

Structural development of the northern Dutch offshore: Paleozoic to present



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Abstract: We used new high-quality 2D and 3D seismic data covering the northern Dutch offshore to develop a structural framework for Paleozoic–recent times. Early Carboniferous extension was accommodated predominantly along WNW–ESE-trending faults, and was characterized by an alternation of highs and lows; in the northern Dutch offshore, the principal high coincides with the present-day Elbow Spit Platform. An Early Carboniferous low, the North Elbow Basin, is present north of this high in the A and B quadrants. Lower Carboniferous deposits have been preserved here and on the Elbow Spit Platform. Late Carboniferous–Early Rotliegend deformation is accommodated primarily along normal faults with a NE–SW trend. These faults commonly show no significant offset of Upper Rotliegend and younger units. Development of the Dutch Central Graben and Step Graben occurred during the Triassic–Early Cretaceous, primarily along north–south-trending faults, but reactivation of pre-existing faults as oblique-slip faults occurred as well. Associated with these north–south-trending faults was another, not previously described, family of WSW–ENE-trending dextral strike-slip faults which are proposed to represent transfer faults that accommodated strain partitioning.

The North Sea is a mature petroleum province where exploration has historically focused on two main fairways: the Southern North Sea area (Fig. 1), where production is mainly from Permian, Carboniferous and Triassic reservoirs; and the Northern and Central North Sea (Fig. 1), where most production is from Mesozoic to Paleogene deposits that are associated with the Central Graben system (e.g. Evans *et al.* 2003; de Jager & Geluk 2007; Doornbal & Stevenson 2010).

Until recently, the hydrocarbon potential of the area situated in-between these two fairways, the Mid North Sea area (Fig. 1), was generally considered to be low. One reason was the supposed absence of reservoir rocks; the reservoir presence of Permian Rotliegend rocks was suspected but unproven this far north (e.g. Geluk 2007). Another reason was the perceived absence of a mature source rock, as the Upper Carboniferous, from which most gas in the Southern North Sea is commonly thought to be sourced, is mostly absent (e.g. van Buggenum & den Hartog Jager 2007).

However, recent discoveries suggest that alternative reservoir and source rocks are present. The Lower Carboniferous is an example. It was not ruled out that this stratigraphic interval had reservoir potential, but its economic potential was generally considered unproven (e.g. de Jager & Geluk 2007). This changed following the discovery of the 20 Bcm (billion cubic metres) Lower Carboniferous Breagh Field in the UK offshore (McPhee *et al.* 2008) (Fig. 1). Further assessment of the potential of the

Lower Carboniferous requires a good understanding of the structural development of the area, as deposition during the Early Carboniferous was strongly fault controlled. Interestingly, not much is known yet about the structural development of the Mid North Sea area during this period.

Another recent game-changing discovery north of the main Southern North Sea fairway is the UK Cygnus Field (Taggart & Catto 2015) (Fig. 1), proving that relatively coarse Rotliegend deposits can be found this far north. Moreover, Carboniferous deposits were encountered that showed better reservoir quality than expected. Apparently, a local high provided a sediment source. Predicting if similar coarse siliciclastic sediments are present in the Dutch sector requires a better understanding of the structural evolution during this period.

A question closely related to this issue is the onset of deformation in the Dutch Central Graben (DCG) and Step Graben (SG) (Fig. 1). The main phase of activity of these structures was during the Triassic and Jurassic, but activity as early as the Devonian has been suggested (e.g. Ziegler 1990). Understanding when these graben were active is a key constraint for depositional models, for modelling source-rock maturation and for predicting reservoir quality. It is also relevant for the Triassic and Jurassic plays in the Mid North Sea area; reservoir-quality rocks have been encountered for both intervals (e.g. de Jager & Geluk 2007; Kortekaas *et al.* 2016). To understand why, and to further predict reservoir presence, a better understanding of the structural

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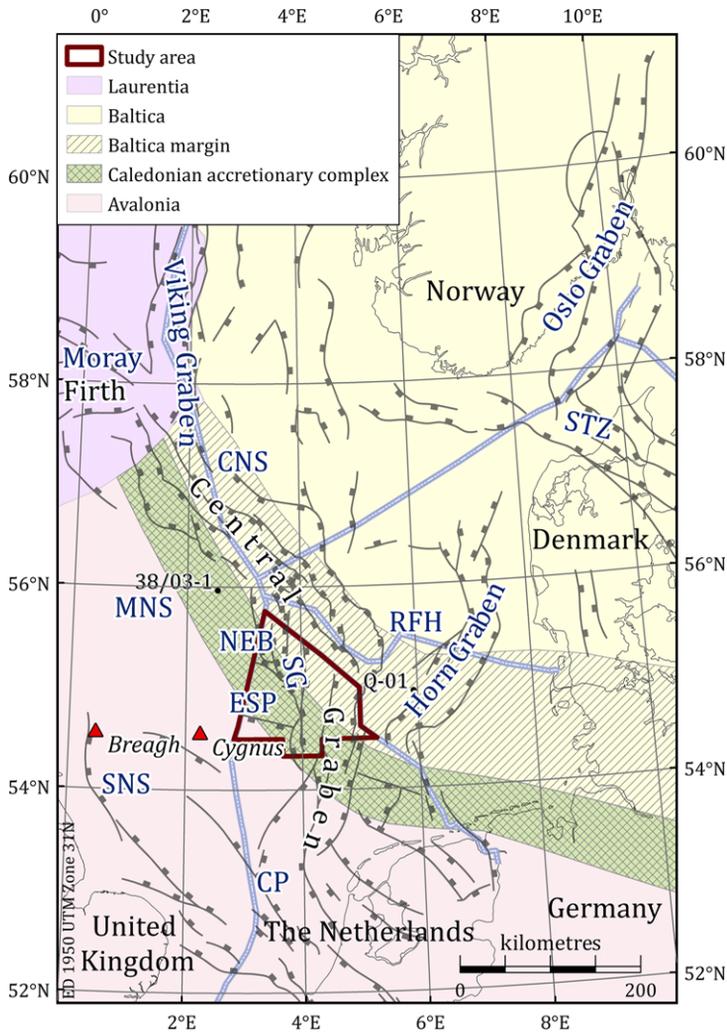


Fig. 1. Regional overview map showing the plate tectonic setting (after Smit *et al.* 2016) and large-scale structures (Ziegler 1990; Wride 1995; McCann *et al.* 2006; de Jager 2007; and this study). CNS, Central North Sea; CP, Cleaver Bank Platform; ESP, Elbow Spit Platform; MNS, Mid North Sea area; NEB, North Elbow Basin; SG, Step Graben; SNS, Southern North Sea; STZ, Sorgenfrei-Tornquist Zone; RFH, Ringkøbing-Fyn High.

evolution is required. This would also aid in establishing migration routes from the Jurassic Posidonia Formation source rock, which is known to be present and mature in the DCG (de Jager & Geluk 2007), to overlying (Jurassic, Chalk) and juxtaposed deposits. Finally, a better understanding of the structural evolution of the area will help in identifying trapping geometries, fault seal and reservoir compartmentalization.

In summary, an improved structural framework for the Mid North Sea area will be of significant benefit for assessing the economic potential of the area. This study will focus on the Dutch part of the Mid

North Sea area: the northern part of the Dutch offshore.

Geological outline

The study area is located on the boundary between different types of basement (Fig. 1). The basement below most of the Dutch offshore is commonly considered to be part of the Avalonia microcontinent, which is presently wedged between two larger palaeocontinents: Baltica to the north and Gondwana to the south (e.g. Pharaoh 1999). Avalonia

Southern North Sea area, there is a 40–60 myr hiatus between Carboniferous and Permian rocks (Fig. 2) (Geluk 2007). The remainder of the Permian is commonly considered a period of relative tectonic quiescence, with long-wavelength thermal subsidence accentuated by minor tectonic pulses (Geluk 2007). During the Late Permian, restricted marine conditions were established, resulting in the widespread deposition of Zechstein evaporites and carbonates (Fig. 2).

During the Triassic, Pangaea started breaking up (Fig. 2), which led to the formation of the Central Graben system in the North Sea area. The fault system essentially consists of three rift arms (Fig. 1): the Central Graben in the south, the Viking Graben in the north and the Moray Firth Basin in the west. Extension in the Central Graben was orientated east–west to NE–SW (Zanella & Coward 2003), and faults in the DCG and SG have a north–south trend (Fig. 1). Extension reached the Southern North Sea in the Middle Triassic (de Jager 2007). During the Middle Jurassic, uplift centred at the triple junction of the three rift segments led to the formation of the Central North Sea Rift Dome (Ziegler 1990; Underhill & Partington 1993). As a result, widespread erosion occurred which extended into the graben only, and sediments were preserved in the graben only. In the Late Jurassic, the region started subsiding again and sedimentation outside the graben resumed. Late in the Early Cretaceous, continental break-up of Pangaea was reached in the North Atlantic. As a result, extension in the Central Graben system died out, leaving the system as a failed rift (Ziegler 1990). From the Late Cretaceous onwards, subsidence resulted predominantly from thermal subsidence. The development of the Alpine orogenic system led to a number of inversion events during the Late Cretaceous and Paleogene (de Jager 2007). The Neogene and Quaternary were periods of relative tectonic quiescence characterized by thermal subsidence (de Jager 2007).

The easternmost part of the study area is dominated by the Triassic–Jurassic DCG (Figs 3 & 4).

West of the graben, we find from north to south (Fig. 1): (1) the SG, a structure that formed during the same period as the DCG, but where significantly less extension was accommodated; (2) the Elbow Spit Platform (ESP), a structurally high area where Lower Carboniferous and Devonian deposits are present at relatively shallow depths; and (3) a relative low situated south of the ESP. The topmost part of the ESP is the Elbow Spit High; here, Upper Cretaceous deposits can be found directly on top of the Devonian. The term Elbow Spit High was previously used for the entire ESP (Kombrink *et al.* 2012). The ESP is commonly considered to be an extension of the Mid North Sea High which formed a high from Permian times onwards, and extends into the UK, German, Danish and Norwegian sectors.

Methods

The dataset used to study fault trends and fault activity consists of 2D and 3D seismic data from a variety of sources. The southern part of the area is covered by the DEF survey, a 7950 km² 3D multiclient survey (Fig. 4, inset) that was acquired in 2011 and 2012. The streamer length for this survey was 7.5 km, allowing for good imaging below the Upper Permian Zechstein salt. The northern part of the study area is partly covered by 3D surveys acquired in the period 1994–2006 that have since been made public. Imaging of the pre-salt units is commonly fair to poor on these surveys. 2D seismic data were used where 3D seismic data were unavailable or where the imaging of the 2D seismic data was better. The entire study area is covered by the North Sea Renaissance (NSR) 2D multiclient survey, which consists of a grid of regional seismic lines shot in NW–SE and NE–SW directions, with a spacing between lines of 5.3 km (Fig. 4, inset). The survey was acquired between 2005 and 2010, and the Dutch part of the survey has since become public. This survey was also acquired with long streamers and imaging of the pre-salt is good.

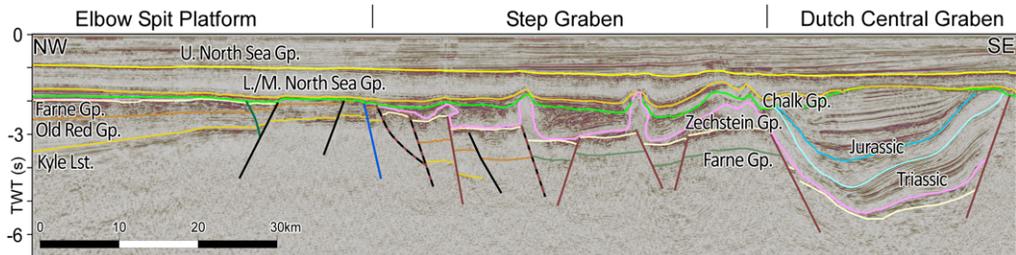


Fig. 3. Seismic section showing the three main structural elements in the study area: Elbow Spit Platform, Step Graben and Dutch Central Graben. The legend to the horizons is given in Figure 2; the location is shown in Figure 4. Public seismic line NSR 1061.

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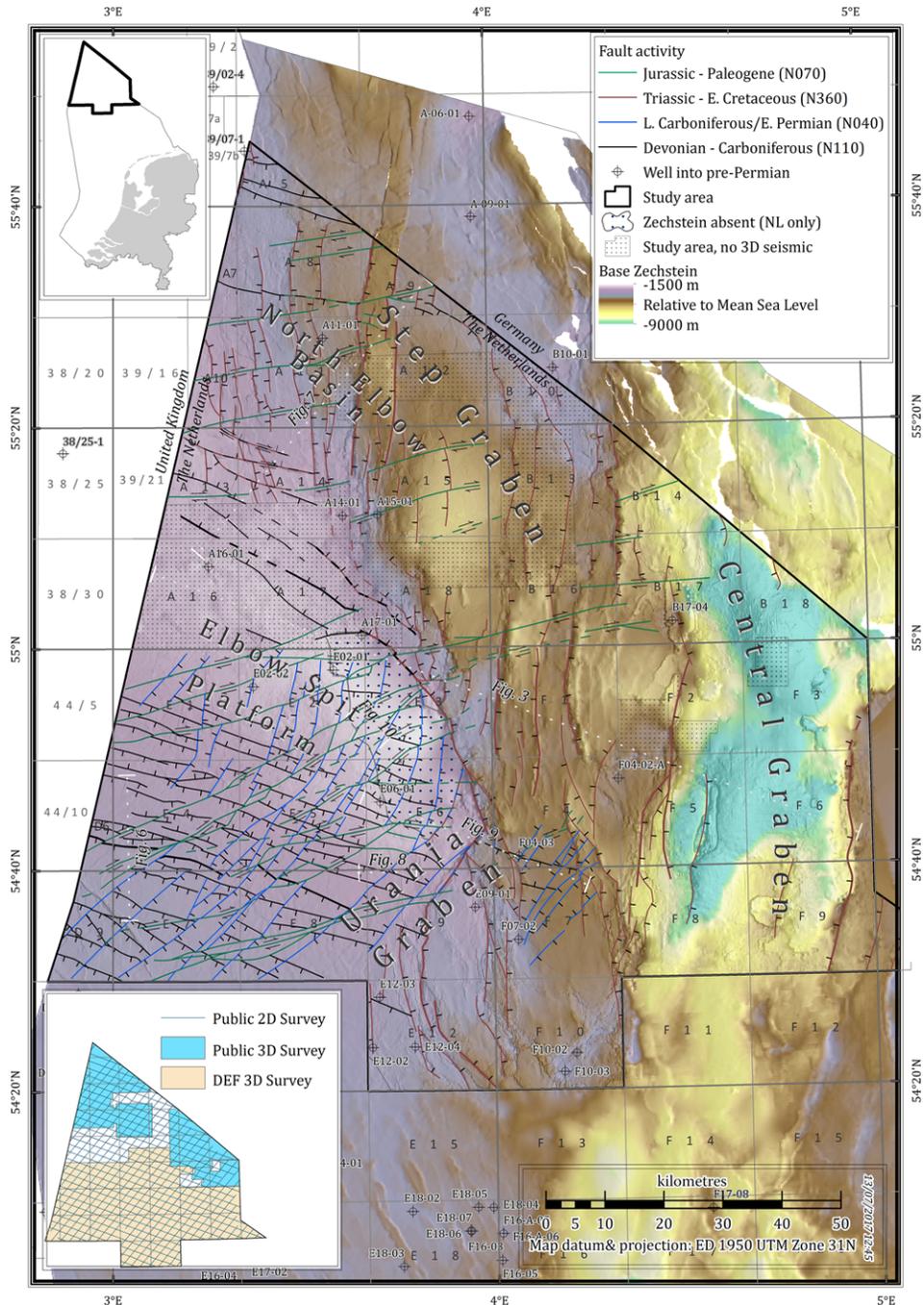


Fig. 4. Structural framework for the northern Dutch offshore. Faults are shown at the Base Permian level or, in case of older fault activity, at the topmost affected horizon. Along with the faults, the depth to the base of the Zechstein Group is shown; where the Zechstein is absent, the base of the first younger unit is shown. The Base Zechstein surface outside the study area is after [Kombriink et al. \(2012\)](#) and [Arfai et al. \(2014\)](#). Faults are coloured according to their activity; reactivated faults are shown with dashed lines. Apparent fault density of the N110° and N040° faults is high on the ESP where seismic imaging is good, and decreases in the DCG and SG. This is thought to be related to imaging, not an actual decrease in fault density.

For horizon interpretation, well data from over 60 wells were used. The wells were tied to the seismic data using check shots. All public seismic surveys and well data were requested from NLOG (<http://www.nlog.nl/>), the Dutch repository for deep subsurface data. Seismic horizons were interpreted in the time domain and converted to depth using a layer-cake velocity model. Between the base of the Chalk Group and the Base Permian Unconformity (BPU), the Velmod-2 velocity model (van Dalfsen *et al.* 2006, 2007) was used. For the Lower–Upper North Sea groups and the Chalk Group pseudo-seismic picks of 82 wells within the study area were used to construct a V_0 map, which was possible because the top and base of the Chalk Group are distinct seismic reflections in the study area. K -constants from Velmod-2 were used. From the BPU downwards, insufficient data points were available in the study area to construct a V_0 map; all wells with check shot or VSP data in the study were investigated and it was concluded that this interval is best modelled using a constant interval velocity of 4200 m s^{-1} .

Fault trends were mapped using coherency cubes in Petrel; structural smoothing was applied to the 3D seismic cubes first, and the variance was calculated subsequently. Mapping of fault trends was done on time slices, and on levels at fixed times below key horizons; these horizons, most prominently the BPU, were interpreted first, and coherency values were subsequently extracted from the coherency cube at this horizon and at fixed time below it. Based on the resulting time slices and horizon extractions, fault trends were mapped, focusing on faults that caused offset at the BPU level. In an iterative process, interpretations were checked and updated using further seismic interpretation. Fault offset and the timing of fault activity were constrained using the interpreted horizons.

Results

The coherency cubes reveal a complex fault pattern (Fig. 5); at least four fault trends can be mapped (Fig. 4): normal faults with a $N110^\circ$ -(WNW–ESE) trend (displayed in black in all figures), normal faults with a $N040^\circ$ -(NE–SW) trend (displayed in blue), normal faults with a $N360^\circ$ -(north–south) trend (brown) and strike-slip faults with a $N070^\circ$ -(WSW–ENE) trend (green).

$N110^\circ$ faults

Faults with a WNW–ESE trend are well represented on the ESP in units subcropping the BPU (Fig. 4; displayed in black). These faults limit the platform on its southern side (Fig. 6) and the offset along the

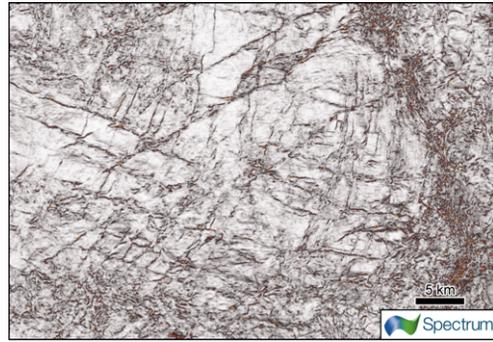


Fig. 5. Coherency cube extraction at 200 ms TWT below the Base Permian Unconformity, showing the main fault trends observable on the Elbow Spit Platform. DEF 3D seismic data courtesy of Spectrum ASA.

faults is commonly normal, varying in magnitude from the resolution of the seismic data (approximately 30 m) to hundreds of metres. Recent long-offset 2D seismic data show for the first time that these faults also limit the ESP at its northern boundary (Fig. 7); Upper Devonian and Lower Carboniferous units thicken and have been downfaulted. Most faults offset the Lower Carboniferous and older units only; the base of the Permian is usually not affected. Where the BPU is affected, the offsets are smaller than the offset within the Carboniferous.

When the offset within the Carboniferous is of the order of hundreds of metres, the thickening of the Lower Carboniferous is accompanied by a

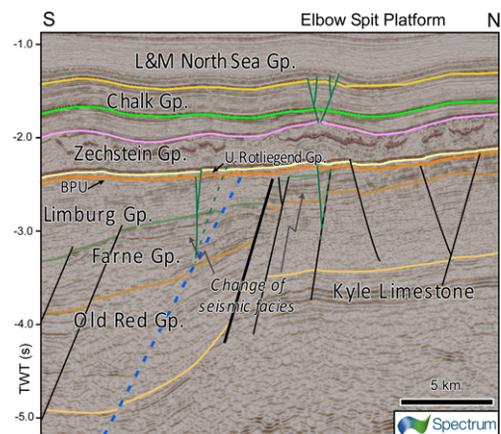


Fig. 6. Late Devonian–Early Carboniferous faulting on the southern flank of the Elbow Spit Platform. The legend to the horizons is given in Figure 2; the approximate location is shown in Figure 4. DEF 3D seismic data courtesy of Spectrum ASA.

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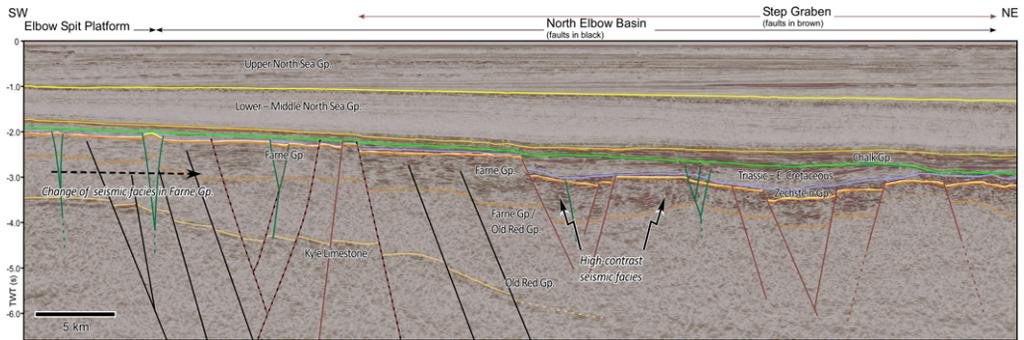


Fig. 7. Seismic section across the North Elbow Basin, a major low that lies hidden within the Step Graben. The Lower Carboniferous Farne Group has a high-contrast seismic facies that is likely to have been caused by the presence of coals. The legend to the horizons is given in [Figure 2](#); the location is shown in [Figure 4](#). Public seismic line NSR32294.

change in seismic facies. Continuous high-frequency parallel reflections are observed above the footwall, while above the hanging wall the configuration of the reflections changes to low-frequency divergent discontinuous ([Fig. 6](#)). This is evident in Upper Devonian, Tournaisian, Visean and Namurian units. Altogether, these observations show that the ESP represented a horst during the Late Devonian–Early Carboniferous, with lows on its northern and southern flanks.

Faults with this trend are also present on the ESP, but here offsets are smaller than on the northern and southern flanks. The faults are observed in all regions when the Carboniferous is sufficiently well imaged, which is the case on the ESP and its southern and northern flanks, and in the part of the SG directly east of the present-day ESP ([Fig. 4](#)). As a result of the large burial depth of the Carboniferous in the DCG and the remainder of the SG, it was not possible to constrain the fault trends in the Carboniferous here. This should not be taken as proof of absence, however.

N040° faults

A second prominent fault trend consists of NE–SW-trending faults ([Fig. 4](#); displayed in blue). Like the N110° trend, these faults show a normal offset of pre-Permian units, and in most cases no offset at the Base Permian level. The magnitude of offset varies greatly; on top of the ESP, for instance in blocks E01 and E02, offset is commonly small, just above the seismic resolution (*c.* 30 m). However, close to the eastern flank of the ESP, in block E06, a fault is present with a vertical offset in the Carboniferous of approximately 0.5 s two-way travel time (TWT) ([Fig. 8](#)), which, assuming an interval velocity for the Carboniferous of 4.2 km s^{-1} , converts to a throw of about 1 km. No significant offset of the Upper

Rotliegend Group is observed, but the overlying Rotliegend deposits show a gentle fold above the crest of the footwall. Further east, faults with similar trends and offsets are observed in the area that is now the SG ([Figs 4 & 9](#)). Again, offset of the Upper Rotliegend Group is small, or absent. Faults from this family offset the Visean Elleboog and Yoredale formations (Farne Group: see [Fig. 2](#)), which can be readily recognized on seismic data because of their distinct high-continuity, medium-contrast seismic facies, showing that activity post-dated the Visean. In blocks D06–E06, the Westphalian appears and can be observed to thicken across these faults.

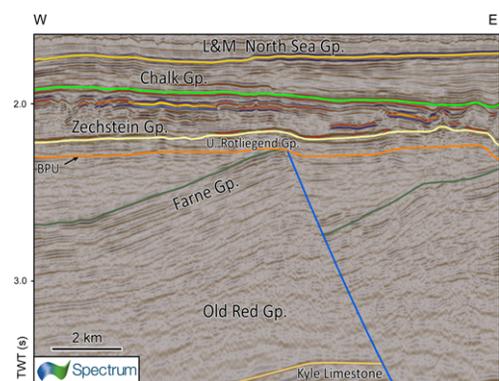


Fig. 8. Section across block E6 showing a N040°-trending fault that has an offset of approximately 0.5 s TWT. The interval velocity within the Carboniferous is approximately 4 km s^{-1} (*c.* 1 km). Activity of the fault post-dates the deposition of the Farne Group and predated the deposition of the Permian Upper Rotliegend Group. The legend to the horizons is given in [Figure 2](#); the approximate location is shown in [Figure 4](#). DEF 3D seismic data courtesy of Spectrum ASA.

In some cases, these faults clearly offset the N110° faults, which is commonly the case when the offset along the N040° fault is significant, of the order of hundreds of metres. When offset is at or just above the seismic resolution, no offset of the N110° faults is evident. Although atypical, faults with a N040° trend offset the Base Permian in a few cases: for instance, in block E09. In that particular case, the post-Carboniferous deformation is associated with the north–south-trending faults that form the SG and DCG, which is described below.

Similar to the N110° trend, these faults can be recognized whenever the Carboniferous is sufficiently well imaged, showing that they constitute a regionally pervasive fabric. This is the case for the parts of the ESP and SG covered by the DEF survey (Fig. 4). In the DCG, the Carboniferous is buried to depths not imaged on the seismic data. In the A quadrant, only vintage 3D data are available and imaging of the Carboniferous is poor. As a consequence, it was not possible to confirm the absence or presence of faults with a N040° trend. Fault throws are limited on the ESP, and are of the order of hundreds of metres to 1 km on the eastern flank of the ESP and the region east of it (Fig. 9).

In summary, these faults were active post-dating the deposition of Visean units (Early Carboniferous) and predating the deposition of the Upper Rotliegend Group.

N360° faults

This fault trend accommodated the opening of the DCG and SG, but did not leave a significant imprint

on the ESP (Fig. 4; displayed in brown). The faults trend north–south, and the offsets are commonly of the order of hundreds of metres up to kilometres. The faults that bound the DCG have a significantly larger offset than any other faults in the area: up to about 3500 m normal offset (Fig. 4). Unlike the previously described fault trends, these faults offset the BPU and affect units as young as the Early Cretaceous. West of the DCG, the SG consists of a number of smaller parallel graben, leading to an alternation of highs and lows. The throw along these faults is significant (up to *c.* 900 m), but is smaller than in the DCG (Fig. 4).

On the northern and eastern flanks of the ESP, north–south-trending faults can be observed to merge with faults with other trends: on the eastern flank, with faults with a N040° trend; and on the northern flank, with faults with a N110° trend (Fig. 4). Where this occurs, these faults offset the Permian, which is atypical for faults with these N110° and N040° trends, suggesting that in these cases these faults have been reactivated when the north–south-trending faults became active (Fig. 9).

Features associated with salt tectonics, such as salt walls and diapirs, commonly align with these faults (Fig. 3) and where this is the case, imaging of the subsalt units, including the fault itself, is poor.

N070° faults

On time slices, a fourth fault trend is visible that offsets all previously described fault trends. The trend of these faults is generally N070°, although the faults undulate locally (Fig. 4; displayed in green). Where

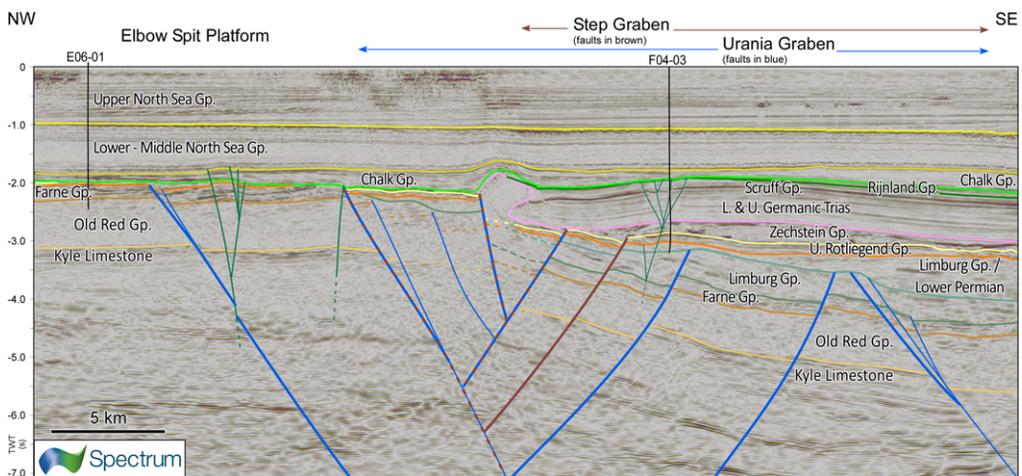


Fig. 9. Seismic section from the Elbow Spit Platform (left) to the Step Graben (right). The section reveals that the Urania Graben is an older structure, present below the Step Graben. Faults are coloured according to the period in which they were active: the legend is shown in Figure 4. The legend to the horizons is given in Figure 2; the approximate location is shown in Figure 4. DEF 3D seismic data courtesy of Spectrum ASA.

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visible, the offsets consist of dextral strike-slip, with offsets of up to 1 km (e.g. Fig. 4, blocks A9 and A11). The faults are especially profound on the ESP, where they can be mapped over distances of over 90 km (Fig. 4). The faults affect units as young as the Late Cretaceous and possibly the Paleogene, but offsets are largest in units older than the Late Cretaceous.

The structural styles of these faults vary systematically; where the faults are observed to undulate in map view, a cross-section of the fault shows pop-up and pop-down geometries (Fig. 10); within these structures vertical offsets of up to hundreds of metres in magnitude are observed. The boundaries of the pop-ups often have trends that coincide with one of the previously described older fault trends (Fig. 4), suggesting that these faults have been reactivated. In-between pop-ups and pop-downs, the vertical offsets along these faults are small and, as a result, the faults are hard to identify on vertical sections. The faults are often readily visible on time slices and horizon extractions from the coherency cubes (Fig. 5).

The Zechstein salt appears to have a strong effect on the structural styles of these faults: where salt is present, the effect on units overlying the Zechstein is mild at most, while offsets at the Base Zechstein level can be significant. The system appears to have been decoupled in these cases, with the Zechstein salt acting as the décollement. When the salt is absent or thin, younger units are affected as well.

These faults are also observed within the SG and Central Graben, but locating them is more difficult than on the ESP; units above thick Zechstein salt

are commonly not affected, meaning that the faults are limited to units below the salt, the base of which is at a significantly greater depth than on the ESP, resulting in poorer imaging of these units. Above salt windows, units younger than the Permian are affected by these faults as well.

Other fault trends

A number of subordinate fault trends have been identified in the study area. In block E12, faults with a NW–SE trend are observed. This fault trend is much more prominent further south: for instance, on the Cleaver Bank Platform and on the Groningen Platform, but seems not to be present north of E12. Above the Zechstein salt, a large number of faults associated with salt movement are present; most prominently, these consist of collapse graben on top of, and of radial faults surrounding, salt features.

Structural framework

Late Devonian–Early Carboniferous extension

Late Devonian–Early Carboniferous extension in the area was accommodated along N110°-trending faults. The newly available seismic data show that a low, the North Elbow Basin, was present north of the Elbow Spit Platform (ESP) (Fig. 1), which is in line with the identification of the North Dogger Basin in the adjacent UK sector (Milton-Worsell *et al.* 2010; Arsenikos *et al.* this volume, in press). The implications of the presence of such a low are major; first, it shows that the Mid North Sea High was not a high

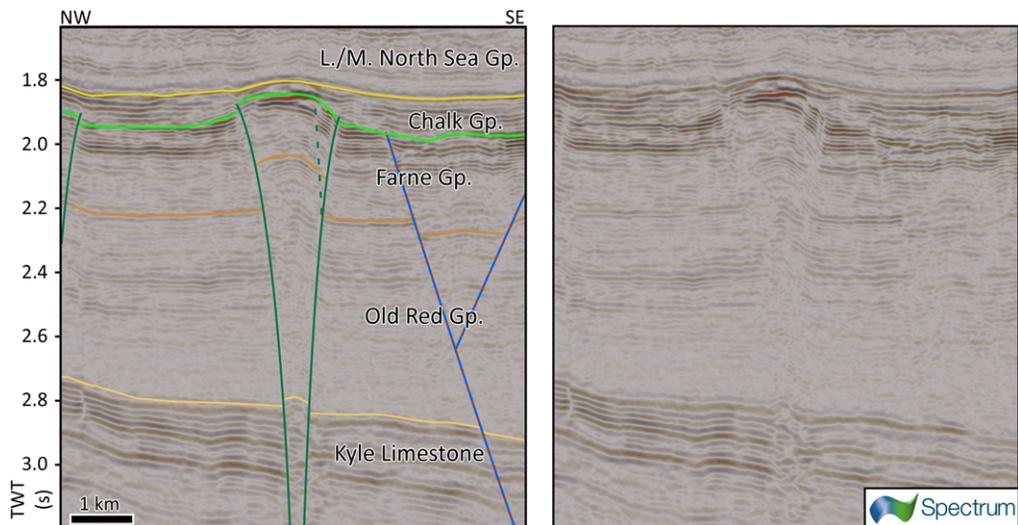


Fig. 10. Pop-up structure in the E2 and E3 blocks, which offsets units as young as the Late Cretaceous. The legend to the horizons is given in Figure 2. DEF 3D seismic data courtesy of Spectrum ASA.

during the Carboniferous but that the area consisted of an alternation of highs and lows. The Mid North Sea High area only became a long-lived high later on. It also leads to a reconsideration of the hydrocarbon potential of the newly identified low and surrounding areas (ter Borgh *et al.* this volume, in press).

Structurally, the picture that emerges is one of granite-cored highs, in line with a concept that was inferred previously in the UK onshore, and was extended to the UK offshore and northern Dutch offshore (Donato *et al.* 1983; Besly 1998). In summary, the granites strengthen the crust locally, and deformation is accommodated in the surrounding, weaker, regions, but not the high itself. On the ESP, biotite monzogranite has been encountered in well A17-01, which was dated at 410 ± 9 Ma (T. Pharaoh pers. comm.; cf. Geluk *et al.* 2007). It should be noted that only 31 m of strongly altered rocks were encountered in the lowermost part of the well; whether they represent the top part of a batholith or core complex, or merely a granitic intrusion, remains uncertain.

The presence of the North Elbow Basin is also reflected in the sedimentary record; the Upper Devonian and Lower Carboniferous are significantly thicker north (Fig. 7) and south (Fig. 6) of the ESP. A condensed Lower Carboniferous section on the ESP is in line with what was observed for the UK onshore Alston block (Kimbell *et al.* 1989), where Viséan deposits were found to increase in thickness from around 400 m above the block to 4000 m in the adjacent low. In that case, deposits on the high were limited to the Asbian and Brigantian (the top part of the Viséan), with older parts of the Viséan being present only in the adjacent low. Extension first created accommodation space in the hanging wall. Subsidence of the footwall was less profound, but sufficient during the later phases of extension to accommodate sedimentation.

The situation on the ESP is largely similar, but not completely. In contrast to the Alston block, where sedimentation occurred only during the latest part of the Viséan (Kimbell *et al.* 1989), all Viséan substages are represented on the ESP, as shown by wells E02-01 and E06-01. A significant part of the thickening that is evident in the North Elbow Basin is seen to occur in the deposits underneath the reflective package. The top of the reflective package is shown by the wells to be of Viséan age, implying that the transparent seismic facies below represents the Tournaisian and/or Upper Devonian and possibly the lower part of the Viséan. We therefore propose that the North Elbow Basin was in an 'overfilled' state, meaning that on average sediment influx into the area exceeded the amount of new accommodation space created by subsidence. This allowed part of the sediment that entered the area from the north (Collinson 2005) to bypass the low,

and be deposited on the ESP. The accommodation space on the platform was limited as well, and part of the sediment therefore bypassed the platform and was deposited in the low south of the platform. The sediment influx there was not high enough to balance the subsidence caused by faulting, leaving the basin south of the ESP in a 'starved' state.

A Devonian–Early Carboniferous proto-Central Graben?

The new, long-offset DEF seismic survey permits an improved reconstruction of fault activity prior to the Zechstein. The seismic data show that a high-contrast continuous Yoredale-type seismic facies also occurs east of the ESP, in the present-day SG area (Fig. 9: blocks F01, F04, F07 and E09). Although the exact depositional environment cannot be constrained based on the seismic facies alone, the facies is similar to the one observed on top of the ESP (Fig. 7) (ter Borgh *et al.* this volume, in press), where well control is available, and distinct from the inferred basinal section south of the ESP. This suggests strongly that in the Early Carboniferous the ESP extended further east than it does at present and that the SG had not formed. Whether shallow-marine to fluvial conditions prevailed as far east as the present-day DCG cannot be derived from the seismic data at present, as the quality of the imaging below the thick infill of the DCG does not permit this.

Although the imaging of the pre-Zechstein is poor below the DCG, the new findings from this study can be used to test the assumptions that were used in the past to propose activity of the DCG during the Devonian and Carboniferous (e.g. Ziegler 1990; de Jager 2007). Precursors to the DCG (the 'proto-Central Graben') have been proposed to have existed as early as the Devonian, based on the presence of the Middle Devonian seaway, as proposed by Ziegler (1990). The constraints that were available when this seaway was proposed were limited; marine Middle Devonian limestones were drilled in a number of UK wells, including well 38/03-1 (Fig. 1), while the Orcadian basin and Caledonian uplands to the NE and north were known to be continental. The palaeogeographical implication of these two observations was that a connection to the marine realm had to be found towards the south and/or east (Belgium, Germany). Continental Devonian deposits had been encountered in Dutch well A17-01 (Fig. 4) and German well Q-01 (Fig. 1), with the latter well containing (possibly reworked) marine fossils (Best *et al.* 1983). The seaway was therefore proposed to have been located in-between these wells, roughly corresponding to part of the later SG and DCG. This interpretation was perfectly plausible with the constraints available then.

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The results from the present study provide additional constraints and lead to a different interpretation; a seismic facies indicative of Devonian ('Kyle') limestones is observed below the ESP, in the area that was interpreted by Ziegler (1990) to be the continental area west of the seaway during the Middle Devonian. The Kyle seismic facies can be observed throughout the parts of the study area where the Devonian is sufficiently well imaged (Figs 3, 6, 7 & 9); Middle Devonian marine deposition affected a much larger part of the study area. Reflection seismic data show that the Kyle seismic facies is, indeed, absent near well A17-01, but appears a few kilometres SE of the well and thickens from thereon. The absence of limestones at the location of this well can be attributed to the fact that the well was drilled at the top of the Elbow Spit High which had already apparently formed a high during the Devonian.

As a consequence of the new findings, it is no longer necessary to interpret a narrow Middle Devonian seaway between wells Q-01 and A17-01; much larger parts of the study area were flooded. Without this seaway, there is no need, or proof, for a Devonian Central Graben either. In summary, significant extension occurred during the Devonian–Early Carboniferous, accommodated along N110°-trending faults.

A Late Carboniferous–Early Permian proto-Central Graben?

Now that it has been shown that it was unlikely that a proto-Central Graben was present during the Devonian–Early Carboniferous, the possibility of the presence of such a feature during the Late Carboniferous–Early Permian will be discussed. During this period, faults with a N040° trend were active in the area (Figs 8 & 9); activity post-dated the deposition of the Viséan–early Namurian Farne Group and predated the deposition of the Upper Rotliegend Group. This fault trend is observed throughout the study area, in places where the imaging of the pre-Rotliegend is sufficient. It has been described in other parts of the Dutch subsurface: for instance, in the Cleaver Bank Platform area, where the vertical offset has been described as 'minimal' (Oudmayer & de Jager 1993). This is also the case for most of the ESP, but elsewhere intra-Carboniferous offsets can be large, even in areas that are commonly considered to be part of a high; an example is the fault shown in Figure 8 that is located on the eastern flank of the ESP in block E06 which has a fault throw of around 1 km. Another example is found in the prerift sequence of the SG, where faults with similar large throws offset the Farne Group (Fig. 9); the combined throw of the Carboniferous units is a few kilometres. The fact that the faults significantly

offset the Carboniferous while offsets at the base of the Permian are commonly insignificant (in this case, most probably the base of the middle Permian-age Upper Rotliegend Group: Fig. 2) shows that significant deformation must have occurred during the Late Carboniferous–middle Permian (Fig. 9).

Effects of Carboniferous–Permian deformation on deposition. Late Carboniferous–Early Permian deformation helps to explain the preservation of progressively younger units below the BPU from west to east; on the ESP, Lower Carboniferous units subcrop the BPU (Fig. 3). Upper Carboniferous deposits, sometimes as young as Westphalian D and, possibly, even Stephanian, were encountered below the BPU east of the ESP in blocks B17, F04, F07, F10, and, possibly, E09 and E12. So far, subcrop maps commonly use north–south-trending faults to explain the presence of these relatively young Carboniferous deposits (van Adrichem Boogaert & Kouwe 1993–1997; Besly 1998; Mijnlief 2003; van Buggenum & den Hartog Jager 2007; Kombrink *et al.* 2010). The newly identified N040°-trending faults should be expected to also affect the subcrop pattern (Fig. 9).

A related issue is the variation in the thickness of the Rotliegend, which is thicker in the SG area than above the ESP (e.g. Geluk 2007). This thickening is sometimes cited as proof that activity along the SG and Central Graben started during the Permian. Figure 9 shows that there is a direct relationship between the thickness of the Westphalian and the Rotliegend: where the Westphalian is thick, so is the Rotliegend. We propose that three processes may have contributed to this change in thickness; first, the fact that extension was relatively large in the area where Westphalian deposits were preserved may have resulted in stronger post-rift thermal subsidence. Secondly, a thicker syndepositional package results in higher subsequent compaction, providing additional accommodation space. This may cause differential compaction between areas located over hanging walls and areas located above footwalls, resulting in gentle folds such as the one described in block E06. Thirdly, erosion may have had a stronger effect on the shale-rich deposits of the Westphalian Step Graben Formation than on the Lower Carboniferous deposits, which contain more competent lithologies, such as limestones and sandstones, analogous to the model proposed by Mijnlief & Geluk (2011).

In summary, significant extension occurred in an area that is now part of the southern SG, but extension was not accommodated along the north–south-trending faults that characterize the Mesozoic SG and DCG but by N040°-trending faults. Referring to the structures formed by the N040° faults as a proto-Central Graben or proto-Step Graben

can therefore be confusing, and we propose to call this structure the Urania Graben system instead. The implications for understanding deposition during the Late Carboniferous and Permian are great; faults with the offsets observed could have affected deposition significantly, and any exploration focusing on deposits of this age should take this into account.

Regional tectonic setting. The finding that significant graben, such as the Urania Graben, formed during the Late Carboniferous–Early Permian is somewhat surprising as this period is generally associated with wrench tectonics, not regional extension (Ziegler 1990; Geluk 2007). Efforts have been made to find strike-slip faults of this age in the study area, but none were found. The study area is not the first region where extension was observed during the Late Carboniferous–Early Permian, however. Near well 39/2- 4 (Fig. 4), just 12 km NW of the study area, Late Carboniferous–Early Permian extensional faulting was observed (Heeremans *et al.* 2004). In the German and Danish offshore, the southern segment of the Horn Graben also shows a NE–SW orientation and is thought to have been active during the Late Carboniferous–Early Permian, although stratigraphic control is poor here (Best *et al.* 1983; Vejbaek 1990; Abramovitz *et al.* 1998; Abramovitz & Thybo 1999). Significant extension also occurred further north, in the Oslo Graben area (Neumann *et al.* 2004). In addition to the structures mentioned, other examples exist in the vicinity, supporting the finding that extension affected a wide region; further south, on the Cleaver Bank Platform, normal displacement along NE–SW-trending faults was also observed, along with strike-slip displacement (Schroot & de Haan 2003). Strain partitioning may have caused the alternation between extension and wrenching; some areas, such as the study area, the Horn Graben and the Oslo Graben, could have been dominated by extension while other zones were dominated by wrenching. The fact that the underlying lithosphere is highly heterogeneous (Fig. 1) may have contributed to strain partitioning.

Late Carboniferous–Early Permian extension is generally considered to be genetically related to magmatism, as igneous rocks and normal faults formed during this period are often observed together (Heeremans *et al.* 2004; Neumann *et al.* 2004). This is also the case in the study area, where Lower Rotliegend igneous rocks are present (e.g. Geluk 2007; de Bruin *et al.* 2015). The causal relationship between the two phenomena is subject to debate: upwelling of hot mantle material may have resulted in magmatism and active rifting above the resulting thermal anomaly or, alternatively, extension resulting from far-field stresses may have caused the lithosphere to heat and melt (Neumann *et al.* 2004).

No major extension had been observed during the Late Carboniferous–Early Permian in the study area before. We explain this from the later Mesozoic rifting, which buried the Urania Graben below Triassic–Jurassic deposits, to depths at which seismic imaging was poor on vintage seismic data. The new seismic surveys used in this study provided the required imaging.

Formation of the Central Graben and the Step Graben (Mesozoic)

The present study improves the mapping of fault geometries of Mesozoic structures. An example is the SG in the A quadrant. On overview maps, the SG is commonly represented by a single NNW-trending fault (e.g. Kombrink *et al.* 2012). The findings from this study underline that the SG is made up of multiple horsts and graben, with a north–south trend (Fig. 4). The transition from the SG to the ESP is marked by a clear-cut change in trends; the north–south faults merge with faults with a N110° trend. We interpret this to reflect a reactivation of these older Carboniferous faults as oblique-slip faults. The boundary coincides roughly with the northern boundary fault that separated the ESP from the North Elbow Basin during the Early Carboniferous, and we propose that this was a rheological boundary; the ESP, which had already withstood Devonian–Early Carboniferous extension, resisted deformation again. The region north of it that had already suffered significant extension during the Early Carboniferous, was again extended during the Triassic–Jurassic.

Reactivation of the other Carboniferous fault trend (N040°) also occurred: for example, on what is now the eastern flank of the ESP, in block E09. Here, the base of the Upper Rotliegend Group was offset by a fault with an orientation parallel to the Urania Graben (Fig. 4).

Although salt tectonics are beyond the scope of this paper, we note that there is a clear relationship between the location of salt walls, pillows and diapirs, and basement faults; the former commonly occur above the latter (Fig. 3).

Late Jurassic–Early Cretaceous strain partitioning

Prominent strike-slip faults were found with a N070° trend. The faults have rather large horizontal offsets, of the order of hundreds of metres to over 1 km where the sense of shear is dextral (Figs 4 & 5). Individual fault zones can be continued over as much as 90 km. On the ESP, where the quality of the seismic imaging is high, the faults are regularly spaced, commonly around 5 km, although outliers exist. In some cases, the faults anastomose and form a fault zone. In

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other cases, the spacing can be as high as 15 km. The faults cause significant offset up to the Early Cretaceous, and minor offsets of units as young as the Paleogene; the former is interpreted to represent the main phase of activity of these faults, and the latter to be a reactivation during Late Cretaceous–Paleogene inversion.

Deformation along these faults was strongly influenced by the presence of Zechstein salt, which, where present, acted as a décollement, meaning that the units above and below the salt were deformed in a different manner. Above the salt, deformation is commonly mild because the salt caused deformation to be distributed over a wide area and, as a result, commonly no faults with significant offsets are visible on seismic data. Below the salt, however, deformation is accommodated by a smaller number of faults, causing clear offset along these faults. Where the salt is absent or thin, units younger than the Zechstein are also deformed. In these cases, flower structures, forming both pop-ups and pop-downs, are commonly present, as faults extended up to the surface. Pop-ups and pop-downs often result from the local reactivation of older fault trends; reactivation of the N110° trend predominantly produces pop-ups, while reactivation of the N040° trend produces pop-downs.

The fact that decoupling in many cases limits offsets to pre-Zechstein units can easily confuse seismic interpreters. As a result, activity along the N070°-trending faults can be erroneously interpreted to have occurred during the Permian: for instance, by linking them to Early Permian wrenching. Activity during this period cannot be ruled out, but supporting evidence is lacking.

Faults with this trend went unrecognized previously in the northern Dutch offshore as a result of three factors: first, strike-slip faults are generally harder to spot on seismic data than normal or reverse faults because vertical offsets occur only locally. Secondly, the fact that deformation during this time was strongly affected by decoupling along the Zechstein salt means that, in many cases, deformation is visible only below the Zechstein salt. Thirdly, the imaging of subsalt units was poor on vintage seismic data. Long-offset seismic surveys, such as NSR and DEF, provide the required imaging below the salt. A combination of the preceding factors mean that identifying such faults in studies carried out at the scale of individual hydrocarbon fields or blocks is particularly challenging.

We propose that these strike-slip faults formed as a result of strain partitioning. North of the study area, in the Danish Central Graben, extension was primarily accommodated along north–south-trending faults up to the Kimmeridgian (Late Jurassic), and along NW–SE-trending faults during the Kimmeridgian, Volgian (Late Jurassic) and Early Cretaceous (e.g.

Møller & Rasmussen 2003). In the DCG, NNW–SSE (c. N155°)-trending Jurassic faults are rare. Similar net strain to the Danish Central Graben could have occurred in the DCG, however, if strain was partitioned with a roughly east–west extension along N360°-trending faults and dextral slip along N070°-trending faults. Transfer faults have previously been proposed as being associated with extension along the Central Graben in the Central North Sea (Fraser *et al.* 2003; Zanella *et al.* 2003) and in the German and Danish parts of the Central Graben (Cartwright 1989; Sundsbø & Magsen 1993; Wride 1995: the so-called ‘transverse zones’).

The recognition of this fault trend could be relevant for estimating the reservoir potential of the Jurassic in the study area; deposition at this time was strongly affected by fault activity (Barnes & Hodgkinson 1993; Bartholomew *et al.* 1993; Sears *et al.* 1993; Wride 1995; Fraser *et al.* 2003; Wonham *et al.* 2014); strike-slip faulting may have contributed to localized uplift and erosion, both as a result of forming pop-ups and by activating salt movement, and may thus have controlled sediment pathways between the highs and the graben.

Inversion events

Compared to the Cleaver Bank Platform area located south of the study area, inversion associated with both the Variscan Orogeny and the Late Cretaceous–Paleogene inversion events is less profound. The effects of the Variscan inversion cannot be identified unequivocally; a gentle folding of the Lower Carboniferous on the ESP could be related to the inversion, but can also be explained by Early Carboniferous extension.

Late Cretaceous and Paleogene inversion in the study area caused activation of salt movement, long-wavelength regional folding and local reactivation of normal faults (van Wijhe 1987; de Jager 2003). A possible example of fault reactivation is the eastern bounding fault of the DCG, where uplift of the Base Chalk within the DCG relative to the area east of the DCG suggests that this fault was reactivated as a reverse fault (van der Molen *et al.* 2005). Unfortunately, imaging of the fault itself is poor as it is overlain by a salt wall, making it difficult to establish what part of the offset of the Base of the Chalk is caused directly by fault movement and what part by salt movement.

Some indications of reactivation can also be observed on the N070°-trending strike-slip faults, but the offset is much smaller than during the Jurassic and Early Cretaceous. It is therefore hard to constrain whether the faults were reactivated at all and, if so, whether they were reactivated as thrusts or as strike-slip faults. The latter seems most likely, considering the nearly vertical dip of the faults. In this

case, sinistral displacement would be expected based on the regional stress field. No sinistral offset was observed on the N070° faults in the study area, but this is to be expected; pre-Late Cretaceous offset along these faults is relatively large (hundreds of metres) and, as long as the offset due to Late Cretaceous–Paleogene inversion is smaller, the net offset will still be dextral.

A notable difference between the study area and the rest of the Dutch subsurface is the paucity of NW–SE-trending faults. These faults are thought to have been active during Variscan inversion and have been reactivated many times since, most recently during the Late Cretaceous–Paleogene inversion (e.g. Frikken 1999). In the study area, they have not been observed north of block E12, which coincides with a major tectonic boundary (Fig. 4): to the north, the lithosphere is thought to consist of remnants of the Caledonian accretionary complex, while the remainder of the Dutch subsurface forms part of the Avalonia microplate (Smit *et al.* 2016) (Fig. 1). We suggest that the contrast in structural style results from this contrast in lithospheric structure.

Hydrocarbon potential

The new structural framework sheds new light on the hydrocarbon potential of the study area. An important factor that has so far discouraged exploration in the northern Dutch offshore is the perceived absence of source rock. Significant amounts of Viséan Scremerston (Lower Carboniferous) coals have been described in the Lower Carboniferous in two nearby wells: 39/07- 1 and A09-01 (Fig. 4) (ter Borgh *et al.* this volume, in press). The age-equivalent interval has not been penetrated by wells in the Dutch A quadrant, and from vintage seismic data it was uncertain whether these deposits were present here. The identification of the North Elbow Basin makes it plausible that the coals have been preserved here (ter Borgh *et al.* this volume, in press).

The structural framework can also be used for assessing reservoir development, source-rock maturation, trap formation and hydrocarbon preservation. An example of the relevance of the N360° trend for trap formation is shown in Figure 4; in the A quadrant, the alternation of horsts and graben creates potential closures. The likely seal for such closures would be the Permian Silverpit Formation and Zechstein salt. Faults with a N040° trend are known to cause reservoir compartmentalization in the Cleaver Bank Platform area (Oudmayer & de Jager 1993; van Hulten 2010) and may also seal on geological timescales. The N110° and N040° trends have the potential for creating intra-Carboniferous closures. Faults with a N070° trend may have controlled deposition

during the Jurassic and Early Cretaceous, and pop-ups formed along this trend may form traps when a seal is present above.

Conclusions

Recently acquired 3D and 2D seismic data allow for a much more detailed reconstruction of fault patterns and fault activity than was possible previously. Extension during the Late Devonian–Early Carboniferous was accommodated along N110°-trending normal faults. The new findings show that an alternation of highs and lows was present in the study area, similar in setting to the UK onshore. The Elbow Spit Platform (ESP) was already a high during this period, and earlier findings that it was bounded on its southern side by a major normal fault are confirmed. In contrast to previous findings, however, a significant low was found to be present north of the present-day ESP: the North Elbow Basin, which we propose is the continuation of the North Dogger Basin in the adjacent UK sector. This has major implications for source-rock and reservoir development, and shows that part of the present-day Mid North Sea High was, in fact, a basin during the Late Devonian–Early Carboniferous.

In most of the A blocks, the North Elbow Basin underlies the SG, which is a younger geological feature. In the easternmost part of the A quadrant, it lies hidden within what is commonly considered to be the extension of the Mid North Sea High. This shows that structural elements as they are present now are, in many cases, not representative of the Paleozoic structuration.

The SG and DCG have previously been proposed to have originated in the Devonian or Early Carboniferous. No indication for activity of these north-south-trending structures during this period was found. Nevertheless, significant extension did occur during the Late Carboniferous and/or Early Permian. The extension was accommodated by the Urania Graben system, which consists of faults with a NE–SW trend, at a 40° angle to the main trend of the DCG and SG. The offset and timing of activity of these faults is consistent with Late Carboniferous–Early Permian normal faulting described elsewhere in Europe.

Although activity of the Urania Graben seems to have predated the deposition of the Upper Rotliegend Group, it is likely that residual topography, post-rift subsidence and compaction still affected deposition and accommodation space. The ESP and Elbow Spit High may have formed a local sediment source, and clastic sediments with reservoir potential similar to the ones found in the Cygnus Field may well be present in the Rotliegend on and off the flanks of the Elbow Spit Platform.

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The SG and DCG formed during the Triassic, Jurassic and Early Cretaceous. The present study has significantly improved the understanding of the geometries of these features. Improved imaging of the pre-salt shows that salt diapirs are often located above normal faults. Extension was associated with N070°-trending transfer faults that are clearly visible below Zechstein salt and in places where the Zechstein salt is absent. Further research on the interaction between these faults and the depositional systems above the salt is recommended.

The structural framework described in this study marks a significant improvement in the understanding of the geological development of the Mid North Sea area from the Devonian to the present. The framework provides a firm basis for assessing the hydrocarbon potential of the area.

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