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Pressure and fluid dynamic characterisation of the Dutch subsurface

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Abstract

This paper presents and discusses the distribution of fluid and leak-off pressure data from the subsurface of onshore and offshore Netherlands in relation to causes of formation fluid overpressure and the permeability framework. The observed fluid pressure conditions demonstrate a clear regional difference between the southern and the north and north-eastern part of the study area. In the southern area, formation fluid pressures are close to normal and well below measured leak-off pressures. In the north, formation fluids are overpressured and may locally even approach the measured leak-off pressures. The regional differences in fluid overpressure can, in large part, be explained by differences in geologic framework and burial history. In the south, relatively low rates of sedimentary loading and the presence of relatively permeable sedimentary units have led to the currently observed normally pressured conditions. In the northern area, relatively rapid Neogene sediment loading plays an important role in explaining the observed overpressure distributions in Cenozoic mudstones, Cretaceous Chalk and Rijnland groups, and probably also in Jurassic units. The permeability framework of the northern and north-eastern area is significantly affected by Zechstein and Triassic salt deposits and structures. These units are characterised by very low permeability and severely restrict fluid flow and pressure dissipation. This has created hydraulically restricted compartments with high overpressures (for example overpressures exceeding 30 MPa in the Lower Germanic Trias Group in the Terschelling Basin and Dutch Central Graben).

Keywords: overpressures, leak-off pressures, fluid dynamics, the Netherlands, Dutch North Sea

Introduction

Worldwide growth in energy demands, as well as environmental concerns related to exploration and use of geo-energy resources affect the exploration and production strategies for these resources globally, and also in the Netherlands. Significant amounts of gas have been discovered and produced over the last 50 years in the Netherlands onshore and offshore and there remain potentially large volumes of gas yet to be found and developed (Herber & De Jager, 2010; EBN, 2011). Finding and producing more conventional and unconventional gas and oil before the currently aging infrastructure is abandoned is a high priority. There is also an increasing focus on alternative geo-energy supplies, such as geothermal energy, and on subsurface storage of hydrocarbon gases and CO_2. This has resulted in a rapid increase in the multiple-use of the Dutch subsurface pore space. It is a great challenge to ensure a responsible present and future use of the subsurface.

In this context, knowledge of the subsurface pressures and fluid dynamic conditions is of critical importance for safely optimising the responsible current and future use of the subsurface. Pre-drill knowledge on pore pressures and leak-off pressure conditions allows for appropriate selection of mud weight, well bore trajectories and drill casing programs, thereby enabling safe and cost-effective drilling. Research on pressure and fluid dynamics in sedimentary basins and the development and application of hydrodynamic analysis for characterising oil and gas resources in the Netherlands started in the late eighties and continued to develop ever since (Verweij, 1990a, b; Bloch et al., 1993; Verweij, 1999, 2003, 2006; Verweij & Simmelink, 2002;

Verweij et al., 2009a, b, 2011). In this paper we present and discuss the distribution of fluid pressures and leak-off pressures in relation to causes of fluid overpressure and the regional permeability framework in particular.

Database

Formation pressures encountered in oil and gas wells have been measured in the Netherlands for over 50 years by a wide range of companies using a variety of different tools and methodologies. An integrated database of pressure, leak-off pressure, temperature and water chemistry data was created during two joint-industry projects executed by TNO and CSIRO from 2002-2007. It was populated with information from about 700 oil and gas wells (Simmelink et al., 2003, 2008). The pore fluid pressures in the database include measured pressures in oil, gas and water phases. The leak-off pressure derived from real leak-off tests corresponds to fracture initiation. Most leak-off pressure data in the database, however, are from formation integrity tests and from reported leak-off pressure values (assumed to represent the highest pressure achieved during testing before actual leak-off) and may underestimate the strength of the tested formations.

From 2007 onward, the pressure and leak-off pressure database was further extended with a selection of measurements derived from about 100 additional onshore and offshore wells to a total amount of about 800 wells (Fig. 1). This pressure database provided the key data for this paper.

Approach

Hydrodynamic-based approaches were used to characterise and analyze the fluid pressure and leak-off pressure distributions in combination with stratigraphic and structural information. The hydrodynamic approaches involve the use of single-well and multi-well pressure-depth plots, regional overpressure maps and hydraulic head maps. Verweij (1993), Dahlberg (1995), Otto et al. (2001), Bachu & Michael (2002) and Verweij et al. (2011) provide an overview of hydrodynamic analysis techniques. Here we present pressure-depth plots, leak-off pressure-depth plots, and a selection of overpressure maps and cross-sections.

The overpressure, or excess pressure, 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 we used a hydrostatic gradient of 0.01 MPa/m that represents seawater density (1020 kg/m^3). In reality, the hydrostatic gradient is determined by the actual density of the formation water which is related to its salinity. The salinity of most of the formation water in the Dutch subsurface is well above that of seawater and shows large variations in all stratigraphic units (Verweij, 2003; Verweij et al., 2011). Fluid overpressures may also incorporate the effect of the density contrast between a petroleum fluid and pore water. Hence fluid overpressures may reflect pore water salinity, the density contrast between a petroleum fluid and pore water (if the pressure was measured in a petroleum fluid), as well as geological causes of overpressuring. In this paper 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'.

General factors of influence on pressure distributions

The virgin pore pressure conditions in the Dutch subsurface are controlled by the combined influence of a) past and/or ongoing pressure-influencing mechanisms, and b) characteristics of the geologic framework.

The existence of pore fluid overpressures indicates that there is disequilibrium between a) and b) in the sense that the fluid pressure regime has not adjusted to the evolving geologic framework and is in a transient state. The time required to propagate or dissipate pore water overpressures by water flow through a water-saturated permeable rock framework is proportional to its hydraulic diffusivity (related to properties such as porosity, permeability, compressibility of the rock and the viscosity and compressibility of the pore fluid). The propagation and dissipation of fluid overpressures by multiphase flow is in addition influenced by differences in capillary pressures of the rock framework.

A variety of mechanisms has been proposed to explain the generation of pore water overpressures in sedimentary basins (Mann & Mackenzie, 1990; Neuzil, 1995; Osborne & Swarbrick, 1997; Grauls, 1998; Yardley & Swarbrick, 2000; Yassir & Addis, 2002; Neuzil, 2003):

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.

Stress-related mechanisms are considered to be the most likely causes of overpressure in many sedimentary basins (e.g. Osborne & Swarbrick, 1997). An important stress-related mechanism is sedimentary loading. In reality, different pressure-influencing mechanisms may operate simultaneously during continuous burial of sedimentary units subject to sedimentary loading: not only the loading itself, but also aquathermal pressuring, dehydration of minerals and/or generation of gas, while fluid movement redistributes pressures continuously. Moss et al. (2003) indicated that stress-related mechanisms,

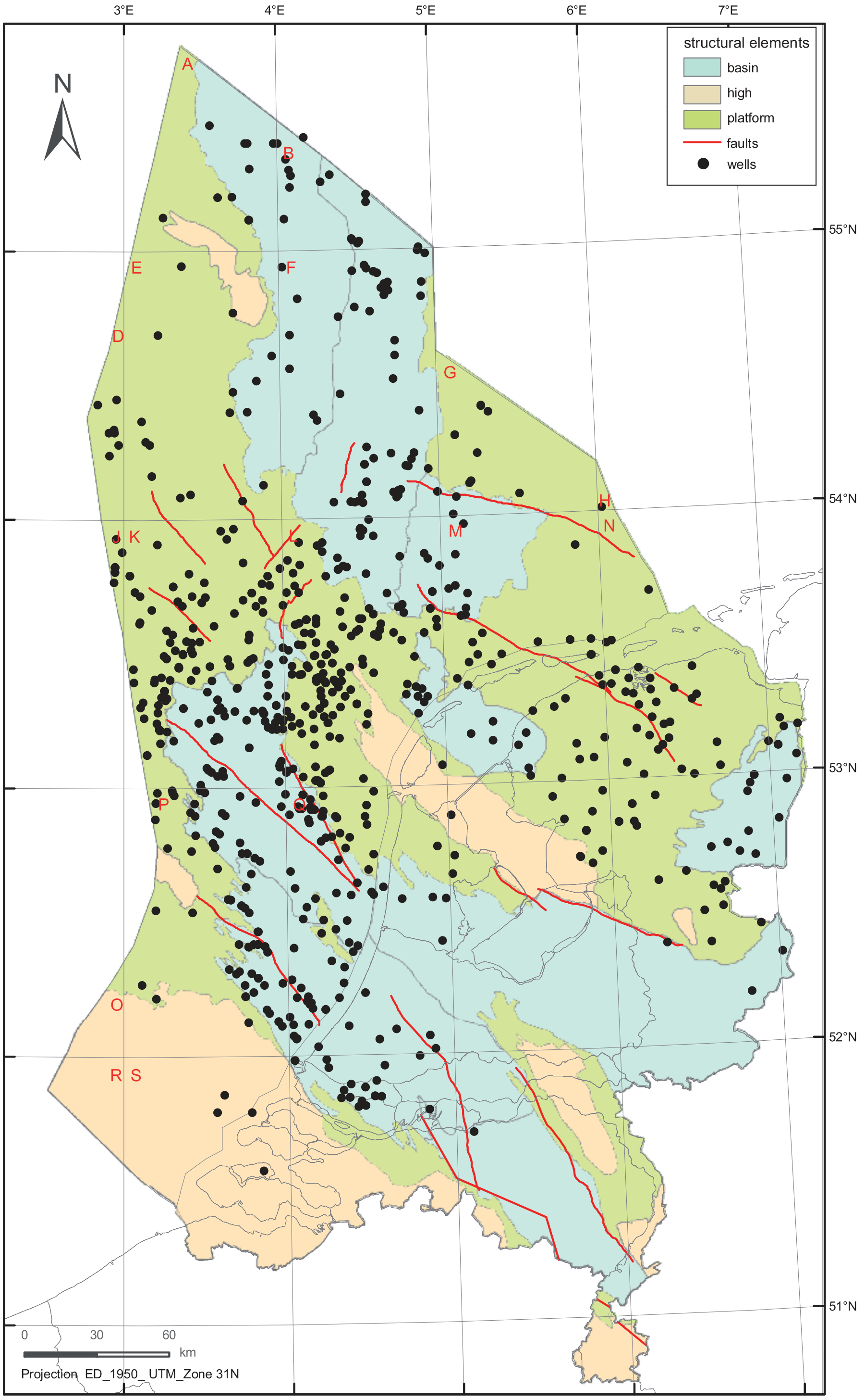


Fig. 1. Location of wells included in the pressure database.

such as sedimentary loading, and gas generation are the two dominant causes thought to contribute to overpressures in Central North Sea basins. These are also important mechanisms in the Dutch subsurface. Sedimentary loading is the most studied and best understood of the overpressure mechanisms.

Assuming that sedimentary loading is the pressure generating mechanism, then the competition between sedimentary loading and the pressure-dissipating mechanism (formation water flow, compaction and dewatering of the rock framework) will control an overpressure distribution. Reservoir rocks in hydraulic communication with the ground surface through continuous permeable reservoir or fault networks will allow flow of formation water induced by sedimentary loading. Equilibrium in such a reservoir is maintained between the increase in overburden load and the expulsion of pore water. However, a rapid increase in overburden load caused by a high sedimentation rate requires faster expulsion of water throughout the porous medium. When sediments are unable to dewater during subsidence, the pore water will bear part of the increase in overburden load and become overpressured. Lithologies – such as mudstones – with high matrix compressibilities as well as low permeabilities are especially susceptible to overpressuring. Overpressuring in such lithologies is accompanied by a slow down or even stop of compaction (a process known as disequilibrium compaction). Lithologies such as sandstones and limestones, with relatively low matrix compressibilities and high permeabilities (aquifers), allow water flow and redistribution of overpressures. The above described mechanical compaction in sedimentary units in response to increases in effective stress slows down as rock loses porosity and becomes more rigid. In addition, sediments also compact chemically during burial, mostly controlled by increasing temperatures (Bjørlykke, 2010).

Geological and fluid geological setting

Geological setting

The main geological characteristics and mechanisms of influence on present-day pressure and fluid flow conditions are summarised below. The mechanisms include past and present processes of different duration. Detailed information on the geology of the Netherlands is given in Van Adrichem Boogaert & Kouwe (1993), TNO-NITG (2004), Duin et al. (2006), Wong et al. (2007), Doornenbal & Stevenson (2010), Kombrink et al. (this issue) and references therein.

The dominant features of the present-day structural framework and stratigraphic build-up of onshore and offshore Netherlands are shown in representative cross-sections in Fig. 2. Figure 3 shows important structural elements in the study area. Numerous deep faults and elongated salt structures disrupt the lateral continuity of pre-Cenozoic sedimentary sequences (Fig. 2). Large elongated salt structures related to basin boundary faults occur especially along the Step Graben, Dutch Central Graben, Terschelling Basin, north-eastern edge of the Broad Fourteens Basin and Lauwerszee Trough. The structural framework reflects the complex history of extension and compression related to world-wide reorganisations of lithospheric plates (Ziegler, 1990; Duin et al., 2006; De Jager, 2007). The regional variation in burial history across the study area is described in Fig. 4.

Geological history

Late Paleozoic

During the Late Carboniferous Namurian and Westphalian, the Netherlands were located in the northern foreland of the Variscan Mountains. Deposition of Westphalian fluvio-deltaic sediments in the area includes carbonaceous shales and a large number of coal layers. Variscan transpressive forces in Early to Middle Permian induced strong uplift and erosion of Carboniferous strata, creating the Base Permian Unconformity. Westphalian coals and carbonaceous shales (the principal source rocks for gas in the Netherlands), are preserved in large part of the area (De Jager & Geluk, 2007). The Carboniferous was covered by Rotliegend, Zechstein, Triassic and Lower Jurassic sediments that were initially deposited in the Southern Permian Basin. Important Upper Permian sediments are the terrestrial coarser grained clastic (conglomerates and sandstones of fluvial and aeolian origin of the Slochteren Formation) and finer grained desert lake deposits (claystones, siltstones and evaporites of the Silverpit Formation) of the Upper Rotliegend Group (Grötsch & Gaupp, 2011). The Slochteren Formation grades northward into the Silverpit Formation. The marine Zechstein evaporites, carbonates and clays overlie the Upper Rotliegend Group. The southern limit of Zechstein salts runs through the southern part of the Broad Fourteens and Central Netherlands basins; in the south the Zechstein is predominantly clastic. The strong influence of the Zechstein salt on the successive structural development is depicted in Fig. 2.

Mesozoic

During the Early Triassic, initially widespread subsidence of the area of the Southern Permian Basin resulted in regional deposition of lacustrine claystones and aeolian and fluvial sandstones of the Lower Germanic Trias Group. Subsequently, sedimentation in the basin became progressively influenced by the development of swells and lows. The Hardegsen event induced uplift of these swells and caused deep erosion of sediments of the Lower Germanic Trias Group on the swells (Geluk & Röhling, 1997; Geluk, 2005). Gradually, marine influence increased during deposition of the Upper Germanic Trias Group that consists mainly of lacustrine and shallow marine claystones, carbonates and evaporites (Röt to Keuper units). The Late Triassic transgression covered most of the previous swells. Thick open marine clays of the Jurassic Altena were deposited regionally during the Early to Middle Jurassic. Restricted conditions during the Toarcian are associated with the deposition of bituminous clays of the Posidonia Shale Formation. The subsequent Mid and Late Kimmerian tectonic phases (Middle-Late Jurassic) accompanied the break-up of the previous Southern Permian Basin. Initially, the Mid- Kimmerian tectonic phase caused erosion of Jurassic and Triassic strata in most parts of the Netherlands. The Late Kimmerian tectonic phases caused a differential dynamic development of the main structural elements in the area shown in Fig. 2. Sedimentation concentrated in rapidly subsiding rift basins during Late Jurassic to earliest Cretaceous times (Mesozoic basins, Figs 3 and 4). Deposition of the Schieland, Scruff, and Niedersachsen groups in the basins was characterised by significant lateral facies changes. The adjacent platforms and highs were uplifted and deeply eroded (affecting the Jurassic Altena Group, Germanic Trias Group and even Zechstein and Rotliegend groups; Figs 2, 3 and 4d-e). Deep erosion (down to Carboniferous) occurred in the Early Cretaceous on the Texel-IJsselmeer High, Winterton High and Peel Block. The siliciclastic Rijnland Group marks the onset of the Cretaceous transgression over the Late Kimmerian

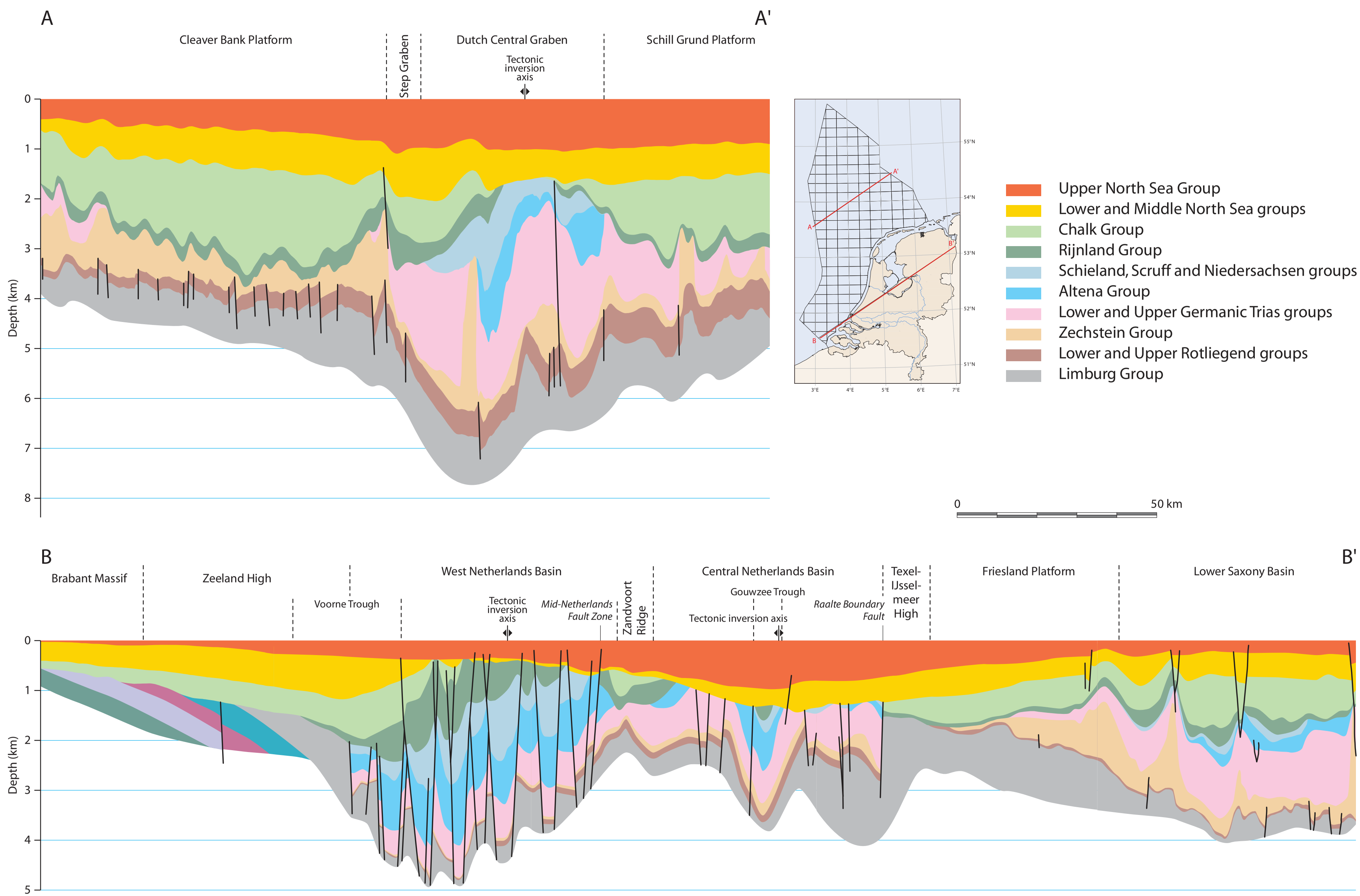


Fig. 2. SW-NE geological cross-sections. The cross-sections show the dominant features of the present-day stratigraphic build-up and structural framework. Note the regional differences in 1) stratigraphic build-up between basins and platforms/highs and 2) between the fault-dominated southwest with deep reaching faults cross-cutting Carboniferous to recent strata, and the northeast with its salt-dominated structural framework.

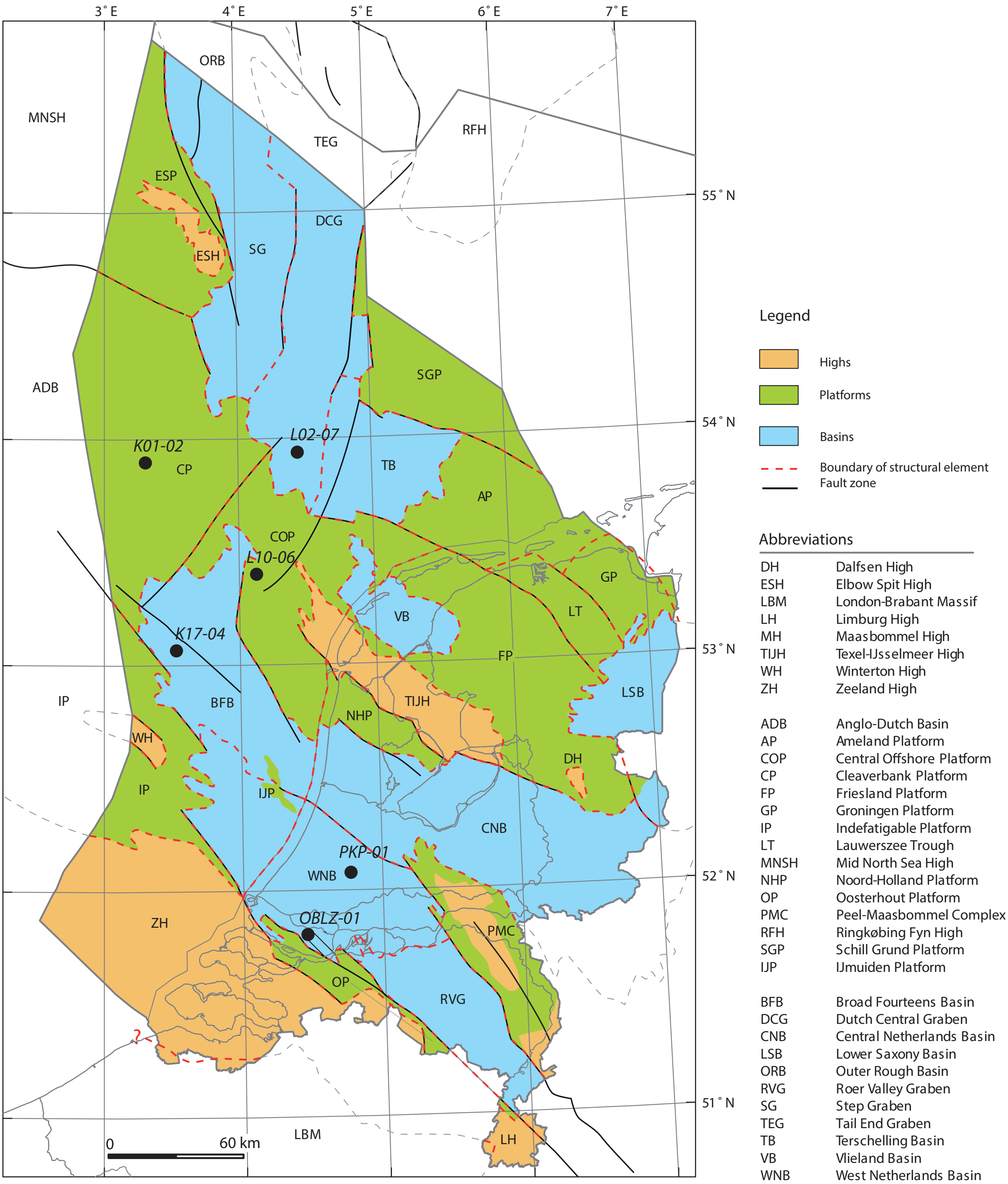


Fig. 3. Mesozoic structural framework (after Kombrink et al., this issue). Location of wells shown in Fig. 4.

Unconformity (Jeremiah et al., 2010). During the Late Cretaceous clastic input into the basin was further reduced and led to widespread deposition of chalk (Chalk Group). Chalk deposition was interrupted in the Mesozoic basins by inversion movements during the Sub-Hercynian tectonic phase. The central parts of the Broad Fourteens, Central Netherlands, West Netherlands Basins, and Roer Valley Graben experienced strong uplift (Fig. 4b, c). Inversion of the Dutch Central Graben was strongest in its southern half. While the sedimentary fill of the basins became folded, uplifted, and subject to erosion, deposition of chalk continued in adjacent areas.

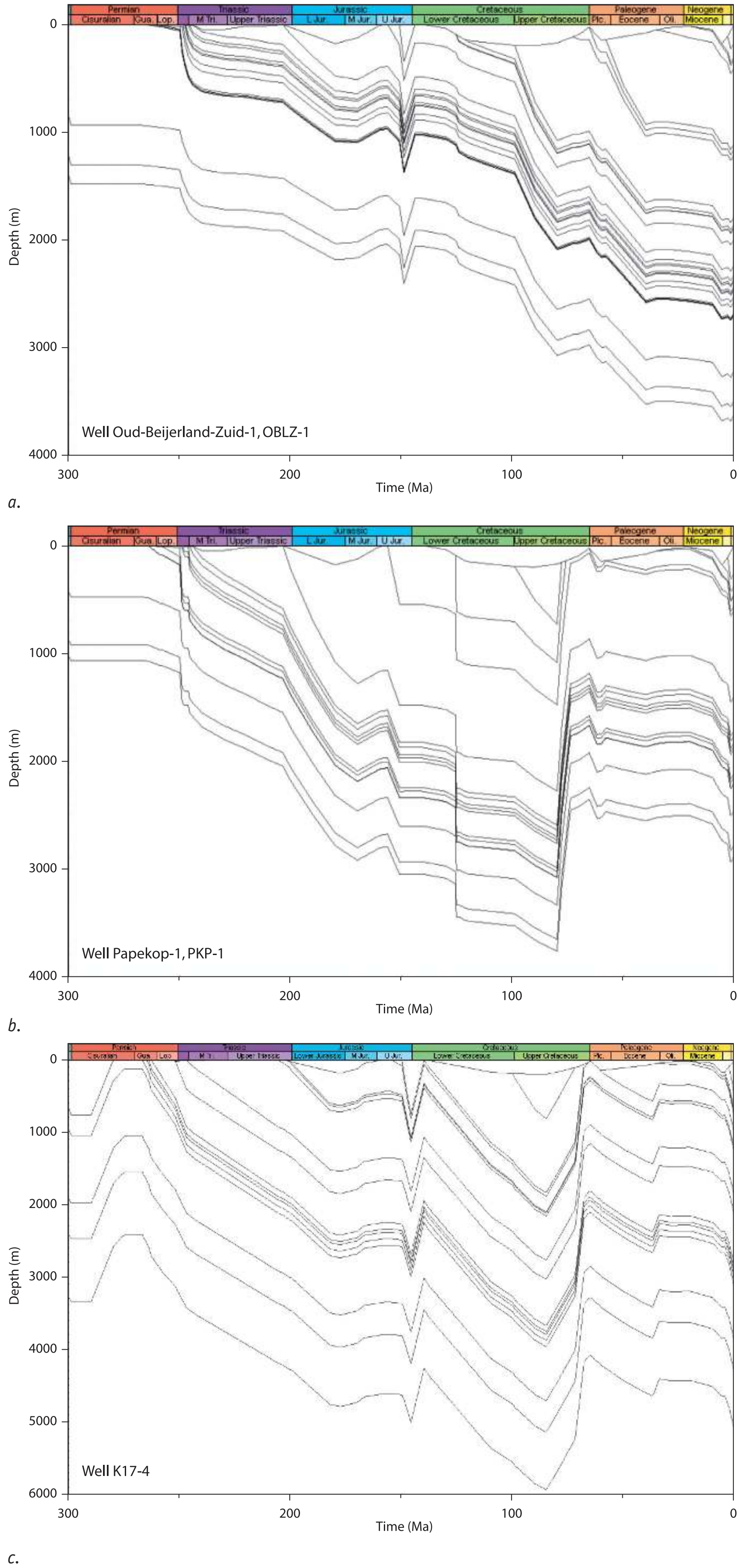
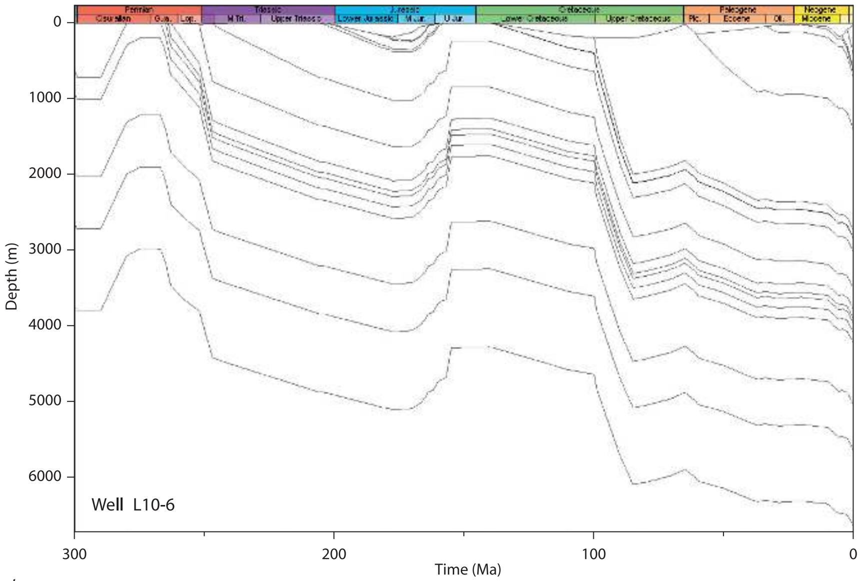
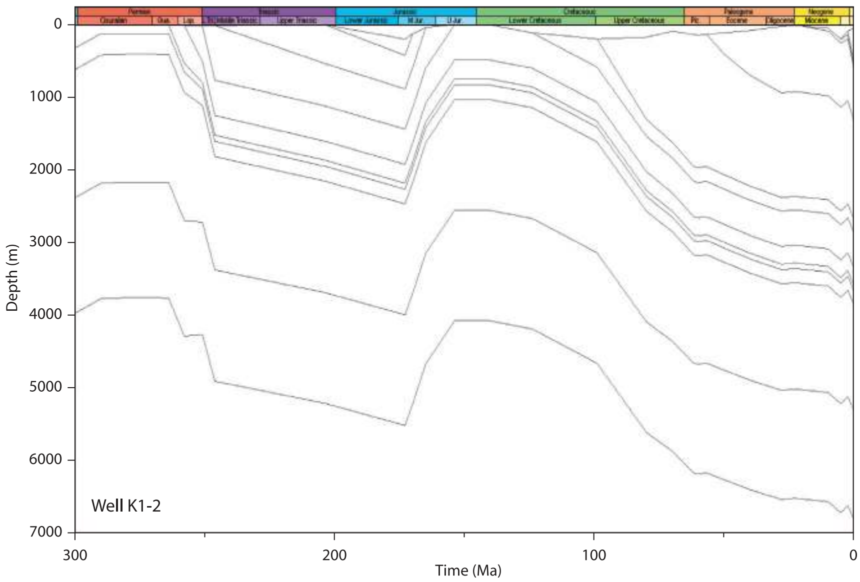


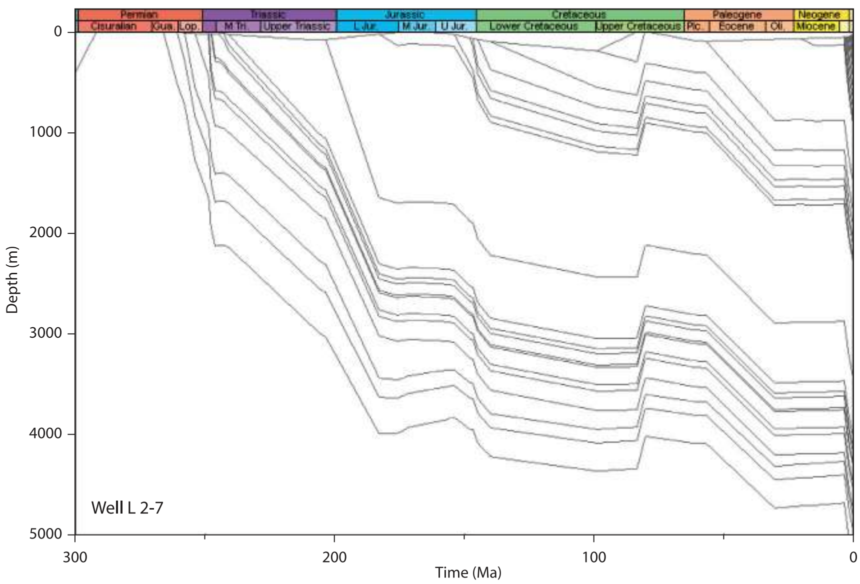
Fig. 4. Overview of burial histories at different locations in onshore and offshore Netherlands; a. southern edge of the West Netherlands Basin; b. inverted centre of the West Netherlands Basin; c. inverted centre of the Broad Fourteens Basin; d. Central Offshore Platform; e. Cleaverbank Platform; f. southern part of the Dutch Central Graben. See Fig. 3 for location of the wells.


Depth (m)
0
1000
2000
3000
4000
5000
6000
Well L10-6
300
200
100
0
Time (Ma)

d.


Depth (m)
0
1000
2000
3000
4000
5000
6000
7000
Well K1-2
300
200
100
0
Time (Ma)

e.


Permian
Triassic
Jurassic
Cretaceous
Paleogene
Neogene
Cisuralian
Gua.
Lop.
M Tri.
Upper Triassic
L Jur.
M Jur.
U Jur.
Lower Cretaceous
Upper Cretaceous
Plc.
Eocene
Oli.
Miocene
Depth (m)
0
1000
2000
3000
4000
5000
Well L 2-7
300
200
100
0
Time (Ma)

f.

Cenozoic

The Laramide regional phase of erosion in Mid-Paleocene terminated the deposition of chalk. This phase was followed by regional subsidence of the Cenozoic North Sea Basin and deposition therein of siliciclastic sediments of the Lower, Middle and Upper North Sea groups (Wong et al., 2007; Fig. 5). The Lower North Sea Group reaches a maximum thickness in the northern offshore and thins toward the south. It consists of predominantly marine clays with sandy deposits along the southern edge of the basin (sedimentation was locally concentrated in the Voorne and Lauwersee Troughs). The regional subsidence was interrupted by the Late Eocene-Early Oligocene uplift, related to the Pyrenean tectonic phase.

Pyrenean compressive tectonics involved uplift and erosion of the southern onshore (West Netherlands Basin) but also extended westward into the offshore (Nalpas et al., 1995; De Lugt et al., 2003). During the Oligocene, the sea transgressed across the previously eroded areas. This resulted in marine deposits of the Middle North Sea Group. Sedimentation was interrupted again at the end of the Oligocene, related to the Savian phase of erosion. In the Neogene, deltas prograded from the south and southeast of the Netherlands and from the Fennoscandia border into the North Sea Basin (Sørenson et al., 1997; Overeem et al., 2001; Kuhlmann et al., 2004). The West Netherlands Basin was uplifted and eroded during the Pyrenean and Savian phases and sedimentation and subsidence was

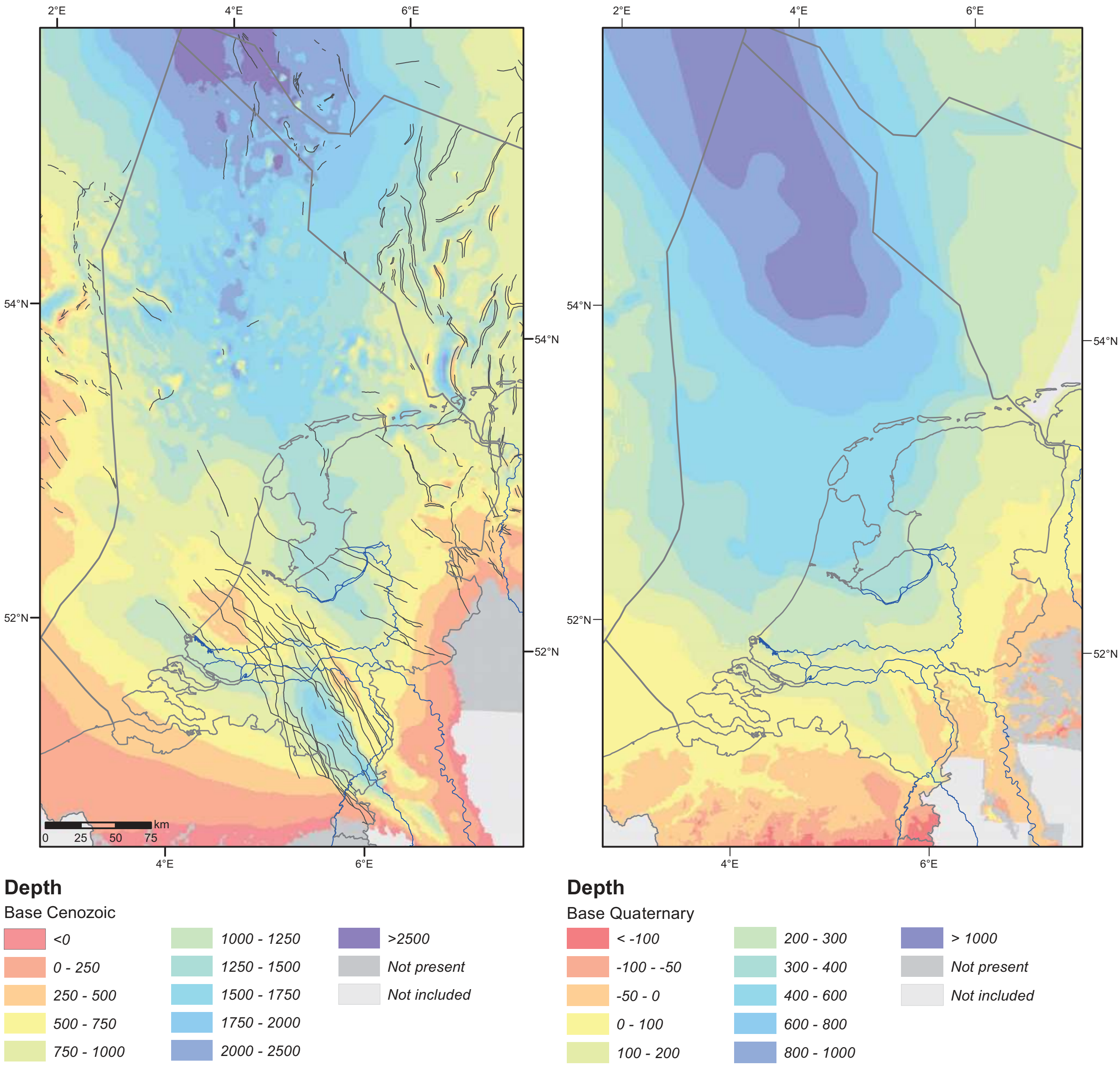


Fig. 5. Depth to near base of the clastic Cenozoic sediments (on the left) and depth to the base of the Quaternary sediments (after Knox et al., 2010).

limited during the Neogene (Fig. 4a, b). In contrast, the Roer Valley Graben and Zuiderzee Basin (located on the former Central Netherlands Basin) developed into depocentres. The Roer Valley Graben was reactivated and developed as part of the NW European rift system from the Late Oligocene onwards (Michon et al., 2003; Van Balen et al., 2005; Worum et al., 2005), with subsidence accelerating during Pliocene and Quaternary.

Major depocentres developed in the northern offshore area after Miocene times (Sørensen et al., 1997; Overeem et al., 2001). Sedimentation rates in the depocentres started to increase during the Pliocene and remained high during the Quaternary (Figs 4c, d, e, f). In the Pleistocene, thick Elsterian and Saalian ice sheets covered the northern on- and offshore during their maximum advance. The thickness maps of the entire North Sea Group and the Upper North Sea Group show the net result of the Cenozoic and Quaternary burial and sedimentation history (Fig. 5).

Petroleum geological setting

In general, hydrocarbon generation from Carboniferous source rocks was widespread until the Middle Jurassic and continued in the basins until Late Cretaceous inversion (De Jager & Geluk, 2007). On the platforms and highs hydrocarbon generation was interrupted due to uplift and erosion in Late Jurassic - Early Cretaceous times. Reburial and associated heating of the Westphalian source rocks in basins, platforms and highs beyond previously experienced temperatures induced a later phase of hydrocarbon generation in Cenozoic times (e.g. along the edges of the West Netherlands Basin, De Jager et al., 1996; Noord-Holland, Central Offshore, Cleaverbank and Friesland Platforms: Verweij, 2003; Verweij et al. 2009c, 2010, 2012; Abdul Fattah et al., 2012). The pore water pressures in the Carboniferous source rocks in these areas may have been affected or are still affected to a greater or lesser extent by gas generation. Most trapped gas is reservoired in the Upper Rotliegend and Triassic sandstones. The Jurassic Posidonia Shale Formation is considered to be the most important source rock for oil in the Netherlands (De Jager & Geluk, 2007).

Lithostratigraphic build up

The position of the Netherlands at the southern edge of large basins during the majority of post-Carboniferous geological history has directly affected the facies distribution. Generally, more coarse-grained clastic deposits 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 (Fig. 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. Its largest thickness occurs in the Mesozoic basins, while in the remaining area it is 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.

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) and Verweij & Simmelink (2002).

The most important lithostratigraphic units controlling formation pressure distribution and flow conditions in the Dutch subsurface are the salt members of the Zechstein Group, because of their extremely low permeability and their regional continuity (Fig. 2). A lesser 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, because of a more restricted distribution. These 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 centre 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: the 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, Cenozoic 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 (see below) result in generally 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 (Fig. 1). Large elongated low permeability salt structures related to basin boundary faults occur especially along the Step Graben, Dutch Central Graben, Terschelling Basin, north-eastern 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.

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

The burial history distribution since Late Cretaceous (Figs 4 and 5), is a potential geological factor of influence on present-day overpressure distributions. There are important regional differences in burial history during this time period: major Late Cretaceous and Early Cenozoic uplift and erosion are concentrated in the south (including West Netherlands, Broad Fourteens, Central Netherlands basins, Roer Valley Graben) with the overall thickness of the North Sea Group increasing northward. Greater sedimentary thickness corresponds to areas of greater subsidence and increased sedimentary loading rates. The thickness of the Upper North Sea Group increases northwards as well, with a local depocentre in the Roer Valley Graben (Fig. 5).

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.

Regional fluid pressure and leak-off pressure distributions

The multi-well cross plots (Figs 6, 7, 8 and 9) present the fluid pressure and leak-off pressure versus depth for each of the main lithostratigraphic units and for important structural elements.

The multi-well cross plots (Figs 6, 7, 8 and 9) reveal a number of interesting features:

A. Leak-off pressures (Figs 6, 7, 8 and 9)

1. There is a general increase in leak-off pressures with depth in all structural elements (Figs 6, 8 and 9);
2. The leak-off pressures gradually approach the lithostatic gradient at greater depths in the Step Graben, Dutch Central Graben, Terschelling Basin, Schill Grund High and Lower Saxony Basin. Similar patterns of leak-off pressure increasing with depth have been observed in the northern and central North Sea (Gaarenstroom et al., 1993; Giles et al. 1999);
3. The cross plots for the Broad Fourteens Basin, Cleaverbank Platform and Central Offshore Platform do not reveal a clear trend of leak-off pressures approaching the lithostatic with depth. Instead the data show a lot of scattering. The leak-off pressures in these structural elements include measurements from various lithologies within the Zechstein Group. In this case, differences in leak-off pressures can be associated with various facies in the Zechstein Group, as shown in Fig. 7. Leak-off pressures in the salt units of the Zechstein Group reach higher values than those in its anhydrite, carbonate and clastic units, both at shallow and greater depth. A similar but less clear facies dependence was observed in the Triassic groups, and for the Upper Rotliegend Group on the Cleaverbank Platform;
4. Leak-off pressures in the West Netherlands Basin, located south of the area of occurrence of Zechstein and Triassic salts, show the least scattering. They fall well below the lithostatic gradient.

B. Fluid pressures (Figs 8 and 9)

1. There is a clear regional difference in overpressure conditions in the southern, northern and north-eastern parts of the area. Fluid overpressures in all stratigraphic units in the southern area (Broad Fourteens Basin, southern part Central Offshore Platform, West Netherlands Basin) are normal or close to normal. Stratigraphic units of pre-Cenozoic age in the northern and north-eastern area (Step Graben, Dutch Central Graben, Terschelling Basin, Schill Grund Platform, Lauwerszee Trough, and to a lesser extent in the Lower Saxony Basin) are overpressured;
2. The fluid pressure conditions on the Cleaverbank, Central Offshore, and Friesland platforms are transitional between the southern and the northern offshore area;
3. Depth exerts a first order control on the fluid pressures:
   a. In the southern area the fluid pressures increase broadly parallel to the density corrected hydrostatic gradient;
   b. In the northern area at shallow depth, the lower-bound of the fluid pressure data distribution increases parallel to the density corrected hydrostatic pressure gradient but deviates from this at greater depths (for example; fluid overpressures all exceed 8 MPa at depths beyond 2250 m in the Terschelling Basin; minimum overpressure reaches magnitudes of approximately 9 MPa at 4 km depth in the southern Dutch Central Graben);
4. Very high values of overpressure were observed in the Limburg Group in the Step Graben (exceeding 30 MPa), the Upper Rotliegend Group in the southern Dutch Central Graben (exceeding 40 MPa) and the onshore Lauwerszee Trough (exceeding 20 MPa), and in the Lower Germanic Trias Group in the Terschelling Basin (exceeding 35 MPa);
5. Fluid overpressures in the Zechstein Group show a wide variation from <1 MPa to >40 MPa (Cleaverbank and Central Offshore platforms, Step Graben). The location of the strata

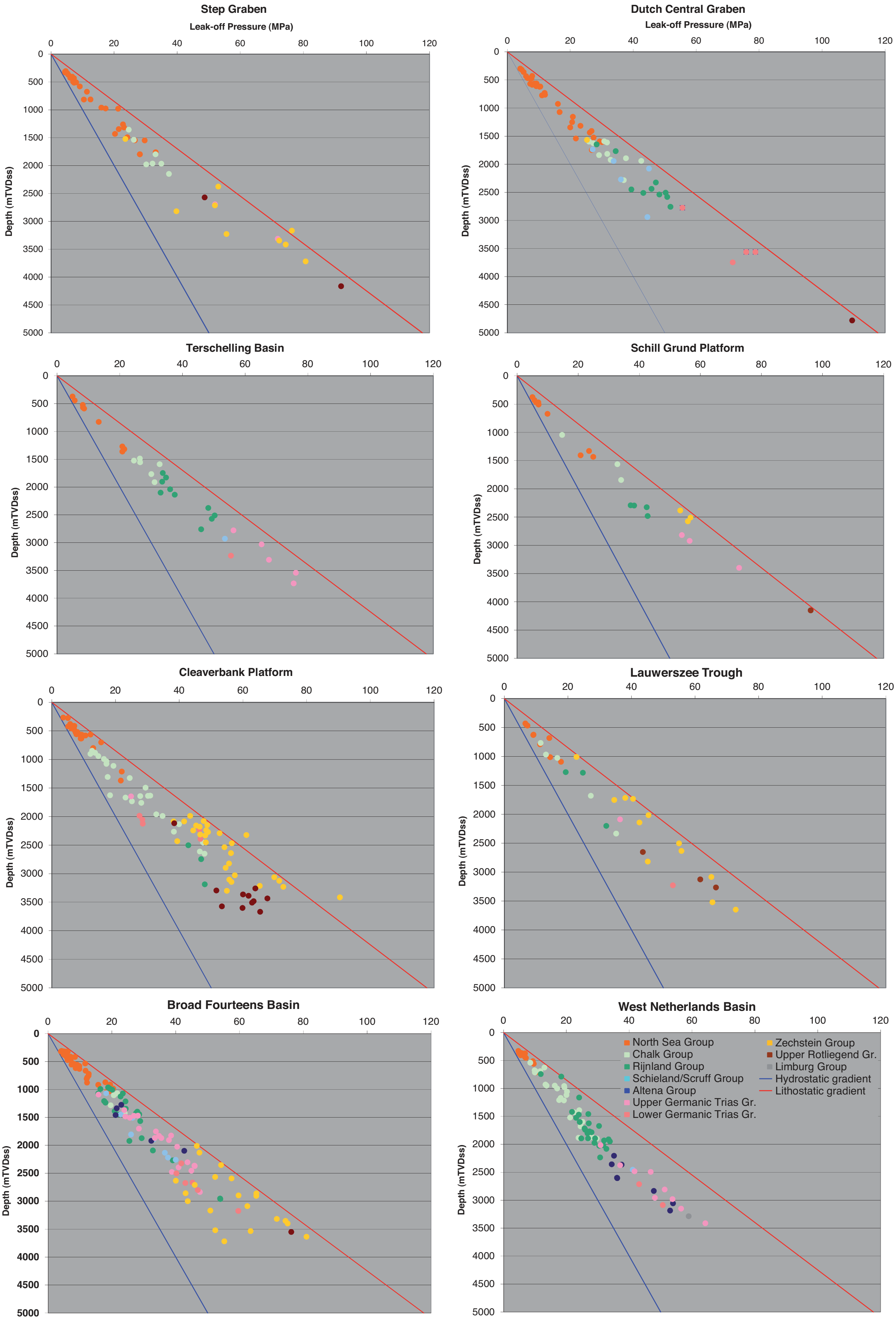
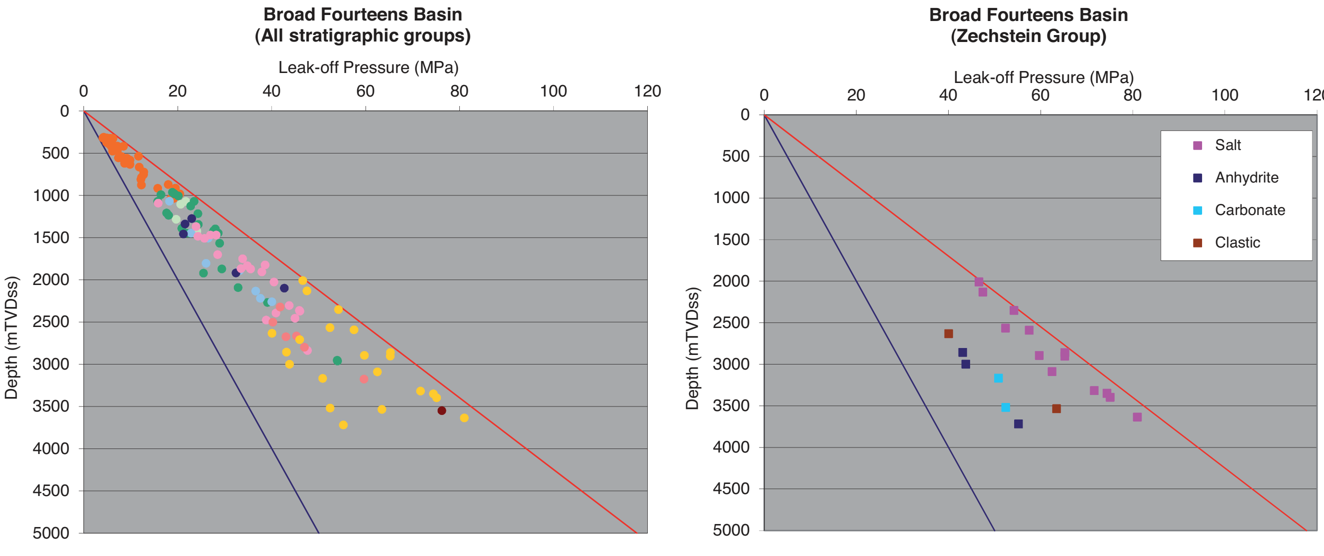


Fig. 6. Multi-well cross plots of leak-off pressure versus depth for the main stratigraphic units and for important structural elements.



a. *b.*

Fig. 7. a. Cross plot of leak-off pressure versus depth in Broad Fourteens Basin for all stratigraphic units (see Fig. 6 for legend); b. Cross plot of leak-off pressure versus depth for Zechstein Group showing facies dependence.

within the Zechstein Group (enclosed in evaporites of the Zechstein Group, or situated at the top or bottom of the group) significantly influence 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), where formation pressures are generally close to hydrostatic in other stratigraphic units, the overpressures in the Zechstein may reach much greater magnitudes;

6. Significant lateral variations in pressure at the same depth of measurement occur in the Lower Germanic Trias Group and along the northern boundary of the Upper Rotliegend sandstone reservoir (e.g. Friesland Platform, Lauwerszee Trough).

C. Relation between fluid pressures and leak-off pressures (Figs 8 and 9)

1. The southern areas characterised by normal or close to normal fluid pressure are well below measured leak-off pressure;
2. The fluid pressures in the northern area may approach the measured leak-off pressures as observed in the Step Graben, Dutch Central Graben, Terschelling Basin, Schill Grund Platform, northern part Friesland Platform and Lauwerszee Trough. This may occur at relatively shallow depths. For example, the pore fluid pressures are near leak-off in: a) the Chalk at depths of <2000 m (Step Graben) and at approximately 1500 m (Dutch Central Graben); b) the Rijnland Group at <2000 m (Dutch Central Graben); and c) the Schieland/Scruff Group at <2500 m (Terschelling Basin). In addition, very high fluid overpressures in the Triassic units in the Terschelling Basin, Schill Grund High and Step Graben also approach the realm of leak-off pressures;
3. The difference between lithostatic (~vertical stress) and leak-off pressure increases with depth in the normally pressured southern part of the area (West Netherlands Basin), but decreases with depth in the northern part at depths with severe overpressures. If we assume that the lower bound of measured leak-off pressures is indicative of the horizontal minimal stress, this is in accordance with the general increase in difference between principal stresses due to the increase of frictional strength of the crust with depth (Zoback, 2010; as observed in the West Netherlands Basin), and with the decrease of this difference as severe overpressure develops due to the decrease of its frictional strength with elevated pore pressure and decreased effective normal stress (Zoback, 2010).

Pressures, fluid dynamics and geological & hydrogeological framework

The multi-well cross plots (Figs 6, 7, 8 and 9) and cross-sections (Figs 10, 11, 14, 15 and 16) illustrate the regional variation in fluid pressure and excess fluid pressure in relation to the geological framework. The following sections present detailed descriptions of the pressure distributions in the main stratigraphic units and discuss the associated fluid dynamics.

Pressure distribution and fluid dynamics in Cenozoic North Sea Group

There are only a limited number of pore pressure measurements available for the North Sea Group and these principally cover the northern offshore (A, B, and northern F blocks). The measurements for the sandy units of the Upper North Sea Group show pore water overpressures not exceeding 0.5 MPa. A

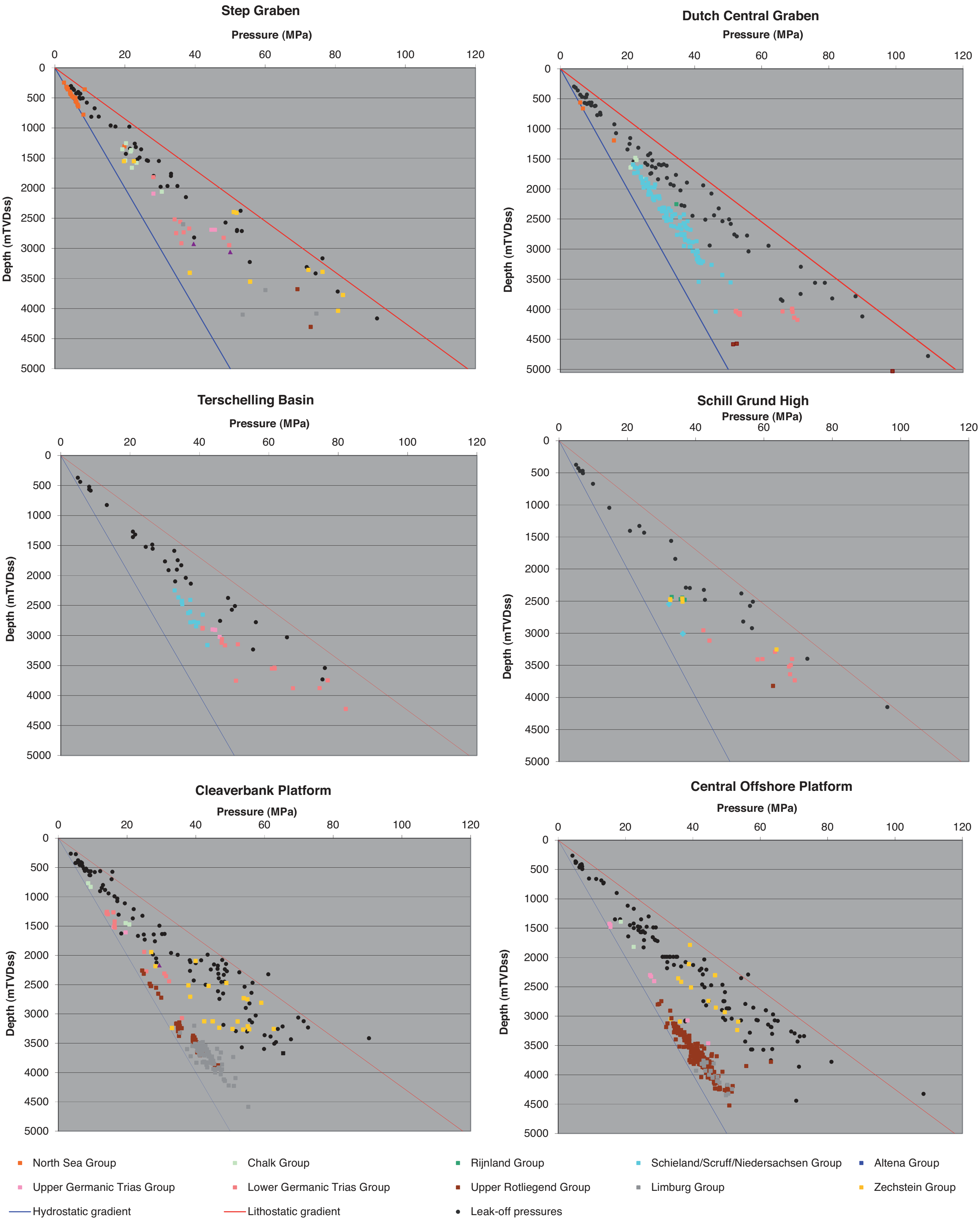


Fig. 8. Multi-well cross plots of fluid pressure and leak-off pressure versus depth for the main stratigraphic units and for important structural elements in the northern offshore.

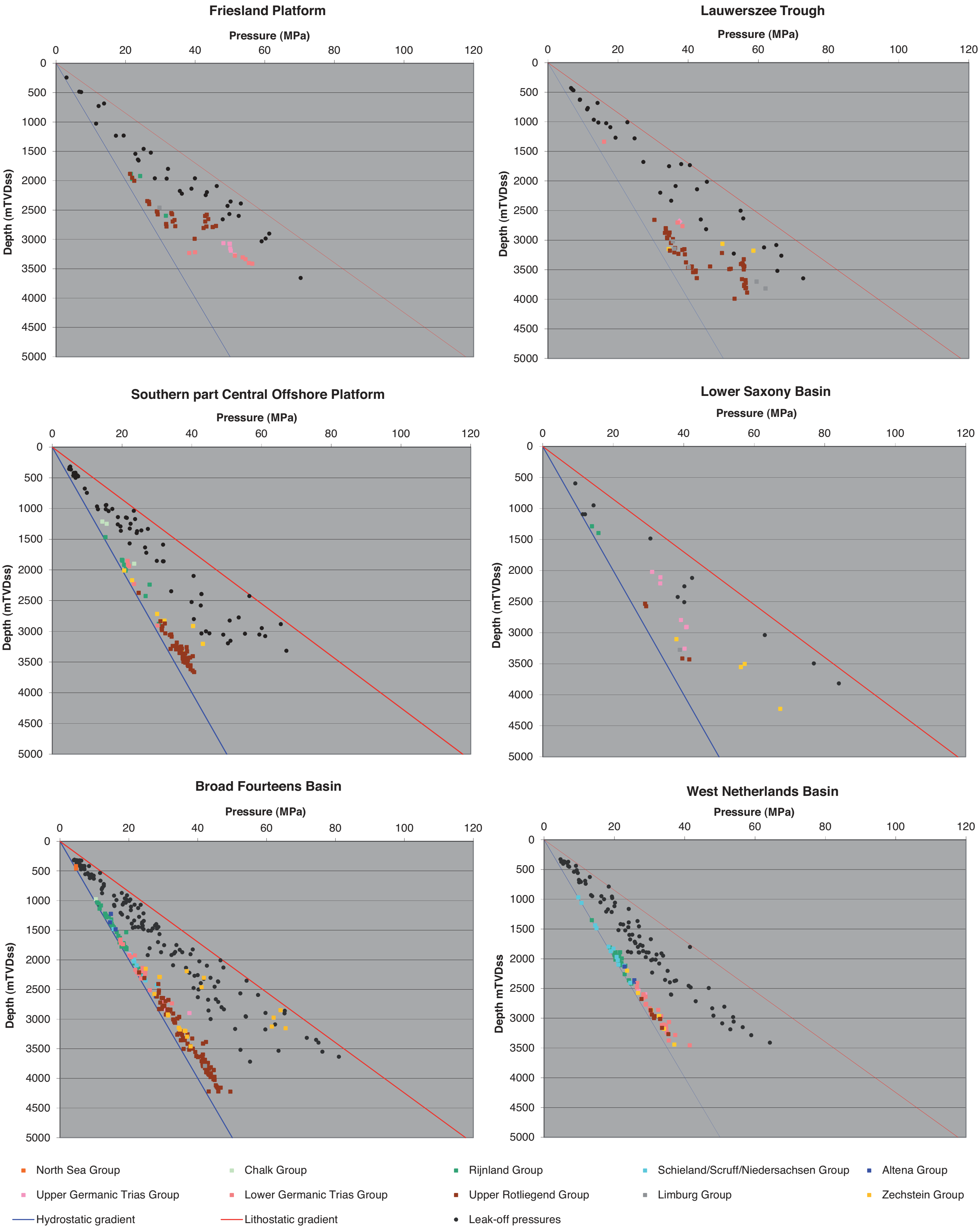


Fig. 9. Multi-well cross plots of fluid pressure and leak-off pressure versus depth for the main lithostratigraphic units and for important structural elements in the southern part of the offshore and the onshore.

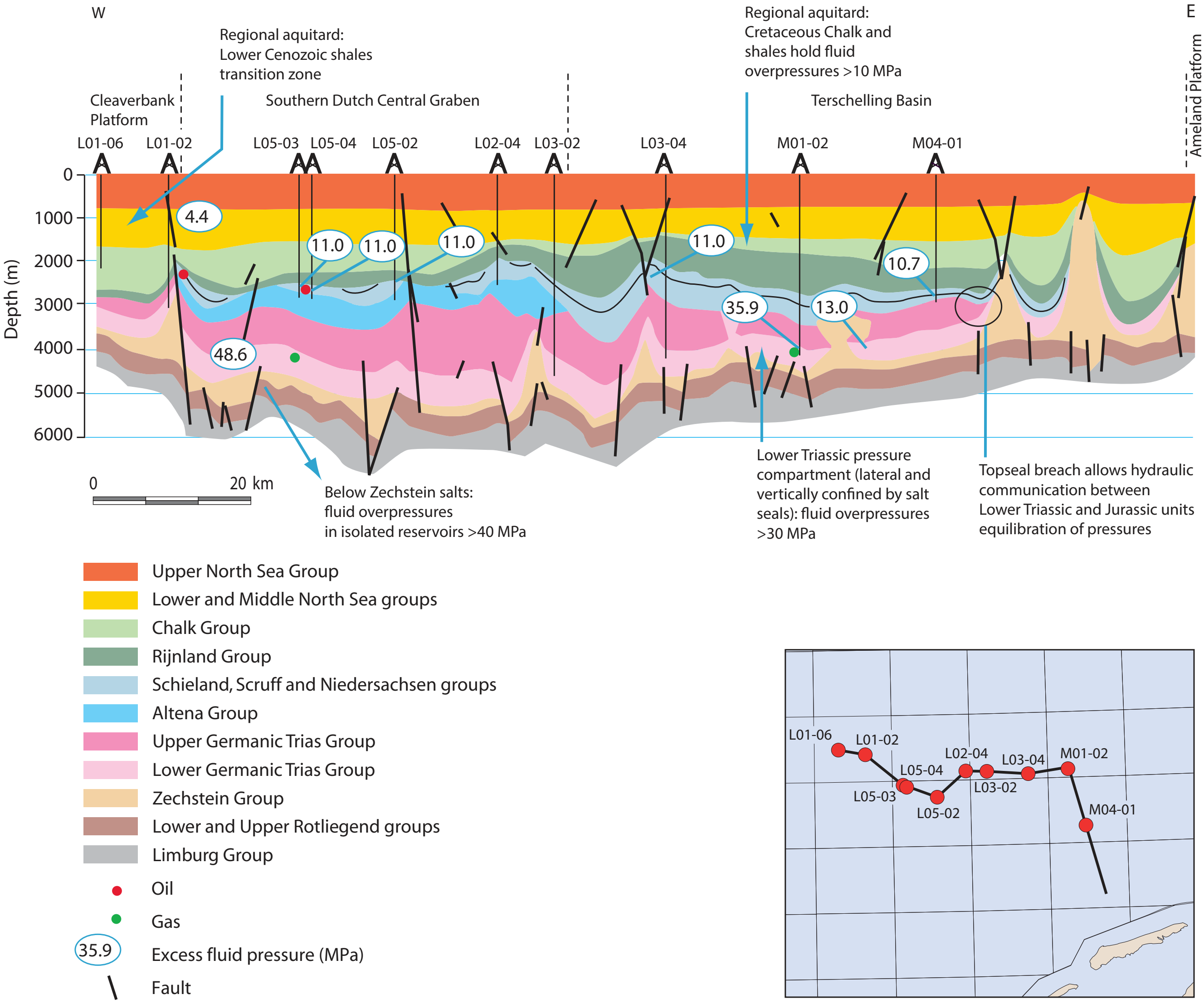


Fig. 10. W-E cross-section through the southern part of the Dutch Central Graben and the Terschelling Basin, showing the distribution of observed fluid overpressures and its relation with the hydrogeological framework.

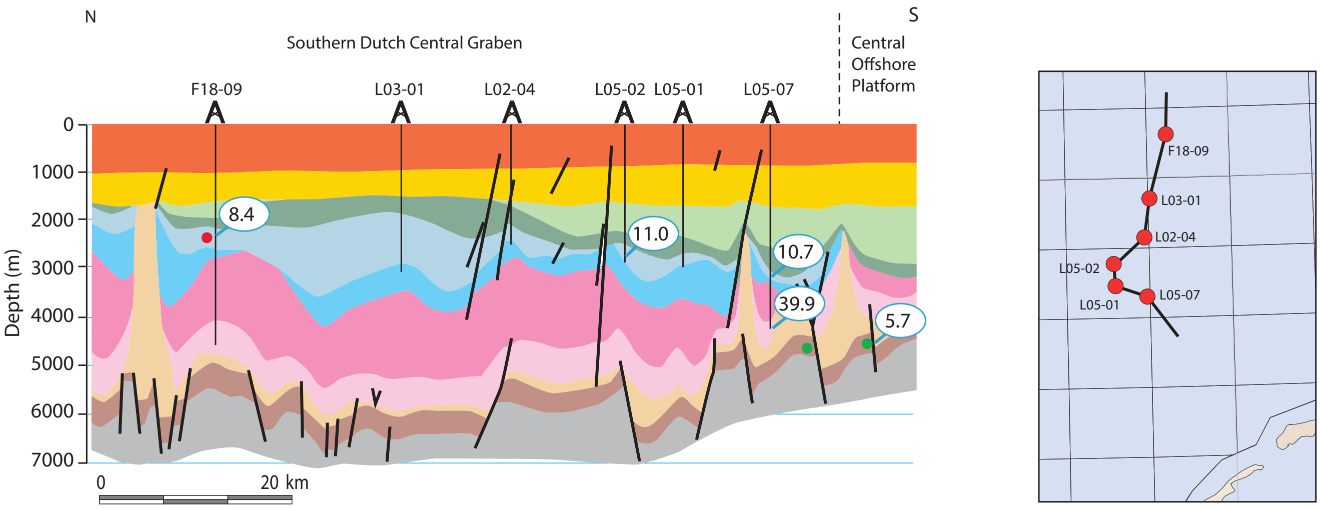


Fig. 11. N-S cross-section through southern Dutch Central Graben, showing the distribution of observed fluid overpressures and its relation with the hydrogeological framework. For legend see Fig. 10.

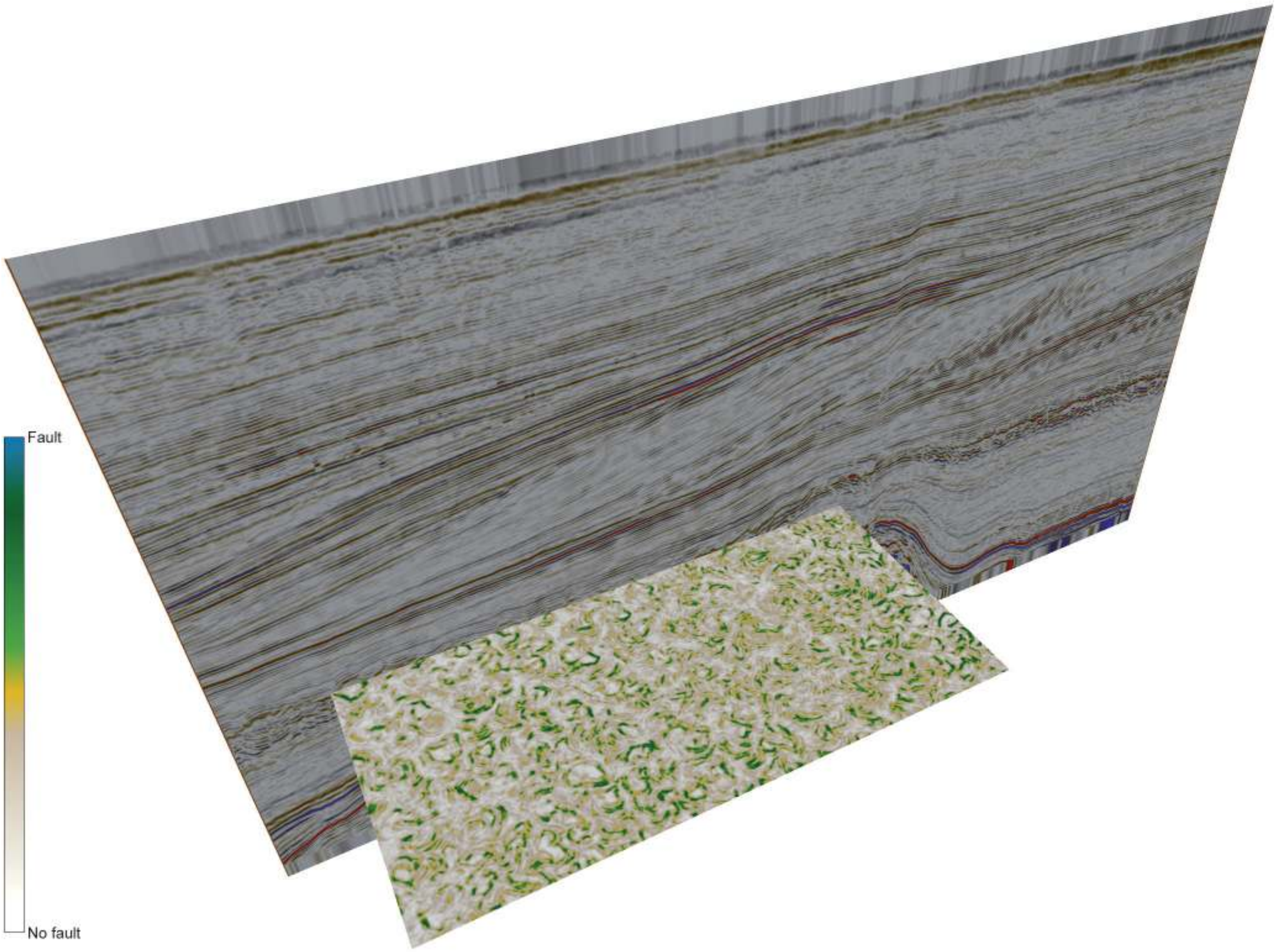


Fig. 12. Seismic cross-section showing layer of intense faulting below the Mid-Miocene Unconformity (block F3 in the Dutch Central Graben). Map view shows the polygonal nature of the faults. These polygonal faults may mark the top of the transition zone between overpressured and normal pressured conditions in Cenozoic sediments.

number of measurements suggest higher pore water overpressure do occur at deeper levels in the Lower North Sea Group. Cenozoic mudstones are known to be susceptible to overpressuring in environments of rapid sedimentation worldwide, for example in the UK, Danish and Norwegian North Sea sectors (Japsen, 1999; Evans et al., 2003). Japsen's (1999) study of interval velocities of the Cenozoic includes the northern parts of offshore Netherlands. He identified an area of relatively low velocities for the depth of burial of the Paleogene in the A and B blocks and northern F blocks and adjacent Central North Sea area. Japsen suggested that the identified velocities of the Paleogene are low relative to depth because of overpressured and undercompacted conditions related to rapid Late Cenozoic loading. The analysis of sonic and 3D seismic data in the southern Dutch Central Graben by Winthaegen & Verweij (2003) confirmed such regional undercompaction and overpressuring of the mudstones of the Lower North Sea Group.

Vejbaek (2008) suggested that the top of a transition zone between overpressured conditions to hydrostatic conditions in the Lower Cenozoic sediments in the Danish North Sea coincides with a layer of intense faulting. Non-tectonic polygonal fault networks have been identified within layer-bound fine-grained sediments in different passively subsiding basins worldwide, including the Central North Sea (e.g. Cartwright & Dewhurst, 1998; Goulty, 2002). The now preferred interpretation for the occurrence of such faults is the exceptionally low coefficient of friction of these fine-grained sediments as measured by Goulty (2002, 2008; Goulty & Swarbrick, 2005). This in combination with a zone of effective stress minimum that, according to Vejbaek (2008), occurs close to the top of the overpressured interval in Cenozoic mudstones in the Danish North Sea explains the relation between the top of the overpressured zone and small-scale intra-formational faulting in the upper part of the Palaeogene. Seismic interpretation by Steegh et al. (2000) revealed a similar layer of intense faulting in the Dongen Clay Formation of the Lower North Sea Group in block L8 in the Dutch North Sea. Recently a layer of intense faulting was also recognised from seismic in different parts of the Dutch North Sea (Schill Grund and Ameland platforms and northern offshore; Fig. 12). Possibly this zone of intense faulting in North Sea

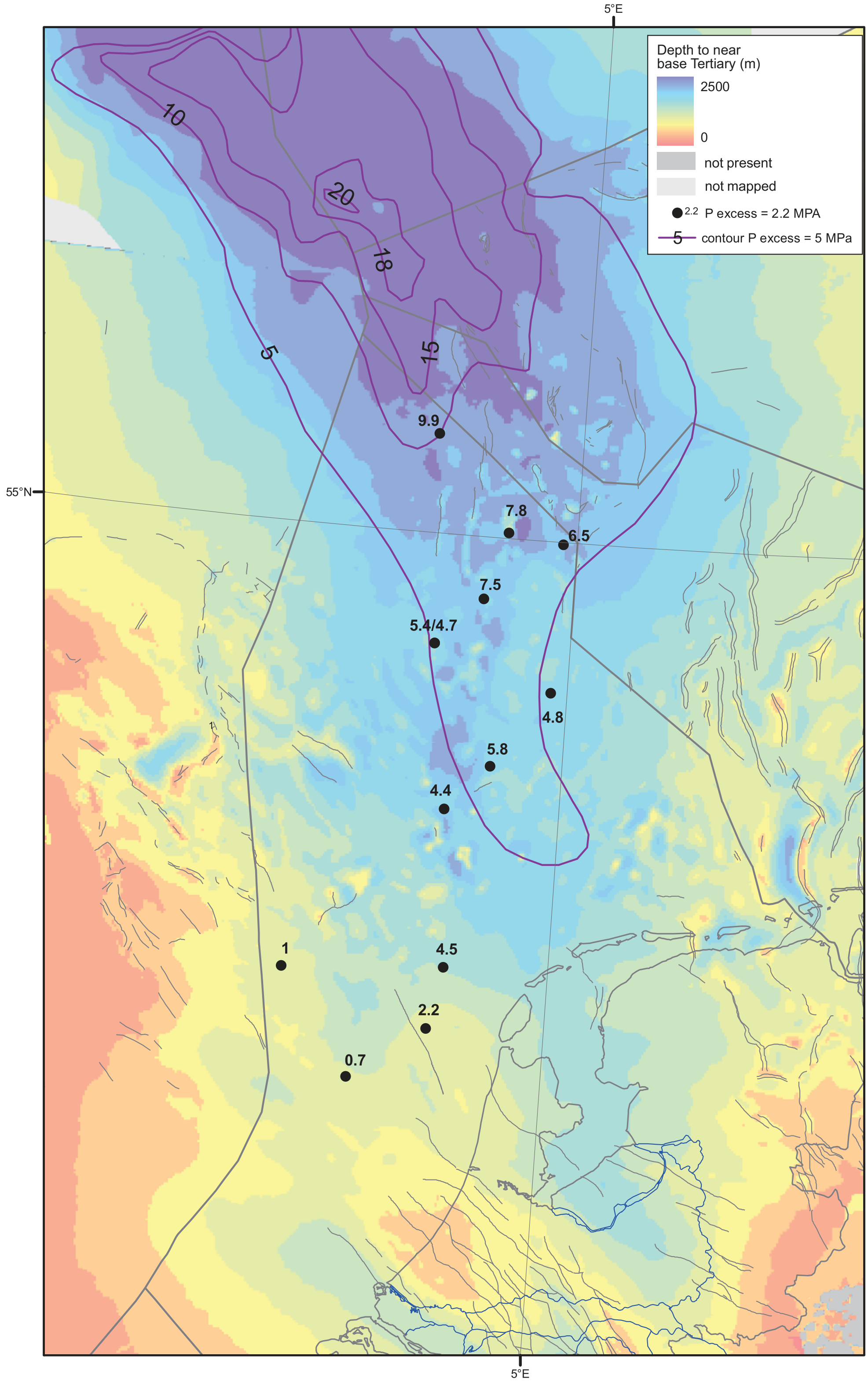


Fig. 13. Distribution of pore water overpressures in the Chalk Group. The underlying colour shaded map represents the regional depth to near base Cenozoic, displayed for reference purposes.

Group mudstones below the Mid-Miocene Unconformity also reflects the top of current palaeo-overpressuring in Lower Cenozoic sediments in offshore Netherlands.

The southward decreasing thickness and increasing sand content of the Lower North Sea Group reduces the likelihood of undercompaction and overpressuring in the southern offshore and onshore.

Pressure distribution and fluid dynamics in the Cretaceous Chalk Group

Figure 13 shows the pore water overpressure distribution in the Chalk Group in the offshore Netherlands and adjacent UK, Norwegian and Danish parts of the Central Graben. The Dutch pressure data are in accordance with results of regional pressure

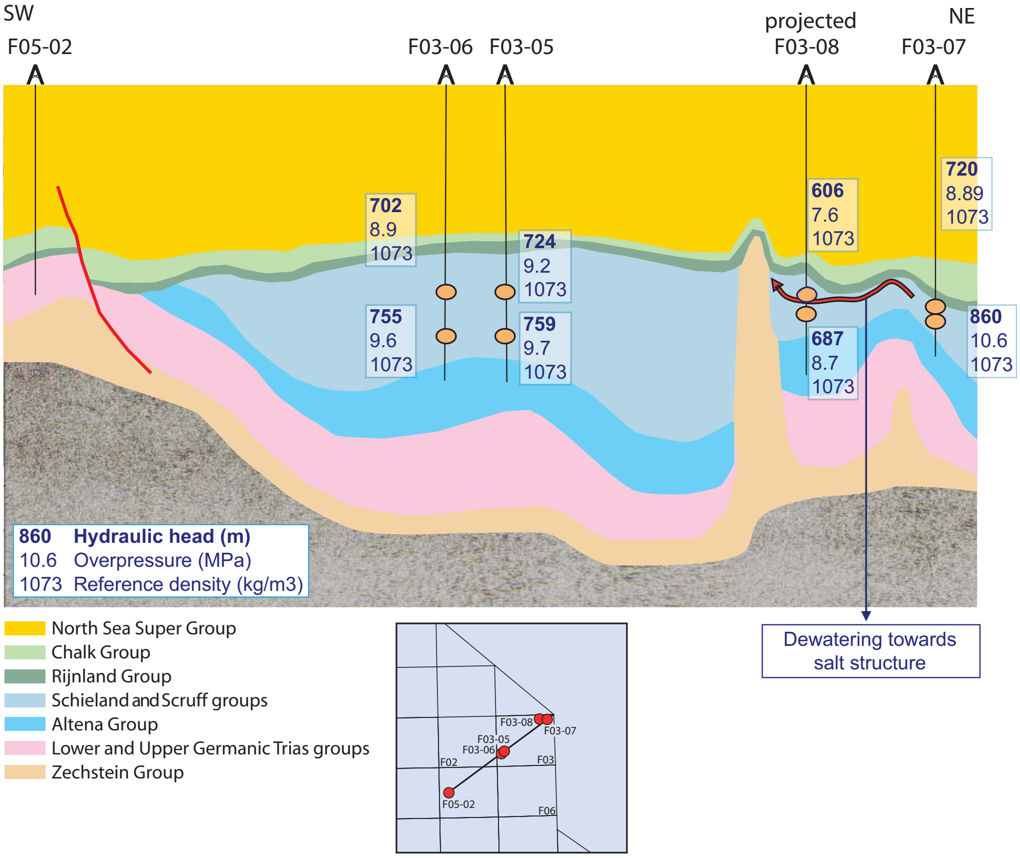


Fig. 14. SW-NE cross-section through the northern part of the Dutch Central Graben showing hydraulic head and pore water overpressure distribution in the Upper Jurassic Schieland/Scruff Group. The decrease of hydraulic head towards the salt diaper in the eastern part of the cross-section suggests that dewatering takes place towards the salt structure. The seismic-based cross-section shows the depth in TWT.

and hydrodynamic studies in the UK, Norwegian and Danish sectors of the Central Graben (Dennis et al., 2000; Moss et al., 2003; Surlyk et al., 2003; Dennis et al., 2005). These studies showed the existence of dynamic basin-wide aquifer conditions with flow directed towards the Step Graben and northern part of the Dutch Central Graben. Cross plots of pressure versus depth in the Chalk in the northern part of the Dutch Central Graben (e.g. in A blocks) showed a change of pressure with depth that follows the hydrostatic gradient. This indicates that the pressures are able to equilibrate vertically and that the Chalk in these locations acts as an aquifer, at least in the vertical direction. The Chalk Group in the UK, Norwegian and Danish sectors of the North Sea include important oil fields. Most of these Chalk fields produce from the uppermost part of

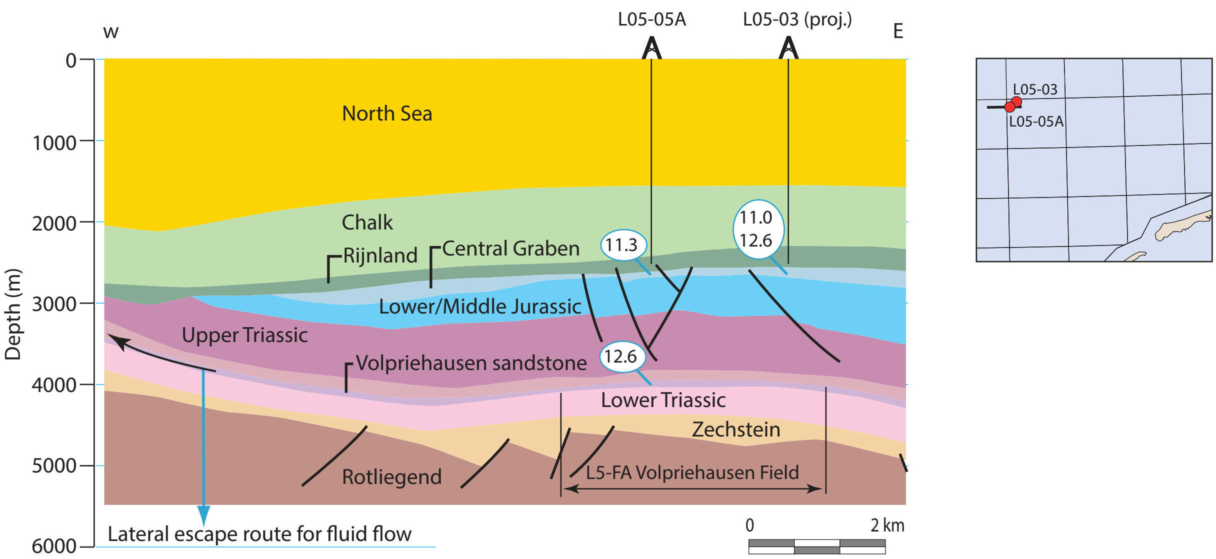


Fig. 15. W-E cross-section through the L5 block in the southern Dutch Central Graben showing the distribution of observed fluid overpressures in the Jurassic Schieland Group and Lower Triassic Volpriehausen Formation. The Upper Germanic Trias Group (including the very low permeable salt units) is absent by erosion in the western part of the cross-section, allowing the pressures in the Lower Trias and Upper Jurassic to equilibrate.

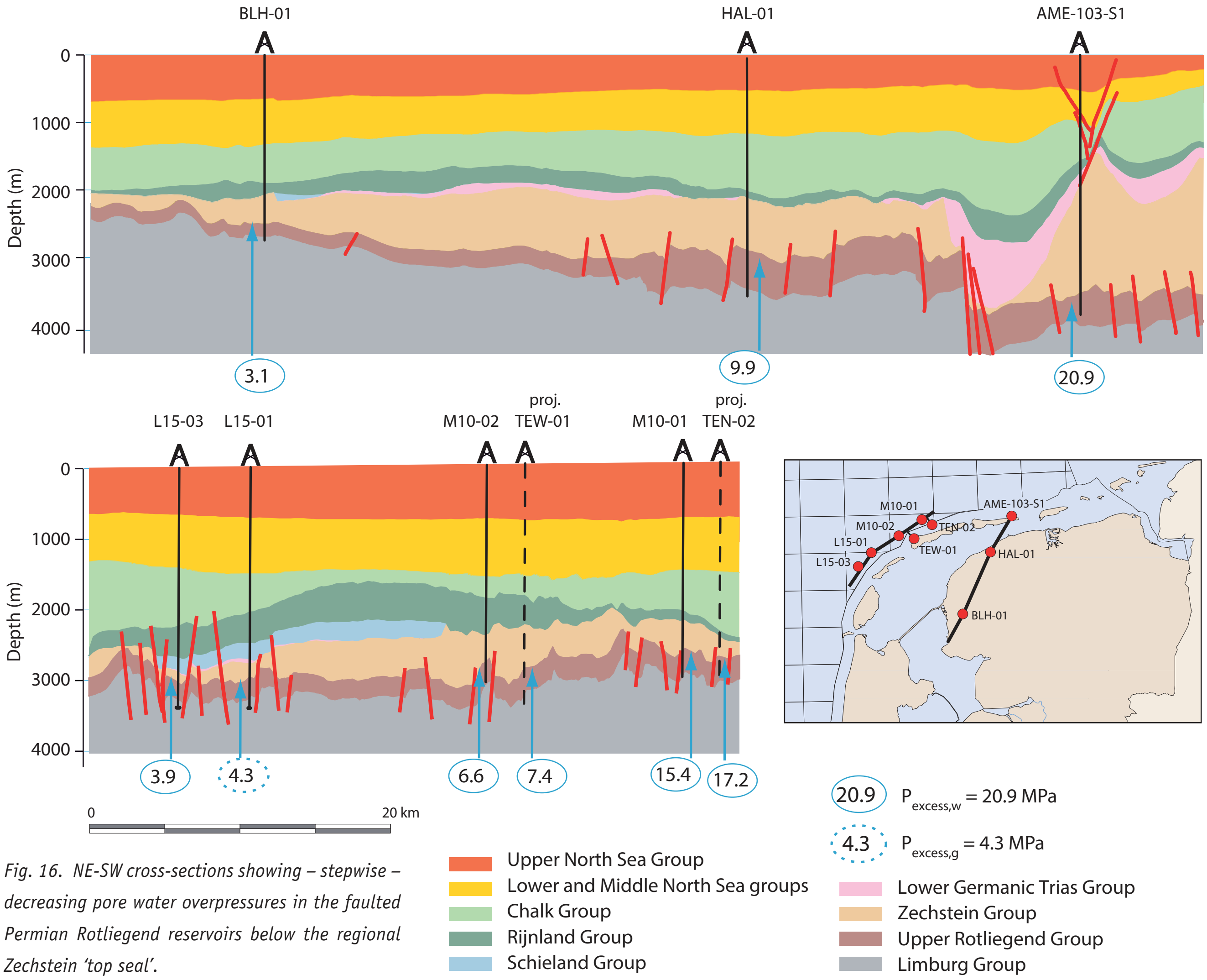


Fig. 16. NE-SW cross-sections showing – stepwise – decreasing pore water overpressures in the faulted Permian Rotliegend reservoirs below the regional Zechstein 'top seal'.

the Chalk, while its lower part, and the lower Cretaceous mudstones act as a regional seal restricting fluid flow (Winefield et al., 2005; Swarbrick et al., 2010).

The observed overpressure distribution seems to be in accordance with the undercompacted nature of the Chalk Group relative to its burial depth in the northern offshore (undercompaction was identified by Van der Molen, 2004; Verweij, 2006). The undercompacted nature of the Chalk Group and the observed overpressures indicate that the Chalk Group is not able to dewater rapidly enough through the overlying Cenozoic mudstones to keep pace with recent sedimentary loading, i.e. the Cenozoic mudstones act as a hydraulic seal. Figure 13 shows that the overpressures clearly reduce towards the inverted centre of the Broad Fourteens Basin, where the Chalk Group is missing by erosion and the thickness of the Lower North Sea Group is greatly reduced.

An important mechanism influencing the development of overpressure and fluid flow in the Chalk Group is sedimentary loading distribution after deposition of the Chalk. The current total thickness of Cenozoic sediments illustrates that the total sedimentary load imposed during the Cenozoic increases northward (Fig. 5). Long-time sedimentation rates varied during the Cenozoic and generally did not exceed 50 m/My, except during the last few million years (Fig. 4). The Quaternary part of the Upper North Sea Group (Fig. 5) also increases northward in thickness and reaches magnitudes exceeding 900 m in the northern part of the Dutch Central Graben and Step Graben corresponding to sedimentation rates of more than 400 m/My.

2D basin modelling studies in the southern part of the Dutch Central Graben showed that the present-day pressure conditions in the Chalk and underlying Jurassic reservoirs, could indeed be related to rapidly increasing rates of sedimentary loading during Pliocene and Quaternary times (Nelskamp et al., this issue).

Pressure distribution and fluid dynamics in the Rijnland Group

The sandstone units of the Rijnland Group occur mainly in the southern half of the area (for example in the southern offshore and to the northeast of Broad Fourteens Basin; onshore in West Netherlands Basin, Lower Saxony Basin, Friesland Platform). In these areas the fluids are normally pressured to only slightly overpressured. For example, the pore water overpressures decrease from 2.5 MPa along the north-eastern sand limit located to the northeast of the Broad Fourteens Basin to 0.2 MPa towards its inverted basin centre (where Rijnland and Chalk groups are missing by erosion). In the West Netherlands Basin the fluid overpressures vary between 0.3 and 2.7 MPa. In the Lower Saxony Basin the fluid pressures are less than 2 MPa (note that these fluid overpressures may also include gas pressures).

Pressure distribution and fluid flow in the Upper Jurassic Schieland/Scruff/Niedersachsen groups

The present-day distribution of the Upper Jurassic sediments is restricted to the basin and graben areas. The pressure-depth plots (Figs 8 and 9) and cross-sections (Figs 10, 11, 14 and 15) show that the Upper Jurassic is overpressured in the northern basins. This is in contrast to the southern basins where normal pressures to only minor overpressures prevail. The maximum fluid overpressures occur in the southern and northern part of the Dutch Central Graben and in the Terschelling Basin.

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 sediments 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 in the Terschelling Basin and Dutch Central Graben. 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 sand-dominated units 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 may form hydraulic barriers and locally creates vertical pathways for fluids.

The vertical dewatering of the sandy Jurassic units is largely controlled by the hydraulic characteristics and thickness of the overburden. The overpressure variations in the northern offshore show a strong relation with the lateral variation in the thickness and hydraulic characteristics of the overburden. Figure 11 reveals this spatial relation between differences in fluid overpressure in the Upper Jurassic Group in the Dutch Central Graben, thickness, and composition of the low permeable units overlying the Upper Jurassic reservoirs. The pore water overpressures exceed 10 MPa in the Upper Jurassic in the southern L5 block (Figs 11 and 15) and 9 MPa in the northern F2/F3 blocks in the Central Graben (Fig. 14). These overpressures are maintained in the Upper Jurassic sandy units by the low permeability mudstones of the Upper Jurassic Group, Rijnland Group, Chalk Group and the mudstones of the Lower North Sea Group. In contrast the pore water overpressures in the Upper Jurassic decrease to magnitudes of approximately 6 MPa in the inverted centre of the graben (e.g. block F17). The Chalk Group is absent through erosion in the inverted centre and its thickness reaches 300 m over most of the graben area. In the southernmost part of the Dutch Central Graben, away from the inverted centre, its thickness increases rapidly. The total thickness of low permeable units capping the Upper Jurassic reservoir 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 (Fig. 11), allowing overpressures to dissipate more rapidly.

The overpressures in the Upper Jurassic, especially in the southern part of the graben, are significantly higher than those observed in the overlying Chalk Group (Figs 10, 11 and 13). This suggests that there is no rapid vertical hydraulic equilibration of overpressures between these units in that area. This is in accordance with previous hydrodynamic analyses of the pressures and mudweights in and below the Chalk Group in the Dutch offshore revealing a lack of hydraulic communication between pre-Cretaceous units and the upper part of the Chalk Group (Verweij, 2006). Similar findings are described for the Central North Sea area (Winefield et al., 2005; Swarbrick et al., 2010).

The overpressures in the Upper Jurassic reservoirs (dominated by the Terschelling Sandstone Member of large areal extent) in the Terschelling Basin do not show the same regional variations as observed in the Dutch Central Graben (Figs 10 and 11): the overpressures all exceed 10 MPa and are comparable in magnitude to those observed in southern part of the Dutch Central Graben. The overpressures are likewise maintained by overlying low permeability mudstones of the Upper Jurassic and Rijnland groups, Chalk Group and mudstones of the Lower North Sea Group. Similar magnitudes of overpressure in the Terschelling Sandstone Formation suggest that overpressures are laterally equilibrated and that there exists lateral hydraulic continuity in these sandstones of large lateral extent.

Locally the pore water overpressure distributions are indicative of vertical communication between Upper Jurassic and Chalk, such as in the northern part of the Dutch Central Graben (block F3). Here the pore water overpressures in both units have similar magnitudes. In addition, the overpressures in the Upper Jurassic decrease towards a salt structure indicating lateral dewatering direction towards the salt structure, and vertically upwards along the salt structure into the Chalk Group (Fig. 14).

Pressure distribution and fluid dynamics in the Germanic Trias groups

Severe overpressures occur in sediments of the Germanic Trias groups in the northern offshore and north-eastern onshore (Figs 8, 10 and 11). The highest pore water overpressures were observed in Triassic sandstones in the Terschelling Basin ($P_{excess,\ w}$ = 35.9 MPa in block M1, P_{excess} = 39.5 MPa in block G16) and Dutch Central Graben ($P_{excess,\ w}$ = 31.7 MPa in block F15; $P_{excess,\ w}$ = 28.9 MPa in block L2; $P_{excess,\ w}$ = 20.3 MPa in block B14). Pore water overpressures reach values of more than 12 MPa on the offshore Schill Grund Platform, while overpressures do not exceed 8 MPa on the platforms and highs to the west of the Dutch Central Graben. The pore water overpressures decrease away from the Dutch Central Graben: from east to west on the Cleaverbank Platform, and from NE to SW towards the Broad Fourteens Basin and southern part Central Offshore Platform. The pore water overpressures reach magnitudes of 11-12 MPa in the Lower Saxony Basin. The pore waters in the southernmost basins are only slightly overpressured with $P_{excess,\ w}$ < 2.8 MPa in Broad Fourteens Basin, and <1.6 MPa in West Netherlands Basin. The pressure-depth plots (Figs 8 and 9) show a large lateral variation in overpressure for the same depth of measurement, especially in the Terschelling Basin and Dutch Central Graben.

The thickest package of Lower and Upper Germanic Trias sediments 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 platform 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).

Comparing the overpressure distribution with the geological framework reveals some interesting relations (Figs 10 and 11). Maximum overpressures occur in Triassic sandstone units 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. 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 sandstones are the Zechstein salt deposits and structures and the evaporites of the Upper Germanic Trias Group.

In those parts of the subsurface where Zechstein salts are present, and Upper Triassic evaporites are missing or do not form a laterally continuous hydraulic seal, the Lower Germanic Trias is still overpressured, but less extreme. Overpressure values approach those observed in Upper Jurassic units (for example in the south-eastern part of the Terschelling Basin, block M4). Figures 10 and 15 illustrate this influence of the distribution of the Upper Triassic evaporites on the overpressure distribution in the Lower Triassic sandstones. The cross-section through the Terschelling Basin (Fig. 10) indicates that the Upper Triassic Group (including the low permeable evaporites) thins out towards the east. 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 and at least partial dissipation of overpressures. The Lower Cretaceous mudstones and the low permeability part of the Chalk Group acts as a top seal for fluids in both Triassic and Jurassic units. A similar situation is depicted in Fig. 15 for the southern part of the Dutch Central Graben.

Pressure distribution and fluid flow in the Upper Rotliegend Group

The distribution of fluid overpressures in Permian Rotliegend sandstone reservoirs in offshore and north-eastern onshore parts of the Netherlands is described in detail by Verweij et al. (2011). The overpressure distribution is characterised by a general regional trend of decreasing fluid overpressures from northeast towards the south (Figs 8 and 9). The fluid overpressure values vary between severe overpressures in the southern part of the Dutch Central Graben (P_{excess} > 40 MPa in block L2) and in the northern part of the Lauwerszee Trough (P_{excess} > 20 MPa) and near hydrostatic pressures in southern offshore and onshore (e.g. P_{excess} < 1.5 MPa in West Netherlands Basin). The highest overpressures occur in a zone following the northern limit of the Permian Rotliegend reservoirs, where Zechstein evaporites restrict vertical bleed off of pressures (Verweij et al., 2011). The rather abrupt changes in overpressure along the northern sandstone limit (Fig. 16) are probably related to fault-related restricted lateral continuity of the Rotliegend reservoir in combination with its decreasing thickness and permeability close to the northern sand limit (Verweij et al., 2011). Fault sealing on a geological timescale was identified to play a major role in explaining present-day location and hydrocarbon column heights of numerous fault-bounded gas fields in the Upper Rotliegend gas play in the Netherlands (Tabor et al., 2003; Corona, 2005, 2010; Van Hulten, 2010).

Pressure distribution and fluid flow in the Limburg Group

The pressure data for the Limburg Group are relatively sparse and scattered over the area. Most data are from the platform areas in the north-western offshore. The highest pore water overpressures were observed in the northernmost offshore in the Step Graben ($P_{excess,w}$ ≈ 23 MPa in block A11; $P_{excess,\ w}$ ≈ 34 MPa in block F7). The pore water overpressures on the adjacent platform areas (D and E quadrants) are much lower ($P_{excess,\ w}$ ≈ 6-7 MPa). The large difference in overpressure between the graben (block F7) and the platform clearly indicates that a permeability barrier (probably related with the basin boundary fault zone) severely hinders equilibration of the overpressures. South of the D and E quadrants the pore water overpressures decrease towards values of approximately 4 MPa in the northern part of the Broad Fourteens Basin. The limited number of data for the onshore Netherlands indicate that the highest magnitudes of all fluid overpressures occur in the northeast ($P_{excess} \approx 16$ MPa at 4 km depth on the eastern part of Groningen High; $P_{excess} \approx 6$ MPa at 3300 m in the Lower Saxony Basin). On the Friesland Platform the observed magnitudes are less than 3.8 MPa. On the Texel-IJsselmeer High, where the Zechstein salt seal is missing and the Limburg Group is at relatively shallow depth, the fluid overpressure varies between 3.5 (at ~2600 m depth) and 5 MPa.

Pressure distribution and fluid dynamics in the Carboniferous Limestone Group

Current information on the pressure condition in the Carboniferous Limestone Group of Dinantian age is restricted to data from 1 well located on the south-eastern part of the Texel-IJsselmeer High. The pore water overpressure reaches a magnitude of 15 MPa at 4600 m. Irrespective of the mechanism that created this high overpressure, the permeability framework largely controls its preservation. There is a difference of 11.5 MPa in overpressure between the Limburg Group at ~2600 m and the Limestone Group at 4600 m depth. Vertical dissipation of overpressure from the Dinantian limestones towards shallower depths is hindered by a 2000 m thick package of predominantly low permeable shale with sandstone intercalations.

Conclusions

The regional distribution of fluid overpressure in the Dutch subsurface shows great spatial variations in magnitude on different scales, both horizontally and vertically. On a regional scale, the observed fluid pressures and leak-off pressures demonstrate a clear difference between fluid overpressure conditions in the southern and those in the north and north-eastern part of the study area. In the southern area, close to normal fluid pressures exist and are well below measured leak-off pressures. In the north, formation fluids are overpressured and approach the measured leak-off pressures in the Step Graben, Dutch Central Graben, Terschelling Basin, Schill Grund Platform and Friesland Platform. The regional differences in fluid overpressure can in large part be explained by a combination of the differences in geological framework and burial history:

– The permeability framework of the northern and north-eastern area is significantly affected by horizontal and vertical permeability barriers created by Zechstein and Triassic salt deposits and structures. These permeability barriers severely restrict fluid flow and dissipation of overpressures. The highest overpressures occur in salt-related hydraulically restricted parts of the subsurface (for example, $P_{excess} > 40$ MPa within the Zechstein Group; $P_{excess} > 30$ MPa in Lower Germanic Trias Group in Terschelling Basin and Dutch Central Graben; $P_{excess} > 40$ MPa in Upper Rotliegend Group in Dutch Central Graben).
– In the north, the pressure systems in Cenozoic mudstones, Cretaceous Chalk and Rijnland Group, and Jurassic units can largely be explained by a balance of differential, relatively rapid Late Cenozoic - Quaternary sedimentary loading which increased the pore pressure, and the dissipation of that pressure controlled by the permeability framework. The distribution and sealing character of the laterally extensive Lower Cenozoic mudstones, the Lower part of the Chalk Group and the mudstones of the Cretaceous Rijnland Formation directly influence the pressure distribution in underlying units by retarding the vertical dissipation of overpressures. This is in accordance with findings concerning the origin of overpressures in the North Sea outside the Dutch territory (e.g. Gaarenstroom et al., 1993; Moss et al., 2003; Winefield et al., 2005).
- In the south the absence of Zechstein and Triassic salt, the relatively low rates of sedimentary loading, and relatively permeable sedimentary units resulted in largely normally pressured conditions.

It is clear that the identified great spatial variations in magnitude of fluid overpressures in the Dutch subsurface requires detailed understanding of the pressure system to ensure a responsible multiple use of the subsurface and safe and cost effective drilling. The regional characterisation of the pressure system presented here, including the identified close link with the geologic framework, provides the regional framework for such understanding.

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