

Lower Triassic reservoir development in the northern Dutch offshore

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Abstract: Sandstones of the Main Buntsandstein Subgroup represent a key element of the well-established Lower Triassic hydrocarbon play in the southern North Sea area. Mixed aeolian and fluvial sediments of the Lower Volpriehausen and Detfurth Sandstone members form the main reservoir rock, sealed by the Solling Claystone and/or Röt Salt. It is generally perceived that reservoir presence and quality decrease towards the north and that the prospectivity of the Main Buntsandstein play in the northern Dutch offshore is therefore limited. Lack of access to hydrocarbon charge from the underlying Carboniferous sediments as a result of the thick Zechstein salt is often identified as an additional risk for this play. Consequently, only a few wells have tested Triassic reservoir and therefore this part of the basin remains under-explored. Seismic interpretation of the Lower Volpriehausen Sandstone Member was conducted and several untested Triassic structures are identified. A comprehensive, regional well analysis suggests the presence of reservoir sands north of the main fairway. The lithologic character and stratigraphic extent of these northern Triassic deposits may suggest an alternative reservoir provenance in the marginal Step Graben system. Fluvial sands with (local) northern provenance may have been preserved in the NW area of the Step Graben system, as seismic interpretation indicates the development of a local depocentre during the Early Triassic. These insights help to improve the chance of finding Lower Buntsandstein reservoir rocks in the northern Dutch offshore.



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The Lower Triassic Main Buntsandstein Subgroup (RBM) (Van Adrichem Boogaert & Kouwe 1994) forms part of an established hydrocarbon play in the southern North Sea. In the Netherlands it is the second-most prolific hydrocarbon play after the Permian Rotliegend play (de Jager & Geluk 2007). Regionally widespread mixed aeolian and fluvial sediments of the Lower Volpriehausen and Lower Detfurth Sandstones form the primary reservoir. It is generally perceived that the sediments of these Lower Triassic reservoir rocks are sourced from the southern Variscan mountains, and reservoir presence and quality decrease towards the north (Fig. 1) (e.g. Geluk & Röhlings 1997; Geluk 2005, 2007; McKie & Williams 2009; Bachmann *et al.* 2010). Consequently, the prospectivity of the RBM play in the northern Dutch offshore is regarded as limited. Access to charge of hydrocarbons from the underlying Carboniferous deposits is often seen as an additional uncertainty for this play (de Jager & Geluk 2007). As a result, only a few wells have been drilled in the study area (17 000 km²) with RBM as a primary or secondary target (Fig. 1).

The observation that Triassic sands which have derived their material from a local source area (Olivarius *et al.* 2017) are present in the North German Basin, together with the release of additional seismic and well data in the northern Dutch offshore, has justified a new review of the Lower Triassic prospectivity of this area (EBN 2015, 2016). A regional study using publicly available wells and seismic data from the northern Dutch offshore and surrounding territories was set up to support the investigation of the reservoir character and distribution of Lower Triassic sands north of the main fairway. A comprehensive well review, including stratigraphic correlation and spatial analysis of reservoir development, was conducted to establish the character and geographic distribution of Main Buntsandstein Subgroup reservoir sands in the northern Dutch offshore. Basins and isolated fault blocks with preserved Main Buntsandstein were delineated from platforms and halokinetic highs by seismic interpretation of the Lower Volpriehausen Sandstone Member. These structural depth grids were used to identify closures for potential hydrocarbon entrapment. Although

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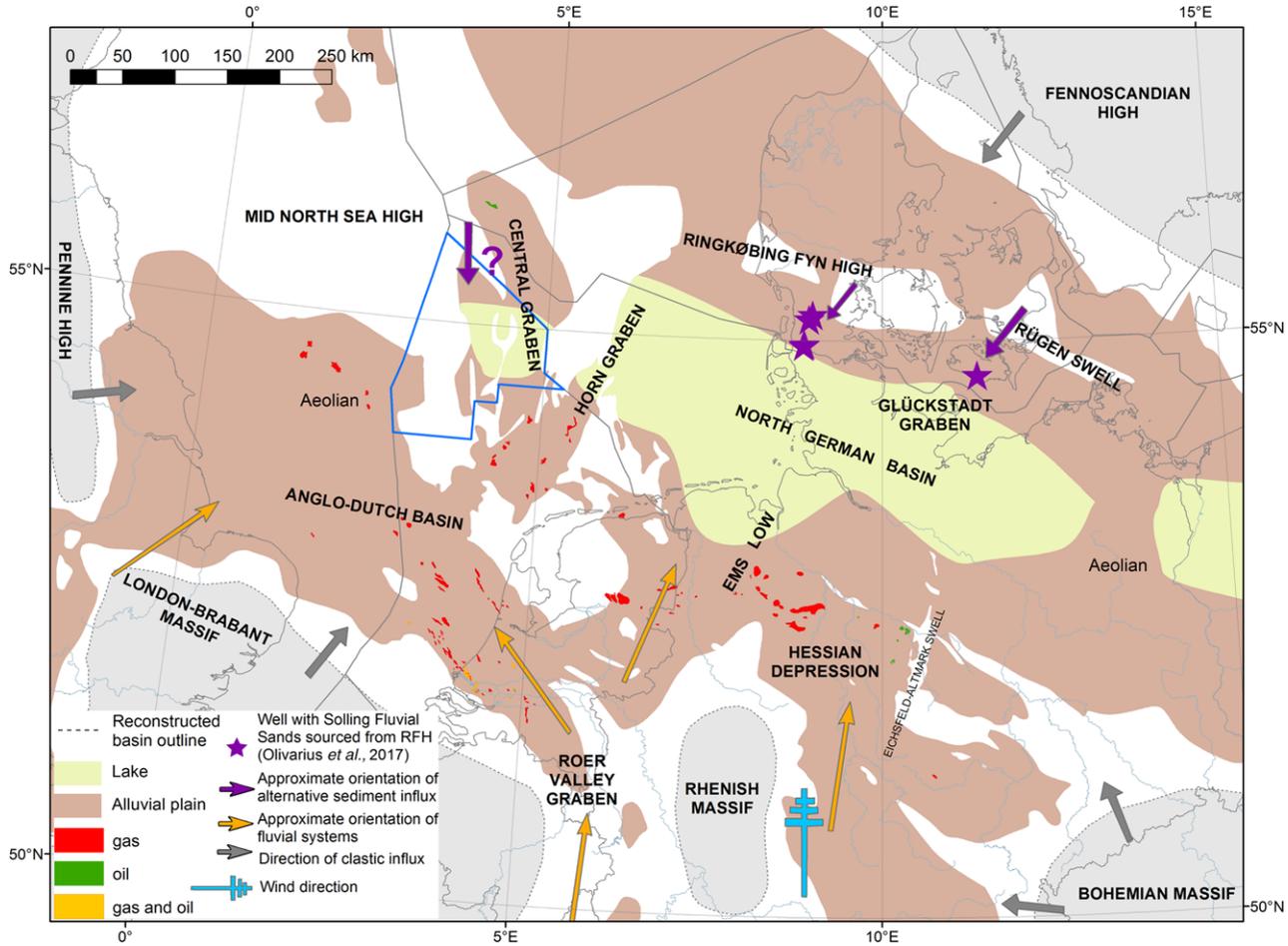


Fig. 1. Palaeogeographical map of the Southern Permian Basin during Early Triassic time, showing the well locations with northern sediment provenance indicated by purple stars (Olivarius *et al.* 2017). The study area is outlined in blue (the palaeogeography is adapted from Bachmann *et al.* 2010, p. 158).

Lower Volpriehausen Sandstone Member thickness cannot be directly mapped on seismic data, intra-Triassic isochron maps do assist in understanding the potential for Early Triassic local depocentre development. A recent study by *ter Borgh et al. (2018b)* provides new insights into the source-rock potential in the study area, while the interpretation of the underlying top and base Zechstein horizons in recent three-dimensional (3D) seismic data demonstrates potential access for hydrocarbon migration pathways.

Geological and tectonostratigraphic setting

The study area is located in the northern part of the east–west-trending Southern Permian Basin (Fig. 1) that formed during Late Permian and Early Triassic times (e.g. *Ziegler 1990*). The northern boundary of the Southern Permian Basin is characterized by a chain of highs, with the Ringkøbing-Fyn High to the east and the Mid North Sea High to the NW of the study area. These highs were relatively stable throughout the Mesozoic (*Wride 1995*) and are considered non-depositional areas during the Triassic (*Geluk 2005, 2007*).

The break-up of Pangea during the Early Triassic initiated as a result of rifting between Greenland and Scandinavia that propagated into the North Sea as well as into the North Atlantic Domain (*Ziegler 1990*). The North Sea rift system transected the Northern and the Southern Permian basins (*Ziegler 1990*), which ultimately led to the formation of the Dutch Central Graben where differential subsidence began during the Permian (*De Jager 2007; Geluk 2007*). At the same time the Step Graben was formed to the west where an alternating set of horst and graben structures indicate a lesser degree of subsidence (e.g. *ter Borgh et al. 2018a*). 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 (*Ziegler 1992*). The thickness of the RBM therefore reflects a combination of enhanced subsidence in the grabens, and uplift, truncation and erosion elsewhere (*Geluk & Röhlings 1997*).

The Main Buntsandstein Subgroup (RBM)

During the Induan age at the onset of the Triassic, clastic deposition of mud-dominated Lower Buntsandstein Formation (RBSH) took place in the Dutch sector; in the UK, mud-dominated sediments of the contemporaneous Smith Bank and Bunter Shale formations are encountered (e.g. *Goldsmith et al. 1995; Bachmann et al. 2010*) (Figs 1, 2). The lithological similarity between these two shale-prone formations that conformably overlie the Permian

Zechstein deposits imply that the depositional conditions in the Central and Southern North Sea basins were very similar. Communication between the Central and Southern North Sea basins possibly occurred during the Induan and probably early Olenekian (*Fisher & Mudge 1990*).

Deposition during the Olenekian in the western part of the Southern Permian Basin is characterized by four widely recognized tectonostratigraphic units bounded by unconformities. The Volpriehausen, Detfurth, Hardegsen and Solling formations each represent large-scale fining-upwards sequences in which mixed fluvial-aeolian sandstones grade upwards into lacustrine clay-siltstone deposits (*Geluk & Röhlings 1997, 1999*). The basal sandstone units of the different formations/sequences have a regional sheet-like character and are commonly referred to as ‘Lower’ (e.g. Volpriehausen) Sandstone Members. The ‘Upper’ Sandstone Members are considered sandy basin-fringe equivalents of the regionally shale-prone (e.g. Volpriehausen Clay-Siltstone) members that are not developed as such in our study area (*Van Adrichem Boogaert & Kouwe 1994*). The layering cyclicity is believed to record the interplay between the low-frequency build-up and subsequent release of regional tensional stresses that caused broad-scale crustal warping, accompanied by reactivation of NNE-trending swells and troughs along the southern margin of the Southern Permian Basin, and the higher-frequency monsoonal rainfall in the Variscan hinterland (e.g. *Geluk 2005; McKie & Williams 2009; Bachmann et al. 2010*). The strongest of these short-lived rifting pulses (*Geluk 2007*) was probably the pre-Solling pulse which culminated during the Olenekian and which resulted in the so-called Hardegsen (or H-) Unconformity (*Röhlings 1991*), thereby delineating the Lower Germanic Trias Group from the base of the Upper Germanic Trias Group at the onset of Solling Sandstone deposition (Fig. 2; *Van Adrichem Boogaert & Kouwe 1994*). Events leading to this Hardegsen Unconformity mainly control preservation of sediments of the Main Buntsandstein Subgroup (*Geluk & Röhlings 1997; Pharaoh et al. 2010*).

Figure 1 shows the reconstruction of the Lower Triassic depositional environment. The Variscan mountains in the south and the Fennoscandian High in the north are considered to be the predominant source areas for sediment (e.g. *Geluk 2005, 2007; McKie & Williams 2009; Bachmann et al. 2010*). Based on heavy mineral analysis on core samples, *Olivarius et al. (2017)* identified a southern Variscan source for the Lower Volpriehausen sands, possibly transported through aeolian mechanisms, and a northern (local) source for the Solling Sandstone Formation from the Ringkøbing-Fyn High, possibly transported through fluvial mechanisms.

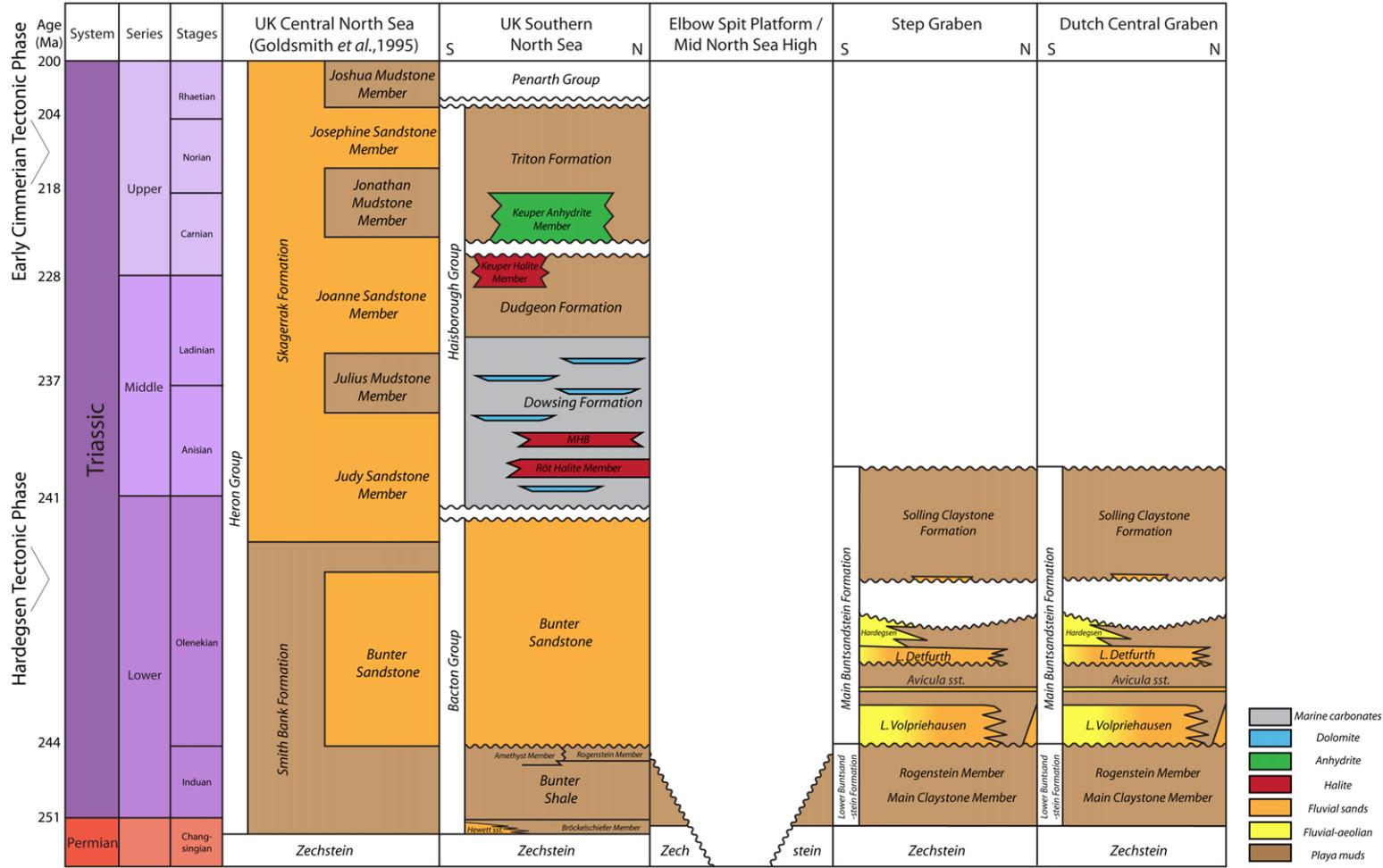


Fig. 2. Lithostratigraphic correlation panel between the UK and the northern Dutch offshore (adapted from van der Kooij 2016).

Post-Hardegsen tectonism and Zechstein salt mobilization

Syn depositional faulting is clearly observable in the Lower Triassic of the NNE–NE-striking Horn Graben, German North Sea (Best *et al.* 1983), Terschelling Basin, Dutch Southern North Sea (Harding & Huuse 2015) and also in the Sole Pit Basin, UK Southern North Sea (Johnson *et al.* 1994). Early generation of salt swells in the Southern Permian Basin area led to synkinematic shortening of the Lower–Middle Triassic cover that detached from Zechstein halite at extensional fault systems (Griffiths *et al.* 1995; Best 1996; Thieme & Rockenbauch 2001). The combination of fault and salt movements resulted in both symmetrical and asymmetrical depocentres that have a strong control on Triassic preservation.

A number of post-Hardegsen rifting pulses took place during the Anisian–Norian. The north–south-oriented fault pattern of this Early Cimmerian tectonic phase suggests east–west- to NE–SW-aligned extension (Zanella *et al.* 2003; de Jager 2007), with accelerated subsidence in the Dutch Central Graben and minor strike-slip movements along a number of fault zones (Geluk 2005, 2007). Basement faulting triggered widespread mobilization of Zechstein salt during the Late Triassic (van Winden 2015).

Middle Cimmerian erosion during Central North Sea doming during the Middle Jurassic led to the separation of Northern and Southern Permian Basins by the Mid North Sea/Ringkøbing-Fyn Highs (Wride 1995). Concurrent erosional truncation of Triassic strata was mostly restricted to the Northern Permian Basin (Underhill & Partington 1993), but also occurred locally on highs such as the eastern shoulder of the German Central Graben (Arfai *et al.* 2014). During the Late Cimmerian phase, which lasted from the Late Jurassic to the Early Cretaceous, the Central Graben subsided and the surrounding platforms were uplifted again (Remmelts 1996), leading to erosion of the Triassic cover (e.g. on the Cleaver Bank High west of the Step Graben system and on the Netherlands Swell to the south of the study area) (Geluk 2007).

The Alpine orogeny led to a number of tectonic inversion events during the Late Cretaceous–Early Paleogene (Spathopoulos *et al.* 2000; de Jager 2007). These were accompanied by NW–SE-oriented dextral strike-slip movements and accelerated salt movements, particularly along lineaments of salt walls that follow regional basement faults (Remmelts 1996; de Jager 2007). Triassic and younger strata were generally displaced and removed during post-Hardegsen erosional events where salt structures pierced the Mesozoic cover.

Data and methods

Seismic and well data

Several 3D and 2D seismic datasets are utilized for structural definition of the Lower Volpriehausen Sandstone Member (Fig. 3). The southern part of the study area (D, E and F blocks) is covered by the 3D Post Stack Time Migrated (PSTM) survey, covering 7950 km² (courtesy of Spectrum ASA) and the 3D TerraCube Offshore (2011) seismic dataset. The northern part of the study area is covered by several released 3D surveys and the entire area is covered by the NW–SE- and NE–SW-oriented 2D North Sea Renaissance (NSR) lines (TGS, 2003–07). In the UK sector, public 2D seismic lines from the 2015 Mid North Sea High Oil and Gas Authority (OGA) survey (OGA 2016) were used. Seismic interpretation was performed in the time domain using the non-SEG seismic convention.

Publicly available well data from 61 wells in the northern Dutch offshore (<http://www.nlog.nl>) are used for reservoir characterization (Figs 3, 4). Public data from wells in the surrounding territory were obtained from the UK OGA and the Danish Geological Survey (GEUS).

Well log interpretation

Wireline logs of all drilled Main Buntsandstein Subgroup sections in the study area were correlated. The vertical profiles were categorized according to log facies display, with the strongest focus on the Lower Volpriehausen Sandstone Member (RBMVL) as the most prominent sand-prone stratigraphic unit. Secondary focus is on the Lower Detfurth Sandstone Member (RBMDL), which is part of the Detfurth tectonostratigraphic cycle that overlies the Volpriehausen cycle (Geluk & Röhlings 1997, 1999).

Lithological interpretation and correlation in terms of sand and shale content were carried out for all drilled RBMVL and RBMDL intervals. First, the gross thickness of the RBMVL and RBMDL intervals were determined by isochore extraction of the well tops. True stratigraphic thickness (TST) was calculated using well path information in combination with the structural dip obtained from the depth-converted seismic marker horizon (see the section ‘Seismic interpretation and time–depth conversion’). Wells with clear fault cut-outs at Main Buntsandstein Subgroup (RBM) level (e.g. F17-01, J03-01) and the few truncated sections (E13-01, E13-02) were removed prior to TST gridding (Fig. 5).

In order to obtain an estimate of net sand thickness, the gamma ray (GR) log of each RBM section was analysed using histograms; all show a bimodal distribution of high-GR values marking the shale intervals, and low-GR values marking sand-prone

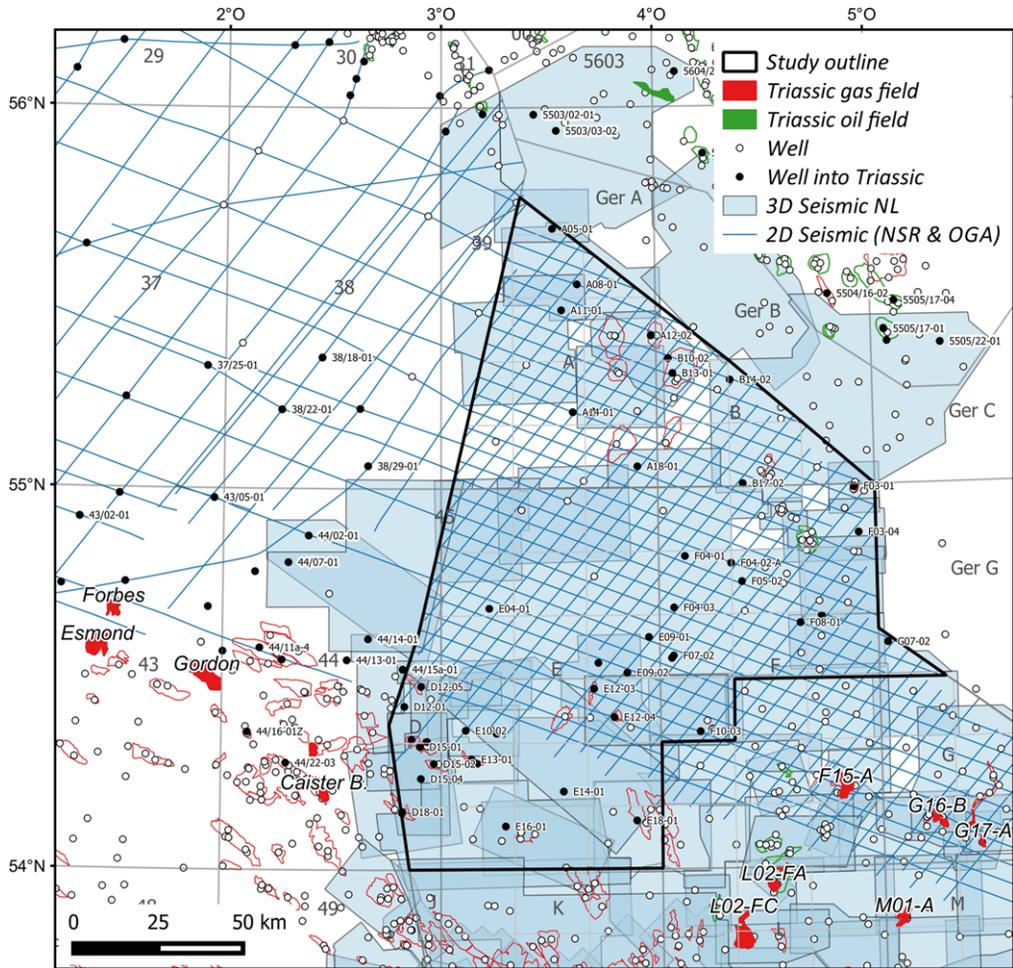


Fig. 3. Overview of study area, available seismic data in the Netherlands, wells and fields (red and green open polygons indicate gas and oil fields, respectively).

intervals. The cut-off for discriminating potential reservoir sandstones from the shales is placed at an intermediate GR value selected for each individual borehole section, and checked against cuttings descriptions. The bimodal GR distribution renders the definition of sand and shale relatively insensitive to the precision of the cut-off value (e.g. Fig. 4), so the cumulative net thicknesses for each section is considered a solid estimate of clean sand content. Regional gridding of the well data is discussed in the section 'Lower Volpriehausen and Detfurth Sandstone lithology mapping'.

Seismic interpretation and time–depth conversion

Seismic interpretation of a Lower Volpriehausen Sandstone marker was performed using the available

3D and 2D seismic surveys. Regional interpretations of the overlying stratigraphic horizons were used for time–depth conversion, including the base Paleocene (base Lower North Sea Group), base Late Cretaceous (base Chalk Group), base Early Cretaceous (base Rijnland Group) and top Triassic. A layer-cake V_0 -k model was used with constant k and varying V_0 -maps based on regional interpretations of EBN. From base Chalk onwards, the VELMOD-2 V_0 -k model was used (Van Dalfsen *et al.* 2007).

Depocentre development

Isochron maps for an early (A) and middle (B) Triassic interval were created for the focus area as indicated by the dashed black outline in Figure 4. The outline of this area has been based on the availability of 3D seismic data (Fig. 3) and on the location

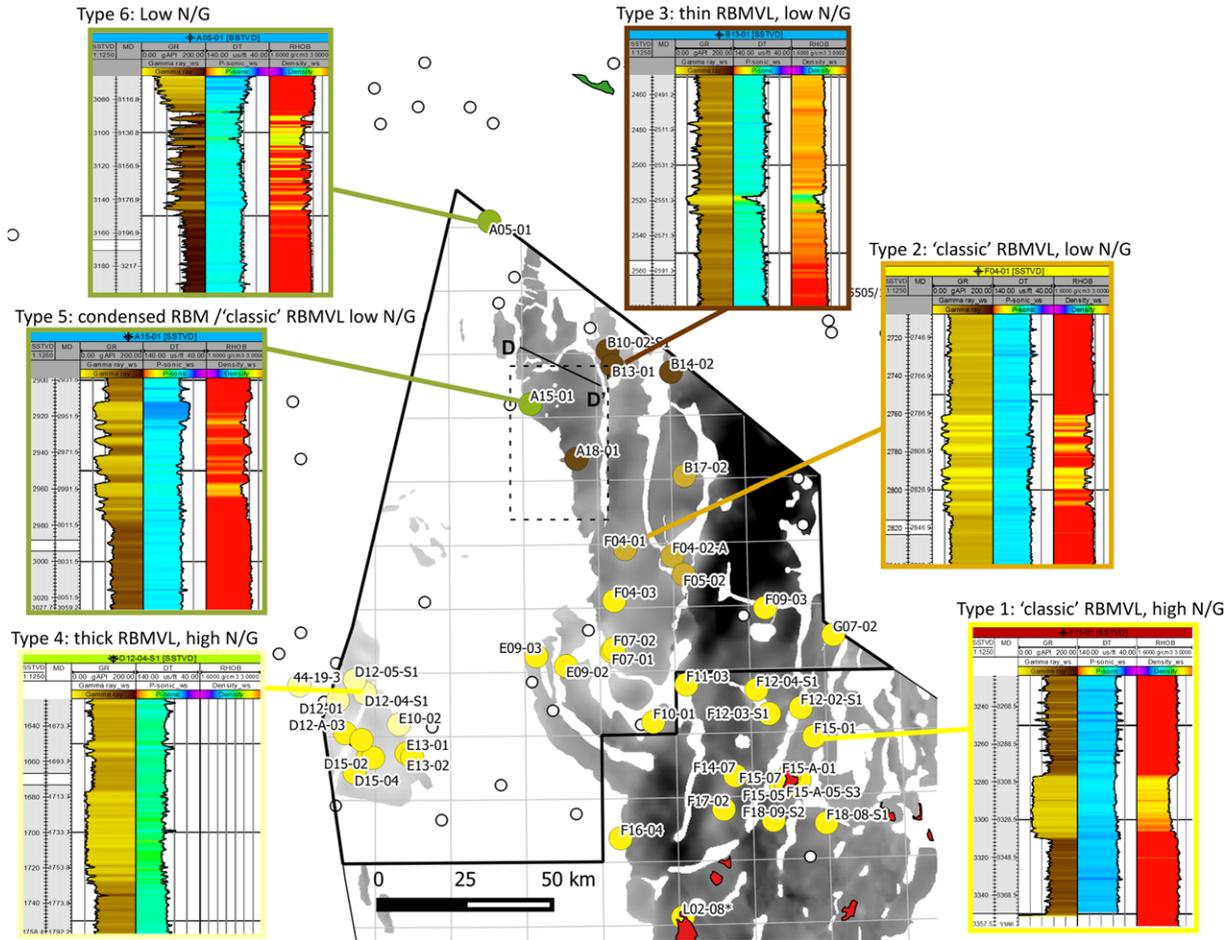


Fig. 4. Distribution of RBM profiles in the northern Dutch offshore. Well locations colour-coded by facies type (numbered according to description in text). Study area of the intra-Triassic isochron mapping (in Fig. 7) is outlined in dashed black. Seismic section from Figure 10 is indicated by black line D–D'. RBMVL reservoir rocks are present in most of the study area. The abundance and thickness of RBMVL decrease from south to north, while sands with local/northern provenance may have developed in the NW area.

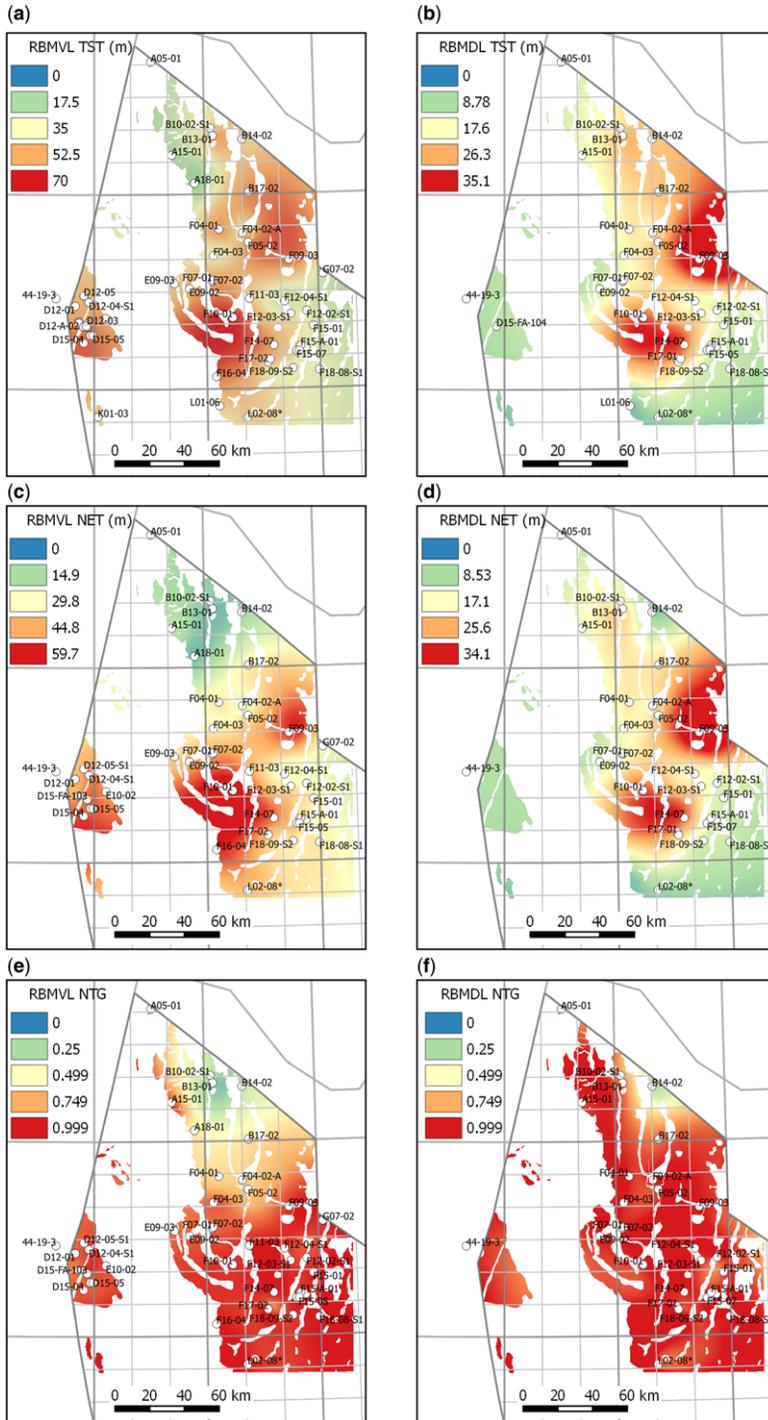


Fig. 5. Series of grids that show (a, b) true stratigraphic thickness (TST), (c, d) net sand thickness (NST) and (e, f) net-to-gross ratios (NTG) for Lower Volpriehausen and Detfurth Sandstone members, respectively. TST and NST are based on well data and both were gridded with the convergent interpolation method. NTG is calculated by dividing the NST grids by TST for each stratigraphic unit. See text for discussion.

of wells A18-01 and A15-01 that both encountered Lower Triassic strata. The isochron maps are used to study accommodation space generation for the two Triassic intervals. The horizons were chosen based on their continuity throughout the TerraCube 2011 seismic dataset. Top Lower Volpriehausen Sandstone was interpreted to represent the top of interval A. The top Röt Evaporite represents the top of interval B.

Lower Triassic reservoir development

Reservoir/sand development

Triassic sandstones are present north of the main fairway, in the Netherlands, UK and Danish territories (Figs 1, 6). Triassic sandstone intervals have been encountered in several wells in the Danish sector (Fig. 6). The Triassic sandstone interval in well 5504/16-02 (U-1X) is approximately 15 m thick and corresponds to deposits of the Main Buntsandstein Subgroup (Michelsen & Andersen 1983; Michelsen & Clausen 2002). Well Bertel-1/1A that drilled the Bertel oilfield possibly drilled Triassic reservoir sandstones. Age dating in this well is inconclusive and the reservoir sandstones might be of Jurassic or Late Triassic (Carnian) age (Schilfsandstein deposits) (GEUS 1993). As the log character of the northernmost well (A05-01) in the Netherlands looks very similar to Bertel-1/1A, it was decided to perform age dating also on A05-01 (Kerstholt & Munsterman 2016). Palynomorphs of both Jurassic and Late Triassic (Carnian) age are found in A05-01. As only a few palynomorphs could be extracted from the cutting samples of A05-01, the age dating remains inconclusive.

Regional mapping of the Lower Volpriehausen Sandstone Member shows that Main Buntsandstein Subgroup reservoir rocks are present in most of the study area (Fig. 4). The Lower Buntsandstein Formation (RBSH) is recognized on seismic cross-section as a uniform low-reflectivity layer overlying the Zechstein evaporites in the entire Dutch offshore sector, unless eroded on the platforms. The reflector representing the Lower Volpriehausen Sandstone Member was clearly traceable in the DEF PSTM survey, but of variable manifestation in the other surveys. As the tectono-cyclic occurrence of sandstones in the Main Buntsandstein Subgroup package cannot be resolved from seismic data in detail, our investigation of the Main Buntsandstein reservoir distribution is largely based on log profile typing and net sand mapping of well data (GR cut-offs). Seismic mapping is mainly used to outline potential traps and areas of post-depositional preservation.

Log profile typing as a means of regional facies analysis. Wireline log profiles of all drilled Main

Buntsandstein Subgroup (RBM) sections in the study area were compared and wells were classified, with focus on the Lower Volpriehausen Sandstone Member (RBMVL) as the most prominent sand-prone stratigraphic unit (Fig. 4):

- Type 1: This category represents a regular set of RBM sandstones with typical 'classic Germanic Triassic' expression (type section F15-01). The high net sand content in the RBMVL may contain 1–2 shale stringers (F07-01, F07-02, F04-03). The core description of F16-04 classifies the RBMVL as an amalgamation of aeolian dune, dry aeolian sandflat, damp sandflat, fluvial channel and fluvial sheetflood deposits that represent the uppermost part of a large-scale coarsening-upwards sequence, overlain by distal sheetflood and lake margin sediments of the Volpriehausen Clay-Siltstone Member (RBMVC).
- Type 2: This group is characterized by a regular RBMVL gross thickness with frequent shale intercalations and thus intermediate net-to-gross ratios (type section F04-01). It represents the transition between type 1 and type 3.
- Type 3: This shaly RBMVL section is characterized by a thin sandstone layer at the top of the succession (type section B13-01). This type section is associated with an ephemeral lake environment (Bachmann *et al.* 2010), where only the topmost layers of sand of the coarsening-upwards sequence described in F16-04 (type 1, see above) are preserved. The log character shows a strong resemblance to the Danish U-1 well (15 m sand; Michelsen & Andersen 1983).
- Type 4: This group is characterized by an amalgamated sandstone section with limited sand/shale contrast (type section D12-04-S1). The type section is typical for the Cleaver Bank High and resembles contemporaneous Middle Bunter Sandstone in the adjacent UK sector (e.g. Cameron *et al.* 1992). The absence of intercalated shale formations suggests non-deposition and possibly sediment bypass during tectonic quiescence (e.g. due to a lack of accommodation space near the basin margin) and/or fringe sandstone equivalents that amalgamate stratigraphically with the classic (type 1) sand-shale cyclicity of Volpriehausen, Detfurth and Hardeggen formations.
- Type 5: This type section is characterized by a condensed RBM sandstone package with very thin intercalated shale formations. It has a single occurrence in A15-01. This profile could either represent a transition between the Bunter (type 4) and regular RBM (type 1), or it could be a local expression of the Volpriehausen sandstone similar to type 2 (discussed further in sections

'Deposition and preservation in the northern sector' and 'Reservoir development').

- Type 6: This category is characterized by a series of relatively thin sandstones with a low GR-contrast to the intercalated and underlying shales. Biostratigraphic analysis is inconclusive, with the exception that Triassic strata is capped by a thin succession of Jurassic sandstone that itself is truncated by the Upper Cimmerian unconformity. This type section has a single occurrence in A05-01 (Kerstholt & Munsterman 2016), and has a strong resemblance to type 5 and to the Bertel-01 oil sandstones in the Danish sector (GEUS 1993).

Lower Volpriehausen and Detfurth Sandstone lithology mapping. Discrimination between Volpriehausen and Detfurth sandstones is equivocal for profiles of type 4 and especially for types 5 and 6. Direct correlation to the regular tectonostratigraphic cyclicity of RBM sandstones in the SW of the study area is hampered by subseismic vertical resolution and commonly barren palynology (e.g. Kerstholt & Munsterman 2016). For gridding purposes we assume that sandstones equivalent to Volpriehausen and Detfurth are preserved in the anomalous RBM profiles, thereby representing overfilled basin conditions where sediment influx outbalances local subsidence and intermittent shale deposits such as the Volpriehausen Clay-Siltstone Member (RBMVC) are preferentially eroded during periods of high-energy sediment bypass (Banham & Mountney 2013). Subdivision of profile types 4–6 into RBMVL and RBMDL equivalents is entirely based on visual correlation of log profiles and should therefore be considered of notional character only.

True stratigraphic thickness (TST) and net sand thickness (NST) are gridded separately using a convergent interpolation algorithm. The interpolation is restricted to the range of the input thicknesses to avoid gridding artefacts. In a second processing step, NST grids were divided by their TST counterparts to obtain a net-to-gross (NTG) map for the RBMVL and RBMDL intervals. TST represents available accommodation space, whereas NTG is considered a proxy for the ratio between net sand influx and relative basin subsidence.

In a general sense the results of the lithology mapping suggest thickness variations within the classic RBM facies expression (type 1), and may also reflect facies change to the north. The interplay between accommodation space and sand deposition in the NW area of the Step Graben is elucidated in the following section; the regional development is discussed in the section on 'Reservoir development'.

Deposition and preservation in the northern sector. Isochron maps of interval A and B in Figure 7 show Lower Triassic thickening on the western margin of the Step Graben in A15 (area of interest,

indicated by dashed boundary in Fig. 4); an extra set of reflectors appears at the thickened section (Fig. 8), while no unconformities or truncations are visible at the boundary between interval A and B. This thickening could indicate the presence of a local depocentre and accommodation space for sediments in A15 during Early Triassic times, with a relatively high influx of sand leading to overfilled conditions *sensu* Banham & Mountney (2013); this would explain the high NTG of the RBMVL in A15-01. No Lower Triassic thickening is seen in block A18 (Fig. 7), where well A18-01 indicates low NTG values of the RBMVL.

Hydrocarbon traps at Lower Volpriehausen Sandstone Member

Regional mapping of the Lower Volpriehausen Sandstone Member facilitates the identification of 42 untested structures (leads) in the study area. These leads roughly cluster in three types and areas (Fig. 9): (1) 'classic' leads with proven types of trap, source, seal and reservoir; (2) leads which may be sourced with hydrocarbons via Tertiary volcanic dykes (discussed in the section on 'Northern limits of Lower Triassic sandstones'); and (3) leads with alternative reservoir provenance in the NW Step Graben (as described in the section on 'Reservoir development').

The Zechstein salt deposits play an important role in the formation of Triassic traps, and the four main salt-related traps can be found in the study area: 4-way dip closures above salt domes (e.g. Caister-B field) (Underhill 2009); 3-way dip closures against salt walls (e.g. M1-A and G16-B fields); turtle-back anticlines (e.g. F15-A and L5-FA fields); and a number of truncation traps (e.g. M07-FA field) (e.g. Bachmann *et al.* 2010; van Eijk 2014).

Discussion

Reservoir development

Regional mapping of the Lower Volpriehausen Sandstone Member shows that the member is present in large parts of the study area (Fig. 4). The presence and thickness of the Lower Volpriehausen Sandstone Member decreases from the south to the north. The well locations, together with their type sections as displayed in Figure 4, illustrate the onset of shaling out of the Lower Triassic sandstone deposits (type 1) into an ephemeral lake environment (type 3) in the northern part of the Dutch F Quadrant, as also described by Geluk (2005, 2007).

Figure 5a shows that RBMVL is thickest on the western flank of the Dutch Central Graben (F10 area) with local maxima at the graben axis (F09) and bordering the UK sector in the west (E10).

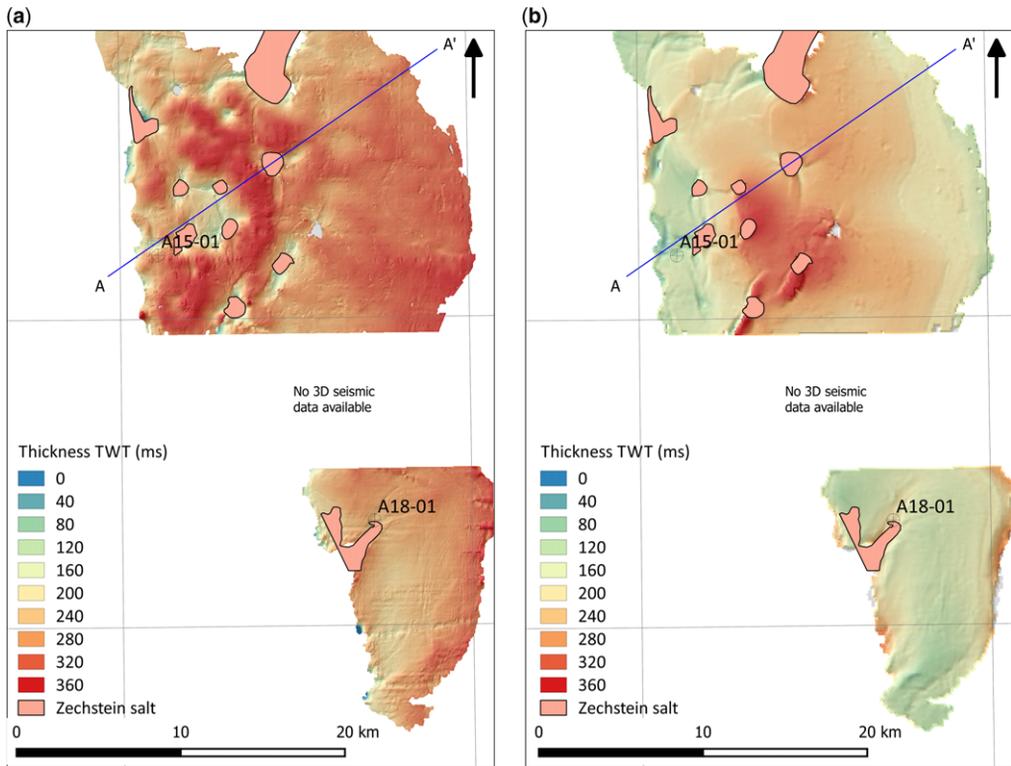


Fig. 7. Time isochore maps of (a) interval A (top Lower Volpriehausen Sandstone to top Zechstein) and (b) interval B (top Röt Evaporite to top Lower Volpriehausen Sandstone) showing thickening of Lower Triassic strata, suggesting Early Triassic local depocentre development in the A15 area.

Thinning in the NW Step Graben adjacent to the Elbow Spit High is prominent, suggesting that differential subsidence in this area was limited at that time. In Figure 5b, thinning in RBMDL appears to

be less localized; this indicates that subsidence in the Step Graben system was more pervasive during deposition of the Detfurth Sandstone Member. In contrast, the SE of the study area appears to

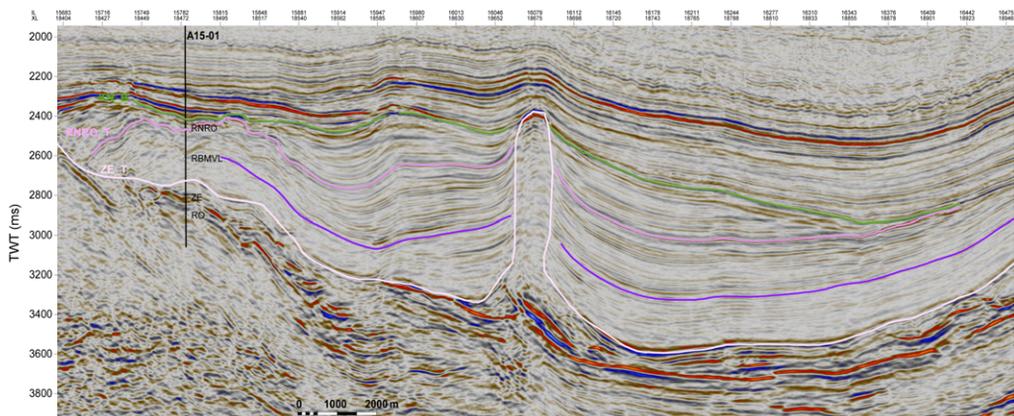


Fig. 8. Seismic section (TWT) along SW-NE transect showing thickening of strata in NW Step Graben area. Location of seismic section indicated in Figure 7.

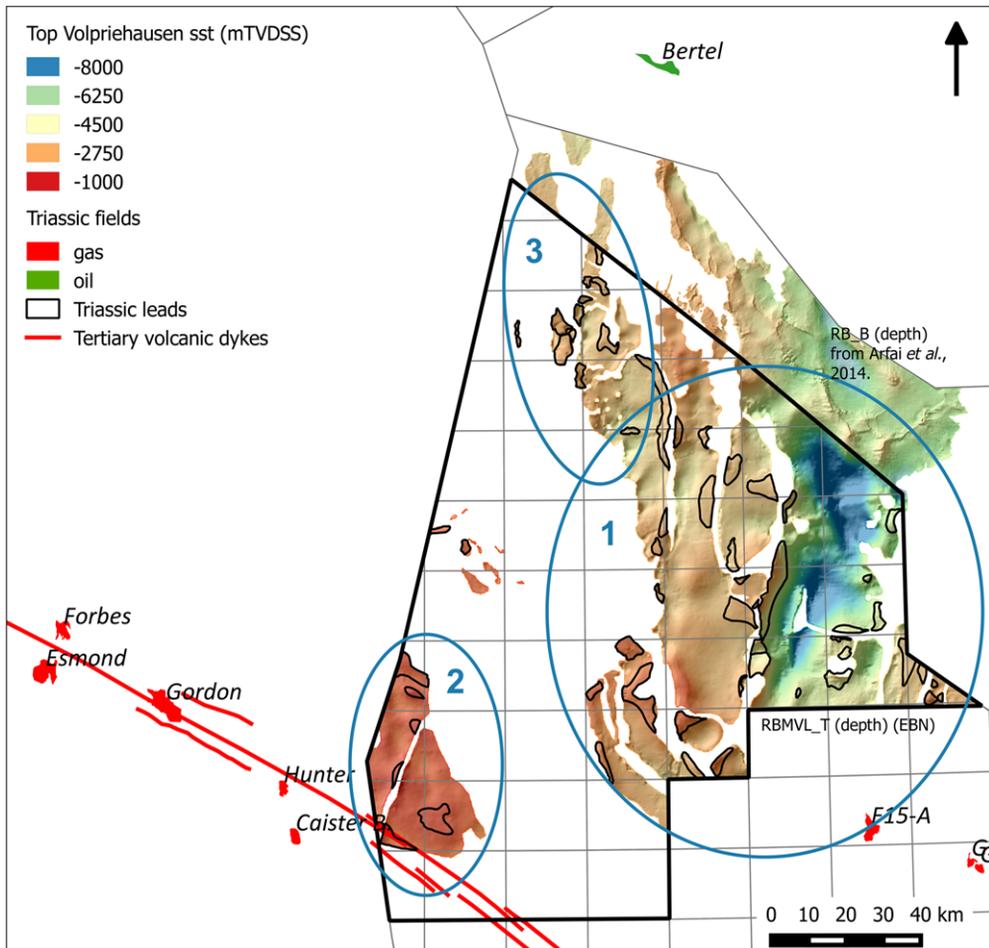


Fig. 9. Top Lower Volpriehausen Sandstone Member depth map in the study area. The identified leads are classified as one of three types: (1) 'classic' with proven types of trap, source, seal and reservoir; (2) leads which may be sourced via Tertiary volcanic dykes; and (3) leads with local/northern reservoir provenance. Triassic fields are shown in red (gas) and green (oil). The UK fields indicated are sourced from the Carboniferous via Tertiary volcanic dykes (Kirton & Donato 1985; Underhill 2009). The volcanic dykes extend into the Dutch sector with leads lining up along their strike.

provide less accommodation space during deposition of RBMDL as compared to RBMVL, suggesting a general shift of RBMVL-concurrent depocentres towards the north. This is supported by the relocation of the RBMVL thickness maxima in F10 towards the graben (F09) axis during Detfurth deposition. NST grids in Figure 5c, d largely follow the TST distribution except for the northern and, in particular, northeastern Step Graben. The NST map of RBMVL (Fig. 5c) clearly shows the limited sand deposition in the north.

The relation between TST and NST is shown in the NTG grids in Figure 5e, f. NTG typically relates to the balance between rate of differential subsidence and the rate of sand supply. Relatively high NTG

ratios in the basin fill are preserved if sand influx outpaces the rate at which accommodation space is supplied through subsidence, leading to overfilled conditions as described by Banham & Mountney (2013). NTG grids of both stratigraphic intervals generally confirm the lacustrine conditions in the centre of the Southern Permian Basin (e.g. Geluk 2007). However, shaling out during Volpriehausen deposition was more gradual and widespread with lowest NTG in the central Step Graben. During Detfurth deposition the basin centre facies appears to have been geographically more confined, with focus on the eastern Step Graben shoulder adjacent to the Dutch Central Graben (Fig. 5f). No wells reached the Triassic in the Central Graben to support

underfilled conditions as a result of accelerated graben subsidence in the period between RBMVL and RBMDL deposition. However, maximum TST and NTG in F09 during deposition of the Detfurth supports the idea that the Central Graben provided increasing accommodation space and acted as a preferred sand discharge route during the course of the Lower Triassic. The high shale content in B13 and also in the Danish U-1 (Michelsen & Andersen 1983) supports the theory that these northeastern areas were distal to the sediment source and the rate of sand supply was clearly outpaced by differential subsidence, probably even more so in the untested Lower Triassic of the German Central Graben. In contrast, NTG at the northwestern Step Graben boundary fault is relatively high at thin TST, indicating a balance between sediment supply and subsidence that favours the preservation of sand in this area.

Assuming a steady supply of sand, it is evident that the westernmost fault block in the Step Graben was subsiding at low rates during deposition of RBMVL (Fig. 5e) compared to the basins that formed to the east, where more lacustrine deposits were preserved. The northern RBMVL facies may therefore be a distal equivalent of the Bunter Sandstone Formation in the UK sector (Johnson *et al.* 1994), where sediment supply and subsidence were in favour of sand preservation. Sand-prone equivalents to the RBMVC and RBMDC are therefore likely to represent basin fringe facies similar to the Upper Volpriehausen Sandstone Member (RBMVU) and Upper Detfurth Sandstone Member (RBMDU) at the southern margin of the Southern Permian Basin (Van Adrichem Boogaert & Kouwe 1994). The transition between Bunter- and RBM-type Lower Triassic is seen in log profiles of the E Quadrant (type 4; section on 'Log profile typing as a means of regional facies analysis') and can be correlated westwards into the Bunter of the UK Southern North Sea (e.g. well 44/19-3). The provenance of the Bunter Sandstone Formation is the Variscan massif of the London-Brabant Platform in the south, with significant contribution from the UK onshore to the west (Cameron *et al.* 1992; Johnson *et al.* 1994). We suggest that the Bunter bypassed the Elbow Spit High and contributed to the transitional log profile described for A15-01 (type 5; section on 'Log profile typing as a means of regional facies analysis'). The western Step Graben blocks subsided rather uniformly during deposition of the Detfurth (Fig. 5f), whereas new accommodation space developed on the eastern Step Graben and possibly Central Graben areas.

Northern limits of Lower Triassic sandstones

The presence and distribution of reservoir sand in the NW sector of the study area, in particular in view

of the condensed sand anomalies in the NW Step Graben (A15-01), and south of the Mid North Sea High (A05-01) requires further investigation.

The NW sector of the Step Graben is marked by an amalgamation of Mesozoic unconformities that truncate Jurassic and Triassic strata increasingly to the north (Mid North Sea High) and the east (Elbow Spit High). The elongated fault blocks of the Step Graben system are increasingly downstepping from the Elbow Spit High in the West towards the Central Graben in the East. Uplift of the western platforms concurrent to subsidence in the Central Graben resulted in erosion of the Mesozoic cover of these platforms (Geluk & Röhling 1999), thereby also affecting the least subsiding Step Graben fault blocks adjacent to the Elbow Spit area.

Evidence of early salt mobilization associated with dextral-transensional movements at WSW–ENE-striking basement fault lines may be found in the seismic section of Figure 10. Zechstein salt accumulation in the footwalls concurrent with block-rotation and syntectonic Lower Triassic infill of the half-graben-style depocentres developed in the subsiding hanging walls (Fig. 10). Limited halite precipitation at the margin of the Zechstein basin and subsequent withdrawal by salt walls that developed towards the basin axis in the east and SE lead to early grounding of these salt pods (Smith *et al.* 1993; Banham & Mountney 2013). Such a depositional environment is described by Smith *et al.* (1993) as a linked pod synform system that facilitates conduits of clastic transport, whereas ephemeral lakes form in temporarily isolated synforms. Switching of the main conduits represents a major obstacle for predicting reservoir development in this environment.

Clearly post-depositional reactivation of the basement faults took place during the Early Cimmerian phase, prior to deposition of the Main Muschelkalk Formation (RNMU), and is in some instances associated with crestal collapse of the Zechstein and gravity infill of the sub-Muschelkalk strata. Similar incisions on intra-pod highs are seen in the NW part of the Step Graben where Lower Triassic strata have been exposed and eroded at the Middle Cimmerian unconformity. Jurassic sediments are sporadically preserved as infill to incised salt swells (e.g. Kimmeridge Clay Formation drilled in A08-01). The entire Triassic–Jurassic sediment package was truncated at the Late Cimmerian Unconformity (also known as the Base Cretaceous Unconformity or BCU) before the entire northern sector was covered by marine clastics (often subseismic and as thin as 10 m; e.g. wells A08-01, A12-02 and A14-01) and chalk. The collapse of early salt swells during the Jurassic is evidence of salt removal by circulating meteoric waters and possibly sub-aerial exposure south of the Five Countries area

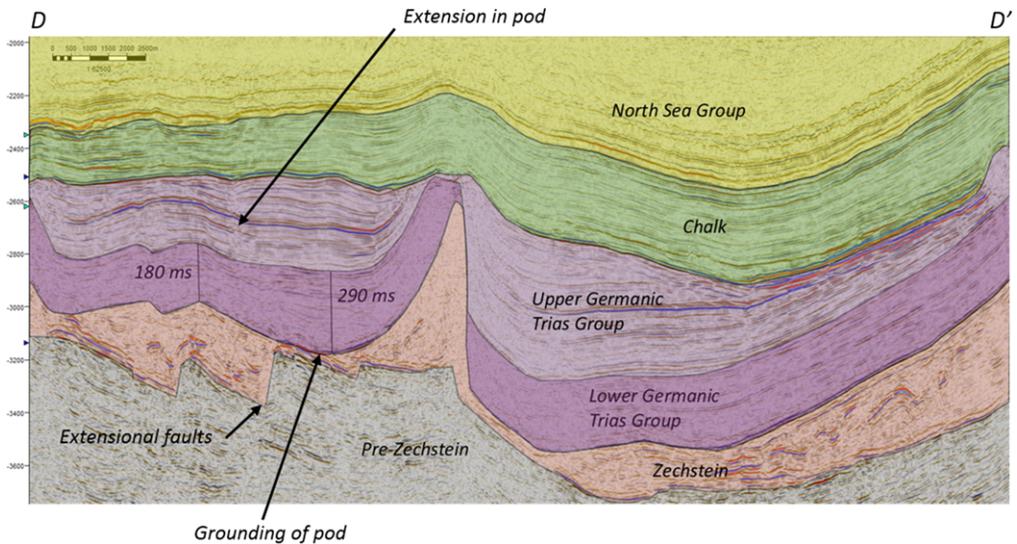


Fig. 10. Seismic section showing extensional faults in the pre-Zechstein deposits with a thin Zechstein layer on top. A thickened Lower Triassic is seen on top of the thin Zechstein layer. See [Figure 4](#) for profile location.

that was repeatedly subject to uplift, non-deposition and erosion, in particular: near the basin margins and at intra-basin swells such as the Mid North Sea high during the Hardegsen phase ([Röhling 1991](#); [Bachmann *et al.* 2010](#); [Pharaoh *et al.* 2010](#)); and by the rifting pulses of the Early Cimmerian phase ([Ziegler 1990](#)), thermal doming during the Middle Cimmerian phase ([Geluk & Röhling 1999](#)) and during Late Cimmerian accelerated subsidence of the Central Graben ([Remmelts 1995, 1996](#)).

Contrary to the general perception of southern provenance of RBM reservoir sands, we propose an alternative provenance of sediments encountered in the NW part of the Step Graben, deposited in a local depositional system similar to the observations in the L09 block where Solling sandstones present a unique gas-bearing reservoir drilled by L09-08 ([de Jager 2012](#)). Here, well and seismic data show that the reservoir package is wedge-shaped, thickening into a listric normal fault that detaches onto the top of the Zechstein salt, adjacent to a salt wall. The aeolian sandstones were clearly preserved in a syn-depositional half-graben, the development of which appears to be related to Early Triassic extension. These locally deposited aeolian wedges were also drilled in L06, but were however salt-plugged ([de Jager & Geluk 2007](#); [de Jager 2012](#)). Similar to such localized Solling 'Fat' sand deposits in the L Quadrant, local depocentres could have existed in the NW Step Graben area, preserving reservoir sands as drilled by A15-01.

The seismic data shows potential for local depocentres in rim-synclines in the A15-01 area near

the Step Graben western boundary fault ([Fig. 8](#); [van der Kooij 2016](#)). Here, a 'pockmark-like field of mini salt domes' records Early Triassic halokinesis, possibly halted by the interplay between (1) restricted halite precipitation at the margin of the Zechstein basin, (2) repeated uplift and removal of cover sediments during Early Triassic rift pulses and subsequent Cimmerian tectonic phases, and (3) withdrawal to salt walls that built up towards the basin centre ([Remmelts 1996](#)). The generation of accommodation space by the proposed pod synform system, analogous to the observation of [Smith *et al.* \(1993\)](#) in the UK Central North Sea, and by concurrent rim syncline formation in the A15-01 area, outlines the potential for local sand deposition during the Early Triassic.

The presence of sands in the unique vertical RBM profile of A15-01 (type 5; [Fig. 4](#)) confirms the exposure of this northernmost area of the Dutch offshore sector to sand erosion and subsequent transport. It is not clear whether the sands at A15-01 represent (1) a condensed section (described above as type 5) of the full tectono-cyclic sandstone package of RBM as a transition between the regular type 1 and the Bunter-like type 4 or (2) shale intercalated RBMVL (similar to type 2), whereas the younger RBM sandstones are absent. Option 1 would suggest the widespread deposition of sands across the NW area, possibly facilitated by relay ramp systems in the transfer zones of the major north-south-striking faults, whereas option 2 would be in favour of RBMVL facies association with the transition to ephemeral lakes at the basin centre to the east and SE.

The different log character of A05-01 and A15-01 (Fig. 4), the indication of a local depocentre in A15 (Fig. 8) and the bimodal grain-size distributions found within samples of these two wells (Bezemer 2016) could indicate an alternative reservoir provenance in the NW Step Graben area. Bimodal grain-size distributions in A05-01 and A15-01 suggest a different transport mechanism or sediment source, in contrast to the unimodal grain-size distributions of all samples from A18-01, F16-04 and L09-08 (Bezemer 2016) that suggest aeolian transport. It should be noted that the samples from A05-01, A15-01 and A18-01 were taken from cutting material, while the other samples were taken from cores.

Fluvial sediments from the local highs could have been deposited in local depocentres. Olivarius *et al.* (2017) show that heavy mineral analyses may help to determine the provenance of Lower Volpriehausen and Solling Sandstone deposits. A feasibility study by Vonk (2016) shows that heavy minerals can also be obtained in the northern Dutch offshore from cutting material from wells A05-01, A15-01 and A18-01. However, only a few samples were taken; it is not possible to conclude the provenance of RBM sands in these three wells from the current dataset. Heavy mineral analyses of both these three northern wells and a number of wells that drilled typical Variscan-sourced Lower Volpriehausen Sandstones could assist in resolving the provenance of RBM sands in the NW Step Graben, and are suggested for future research.

The current evaluation provides new insights into the northern Dutch offshore and surrounding areas, suggesting that local depocentre development is possible at the northern margin of the Southern Permian Basin where locally, westerly or northwesterly sourced reservoir sands may have been preserved. In addition, the log-typing and facies description described in this paper show that good-quality (likely Variscan sourced) RBM reservoir sands also exist up into the northernmost F-blocks.

Lower Triassic prospectivity in the northern Dutch offshore: source rocks, charge and seal mechanisms

Access to mature source rocks and hydrocarbon charge from the underlying Carboniferous is often identified as an additional risk for the Main Buntsandstein play in the northern Dutch offshore, as thick Zechstein salt would prevent hydrocarbon migration into the Main Buntsandstein reservoir layers. The primary source rock of the hydrocarbons retained in producing Triassic gas fields are Upper Carboniferous (Westphalian) and Namurian coals and organic-rich shales (e.g. Fontaine *et al.* 1993; de Jager & Geluk 2007). Upper Carboniferous

coals are present in the southern part of the study area (Kombrink 2008), but the organic-rich shales of the Epen Formation (Namurian) are also expected to be present and mature (Gerling *et al.* 1999; ter Borgh *et al.* 2018b). Recent studies provide new insights into the source-rock potential in the northern part of the study area, where both Namurian shales and coals and Lower Carboniferous coals from the Scremerston (Viséan) and Yoredale (Dinantian) formations are interpreted to be present and mature in the northern Dutch offshore (Schroot *et al.* 2006; Arfai & Lutz 2017; ter Borgh *et al.* 2018b). Lateral oil migration may happen when RBM reservoir sandstones are juxtaposed against Jurassic Posidonia shale without Zechstein salt entering the fault zone (e.g. Geluk 2007).

The migration of hydrocarbons from the Carboniferous into the overburden may occur along faults, through salt windows, along carrier beds and via volcanic dykes. Figure 11 shows the Zechstein salt isochron which illustrates the presence of a large variability in thickness and the presence of potential salt windows near many of the identified structural closures. In the western area (D, E blocks) where Zechstein salt is generally thick, Lower Triassic structures may be charged from Carboniferous coals via volcanic dykes, analogous to UK Triassic gas fields (Kirton & Donato 1985; Brown *et al.* 1994; Underhill 2009). These dykes have been mapped in the UK (Kirton & Donato 1985; Brown *et al.* 1994; Underhill 2009) and can be followed into the Dutch sector (Figs 9, 11) on seismic data (EBN 2015). These dykes may appear as linear features on an amplitude extraction at base Tertiary (Brown *et al.* 1994; EBN 2015). Expansion and contraction caused by heating and cooling of these Paleogene igneous intrusions has created fractures along the sides but also within these intrusions, allowing vertical migration (Underhill 2009). The UK Bunter fields Forbes, Esmond, Gordon, Hunter and Caister B are considered to have been charged via Tertiary dykes, as all fields are located in an area with thick Zechstein salt deposits. Forbes, Esmond and Caister B in particular, as it is positioned >10 km away from a mapped Tertiary dyke, may suggest that significant lateral hydrocarbon migration took place. Cenozoic movement of salt is considered as a major risk for maintaining charge in underfilled turtleback anticlines such as Caister B (Bachmann *et al.* 2010).

In most Triassic fields in the Netherlands the top seal is formed by Triassic Röt salt and Solling shale and, where the Triassic is truncated at the Base Cretaceous Unconformity, by Lower Cretaceous shales (e.g. de Jager & Geluk 2007). The four-way and three-way dip closures are generally dependent on Upper Triassic sealing shales and/or Zechstein side/top seal. Halokinesis can create traps in the

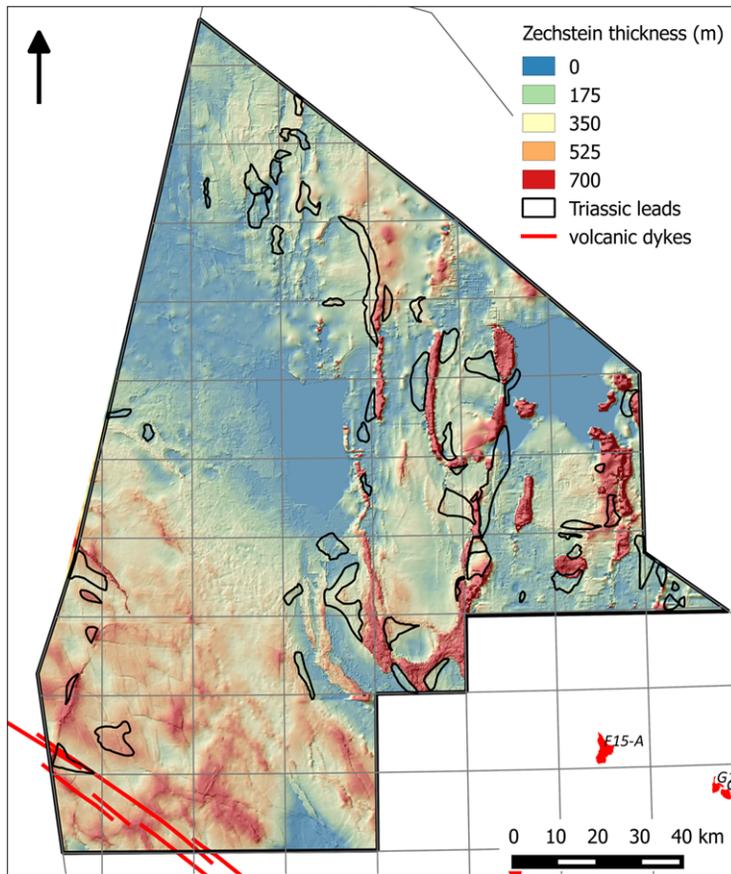


Fig. 11. Zechstein isochron indicating large variability in Zechstein salt thickness (time), which could enable vertical hydrocarbon migration through Zechstein salt windows. Red lines indicate location of Tertiary volcanic dykes. Black polygons indicate the structural closures (leads) at RBMVL level.

Triassic overburden, but the near presence of salt can also cause (partial) salt plugging of reservoir rocks, resulting in reservoir deterioration. Salt-plugged reservoir rocks may even act as a competent side seal (M1-A field) (Bachmann *et al.* 2010). Salt plugging may be recognized on seismic data, but it remains difficult to recognize a salt-plugged reservoir without calibration to nearby well data.

Truncation traps depend on the sealing capacity of overlying Jurassic, Cretaceous or Paleogene strata. The Jurassic part of the Flora field in the UK North Sea sector demonstrates that only a thin veneer (3 m) of Lower Cretaceous marl is sufficient to form the top seal of this truncation trap field (Hayward *et al.* 2003).

Detailed analysis of the sealing potential of the Triassic overburden has not been the focus of this study, but should be performed when evaluating the sealing capacity of the individual leads.

Conclusions

A regional study using wells and seismic data from the northern Dutch offshore and surrounding territories indicates the presence of Triassic reservoir sandstones north of the main, well-understood, fairway. A comprehensive borehole review and log typing in the study area shows the presence of sands in the NW Step Graben area. Seismic interpretation also indicates the presence of Early Triassic local depocentre development in the Step Graben. Syntectonic strata in local depocentres may have been formed in this area due to early halokinesis in the Triassic, in analogy to the Central North Sea described in Smith *et al.* (1993). Grain-size analyses, together with heavy mineral analyses, are proposed to further investigate whether fluvial sands with a (local) northern provenance may have been preserved in the northwestern area of the Step Graben system.

Reservoir gridding allows the investigation of regional trends but does not resolve local depocentres, for example, analogues to the Solling Fat Sand play in the L09 and L06 areas (south of our study area). Depocentres appear in the F09 and F10 areas and may be related to differential subsidence and preferred sediment discharge in the Dutch Central Graben. The northern RBMVL is characterized by high NTG at relatively low stratigraphic thickness, suggesting that differential subsidence in the westernmost Step Graben, adjacent to the Elbow Spit High, controlled sand preservation at rates that were possibly sustained by an influx of fluvial sands from the same source that supplied the Bunter Sandstone province in the west. In contrast, RBMDL thickness is uniform in the Step Graben area and depocentres appear to have shifted eastwards into the Central Graben.

Regional mapping of the Lower Volpriehausen Sandstone in the A, B, D, E and F quadrants in the northern Dutch offshore enabled us to identify 42 untested structures in the study area. Recent studies on the source-rock potential in the northern Dutch territory suggest that source rocks of different ages are present in the study area, while the presence of salt windows (indicated by Zechstein isochron mapping) and dykes (mapped on Base North Sea seismic amplitude extraction maps) allow vertical hydrocarbon migration. We conclude that the remaining prospectivity of the Lower Triassic in this part of the Southern Permian Basin may be rather large.

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