GEOLOGICA BELGICA (2012) 15/4: 284-296

Devono-carboniferous carbonate platform systems of the Netherlands

F.F.N. van HULTEN

EBN B.V. - P.O. Box 19063, 3501 DB - Utrecht, The Netherland; Fokko.hulten-van@ebn.nl

ABSTRACT. Large Palaeozoic carbonate build-ups, globally important for hydrocarbon exploitation, are generally not associated with the Netherlands or with the larger Southern North Sea region. The last ten years, information of new wells and seismic imaging have changed this perception. Recent seismic interpretations have indicated massive reef like carbonate platforms far below conventional petroleum exploration targets in the Netherlands. Some of the platforms are very sizeable and comparison with dimensions of Mississippian build-ups in the Caspian region or Devonian reefs of Canada can be made. New well information, released the last two years, dates the upper part of the platform as Mississippian. Based on seismic interpretation, some platforms most likely contain a Devonian core. UK petroleum exploration on the Mid North Sea High also provides new insights into Devonian carbonate build-ups. Due to the great depth of the Devono-Carboniferous strata in most areas, it is unclear if these carbonate platform reservoirs are a new petroleum exploration frontier or are situated below the economic basement. For many years the same palaeogeographic map could be used for North Western Europe for the Devonian and Mississippian time interval. The new data requires a revised palaeogeography. The following summary provides an overview.

KEYWORDS: North West Europe, Caledonian orogeny, Palaeo-trade winds, Luttelgeest-01, Uithuizermeeden-02, Groningen carbonate platform, Mid North Sea High, Tengiz, Canada.

1. Introduction

The Netherlands is a major hydrocarbon province in western Europe. With more than 5000 oil and gas wells and good seismic coverage, the first two to three kilometres of its subsurface is studied in detail (Wong et al. 2007). Relatively few geological studies were performed of horizons below the Permian Upper Rotliegend (Fig. 1), the major petroleum target in the country. Owing to its coal layers and gas reservoir potential, only the coal bearing Upper Carboniferous Limburg Group, directly below the Base Permian Unconformity, was studied in some detail (Wong et al. 2007). Of the more than 1300 exploration wells in the country, only 22 boreholes were drilled into the Mississippian Zeeland or Devonian Banjaard Group (Figs 1, 2, 3). Due to their depth, generally exceeding 4,000 m, the Devonian or Mississippian age formations are rarely considered a target for hydrocarbon exploration in the Netherlands or in the surrounding countries that share the same basin setting. The few wells drilled to these targets are further concentrated in specific areas. Therefore the geological evolution during the Devono-Mississippian can only be described in general terms. A few geological overviews are available (Glennie, 1998; Wong et al., 2007; Doornenbal & Stevenson, 2010). The new data changes the established palaeogeography. The aim of the study is to provide an overview with the incorporation of all the new information. The few isolated oil and gas finds in Mississippian or Devonian reservoirs in the United Kingdom (UK), like the Mississippian Hardstoft oil field (1919), do not suggest there is a regional Devono-Carboniferous petroleum play for North West Europe (Fraser & Gawthorpe, 1990; Glennie, 1998), however the new insights into the Palaeozoic carbonate platform development in the Netherlands are largely not reflected in these summaries and may change this perception.

2. Geological setting during Devonian and Mississippian (general setting of NW Europe)

After the Caledonian orogeny in the general Southern North Sea region, including the Dutch onshore area, sedimentation started during the Mid and Late Devonian. From that time until recently, sediments can be found in almost every period in the Dutch stratigraphic record (Van Adrichem Boogaert & Kouwe, 1997; Wong et al., 2007). Information from surrounding countries, make it clear that the sedimentary basement is formed during the Silurian as part of a Caledonian triple continental plate collision (Figs 4, 5 and 6). After these Caledonian orogenic events, intracratonic basin-fill is deposited in the vicinity of the Iapetus suture situated at the north west fringes of the presentday Western Europe. To the south east, basins belonging to the continental margin of the Rheic Ocean (Fig. 5), which is in existence till the Pennsylvanian, are characterized by marine deposits.

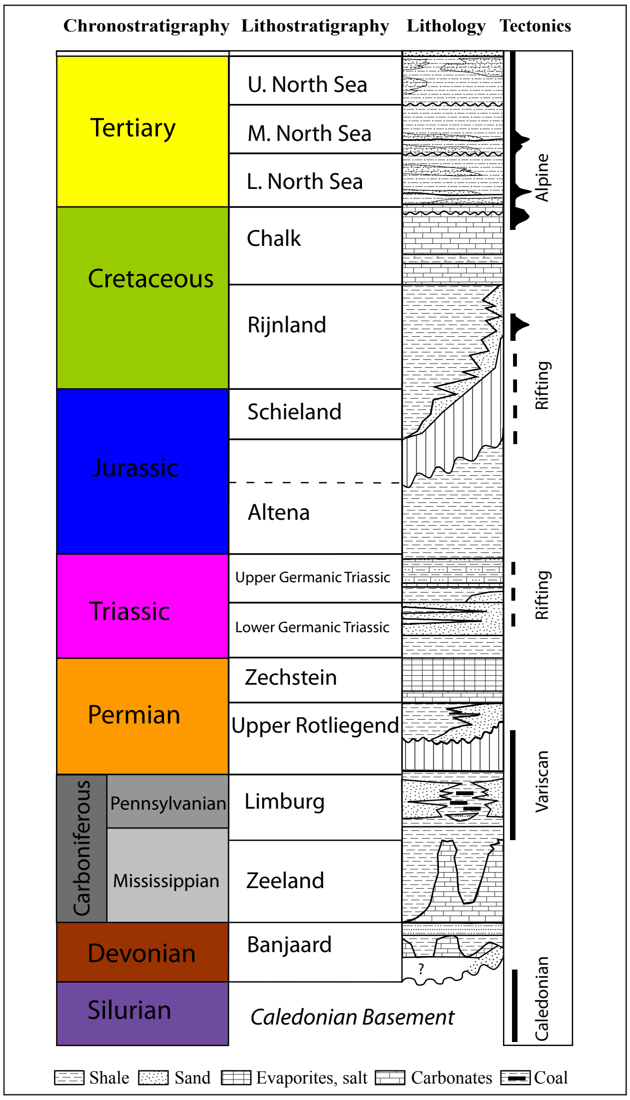

Figure 1. Stratigraphic table for the Netherlands showing the major lithological units on Group level. The Permian Upper Rotliegend (Slochteren Formation) is the major petroleum target in the country. The more shallow (Germanic) Triassic, informally known as Bunter sandstone, is the second most important exploration target. The nomenclature of the Devono-Carboniferous period is based on very few boreholes (see Fig. 3). The Devonian Banjaard Group includes carbonates in the southern part of the country (Wong et al., 2007). They include the Kyle type of limestone, known from the UK to the north of the Dutch offshore. For the Mississippian limestone it is customary to use Zeeland Formation. For the time equivalent basinal shale facies, no formal term has been proposed.

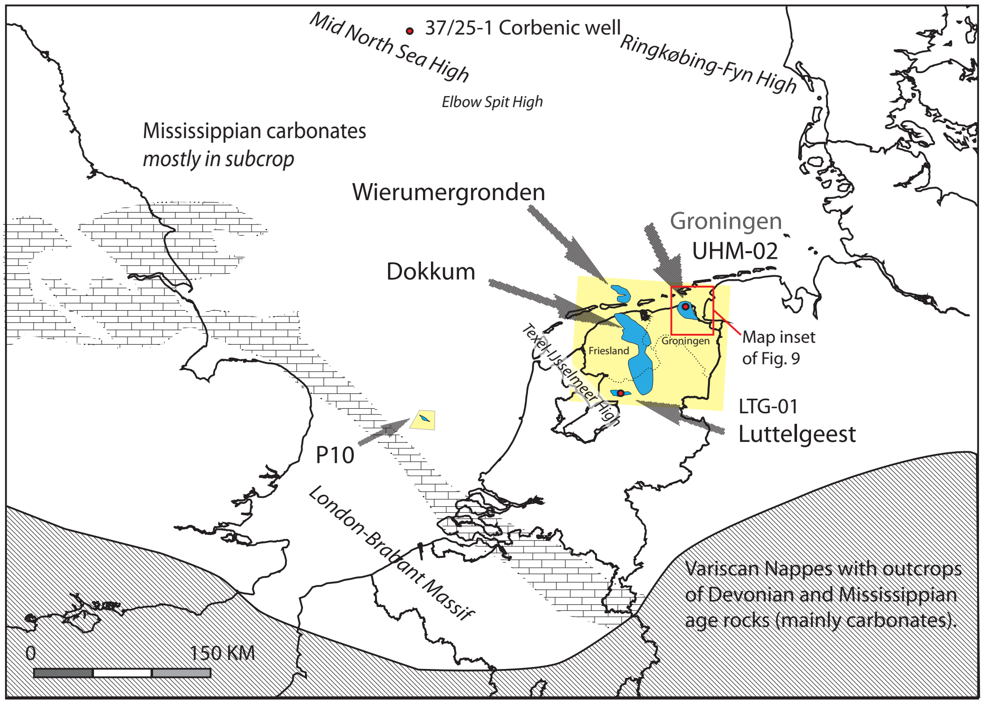

Figure 2. Index map shows recently discovered Devono-Carboniferous reefs and new wells drilled the last ten years. The well-known north west trending Mississippian carbonate (subcrop) trend, which fringes the north side of the London-Brabant Massif, is indicated. Devonian or Mississippian age rock is not present in Dutch outcrops, in contrast to neighbouring countries where these rocks can be studied in many exposures.

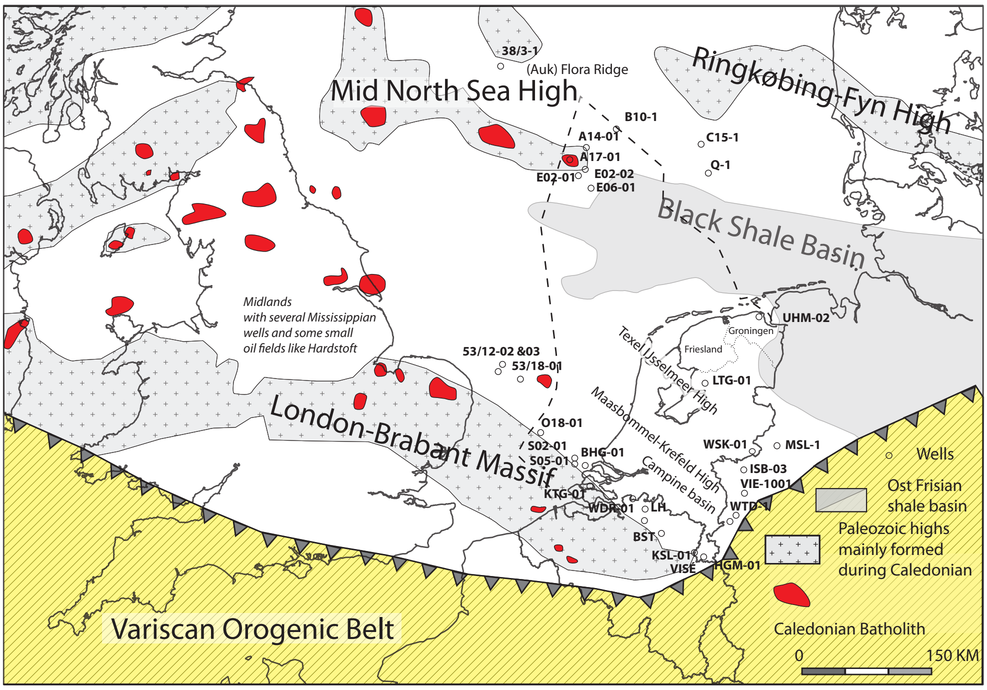

Figure 3. The most important wells, drilled into the Devonian or Mississippian, of the Netherlands and the direct vicinity. The map shows the major highs and batholiths of the Southern North Sea area based on Glennie (2005). The general outline of the (Ost Frisian) black shale basin (in dark for the deepest parts and light grey for shallower parts), based on Van Hulten & Poty (2008). The wells on this map are drilled at least into the Mississippian Zeeland Formation. The well UHM-02 and LTG-01 were the first wells drilled away from the basin fringes. To the south, the Variscan thrust and orogenetic belt has been indicated. This is an area with extensive outcrop information on Devono-Carboniferous carbonates, however also complex because of thrusting and telescoping.

In the Netherlands only few data points are available of wells which reach the pre Devonian basement (Wong et al., 2007). With regional information of the surrounding countries, a generalized depositional framework can be constructed for the earliest infill of the post Caledonian basin. Infill of the Southern North Sea region probably started during the Eifelian or even earlier, comparable to the outcrops in the allochtonous Variscan nappes of southern Belgium (Doornenbal & Stevenson, 2010). The oldest known sediments in the area north of the London-Brabant Massif are of Givetian age (Glennie, 1998; Evans et al., 2003; Wong et al., 2007). This study concerns mainly the carbonate sedimentation, which is dominant during the Devonian ages Givetian and Frasnian and during the Mississippian ages Tournaisian and Viséan. The youngest Devono-Carboniferous carbonates are of Warnantian age in the Netherlands, comparable to the termination of the reef growth in Belgium and the UK. Organic rich shales of Serpukhovian age can be found in the lows between the platforms or even cover the carbonates (Van Hulten & Poty, 2008; Doornenbal & Stevenson, 2010). A detailed discussion of these organic rich shale deposits is outside the scope of this study. The general stratigraphic term Devono-

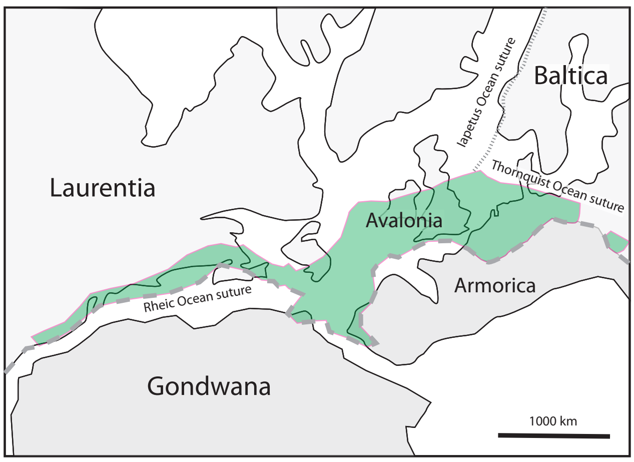

Figure 4. The basement in the Southern North Sea Area is formed during the Silurian as part of a Caledonian triple continental plate collision. Only parts of Avalonia are visible after the Variscan collision. The final Pangea assemblage after the Rheic closure in the late Carboniferous is shown as one sees it today.

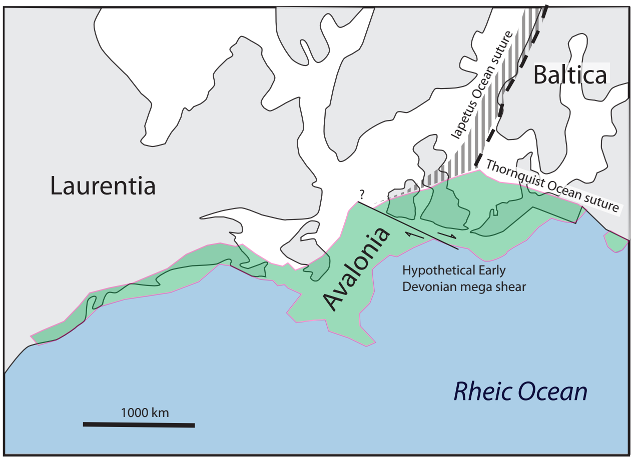

Figure 5. The basement in the Southern North Sea Area is formed during the Silurian as part of a Caledonian triple continental plate collision. The Variscian as shown in Fig. 4 is removed. This illustrates the position of the Netherlands at the continental margin of Laurussia, near the Rheic Ocean during the Devono-Carboniferous. Avalonian mega shear, caused by the early Devonian collision of the South American part of Gondwana with Avalonia (Fig. 12), may explain the extensional tectonics on the northern part of the Avalonia micro craton.

Carboniferous carbonates in this paper is used for carbonate deposits from the Givetian until Serpukhovian age.

3. New focus on Devono-Carboniferous

A number of world class hydrocarbon discoveries were made in Mississippian carbonate reservoirs of the Caspian Sea area and got lots of attention in the 1990's (Weber et al., 2003). As soon as their potential was realized, interest in age equivalent horizons outside that region was stimulated as well. More important were developments in geophysics ten years ago in the Netherlands. New and better quality seismic processing and acquisition made it possible to see deep horizons below the km thick Pennsylvanian section, which before were hidden on older seismic lines. The kilometre size build-ups mapped underneath the northern part of the onshore area of the Netherlands (Kombrink, 2008; Kombrink, 2009; Van Hulten & Poty, 2009; Kombrink et al., 2010) are reminiscent to Devono-Carboniferous bioherms at the eastern margin of the Russian platform like Astrakhan, Zhambay, Karachaganak (Kerogly), Kashagan (Sharburbali) and Tengiz (Weber et al., 2003).

The new seismic interpretations require well data to gain more certainty on the nature of these reefal build-ups. The Devono-Carboniferous depositional model is poorly constrained in the Netherlands, because only few wells, if any, have reached the Mississippian or Devonian formations in basin areas. Most wells were drilled in the southern part of the country at the basin margins (Wong et al., 2007; Van Hulten & Poty, 2008). On seismic, Devonian or Mississippian age formations are therefore rarely interpreted away from the Campine Basin near the London-Brabant Massif in the south of the Netherlands (Figs 2-3) or the Elbow Spit High, part of the larger Mid North Sea High in the northern offshore (Figs 2, 3). Only in the south of the country and the far northern offshore, these formations can be found at a relative shallow depth. Devonian or Mississippian age rock is not present in outcrops of the country, in contrast to neighbouring countries. This implies that the sedimentological setting is generally deduced from detailed information from these countries, like the UK and particularly Belgium (Boulvain, 2007; Boulvain & Wood, 2007; Poty et al., 2002; Paproth et al., 1983). In Belgium these Palaeozoic sections are especially well studied, partly due to the presence of a few classical stratotypes (Coen-Aubert & Boulvain, 2006; Thorez et al., 2006; Hance et al., 2006a, 2006b). Recently important insights were gained in the depositional setting of the Devono-Carboniferous platform carbonates of the Southern North Sea region, when two new exploration wells, Uithuizermeeden-02 (UHM-02) between November 2001 and June 2002 and Luttelgeest-01(LTG-01) between May and October 2004 (Figs 2 and 3), were drilled. The wells proved the existence of two Mississippian carbonate platforms and reached the top of the Devonian (Van Hulten & Poty, 2009; Abbink et al., 2009).

3.1. New seismic data

In the Southern North Sea region, seismic interpretation of Devonian or Mississippian markers is not customary. This is partly because of the strong emphasis on the much shallower Permian Rotliegend Slochteren gas play in the general Southern North Sea area (Glennie, 1998), which requires interpretation of much shallower horizons. It is also due to the poor imaging of these deeper Devono-Carboniferous horizons on conventional seismic. This is often caused by the complexity and disturbance of the seismic signal in the overburden, in particular the Permian Zechstein evaporites, present in the subsurface over large areas of the Netherlands. Multiples of strong reflectors, like the Permian Basal Zechstein Anhydrite horizon, can make interpretation of deeper levels like those of Mississippian or Devonian age carbonates very uncertain (Wong et al., 2007). It is therefore not

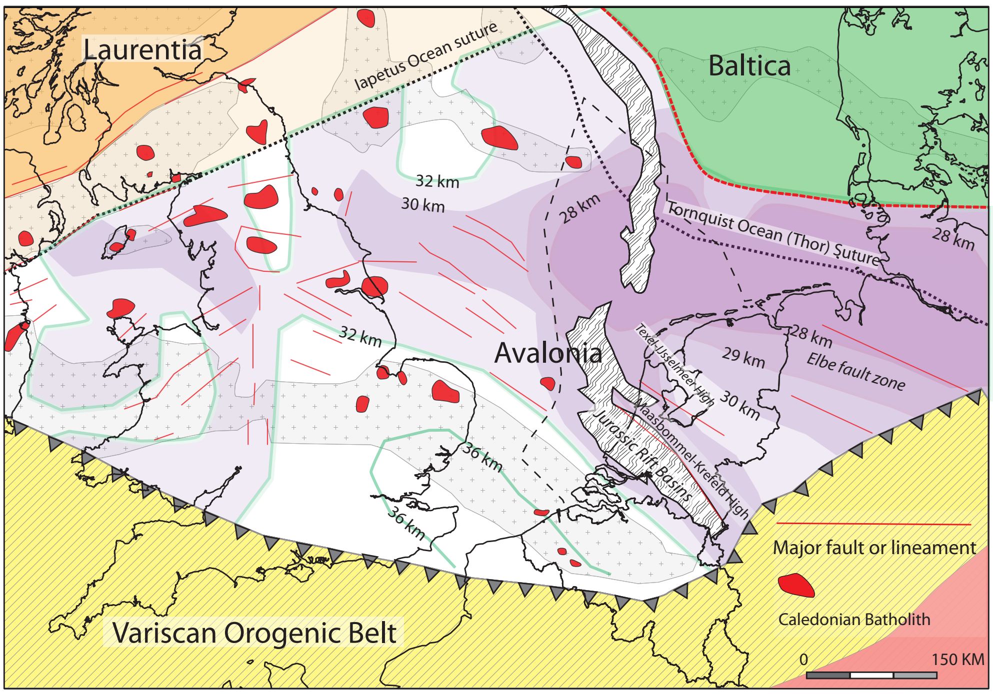

Figure 6. The depositional basement is formed during the Silurian as part of a Caledonian triple continental plate collision. Tectonic elements of the Southern North Sea area are based on very deep (15 seconds) seismic. In green the Baltica terrane, in orange the Laurentian terrane is shown. Structural elements with major faults and lineaments and the crustal terranes are indicated. The depth of the Moho is deduced from a few deep seismic lines only. Based on Moho depth it is suggested that the Avalonian plate can be subdivided in three parts. This is after a correction has been made for the Jurassic rift basins, indicated on the map.

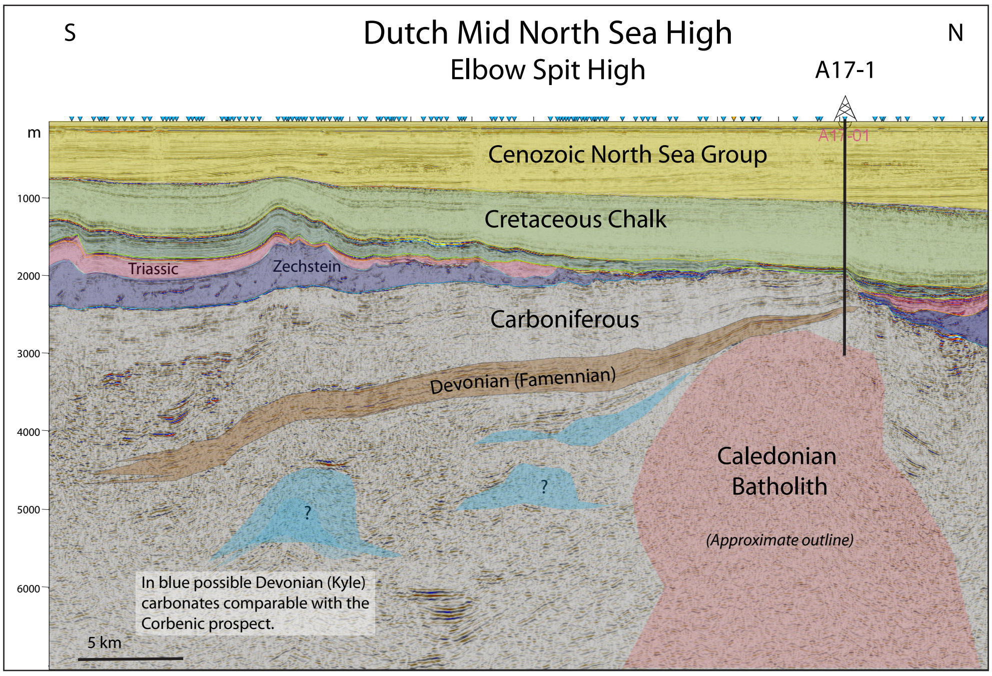

Figure 7. Seismic section of the Mid North Sea High. Note well A17-01. The interpretation shows hypothetical Kyle carbonates underneath Upper Old Red clastics, comparable to the interpretation of the UK Corbenic prospect target of the recent well 37/25-1.

uncommon that lower parts of a commercial seismic line are cut off, because it is perceived to contain mainly noise. The only areas where interpretations of Palaeozoic markers were published are in the Campine Basin, close to the Belgian border, and of the northern parts of the Dutch offshore, at the Mid North Sea High (Figs 2-3).

Interest in deeper horizons increased when in 2003 and 2004 the two, approximately five kilometres deep, exploration wells were drilled. It stimulated the publication of a map of the build-ups in the northern onshore provinces of about 100 km^2, which includes the locations where the two new deep wells are drilled (Kombrink et al., 2008; Kombrink, 2008). Visualization is shown of the Groningen carbonate platform, drilled by UHM-02 and a number of undrilled platforms are described in the Friesland province (Kombrink, 2008).

For most other onshore and offshore areas no interpretation is available of seismic horizons of Mississippian age or older. A few lines are published that give some insight in the geology of the Devono-Carboniferous horizons. De Jager in Wong et al. (2007) shows a deep seismic line which illustrates the thickening of the Carboniferous towards the east into the Lower Saxony Basin with extensive faulting of the basement. Van Hulten & Poty (2008) present a Dinantian structure in the block P10 (Fig. 2). Older seismic and well control in the southern part of the Netherlands (Van Adrichem Boogaert & Kouwe, 1997), cover large parts of the north flank of the London-Brabant Massif in the Campine Basin area. Abbink et al. (2007) show a seismic line with Devono-Carboniferous interpretation over the Campine Basin, which suggests a monotonous Mississippian age carbonate platform development. This seems to contradict the reef like development of that age in Loenhout-Heibaart and other small build-ups as described by Laenen et al. (2004) slightly farther to the east.

In the far north of the Dutch offshore the Mid North Sea High is shown on a few published seismic lines. Quirk (1993) shows a regional N-S line where Late Devonian clastics can be traced from the A17 granite far into the basin territory to the south. De Jager in Wong et al. (2007) and Abbink et al. (2007) also shows a comparable geology with Mississippian and Devonian horizons in more detail, albeit the carbonates underneath the Buchan Formation (Upper Old Red Group of Famennian age) clastics are not visible on their line. In the UK Central North Sea near the Auk and Argyll oil fields, Mid Devonian Kyle carbonates can be clearly seen on seismic (Milton-Worssell et al., 2010). A higher resolution line is shown in Fig. 7, which suggests a hypothetical undrilled Givetian-Frasnian age Kyle carbonates underneath the 'Upper' Old Red clastics, comparable to the Corbenic prospect (Fig. 2) drilled by Exxon in the well 37/25-1 (DECC, 2009).

Very deep (15 seconds) seismic is of importance for the understanding of the structure of the upper crust (Doornenbal & Stevenson, 2010; Abramovitz & Thybo, 2000). The few lines that are (partly) shot over the Netherlands give a better understanding of exceptional crustal conditions underneath the shale basin just north of the Groningen and Friesland platforms (Fig. 6). In the northern offshore part of Germany, adjacent to the Netherlands, the basement in this basin is estimated to be at 12-18 km depth (Ziegler & Louwerens, 1979). This means that the total Devonian may be of substantial thickness there and it supports the conclusion that during the Devono-Mississippian the ocean reached a depth of several kilometers.

3.2. New well data

In the Netherlands about a dozen wells penetrate the Devonian and about 20 reach the Mississippian. When a few wells near the Dutch border in Belgium, Germany, and the UK are added, the total well database hardly exceeds 30 wells (Fig. 3). At the UK side in the North Sea the penetration of Devonian strata has commonly been taken as reason to terminate an exploration well (Glennie, 1998). In the basin area between the major highs, only three or four wells have reached the Devonian in the Netherlands (Wong et al. 2007). In the known wells, no indications of hydrocarbons are described and good reservoir is rare. Because of the scarcity of data, the two new exploration wells were important new data points. Only part of the data has been released, because the UHM-02 well is still confidential until 2013. A zonation based on foraminifera and palynology was published of this borehole (Abbink et al., 2009). This confirmed the Mississippian age of the top part of the platform. The well reached the top of Devonian clastics. This is comparable to the bioherm of LTG-01 (Van Hulten & Poty, 2009). Physical well logs of the two wells are compared in Fig. 8. In both wells the drilling was terminated in the Famennian age clastics.

4. Structural framework

The Devono-Carboniferous palaeogeography of the Southern North Sea region cannot be constructed without general understanding of the Late Palaeozoic structural framework of this part of the Eurasian continental plate. Recent regional updates of the structural development in North West Europe during this period, can be found in Glennie (1998), Bayer et al. (2002), Glennie (2005), Wong et al. (2007), Doornenbal & Stevenson (2010).

The reef building in the Devonian and Mississippian takes place 20-30 Ma after the Caledonian orogeny, which ended during the last part of the Silurian or early Devonian. Substantial

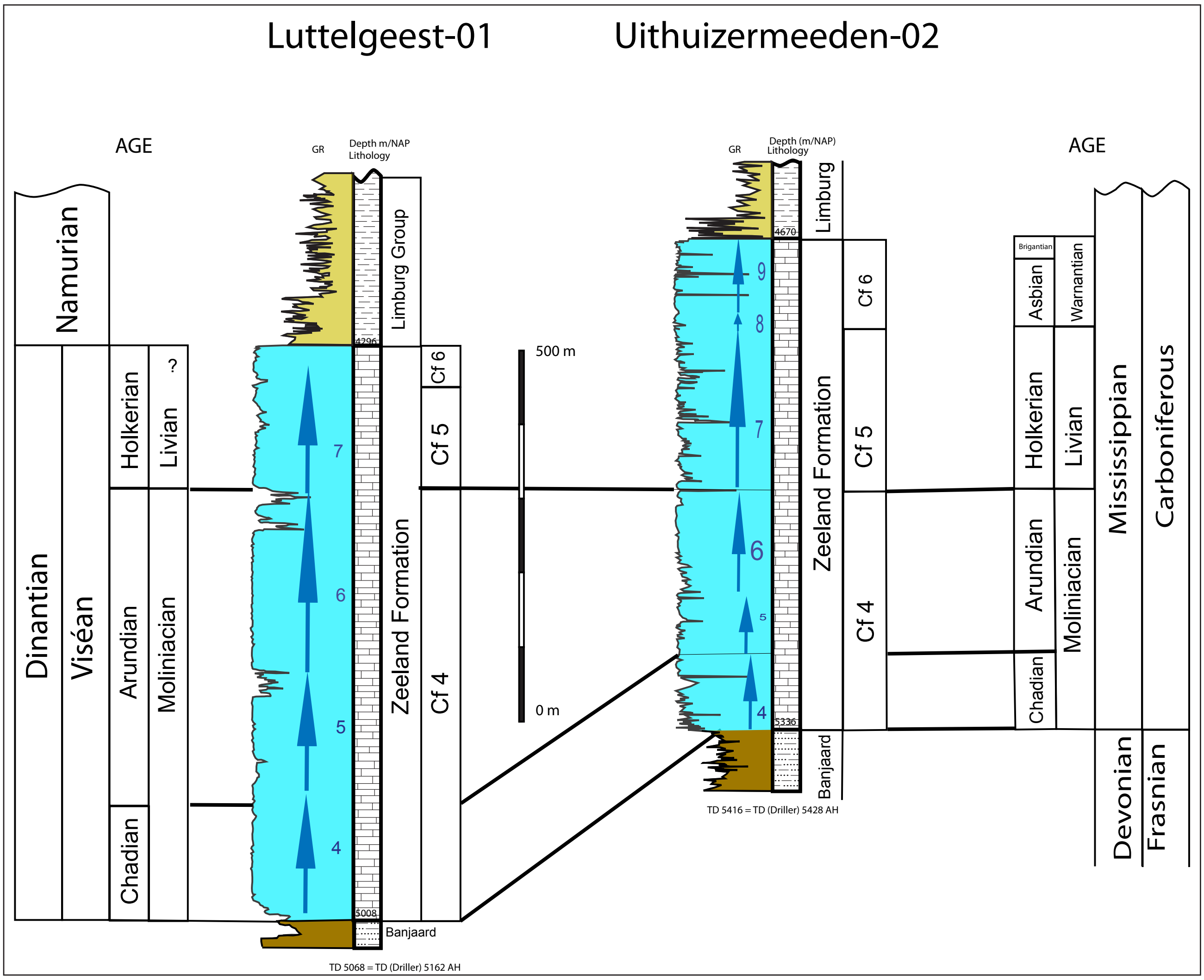

Figure 8. Cross section showing a stratigraphic comparison between the LTG-01 and UHM-02 wells. The Gamma Ray (GR) log of both wells is shown for comparison. Both wells reached TD (Total Depth) in the top of the Famennian clastics. The arrows shows widely recognized 3rd order sequences (Poty et al., 2002). The age interpretation is based on foraminifera (Cf zones). Contrary to the UHM-02 well , the reefgrowth in LTG-01 was terminated before the end of the Viséan.

erosion must have been taking place since the collision. Morphological hard to erode elements like granite landforms can become nuclei for reef growth later. Some aspects of this orogeny are helpful to understand the location of these granite intrusions. In addition, the origins of regional highs and shale basins can be explained.

The Netherlands are a part of the present day Eurasian continental plate. Before the orogeny, its deeper crust belonged to the micro-plate called Avalonia. It became part of the European plate in the Silurian (Torsvik & Cocks, 2004). The collision took place during an early phase of the Caledonian orogeny and resulted in the fusion of the Baltica plate (Scandinavia, Russia) with the Avalonia terrane (Figs 5 and 6). Shortly after this, the Laurentia continental plate (Greenland, North America) joined this fused plate. The Caledonian orogeny can therefore be described as a collision of Laurentia and the Baltica Craton, complicated by the merging with Avalonia (Glennie, 2005). Parts of Avalonia, in particular directly to the south and east of the Netherlands, are obscured by the overthrusting during the Variscan orogeny (Fig. 6) which took place at the end of the Carboniferous approximately 20 Ma later than the carbonate deposition discussed here.

Directly outside the country to the north-northeast, magnetic anomaly maps highlight the Thornquist (Thor) suture. This is indicated by the contrast between the highly magnetic ancient crust of Baltica and the less magnetic Avalonian younger crust SW of the suture (Abramovitz & Thybo, 2000; Williamson et al., 2002; Lyngsie & Thybo, 2007). It is suggested that the Tornquist Ocean between Avalonia and Baltica was closed by oblique convergence (Glennie, 1998). This soft docking is an explanation for the minor structuration along the suture. The major structuration in the Netherlands, which has a NW-SE strike, more or less parallels this suture. It is not quite clear if there is a causal relationship. The NW-SE strike can be found in the westerly part of the UK as well, contrary to the east of the Midlands craton where the strike is SW-NE (Glennie, 1998, 2005). Extensional tectonics provide the mechanism for these large scale structural trends. It is important because it is the mechanism that can explain the half grabens, so dominant in the palaeogeography of that period. Kombrink et al. (2010) list a number of mega-tectonic hypotheses as an explanation for the extensional stress, like back-arc extension or escape tectonics. However Avalonian mega shear (Fig. 5), caused by the early Devonian collision of the South American part of Gondwana with Avalonia (Simancas et al., 2005), instead of Arctic mega shear, may explain the extensional tectonics on the northern part of the Avalonia micro-craton. The Early Devonian timing of the Avalonia collision is more or less coinciding with the Brabantian phase (Verniers et al., 2002).

Differences of properties of the Dutch deep crust can subdivide the Avalonian plate there in three parts (Fig. 6). These three areas react differently to the Early Devonian extensional stress. The three areas display a different structural style, which is reflected in the palaeogeography. From south to north the three parts can be subdivided based on depth of the Moho (Doornenbal & Stevenson, 2010), this is after a correction has been made for the Jurassic and Tertiary rift grabens (Wong et al., 2007).

The most southern part, the London-Brabant Massif, is a Caledonian inversion structure (De Vos et al., 1993; Debacker et al. 2005). The depth of the Mohorovičić discontinuity (Moho) is at 36-38 km (Rijkers et al., 1993). This area is generally a positive geographical feature in the geological history, with mostly shallow water deposits or aerially exposed during the Devono-Mississippian period. This is different from the zone farther to the north were the depth of the Moho decreases to 29-30 km with the exception of the Texel-IJsselmeer High with a 31 km thick crust (Rijkers & Duin, 1994). This zone between the London-Brabant Massif and the zone in the northern part of the country shows a middle and lower crust, in total 10-15 km thick (Doornenbal & Stevenson, 2010). The structural style during the Devono-Mississippian period is characterized by a number of half grabens. This is very comparable to adjacent regions in the UK directly to the west (Fraser & Gawthorpe, 1990).

The third deep crustal zone differs significantly in its properties. In Germany the boundary of the two zones, coincide with a lineament called the Elbe fault zone (Scheck et al., 2002) (Fig. 6). In this last deep crustal zone, the crust is thinner with a Moho at 28 km depth and the crust is two layered. It misses the middle crustal part. The two layered zone has been interpreted as a part of an oceanic plate belonging to Avalonia (Scheck et al., 2002; Scheck-Wenderoth & Lamarche, 2005). The more oceanic crustal properties of this deep crustal zone, which is present in the Dutch northern North Sea and adjacent German basin regions, explain why this constantly "sinking crust" creates an important Palaeozoic depocenter. During the Devono-Mississippian period this area is a deep basin, assumingly partly filled with shale deposits.

Many large granite intrusions can be found in the larger Southern North Sea area, probably subduction related (Glennie, 1998). Most of these plutons are known from the UK close to the Iapetus suture and are explained by the Laurentian plate subducting underneath Avalonia. Some other granite intrusions are linked to local tectonic processes like in the London-Brabant Massif of Belgium (Debacker et al., 2005). The Mid North Sea High shows a number of very large plutons like the Dogger Granite (Glennie, 1998). In the Netherlands, one biotite monzo-granite has been drilled in the well A17-1 (Wong et al., 2007). It is likely that there are more plutons in the Netherlands; however magnetic anomalies are not very strong. The Groningen platform may have an intrusive as nucleus, because a magnetic anomaly was noticed (Kettel, 1983).

5. Devonian and Mississippian bioherms

Based on seismic and well control of both the Groningen and Luttelgeest carbonate build-ups, it is likely that both Devonian and Mississippian age carbonate platforms are present in the Netherlands. Seismic interpretation (Fig. 9) suggests that a very

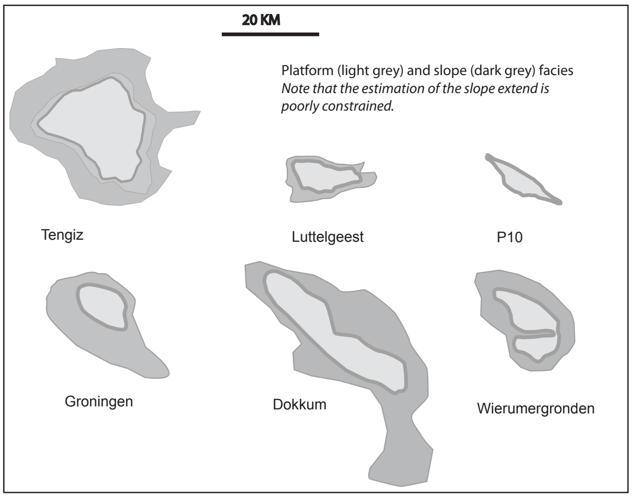

Figure 10. Comparison of the horizontal dimensions of the reefs of the Netherlands and Tengiz (Caspian Sea region). Most of the dimensions have been derived from Kombrink (2008).

thick undrilled Givetian-Frasnian section is present at deeper levels below the Mississippian build-up. This differs from the interpretation of Kombrink et al. (2010) that terminates the build-up of the bioherm on a pre-Carboniferous basement. Their interpretation can be explained by low quality of the seismic lines available for their study. On the section of Groningen (Herber & De Jager, 2010) and to a lesser degree on the Luttelgeest seismic (Van Hulten & Poty, 2009), much more detail can be seen, which makes the presence of Devonian reefal build-ups very plausible. On this additional seismic section of the Groningen carbonate platform, it is almost certain that below the drilled Mississippian part of the platform, a possibly even thicker Devonian build-up is present. The dimensions of the reefs (Figs 10 and 11), can be compared with internationally known examples. Below the Famennian clastics that were logged in the wells and can be seen as a mappable horizon on the seismic, there is most likely a carbonate build-up, probably Givetian-Frasnian in age. The thickness in Groningen of the Devonian part of the build-up seems at least comparable in thickness to the 800 m of the Mississippian top part of the platform.

Bioherms of Devonian age are very common worldwide. The West Canadian Basin in Alberta, Canada, one of the best-known Palaeozoic reef provinces in the world can be used as example (Figs 12-14). Very close to the Netherlands,

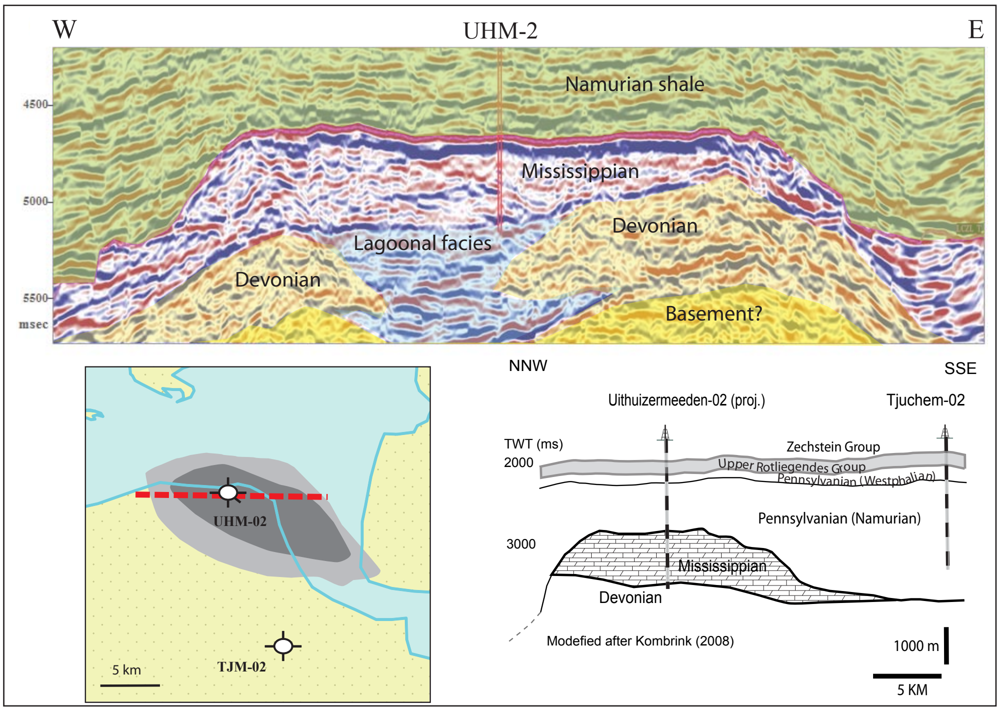

Figure 9. E-W cross section of the Groningen platform. A different interpretation based on a dominant wind direction from the west is published in Herber & De Jager (2010). Here the interpretation suggests a hypothetical presence of a Devonian reef underneath the drilled Mississippian carbonates as well. The well was drilled in the back reef (Menkema) facies. It is possible that better reservoir can be encountered closer to the edge with more grainstone (Meima facies).

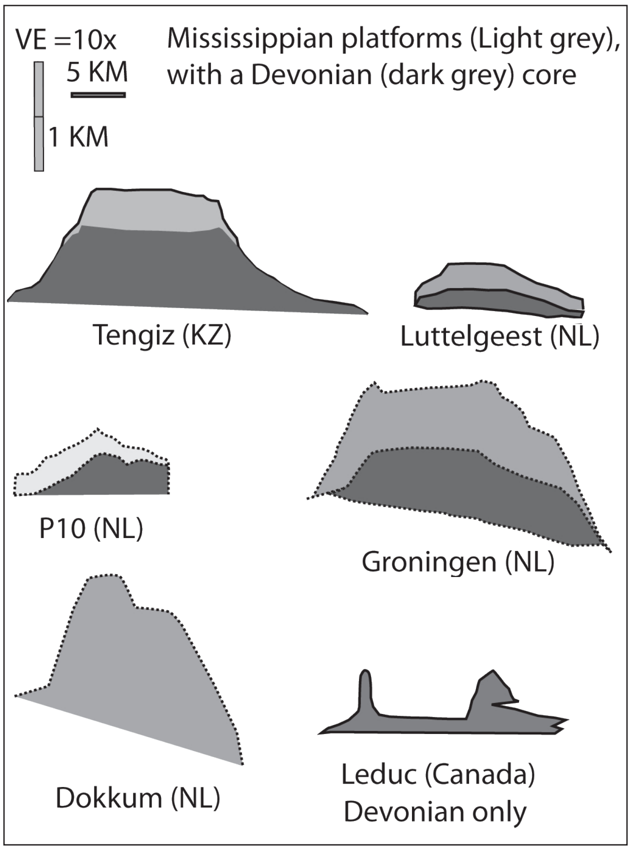

Figure 11. Vertical dimensions of the known reefs in the Netherlands and Tengiz (Caspian Sea region. Most of the Dutch dimensions have been derived from Kombrink (2008).

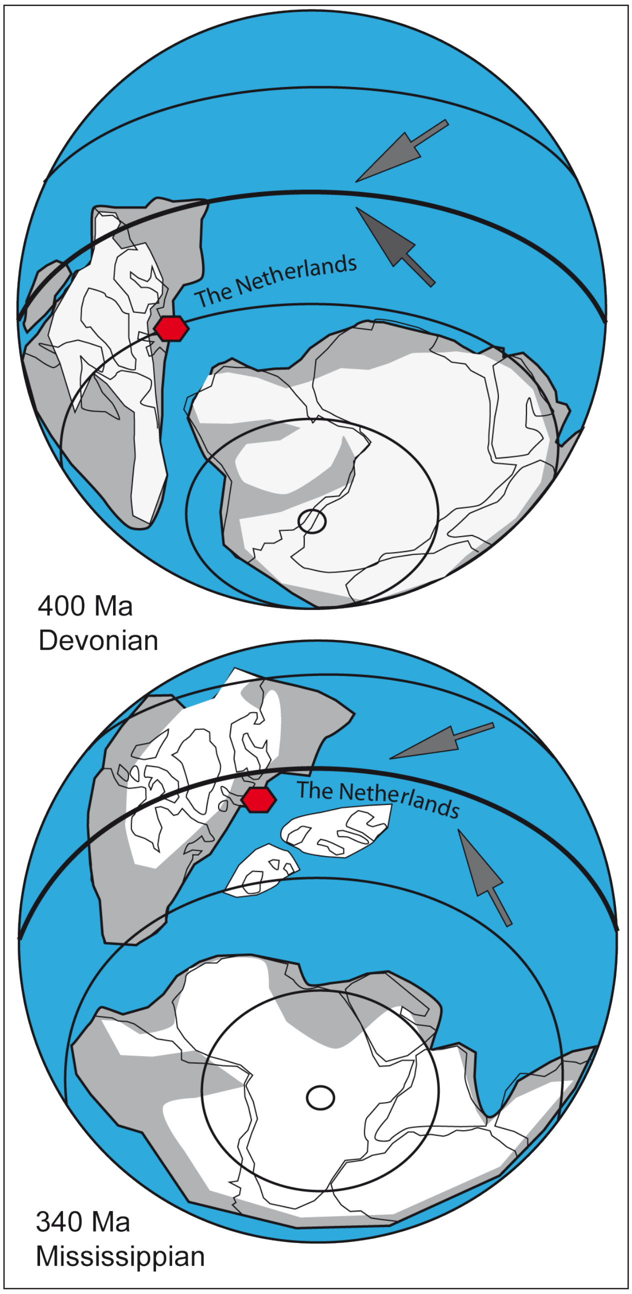

Figure 12. Continental plate position during the Devonian and the Mississippian (Torsvic & Cocks, 2004). Dominant palaeo trade wind directions are very important for the understanding of the reef development. It is likely that the dominant direction is from the south during the Devonian and shifts towards the east during the Mississippian.

well-studied Devonian reefs in Belgium can be seen in outcrops (Tsien 1971, 1975; 1977; Boulvain, 2007). Globally the reef development is arrested at the end of the Frasnian (Copper, 2002). In Belgium and Canada it terminates before the end of that stage (Fig. 14). The transition of the mid Devonian build-ups to the Carboniferous carbonate reefs is more than a temporary halt of the sedimentation pattern. The nature of the reef building changes profoundly. Latest Devonian through mid-Carboniferous time (Famennian - Bashkirian) represents an interval of change in the style and extend of carbonate build-ups and in the composition of build-up communities (Webb, 2002). Globally shallow-water bioherms and reef mounds were still widely distributed during the Famennian despite the Late Frasnian Kellwasser extinction events. They become scarce by the end of the stage (Webb, 2002). The extinction of important reef builders like corals and stromatoporoids at the end of the Frasnian is often cited as the factor which stops reef growth. However, during the Famennian, the dominance of clastic sediment in the North Sea area, explained by rapid eustatic changes, brings carbonate build-up almost to a halt as well in the Netherlands. Reef building and diversity increased again in the Lower Carboniferous and peaked in the late Viséan. Albeit that the global late Viséan diversification trend is not well represented in nearby Belgium (Aretz & Chevalier, 2007).

At the Groningen platform, a resumption of the reef growth, on top of the older presumably Devonian platform, is seen in the Viséan. The platforms in the Groningen and Friesland provinces are quite different from the Belgian or Canadian Tournaisian and Viséan age shelf carbonates. They can be compared in size (Fig. 10 and 11) to the build-ups of the Caspian Sea area (Weber et al. 2003). Very thick carbonate microbialite platforms develop. In the Caspian platforms grainstone shoal deposits display good reservoir potential in the isolated platforms where primary porosity is mainly controlled by intergranular porosity and mud-lean packstone lithofacies. The limited well control in the Dutch carbonate platforms has not shown this kind of porosity. The seismic cross section of Figure 9 clearly shows that different facies types can be distinguished, comparable to the Tengiz platform (Weber et al., 2003) . Based on the seismic it is possible that the Uithuizermeeden-02 well was drilled in back-reef (Menkema) facies (Fig. 9). It is possible that closer to the reef edge grainstones (Meima) facies will be present. Particularly the Devonian section of this seismic line suggests a clear distinction between the reef edge and the lagoonal facies.

In Belgium (Boulvain, 2007) as well as in the Canadian Devonian reef sections (Fig. 14), a number of third order cycles can be distinguished, characterized by periodically arrested reef growth. In the Mississippian age sequences, comparable to Belgian sections, also third order sequences can be distinguished (Fig. 8). Karstification linked to sea-level low stands has been noted at a few intervals in LTG-01 (Van Hulten & Poty, 2009).

The continuation of the carbonate platform development in the Netherlands after the Devonian provides new insights how the bioherms developed during the Mississippian. Because most reef development in the early Mississippian was subdued, it is surprising that carbonate platforms could be so big in the Caspian area. Comparison of the Tengiz bioherm shows that the reefs in the Netherlands are comparable in size. Some Mississippian

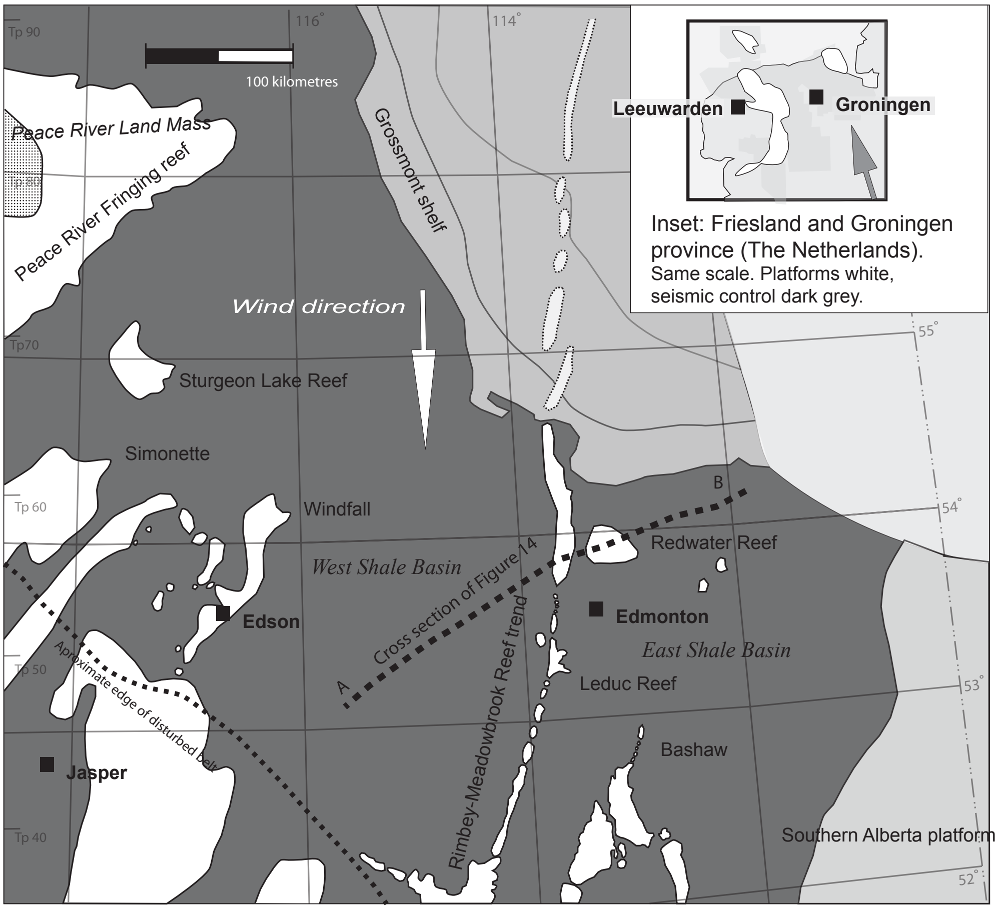

Figure 13. Comparison of the horizontal dimension of the West Canadian Devonian reefs (Mossop & Shetsen, 1994) with the reefs in the Friesland and Groningen province of the Netherlands.

age biohermal development was known in Belgium (Aretz & Chevalier, 2007) and in the UK (Gawthorpe et al., 1989), however the dimensions of those build-ups are significantly smaller.

The large platform complexes are only known from the limited mapping that has been performed in the northern onshore provinces of the Netherlands. The mapped area covers approximately 100 km^{2,} however it is large enough to make some general observations on the distribution of the carbonate platforms during the Devonian and the Mississippian. The lateral extend of the Belgian build-ups is often difficult to estimate, because of complex Variscan structuration (Tsien, 1975). Therefore, parts of the well-studied Devonian reefs of Alberta (Mossop & Shetsen, 1994), have been compared to the carbonate platforms of the Netherlands (Fig. 13).

Important for reef development is the dominance of the wind direction. For an individual Mississippian platform this is described for the Tengiz build-up (Weber et al., 2003). For a regional effect of the wind direction on larger scale carbonate platform development the Devonian Alberta reefs (Mossop & Shetsen, 1994), can be studied.

For the Mississippian in the Netherlands, a case can be made for a dominant wind direction from the east to north-east (Van Hulten & Poty, 2008), this is comparable to the wind direction in the Caspian during that time (Weber et al., 2003). It is in agreement with the general ramp setting of well-studied Belgian Mississippian (Poty et al., 2002). It explains also why no Lower Carboniferous reefs are developed at the Mid North Sea High.

Devonian build-ups are developed in Belgium south of the London-Brabant Massif and at the Mid North Sea High. This suggests a different dominant wind direction. For the Devonian the palaeo position of the Netherlands is south of the equator (Fig. 12). This makes a trade wind direction from the South or Southeast more likely. The nature of the Devonian build-ups in southern Belgium (Boulvain et al., 2005), does not contradict

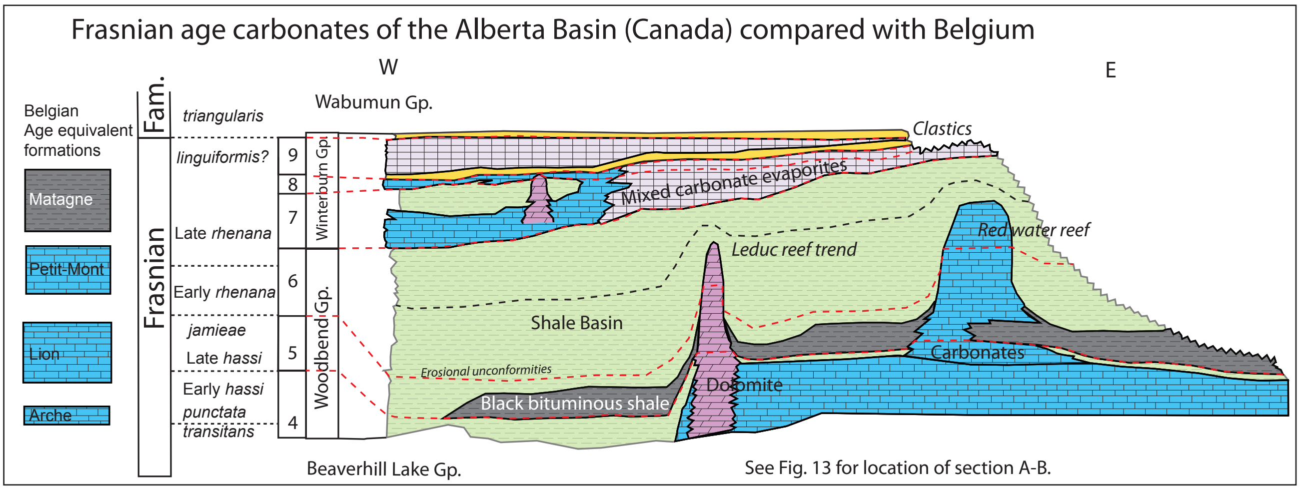

Figure 14. Comparison of the vertical dimensions and the dating of the West Canadian Devonian reef development (Potma et al. 2001; Mossop & Shetsen, 1994,) with the Devonian reefs in Belgium (Bultynck & Dejonghe, 2002). The Frasnian Canadian reefs can reach a thickness of 250 m. The Leduc reef trend terminates in the *rhenana* Conodont zone.

such southern wind direction. The large Dokkum reef trend in Friesland (Fig. 2) may also be Mississippian platform on top of an older Devonian fringe reef. Reminiscing to Canadian Givetian-Frasnian build-ups (Mossop & Shetsen, 1994), the huge Dokkum platform may be originally developed by oblique trade winds from the south comparable to the Devonian reefs in Canada, albeit that the wind in Alberta during the Devonian probably comes from the present day north, north-east (Mossop & Shetsen, 1994). Wells and better quality seismic than used by Kombrink (2008), is required to gain more certainty on this hypothesis.

6. Palaeogeography

From the new data a new palaeogeography for the Devono-Mississippian can be proposed for the larger Southern North Sea area. With the limited data available it is not possible to sketch a detailed palaeogeography, however it is possible to make general maps on Epoch level for the Givetian-Frasnian and Tournaisian-Viséan periods. It should be realized that not too long ago only the most southern part of the country could be mapped with confidence (see for example Bless et al., 1976; 1980). Of importance are cored limestones in the UK like in the well 38/3-1 (Glennie, 1998), close to the Mid North Sea High (Fig. 3). The fossiliferous lime mudstones, wackestones, packstones and grainstones in this well are proof of a marine connection of the Mid North Sea High region with the postulated Devonian Rheic Ocean in the South East (Ziegler, 1990). They give confidence to the idea that carbonate platforms develop during the Givetian-Frasnian on local topographical highs at the Mid North Sea High also in areas now covered with thick Late Devonian and Mississippian Yoredale type clastics (Milton-Worssell et al., 2009). Marine Givetian limestones are described in the German well Q/1 and in the German well Münsterland-1, not too far from the German Dutch border are in agreement with the idea of carbonate sedimentation during the Givetian and Frasnian. In the few wells that penetrate the Devonian in the Netherlands mostly clastic sediments are found. These wells were clustered in the south west part of the country. Frasnian marine shales in some wells like S05-01, make it certain that a coast line covered part of the Netherlands during the Middle Devonian. Not all areas near the London-Brabant Massif display clastic facies. More to the east some biostromal limestones in South Limburg have been found.

The new Devonian and the Mississippian maps share a number of geographical elements like highs and basin areas. The most important shared basin area is the East Frisian Black Shale Basin (Hoffmann et al., 2005; Van Hulten & Poty, 2008), which extends far to the east into northern Germany and connects further to the east to the Rheic Ocean. There is no reason to assume that a deep shale basin, as is postulated for the Mississippian (Van Hulten & Poty, 2008), is not present earlier during the Givetian-Frasnian. Successful magnetotelluric experiments which rely on conductive shales between the deep well Münsterland-1 and the Ringkøbing Fyn High make it more likely that a shale basin was already present in an early stage. The measured conductive shales can be of Devonian or Carboniferous age.

The highs which border the deep shale basin area are nuclei for reef development, provided that there is not too much clastic input. The map of the Devonian and the Mississippian differ. This can be explained because the carbonae platform architecture changes with the shifting dominant (trade) wind direction in time. The high sea level stand during the Givetian-Frasnian and Mississippian halts clastic input. During the periodic low stands of the Famennian there is a dominance of clastic sedimentation.

The prevailing wind direction (Fig. 12) is very important for the development of the reefs, however the Mississippian carbonate platform development can not be studied in isolation without taking into account the Devonian morphology of the previously existing bioherm. When during the Viséan, after a long hiatus, the carbonate build-up development resumes, in Groningen as well as in Luttelgeest, it builds on a massive Devonian platform. The sheer height of approximately 1000 m of the Devonian part of the build-up in the deeper water area makes it almost impossible to build new platforms outside the existing Devonian reefs. In the shallower parts, Mississippian platforms could develop as well. Also in areas with no or limited carbonate sedimentation during the Devonian, like the Campine Basin, platform carbonates are deposited.

6.1 Devonian Palaeogeography

The Devonian palaeogeography in Western Europe (Fig. 15), is often associated with the Old Red sedimentation. The peri-oceanic setting of the Netherlands makes it an unlikely candidate for the continental deposits so well exposed in the UK. With rising sea levels during the Givetian, the influence of the sea probably was present all over the Netherlands. The marine (Kyle) carbonates in the UK Auk and Argyll fields in the Central North Sea made it clear that the Mid Devonian Sea extended far to the north (Ziegler,

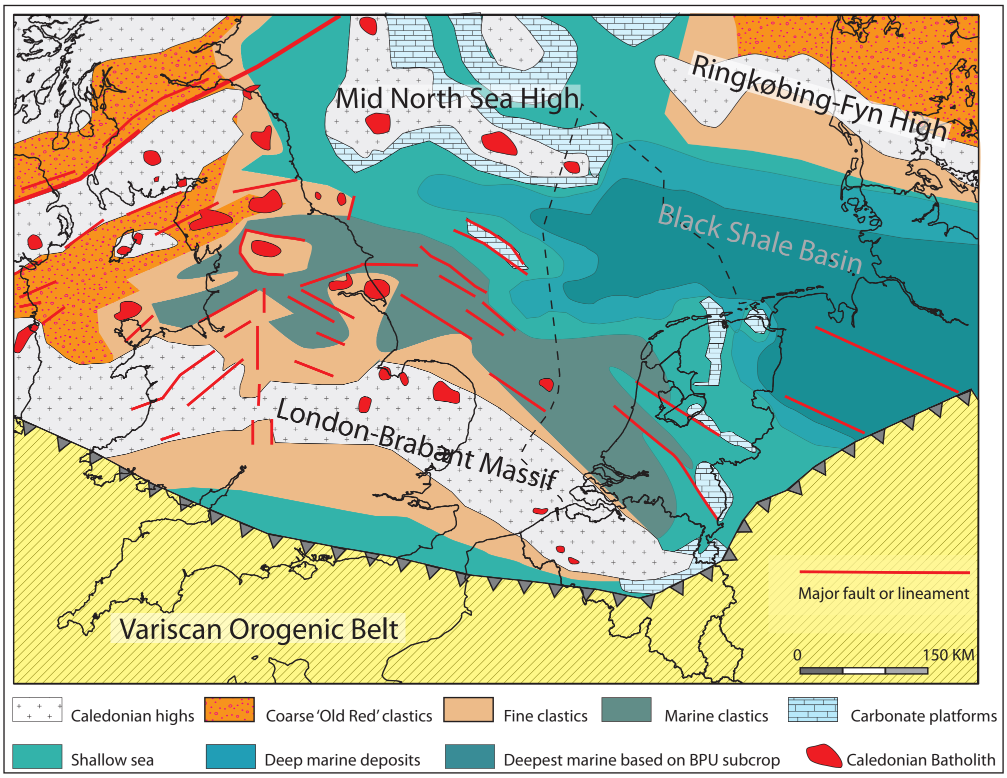

Figure 15. Palaeogeography during the Devonian (Givetian-Frasnian). Reefal limestone are present south of the London-Brabant Massif and at the Mid North High. A few large reefs may have developed in the northern part of the Netherlands. Carbonate platform development is consistent with a dominant wind direction from the south.

1990, Glennie, 1998, Evans et al., 2003). The carbonates have been traced as far north as the (Auk) Flora ridge (Milton-Worssell et al., 2009). During Mid Devonian times palaeogeography of the southern North Sea region is characterized by a deep sea fringed by carbonate platforms and reefs (Fig. 15), with local marine clastic sedimentation in the area just north of the London-Brabant Massif probably in a back reef setting. Towards the west, no marine passage way is known, as exists during the Mississippian. The Devonian sea in this area differs from the situation during the Mississippian where it is a strait, which is connected to present-day North America.

The sea level rise which started in the Eifelian and caused widespread carbonate deposition in the Givetian south of the London-Brabant Massif, affected also the Southern North Sea region north of the Massif. Based on prevailing trade winds it is plausible that platforms developed on batholiths of the Mid North Sea High. Kyle type of carbonates are witness that reef growth is possible in the area, however a sizable carbonate platform development has to be proven. It is likely that reef development has taken place on the other side of the Ost Frisian Shale Basin, in the Dutch Friesland and Groningen onshore provinces, directly north of the Texel-IJsselmeer High (Fig. 3).

The clastic sedimentation in the south western part of the Netherlands, is in agreement with a lee side of the London-Brabant Massif. Because of the relatively good well control in this area, the clastic nature of the Devonian is probably overstated and its deposition is restricted to a smaller sub-basin area. It is unclear if Devonian carbonates are developed on the Maasbommel-Krefeld High (Figs 3, 6).

6.2 Famennian clastics

A major change occurs during the Famennian which is difficult to capture on palaeogeographical maps because many different facies develop. The carbonate deposition of the Devonian and Mississippian halted in the onshore area and at the Mid North Sea High as well. Reef growth terminated there with the clastic influx of the Upper Old Red sandstones (Evans et al., 2003). On the Mid North Sea High most wells have been ended in these clastic facies. On seismic the transition from shale to coarse clastics of the 'Upper Old Red' is clearly traceable (Fig. 7).

The termination comes probably at the same time as in the south. Belgian outcrops provide a good insight in the kind of deposits which can be expected from this period. It ranges from shallow water to deep marine facies (Thorez et al., 2006). Well information in the southern area indicates thick clastic deposits. Even the big carbonate platforms of Groningen and Luttelgeest have a clastic interval. This is remarkable, because there seems no clear explanation how clastics can be deposited on top of a several hundred meter thick and isolated build-up.

6.3 Mississippian Palaeogeography

The geographical position of the Mississippian carbonate platforms (Fig. 16) is not the same as in the Devonian. In the southern part of the Netherlands, carbonate platforms are dominant, where clastic deposition was prevailing during the Devonian. In the Mid North Sea High area, clastic deposition is dominant after the Frasnian. During the Mississippian, this high is dominated by clastic deposits varying from shallow water deltaic to deep marine (Maynard & Dunay, 1999; Van Adrichem Boogaert & Kouwe, 1997).

In the Groningen and Friesland provinces, a continuation of the Devonian platform growth is seen during the Mississippian. In both the Groningen and the Luttelgeest platform area, carbonate sedimentation resumes again during the Viséan. Carbonate sedimentation starts earlier in the southern part of the country during the Tournaisian (Van Adrichem Boogaert and Kouwe 1997). In a number of Dutch wells, at the northern flank of the London-Brabant Massif, 900-1400 m thick light grey, brown carbonates have been encountered. Generally, it consists of a tight limestone ranging in age from Tournaisian to latest Viséan. A well in this area is the type locality for the Zeeland Formation (Van Adrichem Boogaert and Kouwe 1997; Fig. 1). These carbonates are very similar to platform carbonates described in the UK southern North Sea and onshore Midlands (Cameron and Ziegler 1997). The outcrops in the UK, supported by borehole and seismic information, make it likely, that these early Carboniferous carbonates do not consist of one single uniform shelf platform carbonate, but different facies belts exist related to the forming of half grabens (Fraser & Gawthorpe, 1990; Fraser et al., 1990). Towards the west there is a marine passage way towards Ireland. It is likely that there are more areas with carbonate platform development in the Netherlands. The Texel-IJsselmeer High and the Maasbommel-Krefeld High may be comparable to half grabens in the UK with platform carbonates developed on the highs (Fraser & Gawthorpe, 1990; Van Hulten & Poty, 2008). There are no wells that are drilled into the basinal facies. It is assumed, that a large area of the present North Sea area north of the Frisian Islands was a (black) shale basin during

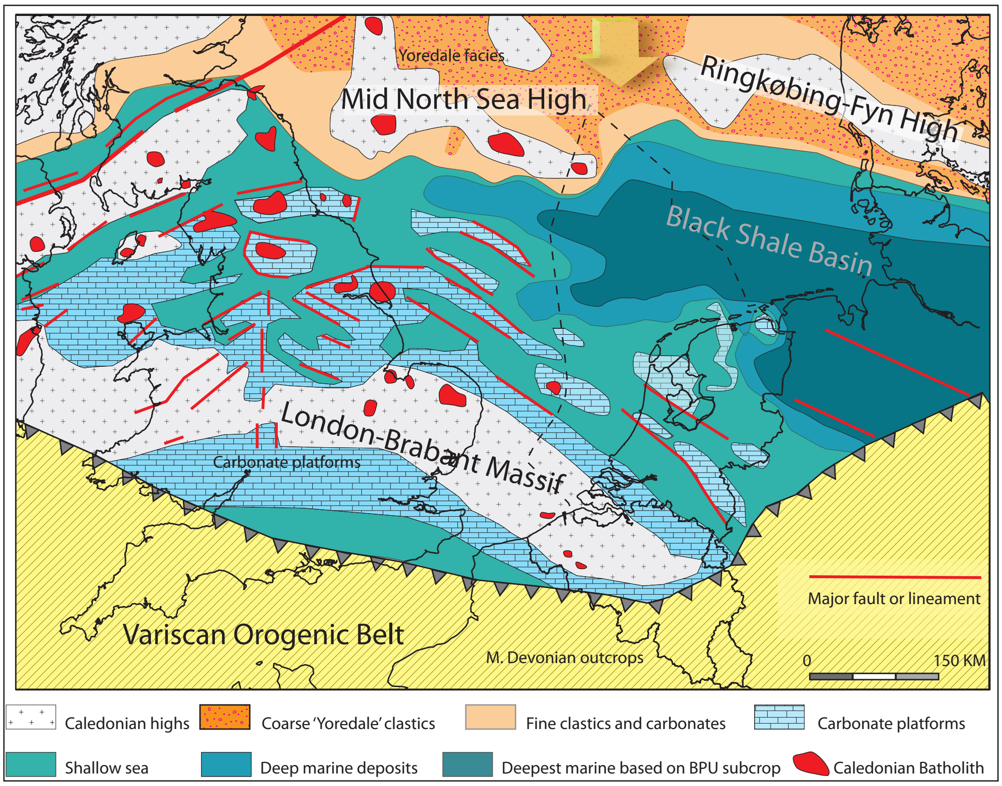

Figure 16. Palaeogeography during the Mississippian. It is very likely that the dominant wind direction during this period is from the North East or East based on the depositional characteristics. Bioherms can develop in the northern part of the Netherlands because the exposure to high energy wave action. There is an open water connection with North America, north of the London-Brabant Massif.

the Mississippian comparable to the Devonian period opening towards the Rheic Ocean in the east.

7. Hydrocarbon exploration

The relevance of the new palaeogeography may be important for oil and gas exploration. It is not the first time that Palaeozoic plays have been discussed (Krebs, 1975, 1978; Fraser & Gawthorpe, 1990; Fraser et al., 1990; Bénard & Bouché, 1991; Gérard, et al., 1993). Van Hulten & Poty (2008) list the major play elements for Mississippian carbonate platforms as trap, that are largely valid for Devonian build-ups as well, with the Pennsylvanian (Namurian) shales as seal and late Mississippian Geverik shales as source. Major risks are the presence of reservoir and the lack of charge because of depth of over 6000 m. A case can be made that the two new exploration wells were drilled in tight (Menkema) facies and that better reservoir quality can be found in grainstone (Meima) facies. Devonian may be better than Mississippian reservoirs, because a higher chance of dolomitisation. Intra Devonian top seal appears to be hardly present in North West Europe, if compared to the Albertan Devonian (Fig. 14), but this is not tested. Because of the very high cost of drilling, these Palaeozoic targets can be considered as a frontier play. With the improvements in seismic acquisition and processing, it is foreseen that more insights are gained in other areas of the Netherlands and more wells will be drilled.

8. Conclusions

In North West Europe, the Devono-Carboniferous section has received new attention, after the drilling in 2001 and 2004 of two deep wells, to very thick Mississippian carbonate build-ups in the Netherlands. The seismic and the well results of the UHM-02 well reveal the existence of a Mississippian carbonate platform that can be compared in size to build-ups in the Caspian region from that same period. Underneath this platform, a undrilled Devonian build-up is likely to be present. At the end of the Viséan carbonate deposition stops in Groningen. The other very deep hole LTG-01 reconfirms the presence of very thick Mississippian carbonates in the northern Netherlands. Carbonate sedimentation of this build-up was arrested much earlier. Based on the findings in these wells, several more than 10 km long reef trends can be mapped with confidence. They extend over large parts of the northern provinces of the Netherlands. Based on the information of the drilled wells and seismic, it is very likely that they have a Devonian carbonate core. The newly discovered carbonate build-ups most likely fringe the southern margin of a deep basin. On the northern margin of this basin at the Mid North Sea High, Givetian-Frasnian carbonates are probably more frequently present than previously thought, despite the failure to find carbonates in the recent UK 37/25-1 (Corbenic) exploration well. There are marked differences between the Devonian and the Mississippian age carbonate deposits. They share a similar depositional setting close to deep water in a transition to very shallow water. A number of depositional elements are well known from classical palaeogeographical maps of the larger North Sea region like highlands in the north west or north in Scotland and Norway. Important variation between these epochs is caused by differences of clastic influx from these highlands. In the classical palaeogeographical view, the more clastic deposition during the Devonian (Old Red) was often contrasted with the more carbonate setting during the Lower Carboniferous. This study showed that in both periods a mixed carbonate clastic system is present. Something which has received less attention, but is important for carbonate platform development, is the northward drift of the Laurussian continent. This probably gradually changed the prevailing tradewind direction, which is very important for reef or carbonate platform development.

9. Acknowledgements

EBN B.V. is acknowledged for the permission to publish this paper. Rien Herber is thanked for providing hi-res copy for figure 9. Bernard Mottequin and Frédéric Boulvain are thanked for their very constructive editing of the paper.

10. References

Abbink, O.A., Schroot, B.M., Van Bergen, F., David, P., Van Eijs, R.M.H.E. & Veld, H., 2007. New Frontiers in Mature Areas-The Hydrocarbon Potential of the Pre-Westphalian in the Netherlands On- and Offshore. European Association of Geoscientists and Engineers, 69th Conference and Technical Exhibition - June 11-14, London, extended abstracts F-038, 5 pp.

Abbink, O.A., Devuyst, F.X., Grötsch, J., Hance, L., Van Hoof, T.B., Kombrink, H. & Van Ojik, K., 2009. The Lower Carboniferous of key-well UHM-02, onshore The Netherlands, and implications for regional basin development. European Association of Geoscientists and Engineers, 71th Conference and Technical Exhibition, June 8-11, Amsterdam, the Netherlands, extended abstracts W031, 5 pp.

Abramovitz, T. & Thybo, H. (2000) Seismic images of Caledonian, lithosphere-scale collision structures in the southeastern North Sea along MONA LISA profile 2. Tectonophysics, 317, 27-54.

Aretz, M. & Chevalier, E., 2007. After the collapse of stromatoporid-coral-reefs - the Famennian and Dinantian reefs of Belgium: much more than Waulsortian mounds. In Álvaro, J.J., Aretz, M., Boulvain, F., Munnecke, A., Vachard, D. & Vennin, E. (eds), Palaeozoic Reefs and Bioaccumulations: Climatic and Evolutionary Controls. The Geological Society of London, Special Publication, 275, 143 -168.

Bayer, U., Grad, M., Pharaoh, T.C., Thybo, H., Guterch, A., Banka, D., Lamarche, J., Lassen, A., Lewerenz, B., Scheck, M. & Marotta, A.M., 2002. The southern margin of the East European Craton: new results from seismic sounding and potential fields between the North Sea and Poland. Tectonophysics, 360, 301-314.

Bénard, F. & Bouché, P., 1991. Aspects of the petroleum geology of the Variscan foreland of Western Europe. In Spencer, A.M. (ed.), Generation, accumulation and production of Europe's hydrocarbons, Proceed. First Conf. EAPG. May 30-June 2, West Berlin, Special Publication of the European Association of Petroleum Geoscientists, no. 1., Oxford University Press, 119-138.

Bless, M.J.M., Bouckaert, J., Bouzet, P., Conil, R., Cornet, P., Fairon-Demaret, M., Groessens, E., Longerstaey, P., Meesen, J.P.M.T., Paproth, E., Pirlet, H., Streel, M., Amerom, H.W.J. & Wolf, M., 1976. Dinantian rocks in the subsurface north of the Brabant and Ardenno-Rhenish Massifs in Belgium, the Netherlands and the Federal Republic of Germany. Mededelingen Rijks Geologische Dienst, nieuwe serie, 27, 81-195.

Bless, M.J.M., Bouckaert, J., Conil, R., Groessens, E., Kasig, W., Paproth, E., Poty, E., Van Steenwinkel, M., Steel, M. & Walter, R., 1980. Pre-Permian depositional environments around the Brabant Massif in Belgium, The Netherlands and Germany. Sedimentary Geology, 27, 1-81.

Boulvain, F., 2007. Frasnian carbonate mounds from Belgium: sedimentology and palaeoceanography. In Álvaro J.J., Aretz, M., Boulvain, F., Munnecke, A., Vachard, D. & Vennin, E. (eds), Palaeozoic Reefs and Bioaccumulations: Climatic and Evolutionary Controls. Geological Society, London, Special Publications, 275, 125-142.

Boulvain, F. & Wood, R. 2007. Devonian. In Vennin, E., Aretz, M., Boulvain, F. & Munnecke, A. (eds), Facies from Palaeozoic reefs and bioaccumulations. Mémoires du Muséum national d'Histoire naturelle, Paris, 195,171-223.

Bultynck, P. & Dejonghe, L. 2002. Devonian lithostratigraphic units (Belgium). Geologica Belgica, 4, 39-69.

Copper, P., 2002. Reef development at the Frasnian/Famennian mass extinction boundary. Palaeogeography, Palaeoclimatology, Palaeoecology, 181/1-3, 27-65.

Cameron, N. & Ziegler, T., 1997. Probing the lower limits of a fairway: further pre-Permian potential in the southern North Sea. In Ziegler, K., Turner, P. & Daines, S.R. (eds), Petroleum Geology of the Southern North Sea: Future Potential. The Geological Society of London, Special Publication, 123, 123-141.

Coen-Aubert, M. & Boulvain, F., 2006. Frasnian. In Dejonghe, L. (ed.), Current status of chronostratigraphic units named from Belgium and adjacent areas. Geologica Belgica, 9/1-2, 19-25.

Debacker, T.N., Dewaele, S., Sintubin, M., Verniers, J., Muchez, P. & Boven, A., 2005. Timing and duration of the progressive deformation of the Brabant Massif, Belgium. Geologica Belgica, 8/4, 20-34.

De Vos, W., Verniers, J., Herbosch, A. & Vanguestaine, M., 1993. A new geological map of the Brabant Massif, Belgium. Geological Magazine, 130/5, 605-611.

Department of Energy and Climate Change, UK (DECC), December 2009. Relinquishment report Esso Exploration and Production UK, Licence P1259. (https://og.decc.gov.uk/assets/og/licences/relinquishments/p1259.pdf).

Doornenbal, J.C. & Stevenson, A.G. (eds). 2010. Petroleum geological atlas of the Southern Permian Basin area. European Association of Geoscientists and Engineers Publications B.V., Houten, The Netherlands, 354 pp.

Evans, D., Graham, C., Armour, A. & Bathurst, P., 2003. Millenium atlas: Petroleum Geology of the Central and the Northern North Sea. Geological Society London, London, 989 pp.

Fraser, A.J. & Gawthorpe, R.L., 1990. Tectono-stratigraphic development and hydrocarbon habitat of the Carboniferous in northern England. In Hardman, R.F.P. & Brooks, J. (eds), Tectonic events responsible for Britain's oil and gas reserves. The Geological Society of London, Special Publication, 55, 49-86.

Fraser, A.J., Nash, D.F., Steele, R.P. & Ebdon, C.C.,1990. A regional assessment of the intra-Carboniferous play of Northern England. In Brooks, J. (ed.), Classic petroleum provinces. The Geological Society of London, Special Publication, 50, 417-440.

Gawthorpe, R.L., Gutteridge, P. & Leeder, M.R, 1989. Late Devonian and Dinantian basin evolution in Northern England and North Wales. In Arthurson, R.S., Gutteridge, P. & Nolan, S. C. (eds), The role of tectonics in Devonian and Carboniferous sedimentation in the British Isles, Yorkshire Geological Society Occasional Publications, 6, 1-23.

Gérard, J., Wheatley, T.J., Ritchie, J.S., Sullivan, M. & Basset, M.G., 1993. Permo-Carboniferous and older plays, their historical development and future potential. In Parker, J.R. (ed.), Petroleum Geology of Northwest Europe: Proceedings of the 4th conference, Geological Society of London, 641-650.

Glennie, K.W. (ed.), 1998. Petroleum Geology of the North Sea, Basic concepts and recent advances. Blackwell Science Ltd, London, 636 pp.

Glennie, K.W., 2005. Regional tectonics in relation to Permo-Carboniferous hydrocarbon potential, Southern North Sea Basin. In Collinson, J.D., Evans, D.J., Holliday, D.W. & Jones, N.S. (eds), Carboniferous Hydrocarbon Geology, the southern North Sea and surrounding onshore areas, Yorkshire Geological Society, Occasional Publication, 7, 1-12.

Hance, L., Poty, E. & Devuyst, F.X., 2006a. Tournaisian. In Dejonghe, L. (ed.), Current status of chronostratigraphic units named from Belgium and adjacent areas. Geologica Belgica, 9/1-2, 47-53.

Hance, L., Poty, E. & Devuyst, F.X., 2006b. Viséan. In Dejonghe, L. (ed.), Current status of chronostratigraphic units named from Belgium and adjacent areas. Geologica Belgica, 9/1-2, 55-62.

Herber, M.A. & De Jager, J., 2010. Oil and gas in the Netherlands - is there a future? Geologie en Mijnbouw/Netherlands Journal of Geosciences, 89/2, 91-107.

Hoffmann, N., Jödicke, H. & Horejschi, L., 2005. Regional distribution of the Lower Carboniferous Culm and Carboniferous limestone facies in the Northern German Basin - derived form magnetotelluric soundings. Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 156/2, 323-339.

Kettel, D., 1983. The East Groningen Massif - Detection of an intrusive body by means of coalification. In Kaasschieter, J.P.H. & Reijers, T.J.A. (eds), Petroleum Geology of the southeastern North Sea and the adjacent onshore areas. Proceedings Conference Petroleum Geological Circle of the Royal Geological and Mining Society of the Netherlands, Nov. 24-26, 1982, The Hague, 203-210.

Kombrink, H., Van Lochem, H. & Van Der Zwan, C.J., 2008. Carbonate platforms in the central part of the northwest European Carboniferous basin, new results from seismic interpretation. 33rd International Geological Congress, 6-14 August, Oslo, Norway, Abstract.

Kombrink, H., 2008. The Carboniferous of the Netherlands and surrounding areas; a basin analysis. Geologica Ultraiectina, 294, Ph.D. thesis University of Utrecht,184 pp .

Kombrink, H., 2009. Seismic interpretation of Dinantian Carbonate Platforms in the Northwest European Carboniferous Basin. European Association of Geoscientists and Engineers, 71th Conference and Technical Exhibition, June 8-11, Amsterdam, the Netherlands, extended abstracts V039, 5 pp.

Kombrink, H., Van Lochem, H. & Van Der Zwan, C.J., 2010. Seismic interpretation of Dinantian carbonate platforms in the Netherlands; implications for the palaeogeographical and structural development of the Northwest European Carboniferous Basin. Journal of the Geological Society of London, 167/1, 99-108.

Krebs, W., 1975. Geologische Aspekte der Tiefenexploration im Paläozoikum Norddeutschlands und der südlichen Nordsee. Erdöl-Erdgas Zeitschrift, 91. Jahrgang, 277-284.

Krebs, W., 1978. Aspekte einer potentiellen Kohlenwasserstoff-Führung in den devonischen Riffen Norddeutschlands. Erdöl-Erdgas Zeitschrift, 94. Jahrgang, 15-25.

Laenen, B., Van Tongeren, P.C.H., Dreesen, R. & Dusar, M., 2004. Carbon dioxide sequestration in the Campine Basin and the adjacent Roer Valley Graben (North Belgium): an inventory. In Baines, S.J. & Worden, R.H. (eds), Geological Storage of Carbon Dioxide, The Geological Society of London, Special Publication, 233, 193-230.

Lyngsie, S.B. & Thybo, H., 2007. A new tectonic model for the Laurentia-Avalonia-Baltica sutures in the North Sea: A case study along MONA LISA profile 3. Tectonophysics, 429, 201-227.

Maynard, J.R. & Dunay, R.E., 1999. Reservoirs of the Dinantian (Lower Carboniferous) play of the Southern North Sea. In Fleet, A.J. & Boldy, S.A.R. (eds), Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, Geological Society of London, 729-745.

Milton-Worssell, R., Smith, K., Mcgrandle, A., Watson, J. & Cameron, D., 2010. The search for a Carboniferous petroleum system beneath the UK Central North Sea. In Vining, B.A. & Pickering, S.C., (eds), From mature basins to new frontiers: Proceedings of the 7th conference on Petroleum Geology of North West Europe, Geological Society of London, 1, 57-77.

Mossop, G.D. & Shetsen, I. [comp.], 1994. Geological Atlas of the Western Canada Sedimentary Basin. Canadian Society of Petroleum Geologists and the Alberta Research Council, Calgary, Alberta.

Paproth, E., Conil, R., Bless, M.J.M., Boonen, P., Bouckaert, J., Carpentier, N., Coen-Aubert, M., Delcambre, B., Deprijck, C., Deuzon, S., Dreesen, R., Groessens, E., Hance, L., Hennebert, M., Hibo, D., Hahn, G., Hahn, R., Hislaire, O., Kasig, W., Laloux, M., Lauwers, A., Lees, A., Lys, M., Op De Beek, K., Overlau, P., Pirlet, H., Poty, E., Ramsbottom, W.,Streel, M., Swennen, R., Thorez, J., Vanguestaine, M., Van Steenwinkel, M. & Vieslet, J.L., 1983. Bio- and lithostratigraphic subdivisions of the Dinantian in Belgium, a review. Annales de la Société Géologique de Belgique, 106, 185-239.

Potma, K., Weissenberger, J.A.W., Wong, P.A.K. & Gilhooly, M.G. 2001. Toward a sequence stratigraphic framework for the Frasnian of the Western Canada Basin. Bulletin of Canadian Petroleum Geology, 49/1, 37-85.

Poty, E., Hance, L., Lees, A. & Hennebert, M. 2002. Dinantian lithostratigraphic units (Belgium). In Bultynck, P. & Dejonghe, L. (eds), Guide to a revised lithostratigraphic scale of Belgium, Geologica Belgica, 4/1-2, 69-94.

Quirk, D.G., 1993, Interpreting the Upper Carboniferous of the Dutch Cleaver Bank High. In Parker, J.R.(ed.), Petroleum Geology of Northwest Europe: Proceedings of the 4th conference, Geological Society of London, 697-706.

Rijkers, R.H.B., Duin, E.J.T., Dusar, M. & Langenaeker, V., 1993. Crustal structure of the London-Brabant Massif, southern North Sea. Geological Magazine, 130, 569-574.

Rijkers, R.H.B. & Duin, E.J.T., 1994. Crustal observations beneath the southern North Sea and their tectonic and geologic implications. Tectonophysics, 240, 215-224.

Scheck, M., Bayer, U., Otto, V., Lamarche, J., Banka, D. & Pharaoh, T.C., 2002. The Elbe Fault System in North Central Europe-a basement controlled zone of crustal weakness. Tectonophysics, 360, 281-299.

Scheck-Wenderoth, M. & Lamarche, J., 2005. Crustal memory and basin evolution in the Central European Basin System - new insights from a 3D structural model. Tectonophysics, 397/1-2, 143-165.

Simancas, J.F., Tahiri, A., Azor, A., Lodeiro, F.G., Martinez Poyatos, D.J. & El Hadi, H., 2005. The tectonic frame of the Variscan-Alleghanian orogen in Southern Europe and Northern Africa. Tectonophysics, 398, 181-198.

Thorez, J., Dreesen, R. & Streel, M., 2006. Famennian. In Dejonghe, L. (ed.), Current status of chronostratigraphic units named from Belgium and adjacent areas. Geologica Belgica, 9/1-2, 27-45.

Torsvik, T.H. & Cocks, L.R.M., 2004. Earth geography from 400 to 250 Ma: a palaeomagnetic, faunal and facies review. Journal of the Geological Society of London, 161, 555-572.

Tsien, H.H., 1971. The Middle and Upper Devonian reef-complexes of Belgium. Petroleum Geology of Taiwan, 8, 119-173.

Tsien, H.H., 1975. Introduction to the Devonian reef development in Belgium. 2nd Symposium International sur les récifs coralliens fossiles. Septembre Paris, livret-guide de l'excursion C, 3-43.

Tsien, H.H., 1977. Morphology and development of Devonian reef complexes in Belgium. Proceedings of the Third International Coral Reef Symposium, May 23-27, Miami, Florida, 191-220.

Van Adrichem Boogaert, H.A. & Kouwe, W.F.P. [comp.], 1997. Stratigraphic nomenclature of the Netherlands, revision and update by RGD and NOGEPA. Mededelingen Rijks Geologische Dienst, nieuwe serie, 50, a - j.

Van Hulten, F.F.N. & Poty, E., 2008. Geological factors controlling Early Carboniferous carbonate platform development in the Netherlands. Geological Journal, 43/2-3, 175-196.

Van Hulten, F.F.N. & Poty, E., 2009. Dinantian Reefs underneath the Netherlands. European Association of Geoscientists and Engineers, 71th Conference and Technical Exhibition, June 8-11, Amsterdam, the Netherlands, extended abstracts W039, 5 pp.

Verniers, J., Pharaoh, T.C., André, L., Debacker, T.N., De Vos, W., Everaerts, M., Herbosch, A., Samuellson, J., Sintubin, M. & Vecoli, M., 2002. The Cambrian to mid Devonian basin development and deformation history of Eastern Avalonia, east of the Midlands Microcraton: new data and a review. In Winchester, J.A., Pharaoh, T.C. & Verniers, J. (eds), Palaeozoic Amalgamation of Central Europe The Geological Society of London, Special Publication, 201,47-93.

Webb, G.E., 2002. Latest Devonian and early Carboniferous reefs: Depressed reef building after the Middle Palaeozoic collapse. In Kiessling, W., Flügel, E. & Golonka, J. (eds), Phanerozoic reef patterns, Society for Economic Palaeontologists and Mineralogists Special publication, 72, 239-269.

Weber, L.J., Francis, B.P., Harris, P.M. & Clark, M., 2003. Stratigraphy, facies, and reservoir characterization - Tengiz Field, Kazakhstan. In Ahr, W.M., Harris, P.M., Morgan, W.A. & Somerville, I.D. (eds.), Permo-Carboniferous Carbonate Platforms and Reefs, Joint SEPM Special Publication no. 78 - American Association of Petroleum Geologists, 83,351-394.

Williamson, J.P., Pharaoh, T.C., Banka, D., Thybo, H., Laigle, M. & Lee, M.K., 2002. Potential field modelling of the Baltica-Avalonia (Thor-Tornquist) suture beneath the southern North Sea. Tectonophysics, 360, 47-60.

Wong, T.E., Batjes, D.A.J. & De Jager, J. (eds.), 2007. Geology of the Netherlands. Royal Netherlands Academy of Arts and Sciences, Amsterdam, 354 pp.

Ziegler, P.A. & Louwerens, C.J., 1979. Tectonics of the North Sea. In Oele, E., Schüttenhelm, R.T.E. & Wiggers, A.J., (eds), The Quaternary history of the North Sea, Acta Universitatis Upsaliensis, 2, 7-22.

Ziegler, P.A., 1990. Geological Atlas of Western and Central Europe (2nd Edition). Shell Internationale Petroleum Maatschappij B.V., Distributed by the Geological Society Publishing House, Bath, 239 pp., 56 encl.

Manuscript received 17.02.2012, accepted in revised form 18.06.2012, available on line 15.09.2012.