interpretation code.

In this chapter an overview is found of the contents of the third version of the Pressure SNS database as has been developed during this project. The process of selection of the wells for the database extension is described, whereas statistics on the amount of data per data type is tabulated. The chapter concludes with the specifics of the database and the pressure information system to which it belongs.

2.1 Selection of wells

The planned extension to the latest version of the database (PSNS12, provided at the start of the project to the participants, see Appendix-A-8.1.1) was planned to consist of data of 400 wells whereas the data generation activities were limited to use only data from wells for which public information was released before, or would be released, during the project on the website *www.nlog.nl*. In April 2013 the following overviews were generated via queries on the DINO database:

A. all exploration and appraisal wells for which data was or would become publicly available before July 2014 (updated during project and for final version see Appendix-A-8.1.5),
B. a subset of these wells for which the queries on the DINO database showed that there is likely no pressure information available.

These two overviews were distributed to the project participants for review and feedback. In a next step the project team proposed in summer 2013 a set of 405 wells to be candidates for the enhanced data coverage for the database, and which consisted of several subsets discussed during earlier years with several project participants, e.g. during a workshop in December 2011, and of a subset of almost 200 wells that had been subject of data inventory activities by TNO in the years 2008-2010.

During the data generation activities for this set of 405 wells it was found for several wells that no pressure data was available, whereas at the same time extra wells (like side tracks) were also considered for data availability by the project team and subject of data generation. The status of this process has been discussed at several moments with the project participants and which was supported by an Excel overview with all the wells considered for the project and the specific data generation status.

In a final discussion on the specific extension of the database it was agreed with the project participants that the extension would cover more than the number of 400 wells with pressure data that were finally proposed to the project participants. The additional wells, next to a set of 400 wells, would include ones:

- that have no pressure data, but for which other relevant data (like on temperature and/or on mudweights) had been found,
- being studied but not complete on all data types.

For a set of 400 wells the following level of completeness on pressure data needed to be established:
- good quality WFT data, or DST/PT data (if available) in case of low quality WFT data, and
- in absence of WFT data, DST/PT as second pressure data source (if available) next to available LOT data.

Hence, DST/PT data would be allowed to be absent for several wells.

As a result for this project, data for 450 wells has been added, with pressure data for 415 wells, to a new third version of the Pressure SNS database and which version has the following characteristics:
- 1145 wells with pressure and/or other relevant data;
- An extension covering wells:
  - Subject of an incomplete inventory by TNO in the years 2008-2010;
  - Released in the period 2007-July 2014;
  - Further selected mid-summer 2013 and which cover mainly onshore wells released before 2007;
  - Entered during the course of the project as described in this chapter.
- Updates of the existing PSNS12 database covering:
  - Reinterpreted basin identifier;
  - Update of lithostratigraphy for several wells;
  - Corrections of pressure data for several wells, including corrections of QC coding;
  - Removal of 6 empty wells and updates and improvements of data for 10 wells as these 16 wells were among the 450 wells studied in the current project.
- Following general updates for entire database such as:
  - Casing data table added;
  - Remark fields added to several data types;
  - Addition of seabed/ground level height;
  - Remarks in case for a well data is expected to be available but not studied.

This database has been delivered in two stages to the project participants, by means of a beta version mid 2014 (see Appendix-A-8.1.2) and by means of the final version in September 2014 (see Appendix-A-8.1.3). A geographical overview of the wells in the database extension (with in background wells of PSNS12 database) has become available, see Appendix-A-8.1.4. Furthermore, Excel overviews were generated and maintained during the project on the lithostratigraphic codes applied in the database, on the status of all wells for which data has become public before July 2014, and on the data collection and generation for all wells considered during the project for the database extension. See Appendix-A-8.1.5 for more details on these Excel overviews.

2.2 Database statistics

The overview on the database extension as found in Appendix-A-8.1.5 shows that the following main data types have been subject of collection, quality control, classification in reliability categories and database storage:

- Mudweights,
- WFT pressures and temperatures,
- DST/PT pressures and temperatures,
- Fluid Contact (both reported and calculated, gradient based),
- Leak Off pressures,
- Formation Water Chemistry,
- Temperature (BHT/BHTx).
- Salinity (reported and calculated, density based)

On request of the project participants for two data types also calculated data has been added to the database where it should be noted that the calculated salinity data has also been delivered via a separate Excel sheet (see chapter 3 and Appendix-A-8.2).

Reported data has been collected from the following sources:

- Pressure related data: Composite logs, well completion reports, wireline formation test logs, drill stem test reports, production test reports, formation integrity test/leak-off test reports, mud reports and logs, weekly/monthly drilling reports (contrary to the previous two projects for which also daily drilling reports were available);
- Temperature related data: Log headers, drill stem test reports, production test reports, formation integrity test reports;
- For hydrochemistry and salinity data: Well logs, drill stem test reports and production test reports;
- For Fluid Contact/Free water level data: Structural maps.

For the PSNS3 extension, where appropriate, such data sources have been reported.in the database.

The final version of the new database has been delivered with overviews of data types, number of data points and wells as present in the PSNS12 part, the PSNS3 extension and in the full PSNS123 database, see Appendix-A-8.1.3. These overviews allow for several statistics to be generated for the extension and for the full database. Several statistics as found in Table 1 have been developed from these overviews.

Data type	**Number of wells (PSNS3/PSNS123)**	**Number of data points (PSNS3/PSNS123)**	**Further characteristics (PSNS3/PSNS123)**
			Wells with pressure data
Wells	450 / 1145	-	415 / 1040
Mudweights	419 / 1027	7203 / 24722	-
			Reliability code
WFT	293 / 714	7950 / 16593	*1*: 1244 / 1639 *2*: 1129 / 3998 *3*: 762 / 880 *4*: 1289 / 3035 *5*: 436 / 835 *F*: 3090 / 6206
DST	105 / 494	172 / 1119	*1*: 14 / 140 *2*: 48 / 304 *3*: 5 / 134 *4*: 10 / 32 *5*: 82 / 331 *F*: 4 / 92 -: 9 / 86
			Quality code
LOT	256 / 619	535 / 1405	*A*: 0 / 0 *B*: 0 / 21 *C*: 24 / 60 *D*: 155 / 561 *E*: 50 / 59 *F*: 306 / 704
Fluid Contact (FWL)	102 / 175	133 / 215	-
Temperature (WFT)	81 / 219	1918 / 4280	-
Temperature (DST)	34 / 271	47 / 515	-
Temperature (BHT/BHTx)	423 / 1031	3836 / 9982	-
Salinity	153 / 304	392 / 759	-
Formation Water Chemistry	42 / 177	127 / 697	-

Table 1: Statistics of third Pressure SNS database

In Table 1 for the main data types subject of the project the number of wells and number of data points are presented, whereas in the last column for some types further characteristics have been given. The following on these statistics can be remarked:

- Original (2007) PSNS12 database consisted of 711 wells, of which 16 (among which 6 that were having no data) have been improved in the current project. Hence, total number of wells of new database concerns 1145 wells;

- The wells with pressure data concern those with data for only the types WFT, DST and LOT. The original PSNS12 database had 688 wells with pressure data and for that number more pressure data types were considered. Taking these additional wells into account the PSNS123 database has 1093 wells with pressure data;
- For the pressure data types considered in the current project over 8600 QC-ed pressures have been added and enhanced;
- Overall the extension of the database concerns a proportion of 40% of the total number of wells and similar proportions are observed for the number of wells per data type, with the exception of the DST and formation water chemistry data types. For DST this is explained from the fact that DST data has not been completely covered in the current project and for water chemistry data this is explained mainly from the number of relative old onshore wells covered in the database extension;
- Number of data points as listed for PSNS3 extension and as listed for PSNS12 (in Simmelink et al., 2008), when added together, do compare rather well with the number of data points for the PSNS123 database. The small differences observed are due to several corrections for the PSNS12 database, whereas larger differences are observed for the WFT pressure and temperature data points and which are explained by the number of (almost 200) data points in common for 10 wells both part of the PSNS12 database and PSNS3 database extension;
- For each data type the proportion of covered PSNS3 wells compares with the proportion of covered data points, with the exception for mudweights. Here, the PSNS3 wells covered are almost 41%, whereas the proportion of data points covered is below 29%. The main causes for this are that for the PSNS12 database also daily drilling reports were used and that mudweight values were reported for different depths of an interval where mudweights do no change;
- Subdivision over reliability/quality codes for the data points for several data types as listed for PSNS3 extension and as listed for PSNS12 (in Simmelink et al., 2008), when added together, do compare rather well with the subdivisions for the PSNS123 database. The differences observed are due to several corrections for the PSNS12 database.

2.3 Database and pressure information system

The third version of the Pressure SNS database has become available via an MS Access project file, see Appendix-A sections 8.1.1-8.1.3. Via the MS Access environment one is able to specify and perform easily queries on the database. Furthermore, a freeware visualization tool may be linked with the MS Access database in order to plot data against depth. This so-called PressurePlot tool can be downloaded from the website *www.pressureplot.com* and one of the latest versions has been supplied to the project participants in April 2013, see Appendix-A-8.1.1. Examples of displays generated with the PressurePlot tool can be found in section 4.2.5.

Working with the database requires some knowledge of MS Access and when doing so one should be aware that changes to the database are irreversible. Hence, for working with the database some version management may be required, i.e. a read-only copy of the original third version or any enhanced version at some point is recommended. Data from the database may be extracted to Excel, e.g. as to integrate such data with an organization's own pressure database. For such export from the MS Access database to Excel some assistance from an ICT-department may be helpful.

The Pressure SNS database is part of a larger pressure information system and which further consists of two databases in Excel format with the following derived data:

- Pore fluid overpressures and pore water overpressures (re-)calculated for those wells in the MS Access database for which pressure test data of sufficient quality is available.
- Fluid densities, salinities and resistivities determined for the wells in the MS Access database extension and for which wireline formation test (WFT) data of sufficient quality is available.

Background information on the analysis methods for calculation of this data is found in section 3.1, whereas the specific Excel files as delivered for the project are found in Appendix-A-8.2.

The pressure information system further consists of visualizations of the measured and derived pressure data, such as:

- Overpressure distributions in map view for the main reservoir units;
- Three cross sections with pressures and overpressure distribution in relation to geologic and fluid geologic framework;
- Cross plots of pressure and leak-off pressure data in relation to standard stress gradients for the main lithostratigraphic units and structural elements.

These types of displays are discussed in section 3.2 in the chapter on the petroleum-hydrogeological research activities on analysis and visualization, whereas all maps that have been generated and delivered for the project via pdf-files are listed in Appendix-B, sections 9.1-9.3. The overpressure maps have been accompanied by the ArcGIS projects used to compile these maps (see Appendix-B-9.1.3).

In further petroleum-hydrogeological research activities results were obtained for a regional interpretation. These results, found in section 4.2, complete the pressure information system and were developed from coupling pressures, stress field and geological framework via the delivered visualizations with identification of characteristic regional pressure, leak-off pressure and lithostatic pressure trends.

3 Data analysis and visualization

3.1 Data analysis

3.1.1 Calculation of overpressures

The overpressure of a fluid (OP_f) at a certain depth (z) is the difference between the measured pore fluid pressure ($P_f = \rho_f gz$, where ρ_f = density of the pore fluid) and the hydrostatic pressure ($P_w = \rho_w gz$ where ρ_w = density of the pore water) at that depth. In the calculations a standard hydrostatic gradient was used of $\rho_w g$ = 0.010006 MPa/m and that represents seawater density (1020 kg/m^3). The overpressure calculation based on the assumed seawater density can be considered to represent the lower bound of hydrostatic pressure in the Dutch subsurface below depths of a few hundred meters. The fluid overpressure is an overpressure of one of the pore fluids: water, gas, condensate, or oil. The calculation of gas, oil, water or fluid overpressure followed the same procedure as used during the previous PSNS12 projects (Simmelink et al., 2004, 2008):

- For wireline formation test (WFT) measurements, the procedure includes the following steps (Figure 1):
  - Fitting gradient through measured WFT pressures;
  - Calculation density from WFT pressure gradient ($\rho_f g$);
  - Density provides information on fluid types (water, oil, gas, fluid);
  - If only one fluid type is recognized from the pressure gradient, an overpressure value is calculated at the top most data point for that gradient;
  - If the pressure gradient crosses more than one stratigraphic unit, overpressure values are calculated for each unit;
  - If pressure data show a hydrocarbon gradient and a water gradient in the same stratigraphic unit, an overpressure value is calculated for each of the gradients separately.

- For well test measurements, the procedure includes the following steps:
  - Assess fluid type (using reported information);
  - Calculation of fluid pressure at mid-perforation depth from the pressure measured at gauge depth, using an assumed fluid gradient (water gradient ~ 0.01 MPa/m; gas gradient ~ 0.002 MPa/m; oil gradient ~ 0.006 MPa/m);
  - Calculation of overpressure at mid-perforation depth.

A total of 777 newly calculated overpressure values have been added to the updated overpressure database and which Excel database (see Appendix-A-8.2) now contains 2025 overpressure values. The database also includes information associated with the calculated overpressure value, such as the pressure gradient, regression error, fluid density and reliability class. Table 2 shows the number of overpressure values per main stratigraphic unit in the combined PSNS123 Excel database.

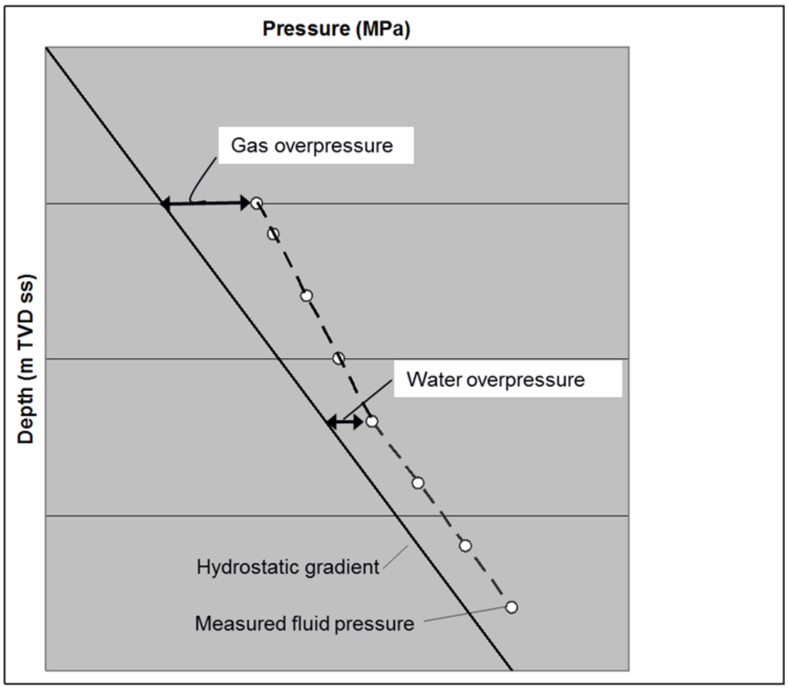


Figure 1: Schematic cross plot of pressure versus depth illustrating the procedure for calculating overpressures from measured WFT data.

	Stratigraphic unit	Number of overpressure values
N	North Sea Supergroup	34
CK	Chalk Group	36
KN	Rijnland Group	139
SG	Scruff Group	28
SL	Schieland Group	163
SK	Niedersachsen Group	2
AT	Altena Group	19
RN	Upper Germanic Trias Group	103
RB	Lower germanic Trias Group	341
ZE	Zechstein Group	169
RO	Upper Rotliegend Group	769
RV	Lower Rotliegend Group	1
DC	Limburg Group	212
CL	Carboniferous Limestone Group	2
CF	Farne Group	5

Table 2: Overview of the distribution of calculated overpressure values per main stratigraphic unit, where two values not covered as to be related to fault.

3.1.2 Lithostatic pressure calculation

The lithostatic pressure (~principal vertical stress S_v) is equivalent to the weight of the overburden (rocks and pore fluids). The magnitude of S_v is equivalent to the integration of bulk densities (of rock and pore fluids) from the surface to the depth of interest, z,

$$S_v = \int_0^z \rho(z) g dz$$

where,

$\rho(z)$ bulk density as a function of depth (kg/m^3),
g acceleration due to gravity (m/s^2).

In the offshore, water depth has to be taken into account as well:

$$S_v = \rho_w g z_w + \int_0^z \rho(z) g dz$$

where,

z_w water depth (m).

The following step-wise approach was used to calculate the lithostatic pressure versus depth at different locations in the Dutch subsurface, both onshore and offshore:
1. Selection of density logs for 25 well locations;
2. Adjustment of density log measurements;
3. Initial calculation of lithostatic pressure versus depth, using the adjusted density log measurements;
4. Adjustment of the lithostatic pressure calculated in step 3, using basin modelling results of bulk density and lithostatic pressure.

3.1.2.1 Step1: Selection of density logs

The lithostatic gradient has been calculated from bulk density measured during drilling of 25 wells as shown in Figure 2. The selection of these wells was based on availability of density logs over a large depth interval, preferably starting at relatively shallow depth, and a good spread of the wells over the area (one well per main structural element). Table 3 shows the depth of the interval for which bulk density measurements were available for each well.

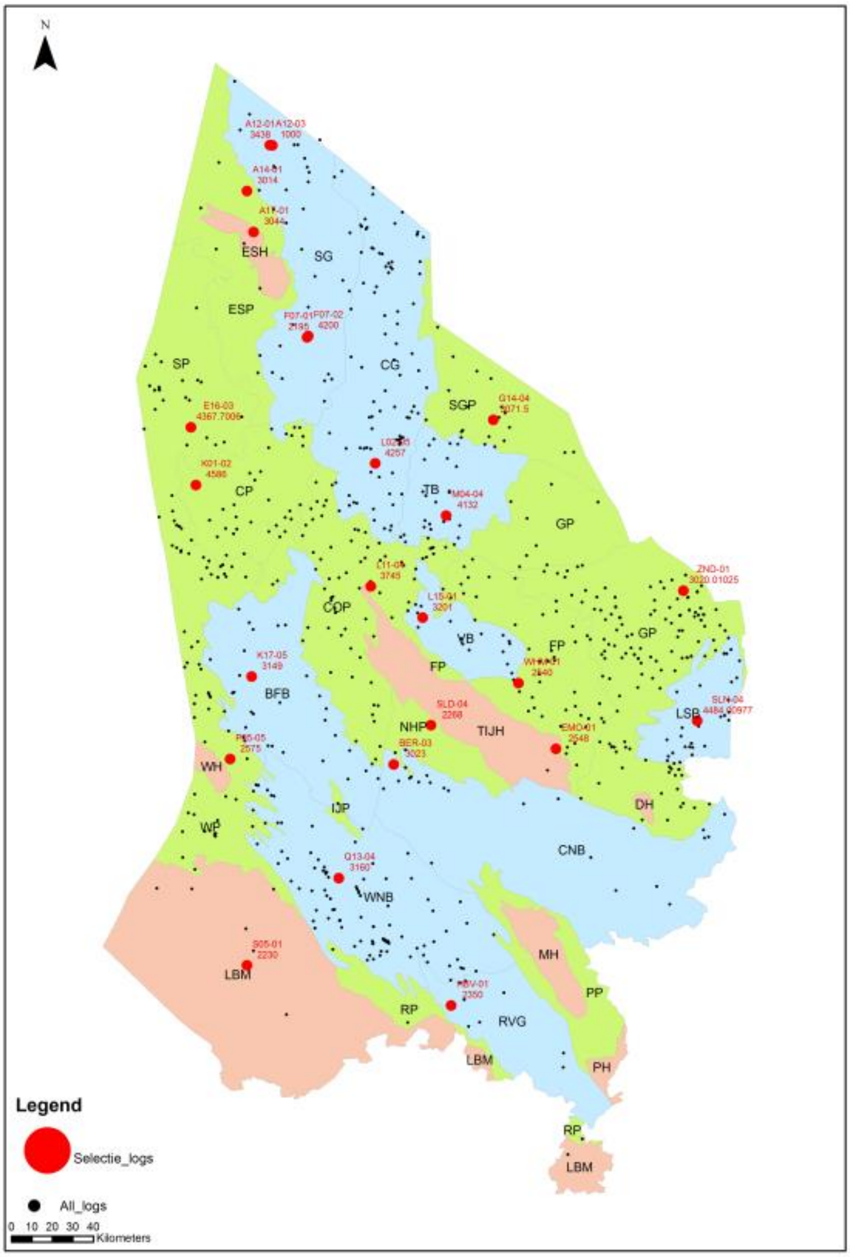


Figure 2: Location of 25 selected wells with density logs (red dots).

UBID	Well Name	Density log Top MD (m)	Density log Bottom MD (m)	Structural Element
7001	A12-01	2000	2832	SG
7825	A12-03	148	969	SG
7003	A14-01	696.2	3014	ESP
7006	A17-01	1385	3039	ESH
7016	B18-02	402	2700	CG
1086	BER-03	1038	3022.9	CNB
7961	E16-03	734	4352	SP
1295	EMO-01	1480	2548	TYH
7046	F07-01	676	2192	SG
8113	F07-02	3210	4157.8	SG
8672	G14-04	2769	3054	SGP
4892	HBV-01	1945	2349.9	RVG
7083	K01-02	454.7	4563	CP
7241	K17-05	448	3149	BFB
7253	L02-05	311.9	4253	CG
7353	L11-04	455	3744	COP
7374	L15-01	508	3197.8	VB
8343	M04-04	2728.5	4145	TB
7552	P05-05	458	2575	WP
7650	Q13-04	575	2949	WNB
7511	S05-01	87.2	2229.9	LBM
2550	SLD-04	1247	2264	NHP
1998	SLN-04	356.5	4483.9	LSB
2515	WHM-01	466	2539.4	FP
2277	ZND-01	277.4	3019.9	GP

Table 3: Depth interval of density logs available for the selected wells.

3.1.2.2 *Step 2: Adjustment density log measurements*

A number of adjustments need to be executed before the density logs can be used to study the bulk densities and to calculate the lithostatic pressures. The following adjustments were carried out:

- Adjustment of the depth scale: Logs are measured along hole (MDRT) and depth was converted from along hole depth to TVD from top of sediments (SWI offshore and ground surface onshore);
- Bulk density measurements are assumed to be inaccurate where DRHO (density log correction curve) is greater than 0.025 g/cm^3 or smaller than -0.025 g/cm^3. The inaccurate density measurements were removed;
- Presence of gas or other factors affecting the bulk density of the overburden locally. These were not removed initially.

3.1.2.3 Step 3: Calculation bulk density versus depth

Density log data were sampled every meter and average bulk density calculated for that depth, using the measured values of the 1 meter depth interval above the sampled point.

3.1.2.4 Step 4: Initial calculation of lithostatic pressure versus depth

The lithostatic pressure was calculated at each well, using the bulk densities from step 3 and equation:

$$S_v = \int_0^z \rho(z) g dz \; .$$

3.1.2.5 Step 5: Adjustment of the lithostatic pressures calculated in Step 4, using basin modeling

In Table 3 it is shown that the density logs start at different depths below the surface (below ground surface in the onshore and below the seabed offshore). Hence, for most of the well locations no lithostatic pressure could be calculated from the density logs for shallow depth intervals. Initial calculations of the lithostatic pressure for the available density log intervals are based on the assumption that the bulk density derived from the top of the density log is also representative for the bulk density of the overburden for the sediments overlying the top of the density log. In general the bulk density is relatively low at shallower depth because of relatively high porosities in recently deposited sediments. If so, the calculated lithostatic pressure at the top of the measured density log will overestimate the lithostatic pressure.

Well name	Top (mTVD from top sediments)	Basin modeling results
A12-01	2005	
A12-03	74	
A14-01	636	
A17-01	1359	
B18-02	366	
BER-03	220	available
E16-03	664	available
EMO-01	1480	available
F07-01	677	
F07-02	3210	
G14-04	3028	available
HBV-01	1840	available
K01-02	395	available
K17-05	397	available
L02-05	312	available
L11-04	456	available
L15-01	457	
M04-04	2652	available
P05-05	387	
Q13-04	517	available
S05-01	30	
SLD-04	1243	available
SLN-04	305	
WHM-01	478	available
ZND-03	264	available

Table 4: Well locations with basin modelling results of depth-dependent bulk density and lithostatic pressures.

Three approaches can be used in order to extend the lithostatic pressure to the surface of the sediments and to correct the lithostatic pressure derived from the density logs:

- Basin modeling: TNO's 3D basin models for the onshore and offshore provided an opportunity to extract simulated present-day bulk density and lithostatic pressure at 14 well locations (Table 4). These simulation results were used to create a lithostatic pressure versus depth plot from the surface downward at those well locations;
- Combination of log results for nearby wells (this was possible for A12-01 & A12-03 and F07-01 & F07-02);
- Calculation of bulk density at different depths based on knowledge on the lithological composition and porosity of the shallow subsurface, but which has not been applied in this project.

From Table 4 it is observed that density log measurements are available for K01-02 over a large depth interval from relatively shallow depth (395 mTVDss) downward. Figure 3 shows the nice agreement of the lithostatic pressure derived from density log measurements and the lithostatic pressures resulting from basin modeling at this well location, until depth of approximately 3000 m corresponding to the top of the Zechstein.

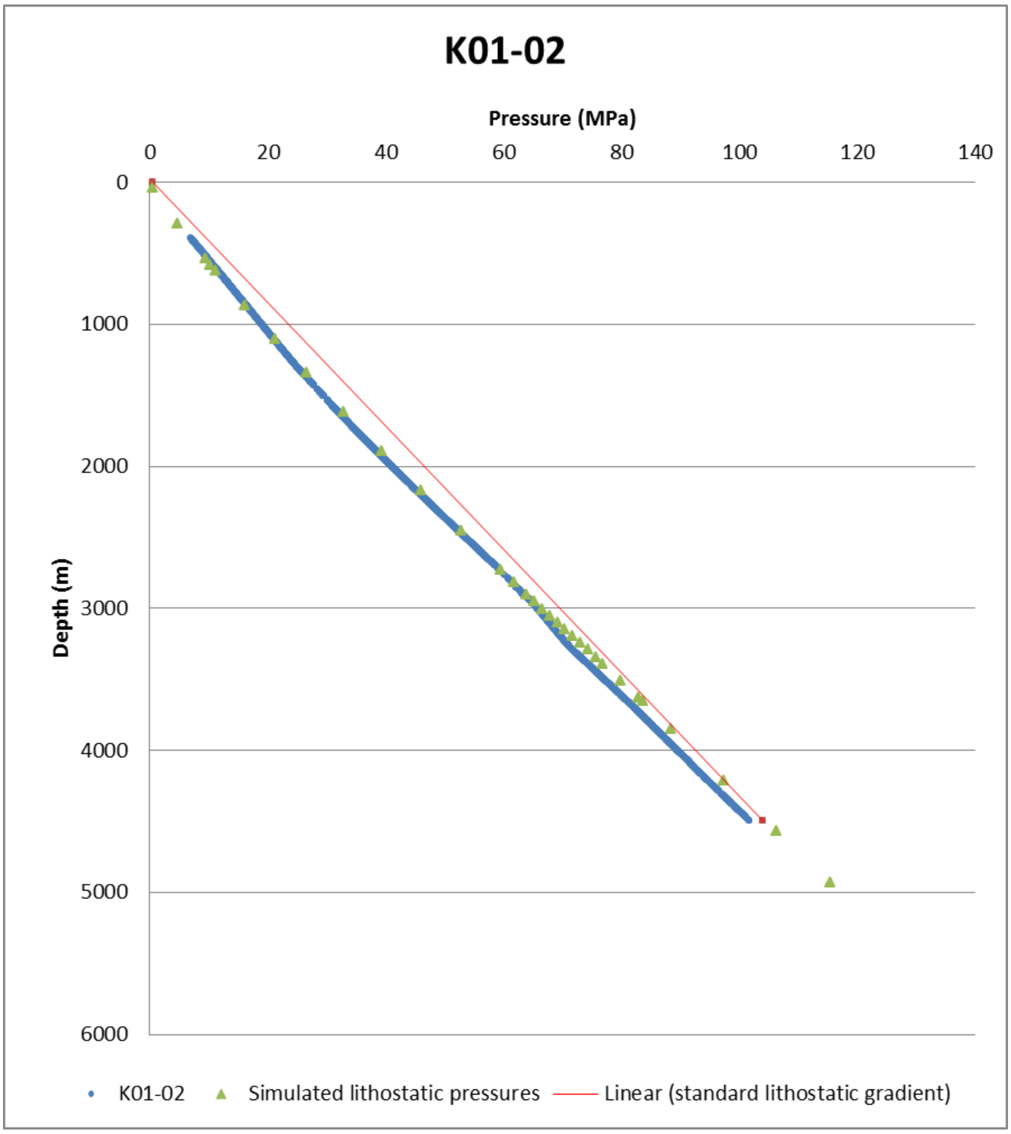


Figure 3: Cross plot showing calculated lithostatic pressure (blue), simulated lithostatic pressure (green) and a standard lithostatic gradient (red) of 23 MPa/km at well K01-02.

Well M04-04 is presented here as a case study example to illustrate the approach to use basin modeling results to derive a lithostatic pressure versus depth relation from SWI downward. Figure 4 shows a comparison between:

- Lithostatic pressures for a standard lithostatic gradient of 23 MPa/km and a pressure at the sediment water interface of 0.339 MPa (calculated for the water depth of 33.9 m at M04-04);
- Initial calculations of lithostatic pressure versus depth based on density log measurements;
- Extraction of 3D Basin modeling simulation of lithostatic pressure versus depth.

The initial lithostatic pressures calculated from the density logs are larger than the simulated pressures. At the top of the density log interval (depth = 2652 m), the log-derived bulk density = 2.466 kg/m^3 and the calculated lithostatic pressure = 64.16 MPa. At the same depth, the simulated bulk density = 2.515 kg/m^3 (varies between 2.478 and 2.529 kg/m^3 in depth interval 2559-2774 m) and the simulated lithostatic pressure = 58.81 MPa. The basin modeling takes the changes in lithology and porosity into account for the depth interval: 0 – 2652 m.

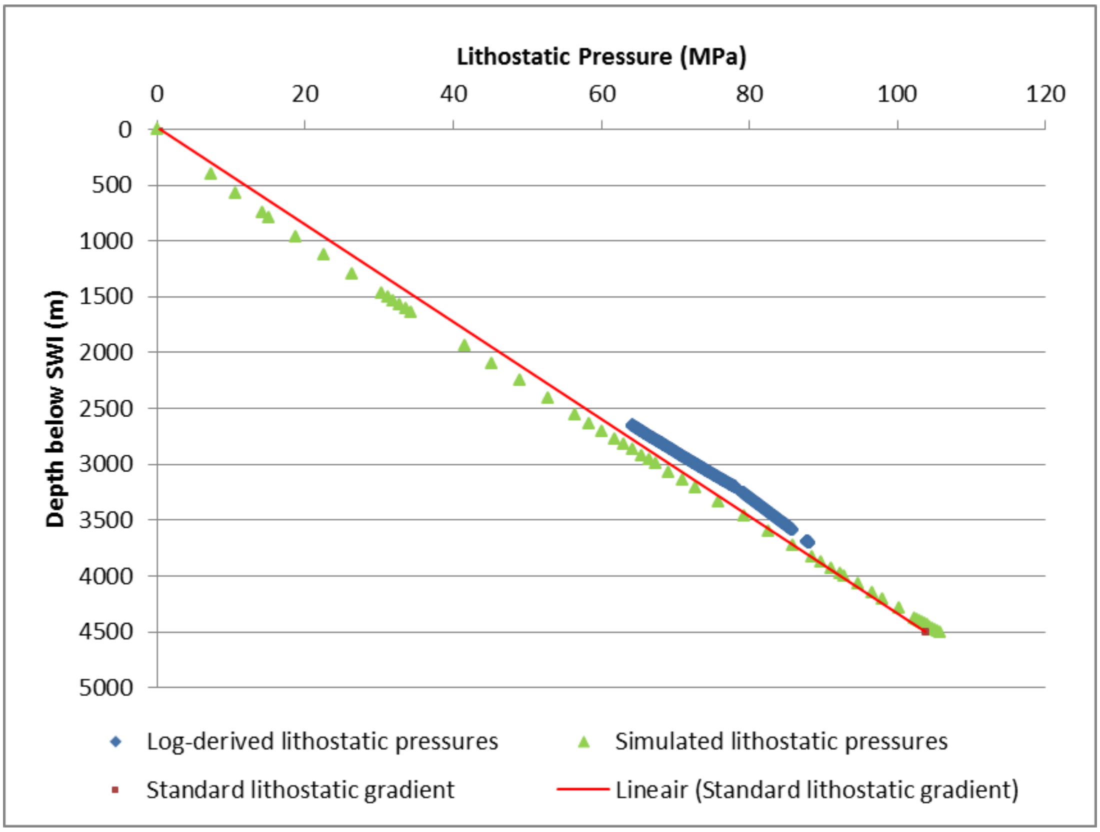


Figure 4: Cross plot showing calculated lithostatic pressure (blue), simulated lithostatic pressure (green) and a standard lithostatic gradient (red) of 23 MPa/km at well M04-04.

The recalculation procedure of the log-based lithostatic pressure versus depth involves the following steps:

1. The simulated bulk densities resulting from the basin modeling at well M04-04 are used for the depth interval 0 – 2652 m;
2. The lithostatic pressures derived from density log from 2652 m to 3706 m are recalculated by integration of the simulated densities from the basin modeling for the first 2652 m.

Finally, the simulated lithostatic pressures and the recalculated lithostatic pressures are combined and the final result is shown in Figure 5.

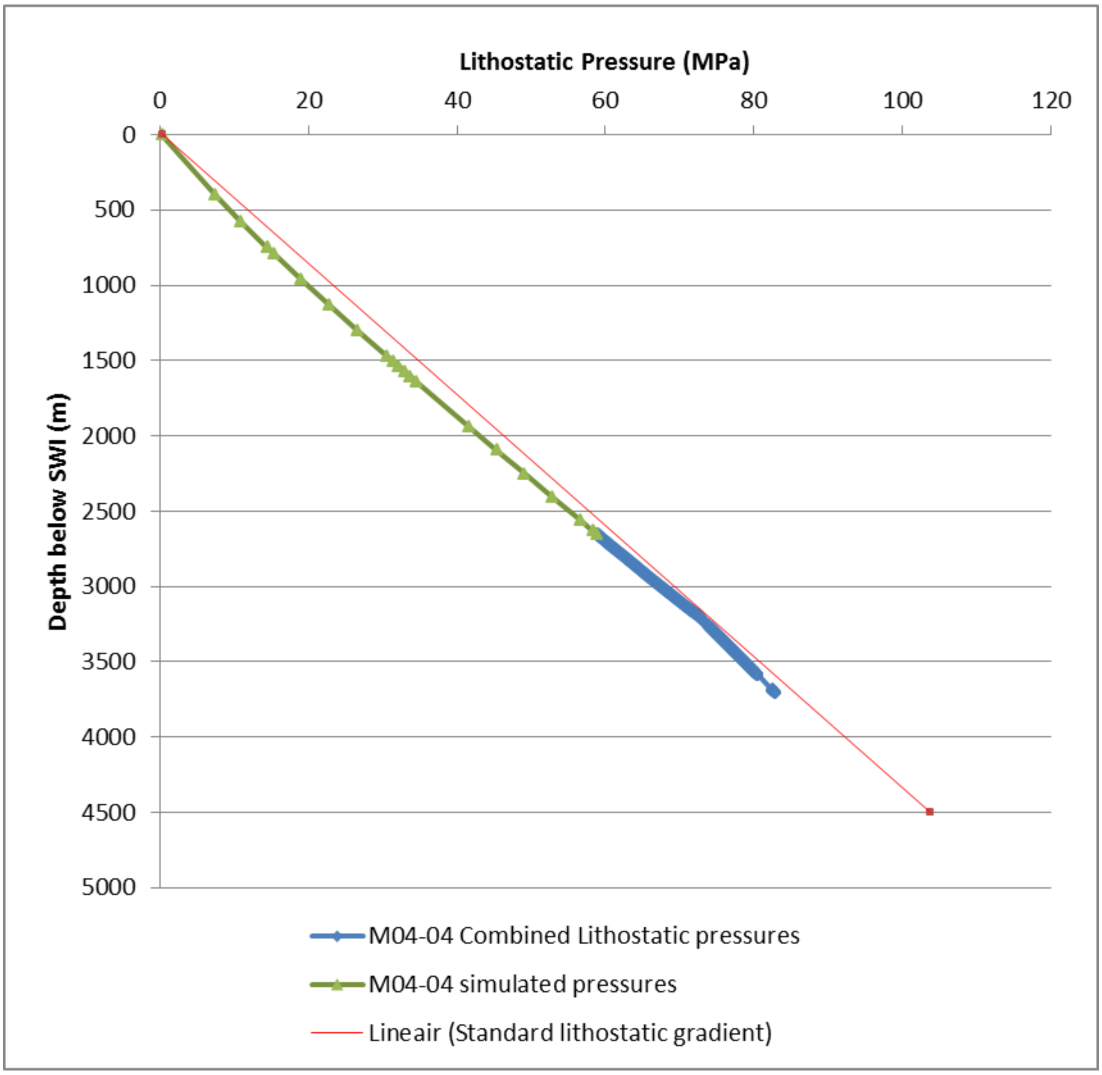


Figure 5: Cross plot of lithostatic pressure versus depth at well M04-04, combining lithostatic pressures resulting from basin modeling (0-2652 m) and adjusted log-derived lithostatic pressures.

3.1.3 *Calculation of salinity and water resistivity (Rw)*

3.1.3.1 *Approach for water salinity*

The gradients derived for the measured WFT pressures (ρg) provided information on the fluid type. The static gradients related to formation water are used to calculate the water density. These water densities are used to estimate water salinity using an in-house approach based on equations published by Batzle & Wang, 1992. These equations relate water density, pressure and temperature as is shown in Figure 6 and which demonstrates that the temperature exert an important influence on the salinity calculations.

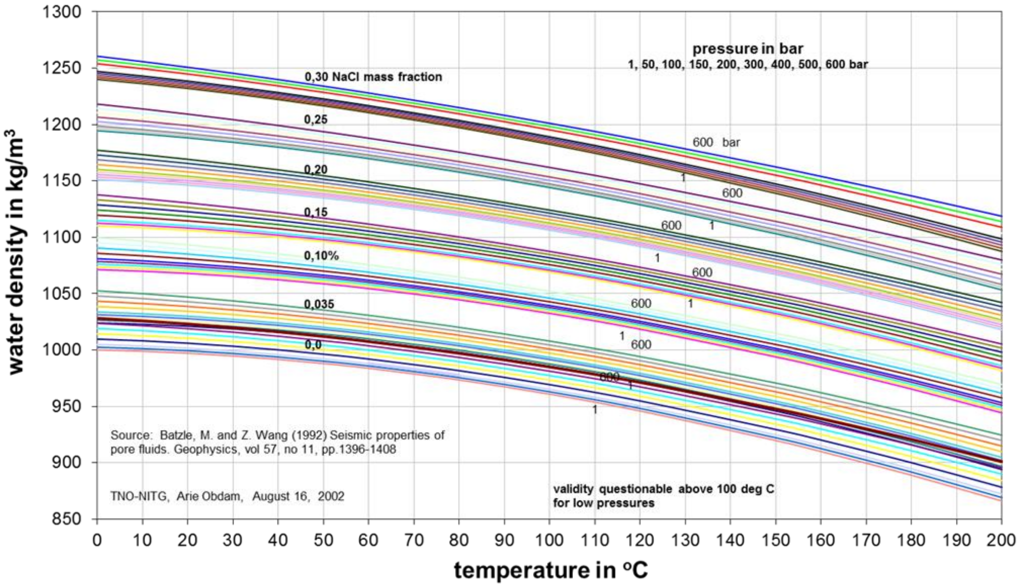


Figure 6: Salinity (as NaCl mass fraction) as a function of water density, temperature and pressure.

The temperature at the depth of interest was estimated using calculated thermal gradients derived from the temperature measurements in the database. Different sources of measured temperatures were used to estimate the temperature at the requested depth (mostly BHT, BHTx and DST). Available temperature measurements were extrapolated to a temperature value at the requested depth. The extrapolation involved the use of a geothermal gradient and a constant surface temperature of 10 °C. Due to the large variety in quality of the measured temperature data, the gradient per individual well was primarily based on the highest quality data available. In case a single data point showed a large deviation from the whole data suite for the same well, or the whole data suite covered a larger depth interval, multiple temperature measurements were taken into account. When temperature measurements were not available for a certain well, temperature measurements were used from nearby wells. In this way 273 salinities (NaCl equivalent in ppm) were calculated and stored in an Excel database (see Appendix-A-8.2). These calculated formation water salinities should be regarded as estimates for the real salinities. The largest uncertainty in the values obtained is due to the uncertainty in the temperatures used in the calculations.

3.1.3.2 Approach for water resistivity (Rw)

Water resistivity was calculated from a published power law salinity-Rw relation derived from measured water sample salinity and Rw data from the Pressure SNS12 database (Simmelink et al., 2008):

Rw = 165.1*salinity$^{-0.6342}$ (salinity in ppm; Rw in Ohmm at 60 °F).

Note that in the previous two projects on the Pressure SNS database the term salinity has been used synonymously with Total Dissolved Solids (TDS) and values reported in ppm were assumed equivalent to mg/l. In reality salinity in mg/l overestimates an equivalent value in ppm. For this project salinity values are reported in ppm.

Appendix-A-8.2 presents the Excel database of 273 water salinity and water resistivity values in combination with associated information on pressure gradient, density, pressure, and temperature.

3.2 Visualization of pressure data

The pressure data from the integrated PSNS123 database have been visualized in multi-well and single well cross plots and on maps and cross sections to show the fluid pressure, leak-off pressure and lithostatic pressure distributions in relation with stratigraphic and structural information of the Dutch subsurface. The visualized fluid pressure data in multi-well cross plots, maps and cross sections concern those “all fluid” (i.e. water, gas, oil, condensates) pressures for which fluid overpressures have been calculated. These plots, maps and cross sections were used to characterize and interpret the observed pressure distributions as described in chapter 4.

3.2.1 Visualization on maps

All fluid pressures and formation water pressures were displayed on maps for which depth maps of the main stratigraphic units, recently compiled maps of reservoir units and permeability maps of reservoir units were used. A distinction was made between reliable & most reliable pressure data and the not reliable data by using a different symbol on the maps. These maps have become available in pdf format (see Appendix-B- 9.1.1 and 9.1.2) whereas the associated ArcGIS projects have also been supplied (see Appendix-B-9.1.3)

The spatial distributions of all fluid pressures are displayed on 20 depth maps of the base of the main stratigraphic units

- North Sea Supergroup (N),
- Chalk Group (CK),
- Rijnland Group (KN),
- Schieland/Scruff/Niedersachsen Group (S),
- Altena Group (AT),
- Upper Germanic Trias Group (RN),
- Lower Germanic Trias Group (RB),
- Zechstein Group (ZE),
- Limburg Group (DC),

and of the following reservoir maps for the stratigraphic units:

- Friesland/Kotter Member (KNNSF_KNNSK),
- Rijswijk/De Lier Member (KNNSR_KNNSL),
- Lower Detfurth Sandstone Member (RBMDL),
- Lower Volpriehausen Sandstone Member (RBMVL),
- Röt Fringe Sandstone Member (RNROF),
- Basal Solling Sandstone Member (RNSOB),
- Lower Slochteren Member (ROSLL),
- Upper Slochteren Member/Slochteren Formation (ROSLU_ROSL),
- Scruff Greensand Formation/Scruff Spiculite Member (SGGS_SGGSP),
- Terschelling Sandstone Member / Scruff Basal Sandstone Member (SLCFT_SGGSB),
- Lower Graben Formation (SLCL).

In addition a selection of all fluid pressure data are displayed on 8 permeability maps for the stratigraphic units KNNSF_KNNSK, KNNSR_KNNSL, RBMDL, RBMVL, RNROF, RNSOB, ROSLL and ROSLU_ROSL.

Furthermore, formation water pressures are shown on 13 maps for the stratigraphic units CK, KN, S, AT, RB, RN, ZE, DC, RBMDL, RBMVL, ROSLL, ROSLU_ROSL and SLCL.

3.2.2 Visualization in cross sections

The regional variation in overpressures have been displayed along 2 offshore and one onshore cross section and which displays have become available in pdf format, see Appendix-B-9.2.

3.2.3 Visualization in cross plots

The cross plots of pore fluid pressure and leak-off pressure versus depth show the pressures in relation to a standard hydrostatic gradient (10.006 MPa/km) and standard lithostatic gradient (23 MPa/km). Pore fluid pressures and leak-off pressures are shown in relation to the main structural elements (shown in Figure 7) and the same main stratigraphic units as listed in section 3.2.1, with in addition:

- Upper Rotliegend Group (RO),
- and sometimes (when pressure data was available for these units) also in:
  - Lower Rotliegend Group (RV),
  - Carboniferous Limestone Group (CL),
  - Farne Group (CF).

The following multi-well cross plots were constructed and became available in pdf format:

- 1 cross plot of all leak-off pressures versus depth for the main stratigraphic units and 10 cross plots of leak-off pressure versus depth per main stratigraphic unit, see Appendix-B-9.3.1
- 20 cross plots of leak-off pressure versus depth for the main stratigraphic units and for the structural elements, see Appendix-B-9.3.2
- 1 cross plot showing all fluid pressures versus depth for the main stratigraphic units and 10 cross plots of fluid pressure versus depth per main stratigraphic unit, see Appendix-B-9.3.3
- 1 cross plot showing all fluid pressures versus depth for the main stratigraphic units in combination with leak-off pressures and 20 cross plots of fluid pressure versus depth for the main stratigraphic units and for the structural elements in combination with leak-off pressures, see Appendix-B-9.3.4

Please note that the pore fluid pressures that are associated with calculated negative values of overpressures are not included in the cross plots. Negative overpressures are available, however, on the maps discussed in section 3.2.1.

In addition cross plots of bulk density versus depth and lithostatic pressure versus depth were created for selected 25 well locations (cross plots only used for project and not made available to project participants).

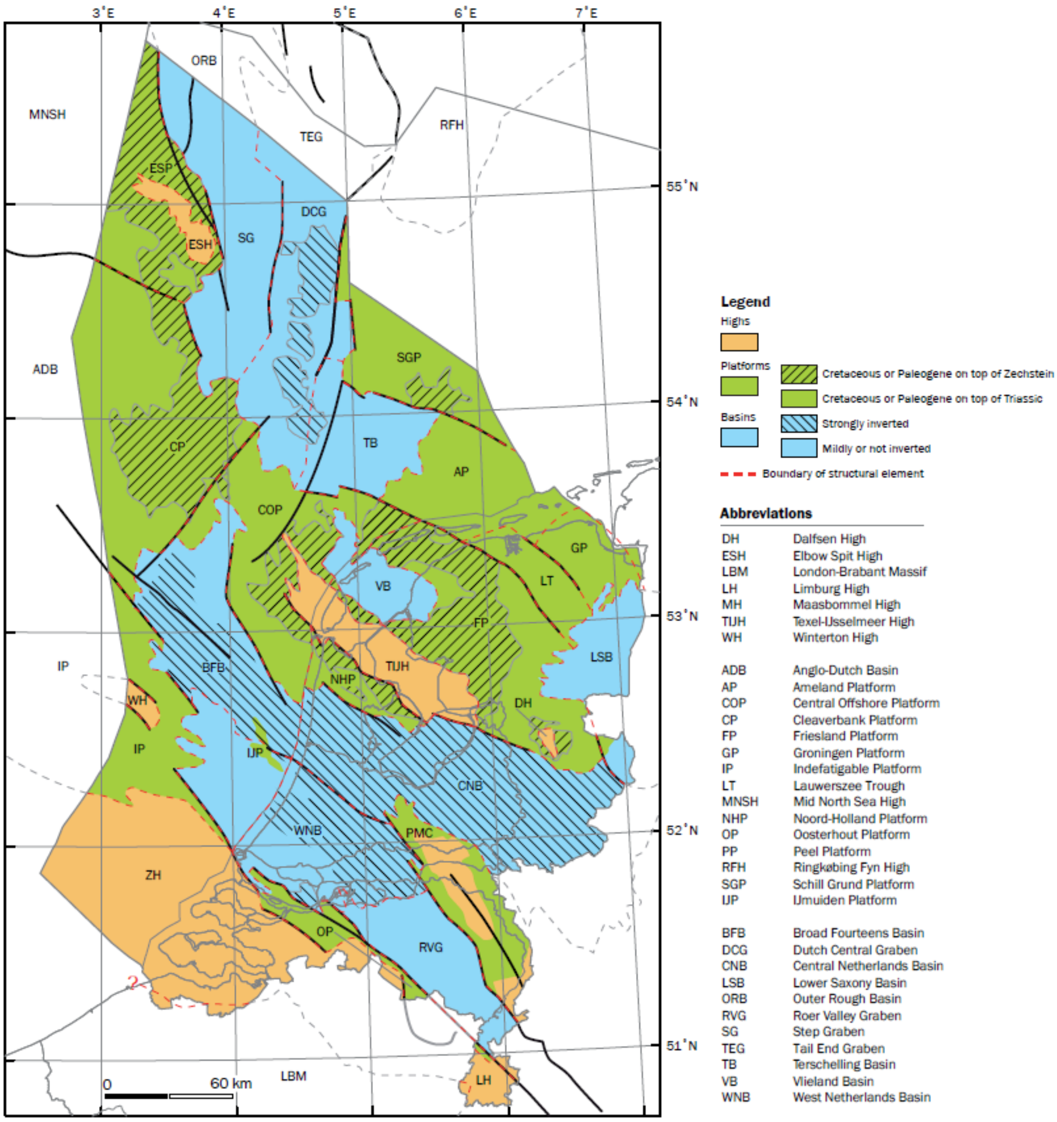


Figure 7: Late Jurassic-Early Cretaceous structural elements of the Netherlands (from Krombrink et al., 2012).

4 Pressure characterization and interpretation

4.1 Introduction

The overpressure of a fluid at a certain depth is the difference between the measured pore fluid pressure and the hydrostatic pressure at that depth. In the calculations a hydrostatic gradient derived for seawater density has been used. In reality, the hydrostatic gradient is determined by the actual density of the formation water which is related to its salinity. The salinity data in the database show that salinity of most of the formation water in the Dutch subsurface is well above that of seawater and also show large variations in salinity in all stratigraphic units (see also Verweij, 2003; Verweij et al., 2011a). Fluid overpressures may also incorporate the effect of the density contrast between a petroleum fluid and pore water. Hence fluid overpressures may reflect:

1. pore water salinity,
2. the density contrast between a petroleum fluid and pore water (if the pressure was measured in a petroleum fluid), as well as
3. geological causes of overpressuring.

A fluid overpressure is an overpressure of one of the pore fluids: Water, gas, condensate, or oil. A pore water overpressure or formation water overpressure concerns the overpressure of the pore fluid ‘water’.

The geological causes of current pore pressure conditions are controlled by the combined influence of past and/or ongoing pressure influencing mechanisms and hydraulic characteristics of the lithostratigraphic build-up and structural framework. Mechanisms that may increase pore pressures include (Verweij et al., 2012 and references therein):

1. An increase in compressive stress, by processes such as sedimentary loading, vertical or lateral tectonic loading and glacial loading;
2. An increase in fluid volume, induced by processes such as temperature increase (aquathermal pressuring), production of water by diagenetic and metamorphic processes (for example mineral dehydration), and hydrocarbon generation (gas generation from late stage source rock maturation and from oil cracking);
3. Fluid movement and associated redistribution of overpressures.

Sedimentary loading, gas generation and pressure transfer by fluid movement are important mechanisms operating in the Dutch subsurface.

4.1.1 Geological and hydrogeological setting

Geological characteristics and past and present geological processes of different duration have influenced present-day pressure and fluid flow conditions to a greater or lesser extent. Detailed information on the geology of the Netherlands is given elsewhere and is not described here (Van Adrichem Boogaert and Kouwe, 1993; TNO-NITG, 2004; Duin et al., 2006, Wong et al., 2007; Doornenbal & Stevenson, 2010; Kombrink et al., 2012).

A summary of important features concerning the geological and hydrogeological setting of influence on present-day pressure and fluid flow conditions, taken from Verweij et al. (2012), is given below.

4.1.1.1 Lithostratigraphic build-up

The position of the Netherlands at the southern edge of large basins during the majority of its post-Carboniferous geological history has directly affected the facies distribution of the deposited sediments. Generally, more coarse-grained clastic sediments occur in the south. Clear differences in facies between the south and the north are apparent in, for example, the Upper Rotliegend Group (sandstones of the Slochteren Formation in the south and mudstones and evaporites of the Silverpit Formation in the north), Zechstein Group (clastics in the south versus evaporites in the north), Upper Germanic Trias Group (salts absent in the south), Rijnland Group (sandstones concentrated in southern half of the area), Lower North Sea Group (sandy in southern onshore).

Stratigraphic groups of large areal extent are (see displays in Appendix-B-9.1 and 9.2): Limburg, Upper Rotliegend, Zechstein, Rijnland and Chalk groups, and the Lower and Upper North Sea groups. The presence of the Germanic Trias and Jurassic Altena groups is more scattered. The largest thickness of these groups occurs in the Mesozoic basins, while in the remaining area the groups are missing entirely or partly due to erosion. The current distribution of the Upper Jurassic Schieland, Scruff and Niedersachsen groups is restricted to the Mesozoic basins.

4.1.1.2 Hydrogeological setting

An extensive overview of the characteristic features of external and internal processes acting on the sedimentary fill of onshore and offshore Netherlands and their role in shaping the hydrogeological setting of the Netherlands from Late Carboniferous to present-day is given in Verweij (1999, 2003), Verweij & Simmelink (2002) and Verweij et al. (2012).

The most important lithostratigraphic units controlling formation water pressure distributions and flow conditions in the Dutch subsurface are the Salt Members of the Zechstein Group, because of their extremely low permeability and their large regional continuity (Appendix-B-9.1 and 9.2). An also important role is played by the evaporite members of the Upper Germanic Trias Group (such as those of the Röt and Keuper formations) and the Silverpit Evaporite Member of the Upper Rotliegend Group in the northern offshore. The Zechstein and Silverpit evaporites are absent in the southern part of onshore and offshore Netherlands. Here clay-rich deposits of low matrix permeability dominate the entire stratigraphic sequence. Mudstones of the Lower North Sea Group are present across the entire offshore with decreasing thickness from north (> 900 m in offshore A block) to south (to less than 100 m in the center of the West Netherlands Basin). Moreover, the Lower North Sea Group sediments become increasingly sandy in the south.

The more permeable stratigraphic units consist of sands, sandstones and carbonates. The main permeable units forming reservoirs (aquifers) are:

- Sandstone members of the Limburg Group and Slochteren Formation of the Upper Rotliegend Group;
- Carbonate members of the Zechstein Group,
- Sandstone members of the Lower Germanic Trias Group;
- Solling Formation of the Upper Germanic Trias Group;
- Sandstone members of the Schieland, Scruff and Niedersachsen groups;
- Vlieland Sandstone Formation of the Rijnland Group;
- Tertiary sands (in southern onshore) and Quaternary sands of the Upper North Sea Group.

The permeability of the Chalk Group varies and both reservoirs and seals (aquitards) occur (Verweij, 2006).

Regional facies distributions over the onshore and offshore Netherlands result generally in more permeable facies in the south and an increasing number of interspersed sealing layers towards the northern part of the study area. This provided vertical barriers to flow and pressure dissipation to a greater degree in the north. In addition, numerous deep faults and elongated salt structures disrupt the lateral hydraulic continuity of pre-Cenozoic fluid-stratigraphic units (see regional cross sections in Appendix-B-9.2). Large elongated low permeability salt structures related to basin boundary faults occur especially along the Step Graben, Dutch Central Graben, Terschelling Basin, northeastern edge of the Broad Fourteens Basin and Lauwerszee Trough.

The dominant features of the permeability framework thus lead to a regional subdivision of the Netherlands onshore and offshore into a more fault-dominated southern and a salt-dominated northern area that define distinct hydraulic characteristics.

4.1.1.3 Regional differences in geological and hydrogeological factors of influence on pressure and fluid flow conditions

The variation in burial history is a potential geological factor of influence on present-day overpressure distributions. There are important regional differences in burial history (Figure 8, Figure 9 and Figure 10).

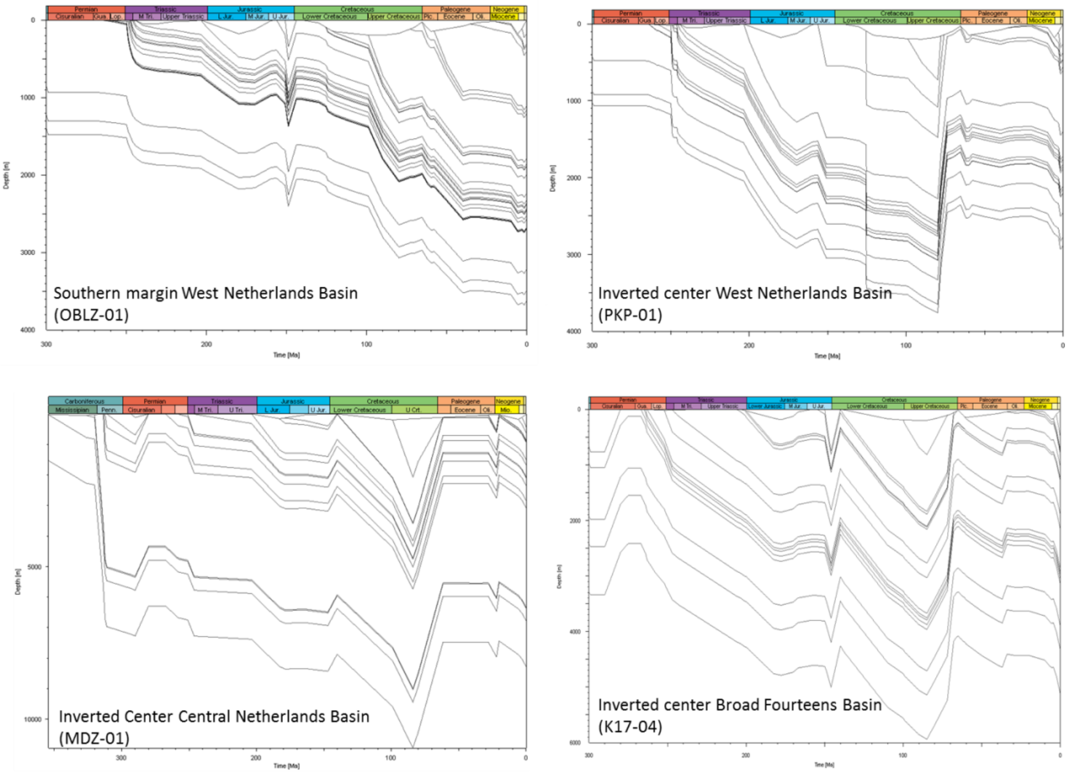


Figure 8: 1D extractions of 3D burial history modelling at different locations in the onshore West Netherlands and Central Netherlands basins and the offshore Broad Fourteens Basin.

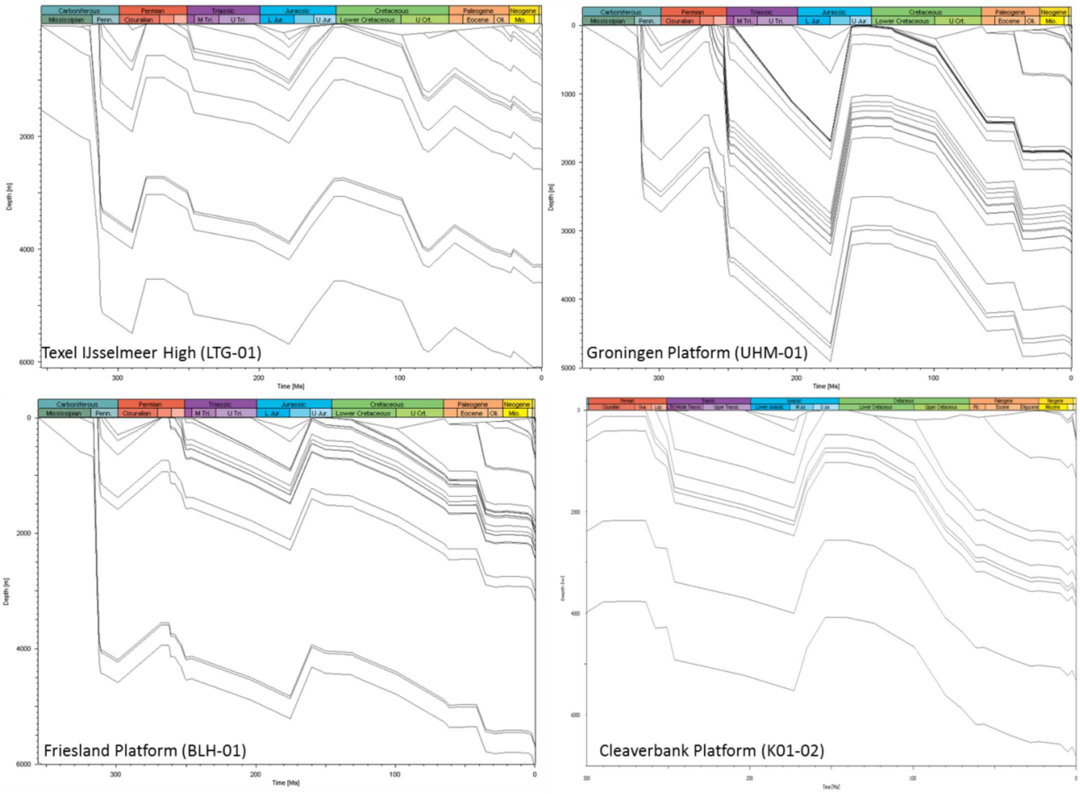


Figure 9: 1D extractions of 3D burial history modelling at different locations in Texel IJsselmeer High, Groningen, Friesland and Cleaverbank platforms.

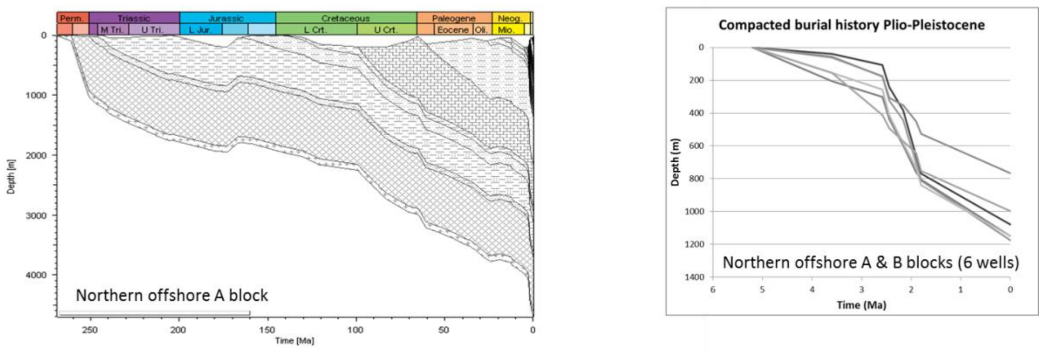


Figure 10: Burial history for the northernmost offshore showing rapid subsidence since Pliocene times.

Regional differences in burial history for the history since Late Cretaceous include: Concentration of Late Cretaceous and Early Paleogene uplift and erosion in the south (including West Netherlands, Broad Fourteens, Central Netherlands, Lower Saxony basins, Roer Valley Graben) followed by an overall northward increase in basin subsidence and associated depositional thickness of Paleogene and Neogene sediments (Figure 11). A thick package of North Sea Supergroup sediments was deposited in the northernmost offshore, reaching thicknesses of more than 2 km. Greater sedimentary thickness corresponds to areas of greater sedimentary loading rates. The thickness of the Upper North Sea Group, especially the Pleistocene to Recent part, increases northwards as well, with a local depocenter in the Roer Valley Graben. In the northernmost offshore very high sedimentation rates of over 1000 m/My were reached in the Early Pleistocene, while sedimentation rates remained high (> 200 m/My) since then. In the Pleistocene, thick Elsterian and Saalian ice sheets covered the northern on- and offshore during their maximum advance in the Pleistocene.

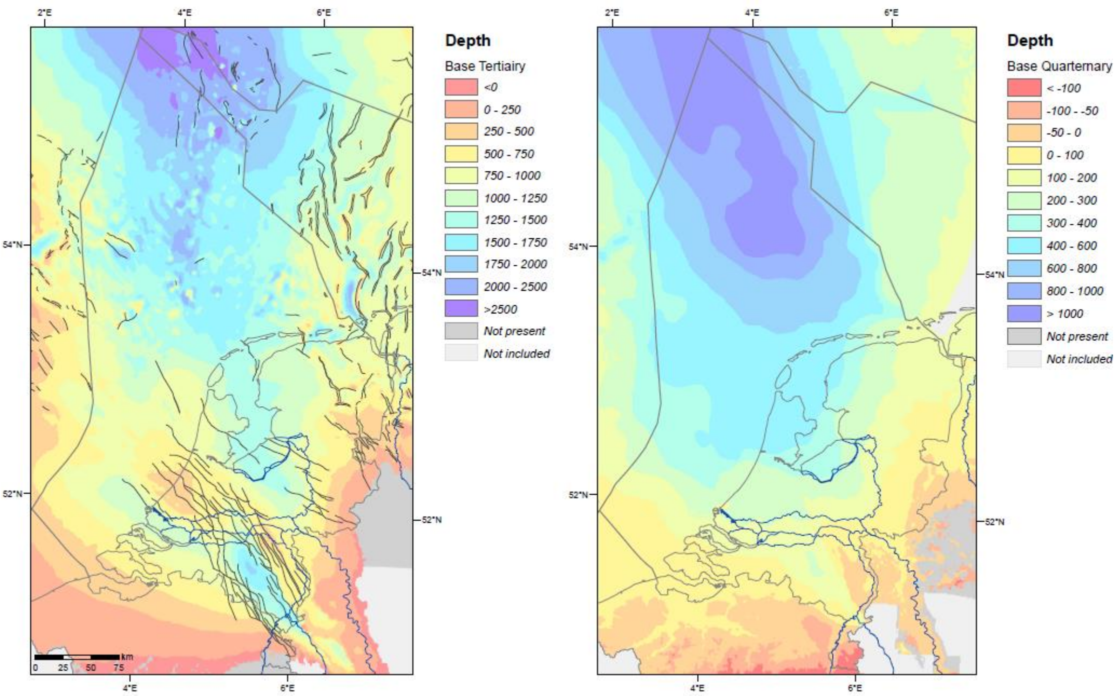


Figure 11: Depth to near base of the clastic Cenozoic sediments (on the left) and depth to the base of the Pleistocene to recent sediments (from Verweij et al., 2012, after Knox et al., 2010).

The observed regional differences in the permeability framework in combination with those of the burial history lead to a regional subdivision of the Netherlands on- and offshore into a southern and northern area with distinct differences in characteristics important for pressure generation and dissipation.

4.2 Spatial variation in pressures

4.2.1 Spatial variation in leak-off pressures

The leak-off pressure data in the database are all reported values. Most of the data were derived from end of well/final well reports or weekly drilling reports. The reported values are from leak-off tests and formation integrity test. Here the term 'leak-off pressure' is used for measurements from both types of test. The characterization of the spatial variation in leak-off pressures given below includes measurements of both types of test and no distinction is made between these test data.

The amount of leak-off pressure measurements are unevenly distributed over the different stratigraphic groups, see Table 5 for the measurements as used for all cross plots. Most measurements are available for the youngest unit (North Sea Supergroup) and the least number of measurements are available for the oldest unit (Limburg Group).

Stratigraphic Group	Number of Leak-off pressure measurements
North Sea Supergroup	373
Chalk Group	291
Rijnland Group	164
Scruff/Schieland Group	38
Altena Group	41
Upper Germanic Trias group	127
Lower Germanic Trias Group	58
Zechstein Group	233
Upper Rotliegend Group	34
Limburg Group	15

Table 5: Number of leak-off pressure measurements per main stratigraphic unit as used in cross plots.

Figure 12 presents a cross plot showing all leak-off pressures versus depth. The leak-off pressures are shown in relation to the standard hydrostatic gradient, standard lithostatic gradient and standard minimum horizontal stress gradient (minimum horizontal stress S_{hmin} = 0.6 x vertical lithostatic stress). Figure 12 shows that

1. there is a large variation of reported leak-off pressures at the same depth of measurement;
2. the lower bound of the leak-off pressures follows the standard minimum horizontal stress gradient to depths of approximately 3500 m and starts to deviate for greater depths.

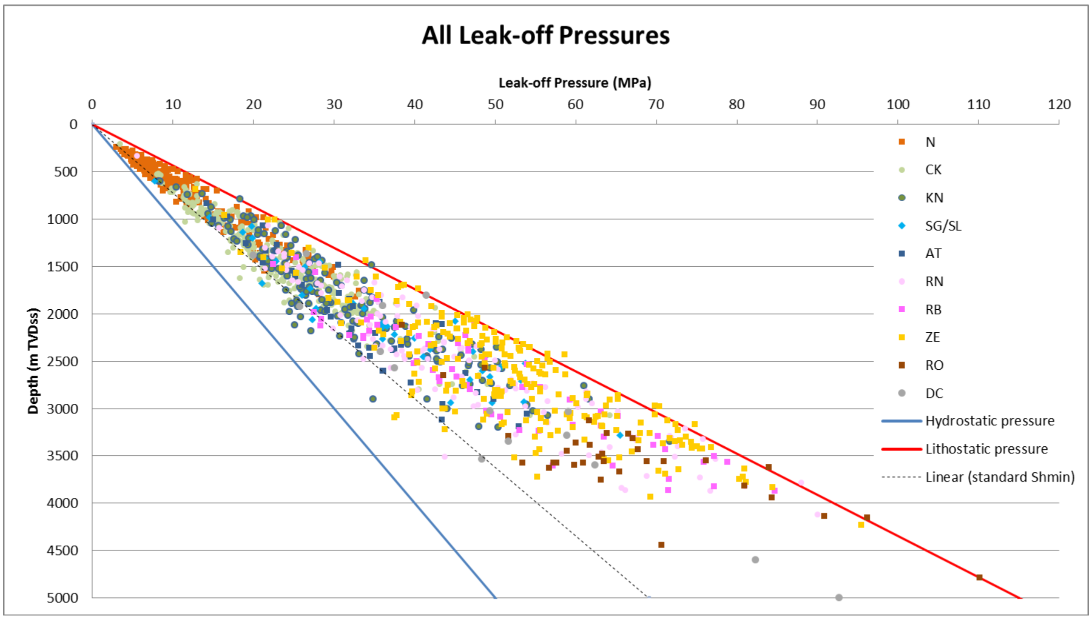


Figure 12: Cross plot of all leak-off pressures versus depth for the main stratigraphic units.

Two types of multi-well cross plots provide a more detailed illustration of the spatial variation of leak-off pressure in the Dutch subsurface:

1. Cross plots of leak-off pressure versus depth for the main stratigraphic units (Appendix-B-9.3.1);
2. Cross plots of leak-off pressure versus depth for the main structural elements in combination with the main stratigraphic units (Appendix-B-9.3.2).

The variation in leak-off pressures (LOPs) for the main stratigraphic units (Appendix-B-9.3.1) shows the following characteristics:

- North Sea Supergroup (clastics):
  - the lower bound of LOPs < standard S_{hmin} at very shallow depths (< 800 m);
  - variation in LOPs at same depth of measurement that range from less than standard S_{hmin} to close to standard lithostatic pressure at very shallow depths of < about 800 m;
  - LOPs do not reach lithostatic pressures at depths > 1000 m.

- Chalk and Rijnland groups (chalk and clastics plus marls, respectively):
  - the lower bound of LOPs largely follows the standard S_{hmin} gradient;

- Scruff/Schieland and Altena groups:
  - the lower bound of LOPs in the clastic Altena Group follows the standard S_{hmin} gradient;
  - the LOPs in the clastic Scruff/Schieland groups provide less clear characteristics.

- Upper and Lower Germanic Trias groups: In contrast to the clastic Lower Germanic Trias Group, the Upper Germanic Trias Group includes widely varying lithologies, such as salt, limestone-dolomite-marl, and claystones. Both units show similar general trends:
  - the lower bound of LOPs deviates from standard S_{hmin} gradient for greater depth;
  - large variation in LOPs at same depth of measurement;
  - highest LOP values reach standard lithostatic pressure.

- Zechstein Group:
  - most of the LOPs were measured in the salt and anhydrite members of the Zechstein Group;
  - the lower bound of LOPs follows the standard S_{hmin} gradient;
  - large variation in LOPs at same depth of measurement (from standard S_{hmin} to standard lithostatic pressure).

- Upper Rotliegend Group:
  - the limited number of data are all from the Silverpit Formation;
  - the data do not show a clear lower bound of LOPs;
  - large variation in LOPs at depths around 3500 m, while all but one (L05-06) of the deepest measured LOPs reach standard lithostatic pressure; the relatively low LOP value at L05-06 is measured in the Silverpit Formation below a large salt structure of 3.8 km thickness;

- Limburg Group: very limited number of data (15) spread over a large depth range (1400-5000 m) do not permit a characterization. It is, however, interesting to note that the 2 LOPs measured in the Epen Formation on the Groningen Platform at very great depths of > 4500 m (UHM-02 and TJM-02) are higher than the standard S_{hmin} at the same depth of measurement, but well below standard lithostatic pressure.

The variation in leak-off pressures for the main structural elements and main stratigraphic units (Appendix-B-9.3.2) shows the following characteristics:

- Northern-northeastern offshore (Step Graben, Dutch Central Graben, Terschelling Basin, Schill Grund Platform, Ameland Platform):
    - the lower bound of LOPs clearly deviates from the standard S_{hmin} gradient with increasing depths, from about 2-2.5 km onward;
    - the lower bound of the LOPs in Triassic, Zechstein and Upper Rotliegend units approaches the standard lithostatic gradient at greater depths;
    - the limited number of LOPs in the North Sea Supergroup, Chalk and Upper Rotliegend groups on the Elbow Spit Platform exceeds the standard S_{hmin} gradient.

- Northwestern offshore **(**Cleaverbank Platform, Central Offshore Platform, Broad Fourteens Basin, Indefatigable Platform):
    - the lower bound of LOPs largely follows the standard S_{hmin} gradient;
    - note the relatively large number of – quite scattered – LOPs measured in the Zechstein Group in these structural elements.

- Northern onshore (Vlieland Basin, Friesland Platform, Lauwerszee Trough, Groningen Platform):
    - the lower bound of LOPs largely follows the standard S_{hmin} gradient until depths of approximately 2.5 km in the Friesland Platform and Lauwerszee Trough;
    - the lower bound of the LOPs in the Lauwerszee Trough deviates from the standard S_{hmin} gradient at greater depths (these LOPs are measured in the Zechstein units and 1 LOP in Triassic);
    - the number of LOP data available for the Vlieland Basin and Groningen Platform is very limited (13 and 8 measurements, respectively) and does not justify a characterization;
    - as indicated above, two measurements in the Epen Formation at depth exceeding 4.5 km are clearly higher than the standard S_{hmin} at the same depth, but well below lithostatic pressure.

- Onshore Lower Saxony Basin:
    - the lower bound of the LOPs follows the standard S_{hmin} gradient until depths of approximately 2.5 km and deviates at greater depths. This observation is based on the relatively limited number of measurements in Triassic and Zechstein units at greater depths.

- Southernmost onshore and offshore (Central Netherlands Basin, West Netherlands Basin, Roer Valley Graben, Zeeland High):
    - the lower bound of LOPs largely follows the standard S_{hmin} gradient.

4.2.2 Spatial variation in fluid pressures/overpressures per structural element

Appendix-B-9.3.4 presents the multi-well cross plots of fluid pressure and leak-off pressure versus depth for the main structural elements. The newly added data in the database confirm the previously identified regional differences in fluid pressure and overpressure conditions in the southern, northern and northeastern part of the Dutch subsurface (Verweij et al., 2012). The characterization of the overpressure conditions given below is an update and refinement of the general description given in Verweij et al. (2012).

The multi-well cross plots reveal the following spatial variation in fluid pressures:

1. There is a clear regional difference in fluid pressure/overpressure conditions:
    - Southernmost structural elements (Central Netherlands Basin, Roer Valley Graben, West Netherlands Basin, Broad Fourteens Basin, Indefatigable Platform, Zeeland High):
        - In general, fluid pressures in all stratigraphic units are normal or close to normal and well below the lower bound of the leak-off pressures;
        - However, Triassic units in the West Netherlands Basin seem to be overpressured locally (for example at P06-S-01, P06-10, P09-08-S1, P09-09, KDZ-02-S1, Q16-02; BRTZ-01).

    - Northern offshore structural elements (Step Graben, Dutch Central Graben, Terschelling Basin):
        - Pore fluids in stratigraphic units below the North Sea Supergroup are overpressured;
        - there is a large variation in fluid pressure at the same depth of measurement, especially in Triassic and Rotliegend units in the Dutch Central Graben and Terschelling Basin, and in Carboniferous units in the Step Graben;
        - Fluid pressures reach leak-off pressures at shallow depth (e.g. in the Chalk Group in the Step and Dutch Central grabens) and at greater depth (e.g. in Triassic, Rotliegend and Carboniferous units).

    - Northeastern offshore platforms (Schillgrund and Ameland platforms):
        - Pressure data indicate that pore fluids are overpressured in Triassic and Rotliegend units (Schillgrund Platform) and in Rotliegend and Carboniferous units (Ameland Platform);
        - Pore fluid pressures in Triassic and Rotliegend units vary at same depth of measurement.

    - Northwestern offshore platforms (Elbow Spit and Cleaverbank platforms):
        - Pressure conditions in Cleaverbank Platform are characterized by:
            - variation in pore fluid pressure between normally pressured and overpressured conditions;
            - there is some variation in pore fluid pressure in other than Zechstein units at same depth of measurement;
            - there is a large variation in pore fluid pressures in Zechstein at same depth of measurement and pressures occur in the realm of leak-off pressures;
            - in general overpressures in other than Zechstein units are mild in comparison with those in the northern offshore structural elements;
            - pressures in Upper Rotliegend units at a depth of about 3255 m (J06-04) and in Chalk units at about 1450 m (D15-02 and E17-01) reach the realm of leak-off pressures. Note that these pressures concern kick measurements of poor reliability.
        - The very limited amount of measured data for the Elbow Spit Platform show that overpressured conditions occur at depths > 2 km.

- Central Offshore Platform: This elongated offshore structural element is situated between the severely overpressured Dutch Central Graben in the north and the normally pressured Central Netherlands Basin in the south. This transitional position is reflected in the pressure variation in the platform area:
  - the cross plot shows variable fluid overpressuring;
  - most fluid pressures in Rotliegend and Carboniferous units vary between near normal to mildly overpressured conditions;
  - in the northern part of the area, however, fluid overpressures reach leak-off pressure values in Triassic units (L09-8,-10,-11,-13) and Rotliegend units (M10-01, M11-01) at depth between about 2.7-3.8 km. The highest fluid pressure shown in the cross plot (P = 53.57 MPa at 2776.44 m in Q05-05) is a kick measurement of poor reliability.

- Northern onshore structural elements (Groningen Platform, Lauwerszee Trough, Friesland Platform, Vlieland Basin, Texel IJsselmeer High):
  - Lauwerszee Trough:
    - plotted pressures are mainly from Rotliegend units measured at relatively great depths between 2.8 and about 4 km;
    - the pore fluids are all overpressured, mostly ranging between 4-6 MPa overpressure;
    - the highest pore water overpressured values occur in MGT-02 (19.17 MPa), WTZ-01 (18.8 MPa), KOL-02 (11.4 MPa);
    - the highest gas and water overpressures occur in the northern part of the trough.
  - Friesland Platform:
    - pressure data cover a shallower depth range than the data in the Lauwerszee Trough;
    - part of the pressures in Upper Rotliegend, Triassic and Carboniferous units follows a near normal trend until depths of about 2.5 km;
    - the pore fluids at greater depths vary between near normal and overpressured values exceeding 17 MPa. These highest water overpressures in the Upper Rotliegend Group occur in the northern part of the platform (17.19 MPa in TEN-02, 18.29 MPa in HOA-01-S6, 11.86 MPa in BLF-102, 7.37 MPa in TEW-01).
  - Vlieland Basin:
    - close to normally pressured until depths of at least 2.5 km;
    - the highest overpressures shown in the cross plot are all measured in one well, namely L12-05. These measurements indicate the existence of overpressured conditions in the Rotliegend, Limburg Group and Zechstein units in the offshore part of the Vlieland Basin.
  - Texel IJsselmeer High:
    - the pressure is near hydrostatic in the Upper Rotliegend units at a depth of 2.258 km, while the 3 pressure measurements in LTG-01 indicate a water overpressure of 13.1 – 14.85 MPa in the Carboniferous Limestone Group at depths exceeding 4.5 km.
  - Groningen Platform:
    - the rather limited data suggests that the fluids are less overpressured in the Upper Rotliegend units at greater depth than observed in the Lauwerszee Trough and Friesland Platform;

    - the pressure in the Carboniferous Limestone Group at depth of 5142 m (overpressure of 19.13 MPa in UHM-02) is well below the leak-off pressure.

- <u>Eastern onshore structural element (Lower Saxony Basin):</u>
    - the most striking characteristics of the fluid pressure condition in the basin are the overpressured conditions in the Triassic units and the condition that fluid pressures in the Triassic are higher than in the Rotliegend or Carboniferous units at the same depth of measurement;
    - fluid pressures in the Triassic units at relatively shallow depth (2000-2200 m) approach the realm of the leak-off pressures.
- Significant lateral variations in pressure at the same depth of measurement occur on a smaller regional scale in the Germanic Trias units within the Dutch Central Graben, Terschelling Basin, Central Offshore Platform) and in the Upper Rotliegend units within the Central Offshore, Ameland and Friesland platforms and Lauwerszee Trough).

2. Depth exerts a first order control on the fluid pressures:
    - In the southern area the fluid pressures increase broadly parallel to the density corrected hydrostatic gradient. The pore water density in the Roer Valley Graben is relatively low and ranges between 1020-1090 kg/m^3 at the points of pressure measurements. This results in a lower bound of fluid pressures that runs roughly parallel to the standard hydrostatic gradient. The pore water density in the Broad Fourteens Basin is more variable and reaches higher values (1030-1200 kg/m^3). This is reflected in the position of the lower bound of the fluid pressures at the right-hand side of the standard hydrostatic gradient.
    - Density of the pore water is much higher in the northern areas in comparison with the southern, for example 1040 - 1250/1300 kg/m^3 in Dutch Central Graben, 1100-1300 kg/m^3 in the Terschelling Basin, and 1060-1300 kg/m^3 on the Cleaverbank Platform. In the northern area at shallow depth, the lower-bound of the fluid pressure data increases parallel to the density corrected hydrostatic pressure gradient, but clearly deviates from this at greater depths (for example; fluid overpressures all exceed 8 MPa at depths beyond 2250 m in the Terschelling Basin, and minimum overpressure values reach magnitudes of approximately 9 MPa at 4 km depth in the southern Dutch Central Graben).

3. Vertical pressure reversals. Pressure not always increases with depth. Pressure reversals occur between highly overpressured Zechstein and underlying less overpressured Upper Rotliegend units, and also between more overpressured compartmentalized Triassic units and less overpressured hydraulically more continuous Rotliegend and Carboniferous units in for example the Lower Saxony Basin and Central Offshore Platform. In addition, even in the generally normally pressured West Netherlands Basin, local pressure reversals occur between overpressured Triassic compartments and normally pressured underlying units (P6-P9 area);

4. Very high values of overpressure were observed in the Limburg Group in the Step Graben (> 30 MPa) and Ameland Platform (> 20 MPa), the Upper Rotliegend Group in the southern Dutch Central Graben (~ 60 MPa), Terschelling Basin (> 35 MPa), Ameland Platform (> 20 MPa), and in the Lower Germanic Trias Group in the Terschelling Basin (> 35 MPa), Dutch Central Graben (> 30 MPa), Central Offshore Platform (~ 25 MPa). See also section 4.2.4 on HPHT conditions;

5. Fluid overpressures in the Zechstein Group show a wide variation in magnitude from < 1 MPa to > 40 MPa. The location of the strata within the Zechstein Group (enclosed in evaporites of the Zechstein Group, or situated at the top or bottom of the group) significantly influences the formation pressure conditions where the highest overpressures are observed in intervals enclosed by evaporitic units. Even in the southern offshore area (Broad Fourteens Basin, Indefatigable Platform), where formation pressures are generally close to hydrostatic in other stratigraphic units, the overpressures in the Zechstein may reach much greater magnitudes. It should be realized though that large part of the pressure measurements in the Zechstein are kick pressures.

4.2.3 Pressure-stress relations and spatial variation in lithostatic pressure trends

The difference between the standard lithostatic pressure gradient (corresponding to the principal vertical stress gradient) and the standard principal minimum horizontal stress gradient increases with depth. This is in accordance with the general increase in difference between principal stresses due to the increase of frictional strength of the rocks with depth under normally pressured conditions (Zoback, 2010). The lower bound of the measured leak-off pressures follows the standard principal minimum horizontal stress gradient at shallow depths (< 2 km) in all structural elements (section 4.2.1 and Appendix-B-9.3.2). Severe overpressure will decrease the frictional strength of the rocks and is associated with a decrease in difference between these principal stresses (Zoback, 2010). This pressure-stress coupling is apparent in the significantly overpressured parts of structural elements in the northern and northeastern offshore (Step Graben, Dutch Central Graben, Terschelling Basin, Schill Grund Platform, Ameland Platform) and onshore (Lauwerszee Trough, Lower Saxony Basin), where the lower bound of the measured leak-off pressures is shifted towards higher values.

4.2.3.1 Spatial variation in lithostatic pressure trends

The lithostatic pressure at a certain depth is equivalent to the weight of the overburden (rocks and pore fluids) at that depth. Lithostatic pressure trends will be similar across areas with a simple layer-cake lithostratigraphic build-up and similar burial history. This condition is not fulfilled for the build-up and burial history of the onshore and offshore Netherlands. Burial histories vary over short distances (Figure 8, Figure 9 and Figure 10) and resulted in highs, platforms and (inverted) basins (Figure 7 and Appendix-B-9.2) with different lithostratigraphic build-ups and porosity distributions.

In order to investigate the spatial variation in lithostatic pressure trends were calculated at 25 well locations using bulk density logs recorded during drilling and simulated lithostatic pressures derived from basin modeling results, see Chapter 3.

Lithostatic pressure at depth z is equivalent to the integration of the bulk density (rock and pore fluids) from surface to depth z. An average bulk density of clastic rocks is ~ 2.3 g/cm^3 (porosity 15%). This results in an increase of overburden pressure with depth of 23 MPa/km (~ 1 psi/ft), i.e. the standard lithostatic pressure gradient used in all the cross-plots (Appendix-B-9.3).

The density logs indicate that relatively low bulk densities are associated with the high porosity recent sediments (North Sea Supergroup, see Figure 13) and with halite (Zechstein salts, see Figure 14).

Figure 13 shows an increase in bulk density for the Lower North Sea Group:

- 1.92 g/cm³ (260-500 m) (log measurements from London Brabant Massif and Groningen Platform)
- 1.97 g/cm³ (501-1000 m)
- 2.02 g/cm³ (1001-1500 m)
- 2.12 g/cm³ (1501-2061 m) (log measurements from Elbow Spit High and Platform)

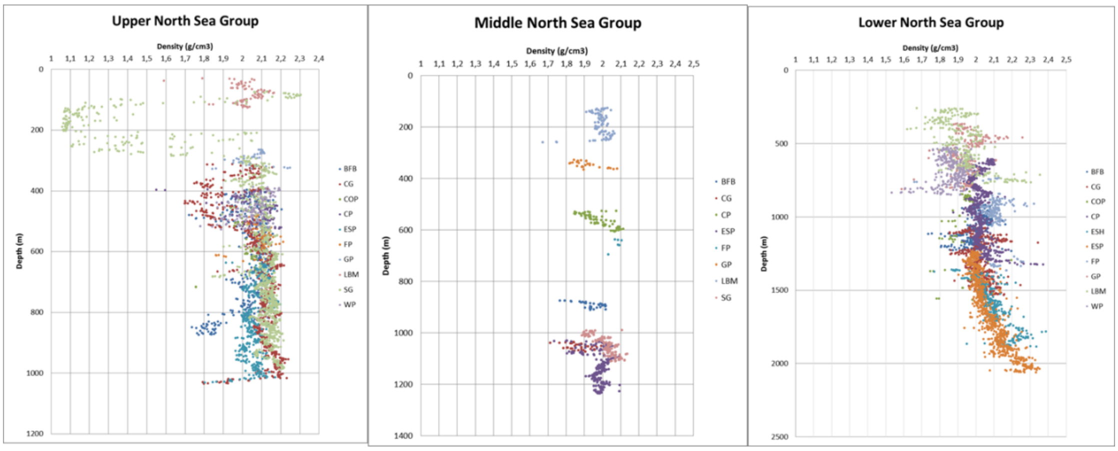


Figure 13: Cross plots of bulk density versus depth for the North Sea Supergroup per structural element: average bulk density is 2.07 g/cm³ in Upper North Sea Group (disregarding density < 1.5 g/cm³); 1.98 g/cm³ in Middle North Sea Group and 2.02 g/cm³ in the Lower North Sea Group.

The bulk density of the Zechstein Group shows a large variation in magnitude for the same depth of measurement (Figure 14). This variation is related to the variation in lithology: The halite members have a very low bulk density of 2 – 2.2 g/cm³, the anhydrite members have a very high density of about 2.9 g/cm³, and the carbonates and clastics have a bulk density of 2.4-2.6 g/cm³.

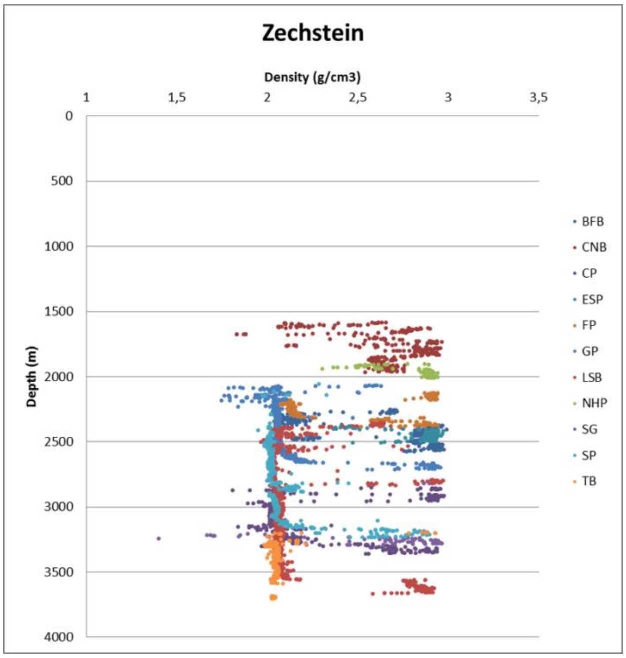


Figure 14: Cross plot of bulk density versus depth for the Zechstein Group per structural element showing the large variation in lithology-related bulk density.

The impact of these stratigraphic units of low bulk density results in the following deviations from the standard lithostatic pressure gradient:

- The low density North Sea Supergroup reduces the magnitude of the lithostatic pressures in the North Sea Supergroup sediments and in underlying older units (Figure 15). This regional effect is largest in areas with the largest thickness of the North Sea Supergroup, i.e. in the northern offshore;
- The influence of low density Zechstein salt structures extends to stratigraphic units underlying the Zechstein Group (Upper Rotliegend and Limburg Group) (Figure 16), where the larger the Zechstein salt structure the greater the reduction in magnitude of the lithostatic pressure. Large salt structures occur in the northern onshore and offshore. The low density salt structure will create lateral differences in lithostatic pressure between e.g. the Zechstein salt structure and adjacent Triassic clastic units, and in the underlying Upper Rotliegend and Limburg groups;
- The largest local deviations from the standard lithostatic pressures occur in areas with a thick package of North Sea group sediments and large salt structures (Figure 17), i.e. in the northern offshore.

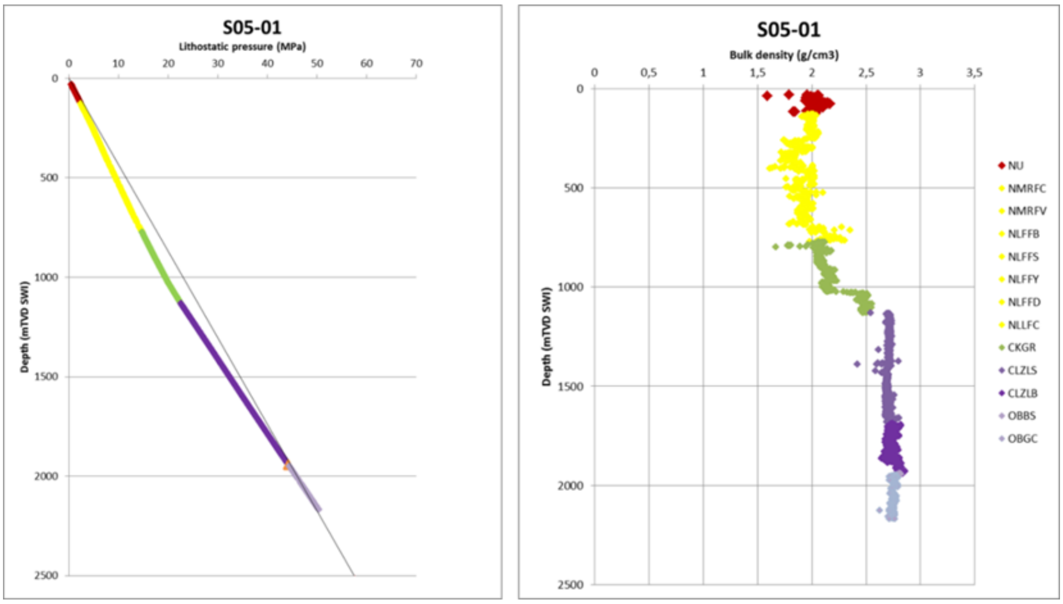


Figure 15: Cross plot of lithostatic pressure versus depth and bulk density versus depth at S05-01 (Zeeland High): influence of low density North Sea group and Upper part of Chalk Group extends into the dense Carboniferous Limestone Group. The calculated lithostatic pressure reaches the standard lithostatic gradient at a depth of about 2 km.

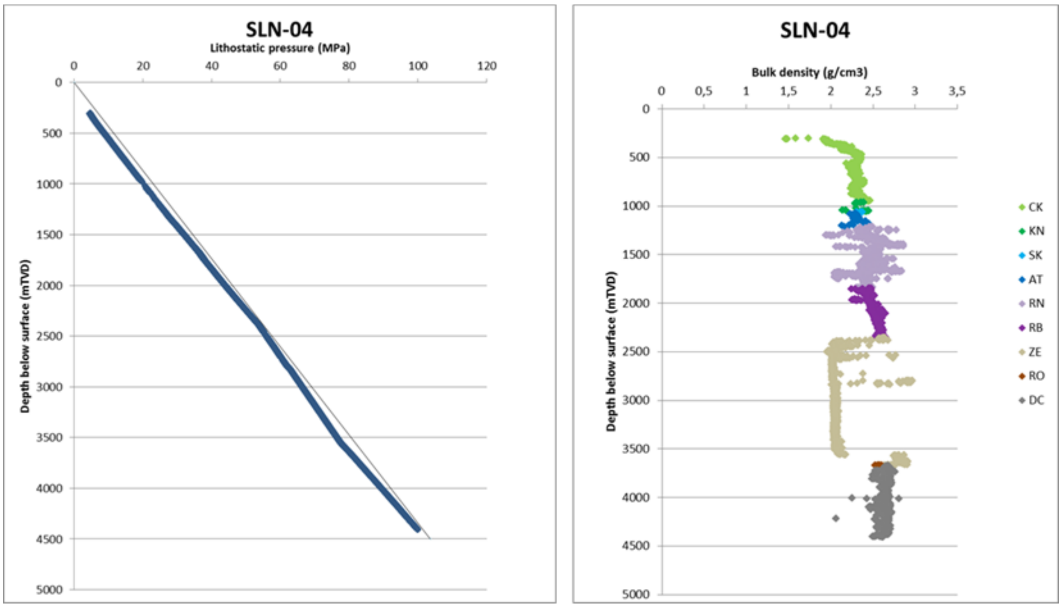


Figure 16: Cross plot of calculated lithostatic pressure versus depth and bulk density versus depth at SLN-04 (Lower Saxony Basin) showing influence of the Zechstein Group salts of low density on reducing the lithostatic pressure.

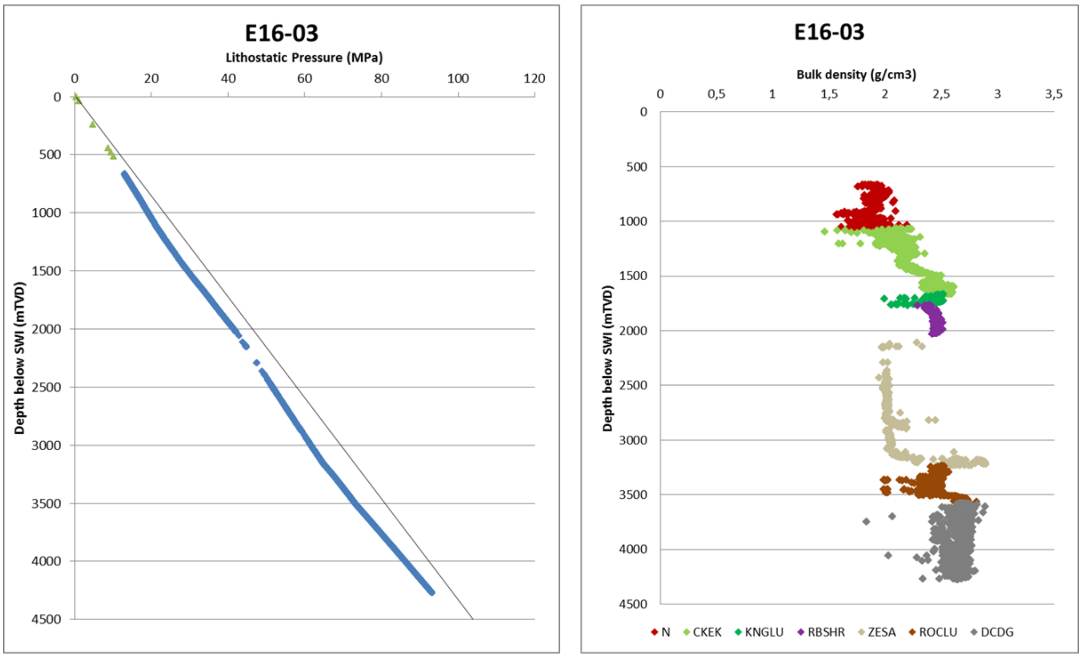


Figure 17: Cross plot of calculated lithostatic pressure versus depth and bulk density versus depth at E16-03 (Cleaverbank Platform) showing the combined influence of North Sea Group, upper part of Chalk Group and Zechstein Group salts of low density to lower the lithostatic pressure below standard lithostatic pressure. This influence extends into the underlying Upper Rotliegend and Limburg Group.

Relatively old and more dense stratigraphic units occur at relatively shallow depth on the highs (e.g. Zeeland High) and in strongly inverted parts of basins. In these areas the lithostatic pressure will reach and follow the standard lithostatic pressure gradient at shallower depths than in other areas: compare e.g. S05-01 on the Zeeland High (Figure 15) with E16-03 on the Cleaver Bank High (Figure 17).

4.2.3.2 Spatial variation in vertical effective stress

The vertical effective stress is the weight of the overburden not supported by pore fluid pressure and as such is the vertical load acting on the rocks. Hence, the vertical effective stress at a certain depth is the lithostatic pressure minus the pore pressure at the same depth. Increasing vertical loading is an important driving mechanism for compaction and associated porosity and permeability reduction of rocks. Porosity-vertical effective stress trends, rather than porosity-depth trends, are helpful for property characterization and prediction. Under hydrostatic conditions and standard lithostatic stress conditions, the vertical effective stress increases with depth.

Fluid overpressures reduce the vertical effective stress in comparison with standard conditions. Overpressured conditions show great spatial variation in the Dutch subsurface. As shown above, the region specific lithostatic pressures may also deviate from standard conditions and reduced lithostatic pressures are associated with reduced vertical effective stresses. These variations should be taken into account in establishing porosity- effective stress relations and predicting reservoir properties. This means that porosity–depth relations constructed in reservoirs should be normalized with the appropriate effective stresses.

4.2.4 HPHT compartments

High pressure, high temperature reservoir conditions are challenging conditions for drilling, completion and production. Different definitions of HPHT conditions are used. Here the project followed Milton-Worsell (2009) definitions for the UK Central Graben. Conventional HPHT conditions are considered to exist where pressures exceed 10000 psi (689.5 bar) and where temperatures exceed 300°F (~ 150°C). Extreme HPHT conditions occur where pressures exceed 15000 psi (~ 1034 bar) and temperatures exceed 350°F (~ 177°C).

Generally, pressures and temperatures increase with depth. Pressures will reach conventional HP conditions (689.5 bar) at depths of 5900 m and 6900 m for hydrostatic pressure conditions and constant pore water density of 1200 and 1020 kg/m^3, respectively. The temperature gradient varies between about 27-36°C per km for the different structural elements in onshore and offshore Netherlands. The temperature will reach conventional HT conditions (~ 150°C) at depths between 3900 and 5200 m. Assuming an average thermal gradient of 32°C/km and a ground surface temperature of 10°C, the HT conditions will be reached at a depth of about 4400 m. Hence, conventional HP&HT conditions can be expected to exist in the Dutch subsurface at depths exceeding about 6 km in areas where hydrostatic pressure conditions prevail from the surface downward. Pore fluid overpressuring may increase the pressures to magnitudes exceeding the HP conditions at shallower depths than 6 km. This is illustrated by the HPHT conditions encountered in the Dutch subsurface.

Table 6 provides an overview of HPHT wells in the database. Most of the pressure measurements concern gas pressures, and – a small – part of the measured pressure is due to the height of the gas column. The listed temperatures are from different sources and should be considered to be only roughly indicative of the real formation temperature. All but one well belong to the conventional HPHT conditions. Well F17-08-S1 encountered extreme HPHT conditions in the Lower Slochteren Sandstone Member in the Dutch Central Graben. Please note that these pressure measurements are qualified as very low reliable.

In the offshore, conventional HPHT conditions were encountered in the Lower Volpriehausen Sandstone Member (RBMVL) and Lower Slochteren Sandstone Member (ROSLL) in the southern part of the Dutch Central Graben and in the Terschelling Basin. The HPHT conditions in ROSLL occur in its northernmost extension into the Dutch Central Graben and Terschelling Basin. In this area, the Silverpit Formation and the Zechstein Group (of variable thickness and composition) overlie the reservoir and restrict vertical bleed-off. The highest pressures of 99.13 MPa (L02-08) and 110.94 MPa (F17-08-S1) were encountered at the greatest measured depths of 5032 and 4972 m, respectively.

Well Name	Depth mTVDss	OP MPa	Pressure MPa	T DEGC	Stratigraphy	Structural Element	Fluid type	Gas field	Test type	Reliability code
L02-05	4142,74	28,26	69,81	154	RBMVL	Dutch Central Graben	G	L02-FB	PT	most reliable
L02-06	4178,20	28,86	70,77	156	RBMVL	Dutch Central Graben	W	L02-FA	WLT	low reliable
L02-07	4007,20	28,90	69,10	155	RBMVL	Dutch Central Graben	G	L02-FA	PT	most reliable
L02-FA-101	4047,23	28,76	69,36	148	RBMVL	Dutch Central Graben	G	L02-FA	WLT	reliable
L02-FA-102	3991,51	29,19	69,23	145	RBMVL	Dutch Central Graben	G	L02-FA	WLT	reliable
F17-08-S1	4972,22	61,09	110,94	178,5	ROSLL	Dutch Central Graben	W?		SRFT	very low reliability
L02-08	5032,29	48,67	99,13	167	ROSLL	Dutch Central Graben	G	L02-FC	WLT	reliable
F15-07	3736,30	31,68	69,17	143	RBMVL	Terschelling Basin	W		WLT	reliable
F18-11	4308,47	27,13	70,34	160	RBMVL	Terschelling Basin	?		MDT	low reliable
G16-05	3749,11	39,49	77,11	142	RBMVL	Terschelling Basin	W		WLT	low reliable
L05-07	4226,30	39,95	82,34	142	RBMVL	Terschelling Basin	W		WLT	low reliable
M01-02	3879,43	35,86	74,78	151	RBMVL	Terschelling Basin	W	M01-FA	WLT	reliable
M01-03	3884,58	35,99	74,96	158,5	RBMVL	Terschelling Basin	G		WT	reliable
M01-03	3893,83	35,13	74,19	158,5	RBMVL	Terschelling Basin	GMW		MDT	moderately reliable
L05-09	4673,04	23,73	70,59	159	ROSLL	Terschelling Basin	G	L05-B	WT	reliable
L05-09	4632,52	23,63	70,08	156	ROSLL	Terschelling Basin	G	L05-B	MDT	most reliable
L05-10	4343,76	26,22	69,78	152	ROSLL	Terschelling Basin	G	L05-C	RCI	reliable
L06-07	4365,72	37,90	81,68	150	ROSLL	Terschelling Basin	G	L06-B	RCI	reliable
UHM-02	5141,97	19,13	70,69	205	CLZLB	Groningen Platform	MW		MDT	low reliable
L05-12-ST	5450		102,3	183	ROSLL		G		(not in Dbase)	

Table 6: HPHT conditions in the Dutch subsurface.

The HPHT conditions in RBMVL reservoirs occur in compartments that overlie the Zechstein Group and are laterally hydraulically restricted (by Zechstein salt structures and/or faults) and are capped by evaporite units of the Upper Germanic Trias Group that restrict vertical dissipation of pressures. In the onshore the deep well UHM-02 on the Groningen Platform penetrated the Beveland Member (CLZLB) of the Carboniferous Limestone Group where HPHT conditions were encountered. Especially remarkable are the reported very high temperatures.

HP conditions occur at several well locations in the Zechstein Group in the Lower Saxony Basin and the Step Graben (Table 7). Please note that most of the measured pressures concern kick pressures in the Step Graben.

Well Name	Depth mTVDss	OP MPa	Pressure MPa	T DEGC	Stratigraphy	Structural Element	Fluid type	Test type	QC code	Reliability code
F04-03	3777,53	44,41	82,31	123	ZEZ1W	Step Graben	W	Kick	C	fair
F04-03	4307,25	29,93	73,13	143	RV	Step Graben	W	Kick	C	fair
F04-03	3358,45	38,74	72,45	98	ZEZ3H	Step Graben	W	Kick	C	fair
F04-03	3391,98	42,44	76,48	98	ZEZ3H	Step Graben	W	Kick	D	poor
B17-04	4039,37	40,38	80,90	117	ZEZ2C	Step Graben	?	Kick	D	poor
F07-02	4085,31	33,76	74,74	131	DCCU	Step Graben	W	Kick	C	fair
B10-02	3680,60	32,42	69,35	113	ROSL	Step Graben	gas show	Kick	D	poor
STK-01-S3	3530,33	35,85	71,28	120	ZE	Lower Saxony Basin	?	WT	A6	reliable

Table 7: HP conditions in the Dutch subsurface.

4.2.5 *Spatial variation in overpressure in relation to geological framework*

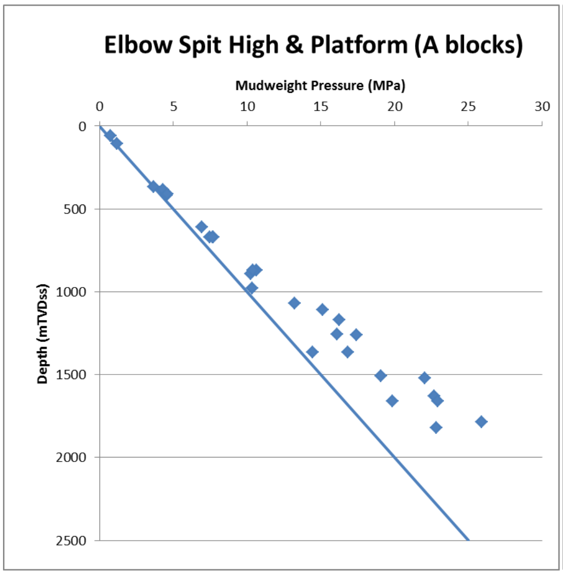
The maps showing all fluid overpressure per stratigraphic unit (Appendix-B-9.1.1), maps showing formation water overpressure per stratigraphic unit (Appendix-B-9.1.2), the regional cross sections showing all fluid overpressures (Appendix-B-9.2), and the multi-well cross plots (Appendix-B-9.3) illustrate the regional variation in fluid pressure and fluid overpressure in relation to the geological framework.

4.2.5.1 Pressure distribution in Cenozoic North Sea Supergroup

There are only a limited number of pore pressure measurements available for the North Sea Supergroup. Most measurements concern the Upper North Sea Group in the northern offshore. The pore water overpressures in the Upper North Sea Group, derived from WLT, MDT and DST measurements, are close to normal in both the offshore (OP_g = 0.11 - 0.48 MPa) and onshore (OP_w ~ 0.10 MPa in the Roer Valley Graben). Slightly higher overpressures were measured in gas in the Step Graben (0.30-0.88 MPa). Two kicks of only fair and poor reliability attain values of 4.97 and 6.75 MPa, respectively.

From previous studies in UK, Danish, Norwegian and Dutch North Sea, it is known that Cenozoic mudstones are susceptible to overpressuring in environments of rapid sedimentation (Japsen, 1999; Evans et al., 2003, Robertson et al., 2013, Winthaegen and Verweij, 2003). The top of overpressure in the Central North Sea occurs at depths around 1000 m (Leonard, 1993; O'Connor and Swarbrick, 2008, Robertson, 2013). Rapid Pliocene to recent sedimentation in combination with the burial depth of Paleogene mudrocks to more than 1000 m in the northern offshore (Figure 10) are favourable conditions for overpressure generation. There is only one pore water overpressure value available for the Lower North Sea Group (OP_w = 5.88 MPa in NLFFT at F17-06, coded as unreliable) to confirm the existence of overpressuring.

Mudweights used during drilling of the North Sea Supergroup are more widely available than measured pore fluid pressures. Mudweight pressures suggest that overpressured conditions indeed occur in the northern offshore at depths greater than around 1000 m: The mudweight pressure values are especially high in the A blocks in the Elbow Spit High and Platform, and A & B blocks in the Step Graben, see Figure 18.



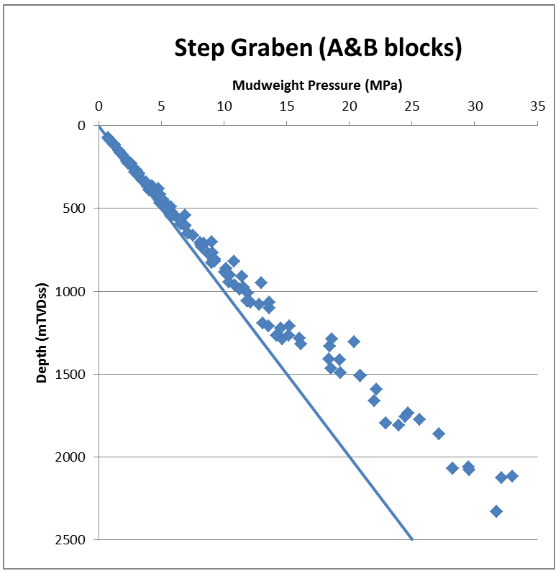


Figure 18: Multi-well cross-plot showing mudweight pressure versus depth in the North Sea Supergroup in the Elbow Spit High & Platform and Step Graben.

The mudweight pressures vary for the same depth of measurement in the Dutch Central Graben, Terschelling Basin and Central Offshore Platform (Figure 19 and Figure 20).

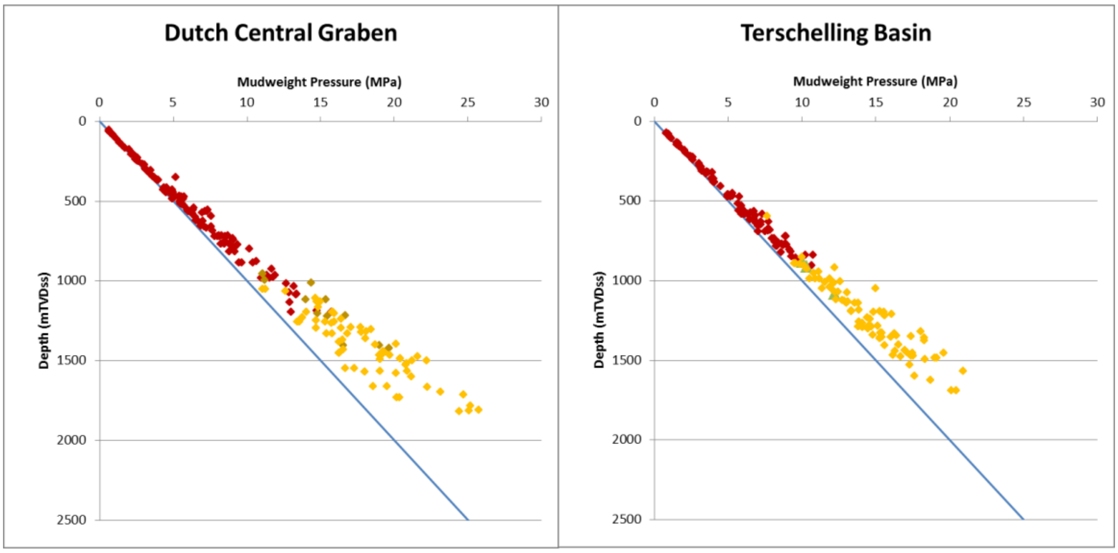


Figure 19: Multi-well cross plot showing mudweight pressure versus depth in Upper, Middle and Lower North Sea Group (indicated in red, brown and yellow, respectively) in the Dutch Central Graben and Terschelling Basin.

The southward decreasing thickness and increasing sand content of the Lower North Sea Group reduces the likelihood of overpressuring of these sediments in the southern offshore and onshore. This is confirmed by the much lower mudweights that were used in the Lower North Sea sediments in the West Netherlands and Broad Fourteens Basin (Figure 21) in comparison with those in the northern offshore (Figure 18, Figure 19, Figure 20).

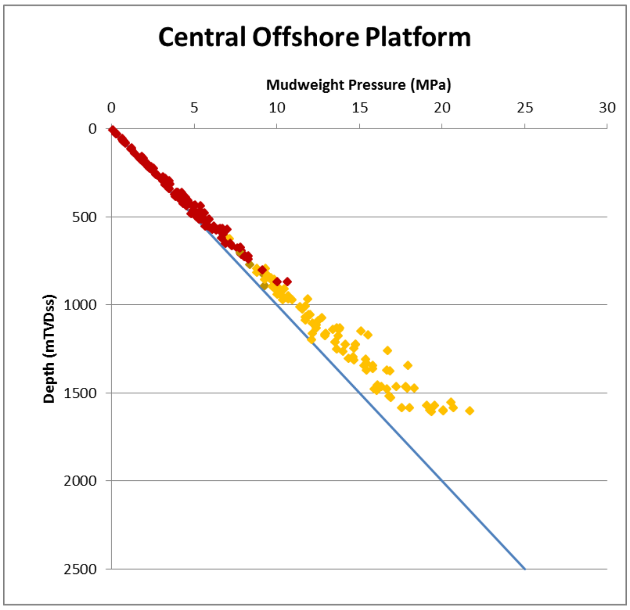


Figure 20: Multi-well cross plot showing mudweight pressure versus depth in Upper, Middle and Lower North Sea Group (indicated in red, brown and yellow, respectively) in the Central Offshore Platform.

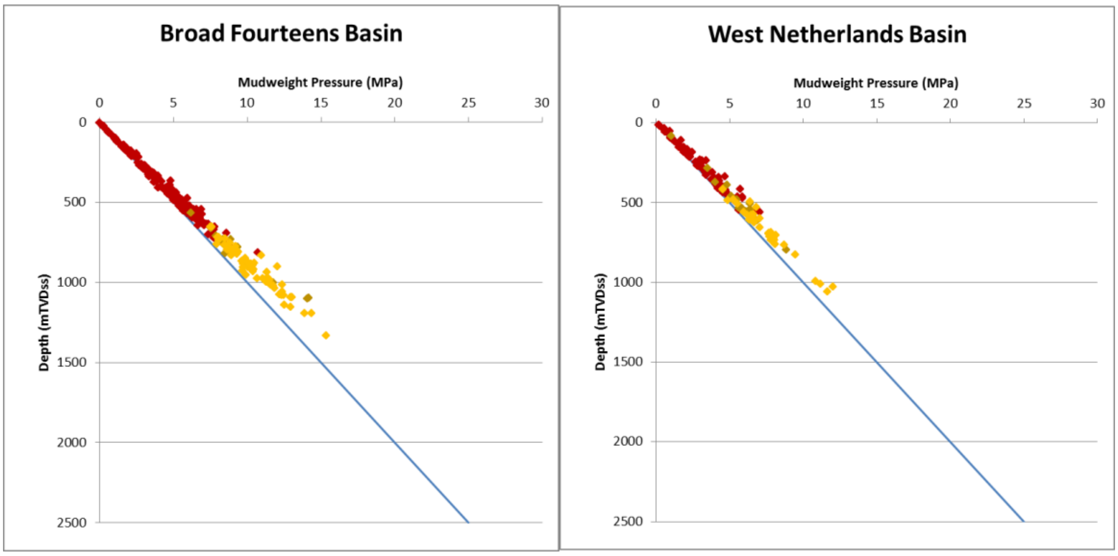


Figure 21: Multi-well cross plots showing mudweight pressure versus depth in Upper, Middle and Lower North Sea Group in the Broad Fourteens and West Netherlands basins.

Figure 22 and Figure 23 present multi-well plots of most reliable and reliable WFT, FITP and kick pressure measurements in the Dutch Central Graben and Step Graben. The pressure-depth plots show a jump in pressure from the normally pressured Upper North Sea Group (depths < 1050 m) to the overpressured pre-Cenozoic units. These plots and the mudweights indicate that the Lower North Sea Group mudstones act as a transition zone between the overpressured Pre-Cenozoic units and the normally pressured Upper North Sea Group sediments in the northern grabens.

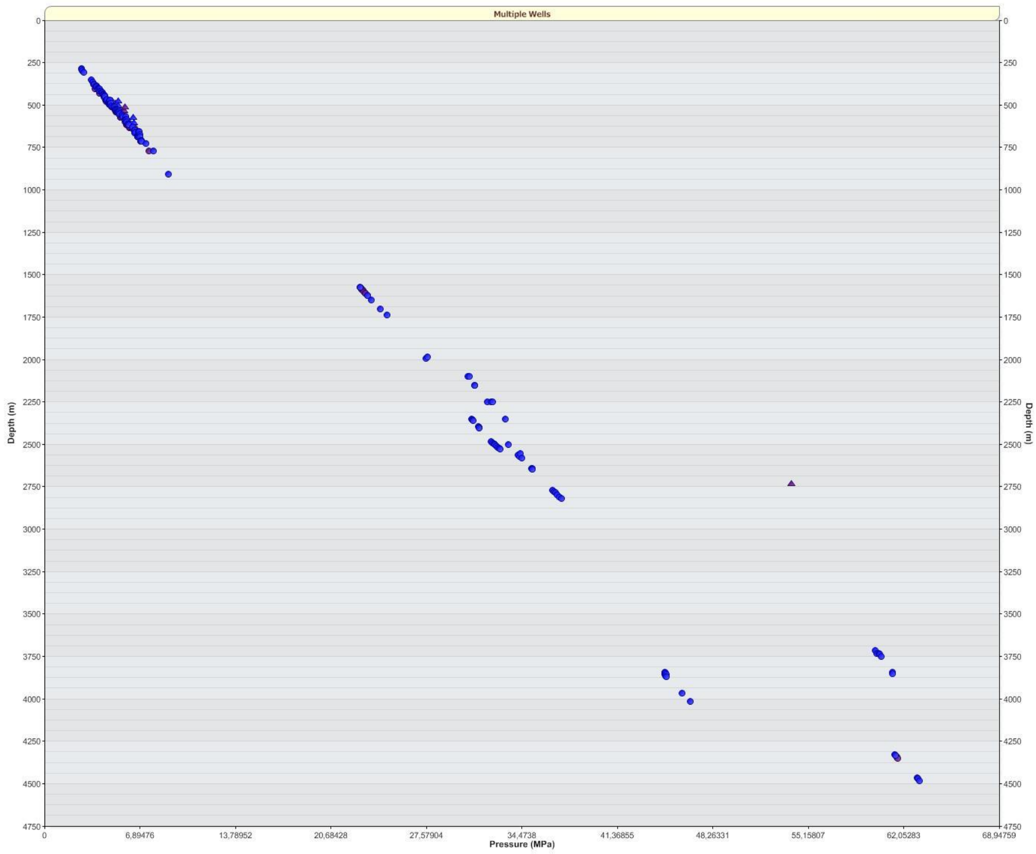


Figure 22: Multi-well cross plot of most reliable and reliable WFT, FITP and kick pressure measurements versus depth in the Step Graben (extracted from the MS Access database with ‘PressurePlot’ tool). Note the stepwise change in pressure between 1 and 1.5 km depth.

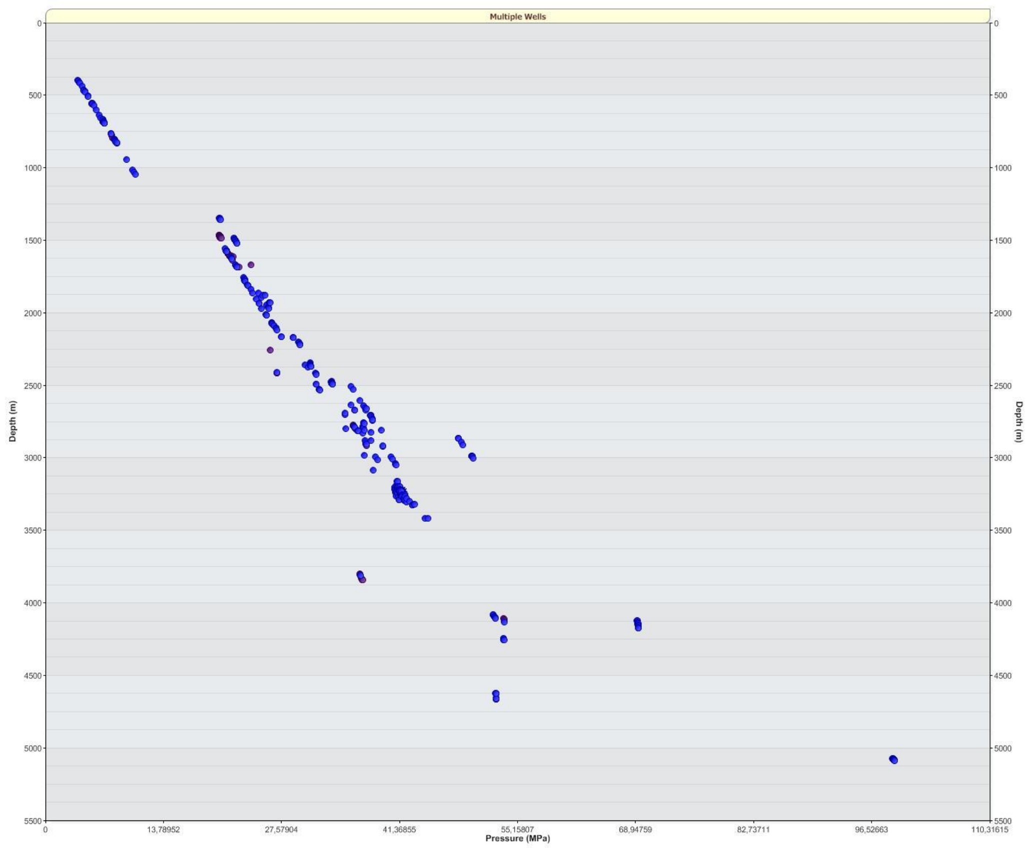


Figure 23: Multi-well cross plot of most reliable and reliable WFT, FITP and kick pressure measurements versus depth in the Dutch Central Graben (extracted from the MS Access database with ‘PressurePlot’ tool). Note the stepwise change in pressure between about 1 km and 1.4 km depth.

4.2.5.2 *Pressure distribution in Chalk Group*

For this paragraph the reader is referred to several overpressure maps delivered as found in Appendix-B-9.1.1 and 9.1.2.

The new all fluid overpressure data in the database from F02-06, F05-04, F05-05, F06-02, and F06-03 confirm the existence of overpressures in the Chalk Group in the Dutch Central Graben in agreement with the previously established general northward increase in overpressure that extends into the UK, Norwegian and Danish parts of the Central Graben (Figure 13 in Verweij et al., 2012). The new pressure data in RTD-01 show that normal pressure conditions prevail in the West Netherlands Basin.

An important mechanism influencing overpressure generation in the Chalk group is the sedimentary loading distribution after deposition of the Chalk. 2D basin modelling studies in the southern part of the Dutch Central Graben showed that the present-day pressure conditions in the Chalk could be related to the rapidly increasing rates of sedimentary loading during Pliocene and Quaternary times (Nelskamp et al., 2012). These late sedimentary loading rates increase northward. The Lower North Sea Group mudstones act as a transition zone between the overpressured Chalk Group and the normally pressured Upper North Sea Group sediments in the northern offshore. These mudstones of low permeability delay the dissipation of overpressure in the Chalk group by vertical Darcy flow. The time required to dissipate overpressure through a layer is proportional to the square of its thickness and is inversely proportional to its hydraulic diffusivity, which in turn is directly proportional to its permeability. The thicker the low permeable unit, the longer it will take for pressures to dissipate. Because the thickness of the Lower North Sea Group increases and its depth-related permeability decreases northward the overpressuring of the Chalk Group can be maintained for longer periods of time towards the north.

Formation water pressures in the Chalk Group in the northern parts of the Step Graben and Dutch Central Graben reach the lower bound of the measured leak-off pressures (Appendix-B-9.3). For example in the Step Graben at A12-02 (OP_w = 9.94 MPa at 2061 m in CKGR), F05-02 (OP_w = 7.50 MPa at 1581 m in CKEK) and F05-05 (OP_w = 7.38 MPa at 1532 m in CKEK); in the Dutch Central Graben at F05-04 (OP_w = 7.15 MPa at 1306 m in CKEK; OP_f = 7.74 MPa at 1392 m in F02-05). Vertical leakage into overlying Cenozoic mudstones can be expected in these areas. Indicators of such vertical leakage of fluids, such as seismic chimneys, have indeed been observed (e.g. at A12-02 and F02-05).

4.2.5.3 Pressure distribution in Rijnland Group

For this paragraph the reader is referred to several overpressure maps delivered as found in Appendix-B-9.1.1 and 9.1.2.

Most of the new all fluid overpressure values in the database are from onshore wells. The Rijnland Group consists of a number of reservoir horizons. The all fluid overpressure distributions were mapped for the entire Rijnland Group and separately for the Friesland & Kotter members and Rijswijk & De Lier members. The Rijswijk & De Lier members only occur in the West Netherlands and Broad Fourteens basins. The all fluid overpressures in these southern basins are all close to normal. The all fluid overpressures in the Kotter Member that is present to the northeast of the Broad Fourteens Basin also indicate close to normal pressure conditions. The all fluid overpressures in the Friesland Member in the Friesland Platform and Vlieland Basin vary between 1.81 and 4.99 MPa and are slightly higher in comparison with the overpressures in the other members. Most of these overpressures concern gas pressures and part of the higher overpressure results from the buoyancy pressure of the gas column. The fluid overpressure of OP_w = 12.07 MPa in L01-03 suggests that overpressured conditions do prevail in the Friesland Member of the Rijnland Group in the Dutch Central Graben. This measurement is situated outside the currently available reservoir map of the Friesland Member.

The pore water overpressure distribution in the Rijnland Group shows that the pore water pressure condition in onshore Netherlands and adjacent southern part of the North Sea is close to normal. The lowest values occur in the West Netherlands Basin. As indicated above there is only one pore water overpressure value available for the northern offshore and this value of 12.07 MPa in L01-03 suggest that pore water overpressured conditions prevail in the Friesland Member in the Dutch Central Graben.

4.2.5.4 Pressure distribution in the Schieland/Scruff/Niedersachsen groups

For this paragraph the reader is referred to several overpressure maps delivered as found in Appendix-B-9.1.1 and 9.1.2.

The present-day distribution of these groups of Late Jurassic-Early Cretaceous age is restricted to the basinal structural elements. The groups contain multiple reservoirs. The fluid overpressures and formation water overpressures have been mapped for the combined groups and for a selection of reservoirs. These maps and the three regional cross sections (see Appendix-B-9.2) all clearly show that fluid and formation water overpressures prevail in the Dutch Central Graben and Terschelling Basin, while in the other basins (Broad Fourteens, West Netherlands and Vlieland basins, Roer Valley Graben) normal pressures to only minor overpressures prevail.

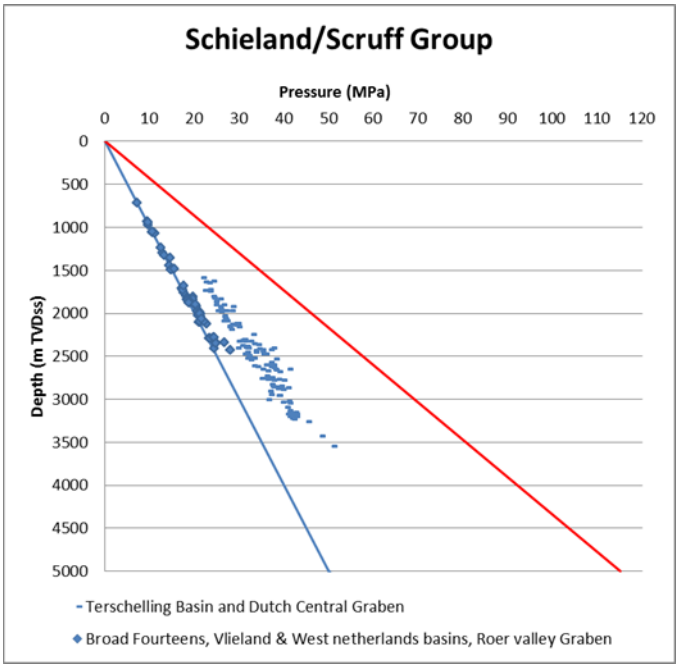


Figure 24: Cross plot of fluid pressure versus depth in the Schieland and Scruff groups. Note the difference between the overpressured condition in the Terschelling Basin and Dutch Central Graben and the close to normal pressures in the other basins.

The maps of formation water overpressures for the combined Schieland/Scruff groups reveal a distinct regional variation: The overpressures exceed 10 MPa in the reservoirs in the Terschelling Basin, southernmost Central Graben (L blocks) and northern F2/F3/B18 blocks in the Dutch Central Graben, while the maximum overpressures in the inverted center of the graben are about 6 MPa.

The overpressure distribution visualized on the reservoir maps adds more detailed insight in the relation between pressure distribution and geological framework. The newly added pressure measurements confirm the general interpretation of the observed regional variation in overpressure given in Verweij et al. (2012). Assuming that late sedimentary loading is the main pressure generating mechanism for the Jurassic sediments, one would expect that the overpressure distribution in the Upper Jurassic reservoirs in the Dutch Central Graben and Terschelling Basin would reflect the northward increasing sedimentation rates in the same way as observed in the Chalk Group. However, the overpressures do not show this relationship. Instead, it seems that in the competition between pressure generation through sedimentary loading and pressure dissipation by fluid flow, the permeability framework has overprinted a dominant influence on the current distribution of overpressure variations in the Upper Jurassic. The Upper Jurassic sediments contain multiple reservoirs that have continuous lateral distributions of variable extent and are intercalated with low permeability mudstone intervals. Lateral dewatering of the Upper Jurassic sediments is influenced by basin boundary faults and large salt structures that form hydraulic barriers and hamper the dissipation of overpressures out of the graben. These structures may locally create vertical pathways for fluids. The vertical dewatering of the reservoir units on a regional scale is controlled by the hydraulic characteristics and thickness of the overburden. The observed regional variations in overpressure show a strong relation with the lateral variation in the thickness and hydraulic characteristics of the overburden. The maps and also the regional offshore cross sections (see Appendix-B-9.2) show this spatial relation between differences in fluid overpressure in the reservoirs and differences in thickness and composition of the low permeable units overlying the reservoirs. The pore water overpressures exceeding 10 MPa in the reservoirs in the Terschelling Basin and Dutch Central Graben are maintained in the reservoirs by the low permeability mudstones of the Upper Jurassic Group, Rijnland Group, Chalk Group and the Cenozoic mudstones. An increase of formation water overpressures with depth within the Schieland/Scruff Groups (for example at F03-06, F03-05, F03-08, F03-07; F18-07) indicate that intercalated low permeability layers within the groups also hamper vertical equilibration of the overpressures. The Chalk Group is absent through erosion in the inverted center of the Dutch Central Graben and its thickness reaches only 300 m over most of the graben area. In the southernmost part of the Dutch Central Graben, away from the inverted center, and in the Terschelling Basin its thickness increases rapidly. The total thickness of low permeable units capping the Upper Jurassic reservoirs in the inverted part of the graben is reduced due to erosion of the Chalk and Rijnland Groups, and reduced depositional thicknesses of the Lower North Sea Group, allowing overpressures to dissipate more rapidly. This is in line with the observed lower overpressure values in the inverted center of the graben.

The above outlined explanation suggests that vertical leakage is the main way for overpressures to dissipate regionally. Lateral dissipation of overpressures out of the graben and basin is hampered by the basin boundary faults and associated large salt structures: The Schieland/Scruff groups in the Terschelling Basin and Dutch Central Graben can be considered to be a pressure compartment with a top seal of variable thickness and sealing capacity. Inside this compartment the overpressures may equilibrate laterally within individual hydraulically continuous reservoir units, as for example in the Terschelling sandstones. The fine to medium grained Terschelling sandstones in the Terschelling Basin were deposited in the form of sheets and channels and only separated by thin intervals of claystones (Munsterman et al., 2012). The formation water overpressures in these sandstones of around 10 MPa do not vary much and seem to have equilibrated laterally. In contrast, the formation water overpressures in the Lower Graben Formation in the northern half of the Dutch Central Graben show a lateral variation from around 6 MPa to above 10 MPa indicating that the lateral hydraulic continuity of the Lower Graben Formation is not large enough to equilibrate the overpressures over the graben area. The lack of regional hydraulic continuity can be explained by the presence of faults and salt structures in the graben as well as by the heterogeneous nature of the Lower Graben Formation. It consists of very fine to fine grained sandstones occurring in beds generally less than 10 m thick with intercalations of claystones and some coal layers, while the individual sand bodies have a rather restricted lateral extent (Munsterman et al., 2012).

Local decrease of formation water overpressure around salt diapirs is indicative of vertical leakage and associated dewatering of Schieland/Scruff groups towards salt diapirs. This was recognized previously in areas surrounding salt wall crossing blocks F15 and F17 (Simmelink et al., 2004), and towards a salt diaper in F3 (Verweij et al., 2012). Additional local leakage and dewatering associated with salt structures occur, for example in the Terschelling Basin. An anomalously low formation water overpressure was recorded in the Terschelling sandstones at L06-05-S1 (OP_w = 5.45 MPa at 2406 m) located at the southern edge of the Terschelling Basin. The well is close to a salt structure with associated faults that extend into the Chalk and North Sea Group units, the Schieland/Scruff groups are missing and the thickness of the Rijnland and Chalk Group is reduced on top of the salt structure. The anomalously low overpressure at L06-05-S1 is probably indicative of lateral dewatering of the Terschelling sandstones towards the salt structure.

4.2.5.5 Pressure distribution in the Germanic Trias groups

For this paragraph the reader is referred to several overpressure maps delivered as found in Appendix-B-9.1.1 and 9.1.2.

The thickest package of Lower and Upper Germanic Trias units is present in the Step Graben, Dutch Central Graben, Terschelling Basin and Lower Saxony Basin, and also in the southern basins. The Triassic was variably eroded during the Late Jurassic from across the platforms and structural highs. It is completely absent on the Texel IJsselmeer High, on large parts of the Friesland and Cleaverbank Platforms, and on parts of the Schill Grund Platform (Duin et al., 2006).

Overpressured conditions in the Germanic Trias groups are more severe and occur over a larger area, including the onshore Lower Saxony Basin, than observed in younger stratigraphic units. The highest formation water overpressures were observed in the Lower Volpriehausen Sandstone Member (RBMVL) in the Terschelling Basin (OP_w = 39.95 MPa in L05-07; OP_w = 35.86 MPa in M01-02; OP_w = 34.23 MPa in F18-08, OP_w = 31.68 MPa in F15-07), Dutch Central Graben (OP_w = 28.86 MPa in L02-06; OP_w = 20.27 MPa in B14-02) and along northern margin of Central Offshore Platform (OP_w = 17.02 MPa in L09-13; also high OP_w = 17.45 and 18.34 MPa in the Lower Triassic RNSOF in L09-11 and L09-10, respectively). Formation water overpressures reach values of more than 12 MPa in the Germanic Trias groups on the offshore Schill Grund Platform, while overpressures do not exceed 8 MPa on the platforms to the west of the Dutch Central Graben. The formation water overpressures decrease away from the Dutch Central Graben: From east to west on the Cleaverbank Platform, from NE to SW towards the Broad Fourteens Basin and southern part Central Offshore Platform. The formation water overpressures reach magnitudes of maximum 13.62 MPa (in RNSOM in JIP-01) in the Lower Saxony Basin. The formation waters are only slightly overpressured to close to normally pressured in the southern basins with OP_w < 3 MPa in Broad Fourteens Basin, < 1.6 MPa in most part of the West Netherlands Basin, and < 0.6 MPa in the Roer Valley Graben. However, as observed in section 4.2.2 there are a number of more local positive overpressure anomalies (P06-S-01, P06-10, P09-08-S1, P09-09, KDZ-02-S1, Q16-02, BRTZ-01) in the West Netherlands Basin that deviate from these general regional observations.

The observed maximum overpressures occur in Triassic reservoirs that overly Zechstein salt, are laterally hydraulically restricted by Zechstein salt structures, and are capped by evaporite/salt units of the Upper Germanic Trias Group (Figure 25). This situation occurs in the Terschelling Basin, Dutch Central Graben, and Lower Saxony Basin. Hence the most important low permeable units controlling the preservation of overpressure in the Triassic reservoirs are the Zechstein salt deposits and structures and the evaporites of the Upper Germanic Trias Group.

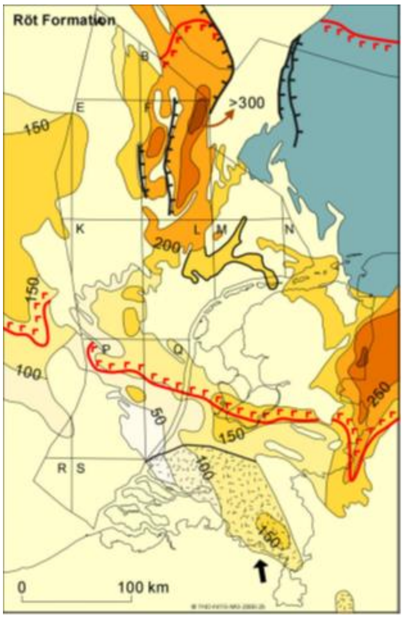


Figure 25: Distribution of the Röt Formation of the Upper Triassic Group (Geluk, 1999).

In those parts of the subsurface in the offshore where Zechstein salts are present and Triassic reservoirs are laterally restricted, but Upper Triassic evaporites are missing or do not form a laterally continuous hydraulic seal, the Lower Germanic Trias units are still overpressured, but less extreme. For example, the Upper Triassic evaporites are missing at M07-02 in the Terschelling Basin and the overpressure is around 10 MPa in RBMVL. Another example from the southeastern part of the Terschelling Basin (block M4) concerns a situation where the Upper Germanic Trias units thin out towards the margin of the basin. As a consequence, the Upper Triassic evaporite seal is missing in the eastern part of the basin allowing lateral dewatering of formation water through the Lower Triassic sandstones into overlying Jurassic units also from locations where the Upper Triassic evaporites are present (for example at M04-03, where OP_w = 12.98 in RBMVL). In areas where the Upper Triassic is largely absent by erosion (e.g. on Ameland, Cleaverbank and Schill Grund Platfoms), no severe overpressured compartments have been encountered in the Triassic reservoirs. This also applies for the Central Offshore Platform south of its northernmost margin.

In the onshore dewatering of the Triassic reservoirs capped by Upper Triassic evaporites will occur if there is no lateral permeability barrier (no salt structure or sealing fault) and/or the seal is not continuous. This may lead to near normal pressure conditions. Such a situation exists just west of the Lower Saxony Basin (Figure 26), where the overpressure of the Triassic reservoirs is close to normal in De Wijk gas field and nearby Wanneperveen fields (OP_f = 1.93 MPa in RBSH in WAV-08) in contrast to the overpressures exceeding 10 MPa in the Lower Saxony Basin.

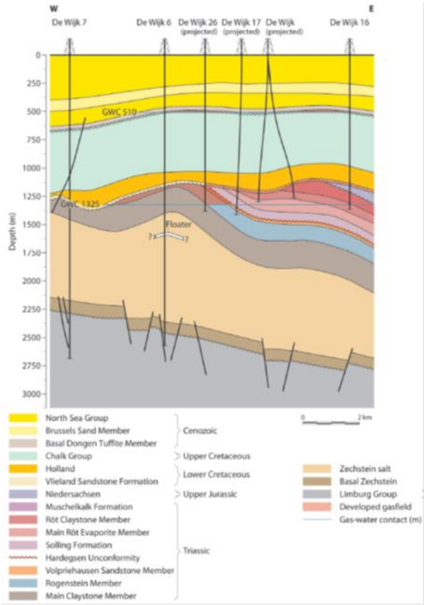


Figure 26: De Wijk gas field at the western edge of the Lower Saxony Basin. Besides the main Triassic reservoirs, gas has also been produced from Cenozoic, Cretaceous, Permian and Carboniferous accumulations (Doornenbal and Stevenson, 2010). Although Röt evaporites overly the Triassic sandstone reservoirs, the formation water pressure is close to normal, because the reservoirs are able to dewater westwards.

Most of the Triassic reservoirs in the West Netherlands Basin are – close to – normally pressured. However, Table 8 shows a number of positive overpressure anomalies.

Well Name	Depth mTVDss	Overpressure MPa	Gas field	Reservoir	Caprock	Fluid type	Source	Reliability
Offshore West Netherlands Basin								
P06-S-01	2899,8	8,60	P6-South	RNSOB	RNRO (+RNMUL, RNMUE)	G	WLT	moderately reliable
P06-10	2976,8	5,06		RNSOB			MDT	moderately reliable
P09-08-S1	3374,0	15,56	P9-B	RNSOB	RNROC (+ RNMUL, RNKPD)		MDT	moderately reliable
P09-08-S1	3452,362	15,72	P9-B	RBMDC	RNROC (+ RNMUL, RNKPD)		MDT	low reliable
P09-09	3158,6	7,28	P9-A	RNSOB	RNROC (+RNMU, RNKP)		MDT	moderately reliable
P09-09	3170,3	7,20	P9-A	RNSOB	RNROC (+RNMU, RNKP)		MDT	moderately reliable
Offshore West Netherlands Basin (Kijkduin High)								
Q16-02	3457,85	6,84		RBMH		W	WLT	low reliable
KDZ-02-S1	3217,285	6,86	Kijkduin Zee	RBMH	RNROU (+RNMUL,RNMUE)	W	RFT	reliable
KDZ-02-S1	3255,12	6,88	Kijkduin Zee	RBMDC	RNROU (+RNMUL,RNMUE)	W	RFT	reliable
Onshore West Netherlands Basin								
BRTZ-01	2636,521	4,68	Barendrecht-Ziedewij	RNROY	RNMUL,RNKPR,RNKPD	G	FMT	most reliable
BRTZ-01	2654,649	4,53	Barendrecht-Ziedewij	RNROF	RNMUL,RNKPR,RNKPD	G	FMT	most reliable

Table 8: Local overpressure ‘anomalies’ in Triassic reservoirs in the West Netherlands Basin.

The P6 and P9 overpressured conditions occur in reservoirs located in the top part of NW-SE oriented narrow upthrown fault bounded blocks along the boundary of the West Netherlands Basin and the Broad Fourteens Basin (Figure 27). The topseal of the gas-filled reservoirs are the Upper Triassic low permeable evaporitic shales. At deeper levels in P06-S-01, the observed overpressure is much lower (OP_g = 3.36 MPa in ZEZ3C at 3460.94 m). A small part of the overpressure anomalies can be explained by buoyancy pressure of the gas column. The remaining part seems to be caused by hydraulic isolation of the formation water/pore water in the reservoirs at the top of these narrow horsts: Vertical escape of pore water from the reservoir is hampered by the low permeable Upper Triassic evaporitic shales, faults (affected by clay smearing, Figure 27) are barriers for lateral flow and the accumulated gas at the crestal part of the reservoir further hampers dissipation of overpressure by pore water flow through the reservoir by reducing the reservoir permeability for water flow.

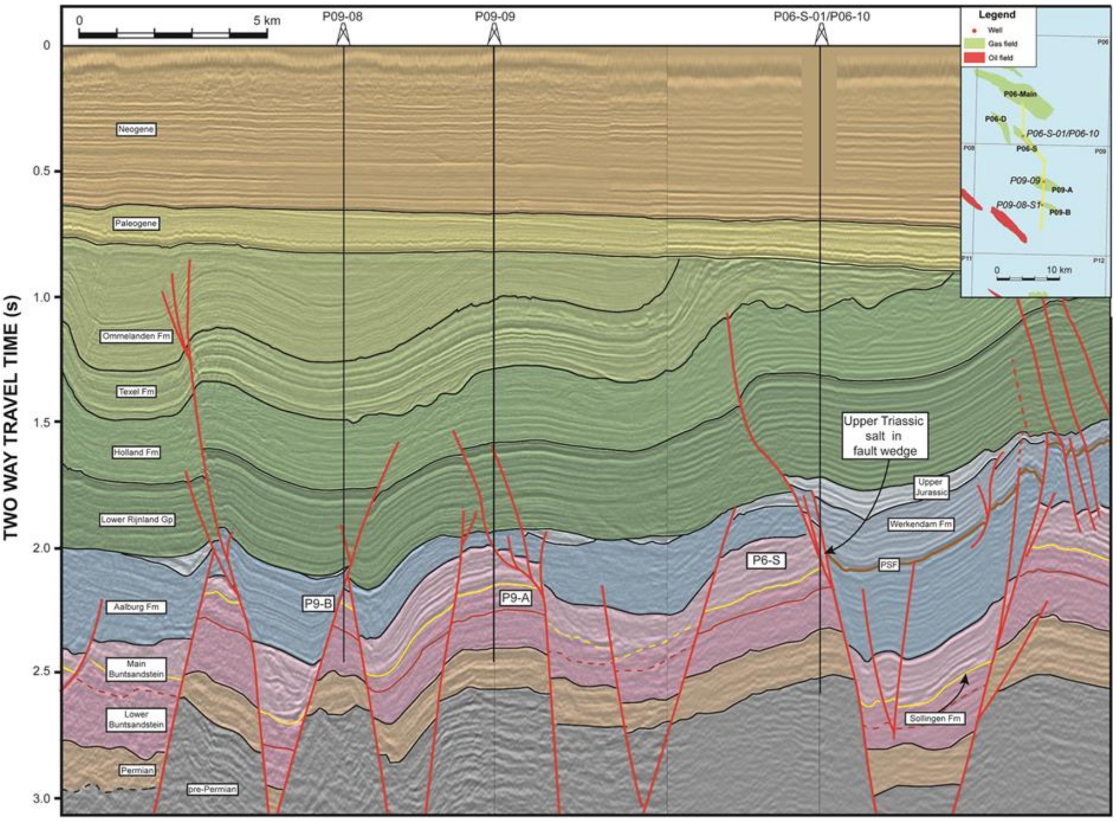


Figure 27: North-south seismic cross-section and interpretation of stratigraphy and structural features through the Triassic gas fields P9B, P9A and P6-S1 (the inset shows the location of the imaged line (in yellow). The cross section shows the position of the overpressured gas fields in the top part of narrow upthrown fault blocks at the boundary between the West Netherlands and Broad Fourteens basins. Upper Triassic evaporitic units are smeared into fault zone (see P06-S-01/P06-10).

The formation water overpressures in Q16-02 and KDZ-02-01 show approximately similar conditions of hydraulic isolation at the crestal parts of the Triassic reservoirs in the Kijkduin High.

The mechanisms responsible for generating the overpressures in these areas have not been investigated. Possibly – paleo – lateral transfer of pressures from deeper buried parts of the reservoir has played a role. Results of 2D basin modelling in the Broad Fourteens Basin (Verweij, 2003) showed such a process: Accumulated gases in crestal parts of the Rotliegend in the P6 area acted as a lateral barrier for late sedimentary loading-induced lateral water flow from deeper parts of the Rotliegend and induced overpressure build-up.

The observed gas overpressure of 4.53 - 4.68 MPa (BRTZ-01) in the crestal part of the Upper Triassic fault bounded reservoir of the Barendrecht Ziedewij gas field can in part be explained by the buoyance pressure of the gas column (from point of measurement to GWC = 2636.5 – 2941 = 304.5 m, Figure 28). The gas column of 304.5 m produces an overpressure of ~ 2.54 MPa (in situ gas density ~170 kg/m^3, gas gradient ~0.00167 MPa/m). The remaining pore water overpressure is ~ 2 MPa relative to standard hydrostatic pressure related to seawater density. In nearby well BRT-02-S1 the formation water salinity was calculated from the water pressure gradient (0.01054 MPa/m) to be much higher than sea water salinity, namely about

140000 ppm. The gas column height and the high salinity of the formation water appear to be largely responsible for the observed relatively high gas overpressure of 4.53 - 4.68 MPa at BRTZ-01.

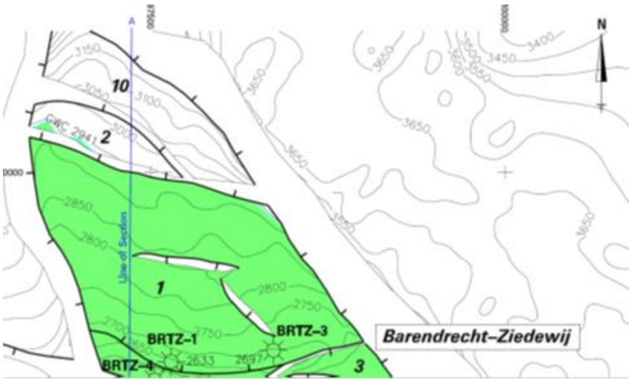


Figure 28: Structural map gas field Barendrecht-Ziedewij (retrieved from *www.nlog.nl*, December 2014).

4.2.5.6 Pressure distribution in the Zechstein Group

For this paragraph the reader is referred to several overpressure maps delivered as found in Appendix-B-9.1.1 and 9.1.2.

Fluid pressures in the Zechstein Group show a wide variation in magnitude at the same depth of measurement from close to normal to close to lithostatic. This is observed in structural elements in the area of distribution of Zechstein salt (such as Cleaverbank Platform, Step Graben, Central Offshore Platform, Broad Fourteens Basin and Lower Saxony Basin). Large vertical pressure reversals may occur in the salt-dominated area between highly overpressured Zechstein units and less overpressured underlying Rotliegend and Carboniferous units.

In the southernmost basins, where the Zechstein sediments are clastic, no significant overpressuring has been measured in the Zechstein Group (West Netherlands basin, Central Netherlands Basin).

4.2.5.7 Pressure distribution in the Upper Rotliegend Group

For this paragraph the reader is referred to several overpressure maps delivered as found in Appendix-B-9.1.1 and 9.1.2.

The Group is composed of the Slochteren and Silverpit formations, which are each other's lateral equivalent. The Slochteren Formation, the main reservoir, interfingers along its northern margin with the finer-grained Silverpit Formation (claystones, siltstones and evaporites). In this transition zone, the Slochteren Formation splits up into the two Slochteren sandstone members that are separated by clay- and siltstones. The Lower Slochteren Member extends further north into the Dutch Central Graben compared to the Upper Slochteren Member (Mijnlieff and Geluk, 2011). Both Slochteren members grade northward into the siltstones and - evaporitic - claystones of the Silverpit Formation. The lateral hydraulic continuity of the Rotliegend reservoirs is affected by the numerous faults cross-cutting the reservoirs. Van Hulten (2010) observed that the northern zone of the Rotliegend reservoir is especially prone to compartmentalization by faults, because the reservoir in this zone is thin and characterized by many shale layers. Low permeable fault zones slow down dewatering of the Slochteren reservoirs. The evaporites of the Zechstein Group provide a regional top seal for vertical fluid flow from the Upper Rotliegend Group in the northern part of the area. The evaporites of the Zechstein Group are missing in the south. Both the Slochteren reservoir and Zechstein salt seal are missing on the Texel IJsselmeer High.

The newly added fluid pressure data confirm the general trend of decreasing overpressures in the reservoirs of the Upper Rotliegend Group from north to south (Figure 29 and Figure 30, and Verweij et al, 2011, 2012). The most remarkable findings from the new data concern the high overpressures in F17-08-S1 in the Dutch Central Graben (OP_f = 61.08 MPa), L06-07, L05-10 and L05-09 in the Terschelling Basin (OP_g = 37.89, 26.22 and 23.63 MPa, respectively). In addition, high overpressures were confirmed to exist on the Ameland Platform (M09-03: OP_f = 22.81 MPa), Lauwerszee Trough (WTZ-01: OP_w = 18.81 MPa) and Friesland Platform (HOA-01-S6: OP_f = 18.29 MPa). The overpressures in the Slochteren Formation in the Lower Saxony Basin (VLV-01, LNB-01, BTA-01, DAL-01 of OP_f = 9.86, 8.81, 7.35 and 6.58 MPa, respectively) were found to be higher than those to the north and west of the basin, and lower than in the Triassic at the same location.

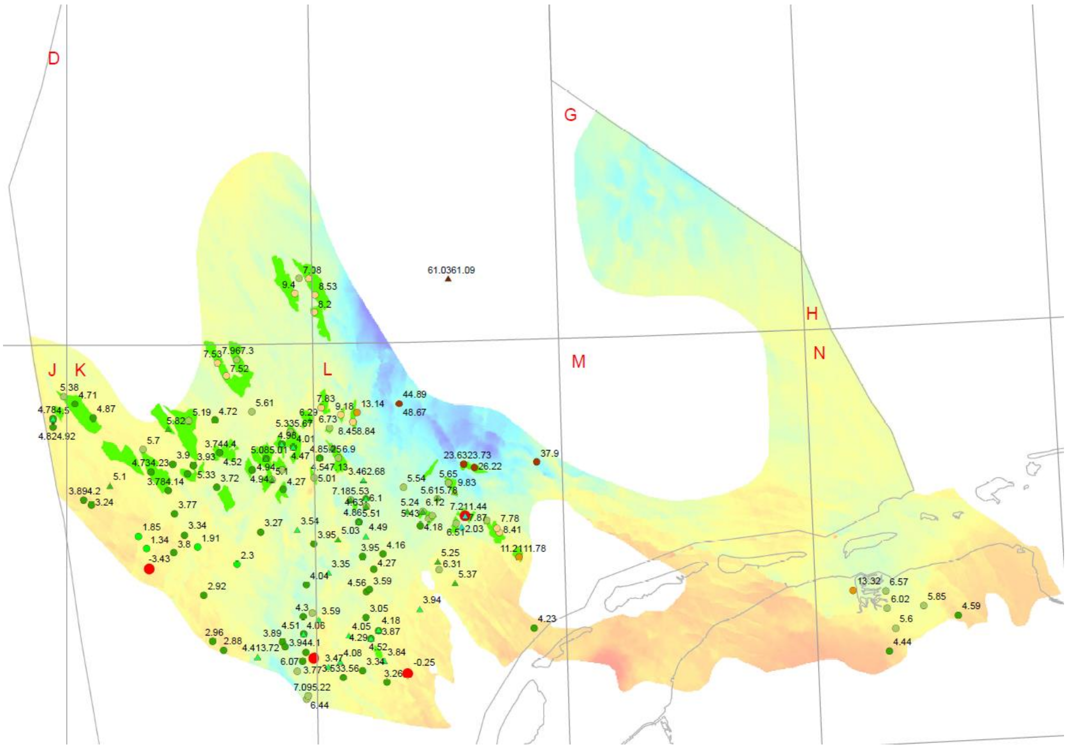


Figure 29: Distribution of all fluid overpressures in the Lower Slochteren Member showing abrupt changes in overpressure between the severe overpressures of > 30 MPa in Dutch Central Graben and Terschelling Basin and those south and west of the basins.

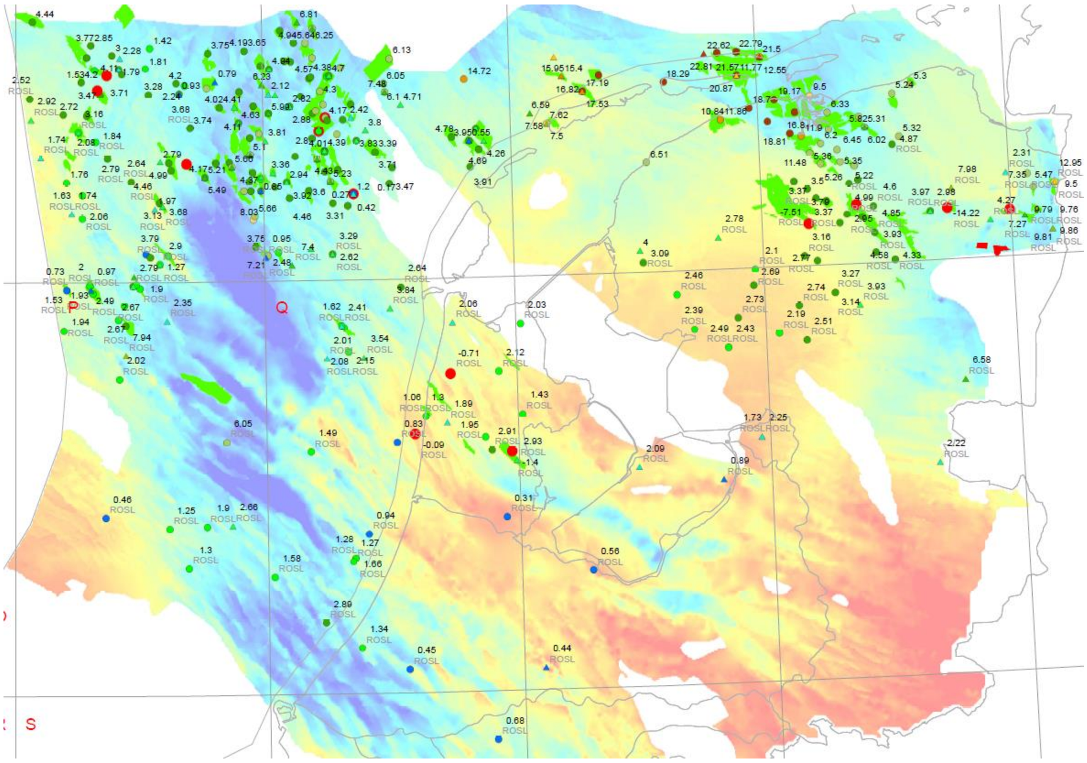


Figure 30: Distribution of all fluid overpressures in the Upper Slochteren Member/Slochteren Formation.

The fluid pressures in the Upper Rotliegend Group vary between severe overpressured conditions in the HPHT areas of the Lower Slochteren Member in the Dutch Central Graben and Terschelling Basin (Table 6) and normally pressured conditions in the Slochteren Formation in the Central Netherlands and West Netherlands basins. The highest overpressures occur along the deeply buried northern part of the Lower Slochteren Member, where it is overlain by the Silverpit Formation and Zechstein evaporites that restrict the vertical dissipation of overpressures, while the lateral hydraulic continuity of the Slochteren reservoir is restricted by fault-induced compartmentalization. The lowest overpressured values occur around the Texel IJsselmeer High (Figure 30), where the Zechstein and Upper Rotliegend units are missing allowing lateral drainage through the Slochteren reservoirs towards the Texel IJsselmeer High and vertical leakage, and in the southern basins, where the Zechstein salt seal is missing. The general decrease of overpressures away from the severely overpressured conditions in the Graben and Terschelling Basin is influenced by the faulted nature of the Upper Rotliegend (e.g. Peters and Verweij, 2012). This is most clearly illustrated by the large difference in overpressure between those encountered in the Dutch Central Graben and those to the south of the graben (Central Offshore and Friesland Platforms) and west of the graben (Cleaverbank Platform), and is also apparent in the stepwise changes of overpressures in the platform areas (see Figure 31, Peters and Verweij, 2012) and within the Lauwerszee Trough from NW to SE (Corona, 2005, Corona et al., 2010) (OP_w = 19.17 MPa at MGT-02 to OP_w = 4.33 MPa at ASN-01).

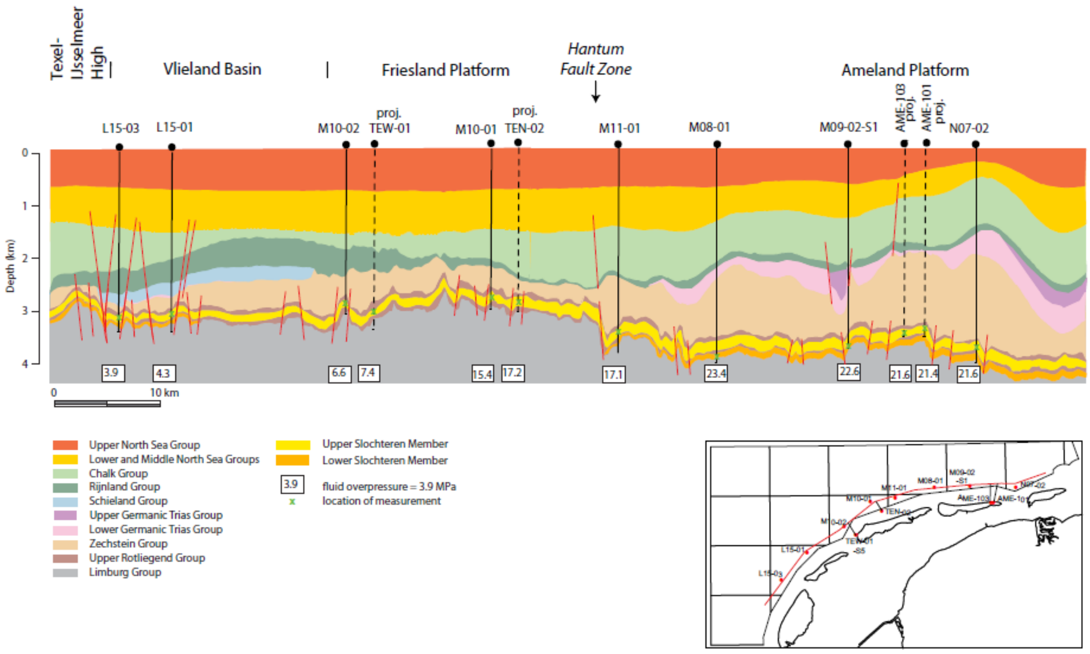


Figure 31: Step-wise decrease of fluid overpressure from Ameland Platform and Friesland Platform towards Texel IJsselmeer High.

4.2.5.8 *Pressure distribution in the Limburg Group*

For this paragraph the reader is referred to several overpressure maps delivered as found in Appendix-B-9.1.1 and 9.1.2.

The fluid and formation water overpressures in the Limburg Group have been measured in reservoirs belonging to different subgroups and formations. Currently there are no distribution maps available for the different reservoirs in the Limburg Group.

The overpressures are visualized on depth maps of the top of the Carboniferous Limburg Group. These maps show that the highest overpressures occur in the Step Graben (OP_w = 23.13 MPa at 3696 m in A11-01, OP_{w_kick} = 33.76 MPa at 4085 m in F07-02, OP_w = 18.80 MPa at 4408 m in F10-03) and southern part of the Ameland Platform (OP_w = 23.86 at 3819 m in M08-01). The Limburg Group reaches its greatest burial depth in the Dutch Central Graben and western part of the Terschelling Basin. The highest overpressures in the Rotliegend reservoirs were measured in the Dutch Central Graben and Terschelling Basin. There are no pressure measurements available for the Limburg Group in these structural elements to indicate if the Carboniferous reservoirs also reach such high overpressured conditions.

The fluid overpressures on the Elbow Spit Platform (OP_w = 10.59 MPa at 2602 m in A14-01, OP_w = 7.69 MPa at 2170 m in E06-01) and Cleaverbank Platform (with maximum values of OP_f = 10.87 MPa at 4210 m in E18-04, OP_w = 7.35 MPa at 4223m in E12-02, OP_w = 6.18 MPa at 3496 m in E12-03, OP_g = 7.89 MPa at 4167 m in F16-03-S1) are much lower than in the adjacent Step Graben. The large difference in overpressure conditions suggests that a permeability barrier (probably related with the basin boundary fault zones) hinders lateral dewatering of the Limburg Group from the Step Graben towards the platforms. The variation in formation water overpressure values on the platform is small in the D and E blocks (between 5 and 6 MPa), while the values decrease southwards to values of less than 5 MPa in the K blocks. The relatively high values encountered in E10-02 (OP_w = 10.19 MPa) and E13-02 (OP_w = 13.53 MPa) are an exception to this regional picture. The formation water overpressures in the Central Offshore Platform south of the Dutch Central Graben vary between and 8.48 and 5.53 MPa. The cross plots of pressure versus depth for the Cleaverbank Platform already showed that the magnitude of overpressuring in the Rotliegend and Limburg groups are largely overlapping, suggesting that there is hydraulic communication between the reservoirs in these groups.

The overpressured conditions in the Limburg Group extend spatially into the northern onshore (Lauwerszee Trough, Groningen High and Lower Saxony Basin). Overpressures dissipate on the Friesland Platform. No overpressured conditions were encountered in the Limburg Group in the southern structural elements (Central Netherlands and West Netherlands basins, Roer Valley graben, Zeeland High).

4.2.5.9 Pressure distribution in the Carboniferous Limestone Group

For this paragraph the reader is referred to several overpressure maps delivered as found in Appendix-B-9.1.1 and 9.1.2.

Dinantian Carbonates were recognized on seismic in the northern onshore. These carbonates developed as isolated carbonate build-ups on paleo highs, while deep water shales were deposited in the lows (Kombrink, 2008; Jaarsma et al., 2013). LTG-01 on the Texel IJsselmeer High and UHM-02 on the Groningen Platform penetrate two carbonate build-ups that are separated by the Lauwerszee Trough. These two wells encountered overpressured conditions in the carbonate build-ups: OP_f = 13.10 MPa at 4997 m (LTG-01) and OP_f = 19.13 MPa at 5142 m (UHM-02). Much lower magnitudes of overpressure occur in the Upper Rotliegend units on the Texel IJsselmeer High (OP_w = 2.03 MPa at 2258 m in WGF-01) and Groningen Platform (OP_f = 4.59 MPa at 3052.1 m in BDM-01).The burial histories of both structural elements are comparable (Figure 32) and so are the hydraulically isolated positions of the carbonate build-ups that hampers dissipation of overpressures by lateral and/or vertical dewatering. The shales that surround the carbonate build-up isolate the carbonates laterally. The Carboniferous Limestone Group is separated from the Upper Rotliegend in both locations by a thick package of the shaly Limburg Group sediments of low permeability (1.5 km thickness at UHM-01 and 2.5 km at LTG-01) that greatly retard vertical equilibration of overpressures by Darcy flow. The overpressures in the carbonate build-up on the Groningen High are well below the reported leak-off pressures. Hence, it is not likely that the current overpressures are high enough to create permeability by inducing hydraulic fracturing or reactivating fractures. There is no publicly available study on the creation of overpressures in the Carboniferous Limestones. Possible mechanisms include sedimentary loading and processes related to increasing burial depth. Burial history (Figure 32) shows subsidence of the Dinantian carbonates since Early Cretaceous, but also shows that current burial depths do not, or only just a little, exceed previous burial depths. The sedimentary loading of the already compacted Dinantian carbonates will have a much smaller impact on overpressure build-up than during previous loading events. Lateral transfer of pressures by fluid flow from hydraulically connected units on the platform areas surrounding the highs may have played an additional role in the build-up of overpressure.

There is a big difference in magnitude of overpressures at the same depth of about 5 km between the severe overpressures measured in the Upper Rotliegend Group in the Dutch

Central Graben (48.67 and 61.09 MPa) and those reported for the Carboniferous Limestone Group in the Texel IJsselmeer High and Groningen Platform. Taking into account that the hydraulic isolation of the Dinantian Carbonate build-ups could have been created much earlier in geologic history in comparison with that of the Permian Upper Rotliegend units, the big difference must be related to differences in geologic mechanisms creating overpressures that are illustrated by the big differences in their burial histories (Figure 32 and Figure 33).

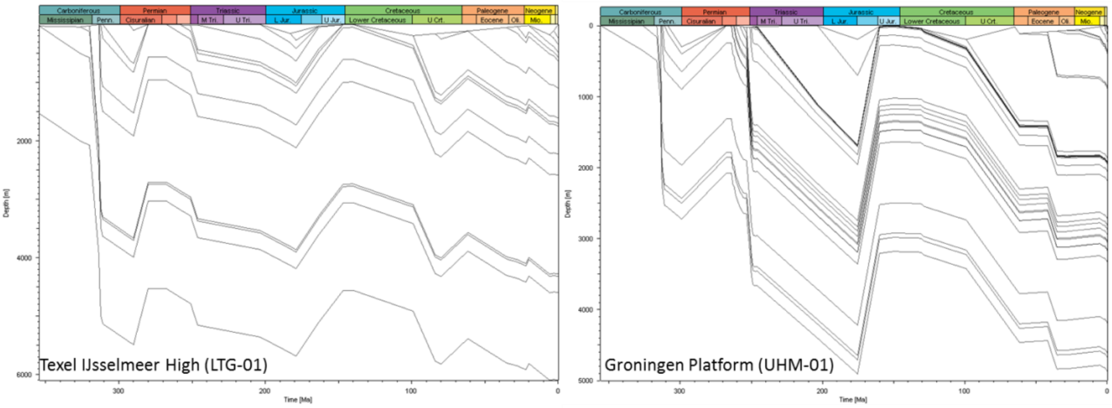


Figure 32: Burial history at LTG-01 and UHM-01 showing that the current burial depth of the Carboniferous does not (or hardly) exceed previous burial depths at the Groningen Platform and Texel IJsselmeer High, respectively.

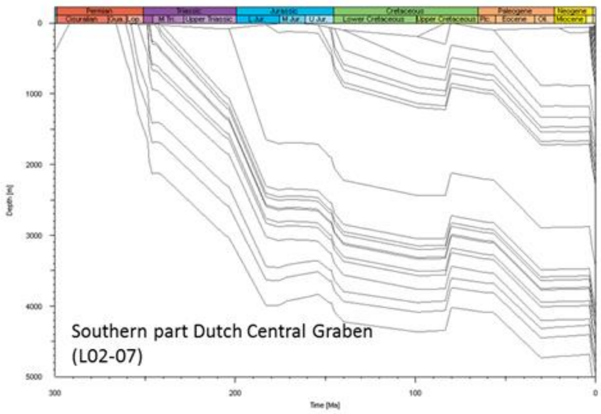


Figure 33: Burial history at L02-07 showing that the Upper Rotliegend is at maximum burial depth today.

5 Project process discussion

This chapter discusses several aspects of the project's process such as the execution of the project, confidentiality status of the project results and deliverables, and further follow-up activities on the pressure information system.

5.1 Project execution

The previous two projects on the Pressure SNS database were executed several years ago by a small team consisting of members of TNO and CSIRO, Australia. The current project was executed only by TNO under responsibility of a lead senior scientist and a project coordinator, in addition to an operational project team with sufficient skills and knowledge for the project activities. Additional senior expertise, next to the lead senior scientist, was reserved during the first months of the project to assist junior and medior project team members.

Although the approaches followed in the current project were the same as the ones for the two projects executed in previous decade, there were also a few differences: Where data collection in the previous project was mainly performed per well and by one person, the fact that a subset of wells for the database extension consisted of an incomplete inventory (done in 2008-2010 by TNO, see also section 2.1), data collection in the current project was done (in a so-called vertical approach) per data type. Furthermore, where the projects executed previously were mainly relying on paper versions of documents such as reports and logs, this current project was relying only on digitized versions of such documents as available on the website *www.nlog.nl*.

This vertical approach for data collection, the fact that for wells often a number of digital documents needed to be studied (before conclusion could be drawn on data availability for a specific data type) and a decision that was made during the project to let all WFT data from the 2008-2010 inventory be re-assessed, lead to considerable delays in the data collection part of the project. To minimize delay, additional assistance of cheap personnel was organized to assist in basic tasks connected to the data collection, and some semi-automation was introduced for the WFT data collection and calculations.

For several of the wells, selected together with the project participants in 2013 for the database extension, and for which queries on the DINO database revealed that pressure data would be present, the data collection process confirmed absence of pressure data. This has been discussed during project progress meetings and project participants were given the opportunity to review and comment on the data status for all wells at some intermediate points, see also section 2.1. Via interaction with the participants on data status, an agreement was obtained on the final set of wells to become the subject of the database extension.

Six projects meetings took place and which consisted of one kick-off meeting, four progress meetings and one final meeting. Minutes of these meetings were made and distributed to the participants and which were accompanied by the meeting presentations. In each meeting the status of the project activities were presented and discussed, whereas upcoming activities and approaches were explained and the subject of feedback. At several meetings some project participants took the opportunity to present on specific aspects of, relevance for and on application of a pressure database in their organization.

The project participants agreed to have a steering committee in place in line with the role as described in the project participation agreement. This committee had a representative from each of the project participants, including a representative from TNO, and took the opportunity on two occasions to discuss on the project status and to provide feedback and requests to the project team. During the project progress meetings that took place in the first half of 2014 the project team started to discuss specifics, set-up and usability issues of the deliverables of the project. As a result it was agreed to issue a request to the subsidy provider RVO for an administrative extension of three months for the project, in order to be able to provide the deliverables and finish the project after summer 2014, instead of by the end of July 2014.

Quarterly project status reports for TKI Gas were provided to the subsidy provider RVO which were short reports (Excel-sheet reporting financial status and pdf-form on progress of the project work packages), that were not shared with the project participants. Furthermore, during the project two times the project has been presented and which concerned:

- Presentation together with one of the project participants at the Innovation Program Upstream Gas Symposium December 2, 2013, Scheveningen, the Netherlands.
- Poster “Pressure Information System of the onshore and offshore Netherlands” at the 76th EAGE Conference & Exhibition 2014, Amsterdam, June 2014.

5.2 Confidentiality of project results and follow-up activities

<THIS PAGE IS INTENTIONALLY FURTHER LEFT BLANK>

6 Conclusions and recommendations

In this project on the integrated pressure information system for the onshore and offshore Dutch subsurface the following results have been obtained.

The system's MS Access database has been extended with data from 450 wells and which includes 415 wells with pressure data. Not all wells have been subject of a complete study on pressure condition data as mainly DST measurements were not always taken into account. Quality coding has been applied in the same way as for the 2007 version of the database and information of this existing database has been enhanced and updated. The new database now contains 1145 wells, with almost 1100 wells with pressure data. On average the database information content has been extended by 37%, where the extension of data added for mudweights, DST pressures and temperatures and for formation water chemistry is somewhat lower (10-30%) For several other data types the extension is higher.

To the overpressure database, 777 calculated overpressure values were added, and the database now contains a total of 2025 values. Furthermore, a database with 273 water salinity and water resistivity values for a subset of wells in the MS Access database extension was developed. Both databases contain the additional information required for the specific calculation methods applied in the project to determine the overpressure and salinity/resistivity values.

The new pressure data compiled in the project provides hitherto lacking information on the central and southern part of the Dutch onshore subsurface and allowed a more detailed characterization and interpretation of the pressure condition for the entire Dutch onshore and offshore subsurface. The regional distribution of fluid pressures in the onshore and offshore subsurface shows great spatial variations on different scales, both laterally in individual reservoirs and vertically. On a large regional scale the fluid pressures and leak-off pressures show a clear difference between conditions in the southernmost structural elements (Central Netherlands Basin, Western Netherlands Basin, Roer Valley Graben, southern part Broad Fourteens Basin, Indefatigable Platform, Zeeland High), where close to normal fluid pressures exist that are well below leak-off pressures and conditions in the north and northeast, where fluids in pre-Cenozoic units exhibit - in varying degrees - overpressuring. As observed before, the regional difference in fluid overpressure can in large part be explained by differences in lithostratigraphic build-up and structural framework in combination with burial history.

The new data revealed a number of new and interesting features:

- The occurrence of formation water overpressures in Schieland/Scruff Group and younger units is restricted to the offshore north of the Wadden Islands. Overpressures extend southward into the northern and north eastern onshore (in Rotliegend in Lauwerszee Trough and Groningen Platform, in Triassic, Rotliegend and Carboniferous Limburg Group in Lower Saxony Basin, in Carbonifeous Limestone Group in Groningen Platform and Texel IJsselmeer High).
- High Pressure High Temperature conditions were encountered in the Lower Volpriehausen Sandstone Member and Lower Slochteren Sandstone Member in the southern part of the Dutch Central Graben and Terschelling Basin, and in the Carboniferous Limestone Group in the northern part of the Groningen Platform.
- Thick Paleogene mudstones of large regional extent form a transition zone between the normally pressured Upper North Sea group sediments and overpressured pre-Cenozoic units in the northern offshore.

- Zechstein salt structures, evaporite members of the Upper Germanic Trias Group, and the Silverpit Evaporite Member are the most important low permeable units restricting fluid flow and preserving overpressured conditions at greater depth. This is apparent in the highly overpressured Jurassic and Triassic units that are laterally hydraulically restricted by Zechstein salt structures and vertically restricted by Upper Triassic evaporite units in e.g. the Terschelling Basin and Dutch Central Graben, and in Rotliegend units below the Zechstein. Local overpressured compartments have been identified in the P6/P9 fault zone in the otherwise normally pressured West Netherlands Basin. The narrow fault bounded overpressured compartments have Upper Triassic evaporite members as top seal, while the permeability of the bounding faults have probably been reduced by smearing with evaporitic clay from these Upper Triassic units.
- In addition to the above mentioned low permeable stratigraphic units, the new pressure data from the deep wells (UHM-02 and LTG-01) show that the pressure condition in older deeply buried units have been preserved by large thickness of overlying sediments of decreased permeability that increase vertical dissipation times of overpressure by Darcy flow.
- Although depth exerts a first order control on the magnitude of fluid pressures, pressure does not always increase with depth. Pressure reversals occur between highly overpressured Zechstein units and underlying less overpressured Upper Rotliegend units, and also between more overpressured compartmentalized Triassic units and less overpressured hydraulically more continuous Rotliegend and Carboniferous units in for example the Lower Saxony Basin and Central Offshore Platform.
- The characterization of the fluid pressure, leak-off pressure and lithostatic pressure trends per structural element have provided a more detailed insight into the variation in pressure-stress relations, including the following observations:
    - The lower bound of the leak-off pressures follows the standard principal minimum horizontal stress gradient at shallow depths (< 2 km) in all structural elements. Pressure stress coupling is apparent in the significantly overpressured parts of structural elements in the northern and northeastern offshore (Step Graben, Dutch Central Graben, Terschelling Basin, Schill Grund Platform) and in the onshore (Lauwerszee Trough, Lower Saxony Basin) where the lower bound of the measured leak-off pressures is shifted to higher values.
    - Fluid pressures reach leak-off pressures at shallow depth (e.g. in Chalk Group, in Step and Dutch Central grabens) and at greater depth (e.g. in Triassic and Rotliegend units in the grabens, Terschelling Basin and northern part Central Offshore Platform)
    - Spatial variation in lithostatic pressure trends were calculated at 25 well locations representative of the different structural elements. The calculations were based on density logs and in addition, at 14 well locations, with simulated density and lithostatic pressures from basin modeling results. The presence of low density recent sediments of the North Sea Supergroup and of halite units of the Zechstein Group were found to result in deviations of the standard lithostatic pressure gradients of 23 MPa/km. The regional effect of the low density North Sea Supergroup reduces the lithostatic pressures in these sediments and in underlying older units and is greatest in areas with the largest thickness of the North Sea Supergroup sediments, i.e. in the northern offshore. The reduction in lithostatic pressure due to the presence of Zechstein halites is greatest in areas where large salt structures occur, i.e. in northern onshore and offshore. The largest local deviations from the standard lithostatic pressure gradient occur in areas with a thick package of North Sea Super Group sediments and large salt structures.

The new pressure information system for the on- and offshore Dutch subsurface accomplished in this project, and which consists of several components, has been delivered in steps to the participating operators in the second part of 2014 and the beginning of 2015. An entire listing of all components is found in the two appendices of this report. With the new system, quantitative knowledge and understanding of the distribution of pore fluid pressures and fluid dynamic conditions in the onshore and offshore Dutch subsurface has been improved and can be further improved by use of the MS Access databases and the other components of the system.

The new system includes a regional overview, characterization and interpretation of fluid pressure distributions in relation to leak-off pressures, standard hydrostatic and lithostatic pressures and geological framework. The wealth of pressure, temperature, salinity and hydrochemistry data in the database makes a more detailed characterization and interpretation of the pressure data possible. Analysis of temperature, salinity and hydrochemistry data was not part of the current project. It is recommended for future research projects to use all the data in the database in relation to the geological framework and geological history, e.g. for mapping pressure compartments and vertical leakage zones and for identifying reservoir continuity.

Furthermore, it is recommended to keep on having a platform to exchange information and knowledge on a regular basis on the application of the results of the project, such as the databases. Such a platform can identify further scope for enhancement and updates of the databases such as to cover any observations on the information already included, information on specific wells not yet included, information for exploration and appraisal wells that becomes public during the coming years, and to cover additional data sets on Dutch boreholes that may be available. Follow-up activities for the participating operators have been identified, and the project that is expected to be defined will hopefully be a means to establish such a platform. More organizations active in the Dutch on- and offshore should get the option to join such a platform.

7 References

Batzle, M & Wang, Z., 1992. Seismic properties of pore fluids. Geophysics, Vol. 57, no. 11, 1396-1408.

Corona, F.V., 2005. Fault trap analysis of the Permian Rotliegend gas play, Lauwerszee Trough, NE Netherlands. In: Dore, A.G. & Vining, B.A. (eds). Petroleum Geology: North-West Europe and global perspectives: Proceedings of the 6th Petroleum Geology Conference: 327-335.

Corona, F.V., Davis, J.S., Hippler, S.J. & Vrolijk, P.J., 2010. Multi-fault analysis scorecard: testing the stochastic approach in fault seal prediction. In: Jolley, S.J., Fisher, Q.J., Ainsworth, R.B., Vrolijk, P.J., Delisle, S. (eds). Reservoir Compartmentalization. Geological Society Special Publication 347. The Geological Society (London): 317-332.

Doornenbal, J.C. & Stevenson, A.G. (eds), 2010. Petroleum Geological Atlas of the Southern Permian Basin Area. EAGE Publications b.v. (Houten, the Netherlands).

Duin, E.J.T., Doornenbal, J.C., Rijkers, R.H.B., Verbeek, J.W. & Wong, Th.E., 2006. Subsurface structure of the Netherlands – results of recent onshore and offshore mapping. Netherlands Journal of Geosciences – Geologie en Mijnbouw 85 (4): 245-276.

Evans, D., Graham, C., Armour, A. & Bathurst, P.(eds), 2003. The Millennium Atlas: Petroleum geology of the central and northern North Sea. Geological Society of London.

Geluk, M.C., 1999. Paleogeographic and structural development of the Triassic in the Netherlands – new insights. In: Bachmann, G.H. & Lerche, I. (eds). The epicontinental Triassic. Zentralblatt für Geologie and Paläontology 7-8: 727-745.

Jaarsma, B., Brolsma, M.J., Hoetz, G. & Lutgert, J.E., 2013. Exploring Dinantian Carbonates in the SNS – New data offering new insights. Extended abstract. 75th EAGE Conference & Exhibition incorporating SPE EUROPEC 2013, London, UK, 10-13 June 2013.

Japsen, P., 1999. Overpressured Cenozoic shale mapped from velocity anomalies relative to a baseline for marine shale, North Sea. Petroleum Geoscience 5: 321-336.

Kombrink, H., 2008. The Carboniferous of the Netherlands and surrounding areas; a basin analysis. PhD thesis. GEOLOGICA ULTRAIECTINA Mededelingen van de Faculteit Geowetenschappen departement Aardwetenschappen Universiteit Utrecht No. 294, 184 p.

Kombrink, H., Doornenbal, J.C., Duin, E.J.T., Den Dulk, M., Van Gessel, S.F., Ten Veen, J.H. & Witmans, N., 2012. The geological structure of the Netherlands Continental Shelf; results of a detailed mapping project. Netherlands Journal of Geosciences, Volume 91 (4), 403-418.

Leonard, R.C., 1993. Distribution of sub-surface pressure in the Norwegian Central Graben and applications for exploration. In: Parker, J. R. (ed) Petroleum Geology of the Northwest Europe: Proceedings of the 4th Conference. Geological Society, London, 1295-1303.

Mijnlieff, H. & Geluk, M., 2012. Palaeotopography-governed sediment distribution—a new predictive model for the Permian Upper Rotliegend in the Dutch sector of the Southern

Permian Basin. In: Grötsch, J. & Gaupp, R. (eds). The Permian Rotliegend of the Netherlands. SEPM Special publication 98, SEPM Society of Sedimentary Geology (Tulsa, USA): 147-160.

Milton-Worssell, R., 2009. Potential to Production – Conventional HPHT (300 ºF 10,000psi) to extreme HPHT (350 ºF 15,000 psi) on the UKCS, 2009, HPHT Arena 2009. A one day workshop dedicated to the North Sea's hottest plays, 11 December 2009.

Munsterman, D.K., Verreussel, R.M.C.H., Mijnlieff, H.F., Witmans, N., Kerstholt-Boegehold, S. & Abbink, O.A., 2012. Revision and update of the Callovian-Ryazanian Stratigraphic nomenclature in the northern Dutch offshore, i.e. Central Graben Subgroup and Scruff Group. Netherlands Journal of Geosciences, Volume 91 (4), 555-590.

Nelskamp. S., Verweij, J.M. & Witmans, N., 2012. The role of salt tectonics and overburden in the generation of overpressure in the Dutch North Sea area. Netherlands Journal of Geosciences, Volume 91 (4), 517-534.

O'Connor, S.A. & Swarbrick, R.E., 2008. Pressure regression, fluid drainage and a hydrodynamically controlled fluid contact in the North Sea, Lower Cretaceous, Britannia Sandstone Formation. Petroleum geoscience, Vol.14, 116-126.

Peters, E., Verweij, J.M., 2012. An investigation of fault sealing in the Dutch offshore based on virgin overpressures. TNO report TNO-060-UT-011-02158, 46p.

Robertson, J. 2013. Overpressure and lateral drainage in the Paleogene strata of the Central North Sea. Durham theses, Durham University. Available at Durham E-Theses online (http://etheses.dur.ac.uk/9452/), 252 pp.

Robertson, J., Goulty, N. R. & Swarbrick, R. E. 2013. Overpressure distributions in Palaeogene reservoirs of the UK Central North Sea and implications for lateral and vertical fluid flow. Petroleum Geoscience, v. 19, p. 223-236.

Simmelink, H.J., Underschultz, J.R., Verweij, J.M. & Otto, C.J., 2004. A pressure and fluid dynamic study of the Southern North Sea Basin – Final report. Netherlands Institute of Applied Geoscience TNO-National Geological Survey. TNO-report NITG 04-94-C.

Simmelink, H.J., Verweij, J.M. & Underschultz, J., 2008. PressureSNS-2-Pressure and fluid dynamic study of the Offshore and northern Onshore Netherlands. TNO Built Environment and Geosciences-National Geological Survey, Utrecht, the Netherlands. TNO report 2008-U-R-0509/C.

TNO-NITG, 2004. Geological Atlas of the Subsurface of the Netherlands –onshore. Netherlands Institute of Applied Geoscience TNO- National Geological Survey (Utrecht): 103 pp.

Van Adrichem Boogaert, H.A. & Kouwe, W.F.P. (eds), 1993-1997. Stratigraphic nomenclature of the Netherlands, revision and update by RGD and NOGEPA. Mededelingen Rijks Geologische Dienst 50.

Van Hulten, F.F.N., 2010. Geological factors effecting compartmentalization of Rotliegend gas fields in the Netherlands. In: Jolley, S.J., Fisher, Q.J., Ainsworth, R.B., Vrolijk, P.J. & Delisle,

S. (eds). Reservoir Compartmentalization. Geological Society Special Publication 347. The Geological Society (London): 301-315.

Verweij, H., 2006. Dual hydraulic behaviour of the Chalk in the Netherlands North Sea. Journal of Geochemical Exploration 89: 405-408.

Verweij, H., Simmelink, E. & Underschultz, J., 2011. Pressure and fluid flow systems in the

Permian Rotliegend in the Netherlands on- and offshore. In: Grötsch, J. & Gaupp, R. (eds). The Permian Rotliegend of the Netherlands. SEPM Special publication 98, SEPM Society of Sedimentary Geology (Tulsa, USA): 247-263.

Verweij, J.M. & Simmelink, H.J., 2002. Geodynamic and hydrodynamic evolution of the Broad Fourteens Basin (the Netherlands) in relation to its petroleum systems. Marine and Petroleum Geology 19: 339-359.

Verweij, J.M., 1999. Application of fluid flow systems analysis to reconstruct the post-Carboniferous hydrogeohistory of the onshore and offshore Netherlands. Marine and Petroleum Geology 16: 561-579.

Verweij, J.M., 2003. Fluid flow systems analysis on geological timescales in onshore and offshore Netherlands; with special reference to the Broad Fourteens Basin. Netherlands Institute of Applied Geoscience TNO-National Geological Survey, Utrecht, the Netherlands. PhD-thesis. ISBN 90-5986-035-7, 278 p. (Pdf-copy for download available at *www.nlog.nl*).

Verweij, J.M., Simmelink, H.J., Underschultz, J. & Witmans, N., 2012. Pressure and fluid dynamic characterisation of the Dutch subsurface. Netherlands Journal of Geosciences, Volume 91 (4), 465-490.

Winthaegen, P.L.A. & Verweij, J.M., 2003. Estimating regional pore pressure distribution using 3D seismic velocities in the Dutch Central North Sea Graben. Journal of Geochemical Exploration 78-79: 203-207.

Wong, Th.E., Batjes, D.A.J. & De Jager, J. (eds), 2007. Geology of the Netherlands. Royal Netherlands Academy of Arts and Sciences: 354 pp.

Zoback, M.D., 2010. Reservoir Geomechanics. Cambridge University Press (United Kingdom): 449 pp.

8 APPENDIX-A Databases

8.1 Quality-controlled MS Access pressure-hydrodynamics database

Two versions of this pressure-hydrodynamics database have been delivered for this project: one beta version by the end of June 2014 and the final version mid-September 2014. Furthermore, soon after the start of the project in April 2013 the MS Access database compiled in the previous decade (and all other results like the project reports) in two joint-industry projects (executed by TNO together with CSIRO, Australia) were made available (again) to the 7 participating Dutch operators in the current project

8.1.1 MS Access database, version 2010, delivered April 2013

So-called PSNS12 database has been delivered via the archive

PSNS1-2_release.zip

with as main contents:
- Folder *database_msaccess_2000* with pressure-hydrodynamics database for office versions 2000-2003,
- Folder *database_msaccess_2010* with pressure-hydrodynamics database for office versions 2007-2010,
- Folder *pressureplot_CSIRO_downloads* with visualization tool for this pressure-hydrodynamics database as developed by CSIRO,
- Folder *PressureSNS1&2_2002-2007* with final reports of the projects of previous decade and Excel overview of data types and wells present,
- Two documents with instructions for picking up contents of archive.

8.1.2 MS Access database Beta version, June 2014

Beta version of pressure-hydrodynamics database, only for office versions 2007-2010, has been delivered via the archive

PressureSNS-123_databaseV3_MS2_26062014.7z

with as contents:
- File *PressureSNS-12_databaseV3_MS2_26062014.accd*b with PSNS12 database, beta-version June 2014,
- File *DataOverView_PSNS12_MS2.xlxs* with overview of data types, number of data points and wells present in PSNS12 database,
- File *PressureSNS-3_databaseV3_MS2_26062014.accdb* with so-called PSNS3 database extension (as developed in current project), beta-version June 2014,
- File *DataOverView_PSNS3_MS2.xlsx* with overview of data types, number of data points and wells present in PSNS3 database,
- File *PressureSNS-123_databaseV3_MS2_26062014.accdb* with PSNS123 database (integrated from PSNS12 and PSNS3 databases), beta-version June 2014,
- File *DataOverView_PSNS123_MS2.xlsx* with overview of data types, number of data points and wells present in PSNS123 database.

8.1.3 MS Access database final version, September 2014

Final version for project of pressure-hydrodynamics database, only for office versions 2007-2010, has been delivered via the archive

JIP_PSNS_MSACCESS_DB_V3_Sep2014.zip

with as contents:
- File *PressureSNS-12_database_V3_Sep2014.accdb* with PSNS12 database, final version September 2014,
- File *DataOverView_PSNS12_V3_Sep2014.xlsx* with overview of data types, number of data points and wells present in PSNS12 database,
- File *PressureSNS-3_database_V3_Sep2014.accdb* with so-called PSNS3 database extension (as developed in current project), final version September 2014,
- File *DataOverView_PSNS3_V3_Sep2014.xlsx* with overview of data types, number of data points and wells present in PSNS3 database,
- File *PressureSNS-123_database_V3_Sep2014.accdb* with PSNS123 database (integrated from PSNS12 and PSNS3 databases), final version September 2014,
- File *DataOverView_PSNS123_V3_Sep2014.xlsx* with overview of data types, number of data points and wells present in PSNS123 database.

8.1.4 Geographical overview of wells in database extension

The wells in the database extension have been displayed in a geographical overview (with in background wells of PSNS12 database) via the following two files:
- Structural_elements_2012_psns3wells.pdf,
- Structural_elements_2012_psns3wells_A0.pdf

8.1.5 Additional overviews for database

Overviews were delivered and which have been generated and maintained during the current project and which concern the following files:
- *All expl&eval wells Public before end July 2014.xlsx*: Overview of (mainly) all exploration and evaluation wells for which data became public before July 2014 together with any status for the PSNS123 database and/or indication of availability of any relevant pressure data,
- *JIP_PSNS_DB_data_overview_14102014.xlsx*: Overview of all exploration and evaluation wells (subset of the wells in *All expl&eval wells Public before end July 2014.xlsx*) that have been subject of project for the PSNS3 database extension,
- *JIP_PSNS_lithostrat_codes.xls*: Overview of the lithostratigraphic codes as applied in the database.

8.2 Databases with calculated data

The following databases in Excel format with derived data have been developed for the project and which became available to the project participants:

- *20140923_OP_PSNS123.xls*: Contains pore fluid overpressures and pore water overpressures calculated for those wells in the MS Access database for which appropriate pressure test data is available,
- *Density_Salinity_Rw_08092014.xlsx*: Fluid densities, salinities and resistivities determined for the wells in the MS Access database for which wireline formation test (WFT) data of sufficient quality is available.

9 APPENDIX-B Visualization products

9.1 Overpressure distributions in map view

For the main reservoirs units distributions of pore fluid and pore water overpressure in map view have been delivered and which displays are listed in the following sections. Furthermore, the ArcGIS projects used to generate these maps have been delivered with these displays.

9.1.1 Pore fluid overpressures

Maps with pore fluid overpressure with the following titles (in alphabetic order) have become available:

i. All fluid Overpressure Altena Group
File name: *OP_depth_AT_05_09_2014.pdf*,

ii. All fluid Overpressure Chalk Group
File name: *OP_depth_CK_05_09_2014.pdf*,

iii. All fluid Overpressure Limburg Group
File name: *OP_depth_DC_05_09_2014.pdf*,

iv. All fluid Overpressure Rijnland Group
File name: *OP_depth_KN_08_09_2014.pdf*,

v. All fluid Overpressure Friesland/Kotter Member (KNNSF/KNNSK)
File name: *OP_depth_KNNSF_KNNSK_08_09_2014.pdf*,

vi. All fluid Overpressure Rijswijk /De Lier Member (KNNSR/KNNSL)
File name: *OP_depth_KNNSR_KNNSL_08_09_2014.pdf*,

vii. All fluid Overpressure North Sea Group
File name: *OP_depth_N_05_09_2014.pdf*,

viii. All fluid Overpressure Lower GermanicTrias Group
File name: *OP_depth_RB_05_09_2014.pdf*,

ix. All fluid Overpressure Lower Detfurth Sandstone Member (RBMDL)
File name: *OP_depth_RBMDL_08_09_2014.pdf*,

x. All fluid Overpressure Lower Volpriehausen Sandstone Member (RBMVL)
File name: *OP_depth_RBMVL_05_09_2014.pdf*,

xi. All fluid Overpressure Upper GermanicTrias Group
File name: *OP_depth_RN_05_09_2014.pdf*,

xii. All fluid Overpressure Röt Fringe Sandstone Member (RNROF)
File name: *OP_depth_RNROF_05_09_2014.pdf*,

xiii. All fluid Overpressure Basal Solling Sandstone Member (RNSOB)
File name: *OP_depth_RNSOB_05_09_2014.pdf*,

xiv. All fluid Overpressure Lower Slochteren Member (ROSLL)
File name: *OP_depth_ROSLL_08_09_2014.pdf*,

xv. All fluid Overpressure Upper Slochteren Member/ Slochteren Formation (ROSLU/ROSL)
File name: *OP_depth_ROSLU_ROSL_08_09_2014.pdf*,

xvi. All fluid Overpressure Schieland/Scruff/Niedersachsen Group
File name: *OP_depth_S_08_09_2014.pdf*,

xvii. All fluid Overpressure Scruff Greensand Formation / Scruff Spiculite Member (SGGS/SGGSP)
File name: *OP_depth_SGGS_SGGSP_08_09_2014.pdf*,

xviii. All fluid Overpressure Terschelling Sandstone Member / Scruff Basal Sandstone Member (SLCFT/SGGSB)

File name: *OP_depth_SLCFT_SGGSB_05_09_2014.pdf*,

xix. All fluid Overpressure Lower Graben Formation (SLCL)
File name: *OP_depth_SLCL_05_09_2014.pdf*,

xx. All fluid Overpressure Zechstein Group
File name: *OP_depth_ZE_05_09_2014.pdf*,

xxi. All fluid Overpressure Friesland/Kotter Member (KNNSF/KNNSK)
File name: *OP_permeab_KNNSF_KNNSK_08_09_2014.pdf*,

xxii. All fluid Overpressure Rijswijk /De Lier Member (KNNSR/KNNSL)
File name: *OP_permeab_KNNSR_KNNSL_08_09_2014.pdf*,

xxiii. All fluid Overpressure Lower Detfurth Sandstone Member (RBMDL)
File name: *OP_permeab_RBMDL_08_09_2014.pdf*,

xxiv. All fluid Overpressure Lower Volpriehausen Sandstone Member (RBMVL)
File name: *OP_permeab_RBMVL_05_09_2014.pdf*,

xxv. All fluid Overpressure Röt Fringe Sandstone Member (RNROF)
File name: *OP_permeab_RNROF_05_09_2014.pdf*

xxvi. All fluid Overpressure Basal Solling Sandstone Member (RNSOB)
File name: *OP_permeab_RNSOB_05_09_2014.pdf*,

xxvii. All fluid Overpressure Lower Slochteren Member (ROSLL)
File name: *OP_permeab_ROSLL_08_09_2014.pdf*,

xxviii. All fluid Overpressure Upper Slochteren Member/Slochteren Formation (ROSLU/ROSL)
File name: *OP_permeab_ROSLU_ROSL_08_09_2014.pdf*.

9.1.2 Pore water overpressures

Maps with pore water overpressure with the following titles (in alphabetic order) have become available:

i. Formation water Overpressure Altena Group
File name: *FWOP_AT_05_09_2014.pdf*,

ii. Formation water Overpressure Chalk Group
File name: *FWOP_CK_05_09_2014.pdf*,

iii. Formation water Overpressure Limburg Group
File name: *FWOP_DC_05_09_2014.pdf*,

iv. Formation water Overpressure Rijnland Group
File name: *FWOP_KN_08_09_2014.pdf*,

v. Formation water Overpressure Lower GermanicTrias Group
File name: *FWOP_RB_05_09_2014.pdf*,

vi. Formation water Overpressure Lower Dethfurt Sandstone Member (RBMDL)
File name: *FWOP_RBMDL_05_09_2014.pdf*,

vii. Formation water Overpressure Lower Volpriehausen Sandstone Member (RBMVL)
File name: *FWOP_RBMVL_05_09_2014.pdf*,

viii. Formation water Overpressure Upper GermanicTrias Group
File name: *FWOP_RN_05_09_2014.pdf*,

ix. Formation water Overpressure Lower Slochteren Member (ROSLL)
File name: *FWOP_ROSLL_09_09_2014.pdf*,

x. Formation water Overpressure Upper SlochterenMember/Slochteren Formation (ROSLU/ROSL)
File name: *FWOP_ROSLU_ROSL_08_09_2014.pdf*,

xi. Formation water Overpressure Schieland/Scruff Group
File name: *FWOP_S_05_09_2014.pdf*,

xii. Formation water Overpressure Lower Graben Formation (SLCL)

File name: *FWOP_SLCL_05_09_2014.pdf*,

xiii. Formation water Overpressure Zechstein Group
File name: *FWOP_ZE_05_09_2014.pdf*.

9.1.3 ArcGIS projects

The maps as listed in the previous sections have been generated with ArcGIS and the specific projects have been made available via the archives

JIP_PSNS_digitalmaps_26092014.zip
JIP_PSNS_ArcGISProject_Update_29092014.zip

where the latter archive contains an update for several ArcGIS projects to have proper relatives paths.

The set-up and contents of the main

ArcGISProject

folder concern:

- Subfolders for the different main geological units N – ZE under which subfolders reside with the grids used and the set-up of the legend applied.
- *shape* subfolder for the GIS-files with general topographical features applied
- *excel* subfolder where the overpressure database (see Appendix-A-8.2) should be located
- ArcGIS projects (*mxd*-files) with relative paths such that when main folder is copied all data keeps on being available for the projects. E.g. when overpressure database would be further enhanced all projects are automatically updated.

9.2 Pressure distributions in cross section view

Three cross sections with pressures and overpressure distribution in relation to geologic and fluid geologic framework have been generated and which concern:

i. Regional SW to NE cross section through onshore Netherlands, showing the distribution of observed fluid overpressures and its relation with the geological framework.
File name: *profiel_offshore_WO.pdf*,

ii. Regional W to E cross section through offshore Netherlands (Cleaverbank Platform, Dutch Central Graben, Terschelling Basin, Schill Grund High), showing the distribution of observed fluid overpressures and its relation with the geological framework.
File name: *profiel_offshoreZN.pdf*,

iii. Regional S to N cross section through offshore Netherlands (Central Offshore Platform, Terschelling Basin, Schill Grund High), showing the distribution of observed fluid overpressures and its relation with the geological framework.
File name: *profiel_onshore_NZ.pdf*.

9.3 Leak-off pressure and pore fluid pressure data in cross plots

Several cross plots of leak-off and pore fluid pressure data in relation to standard stress gradients for the main lithostratigraphic units and structural elements have been generated for the project. These have been delivered in four pdf-files and which contents are listed in the following sections.

9.3.1 Multi-well cross plots of leak-off pressure versus depth per main stratigraphic units

File name: *Plots_LOPs_Strat.pdf*
With the following plots after an introduction starting on page 4:

i. Cross plot of all leak-off pressures versus depth for the main stratigraphic units,
ii. Cross plot of leak-off pressure versus depth for the North Sea Supergroup,
iii. Cross plot of leak-off pressure versus depth for the Chalk Group,
iv. Cross plot of leak-off pressure versus depth for the Rijnland Group,
v. Cross plot of leak-off pressure versus depth for the Scruff/Schieland groups,
vi. Cross plot of leak-off pressure versus depth for the Altena Group,
vii. Cross plot of leak-off pressure versus depth for the Upper Germanic Trias Group,
viii. Cross plot of leak-off pressure versus depth for the Lower Germanic Trias Group,
ix. Cross plot of leak-off pressure versus depth for the Zechstein Group,
x. Cross plot of leak-off pressure versus depth for the Upper Rotliegend Group,
xi. Cross plot of leak-off pressure versus depth for the Limburg Group.

9.3.2 Multi-well cross plots of leak-off pressure versus depth per main structural elements and main stratigraphic units

File name: *Plots_LOPs_Struct&Strat.pdf*
With the following plots starting on page 3:

i. Cross plot of leak-off pressure versus depth for the Step Graben,
ii. Cross plot of leak-off pressure versus depth for the Dutch Central Graben,
iii. Cross plot of leak-off pressure versus depth for the Terschelling Basin,
iv. Cross plot of leak-off pressure versus depth for the Schillgrund Platform,
v. Cross plot of leak-off pressure versus depth for the Ameland Platform,
vi. Cross plot of leak-off pressure versus depth for the Elbow Spit Platform,
vii. Cross plot of leak-off pressure versus depth for the Cleaverbank Platform,
viii. Cross plot of leak-off pressure versus depth for the Central Offshore Platform,
ix. Cross plot of leak-off pressure versus depth for the Broad Fourteens Basin,
x. Cross plot of leak-off pressure versus depth for the Indefatigable Platform,
xi. Cross plot of leak-off pressure versus depth for the Vlieland basin,
xii. Cross plot of leak-off pressure versus depth for the Friesland Platform,
xiii. Cross plot of leak-off pressure versus depth for the Lauwerszee trough,
xiv. Cross plot of leak-off pressure versus depth for the Groningen platform,
xv. Cross plot of leak-off pressure versus depth for the Texel IJsselmeer High,
xvi. Cross plot of leak-off pressure versus depth for the Lower Saxony basin,
xvii. Cross plot of leak-off pressure versus depth for the Central Netherlands Basin,
xviii. Cross plot of leak-off pressure versus depth for the West Netherlands Basin,
xix. Cross plot of leak-off pressure versus depth for the Roer Valley Graben,
xx. Cross plot of leak-off pressure versus depth for the Zeeland High.

9.3.3 Multi-well cross plots of fluid pressure versus depth per main stratigraphic units

File name: *Plots_P_Strat.pdf*
With the following plots after an introduction starting on page 3:

i. Cross plot of all fluid pressure versus depth for the main stratigraphic units,
ii. Cross plot of fluid pressure versus depth for the North Sea Supergroup,
iii. Cross plot of fluid pressure versus depth for the Chalk Group,
iv. Cross plot of fluid pressure versus depth for the Rijnland Group,
v. Cross plot of fluid pressure versus depth for the Scruff/Schieland/Niedersachsen groups,
vi. Cross plot of fluid pressure versus depth for the Altena Group,
vii. Cross plot of fluid pressure versus depth for the Upper Germanic Trias Group,
viii. Cross plot of fluid pressure versus depth for the Lower Germanic Trias Group,
ix. Cross plot of fluid pressure versus depth for the Zechstein Group,
x. Cross plot of fluid pressure versus depth for the Upper Rotliegend Group,
xi. Cross plot of fluid pressure versus depth for the Limburg Group.

9.3.4 Multi-well cross plots of fluid pressure and leak-off pressure versus depth per main structural elements and stratigraphic units

File name: *Plots_P&LOPs_Struct&Strat.pdf*
With the following plots after an introduction starting on page 4:

i. Cross plot showing all fluid pressures versus depth for the main stratigraphic units in combination with leak-off pressures,
ii. Cross plot of pressure and leak-off pressure versus depth for the Step Graben,
iii. Cross plot of pressure and leak-off pressure versus depth for the Dutch Central Graben,
iv. Cross plot of pressure and leak-off pressure versus depth for the Terschelling Basin,
v. Cross plot of pressure and leak-off pressure versus depth for the Schillgrund Platform,
vi. Cross plot of pressure and leak-off pressure versus depth for the Ameland Platform,
vii. Cross plot of pressure and leak-off pressure versus depth for the Elbow Spit Platform,
viii. Cross plot of pressure and leak-off pressure versus depth for the Cleaverbank Platform,
ix. Cross plot of pressure and leak-off pressure versus depth for the Central Offshore Platform,
x. Cross plot of pressure and leak-off pressure versus depth for the Groningen platform,
xi. Cross plot of pressure and leak-off pressure versus depth for the Lauwerszee trough,
xii. Cross plot of pressure and leak-off pressure versus depth for the Friesland Platform,
xiii. Cross plot of pressure and leak-off pressure versus depth for the Vlieland basin,
xiv. Cross plot of pressure and leak-off pressure versus depth for the Texel IJsselmeer High,
xv. Cross plot of pressure and leak-off pressure versus depth for the Lower Saxony basin,
xvi. Cross plot of pressure and leak-off pressure versus depth for the Central Netherlands Basin,
xvii. Cross plot of pressure and leak-off pressure versus depth for the Roer Valley Graben,
xviii. Cross plot of pressure and leak-off pressure versus depth for the West Netherlands Basin,

xix. Cross plot of pressure and leak-off pressure versus depth for the Broad Fourteens Basin,
xx. Cross plot of pressure and leak-off pressure versus depth for the Indefatigable Platform,
xxi. Cross plot of pressure and leak-off pressure versus depth for the Zeeland High.