Triassic reservoir development in the northern Dutch offshore

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Helgoland, German North Sea[1]. The Volpriehausen and Detfurth formations. The formation boundary is at the thick interval of white aeolian 'Katersande' seen on the top of the 'Lange Anna' sea stack and on the top of the cliff.

[1] Taken by Dirk Vorderstraße: https://www.flickr.com/photos/107086296@N08/10559645584

Abstract

The Triassic Main Buntsandstein Sugbroup (RBM) play is established in the Southern North Sea. After the Rotliegend play, the RBM play is the most prolific hydrocarbon play in Dutch exploration. In the DEFAB area a P50 GIIP of 80 BCM (unrisked) of gas is still to be found (EBN, 2016). The Lower Volpriehausen Sandstone Member (RBMVL) deposits form the main reservoir rock in the RBM play. It is generally perceived that the reservoir quality decreases towards the north and that Triassic prospectivity is limited in the northern Dutch offshore. However, the northern Dutch offshore is relatively under-explored and only a few wells have actually tested Triassic reservoir rocks in this region. A recent study by EBN (2015) suggests the possibility for an alternative reservoir provenance in the marginal Step Graben. To better understand the Triassic depositional environment a regional study on wells and seismic data in the northern Dutch offshore and the surrounding territories (Five Countries Area) has been performed in this study. Ongoing Triassic sedimentation on top of Zechstein salt deposits often forms sediment pods (e.g. Smith et al., 1993). The formation of these syn-tectonic deposits in local depocentres may have formed due to early halokinesis in the Triassic. In this study accommodation space generation in the Step Graben is assessed by creating time-isochore maps for three Triassic intervals in Dutch blocks A15 and A18. The time-isochore maps show thick time anomalies likely related to early Triassic salt movement and faulting. This study proposes that oblique pull-apart faults are more likely to form at the north and south flanks of the Elbow Spit High, causing enhanced roof top weakening and development of local depocentres. In the observed areas with enhanced accommodation space sand might have accumulated from either a local source or a more distal southern Variscan source. Two BSc projects have been set-up to provide data on heavy mineral assemblages (sediment provenance) and grain size distribution analysis (transport mechanism) on wells in the northern Dutch offshore. Heavy mineral assemblages suggest the contribution from the local Mid North Sea High – Ringkøbing Fyn High. In the local depocentres an interplay between accommodation space generation, erosional processes, and sand supply is established. This interplay plays an important role in the development of potential reservoir rock. A thick Early Triassic interval might indicate axial fluvial sedimentation pathways. Heavy mineral analyses (Vonk, 2016) suggests that both a northern and a southern provenance of sediment is established in the northern Dutch offshore (Step Graben). Triassic reservoir development in the northern Dutch offshore is also seen in the offshore of the United Kingdom and Denmark. Uncertainty of the paleogeography is large, therefore making it difficult to assign local highs as the main sediment source for reservoir rock. Besides the early Triassic RBM sandstones, the Bertel-1 (DK) and A05-01 wells possibly suggest late Triassic Schilfsandstein deposits.

Keywords: Early Triassic, Volpriehausen, sandstone, reservoir, sediment pod, halokinesis, Step Graben, northern Dutch offshore

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Abbreviations

ADB:	Anglo Dutch Basin
BCM:	Billion Cubic Metres
CP:	Cleaverbank Platform
DCG:	Dutch Central Graben
DEFAB	D, E, F, A, and B offshore blocks in the Dutch sector.
DEF-survey:	3D seismic survey in the northern Dutch offshore D, E, and F blocks.
EBN:	Energie Beheer Nederland
ESH:	Elbow Spit High
ESP:	Elbow Spit Platform
GIIP:	Gas Initially In Place
GEUS:	Danmarks Og Grønlands Geologiske Undersøgelse
NLOG:	Nederlands Olie- en Gasportaal
MSNH:	Mid North Sea High
OGA:	United Kingdom Oil and Gas Authority
RBM:	Main Buntsandstein Subgroup
RBMD:	Detfurth Formation
RBMDL:	Lower Detfurth Sandstone Member
RBMDU:	Upper Detfurth Sandstone Member
RBMVA:	Volpriehausen Avicula Member
RBMVC:	Volpriehausen Clay-siltstone Member
RBMVL:	Lower Volpriehausen Sandstone Member
RBMVU:	Upper Volpriehausen Sandstone Member
RBSH:	Lower Buntsandstein Formation
RNKPM:	Middle Keuper Claystone Member or alternatively Schilfsandstein
RNMUE:	Muschelkalk Evaporite Member
RNRO1:	Main Röt Evaporite Member
RFH:	Ringkøbing-Fyn High
SPBA:	Southern Permian Basin Atlas
SG:	Step Graben
SGP:	Schill Grund Platform
TB:	Terschelling Basin
TNO:	Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek
TZE:	Top Zechstein

1. Introduction

The Triassic Main Buntsandstein Sugbroup (RBM) play is established in the Southern North Sea. After the Rotliegend play, the RBM play is the most prolific hydrocarbon play in Dutch exploration. In the DEFAB area a P50 GIIP of 80 BCM (unrisked) of gas is still to be found (EBN, 2016). The Lower Volpriehausen Sandstone Member (RBMVL) deposits form the main reservoir rock. The abundance and thickness of aeolian RBMVL decreases from south to north. It is generally perceived that the reservoir quality decreases towards the north and that Triassic prospectivity is limited in the northern Dutch offshore. However, the northern Dutch offshore is relatively under-explored and few wells have actually tested Triassic reservoir rocks in this region (fig. 1).

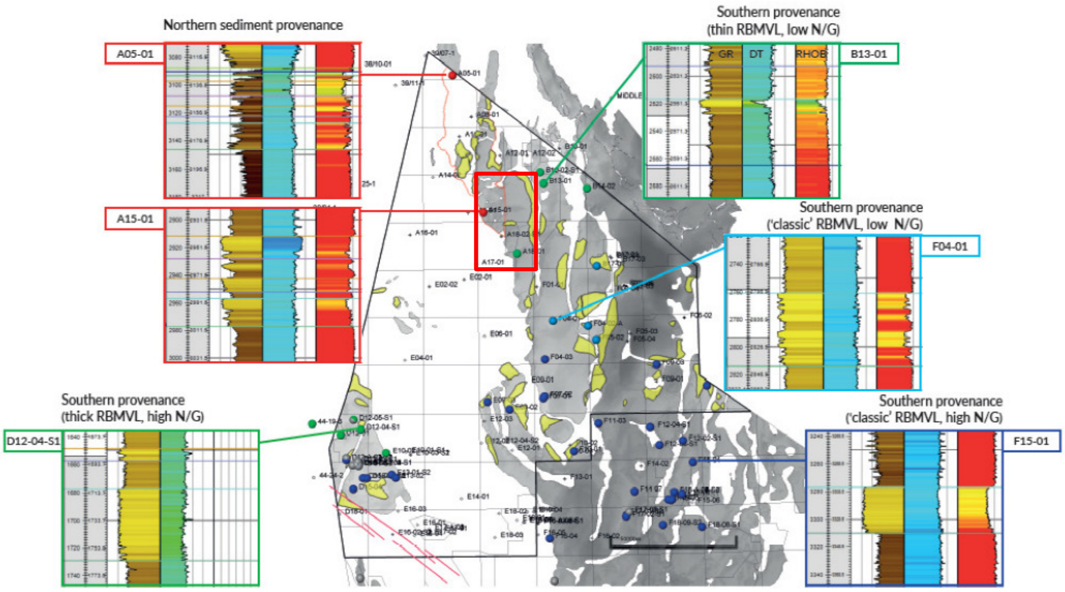


Figure 1. Regional reservoir architecture. Typical well log response for different types of the Lower Volpriehausen Sandstone Member (RBMVL) (EBN, 2015). Red outline indicates the focus area.

EBN has recently evaluated the RBMVL play in the northern offshore region (EBN, 2015) and postulates that fluvial sands with northern provenance may have developed in the north-western area of the Step Graben. Syn-tectonic strata in local depocentres could be preserved here due to early halokinesis in the Triassic (Smith et al. 1993). Olivarius et al. (2015) describe a southern source of aeolian sands from the Variscan mountains and a northern (local) source of fluvial sands from the Ringkøbing-Fyn High in the Northern German Basin. The different log character of well A15-01 (Placid, 1977) and A05-01 (Amerada Hess, 1999) in this north-western area could indicate a similar local sediment provenance. Local highs may have provided sediments. The Danish Bertel-01 well (50 km north of the A-blocks) discovered a Triassic oil field and shows a similar log response. However, in both A05-01 and Bertel-01 there is an age-dating uncertainty for the Triassic rocks which could also be reworked Jurassic rocks, therefore study of available cuttings is necessary. A better understanding of the early Triassic depositional environment in the northern Dutch offshore and surrounding areas will improve assessing Triassic prospectivity here.

Aeolian sands can accumulate against a footwall of graben structures (Prossner, 1993). A possible modern analogue for these kind of aeolian sands can be found in the Alamosa basin in Colorado (USA). Generally, preservation potential is low as aeolian sands are easily blown away. The best potential for aeolian sands to be preserved over geological time is when groundwater is somewhat higher than its surroundings causing the sand grains to stick together (e.g. De Jager, 2012; Mountney & Thompson 2002). This can occur in places where subsidence is greater than in the surrounding areas. The depocentres can either develop by saltdoming (Fat Sand Play e.g. De Jager, 2012), by horst-graben structures, or a combination of the two. This study will involve a reconstruction of the accommodation space in the focus area and evaluate the potential of early Triassic depocentre development.

Improving the assessment of Triassic prospectivity in the northern Dutch offshore requires a better understanding of reservoir provenance, local geological history and climate, and analogue Triassic fields (in DK, DE and UK). A joint research project between EBN and the Sedimentology Department of Utrecht University is set up. Apart from this MSc internship project, two BSc thesis projects ran simultaneously. The first BSc project studies heavy mineral assemblages and dispersal patterns of core and cutting material of Triassic sections of the A05-01, A15-01, A18-01 wells. These results could assist us in understanding the provenance of the sands (Vonk, 2016). The second BSc project will study the grain-size distributions to better understand the depositional environment (climate conditions and transport mechanisms) (Bezemer, 2016).

1.1 Objective and research questions

The main objective of this internship is to improve our understanding of the Triassic depositional environment in the northernmost Dutch offshore by addressing the following:

- Improve our understanding of the early Triassic depositional environment in the northern Dutch offshore and neighbouring countries (Five Countries Area).
- Development of accommodation space during the early Triassic in the northern Dutch offshore.
- Early Triassic sand provenance in the northern Dutch offshore, can a distinction between a local and a regional sand provenance be made?
- What was the transport mechanism of the early Triassic sandstones, is there a difference between well locations? Is it possible to make a distinction between fluvial and aeolian sand transport?

1.2 Approach

To answer the research questions, this study consists of the following parts:

- Literature study on the structural and depositional geology of the northern Dutch offshore and the neighbouring countries (Five Countries Area).
- Seismic interpretation of the UK and NL public lines to study syn-tectonic features in the Triassic.
- Well log interpretation of NL, UK, and DK wells, and study of Triassic fields in NL, UK, and DK.
- Two BSc projects will provide the following data:
    - Heavy mineral assemblages and clay mineralogy of samples of A05-01, A15-01, and A18-01 wells. This will provide information on sediment provenance (Vonk, 2016).
    - Grain size distribution of samples from A05-01, A15-01, and A18-01 wells. This will provide information about the depositional environment (Bezemer, 2016).

2. Geological and stratigraphic setting

2.1 Structural elements of the Five Countries Area

The Five Countries Area is positioned at the confluence of two structural trends: the NW-SE trending part of the Central Graben to the north and the N-S trending part of the south (fig. 2) (Spathopoulos et al. 2000). The Five Countries Area is bounded by three main highs; the Mid North Sea High to the west, the Ringkøbing-Fyn High to the east, the Elbow Spit High to the south. These highs were relatively stable throughout the Mesozoic (Wride, 1995). However, when comparing different paleogeographic reconstructions of Early Triassic highs from literature differences appear (fig. 3). The paleogeography reconstruction of Lervik (2012) is mostly based on well data from Cameron et al. (1992). The paleogeographic reconstructions of Goldsmith et al. (1995) are based on seismic and well data. The basis for the paleogeographic reconstruction of the Millenium Atlas (figure 9.1) is not described. The paleogeographic reconstructions of McKie & Williams (2009) is built on previously published work on the Southern North Sea (Geluk, 2005), Central and Northern North Sea (Goldsmith et al., 2003) and is regionally following Ziegler (1992). In summary, a western Mid North Sea High and an eastern Ringkøbing-Fyn High is shown in all paleogeographic reconstructions, although the outlines of the highs vary considerable. Therefore, this study will follow the western outlines of the RBMVL (EBN, 2015) for the Dutch outline of the Mid North Sea High, while in the UK sector the outline of the high is based on well data from the OGA Survey 2015 and the outlines of McKie & Williams (2009) (see green outline figure 3). This study will consider the “highs” as non-depositional areas; where sediment either has not been deposited, is subsequently eroded, or is composed of a relatively thin mudstone layer <10 m.

2.2 Deformation history of the Five Countries Area

Overprinting of several deformation phases of both contraction and extension, resulted in a complex structural setting of the Five Countries Area. The transverse zones in the Outer Rough Basin caused the rift and fault trends to be transected into a structural mosaic of rhomboidal segments (Wride, 1995). The tectonic segmentation of the Central Graben by tranverse zones, caused the formation of extensional pull-apart basins and contractional pop-up features within one shear zone (Bartholomew et al. 1993). Towards the Step Graben transverse faulting is observed but is not strongly expressed in the post-Zechstein strata (Ter Borgh, pers. comm.). In the northern part of the Step Graben, Permo-Jurassic normal faults accommodated the E-W extension. The E-W extension in the northern part of the Step Graben caused basins to form in between normal faults. Early Triassic mudstones have been deposited locally on the Elbow Spit Platform. The Elbow Spit High in the south acted as an relatively stable structural element throughout the Mesozoic. The Elbow Spit High might have influenced the E-W extension of the Step Graben, where in the north normal faulting is dominant and towards the south oblique faulting is more dominant.

Four major tectonic events influenced the Five Countries Area since the Cambrian: (1) the Caledonian collision during the Late Ordovician to Early Silurian, (2) subsequent extension in the Carboniferous of probable Dinantian age as recorded from the Southern North Sea, (3) a series of extensional and compressional events at the Permo-Carboniferous combined with extrusive volcanism, (4) Mesozoic rifting and graben formation, and (4) inversion during the Late Cretaceous to Early Tertiary (Spathopoulos et al. 2000; Ziegler, 1992).

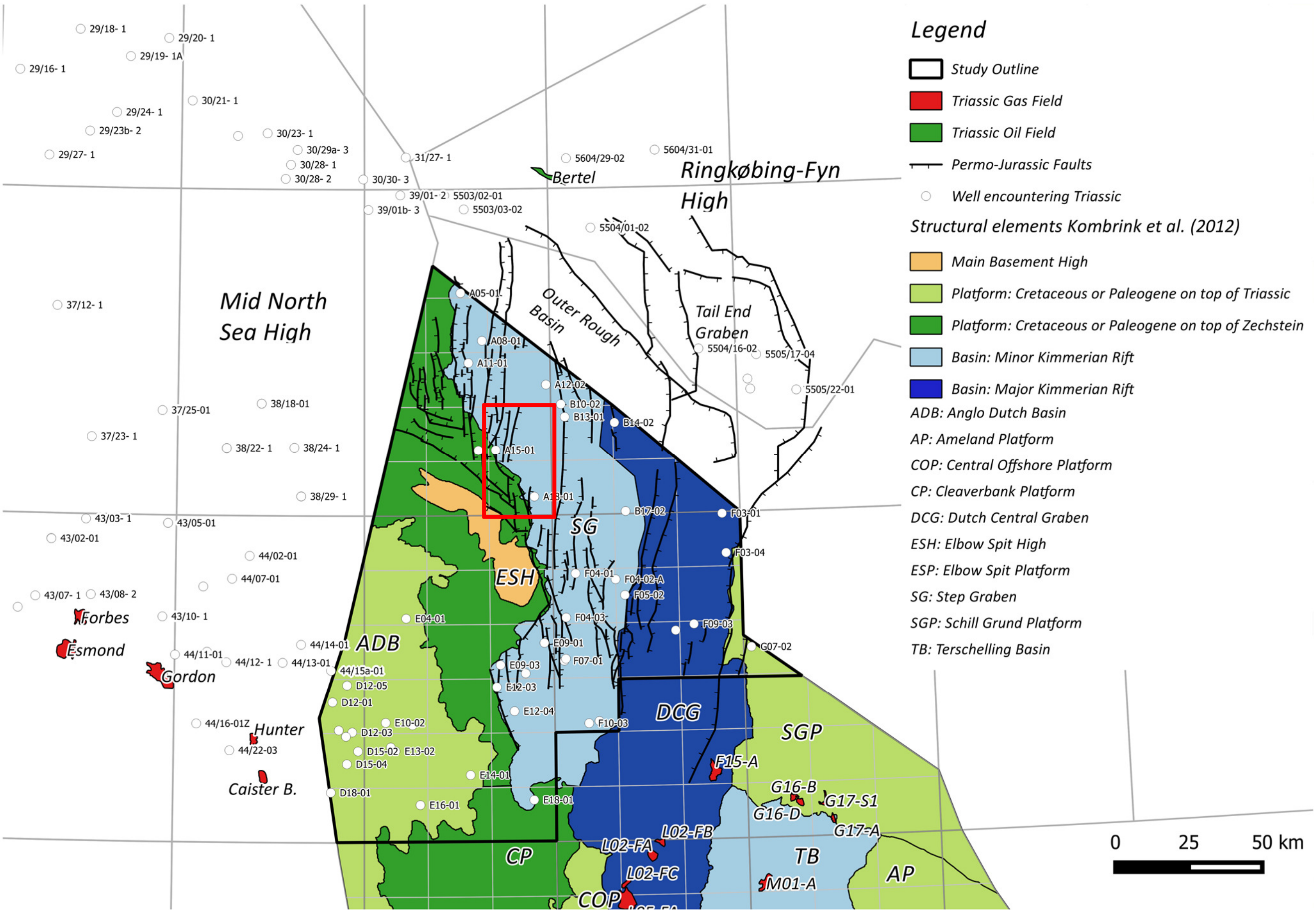


Figure 2. Structural elements after Kombrink et al. 2012. In the red square the focus study area can be seen.

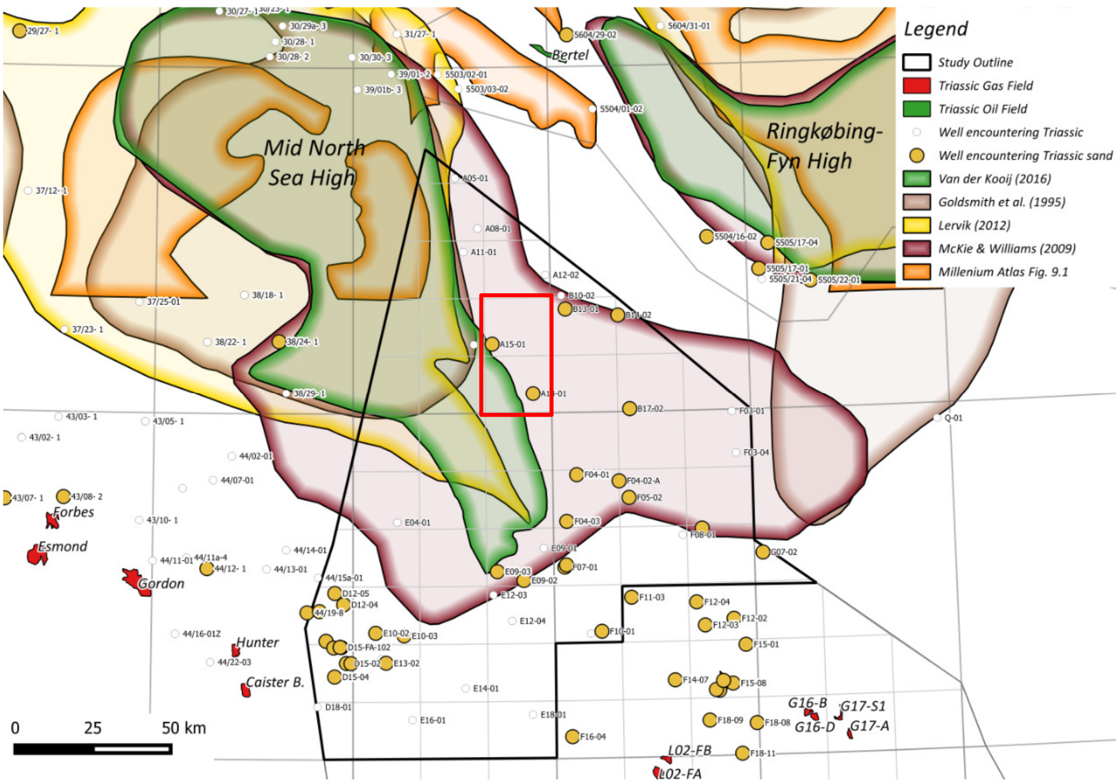


Figure 3. Map showing the differences in paleo-highs postulated by several authors. The outline that is used for this report can be seen in green. The outline of the paleo-high in this report is based on well data, seismic data, and literature (McKie et al., 2010).

After a volcanic episode at the Permo-Carboniferous boundary, western Europe became affected by late-Variscan post-orogenic tectonism. Wrench-faulting associated with intrusive and extrusive magmatism and thermal uplift caused widespread deep erosion resulting in the Base Permian Unconformity (Ziegler et al., 2004). Broad NW-SE trending swells formed, which can be traced on the subcrop map of Westphalian units at the Base Permian Unconformity (BPU). After this volcanic period, the Saalian Unconformity separated the volcanics from the sediments of the Rotliegend Altmark Subgroup. This episode corresponds to the closure of the Rheic Ocean and occurred at the culmination of the Variscan orogeny (Fraser & Gawthorpe, 1990).

The first post-orogenic deposits preserved in the Five Countries Area are those of the Upper Permian aged Slochteren Formation (NL) or Auk Formation (UK). This formation shows thickening into the basin-bounding faults indicating that deposition occurred during a phase of extension. At the start of the Zechstein in the Late Permian, marine transgression occurred. During this marine transgression, mudstones of the Coppershale Member were deposited in the embayments of the Five Countries Area (Spathopoulos et al., 2000). The Zechstein deposits on the platform highs mainly consist of dolomite and anhydrite of the Z1 (Werra) Formation, lacking halite deposition. The simultaneous deposition of the Z1 Carbonate Member within the Five Countries Area, indicates that a bathymetry was present, either reflecting the underlying structure, or a continuing extension (Spathopoulos et al., 2000).

During the Early Triassic, rifting between Greenland and Scandinavia intensified and propagated into the North Sea as well as into the North Atlantic Domain (Ziegler, 1990a). The North Sea rift system transected the Northern and the Southern Permian basins (Ziegler, 1990a). The lithosphere of these basins was still considerably thinner and weaker than the lithosphere of Fennoscandia to the north and the Anglo-Brabant and Variscan massifs to the south. During the Early Triassic the Southern Permian Basin was mud-dominated (fig. 4). This was the result of thermal subsidence in the basin during the Early Triassic (Ziegler, 1992). In the Dutch sector deposition of mud-dominated Lower Buntsandstein Formation (RBSH) took place during the thermal subsidence. In the UK, mud dominated early Triassic sediments of the Smith Bank Formation and the Bunter Shale Formation can be found. Only locally has the RBSH been deposited on the Elbow Spit High, indicating either non-deposition or post-depositional erosion. However, it is more likely that non-deposition occurred on the Elbow Spit High because it had been structurally elevated in earlier times (Spathopoulos et al., 2000).

An important structural reorganisation initiated at the beginning of the Olenekian (244 Ma). Tensional and transtensional stresses created NNE-WSW trending highs and lows that dissected the RBSH depositional areas and resulted in variable amounts of subsidence. The thickness of the RBM reflects a combination of enhanced subsidence in the grabens, and uplift and erosion elsewhere (Geluk & Röhling, 1997, 1999). Five short-lived rifting pulses (pre-Quickborn, pre-Volpriehausen, the pre-Detfurth, the pre-Solling, and intra-Solling) have been identified during the deposition of the RBM (Geluk, 2007). The strongest was probably the pre-Solling pulse which culminated during the Olenekian and resulted in the Hardegsen Unconformity (fig. 4). The Hardegsen Unconformity mainly controls preservation of sediments of the RBM. The cause of the Hardegsen Unconformity is still under debate and can either be the result of tectonics (Röhling, 1991), or deformation of the crust in response to built-up intraplate stresses (Cloetingh, 1986).

During the Anisian to Norian the Early Kimmerian tectonic phase took place and is subdivided into five rifting pulses (Geluk, 2007). These pulses resulted in a progressive structural modification of the Southern Permian Basin, which became dissected by rifts and split up into smaller units. The Early Kimmerian tectonic phases I and II, affected the thickness and salt distribution of the Röt, Muschelkalk and Keuper formations. It resulted in two unconformities, at the base of the Red Keuper Claystone (Early Kimmerian I) and at the base of the Sleen Formation (Early Kimmerian II). The Early Kimmerian phase marked the beginning of differential movement of the Dutch Central Graben. The Early Kimmerian movements continued intermittently during much of the Triassic, of which the strongest pulse occurred during the Carnian (Geluk, 2007).

Gradual uplift and erosion of the Clever Bank High and the Netherlands Swell during the Mid Kimmerian phase in the Jurassic, removed much of their Triassic cover. Analysis of Geluk & Röhling (1999) indicates that subsidence was spasmodic and shifted northwards with time, from the Roer Valley Graben and West Netherlands Basin to the Ems Low and the Dutch Central Graben. This was accompanied by strong uplift of the Mid North Sea and Ringkøbing-Fyn highs. The N-S fault pattern of this phase suggests an E-W extension, with minor strike-slip movements along a number of fault zones (Geluk, 2007). Basement faulting triggered widespread mobilization of Zechstein salt. These salt movements resulted in both symmetrical and asymmetrical depocentres and mainly controls Triassic preservation in Central North Sea. During the Late Kimmerian phase, which lasted from the Late Jurassic to the Early Cretaceous, the Central Graben subsided and the surrounding platforms were uplifted again (Remmelts, 1996). During the Cretaceous E-W extension of Pangea was mainly accommodated by rifting between Greenland and the UK and Norway. This extension rapidly decreased towards the Dutch North Sea area (De Jager, 2007). During the Cretaceous thermal subsidence continued in the North Sea and global eustatic sea level rose resulting in deposition of the Chalk Group. In the Dutch northern offshore this extension was accommodated in the Dutch Central Graben by transpression and transtensional basins (e.g. SPBA 3.18d).

Late Cretaceous indentation and rotation of the African plate into the Eurasian plate initiated the closing of the Tethys ocean and development of the Alpine orogeny. The contraction caused inversion of several North Sea basins. However, the amount of inversion varies in the different basins and is also influenced by the amount of Zechstein deposits. Inversion within the Dutch Central Graben was less than in other northern basins. While the centre of the Central Graben was inverted, platforms flanking the graben continued to subside. During the last strong inversion pulse (Late Eocene-Early Oligocene) NW-SE dextral strike-slip movements took place, accompanied by accelerated salt movements (Remmelts, 1996; De Jager, 2007).

2.3 Stratigraphy

Pre-Mesozoic basement rocks of the northern Dutch offshore mostly comprise of continental to paralic Carboniferous deposits and Permian Upper Rotliegend anhydritic shales. Overlying this basement, Zechstein evaporites of Late Permian age have been deposited. Figure 4 shows a detailed overview of the Triassic lithostratigraphy in the North Sea. In figure 5 an overview of the regional stratigraphy between the Northern and the Southern Permian Basin can be seen. The Triassic of the Dutch sector is subdivided into two groups (e.g. Van Adrichem Boogaert & Kouwe, 1994): the Lower Germanic Trias Group (latest Permian – Olenekian) and the Upper Germanic Trias Group (Olenekian – Norian). The Lower Germanic Group mainly contains fine-grained clastic deposits with sandstone and oolite intercalations, changing to predominantly sandstone deposits at the southern margin (Geluk, 2007). The Upper Germanic Trias Group comprises an alternation of fine-grained-clastics, sandstones, and evaporites (Geluk, 2007). Several intra-Triassic unconformities are visible over a large area of the Southern Permian Basin and are most visible on the swells and towards the basin margins. There is, however, uncertainty about some of these unconformities as they are largely undocumented in the UK and DK.

The main problem with terrestrial sediments is age dating. Ages used in this report are after the ICS (2003). Noteworthy, the only officially approved age is the Permian-Triassic boundary (251 Ma). Astronomical calibration has been used by Geluk & Röhling (1997) to improve the numerical ages. The Germanic Triassic is especially suitable for such calibration as it has a well-developed cyclicity, both at outcrop and in well logs.

2.3.1 Lower Germanic Trias Group (RB)

The Lower Germanic Trias Group (RB) is subdivided into the Lower Buntsandstein (RBSH), Volpriehausen (RBMV), Detfurth (RBMD) and Hardegsen (RBMH) formations. The last three formations together form the Main Buntsandstein Subgroup (RBM) and the sandstones intervals form the primary Triassic hydrocarbon reservoir target in the Dutch sector. In the Central Graben and along the Norwegian-Danish Basin (both located north of the Mid North Sea High) the Main Buntsandstein equivalent (Bunter Sandstone) was sourced by erosion from the Fennoscandian Shield hinterland. Sediment input north of the Mid North Sea – Ringkøbing-Fyn High into the study area was restricted (Best et al., 1983; Michelsen & Andersen, 1983; Cartwright, 1990).

Lower Buntsandstein (RBSH)

The Lower Buntsandstein (RBSH) mostly consist of a cyclic alternation of fluvio-lacustrine fine-grained sandstones and clayey siltstones (Geluk & Röhling, 1997). The thickness, seismic character, and organisation of the high-resolution sequences indicates a very uniform basin subsidence. Sedimentation was therefore controlled by cyclic, climatic variations in humidity (Geluk & Röhling, 1997). The RBSH is mostly between 200 to 300 m thick and can be correlated over distances of several 100 km (Geluk & Röling, 1997). The strongest subsidence occurred west of the Cleaver Bank High and east of the Schill Grund High where the formation is up to 400 m thick (Geluk, 2005). The fine-grained character of the RBSH is also recorded north of the Mid North Sea High in the lower part of the Smith Bank Formation (Goldsmith et al., 1995). This, combined with the absence of sandy deposits around this high, indicates that it was originally entirely covered by RBSH deposits (Geluk, 2007).

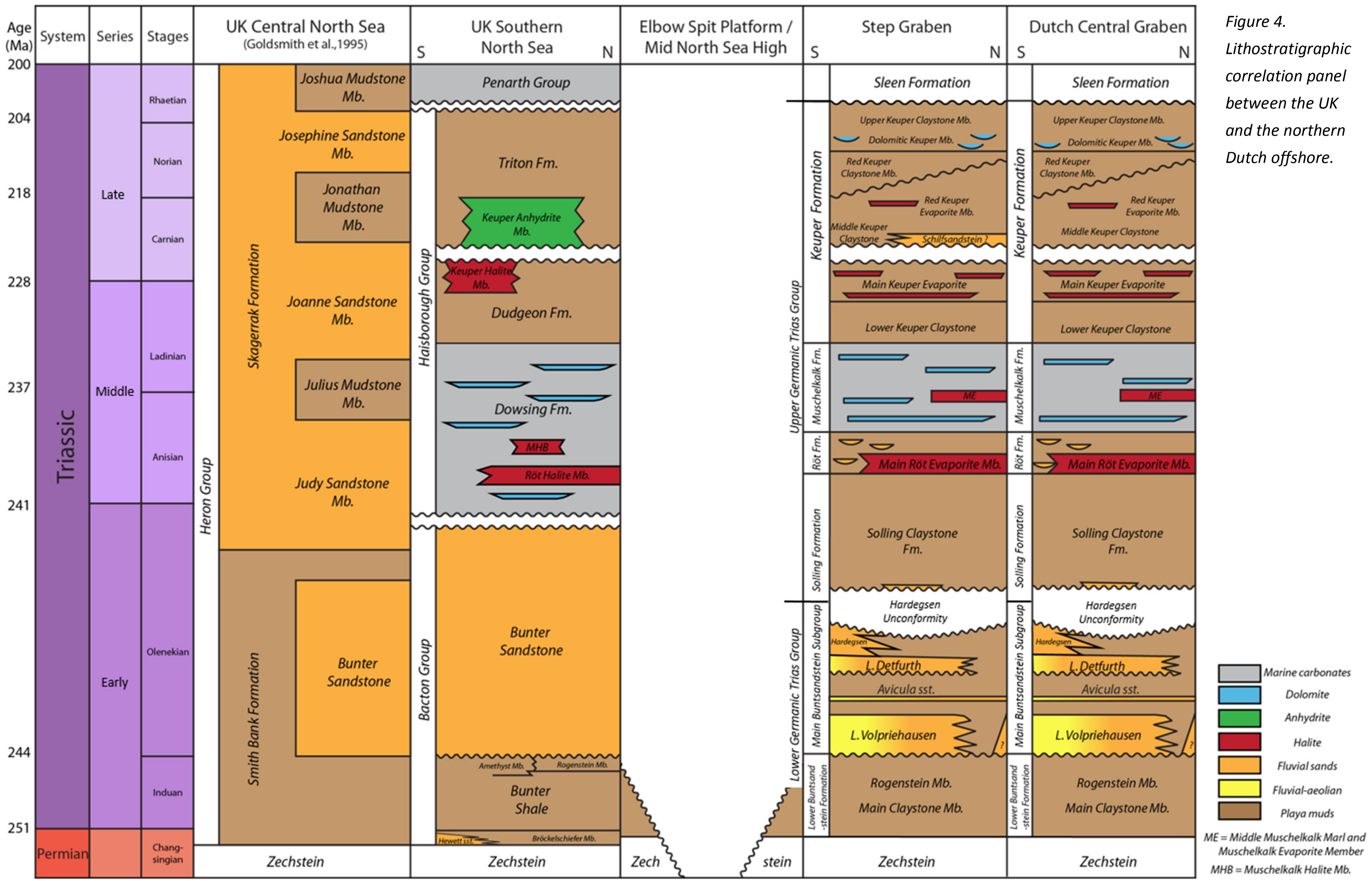


Figure 4. Lithostratigraphic correlation panel between the UK and the northern Dutch offshore.

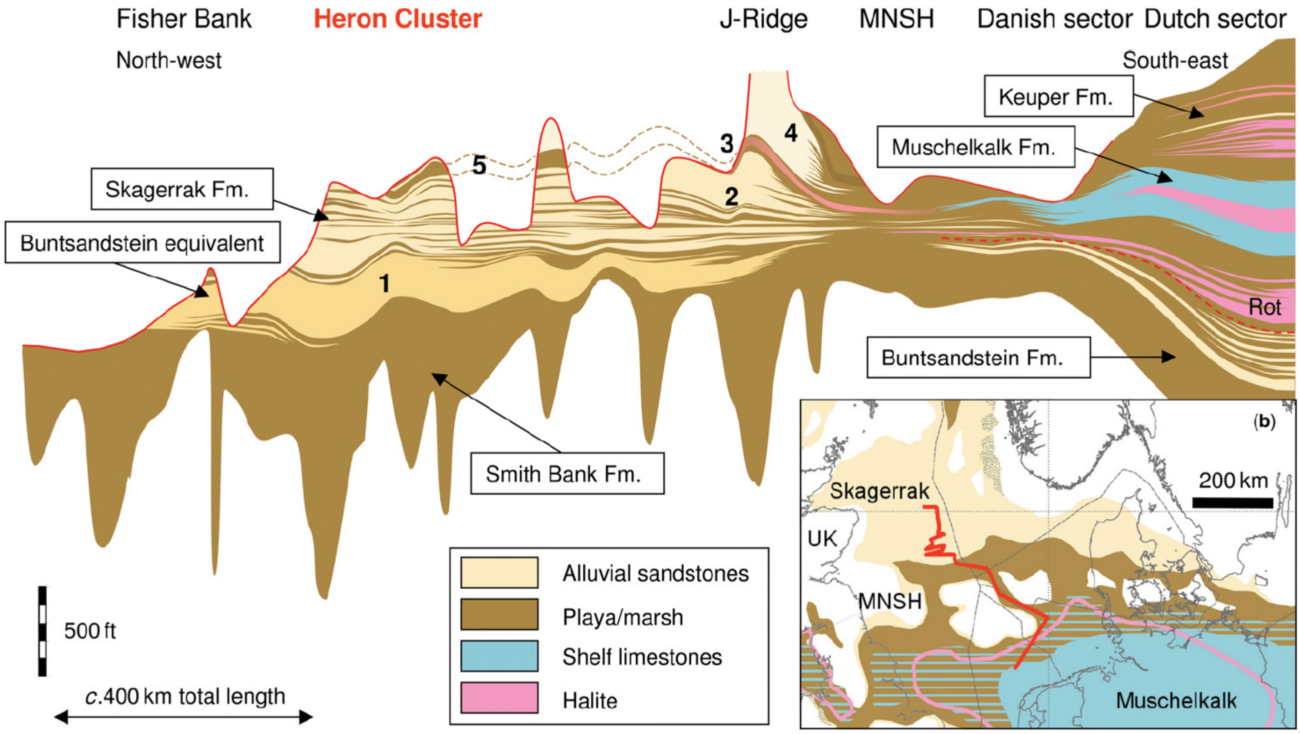


Figure 5. a) Stratigraphic correlation pan between the Northern Permian Basin and the Southern Permian Basin. 1, Buntsandstein equivalent; 2, Judy Member; 3, Julius Mudstone Member; 4, Joanne Member; and 5, Heron Shale. The overall transition from Central North Sea 'Skagerrak' facies into the 'Germanic' successions of Bunter, Muschelkalk, and Keuper occurs across the Mid North Sea High region, which appears to have acted as an area of reduced subsidence which prevented marine ingress into the Central North Sea. b) Middle Triassic paleogeographical setting illustrating the dominantly alluvial facies in the Central North Sea and the relationship to the marine carbonates of the Muschelkalk to the south in the Southern North Sea. After McKie et al. (2010).

Main Buntsandstein Subgroup (RBM)

Sedimentation in the Main Buntsandstein Subgroup (RBM) was controlled by Milankovitch climate cycles. In humid periods a higher fluvial activity resulted in alluvial systems building out from the Variscan mountains into the Southern Permian Basin. The RBM sandstones were deposited during such humid periods. During dry periods aeolian activity redistributed these sands (Geluk, 2005). An overview of the depositional environment can be seen in figure 6a. The Volpriehausen Formation (RBMV) marks the beginning of the RBM and is composed of sand and claystone intervals. The Lower and Upper Volpriehausen Sandstone Members (RBMVL and RBMVU respectively) together with the Lower and Upper Detfurth Sandstone Members (RBMDL and RBMDU respectively) form the main hydrocarbon reservoirs of the RBM. It is commonly thought that deposition of the RBMVL took place in a large intra-cratonic basin in a fluvio-lacustrine environment (Geluk, 2005). During deposition of the RBMVL, base level had lowered due to rifting and fluvial systems from the Variscan hinterland were able to build out towards the north into the Southern Permian Basin. The RBMVL is dominated by fluvial sedimentation in the southern Dutch offshore. Towards the north aeolian processes dominate sedimentation of the RBMVL. The aeolian sandstones eventually shale out towards in the northernmost Dutch offshore (Geluk, 2007). According to Geluk & Röhling (1997, 1999) and Geluk (2005) thickness variations in the RBMVL have multiple causes. These include syn-depositional thickening, facies transitions, and erosion.

2.3.2 Upper Germanic Trias Group (RN)

Skagerrak Formation (UK)

North of the Mid North Sea High, sandstones of the Skagerrak Formation prograde over Smith Bank Formation shales and Bunter Sandstones (fig. 5) and were deposited as sheetflood and ephemeral braided-stream sands on an extensive alluvial plain. Sands of the Skagerrak Formation were commonly trapped in deep, narrow, north-south- orientated belts adjacent to the hinterland, especially during rapid subsidence. As sand deposition gradually waned, these sub-basins became back-filled by fine-grained lacustrine/flood-basin sediments.

Fat Sand (RNSOF)

The Fat Sand Play or officially Middle Solling Sandstone member (RNSOF), is a local sand body that has been found by the NAM in the L9 block of the Dutch offshore in 1992. The RNSOF was found unexpected by the L09-07 well, which had the RBMVL as its main objective. In the follow-up well L09-08, approximately 125 m RNSOF was found, with an estimated total recoverable gas volume of 28 BCM (De Jager, 2012). The entire RNSOF interval was cored by the NAM and the sedimentological observations clearly indicate that most of the interval is made up of aeolian sand. The sandstone is present in a wedge-like depression near a salt dome, indicating Early Triassic salt movement.

Schilfsandstein (RNKPM)

During the Early to Middle Triassic, the Variscan mountains formed the main sediment source for the Southern Permian Basin (fig. 6a). This led to deposition of fringing terminal fluvial facies that extended tens of kilometres northward into the basin (Hornung & Aigner, 2002ab; Geluk, 2005). Palaeocurrent data generally indicate a northward sediment transport from the Variscan mountain range into the basin through intervening ‘gates’ (McKie & Williams, 2009). In contrast to Early and Middle Triassic sedimentation, the Carnian aged (224 ± 14 Ma) Schilfsandstein (RNKPM) was sourced from the northern Fennoscandian high (fig. 6b). A large fluvial system drained from the Fennoscandian high to cross the Southern North Sea and the German Basin eventually entering the Tethys (Köppen & Carter, 2000; Geluk, 2007). The rapid Carnian uplift of Fennoscandia occurred in response to the formation of the Kimmerian orogeny in the Black Sea (Ziegler, 1998). During this period climatic conditions were probably more humid (McKie & Williams, 2009). Additionally, minor drainage from the UK entered the basin from the west (McKie & Williams, 2009). There is not much contribution of sediments from the Skagerrak Formation, which appears to have largely become mud-dominated immediately north of the Mid North Sea High, and supplied little or no fluvial sand through gaps between the highs (McKie & Williams, 2009).

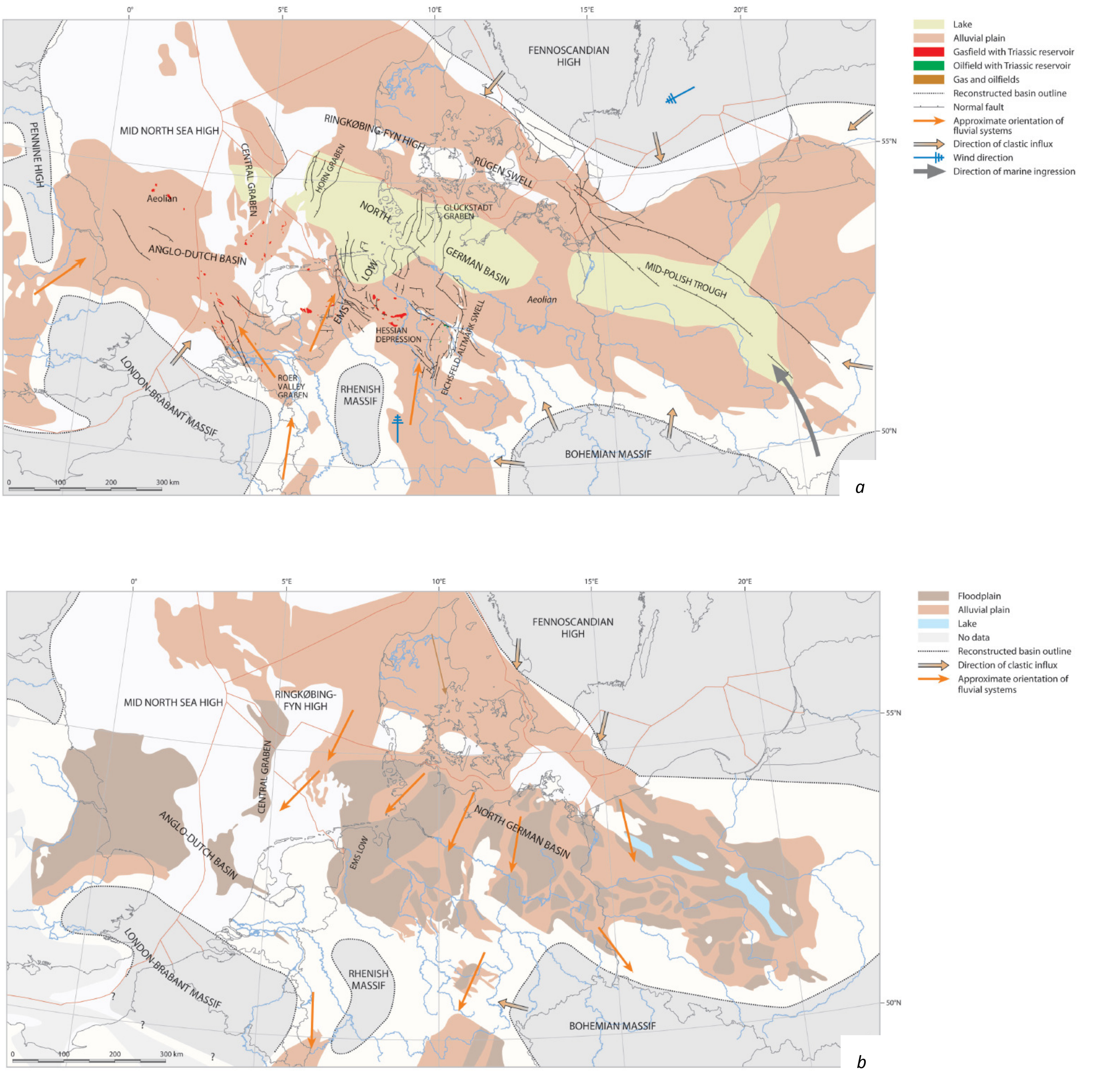


Figure 6 a) Overview of the Main Buntsandstein Facies (Early Triassic, Olenekian) distribution in the Southern Permian Basin (SPBA, 2010). b) Present-day distribution and facies map of the Schilfsandstein (Late Triassic, Carnian) (Geluk, 2007). Here, the main sediment supply originated from Fennoscandia. Solid lines represent the reconstructed basin outline. Arrows indicate transport direction and clastic influx.

The RNKPM (Geluk, 2005) is mainly composed of reddish claystones. Locally in the southern Dutch Central Graben, however, it includes its basal part up to 10-m-thick, minerologically immature, mica bearing, grey to green-coloured, high-gamma-ray sandstones. Geluk (2005) notes that this member is prone to be misinterpreted for mudstone due to its high gamma-ray readings. The Dutch sector was predominantly bypassed by the main fluvial channel belts, which ran off towards the south via the Hessian Depression and the Trier Embayment (Geluk, 2005). However, in the Dutch Central Graben and in the P block the RNKPM reaches a thickness of 100 m. In other areas in the Dutch sector this thickness varies between 10 to 50 m. In Germany the RNKPM unconformibly overlies the older Keuper members. In the Dutch sector the member overlies the Lower Gipskeuper with one exception in the south where based on palynological evidence, RNKPM has been found overlying uppermost Muschelkalk (well Nederweert-1; NITG, 2001).

In terms of prospectivity the RNKPM has not yet been a reservoir interval of interest for the Dutch subsurface. This has multiple reasons; (1) it has not been deposited in a vast area in the Dutch sector, (2) the reservoir quality is mostly poor in the Dutch sector, (3) it has not been penetrated by numerous wells, and (4) it is hard to recognise on logs. Onshore the best reservoir quality of the RNKPM is expected to be in the Lower Saxony Basin (Geluk, 2005). The potential for RNKPM reservoir development is discussed in §6.1. A recent TNO biostratigraphic study on well A05-01 indicates that Carnian aged sediments might have been deposited in this well (fig. 9 and Appendix C).

3. The Triassic play

3.1.1 Characteristics of the Triassic play

Economic Triassic hydrocarbon accumulations have been found mainly in the western part of the Southern Permian Basin. Gas is the most common constituent, although oil accumulations have also been found in the West Netherlands Basin and in the Danish offshore. Gas is mostly found in sand reservoirs of the RBM (e.g. Volpriehausen, Detfurth, and Hardegsen Formations). Triassic oil reservoirs, to the contrary, are divided between the Lower Triassic Buntsandstein Group and the Upper Triassic Keuper group. Triassic reservoirs mainly compose of clastic rocks composed of both fluvial to aeolian sand intervals. Failure of the play is mostly attributed to absence of charge windows through the thick sealing claystones and evaporites of the Rotliegend and Zechstein. Absence of seal has been described as well. In terms of source rocks, the Triassic gas play shares the Upper Carboniferous coals and Namurian shales with the Rotliegend, Zechstein, and Carboniferous plays. The Triassic gas play therefore only works where the Zechstein salt, the regional top seal of these other plays, was either not deposited or is locally breached by salt withdrawal, faulting, or volcanic dykes (e.g. Caister-B field, UK). The regional top seal of the RBM gas-fields is formed by the Solling Claystone and Röt Evaporite (Geluk et al., 1996). Analogue fields show that very thin clay/marl layers can also act as seal, e.g. the Jurassic Flora gas field (UK) where a thin layer of Lower Cretaceous claystones and marls form the seal of this truncation trap (Hayward et al., 2003).

Trap styles of Triassic gas-fields can be subdivided between areas with and without salt. In areas where salt is thin or absent (e.g. West Netherlands and Broad Fourteens basins) the typical play consists of Late Jurassic horst blocks in which the reservoir is vertically sealed by Upper Triassic evaporitic shales and laterally by Upper Triassic to Lower Jurassic shales (De Jager et al., 1996). Salt plays an important role in the development of accommodation space during the Triassic in the North Sea. Timing of salt tectonics together with sediment supply is key. The complex interplay between sediment supply and salt induced topography, complicates the prediction of reservoir development.

3.1.2 Halokinesis

In the North Sea area, Zechstein deposits compose of minor amounts of anhydrite, clastics, and other evaporites besides halite. Anhydrite, carbonates, and clastics are mostly found on the basin margins and basement highs. The rock mechanical properties of salt are different from clastic, anhydrite, and carbonate rocks. Over geological time salt behaves visco-elastic instead of brittle. Because salt is incompressible the system will become buoyantly unstable. To initiate the buoyant rising of salt, a perturbation in the system caused by stress differential loading and roof strength weakening is necessary (Hudec, 2007; Vendeville & Jackson, 1992; Vendeville, 2002). The differential loading and roof strength weakening can be induced by active faulting. The ongoing rising of salt (Rayleigh-Taylor instability) will only occur when salt is buried below a depth of 1600 m (Baldwin & Butler, 1985). In the northern Dutch offshores salt diapirs, pillows, and walls have developed. An overview of the different salt structures can be seen in figure 7. Salt movement is typically controlled by an interplay of several factors: weakening of the overburden by active faulting, differential loading induced by fault controlled accommodation space generation, and buoyant behaviour of salt (Hudec et al. 2009). Once the salt movement has been initiated, it causes the structural style of the basin to differ significantly from basins that do not contain salt.

Salt movement can initiate the formation of mini-basins, which can subside at rates of >1 km/Ma for several millions of years (Hudec et al., 2009). In the Gulf of Mexico subsidence rates have been recorded up to 10 km/Ma (Prather, 2000). These mini-basins are the result of an interplay between sediment supply and accommodation space. They form 8 to 15 km wide basins in the Central North Sea, but their geometry varies as a function of initiation mechanism (Banham & Mountney, 2013). In the Central North Sea, the deposition of the Triassic Skagerrak Formation is influenced by the formation of mini-basins. Initiation of halokinesis occurred during the Early Triassic in response to differential loading of the salt by prograding clastic fluvial wedges from the north, and thin-skinned extension causing reactive diapirism (Stewart & Clarke, 1999). It is likely that basement faults exerted a fundamental control on the orientation and distribution of salt walls, which follow the primary NNW-SSE-oriented fault trends of the Central Graben (Peacock, 2004). The duration of halokinesis in the Central North Sea was dictated by the thickness of salt beneath the mini-basins. Basins developed first over paleo-highs where the salt was thinner, and grounded on the pre-salt basement during the Middle Triassic. Salt basins that formed over thicker successions of salt, grounded in the Late Triassic or Jurassic (Smith et al., 1993). Provenance of the Skagerrak Formation indicates an early sediment source almost exclusively from the Fennoscandian Shield, with sediments in the upper parts of the formation having been sourced from both Scotland and Fennoscandia (Mange-Rajetzkey, 1995). This temporal change in sediment provenance could be explained by climate change, a change in tectonic regime on the Fennoscandian margin, or a change in rate of halokinesis that could have resulted in a change of configuration of sediment supply (Banham & Mountney, 2013). These mini-basins can also be identified in the Triassic of the Dutch Step Graben and are surrounded by Zechstein diapirs.

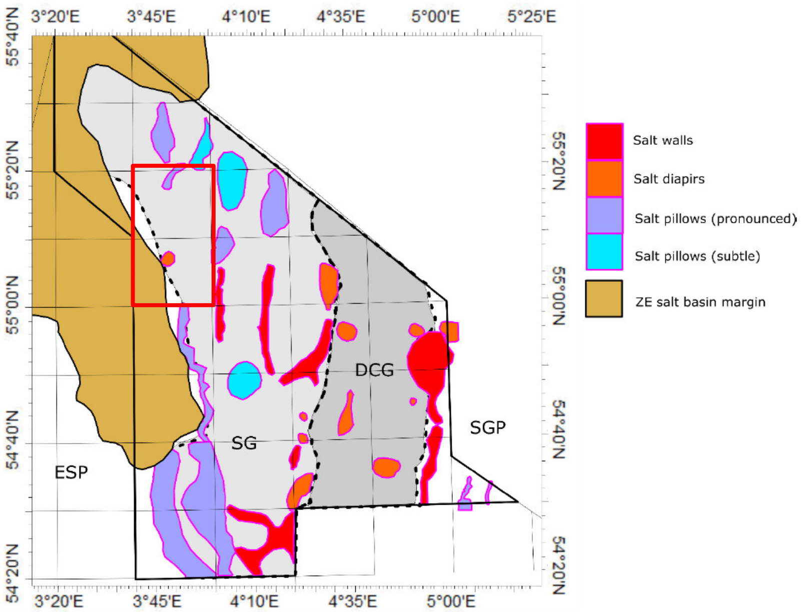


Figure 7. Distribution of salt structure types as defined by Van Winden (2015). The red outline represents the focus area in this study.

Salt withdrawal could have opened windows through which Pre-Zechstein hydrocarbons can migrate in the Triassic reservoirs. Migration can either be established by the complete removal of salt by withdrawal, by migration along faults penetrating the salt, or along intrusions of (Tertiary) volcanic dykes (e.g. Caister-B field, UK) (Underhill, 2009). Noteworthy, not only the Zechstein salt layers have to be bypassed to charge Triassic reservoirs, but also the Slochteren Shale, Zechstein Claystone, and shales from the RBSH Formation.

The Zechstein salt deposits play an important role in the formation of Triassic traps. Three main salt related traps in the Triassic interval have been identified in the Southern North Sea. The 4-way dip-closures above salt domes/diapirs (e.g. Caister-B field), 3-way dip closures against salt walls (e.g. M1-A, and G16-B fields), and turtle-back anticlines (e.g. the F15-A and L5-FA fields). Halokinesis can create traps in Triassic overburden, but the near-presence of salt can also cause (partially) salt-plugging of reservoir rocks resulting in reservoir deterioration. Salt plugged reservoir rocks can even act as a side-seal (M1-A). Salt plugging may be recognized on seismic data as an amplitude decrease and seismic phase change. When a reservoir is completely salt plugged a polarity reversal can occur. However, it remains difficult to recognize a salt-plugged reservoir without well-data, because seismic amplitude depends on reservoir quality and fluid fill at the same time (Van Eijk, 2014).

4. Data and methodology

4.1 Data

For this study public well data from 61 wells in the northern Dutch offshore is used (fig. 8). In the UK sector wells from the OGA Mid North Sea High 2015 survey are also incorporated in the well-analysis. Public well data from the GEUS database has also been incorporated. Seismic data is composed of the TerraCube Offshore 2011 Area-1 survey, DEF 2012 survey (courtesy of Spectrum ASA), and public 2D NSR lines from a range of surveys. In the UK sector public 2D seismic lines from the 2015 OGA survey have been used.

Samples used for heavy mineral analysis, biostratigraphy, and grain size distribution analysis were taken from cuttings of well A05-01, A15-01, and A18-01 (fig. 9). The samples were taken at the TNO core storage in Zeist.

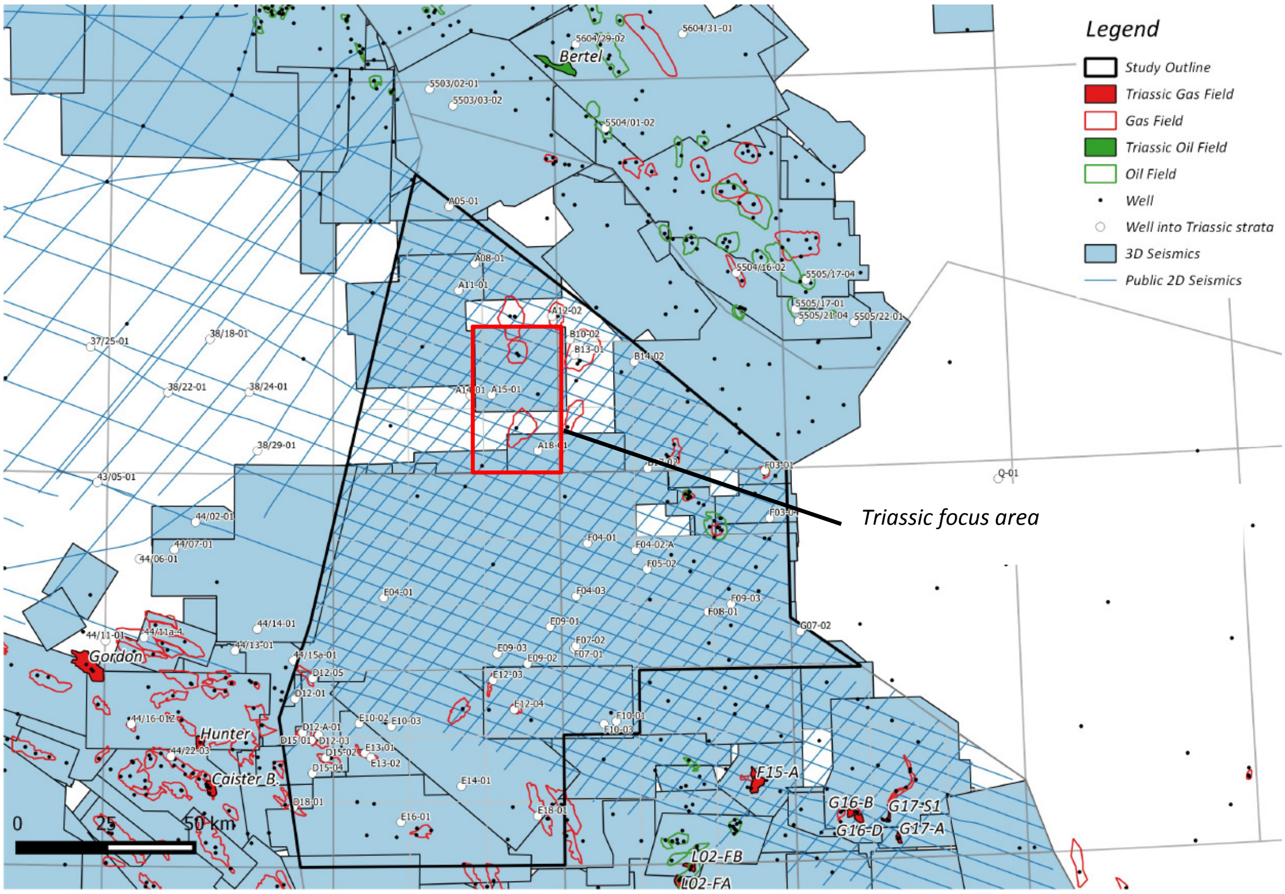


Figure 8. Overview of the study area and the available data. Note that the 3D data outside the Dutch territory is not available for EBN.

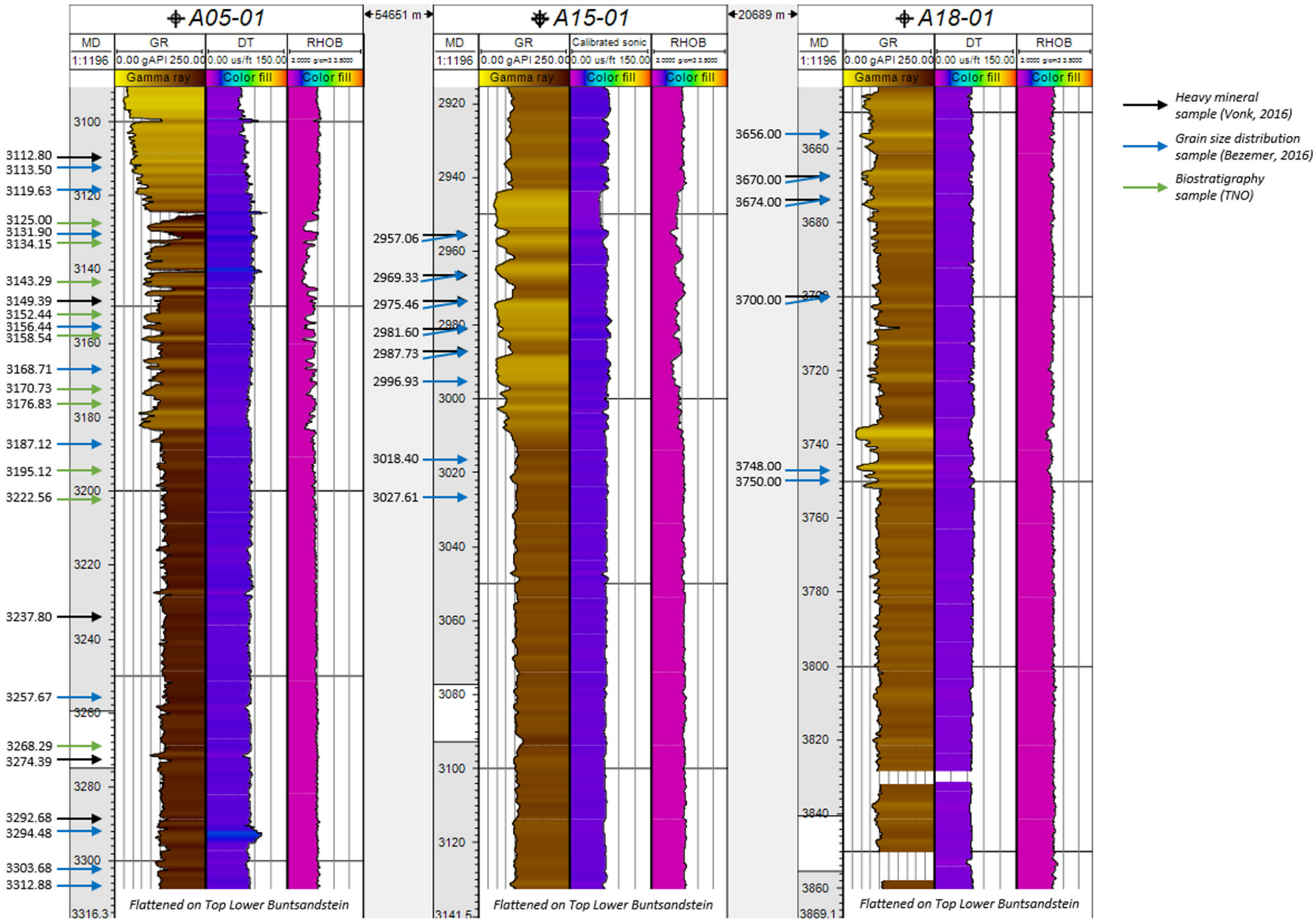


Figure 9. Overview of the samples taken for biostratigraphy, heavy mineral analysis, and gain size distribution analysis.

4.2 Methods

4.2.1 Seismic interpretation

Most of the European E&P companies use the non-SEG convention for their seismic interpretation. In the non-SEG convention an increase in acoustic impedance over an interface is displayed as a trough and a decrease in acoustic impedance over an interface is displayed as a peak. This study uses the non-SEG convention. In the TerraCube 2011 dataset the signal has not entirely been processed to a zero phase signal. Instead a hard kick, meaning an increase in acoustic impedance, is first displayed by a negative signal directly followed by a mostly stronger positive signal (fig. 10). The TerraCube 2011 survey was bulk-shifted 18 ms TWT downward, to enable continuous interpretation with the DEF 2012 and NSR surveys.

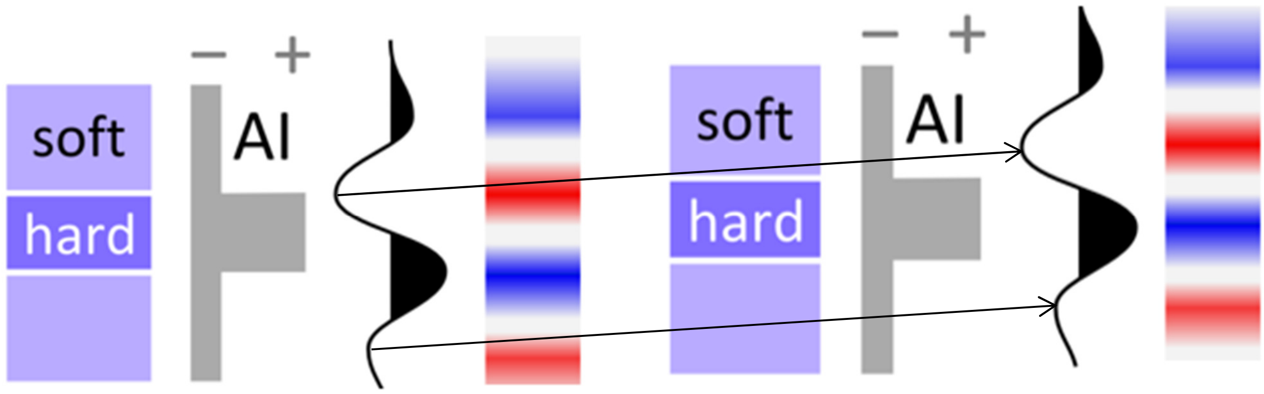


Figure 10. Left: in the DEF 2012 survey the non-SEG zero phase is used. The TerraCube 2011 survey (right) has not entirely been processed to a zero phase signal. So, in the TerraCube 2011 survey an increase in acoustic impedance is displayed by a negative signal directly followed by a mostly stronger positive signal.

4.2.2 Depocentre development

The outline of the focus area has been defined on the availability of 3D data (fig. 8) and on the location of wells A18-01 and A15-01 that both encounter early Triassic strata. The focus area is positioned in the most western graben of the Step Graben system. Time-isochore maps have been made for three Triassic intervals in the Step Graben focus area (fig. 16a-c). These maps were used to interpret accommodation space generation for the three Triassic intervals. The horizons that were picked were chosen on the basis of traceability throughout the TerraCube 2011 survey. With the help of a composite line composed of 3D seismic data and 2D NSR-lines it was possible to tie the reflectors to the well-tops in A18-01 (fig. 14). A seismic well-tie for A15-01 was poor due to low seismic resolution in the Triassic interval at A15-01. The reflector representing the RBMVL is traceable in the DEF 2012 survey, whereas it is difficult to trace in the TerraCube 2011 survey. The lack of a good traceable reflector in the TerraCube 2011 survey is either because of a low relative acoustic impedance difference, a thin or absent RBMVL, or low seismic quality in the Triassic interval.

Regional mapping of the RBMVL has been performed by EBN for the extended DEFAB area on the basis of 2D and 3D seismic surveys (EBN, 2015). In order to compare both time-isochore maps of the DEF 2012 and

TerraCube 2011 surveys, the traceable Main Röt Evaporite Member (RNRO1) reflector was interpreted to represent the top of the Lower Triassic interval. Top Muschelkalk Evaporite Member (RNMUE) was picked to time-isochore the Middle Triassic. For the Upper Triassic the base Rijnland Group was picked. In the Dutch Central Graben this would not be possible because of the presence of Jurassic sediments, however in the Step Graben the Jurassic is absent.

For the construction of a net thickness map of the RBMVL a time-isochore map has been constructed between the RBMVL regional grid and the Top Zechstein Group (TZE) regional grid. This time-isochore map was used for the collocated co-kriging workflow:

1. Time-isochore maps between Top RBMVL regional grid and the TZE regional grid were made. This time-isochore map represents the earliest accommodation space generation deposition of the RBMVL.
2. Isochore points created between the well tops TZE and RBSH are the main input (make/edit surface utility in Petrel).
3. Interpolation of the isochore points was done by kriging (Gaussian interpolation). This method gives the best linear unbiased prediction of the intermediate values.
4. The following parameters were used in the kriging workflow:
    a. Nugget: 0.0001
    b. Variogram type: Gaussian
    c. Anisotropy range: 25 x 25 km and 5 x 5 km
    d. Collocated co-kriging with a second variable: time-isochore between the Top RBMVL and the TZE. Correlation coefficient of 80% was chosen. A lower correlation coefficient would increase the influence of the isochore point data from wells in the final map. The collocated co-kriging results is a best estimate of the RBSH gross thickness in the study area based on thicknesses in wells and on the geometry of the time-isochore map.
5. A map of the net RBMVL thickness is created using the following relationship:
$$RBMVL_{Net} = 0{,}35\ RBSH_{Gross} - 75{,}41$$
This relationship is based on well analysis of 19 wells from the northern Dutch offshore that have fully penetrated RBSH (fig. 17). Negative values for the RBMVL were filtered out with the following "if" statement:
$$RBMVL_{Net} = if(((0.35 * RBSH_{Gross}) - 75.41) < 0{,}0, (0.35 * RBSH_{Gross}) - 75.41)$$

5. Results

5.1 Well analysis

All wells in the study area have been analysed on the presence and facies of Triassic sediments (fig. 13). Figure 11a shows the location of the cross-sections in the study area. Well-tops presented in this report have been interpreted during an earlier regional study at EBN (2015). All cross-sections have been flattened on the top of the RBSH (equivalent to the base of the RBM). Generally, the well panels show a northward decrease in sand thickness in the RBMVL (e.g. figure 11b). The gamma-ray log response of the RBMVL in the southern wells F10-01, F04-03, and F04-03 show high net to gross values. The thickness of the RBMVL in the cross-section of figure 11c is decreasing from the Anglo Dutch Basin towards the Step Graben, Dutch Central Graben, and Schill Grund Platform. In the cross-section of figure 11f the RBMVL shows a relatively lower net to gross in well F05-02 compared to wells F04-02A and F04-03. In the cross-section of figure 11d the intepreted RBMVL becomes significantly thicker towards wells B10-01-S1 and B13-01. A decrease in net to gross can be observed in wells B10-01-S1 and B13-01 (figure 11d). Figure 11g shows a well panel for UK wells encountering Triassic strata.

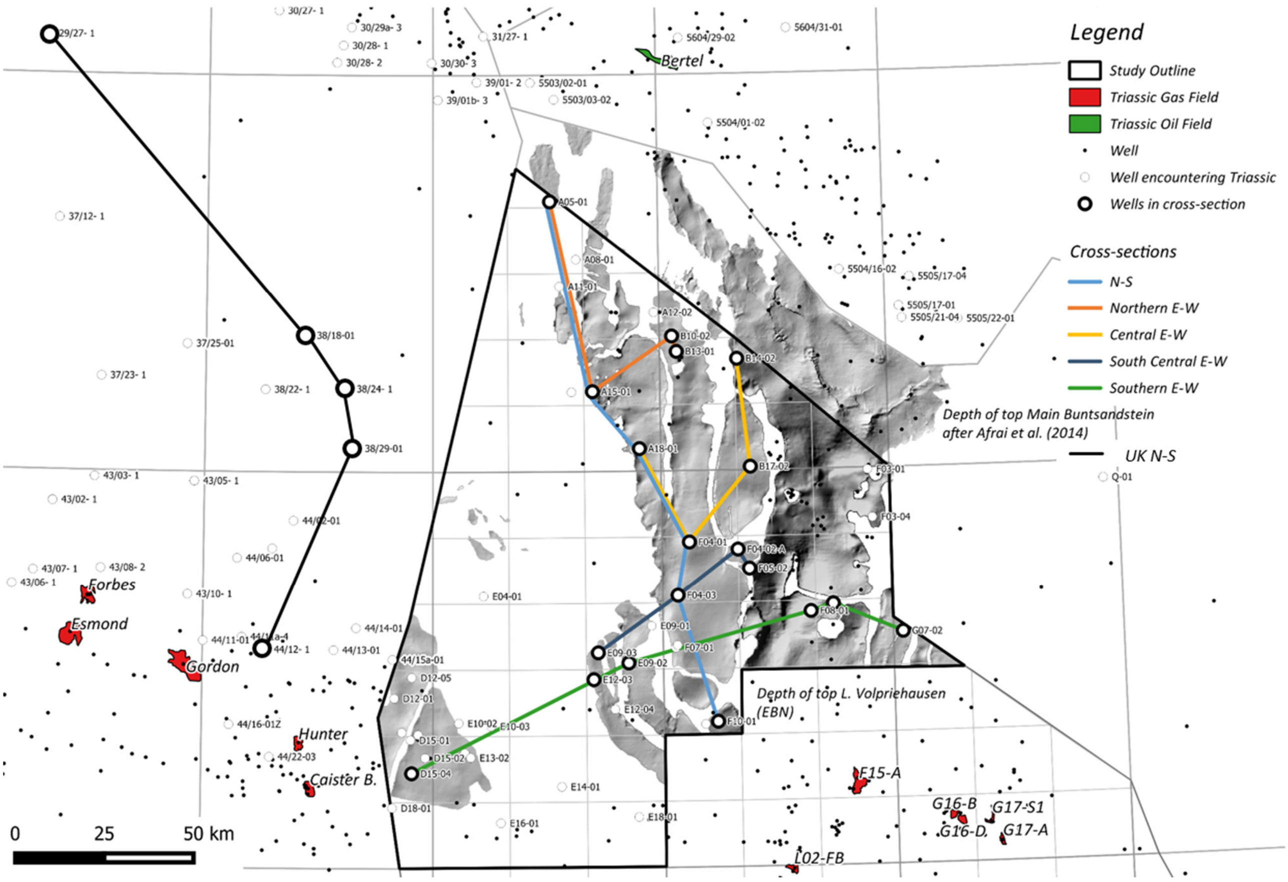


Figure 11. a) Overview of the cross-sections plotted on the top RBMVL regional grid.

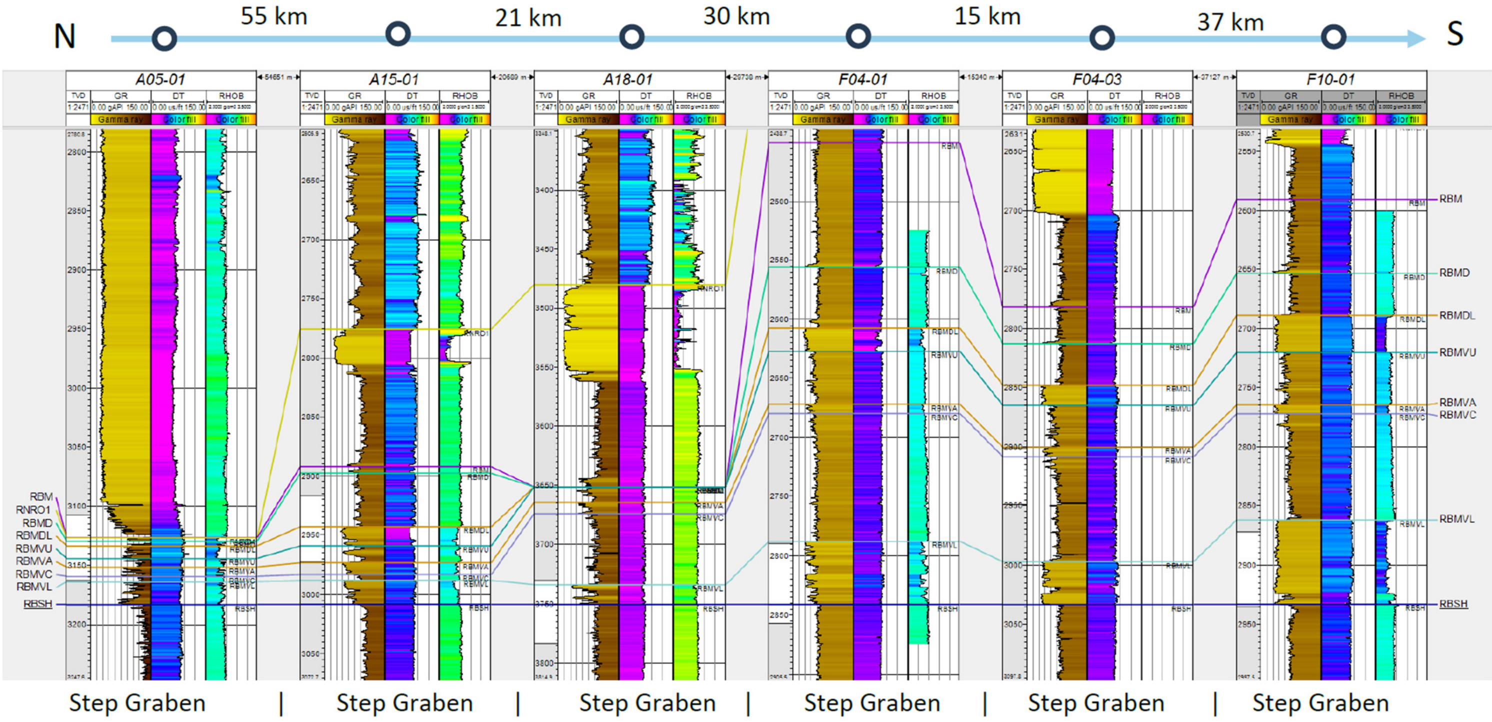


Figure 11. b) Cross-section from north to south.

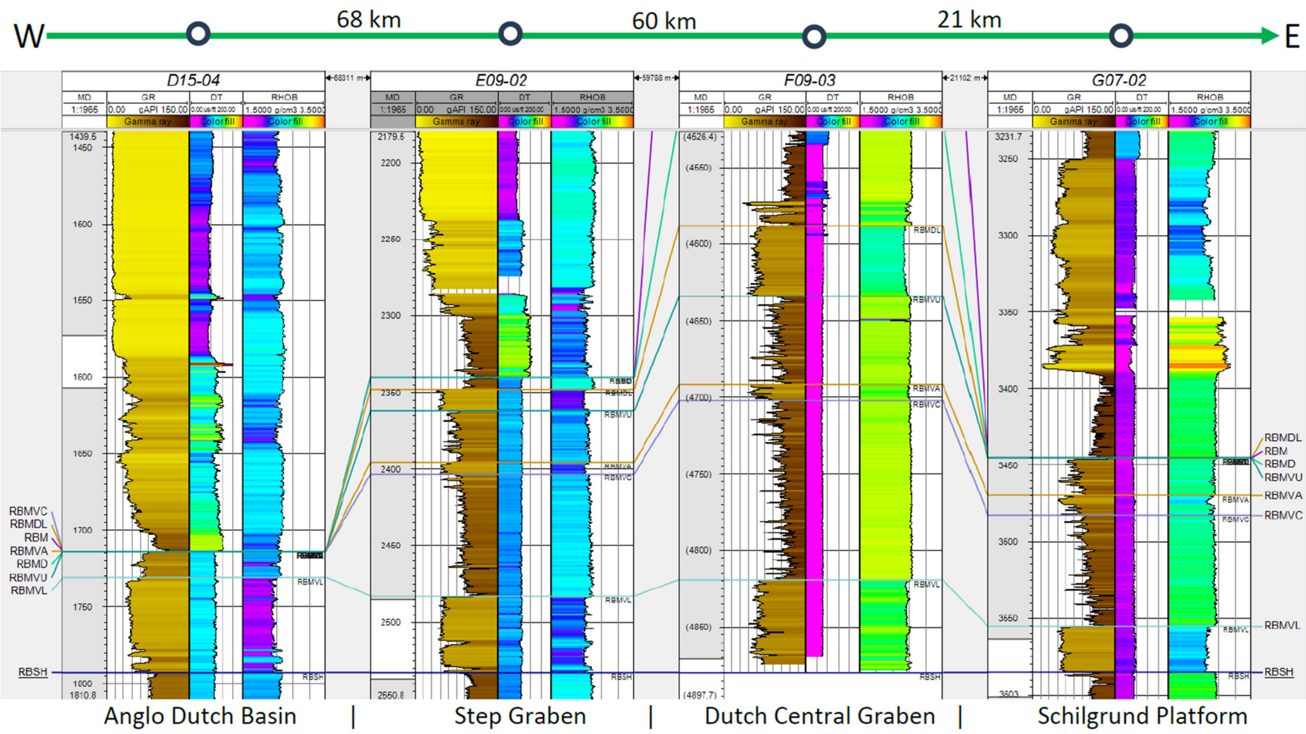


Figure 11. c) Southern cross-section west to east .

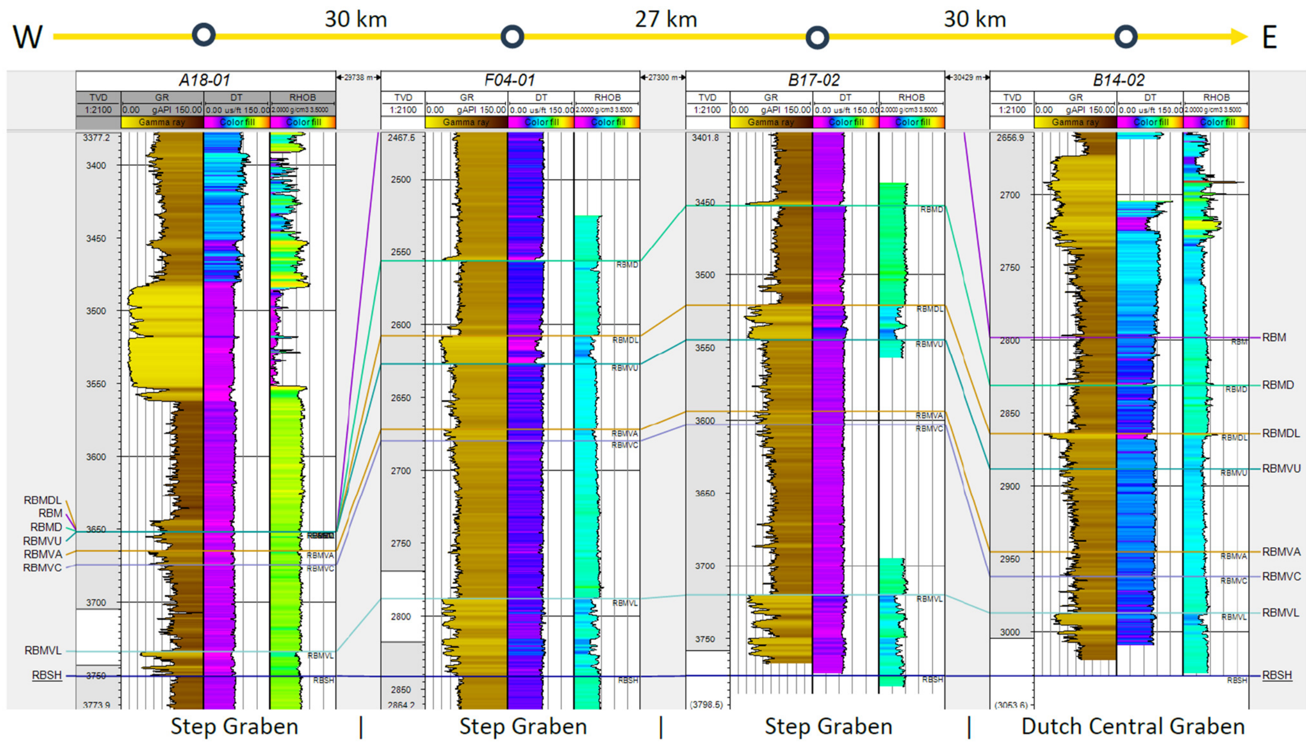


Figure 11. d) Central cross-section west to east .

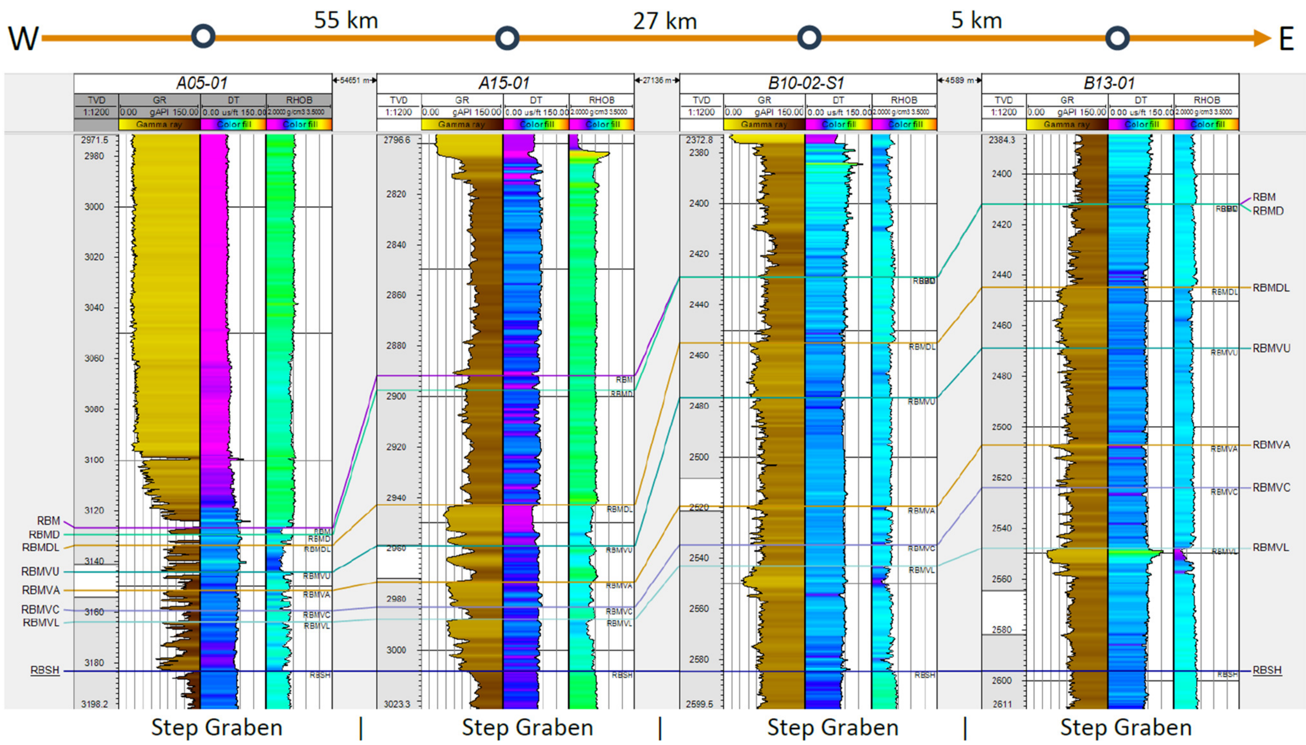


Figure 11. e) Northern cross-section west to east .

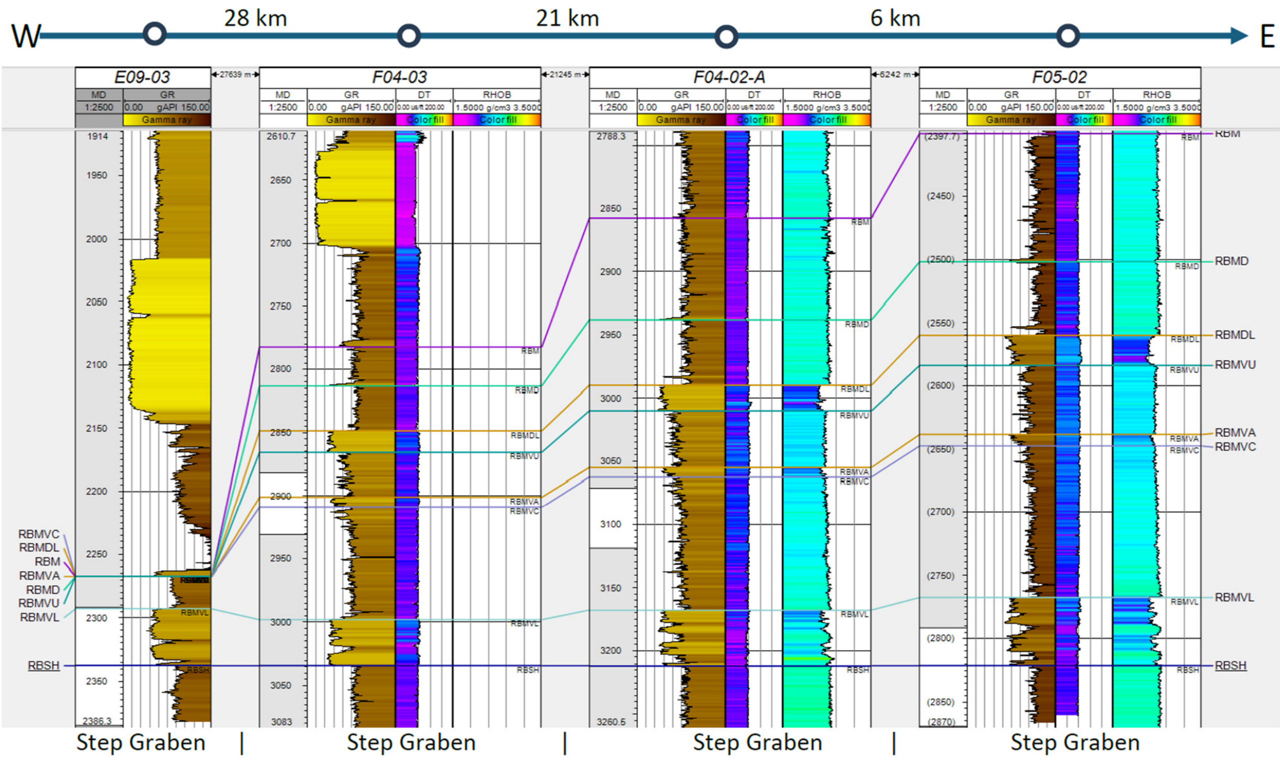


Figure 11. f) South central cross-section west to east .

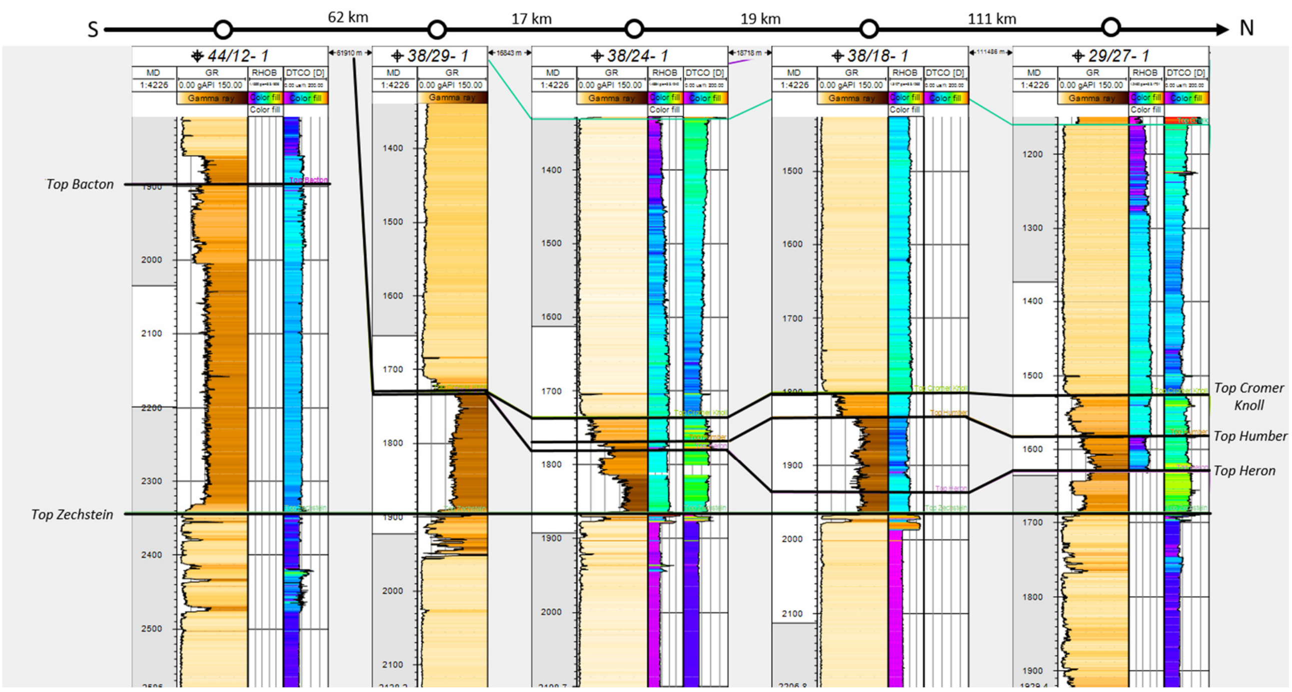
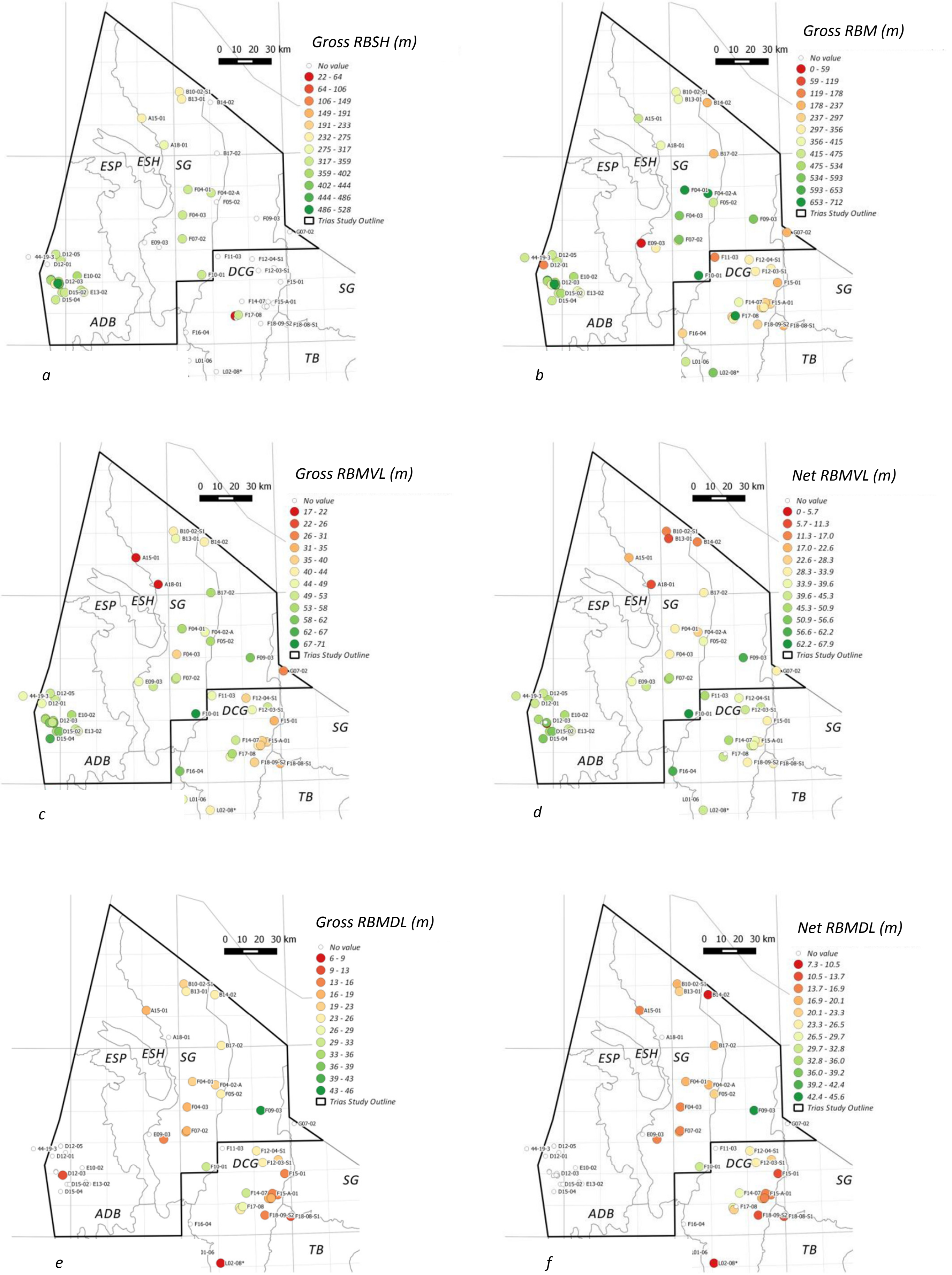


Figure 11. g) South to north well panel from OGA Mid North Sea High 2015 data-set. The correlation with the Dutch lithostratigraphy can be seen in figure 4. Cromer Knoll is deposited in the Cretaceous. The Humber Group is deposited in the Jurassic.

Figure 12 a-h shows an overview of the thickness of the RBSH, RBM, RBMVL, and RBMDL in the study area. The net values have been calculated from the logs by a 60% gamma-ray cut-off. The gross thickness of the RBSH is relatively constant (fig. 12a) compared to the gross thickness of the RBM (fig. 12b). In the Anglo Dutch Basin the gross RBSH is thicker than in other basins in the study area. Data points for gross thickness of the RBSH in the Dutch Central Graben is somewhat scarce. This is either because the RBSH has not been drilled completely, or has not been drilled at all (e.g. in the northern Dutch Central Graben). In well A15-01 the NLOG lithostratigraphic data suggests that the RBSH is around 250 m. However, the composite log (NLOG) shows a gross thickness of ~350 m.

The gross and net thickness of the RBMVL decreases towards the north (fig 12c,d). The gross thickness of the RBMVL in A15-01 and A18-01 is thinner than in the closest (~30 km) wells to the east. This can also be seen in the well cross-sections (fig. 11b). The RBMDL is absent in the Anglo Dutch Basin area (fig. 12e,f). The RBMDL is thicker in the centre of the Dutch Central Graben than in the Step Graben. The net to gross of the RBMVL decreases towards the north except for A15-01 (fig. 12g). The net to gross of the RBMDL (fig. 12h) decreases towards the north and generally shows higher net to gross values compared to the RBMVL (fig. 12g).


Gross RBSH (m)
0 10 20 30 km
No value
22 - 64
64 - 106
106 - 149
149 - 191
191 - 233
232 - 275
275 - 317
317 - 359
359 - 402
402 - 444
444 - 486
486 - 528
Trias Study Outline
ESP
ESH
SG
DCG
SG
ADB
TB
a
Gross RBM (m)
0 10 20 30 km
No value
0 - 59
59 - 119
119 - 178
178 - 237
237 - 297
297 - 356
356 - 415
415 - 475
475 - 534
534 - 593
593 - 653
653 - 712
Trias Study Outline
ESP
ESH
SG
DCG
SG
ADB
TB
b
Gross RBMVL (m)
0 10 20 30 km
No value
17 - 22
22 - 26
26 - 31
31 - 35
35 - 40
40 - 44
44 - 49
49 - 53
53 - 58
58 - 62
62 - 67
67 - 71
Trias Study Outline
ESP
ESH
SG
DCG
SG
ADB
TB
c
Net RBMVL (m)
0 10 20 30 km
No value
0 - 5.7
5.7 - 11.3
11.3 - 17.0
17.0 - 22.6
22.6 - 28.3
28.3 - 33.9
33.9 - 39.6
39.6 - 45.3
45.3 - 50.9
50.9 - 56.6
56.6 - 62.2
62.2 - 67.9
Trias Study Outline
ESP
ESH
SG
DCG
SG
ADB
TB
d
Gross RBMDL (m)
0 10 20 30 km
No value
6 - 9
9 - 13
13 - 16
16 - 19
19 - 23
23 - 26
26 - 29
29 - 33
33 - 36
36 - 39
39 - 43
43 - 46
Trias Study Outline
ESP
ESH
SG
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e
Net RBMDL (m)
0 10 20 30 km
No value
7.3 - 10.5
10.5 - 13.7
13.7 - 16.9
16.9 - 20.1
20.1 - 23.3
23.3 - 26.5
26.5 - 29.7
29.7 - 32.8
32.8 - 36.0
36.0 - 39.2
39.2 - 42.4
42.4 - 45.6
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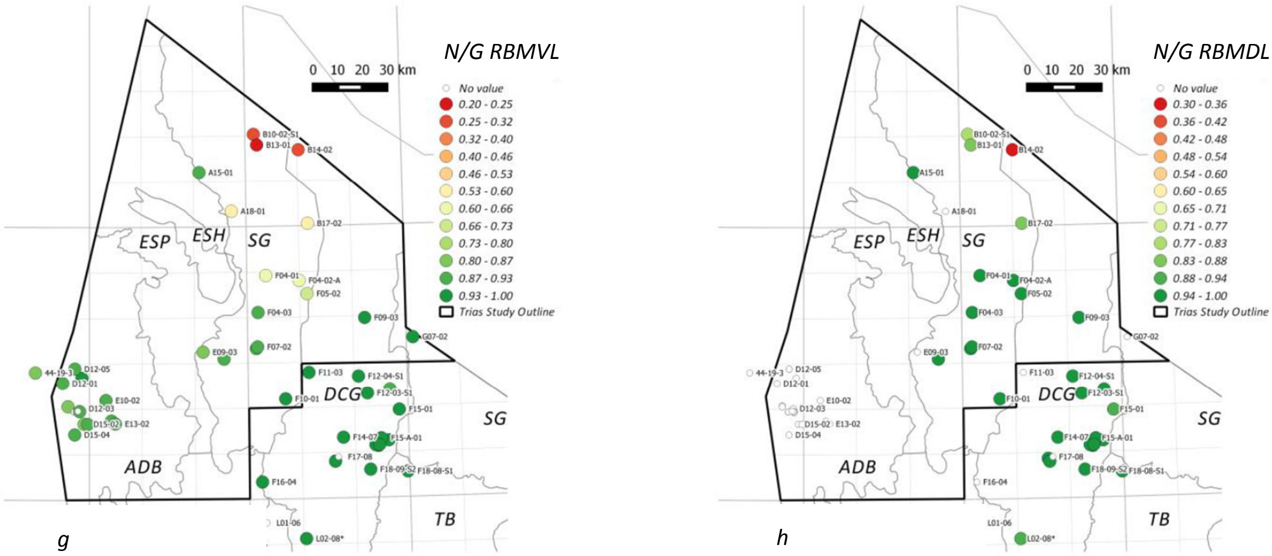

Figure 12. a) Gross thickness of the Lower Buntsandstein Formation (RBSH). b) Gross thickness of the Main Buntsandstein Subgroup (RBM). c) Gross thickness of the Lower Volpriehausen Sandstone Member (RBMVL). d) Net sand thickness of the RBMVL. e) Gross thickness of the Lower Detfurth Sandstone Member (RBMDL). f) Net thickness of the RBMDL. g) Net to gross of the RBMVL. h) Net to gross of the RBMDL.

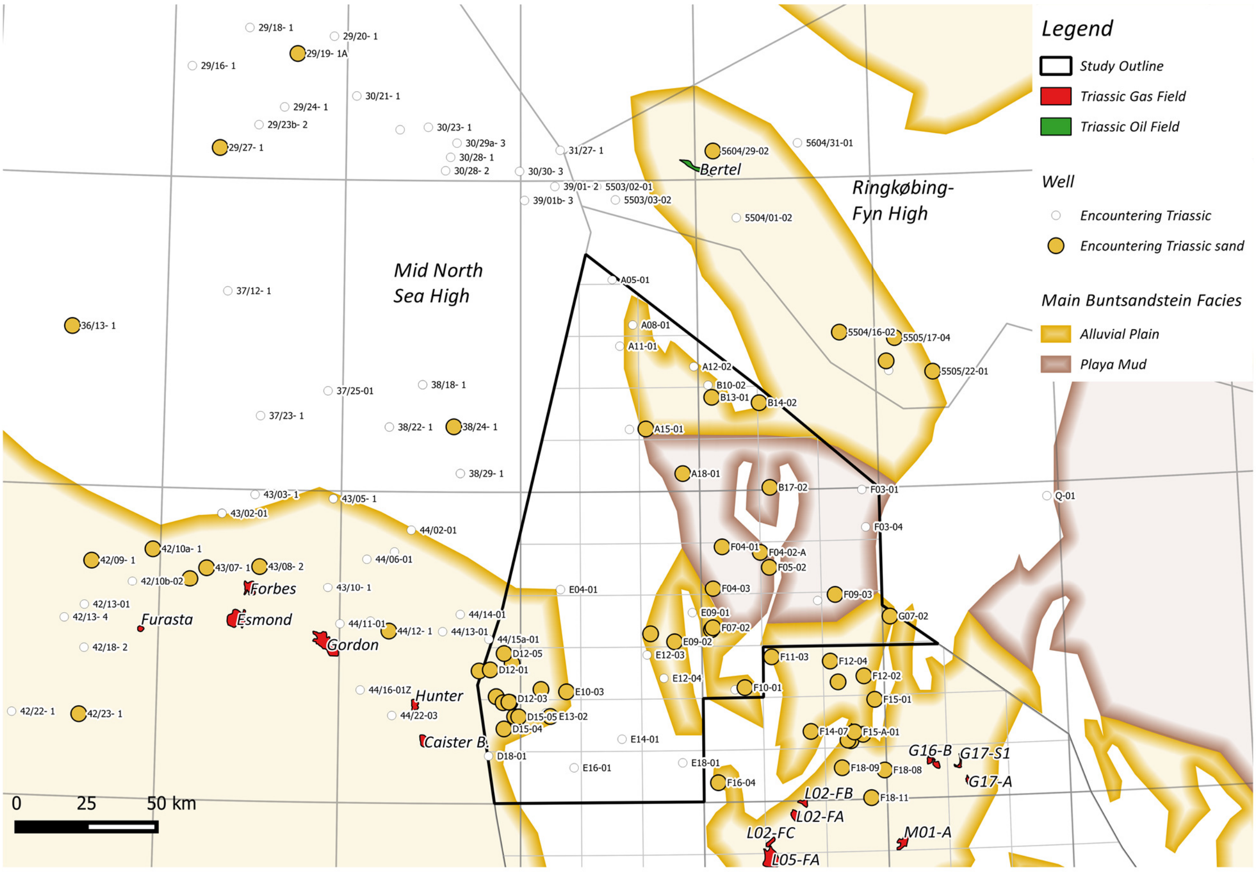

Figure 13.Well results of the Triassic shown on a facies map of the Main Buntsandstein Subgroup from the SPBA (2010).

The remainder of this report contains information that is (temporarily) confidential.