Hydrocarbon potential of the Visean and Namurian in the northern Dutch offshore

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Abstract: Following the play-opening successes of the Breagh and Pegasus gas fields, we evaluated the potential of the Visean and Namurian (Carboniferous) petroleum plays in the northern Dutch offshore. This evaluation incorporated seismic and well data from the Dutch, British and German North Sea sectors. The abundance and thickness of reservoir-quality Visean–Namurian sandstones was found to increase from Breagh towards the NE. Visean–Namurian coals and shales are considered promising source rocks to charge these reservoirs in the Dutch Central Graben (DCG) and Step Graben (SG). The presence of a mature Paleozoic source rock in the SG and DCG is supported by hydrocarbon shows and vitrinite reflectance data. In the southern E and F blocks, charge may also occur laterally from Upper Carboniferous Westphalian coals. A regional post-well analysis showed that the Visean and Namurian plays are virtually untested in the Dutch northern offshore. Two tests were positive but had high N₂ contents, one was negative, while 10 wells were drilled off-structure and are therefore considered invalid tests of this play. Hence, it is concluded that the Visean and Namurian in the northern Dutch offshore have significant hydrocarbon potential.

Production of hydrocarbons from Carboniferous reservoirs in the Southern North Sea comes primarily from the Westphalian. The discovery and development of gas fields with reservoirs in the pre-Westphalian, such as the Visean Breagh Field (Fig. 1) (McPhee et al. 2008) and the Namurian Pegasus Field, triggered new interest in the hydrocarbon potential of the Visean and Namurian in the Southern North Sea and Mid North Sea High area. In this study, a regional analysis of the hydrocarbon potential of this stratigraphic interval is presented focusing on the Dutch offshore, while incorporating data from the UK and German offshore.

To assess the viability of the Visean and Namurian plays, well results were analysed initially. Next, well and seismic data were used to constrain depositional trends and palaeogeography, and, based on this analysis, the distribution of potential reservoirs was established. To further quantify the reservoir potential, core-plug measurements are used. To establish the chances of hydrocarbon charge and migration, shows of hydrocarbons in deep part of the basin (Ziegler 1990). Brabant Massif forms the southern margin of the  

Geological setting

During the Early Carboniferous, the study area was located on the southern margin of the continent Laurussia, which had formed during the Ordovician–Silurian collision of three older continents during the Caledonian Orogeny: Avalonia, Baltica and Laurentia (e.g. Ziegler 1990; Smit et al. 2016). During the Early Carboniferous Laurussia was converging with Gondwana, located to the south of Laurussia, which resulted in significant extension on Laurussia’s southern margin due to either back-arc extension (e.g. Leeder 1988), continental escape (e.g. Maynard et al. 1997) or a combination of both (e.g. Coward 1993). This caused a roughly east–west-oriented basin to form between present-day Ireland and Poland.

Sediment influx into the basin occurred from the Caledonides in the north (e.g. Collinson 2005). In the northern part of the basin, fluvial and paralic conditions prevailed, while greater water depths developed in the central part of the basin. The study area is located at the boundary between these two domains (Smit et al. 2016). The London–Brabant Massif forms the southern margin of the deep part of the basin (Ziegler 1990).

Extension was distributed over a wide area, and resulted in a large-scale alternation of highs and lows, with widths of the order of tens of kilometres each. The highs in many cases have a core that
consists of a Caledonian granite (Donato et al. 1983). The Elbow Spit Platform (ESP), located in the northern Dutch offshore (Figs 1 & 2), is an example of such a high. At its northern side, it is bounded by the North Elbow Basin, where subsidence rates were higher than on the ESP, but not high enough for significant water depths to develop as sedimentation rates exceeded subsidence (Figs 2 & 3). As a result, sedimentation extended onto the ESP. Sedimentation also occurred south of the ESP, but sediment influx during the Visean was insufficient to fill this part of the basin completely (ter Borgh et al. this volume, in press) and significant water depths developed there, except on intra-basinal highs where carbonate platforms formed (Kombrink et al. 2010b; van Hulten 2012).

Continental collision of Laurussia and Gondwana finally occurred during the late Visean–Westphalian, leading to the Variscan Orogeny. Extension ceased and inversion of the basin occurred, causing folding and erosion of the basin fill (Ziegler 1990). Late Carboniferous–Early Permian volcanism was accompanied by additional uplift and erosion. Inversion and thermal uplift resulted in the formation of the Base Permian Unconformity (BPU). During the Permian, sedimentation resumed following a 40–60 myr hiatus with the deposition of Upper Rotliegend reservoirs, and Silverpit and Zechstein Formation seals (Geluk 2007). The subcrop at the BPU in the study area varies from Lower Carboniferous to Lower Permian.

During the Mesozoic, the Central Graben system formed, leading to the formation of the Dutch Central Graben (DCG) and the Step Graben (SG) in the study area (Fig. 1). Extension along these structures has been proposed to have started as early as the Devonian, but recent data suggest otherwise (ter Borgh et al. this volume, in press). Extension led to regional subsidence and progressive burial of the Carboniferous, but subsidence was interrupted during the Middle Jurassic, when uplift centred at the triple junction of the three rift segments of the Central Graben system led to the formation of the Central North Sea Rift Dome (Ziegler 1990; Underhill & Partington 1993). Extension and subsidence subsequently resumed. Extension ceased in the Early Cretaceous, but post-rift subsidence allowed for the deposition of up to 2 km of Cenozoic deposits.

As a result of the post-Carboniferous development of the area, the present-day burial depth of Carboniferous deposits varies from about 2.2 km on the crest of the ESP to over 9 km in the DCG. As a result, reservoir quality may be expected to range from very good to very poor, and source-rock maturity from immature to over mature.
Fig. 2. Structural elements during the Visean. UK sector after Milton-Worsell et al. (2010), Arsenikos et al. (2015) and Kearsey et al. (2015). AFR, Auk-Flora Ridge; DH, Dogger High; ESP, Elbow Spit Platform; FG, Farne Granite; NDB, North Dogger Basin; NEB, North Elbow Basin.

Fig. 3. Diagram illustrating the structural geology and play elements of the Visean and Namurian in the Mid North Sea area. The Elbow Spit Platform is an example of a high (C), while the North Elbow Low is an example of an overfilled basin (D). South of the study area, carbonate platforms are present on intra-basinal highs such as the Groningen High (A) (Kombrink et al. 2010b; van Hulten 2012). Between the highs, basins were present where subsidence exceeded sedimentation (B).
**Stratigraphical framework**

This publication focuses on the two Carboniferous stages predating the Westphalian: the Visean and the Namurian (Fig. 4). The stratigraphic subdivision of the Carboniferous commonly used in Western Europe is distinct from the international system (Kombrink et al. 2010a) (Fig. 4). The subdivision of the Carboniferous in The Netherlands has historically been based on lithostratigraphy, not chronostratigraphy (Kombrink et al. 2010a). This has a significant impact as many formation boundaries

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**Fig. 4.** Stratigraphic chart for the Visean and Namurian of the Mid North Sea area. Well penetrations are shown. Colours in the substage column refer to the maps in Figure 5.
within the Carboniferous are diachronous; the base of the Yoredale Formation, for instance, is known in northern England to range from the early Brigantian to the Pendleian (Waters et al. 2007). To predict where reservoir rocks and source rocks were deposited, it is necessary to reconstruct the depositional system and, hence, to know which sections are age equivalent. Where available, biostratigraphic constraints have therefore been used to correlate between wells, using the results from the study by Schroot et al. (2006) as a starting point. The resolution of biostratigraphy during this time interval is limited, however, and significant uncertainties remain.

Data and methods

Seismic and well data

2D and 3D seismic data from various vintages were used. The DEF survey, a 7950 km² 3D multiclient survey, covers the Dutch D quadrant and the southern E and F quadrants (Fig. 1). The northern E and F, and the A and B quadrants are partly covered by publicly available 3D surveys acquired in the period between 1994 and 2006. 2D data were used in places where no 3D data were available: 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 the NW–SE and NE–SW directions, with a spacing between lines of 5.3 km. The survey was acquired between 2005 and 2010, and the Dutch part of the survey has since become public. Seismic interpretation was carried out in the time domain and the non-SEGY seismic convention was used.

For the Dutch part of the area, data from over 60 wells acquired from NLOG (http://www.nlog.nl/) were used for seismic interpretation, 14 of which encountered the Visean and/or Namurian (Fig. 1). In the UK sector, data from eight public wells that encountered these stages were used (Fig. 1). Data availability from the German sector was limited to a well that was formerly located in the Dutch sector (B10-01) and a well published in the Southern Permian Basin atlas (A-09-01: Kombrink et al. 2010a). The wells were tied to seismic data using checkshots.

Analysis of well results

To assess the hydrocarbon potential of the Visean and Namurian, the results from existing wells in the northern Dutch offshore were evaluated with the aim of establishing whether a particular well can be considered a valid test of the Visean and Namurian plays, and, if so, whether the result was positive or negative. This evaluation consisted of four steps:

1. The presently available seismic data were used to establish whether a valid trap is present at the well location. If it is clear from the seismic data that no trap is present, the well is considered an invalid test. This commonly occurs when a well targeted a closure at another level; if the well targeted a closure at the Chalk level, for instance, no structure needs to be present within the Visean. Another common reason for an invalid test due to the absence of a valid trap is that old 2D data were used.

2. Establish the presence of reservoir from well data. This was considered positive if enough reservoir rock is present within the stratigraphic interval so that if gas bearing, the well would have been a technical success.

3. Evaluate the presence of a seal.

4. Finally, the presence of hydrocarbons (‘charge’) was evaluated. If enough hydrocarbons are present to consider the well a technical success, the well was considered a valid positive test.

If the test is considered valid (see step 1) and either reservoir, seal or charge is absent or ineffective, the well was considered a valid negative test.

Lithological classification

To assess the source-rock and reservoir potential of the Visean and Namurian, a lithological classification was performed for all selected wells based on wireline logs, including the gamma-ray and sonic logs. Cut-off values to constrain lithological classes were defined empirically by comparing log response, mud logs, and previous interpretations by Collinson Jones Consulting (1997) and Schroot et al. (2006). An overview of the classes and cut-off values used is given in Table 1. The lithological classification was checked against cuttings descriptions if available.

Porosity and permeability measurements

To assess the reservoir potential, an analysis of porosity and permeability data was carried out. For Dutch wells, core-plug measurements were acquired from reports and data available on http://www.nlog.nl/. For the UK wells, data from publicly available well reports were used. To each measurement, the result from the lithological classification was added in order to establish the reservoir properties for each lithological class.

Results

Well results

As the number of wells penetrating the Visean and Namurian in the northern Dutch offshore is low, only two play types are distinguished. In principle,
it would be possible to make a more detailed classification but this would not yield statistically meaningful results:

- The Visean clastics play: reservoirs in the Elleboog Formation or Yoredale Formation, sourced from Visean coals, Visean–Namurian basinal shales, Westphalian coals or Zechstein Group source rocks, and trapped below the Permian Silverpit Formation or Zechstein Group deposits.

- The Namurian clastics play: source and seal as above, but with a Namurian (post-Yoredale) reservoir.

Visean play. Five out of six wells penetrating the Visean in the study area are considered invalid tests of the Visean play as they did not drill valid structures, results from the sixth well are inconclusive. This is not unexpected, as none of these wells targeted the Visean. In addition to this, most wells were drilled in a period when 3D seismic data were not widely available; the most recent well that encountered the Visean was drilled in 1990 (E02-02), the other wells were drilled between 1972 and 1983. In most cases the presently available seismic data show that no structure is present at the well location, whereas vintage 2D seismic data may have suggested that a closure was present.

All wells contained at least some layers with reservoir potential (Table 2). Rocks with sealing potential were present in most cases. In four wells, sealing was provided by relatively low-risk Silverpit shales. In one case, an intra-Carboniferous seal may have been present but as a trap was absent in this case, it is unclear whether the seal was effective. In well E02-01, the Carboniferous was overlain by Chalk deposits. The Chalk is considered a riskier seal than the Silverpit and no detailed analysis was carried out to assess its sealing potential here. Minor or doubtful shows were found in two wells. The absence of shows in the other wells should not be used to conclude that charge was absent; as traps were absent, no trapping of hydrocarbons would be expected to occur in the first place.

Namurian play. Eight wells in the study area encountered the Namurian (Table 3). Similar to the findings for the Visean, six of these wells are considered invalid tests as presently available seismic data show that the wells did not drill a valid structure. In two cases, accumulations were found: the Tulp and Lelie fields (Fig. 2), which are likely to have been charged from downthrown Westphalian Coal Measures and possibly the Namurian. As all play elements worked and gas was tested at economic flow rates, these two wells are considered technical successes and valid tests. It should be noted, however, that significant amounts of N₂ were encountered in both wells, rendering these discoveries uneconomic.

Further north, where no Westphalian Coal Measures are expected, well A15-01 (Fig. 1) drilled only a thin section of Namurian rocks but the overlying Zechstein carbonates were found to be gas bearing, with oil shows. The interval was tested and a flare was lit, but production rates were low. The test was adversely affected by a poor cement job, which makes it likely that communication existed between the tested carbonates and previously tested...
water-bearing intervals. Nitrogen was present, but not in problematic quantities (16%). Although it remains unclear what source the gas was derived from, the test proves that a mature Paleozoic source rock is present. Candidates are the Visean and Namurian (Elleboog, Klaverbank and Yoredale formations), the Zechstein itself, and the Devonian.

Reservoir: porosity, permeability and net-to-gross ratios

Visean. To constrain the distribution of reservoir rocks, the results from the lithological classification were summed for each stratigraphic interval, and the results were displayed in map view (Fig. 5). The results show in broad terms that most formations become more sand-rich towards the north. The characteristics of core plugs taken from intervals classified as sandstone or shaly sandstone are shown in Figure 6, confirming the presence of reservoir quality sandstones within the Visean and Namurian; based on this result, intervals classified as sandstone are considered net reservoir. Intervals classified as shaly sandstone can be considered upside. Based on the data, no clear lower limit for the reservoir potential can be given; the deepest well with significant amounts of data, E12-01, shows decent porosities (average 12.7%, \(\sigma=3.0\)) at 3.8 km. The reservoir potential of the Visean is probably higher than the core-plug measurements suggest; channel-fill sandstones are commonly considered the best Visean reservoirs and, although indications for such sandstones are present in all wells penetrating the Farne Group in the northern Dutch offshore, they have only been cored in well E02-01. Porosities as high as 25% (average 12.9%, \(\sigma=4.1\)) and permeabilities as high as 269 mD (average 42.7 mD) were measured here (Fig. 6).

Net-to-gross ratios vary per interval (Fig. 5). In general, proximal deposits have greater amounts of sand, meaning that net-to-gross ratios increase towards the north/NE. However, reservoir rocks may occur in all parts of the system. Figure 5 shows a map with lithological characteristics for the first 100 m below the BPU, giving an indication of net-to-gross ratios for closures at the Base Permian level.

Namurian. Sandstone intervals with a sharp base and top, and little internal variation on log data (‘blocky’ sandstones) are found throughout the Namurian Klaverbank Formation in the study area. These sandstones resemble producing Westphalian Klaverbank Formation reservoirs from the D and southern E quadrants (Fig. 4); the depositional environments are similar but, as progradation progressed from north to south, they differ in age. The net-to-gross ratio of this stratigraphic interval is generally high (c. 45%: Fig. 5a); not just in the E12 quadrant but also further north.

Visean–Namurian source rocks

In the British and German offshore. Visean and Namurian coals are predominantly found in the Scemerston Formation. The Dutch equivalent, the Elleboog Formation, has been encountered in three wells in The Netherlands: E02-01, E02-02 and E06-01. Coal streaks recognizable on logs have been found in well E02-01, and thin coal seams below the resolution of log data have been identified in cores and mud logs from wells E06-01 and E02-01. Although the number of wells is limited, the coal content of the Scemerston Formation appears to increase northwards (Fig. 5c): well 39/07-1, located less than 1 km across the median line from the A quadrant, contains 23 m of coal (Figs 7 & 8), but this should be considered a minimum thickness as the base of the Scemerston Formation was not reached in this well. German well A-09-01, located 13 km across the border, captures a complete Scemerston section (Kombrink et al. 2010a) (Figs 7 & 9); proportionally, it has a similar amount of coal (14%) but,
Fig. 5. (a)–(d) Palaeogeographical charts and lithological statistics, see also Figure 4. (e) Lithological statistics for the first 100 m below the Base Permian Unconformity (BPU), showing that the chances of encountering sandstone in the Visean or Namurian below the Silverpit Formation and Zechstein Group seals are good. Note that not all wells represent full penetrations of a given interval; see Figures 7–9. UK palaeogeography after Kearsey et al. (2015; this volume, in review); UK structures after Arsenikos et al. (2015). ESP, Elbow Spit Platform; NDB, North Dogger Basin; NEB, North Elbow Basin.
because the formation is completely penetrated, the total amount of coal encountered is greater (30 m).

In well 39/07-1, the presence of coals is accompanied by a typically high-contrast seismic facies. This facies can be mapped a small distance into the Dutch offshore, but cannot be continued across a WNW–ESE-trending normal fault south of the well location that downthrows the Visean (Fig. 2). It may be the case that deposition and preservation of the coals is fault-controlled, but the downthrown fault block does not appear to be imaged on the seismic data covering this area. Further west, indications for the presence of coals are given by NSR line 32294, which has a better imaging quality at these depths (Fig. 10); on the ESP, the seismic facies shows only moderate contrast, but further north and up to the German border the contrast increases (Fig. 10). In the continuation of the line, 13 km further to the NE, the coal-bearing well A-09-01 is located (Fig. 1). Altogether, these observations are compatible with the presence of coals in the region north of the ESP, although the higher contrast may also result from lithologies other than coal.

Coals have also been encountered in the Yoredale Formation: 4 m in 39/07-1, 3 m in well A-09-01, 4 m in well A16-01, 0.3 m in A14-01 and 2.7 m in E06-01. The same is true for the Namurian: wells 39/07-1, B17-04, E09-01, E10-03, E12-02, E12-03 and E12-04-S2 all contain between 1 and 3 m of coal. The estimates given are conservative as they only take into account coal seams that are thick enough to be distinguishable on the sonic log.

**Maturity measurements**

The available well data are of limited use for assessing maturity as it primarily covers the present-day highs (Fig. 1), and not the lows where source rocks have been buried to greater depths and hydrocarbon kitchens are expected. The base of the Carboniferous is located at approximately 2000 m true vertical depth (TVD) in well E02-01 and at 2200 m in well E06-01, while the Carboniferous is locally buried up to depths of more than 5500 m in the SG, and to even greater depths in the DCG.
The only well that can be considered representative of the present-day lows (i.e. the SG and DCG) in terms of maturity is well B17-04, where mature coals were found. Palynological dating suggests a Namurian (Pendleian–Arnsbergian) age (Cutler & Darlington 1990), and vitrinite reflectance data show that the coals have reached the peak gas window (1.4%Ro).

Maturity data from the present-day highs show that source-rock-bearing intervals are presently in the late oil–early gas window. In well A14-01, a value of c. 0.74%Ro was measured at around 2850 m and well 39/07-1 shows a value of c. 0.8%Ro at 3500 m. In well 38/16-1, the vitrinite reflectance increases from 0.75 to 1.00%Ro over an interval of 200 m. A similar gradient is apparent in well 41/24a-2. The measurements from well E06-01 do not display any relationship with depth; vitrinite reflectances vary around 1.0%Ro. This may result from the (local) occurrence of igneous intrusions near this well, which could have led to a local increase in temperature.

Geological evolution and palaeogeography

During the Early Carboniferous, the northern Dutch offshore experienced siliciclastic influx from the north. The region was subject to lithosphere-scale extension, leading to an alternation of highs and lows (Fig. 3). A major facies boundary traversed the E and F quadrants, roughly trending WNW–ESE (Figs 2 & 5). To the north of the boundary, paralic conditions prevailed and to the south of it predominantly deeper-water conditions.

The facies boundary was structurally controlled and coincided with a major normal fault. North of the fault, a long-lived high was present: the ESP (Figs 2 & 5). The facies boundary represents the area where sediment influx and subsidence were
roughly in balance. North of the boundary, sediment influx was higher than subsidence, leading to overfilled basins; south of the boundary, subsidence was higher than sediment influx, leading to starved basins (Fig. 3). Seismic data, however, indicate that the Lower Carboniferous and Devonian also thicken north of the ESP, and this is interpreted to result from the presence of the North Elbow Low (Figs 3 & 10).

Although the boundary between deep water and shallow water is thought to have existed throughout the Visean (Fig. 5), fluctuations of relative sea level caused the overfilled area to drown episodically, establishing shallow-water marine conditions, followed by an infilling of the accommodation space by fluvial processes. On the ESP, this led to a cyclic alternation of shallow-marine carbonates and fluviodeltaic clastic sediments, including back-swamp deposits and coals: the so-called Yoredale cycles (e.g. Waters et al. 2007). The Yoredale Formation is best known for this type of cyclicity but similar cycles can be observed in the older formations. These short timescale sea-level fluctuations were accompanied by steady regional tectonic subsidence, allowing for the preservation of sediments.

Towards the north, depositional environments were progressively more proximal, as can be inferred from a decrease in the amount of carbonate, and an increase in clastics and coals (Fig. 5). Carbonate beds are present at least as far north as well

Fig. 8. Well correlation panel, Visean, UK offshore. The location is shown in Figure 5.
39/07-1, however, suggesting that the entire study area experienced episodic drowning. An alternative explanation for the presence of these beds that cannot be ruled out at present is that they formed in a lacustrine setting.

**Courceyan–Chadian: Tayport and Cementstone Formation**

Courceyan–Chadian (Tournaisian–lowermost Viséan: Fig. 4) deposits have been encountered in the Dutch northern offshore in wells E06-01, E02-01 and, possibly, in well E02-02, for which no biostratigraphic constraints are available. The oldest deposits found are fluvial and playa lake deposits from the Tayport Formation (Old Red Group); the majority of the Old Red Group, including the lower part of this formation, is Devonian in age, but sedimentation continued into the Tournaisian (Early Carboniferous) (Cameron 1993; van Adrichem Booigaert & Kouwe 1993–97) (Fig. 4).

The Tayport Formation is covered conformably by the sediments of the Cementstone Formation, which is characterized by metre-scale alternations of carbonates and fine clastic sediments, representative of deposition in an alluvial-plain to marginal-marine flat environment that was affected by periodic desiccation and fluctuations in salinity, in a semi-arid climate (e.g. Waters et al. 2007). In the UK onshore, the occurrence of cementstone facies is commonly limited to troughs associated with (half-) graben; on the highs, the laterally equivalent cornstone facies is developed (Waters et al. 2007). As the Tayport Formation can be considered to have been developed in the cornstone facies (Waters et al. 2007), it cannot be ruled out that the Tayport Formation and Cementstone Formation are laterally equivalent with the boundary between the two formations being diachronous.
Fig. 10. Seismic section across the North Elbow Basin. The Visean Elleboog Formation (see Fig. 4) has a high-contrast seismic facies that is likely to have been caused by the presence of coals. The location is shown in Figure 1. Public seismic line NSR32294. TWT, two-way travel time.
Owing to the limited well penetrations in the Dutch offshore, little is known about the direction of sediment transport but it seems likely that the sediment source area was located in the north, as has been inferred for the rest of the Visean. It is likely that local palaeocurrents were affected by tectonics, aligning to the axes of (half)graben. As only very limited well data are available for this stratigraphic interval in the Dutch sector (Fig. 7), little is known about the basin structure during this period. Local highs may have existed on which no deposition occurred or, in the case of sufficient sediment influx and accommodation space, fluvial and/or playa lake deposits may have been deposited. A transition to deeper-marine conditions further south and a gradual transition to more proximal facies to the north may be inferred.

**Arundian–Holkerian: lower part of the Elleboog Formation**

During the Arundian–Holkerian, deposition occurred in a fluvial to paralic setting; rivers deposited thick stacked channel fills, whilst shales and carbonates were being deposited in areas experiencing a marine influence (Cameron 1993; van Adrichem Boogaert & Kouwe 1993–97).

We interpret the thick sand bodies at the base of the Elleboog Formation in wells E02-01 and E02-02 as representing a more distal equivalent of the more massive sandstones of the Fell Formation of the UK offshore (Cameron 1993). The north–south proximal–distal trend is further illustrated by sediments encountered in well E06-01, which were deposited close to the basin edge (Fig. 5d), where carbonate beds appear, alternated with shales and blocky sandstones. This alternation is interpreted to be similar to the cyclically observed in the Asbian–Pendleian Yoredale Formation. It is hard to place this well in the standard lithostratigraphic nomenclature (van Adrichem Boogaert & Kouwe 1993–97); in The Netherlands, it is commonly placed in the Elleboog Formation, but the presence of carbonate beds is at odds with the definition of this formation. This is due to its position close to the platform edge; the current lithostratigraphic framework works better for deposits in a more proximal setting.

**Asbian: upper part of the Elleboog Formation**

Asbian deposits on the ESP are generally characterized by an alternation of sandstone, shale and carbonate, interpreted to have been deposited in a paralic setting, and more shale and coal-rich deposits in back-swamp areas. They form the upper part of the Elleboog Formation which, as mentioned earlier, is the Dutch equivalent of the UK Scremerston Formation. Similar to the preceding period, the well-derived facies show a transition from proximal to distal towards the south (Cameron 1993; van Adrichem Boogaert & Kouwe 1993–97). On seismic data, this alternation of deposits produces a distinct high-frequency, high-continuity seismic facies, which is continuous over the ESP. A change in seismic facies to lower frequencies and lower continuity occurs across the major normal fault that bounds the platform on its southern side; this is interpreted to represent the transition to basinal conditions (Fig. 11). This change in seismic facies was mapped as a palaeogeographical boundary (Fig. 5c). Deposits from this interval show a gradual northwards change to more proximal conditions, reflected in an increasing sand and coal content, and a decreasing carbonate and shale content.

**Late Asbian–Pendleian: Yoredale Formation**

Towards the end of the Asbian, a gradual relative sea-level rise occurred, as can be inferred from an upwards increase in the incidence and thickness of carbonate beds (Figs 7 & 8). This trend continues into the Brigantian. The Yoredale Formation consists of a cyclic alternation of carbonates and clastics, with rare coal seams (Fig. 4). It was deposited in a paralic setting and the cyclicity resulted from sea-level fluctuations. A typical Yoredale cycle starts with a sea-level rise establishing marine conditions, resulting in the deposition of carbonates and clays. Progradation subsequently results in a coarsening-upward clastic succession that may end with a coal layer or palaeosol (Waters et al. 2007). Similar to the situation during the Asbian, the deposits are sandier in the north; the Brigantian in well E06-01...
in the SE consists almost entirely of carbonate, in well A16-01 of roughly equal amounts of carbonate, clay and sand, whilst well 39/07-1 in the NE consists mostly of sand and clay with minor carbonate beds (Figs 5b & 7). The youngest Yoredale deposits encountered in wells in the Dutch northern offshore that have been dated with reasonable certainty are Brigantian in age. Deposits from the Pendleian, the earliest substage of the Namurian (Fig. 4), may have been drilled locally (for instance, in well A16-01), meaning that Yoredale-type deposition possibly continued into the early Namurian.

Namurian

At the start of the Namurian, the Visean bathymetry essentially still existed. It is commonly viewed that extension had ceased, although indications exist that significant extension must still have occurred (Kombrink et al. 2008). During the Namurian, a turbidite-fronted delta system prograded southwards, the sediment source area was located towards the north (Collinson 2005). South of the delta, shales and turbidites were deposited. Whilst no penetrations of this interval exist in the northern Dutch offshore (Fig. 4), their presence can be inferred from correlations to the UK onshore and well 43/17-2 (Fig. 2) (Collinson Jones Consulting 1995; Collinson 2005). The foresets of the prograding delta were characterized by Millstone Grit and Klaverbank deposition (Fig. 4). Since the system was prograding, the formation boundaries are diachronous and expected to be older in the north than in the south. This progradation continued during the Westphalian; Namurian Klaverbank deltaic deposits, for instance, closely resemble Westphalian A Klaverbank deltaic deposits, but these facies were located further north during the Namurian. Similar to the rest of the Carboniferous, significant higher-order cyclicity occurred during this period. Once a basin (or part of a basin) had been filled, however, the basin never reverted back to fully basinal conditions (Collinson 2005).

Discussion

Reservoir potential

Visean. Two end-member models exist for predicting reservoir presence in the Visean: one model predicts reservoir presence based on fault control (Turner et al. 1993); the other focuses on the transgressive infill of palaeovalleys that incised during a sea-level drop (Maynard & Dunay 1999). Both models are probably valid end members.

The incised valley model is highly relevant, in particular for the area close to the basin edge, as is the case for the Breagh Field example. A prediction of reservoir presence here requires an understanding of the location of the valleys, which is challenging owing to their limited thickness and the limited well control. Somewhat surprisingly, the Breagh Field is located in a zone with a relatively large proportion of shales (Fig. 5: well 42/13-2).

The ESP (Fig. 2) was affected by episodic drowning and progradation, expressed in the cyclic alternation of sandstones, shales, coals and carbonates. This is well documented for the Yoredale Formation, but the results from this study show that this cyclicity is also present in the underlying Elleboog Formation. The well data suggest that the proportion of clastics in both formations increases northwards. North of the ESP, Late Devonian–Early Carboniferous faulting led to the formation of the North Elbow Basin (Fig. 2) (ter Borgh et al. this volume, in press). The basin trends WNW–ESE, measures about 60 km from SSE to NNW and can be continued across the median line (Fig. 2) (Milton-Worsell et al. 2010; Arsenikos et al. 2018). More accommodation space was available in the basin during the Visean; the exact impact on reservoir potential is unclear and requires further study, but the overall trend of an increasing clastic sediment content towards the north is supported by wells north of this basin.

The results from this study and the structural framework developed for the study area (ter Borgh et al. this volume, in press) demonstrate the activity of syndepositional WNW–ESE-trending faults during the Late Devonian–Early Carboniferous, with the southern boundary fault of the ESP as the most prominent example. South of it, basinal conditions prevailed; north of it, paralic conditions. Considering the significant offset at the fault and the rapid change of seismic facies across it, mass-flow processes should be expected, and, although undrilled, reservoir-bearing turbidites may be present south of the fault (Fig. 11).

Namurian. The Namurian part of the Klaverbank Formation shows high net-to-gross deltaic sandstones across the study area, in line with some of the most prospective reservoir intervals of the Westphalian (Figs 5 & 9). The Tulp and Lelie fields (Fig. 1) confirm the reservoir potential of this interval.

Hydrocarbon charge from the Visean and Namurian

An important factor that has so far discouraged exploration in the northern Dutch offshore is the perceived absence of source rock outside the DCG. As of yet, producing gas fields in this area are limited to Mesozoic fields charged from the Early Jurassic Posidonia Shale Formation, and Neogene shallow
gas fields. Whether shallow gas originates from thermogenic or biogenic sources is subject to debate, although a substantial biogenic contribution seems likely (Schroot & Schüttenhelm 2003; van den Boogaard & Hoetz 2014).

There is a significant sampling bias of potential source-rock intervals towards samples from the present-day structural highs and towards samples of coals. The bias towards the highs results from the fact that the wells have been primarily drilled here. The bias to coals results from the often-made assumption that all gas from the Carboniferous is sourced from coals, meaning that sampling and observations focused on these coals. Shales and dispersed organic (plant) material may also have significant potential (e.g. Besly 2016), however, but have historically been sampled less frequently. Coals are present not only in the Westphalian, but also within the Visean Elleboog Formation (the upper part of which is the equivalent of the UK Scremerston Formation), the Yoredale Formation and the Namurian Klaverbank Formation (Fig. 4).

The sampling bias towards samples from the present-day highs also affects maturity data – the available maturity data come mostly from the highs, and maturity in the lows should be expected to be higher. The source rocks in these lows are expected to have reached maximum burial during the Neogene. The Lower Carboniferous on the present-day highs is also expected to be at or close to maximum burial; Visean and Namurian deposits may have been exhumed during the formation of the BPU by about 1250 m (van Buggenum & den Hartog Jager 2007), but have since been buried again to depths greater than 1900 m. It is therefore encouraging that the measurements from wells E02-01 and E06-01, taken on the Elbow Spit High, are already in the late oil–early gas window. Wells A14-01 and A16-01 only penetrate part of the Namurian; this interval is in the oil window and immature for gas. The Visean has not been penetrated in these wells. The only sample representative for the present-day lows, from well B17-04, show that the Carboniferous has entered the main gas window here.

Well and seismic data show that it is likely that significant amounts of Visean Scremerston coals are present north of the ESP. This probably results from a facies shift; the wells in the E quadrant were located close to the shoreline, where limited amounts of coals have been preserved; wells 39/07-1 and A-09-01 that contain significant amounts of coal are located in a more proximal setting (Fig. 5c). The trend of increasing coal content towards the north has been recognized previously in the UK offshore (Leeder 1988; Cameron 1993). The deposits are presently buried in the SG area to depths of up to at least 5500 m, with most of the deposits at depths of between 3000 and 5000 m, meaning that if coals are, indeed, present they are most likely to be gas mature.

Organic material is dispersed throughout Visean and Namurian units, and the source-rock potential of these deposits can be assessed using samples from the UK onshore, and from the offshore well 43/17-2, that drilled the Namurian in a basinal section. The so-called marine bands within the basinal sequence show an average total organic content (TOC) of 4.1 ± 0.78%, and the non-marine bands 1.89 ± 0.6%. Within the delta, these values are 3.86 ± 2.47 and 1.6 ± 0.76%, respectively (Collinson Jones Consulting 1995). Similar deposits are to be expected in the southernmost part of the E and F quadrants.

Basin modelling in the German offshore directly north of the study area (Arfai & Lutz 2018) shows that Visean–Namurian source rocks first become mature in the Late Carboniferous, and that peak generation and expulsion in the SG area occurs prior to Late Cretaceous inversion and continues to the present day. Visean–Namurian source rocks are interpreted to have charged the A6-A gas field (Fig. 1, well A-06-01). In the Central Graben, generation occurred until the Late Jurassic, at which point the source rocks were buried to depths where they became overmature (Arfai & Lutz 2018).

**Hydrocarbon charge from other source rocks**

In the F quadrant and the eastern and southern parts of the E quadrant, Westphalian Coal Measures – the predominant source rock in the Dutch onshore and offshore – are mature present day. A lateral charge of Westphalian gas into Visean and Namurian reservoirs is possible on the southern flank of the ESP, as the large-scale structure permits updip migration from downthrown kitchens (Fig. 3).

Charge was confirmed in blocks E12 and E09, but these discoveries were uneconomic as a result of the high nitrogen content of the gas (Table 3). Possible sources of the nitrogen include very early mature or overmature organic sources and inorganic sources. In a regional evaluation, Verweij et al. (2017) proposed that, in the case of the E12 and E09 blocks, the nitrogen originated from coals and shales that were rapidly heated by magmatic intrusions. Intrusions were identified in two of the three wells with high nitrogen contents (Table 3 & Fig. 9). Vitrinite reflectance data show that coals directly adjacent to the intrusion are overmature (>5%Ro) (Philippe et al. 1992). Sills are often readily observed on seismic data in this area, allowing for an assessment of the economic risks associated with high nitrogen contents. The only other gas sample from a Paleozoic reservoir in the northern Dutch offshore showed acceptable nitrogen values (Table 3, A15-01: 16%).

Considering the significant normal faulting in the DCG and SG, lateral charge from stratigraphically
younger units is possible. Within the DCG, the organic-rich Jurassic Posidonia Shale Formation is preserved; indeed, a number of oil discoveries in the DCG show that the formation is oil mature and locally gas mature. Basinal facies within the Zechstein also have source-rock potential, and the

Fig. 12. Structures at the BPU level in the A quadrant, illustrating the types of structures that may form traps for hydrocarbons. The figure should not be regarded a detailed assessment of the prospectivity of the area as it is based on a regional seismic interpretation and time–depth conversion, and only structures with a height greater than the contour interval (62.5 m) are indicated. MSL, mean sea level; see Figure 1 for other abbreviations.
Kupferschiefer at the base of the Zechstein may form an auxiliary source rock too. Although often overlooked, significant shows occur in Paleozoic and Mesozoic units in a number of wells in the A quadrant, providing proof that a mature source rock is present in this area as well. The number of wells that drilled into Paleozoic strata in this area is limited, but most of the wells that are available have significant shows; well A15-01 tested gas from tight Zechstein carbonates and had oil shows in the Zechstein and Triassic. Well A08-01 and A12-01 had gas shows throughout the Mesozoic and down to the Zechstein, and well A12-02 had oil shows in the Chalk Group.

Trap formation, top seal and fault seal

The structural geology of the study area is discussed in detail in ter Borgh et al. (this volume, in press). Based on that study, trap formation is discussed. An example of the relevance of the SG trend for trap formation is shown in Figure 12; in the A quadrant, the alternation of horsts and graben creates potential closures. The likely seal for such closures would be provided by the Rotliegend Silverpit Formation and the Zechstein salt, the latter of which can, in some cases, be observed to drape the horsts. The main risks for these traps is the presence of an effective seal, as the Zechstein salt thins out towards the west, and the Silverpit Formation may, in fact, contain sandstone streaks locally. In the case that these are of sufficient reservoir quality they may be the target, but otherwise they form a waste zone. Another reservoir and potential target that may be present below the Silverpit and Zechstein are the Lower Rotliegend volcanics (de Bruin et al. 2015), although the flow capacity of this unit has not been demonstrated.

Faults with a N040° trend are known to cause compartmentalization in the Cleaverbank High area (Oudmayer & de Jager 1993; van Hulten 2010), and it is not unlikely that they would have the same effect in the study area. On the Cleaverbank High, vertical offsets are generally in the order of tens of metres. This is also true for part of the study area, but large offsets (hundreds of metres to 1 km) occur as well, with the Urania Graben located on the eastern flank of the ESP as the most prominent example (ter Borgh et al. this volume, in press). Establishing under what conditions these faults act as a seal, and whether an increase in offset improves or degrades the sealing and compartmentalization potential of the faults, could help to de-risk the sealing potential of this fault trend.

The N110° and N040° trends have the potential for creating intra-Carboniferous closures; for instance, in horsts or footwalls created by the N110° trend (Fig. 13). The hydrocarbon potential of these structures depends on the presence of either the Silverpit Formation or intra-Carboniferous seals as a top seal, combined with side seals along or across the fault. The charge would have to be provided from downthrown Upper Carboniferous sources. The charge and sealing risks for these structures are considerable. This may be offset by their relatively large volumes.

Strike-slip faults with a N070° trend were recently identified on the ESP (ter Borgh et al. this volume, in press). As they have not been identified in public literature before, no studies are presently available to assess their sealing potential. Where pop-up features are overlain by a seal, traps may be present.

Conclusions

Visean and Namurian deposits in the northern Dutch offshore are found to offer a significant hydrocarbon potential. The post-well analysis shows that out of the 14 wells that encountered the Visean and Namurian in the northern Dutch offshore, only three can be considered a valid test: two were positive and one negative. The other wells were invalid tests of the play because they did not test a valid structure. This has two main causes: first, all but two wells were
targeting a structure at another stratigraphic level, whereas no structure was present in the Visean or Namurian; and, secondly, often structures were mapped using 2D seismic data only, whereas presently available 3D data show that no structure is present at these well locations. Structures do exist, however: in the Step Graben (SG) area Triassic–Early Cretaceous extension caused structures to form, with closures in footwalls. Top and, in some cases, side seals would have to be provided primarily by the Permian Silverpit and Zechstein Group deposits. Carboniferous–Early Permian extension caused structures to form on the Elbow Spit Platform (ESP); traps at these levels would require intraCarboniferous seals.

Core-plug data confirm that sandstones of Visean and Namurian age with sufficient reservoir quality are present across the area. Chances of encountering reservoir rocks increase towards the north; the Breagh Field, although a commercial success, is located on the southern edge of the area where Visean–Namurian fluvial and shallow-marine reservoir rocks are expected.

A number of potential source rocks have been identified: the presence of coal in nearby wells and the palaeogeographical reconstruction suggest that significant amounts of Visean Scremerston coals may have been preserved in the A and B quadrants. Additional coals were found in the Yoredale Formation and the Namurian, and TOC measurements show that dispersed organic material is present within the Visean and Namurian. In the southern E and F quadrants, lateral charge may have come from downthrown Westphalian deposits, and from basinal Visean and Namurian shales that have not been drilled but whose presence may be inferred from the palaeogeographical reconstruction. Additional charge may have come from downthrown basinal Zechstein deposits and by long-distance migration from the Lower Jurassic Posidonia Shale Formation in the Dutch Central Graben (DCG). Hydrocarbon shows that support this do occur. Hydrocarbon generation and expulsion is expected to have occurred north, east and south of the ESP, and updip migration onto the platform is considered possible.

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