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Geological factors controlling Early Carboniferous carbonate platform development in the Netherlands

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A deep pre-Silesian carbonate play has recently come into focus in the Netherlands and poses some real opportunities and challenges to the explorationist. Underneath the very thick cover of Westphalian and Namurian clastic sediments, which cover almost the entire Netherlands, a yet undiscovered petroleum system may be present in Dinantian carbonates. However, lack of well control and the significant depth involved has caused pre-Silesian formations to be under-explored. Furthermore, seismic definition below the widespread Permian Zechstein evaporites is often very poor. Nevertheless, recent discoveries in the Caspian Sea area have shown that during the Lower Carboniferous very thick carbonate bioherms can develop. These giant reservoirs related to large build-ups can provide the required size for deep pre-Silesian prospects in the southern North Sea area and Dutch onshore. From the sparse well control and extrapolation of limited geological data in the Netherlands, the United Kingdom, Belgium and Germany, it is suggested that thick Dinantian platform carbonates may be present at the northern fringe of the London-Brabant Massif. For realistic reservoir models of these platforms, areas outside the Netherlands have to be studied, for example the UK Midlands, and south of the London-Brabant Massif, in eastern and southern Belgium. Although, the latter area has been affected by the Variscan Orogeny, the Dinantian-aged rocks at outcrop provide a good model for the understanding of the frequency of the major depositional cycles, solution collapse, erosion and dolomitization processes.

Dolomitization may be one of the most important processes that can provide good reservoir quality, and primary porosity related to reef growth, the second important process. Reservoir studies show, that significant reef growth, with associated grainstone facies on the windward side, is an important factor, to understand Dinantian-aged reservoirs in the Caspian Sea area. Similarly, a dominant east to west wind direction may explain, the development of build-ups and grainstone facies as an eastern fringe to the Dutch Dinantian platforms, but not on the leeward-side of the London-Brabant Massif in southern Belgium.

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1. INTRODUCTION

The play, discussed in this paper, concerns potential hydrocarbon accumulations in Dinantian-aged carbonate build-ups. Several authors have mentioned the virtually unexplored Lower Carboniferous (Tournaisian and Viséan = Lower and Middle Mississippian of Heckel and Clayton 2006) carbonates in the larger southern North Sea area, as a potential regional exploration play (Tubb *et al*. 1986; Cameron and Ziegler 1997). On a more local

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level, exploration potential of these deep carbonates was mentioned by Bless *et al.* (1976) in the Netherlands and by Krebs (1975) and Von Bender and Hedemann (1983) in Germany.

However, most explorationists have generally focused their work on shallower conventional targets. The Netherlands is a major hydrocarbon producing province of NW Europe. It ranks third after Norway and the UK. Exploration of classical Rotliegend and Triassic gas plays in the area continue to yield new discoveries every year. After more than 40 years exploration, following the discovery of the Groningen gas field, the cumulative discoveries do not indicate a hyperbolic flattening ('creaming') when compared with the number of exploration wells (new field wildcats over time) (Breunese *et al*. 2005). Despite these successes, exploration activity in the country has declined, both onshore and offshore. Consequently, a steep decline in gas production is predicted for the coming years. Before the existing infrastructure disappears in the country, it is critical to investigate all remaining exploration potential. This includes deep pre-Permian plays.

Until recently, interest in pre-Silesian targets in the Netherlands was very limited, because of the prohibitive depth of the prospective formations and the high risks related to poor well control. Below the very thick upper Silesian section, the seismic expression of Dinantian marker beds is very weak. Dinantian stratigraphic information is seriously limited, because the few wells that have reached the carbonates are mostly clustered at the basin fringes.

In this study (Figure 1) the generally accepted stratigraphic nomenclature of the Netherlands has been applied (Van Adrichem Boogaert and Kouwe 1997). This nomenclature can also be used for the lithostratigraphic description and definition of the various Carboniferous formations of the Netherlands (for the Dinantian of Belgium, see Poty *et al*. 2002b; Laenen, 2003).

Cameron and Ziegler (1997) challenged explorationists to return to the literature and re-examine the pre-Silesian geology. Helped by recent major discoveries in the Caspian area (e.g. Weber *et al*. 2003) and improving seismic techniques, renewed attention for a deep carbonate play in the country resulted in the drilling of two deep wells Uithuizermeeden UHM-02 in 2002 and Luttelgeest LTG-01 in 2004 (based on reconnaissance exploration data of Fugro Data Solutions; well information is still confidential (Figure 2)). The carbonate play area covers potentially large areas of the country, in an area bordered by the London-Brabant Massif to the south, and the Mid North Sea High to the north. The limits of the play to the east and to the west are not clear and this play may be of interest for some bordering countries (Figure 2). The purpose of this overview is to come to a better understanding of the play area, by comparing the Dinantian sedimentation model of the area north of the London-Brabant Massif with well-known areas like southern Belgium on the south side of the Massif.

<table>
<tr><th colspan="5">Chronostratigraphy</th><th colspan="3">Lithostratigraphy</th></tr>
<tr><th colspan="3">Global</th><th colspan="2">Local</th><th colspan="3">(South) The Netherlands (North)</th></tr>
<tr><td rowspan="9">Palaeozoic</td><td colspan="4" rowspan="2">Permian</td><td colspan="3">Zechstein Gp.</td></tr>
<tr><td colspan="3">Rotliegend Gp.</td></tr>
<tr><td rowspan="5">Carboniferous</td><td rowspan="3">Pennsylvanian</td><td rowspan="3">Silesian</td><td>Stephanian</td><td colspan="3" rowspan="3">Limburg Group</td></tr>
<tr><td>Westphalian</td></tr>
<tr><td>Namurian</td></tr>
<tr><td rowspan="2">Mississippian</td><td rowspan="2">Dinantian</td><td>Viséan</td><td rowspan="2">Zeeland Formation</td><td rowspan="2">Unnamed shale facies</td><td rowspan="2">Farne Group</td></tr>
<tr><td>Tournaisian</td></tr>
<tr><td colspan="4">Devonian</td><td colspan="3">Banjaard Group   Old Red Group</td></tr>
<tr><td colspan="4">Silurian, Ordovician and older</td><td colspan="3">Caledonian basement
(unnamed, largely unknown)</td></tr>
</table>

Figure 1. Stratigraphic table for the Upper Palaeozoic of the Netherlands. Two major unconformities are present: At the base of the Banjaard Group related to the Caledonian Orogeny and at the base of the Rotliegend Group related to the Variscan Orogeny.

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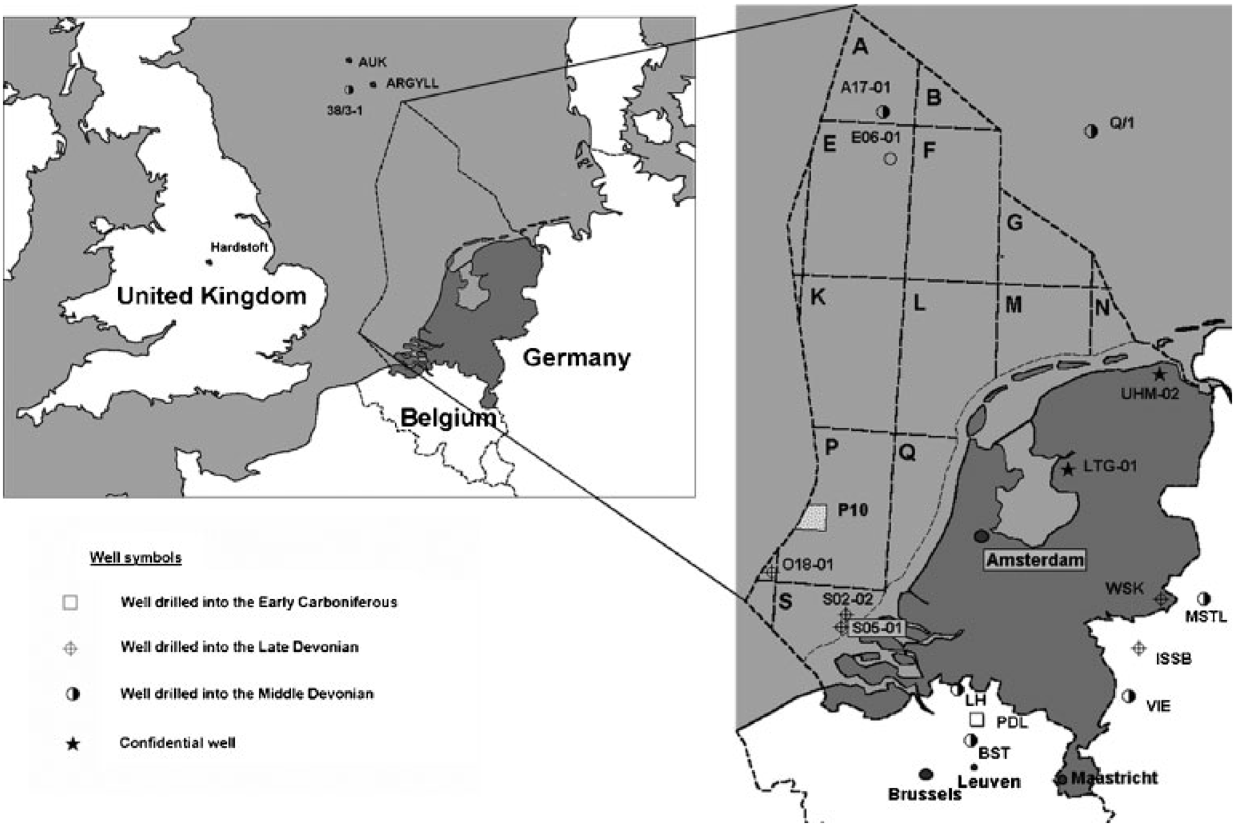

Figure 2. Index map with the location of the Netherlands on- and off-shore. The block P10 (Figure 3) is indicated with shading. The locations of referred wells are indicated: BST = Booischot (KB-132), GVK-1 = Geverik-1, ISSB = Isselburg-3, LH = Loenhout/Heibaart (DzH-1), LTG-01 = Luttelgeest-01, MSTL = Münsterland-1, PDL = Poederlee, UHM-02 = Uithuizermeeden-02, VIE = Viersen-1001, WSK = Winterswijk-01.

1.1. Seismic interpretation analysis

This study was triggered by the serendipitous find of a large structure on seismic sections (Figure 3) in the Dutch offshore license block P10 (Figure 2) in the western part of the Dutch shelf, far below conventional targets. The large structure is interpreted to be formed by Dinantian-aged carbonates. The biohermal nature of part of the structure is suggested by the onlap of the overlying Namurian shales. The kind of detail, visible on seismic over this deep structure is exceptional when compared with other areas of the country. The better seismic definition can largely be explained by the absence of Zechstein carbonates and evaporites in the overburden in this particular location. The depth of the structure, at about 3800 m, is not deep compared with the depth of Dinantian carbonates in other parts of the Netherlands (see Wong *et al*. 2007 for schematic depth map). Dinantian structures are mostly difficult to contour because of their weak reflection. Reflections of the Dinantian carbonates are often hard to distinguish from multiples generated by Zechstein carbonates. ‘Noise’ from Westphalian coals can also complicate the mapping of Dinantian markers. Because of these complicating factors in the overburden, seismic interpretation and mapping of the top of the Dinantian carbonates or other deep markers is rarely performed. The significant depth of the Dinantian markers is a reason as well. Improved acquisition and better processing will facilitate work on deep markers in the future. At present, no regional mapping of these deep markers, based on seismic, comparable to the work in the Campine Basin (Dreesen *et al*. 1987), is publicly available in the Netherlands. However, new studies have been started (Abbink *et al*. 2007). In the Belgian part of the Campine Basin, as in the Dutch southern Limburg

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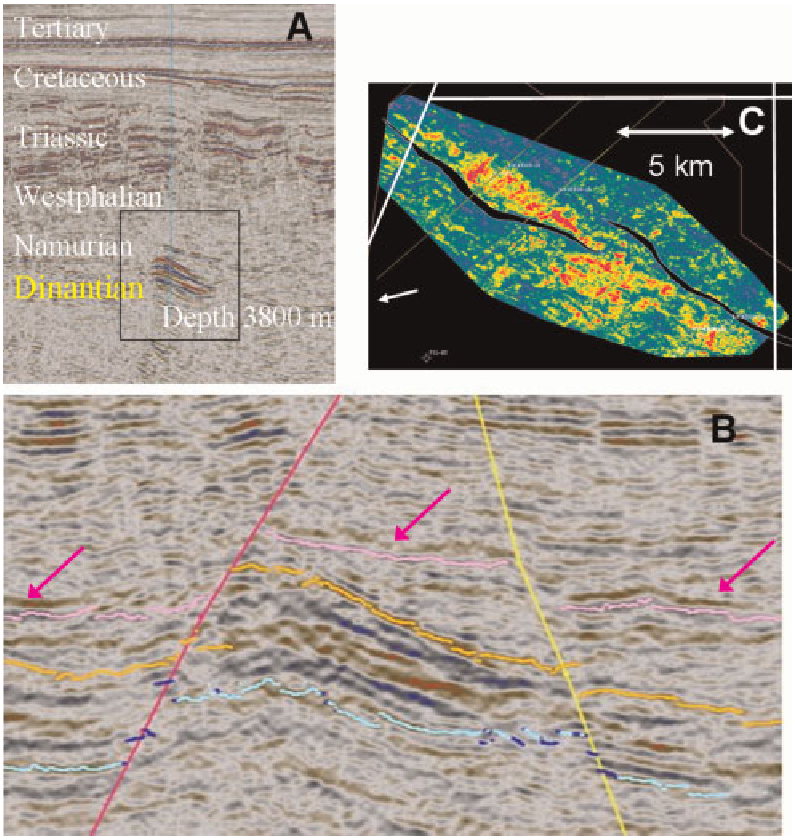

Figure 3. Large Carboniferous structure in the license block P10 in the Netherlands. A few screenshots (time domain) show the large structure on a section from SW to NE (Figure **3A**), at about 3800 m, far below the normal Triassic and Permian targets in the area. The onlap of the Namurian shales (purple horizon arrowed in Figure **3B**) is interpreted as an indication for the presence of a bioherm. The amplitude anomaly at the top of the Dinantian Zeeland Formation (orange horizon) covers an area of about 5–10 km and may be an indication for gas because an amplitude anomaly (Figure **3C**) seems to be structure conformable.

area, the top of the Dinantian can be found at a depth of less than 1000 m (Bless *et al*. 1976). The mapping in that area is not very representative for the rest of the country, with the top of the Dinantian at a depth of 3000–6000 m, sometimes exceeding 10 000 m.

There is a lack of relevant information on P10-type Dinantian structures and the reservoir quality that can be expected. In order to estimate their exploration potential, this study was launched. Because of its depth, it is clear that potential Dinantian exploration targets must be sizable. Such prospects can be expected in large bioherms assuming they have reservoir quality. It is encouraging that over 20 years ago, carbonate build-ups were recognized on seismic lines along block fault edges in the UK (Tubb *et al*. 1986). For a long time it was assumed that these build-ups were most likely some kind of mud-mounds. In North West Europe these bioherms were assigned poor reservoir quality. However, new finds in the Caspian region have shown that sizeable Dinantian carbonate build-ups exist and can have good reservoir potential (Weber *et al*. 2003). In the following sections the question will be answered if bioherms with good reservoir quality can exist in the Netherlands. A brief overview of the Dinantian carbonate play is given first, before focusing on carbonate build-ups. Information from southern Belgium is used to quantify some of the reservoir risks.

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2. HYDROCARBON SOURCE ROCK

The Westphalian coals and organic-rich shales, that form the most important source rock for the Netherlands, are an unlikely source of hydrocarbons for pre-Silesian plays. It is virtually impossible, that these horizons can charge the stratigraphically much deeper positioned, Dinantian reservoirs (Figure 4). Because the thickness of the intervening Namurian shales is in excess of 500 m, Westphalian and Dinantian-aged layers will rarely be juxtaposed.

In the UK, oil-prone source rocks have been found at stratigraphically much deeper levels than the Westphalian coals. These Bowland and Edale shales are known to have charged Dinantian carbonate reservoirs (Fraser *et al*. 1990; Glennie 1998). These early Namurian (Serpukhovian) shales are present onshore in the UK and have sourced several producing oilfields, for example the Hardstoft field in Derbyshire (Figure 2). These Namurian shales are associated with the initial siliciclastic infill of former rift basins (Fraser and Gawthorpe 1990; Figure 4).

Bituminous claystones of comparable early Namurian age have been found in the Dutch Geverik-1 well, drilled in the southern part of the Netherlands. In this well, positioned just north of the town of Maastricht (Figures 2 and 10), a Type II source rock has been postulated for the basal marine Namurian hot shales, based on the presence of bitumen. In the well, the source rock has a total thickness of 15–25 m and a TOC of about 8% (Van Adrichem Boogaert and Kouwe 1997; Van Balen *et al*. 2000). These hot black shales have been interpreted as having settled from suspension in an anoxic basin with restricted circulation. Based on intra-Namurian correlation, it is postulated that the Geverik shales are deposited in a basin that is at least 200 m deeper than the surrounding high areas (Pagnier *et al*. 2003). The information from this well supports the suggestion that in the Netherlands, underneath the kilometre(s)-thick cover of Westphalian and Namurian clastic sediments, which cover almost the entire country, an alternative, albeit hypothetical petroleum system, may be present.

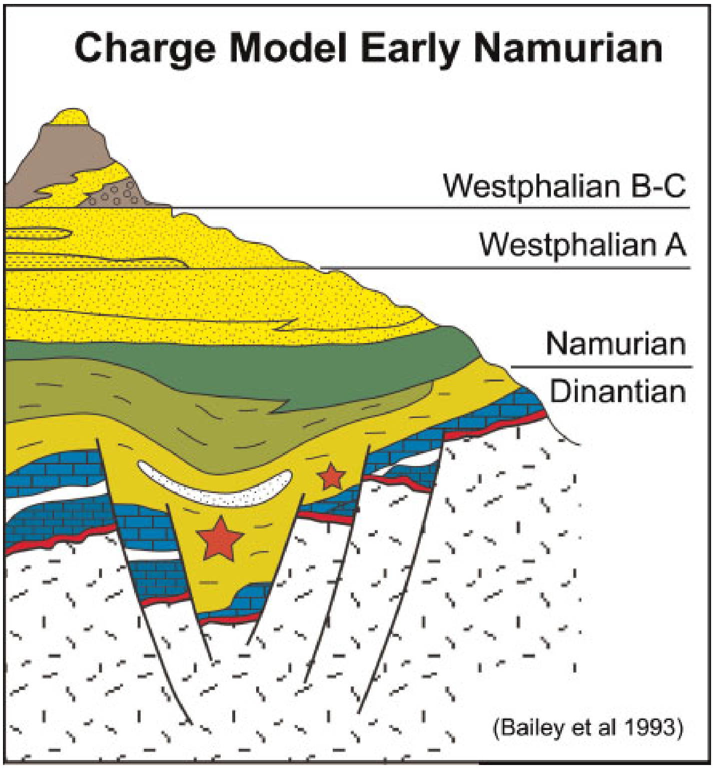

Figure 4. Hydrocarbon habitat of the Lower Carboniferous carbonate play. The sketch shows the Early Namurian hot shales that develop in topographic lows. The shales (indicated with a star) charge Dinantian carbonate reservoirs. The Westphalian coals are positioned stratigraphically much higher and are an unlikely source for Dinantian reservoirs (adapted from Bailey *et al*. 1993). This figure is available in colour online at www.interscience.wiley.com/journal/gj

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Cameron and Ziegler (1997) assumed that traces of pre-Jurassic oil-prone source rocks were proven in the larger Campine Basin area, because of oil present in Permian and Triassic reservoirs that was different from Jurassic source rock-derived oil (Winstanley 1993; De Jager *et al*. 1996). However, these compositional differences were questioned later, because the oils turned out to be more similar to those in the Lower Jurassic shales, than previously thought (Van Balen *et al*. 2000). Also, another suspected Lower Carboniferous oil show was eliminated. After discussions (Van Riessen and Vandenberghe 1996; Van Herreweghe *et al*. 2003), this possible degraded oil, generated from marine type II Mesozoic source rocks of Jurassic or Carboniferous age in the area of Leuven, was established as non-existent. The oil seepage on the edge of the Campine Basin turned out to be a podsol. Based on oil tracing there are not many clear indications that a Lower Carboniferous source exists, but perhaps one should look for gas. It is noted that because of the high temperatures and pressures in the present day Dinantian, the oils derived from these Namurian hot shales will be converted to gas by secondary cracking (Van Balen *et al*. 2000). The current Dinantian prospects will therefore have a higher chance for gas charge than for oil. A new comprehensive basin modelling study confirms good timing of hydrocarbon generation can be expected in the southern North Sea area (Abbink *et al*. 2007).

Source rock potential from deeper horizons, like some intra-Dinantian beds or late- or mid-Devonian beds, is not proven anywhere in the Netherlands or in the surrounding area. There is certainly no indication yet, that there could be a separate Devonian petroleum system present, comparable to the Canadian Devonian (Mossop and Shetsen 1994; Fowler *et al*. 2001). Source potential below the Caledonian unconformity in the Netherlands is unlikely, because of high grades of metamorphism observed in these rocks in a few Dutch wells (Ziegler 1990; Bless *et al*. 1983).

3. SEALS FOR HYDROCARBONS

Namurian shales can provide a seal for pre-Silesian prospects. These shales can be several hundreds of metres thick (Van Adrichem Boogaert and Kouwe 1997; Wong *et al*. 2007). During the Namurian and the Westphalian, sediments were originally deposited in a foreland-basin with a fill over 3000 m thick (Drozdzewski 1993). The upper part is eroded after the Saalian tectonic event, but significant erosion of this cover down to Namurian level occurs only close to the London-Brabant Massif in the south and at the Mid North Sea High in the north. Because of the poor definition of the top Dinantian, there is no regional map that outlines the Namurian shale thickness. The sheet-like isopach map in Wong *et al*. 2007 (Silesian Chapter, fig. 9.) that suggests a 1500–2000 m thickness over most of the Netherlands does not account for significant relief in the underlying Dinantian. A minimum average of a few hundred metres thickness of the Namurian shale seems to be present in most places. In topographic lows the shales may be significantly thicker (Figure 4). A good (Namurian) seal is therefore assumed to be present over most of the Netherlands (Ziegler 1990; Bless *et al*. 1983).

4. HYDROCARBON RESERVOIRS

An important exploration risk for Dinantian prospects is reservoir quality. In their summary of pre-Silesian potential reservoir units, the geologists of Exploration Consultants (Tubb *et al*. 1986) noted that the Dinantian limestones encountered in the UK sector of the North Sea should not be written off as generally tight and non-porous. They are convinced that some promising primary facies may be present. Biohermal facies are mentioned as a potential primary reservoir. Other processes that can create reservoir are karstification (Tubb *et al*. 1986) and dolomitization.

In order to understand the regional distribution of these reservoir types a brief overview of the structural framework and the post-Caledonian geological history is presented. The post-Caledonian structural framework is of importance for the understanding of the early Carboniferous depositional setting that explains reef growth, karstification and dolomitization.

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4.1. Structural framework

The general structural framework of the Dinantian is mainly a theoretical consideration, because the contribution of the detailed seismic analysis is very limited. There is not that much information with respect to the nature of the structural framework. Many publications on the structural development of the Netherlands refer to the post-Variscan structural evolution, and are therefore of limited value for the earlier pre-Variscan setting.

One can glimpse at the post-Caledonian structural configuration in the Netherlands in more detail at the fringes of the London-Brabant Massif and at the Mid North Sea High. These two highs have acted as a positive structural feature after the Caledonian Orogeny. The nature of these massifs is not very clear. Some granites have been described in the UK and Belgian part of the London-Brabant Massif (Glennie 1998; Wong *et al*. 2007). In the Netherlands, granite has been encountered only in the A17-01 well on the Mid North Sea High (Sissingh 2004; Figures 2 and 5). In his summary of all igneous activity of the country, this author does not show other potential granite intrusions in the Netherlands, with the possible exception of the Groningen High. When the Dutch Caledonian features are compared to the UK pattern, it is likely that a few more, not yet recognized, batholiths may be present in the Netherlands.

For the understanding of the pre-Variscan structural framework, it is important to focus on known Caledonian structural elements. The major Caledonian collision zones are situated outside the country, however the pattern of Caledonian micro-continents, batholiths and basin areas (Glennie 2005), that characterize the UK Midlands may very well extend eastward into the Netherlands (Figure 5). After the Caledonian events, up to the present day, the Netherlands were part of a larger North West European intra-cratonic basin. This basin was occasionally affected by tectonic events far outside the Netherlands (Glennie 1998), however these events happened after the Dinantian.

The general structural features during the Devonian and the Lower Carboniferous are assumed to be similar. A block and basin setting related to back-arc stretching is used to describe the structural style in the area north of the London-Brabant Massif (Grayson and Oldham 1987; Fraser and Gawthorpe 1990). This structural style has been extensively studied for the blocks of the UK Midlands and a similar structural style can also be applied in the Belgian Campine Basin (Dreesen *et al*. 1987; Muchez and Langenaeker 1993), the only area north of the London-Brabant Massif shallow enough to be studied in some detail.

In the Netherlands, a general NW–SE fault pattern is assumed to be of pre-Variscan origin (Quirk 1993). This was based on the structural trends in the northern offshore Dutch sector. These trends can also be observed in major Dutch structural elements (Van Adrichem Boogaert and Kouwe 1997). Important structural elements like the Texel-IJsselmeer High and Maasbommel High (Figure 6) show this NW–SE trend. This pattern more or less parallels the Tornquist Suture and can be explained by continued reactivation of this Lower Palaeozoic trend in extensional, compressional and strike slip regimes (Fraser and Gawthorpe 1990).

A characteristic feature for this structural style is the forming of half grabens. It has to be noted, though, that half grabens with their tilted block tectonics can be very misleading for regional correlation of Devonian or Lower Carboniferous strata when there are only a few wells present (Muchez and Langenaeker 1993). Layers in the high part of the block can be eroded and will then be missed by a well.

The fusing of the Laurussian plate with Armorica and Gondwana during the Late Carboniferous took place outside the Netherlands. The effect of this Variscan Orogeny on the structural configuration in the Netherlands is not severe and is probably limited to repeated rejuvenation of upwarp and subsidence along existing fault lines (Bless *et al*. 1983). Intense deformation, with thrusting, can be observed in Germany and Belgium (Bless *et al*. 1983), but stopped just south and east of the Dutch border (Variscan Thrust Front; Figure 5).

4.2. Devonian in the Netherlands

The first sedimentation after the Caledonian events and subsequent erosion took place in the Devonian. Unfortunately, there are only a few Dutch wells that reached Devonian-aged rocks (see Wong *et al*. 2007). Most information with respect to the distribution of the Devonian sediments comes from surrounding countries. The UK Old Red continent, with its fluvial braid plain deposits, may have reached the west of the Netherlands in the early

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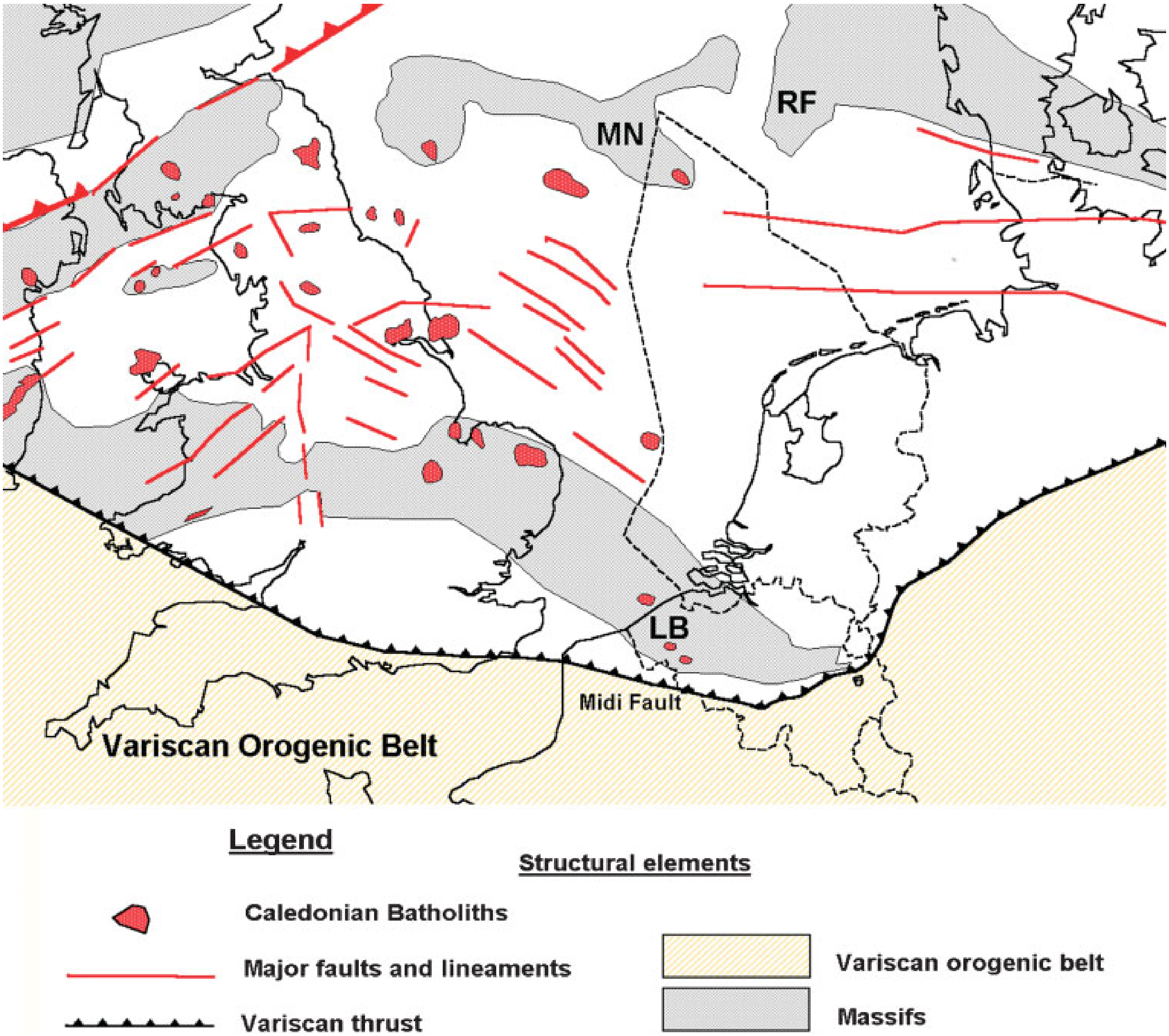

Figure 5. Structural elements north of the London-Brabant Massif in the UK and the Netherlands (UK part modified after Glennie 2005). Location of major faults have been indicated by red lines. North of the Netherlands some major lineaments to the north east of the Netherlands parallel the Tornquist Suture and may be formed by reactivation of this Palaeozoic trend. RF = Ringkøbing-Fyn High; MN = Mid North Sea High; LB = London-Brabant Massif, Variscan orogenic belt south of Variscan thrust, in Belgium called Midi (-Eifelian) thrust.

Devonian. A few wells on the Mid North Sea High e.g. A17-01 and E06-01 (Old Red Group, Van Adrichem Boogaert and Kouwe 1997) display continental facies comparable to the UK. With the advent of the Middle Devonian the supply of terrigenous clastics became drastically reduced and marine sediments can be found at several locations in the North Sea area (Auk and Argyll fields, UK; Figure 2). Carbonate platforms, separated by argillaceous basin belts, developed. From the well-studied outcrops of southern Belgium the development of reef-fringed carbonate platforms in the Frasnian is well known. North of the London-Brabant Massif our knowledge of Devonian depositional environments is very sketchy. In well 38/3-1 (Figure 2), on the Mid North Sea High not too far from the Dutch A and B quadrants, the limestones are cored and found to comprise fossiliferous lime mudstones, wackestones, packstones and rare grainstones, with a macrofauna including corals, bryozoans,

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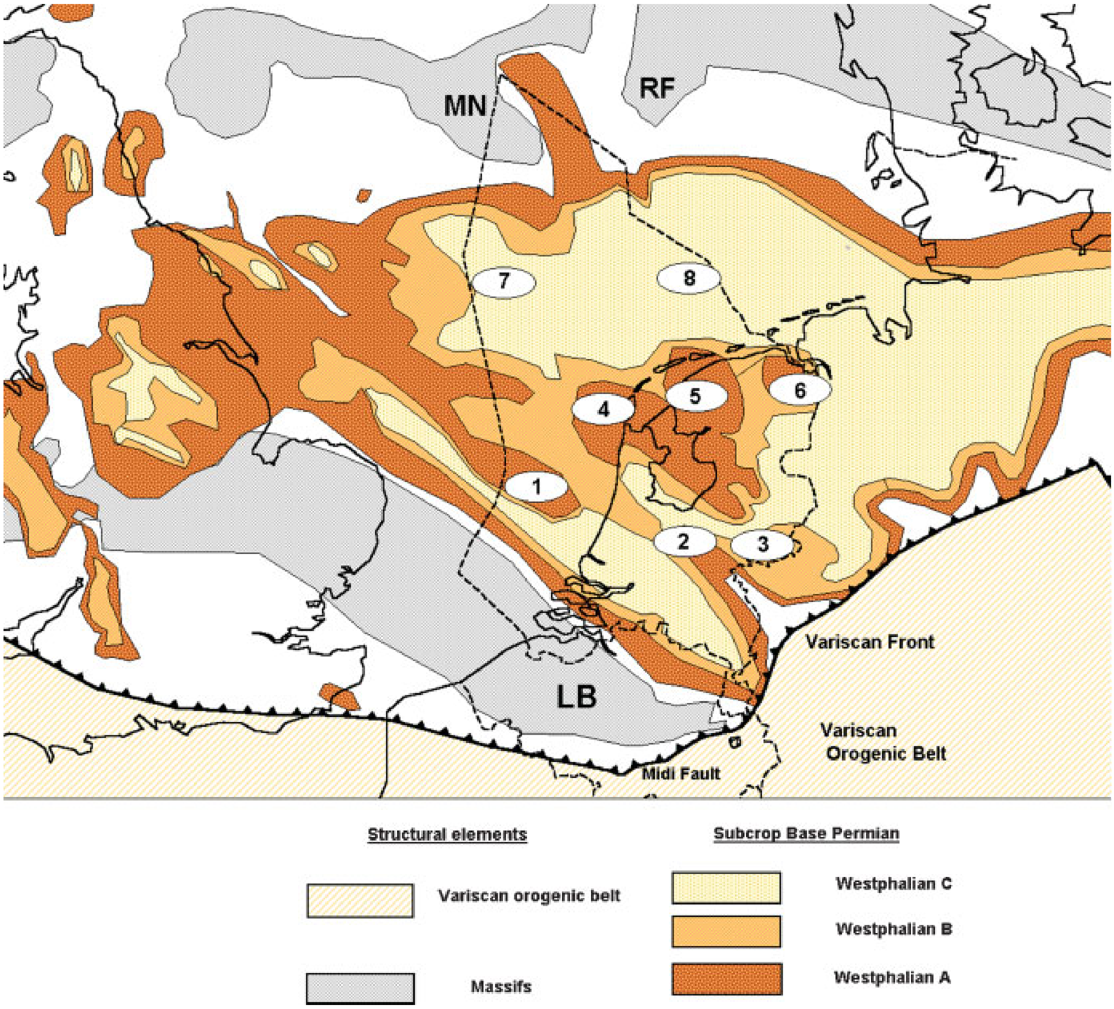

Figure 6. The pre-Permian subcrop pattern (yellow = Westphalian C, brown = Westphalian A), reflects partly the Variscan Orogeny but the major Dinantian blocks and basins can be recognized: (1) the Winterton High; (2) the Maasbommel-Krefeld High; (3) the Achterhoek High; (4) the Texel-IJsselmeer High; (5) the Friesland Platform; (6) the Groningen High. The Cleaver Bank High (7) and the Schill Grund High (8) are not Dinantian blocks. RF = Ringkøbing-Fyn High; MN = Mid North Sea High; LB = London-Brabant Massif.

brachiopods and crinoids. The sequence is interpreted as 'fore reef' or 'reef transition' (Glennie 1998). It is certainly not impossible that thick carbonate build-ups are present in the basin further south and may form the nuclei of the Lower Carboniferous platforms. However, their existence is of a hypothetical nature, because of the lack of hard data. No such Devonian reefs are described in the Netherlands, but from the few data points it is clear that we can expect a coastal setting. Marine Givetian limestones are found in the offshore German Q/1 well (Wong *et al*. 2007; Q/1 has been renamed G3-1, Figure 2) and massive carbonates of Givetian or Lower Frasnian age can be found in the Münsterland-1 well (Wolburg 1963), not too far from the Dutch border in Germany (MSTL, Figure 2). Directly north of the London-Brabant Massif hardly any Givetian or Frasnian rock has been drilled, apart from 33 m of limestone in Loenhout (LH = DzH-1, Figure 2) and biostromal limestones in southern Limburg (Wong *et al*. 2007). There are several wells with clastic deposits from that period, like the 385 m of Givetian-Frasnian conglomerates from Booischot (BST = KB-132, Figure 2) and conglomerates in Viersen-1001

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(VIE, Figure 2) of about that age (Wong *et al*. 2007). Some 175 m of Frasnian marine shales (Muchez and Langenaeker 1993) have been found in the Campine Basin. These shales are similar to marine deposits of the same age in the Netherlands (Bollen claystone of the Banjaard Group in well S05-01, Van Adrichem Boogaert and Kouwe 1997; well location Figure 2).

The regional regression at the end of the Devonian led to the sedimentation of complex clastic deposits during the Famennian period. These deposits are found in several wells north of the London-Brabant Massif (Van Adrichem Boogaert and Kouwe 1997; Wong *et al*. 2007). No indications of an anoxic basin with hot shales, well known from the North American Exshaw shales, have been found in the existing well data of the Netherlands. The Exshaw shales, so important for charging the Mississippian there, displays a TOC 10 wt% ranging from 0–21% and Hydrogen Indices of 400–600 mg HC/g TOC ranging from 100 to 1100 mg HC/g TOC, indicating a Type II organic matter (Fowler *et al*. 2001). Time-equivalent shales are present over a vast area of the North American cratonic platform. The (lower) Exshaw black shales of Canada are equivalent to parts of the Sappington, Chattanooga and Woodford shales in the USA (See Mossop and Shetsen 1994 for a general overview). The lower Exshaw shale unit is of the same age as the lower Bakken shale member (Williston Basin) and is dated as Upper Devonian *expansa* Zone (Meijer Drees and Johnston 1996). The shales, interpreted as deep water deposits, have a high TOC because of eutrophication of a shelf environment caused by upwelling related to increased primary production (Caplan and Bustin 1998).

4.3. Dinantian of the Netherlands

In a number of Dutch wells, at the northern flank of the London-Brabant Massif, 900–1400 m of thick light grey, brown carbonates have been encountered (Figure 7). Generally, it consists of a tight limestone that ranges in age from Tournaisian to latest Viséan and is called the Zeeland Formation (Van Adrichem Boogaert and Kouwe 1997; Figure 1). Sedimentologically they confirm a carbonate platform setting. These carbonates are very similar to platform carbonates described in the UK southern North Sea and onshore (Cameron and Ziegler 1997). The outcrops in the UK Midlands, supported by borehole and seismic information, make it likely, that these early Carboniferous carbonates do not consist of one uniform shelf platform carbonate, but that different facies belts exist related to the forming of half grabens (Fraser and Gawthorpe 1990).

4.4. Dinantian bioherms

Compared to the Devonian, reef development during the Dinantian is quite different. Microbialite build-ups from the Lower Carboniferous differ strongly from the earlier Devonian stromatoporoid and coral framework reefs. In the late Devonian and early Carboniferous the reefal communities take the form of carbonate mud-mounds till the Late Viséan when skeletal framework reefs reappear (Bridges *et al*. 1995; Webb 1996, 2002). It is understandable that the presence of mud-mounds did little to encourage exploration of Dinantian-aged build-ups. The assumption that these mounds had no primary porosity, however, had to be revised, after significant hydrocarbon discoveries were made in the Caspian Sea area. Fields like Tengiz showed that during the Dinantian very thick carbonate microbialite reefs exist with associated good reservoir quality (Weber *et al*. 2003). Grainstone shoal deposits display good reservoir potential in the isolated Caspian platforms where primary porosity is mainly controlled by intergranular porosity and mud-lean packstone lithofacies. Similar facies are not unknown in the Dinantian carbonate fringe area of the Netherlands and Belgium. Grainstones are described in the Campine Basin, directly north of the London-Brabant Massif, in reef-like build-ups (Muchez *et al*. 1990; Aretz and Chevalier 2007). The associated algal mound in the Loenhout-Heibaart Borehole is 74 m thick and is developed close to the margin of the shelf. Similar facies have been observed in the UK (Fraser *et al*. 1990; Tubb *et al*. 1986). This demonstrates that build-ups can be expected in the area north of the London-Brabant Massif. The next question is, where can we find the high-energy facies related to these build-ups or rimmed shelf complexes?

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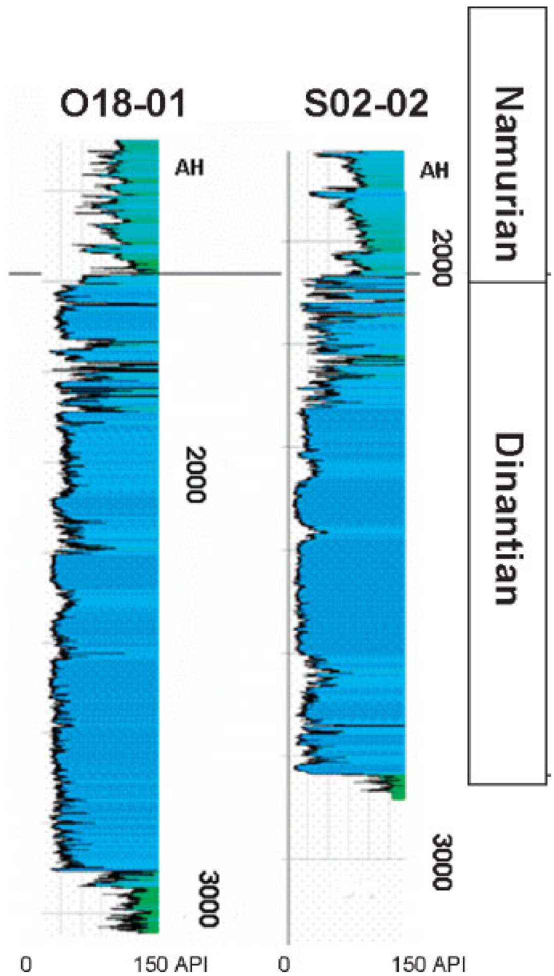

Figure 7. Two Gamma-ray logs from the Dinantian-aged Zeeland Formation. This Formation, which consists of 900–1400 m of light grey brown carbonates, contains little shale as it can be seen on the logs. The basal part is of Tournaisian age, the top part of Viséan age. The underlying shales are of Frasnian age. The overlying shales are of Namurian age. The boundaries with these shales are sharp. The well S02-02 is one of the type sections of the Zeeland Formation (Van Adrichem Boogaert and Kouwe 1997) (see Figure 2 for location of wells O18-01 and S02-02).

4.5. Palaeogeography of Lower Carboniferous reefs

Based on palaeomagnetic, phytogenetic, stratigraphic and tectonic data the palaeogeographical position of NW Europe during the early Carboniferous (Figure 8) is close to or at the equator (Scotese 2003). There are still large uncertainties on major global palaeogeographic issues like the position of Laurussia to Gondwana (Torsvik and Cocks 2004), but deposition during the Dinantian in the Netherlands can be understood better using both global and local palaeogeography. The area north of the London-Brabant Massif is part of a seaway connecting the Russian Platform in the east with oceans bordering the North American craton via the UK and Ireland.

Based on isotope studies and biogeographical evidence, it is likely that surface ocean water could freely circulate between the western and the eastern part of Laurussia (Mii *et al*. 1999; Zhuravlev 2007). In contrast to what the palaeogeographic reconstruction suggests (Figure 8), the relatively small seaway north of the London-Brabant Massif was more important for the circulation than the sea south of the Massif. Biodiversity and affinities with north-eastern America (Nova Scotia) corals is higher in the area north of the Massif (Poty 2002).

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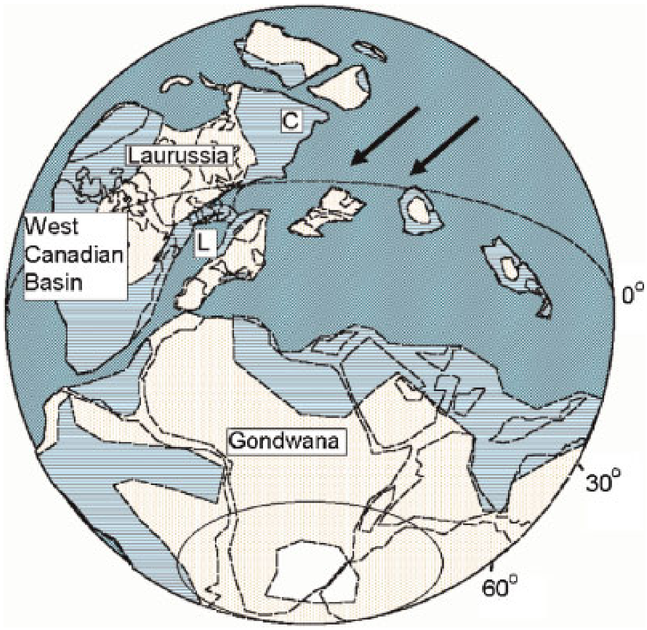

Figure 8. Global palaeogeography of the Lower Carboniferous (modification of Scotese 2003). There are still uncertainties with regard to the position of Gondwana and the Armorican and Rheno-Hercynian terranes relative to the North Sea area. Oceans and shelf seas are indicated. The land sea boundary is hypothetical, because global highstand deposits as to be expected during the Dinantian are often eroded later over large areas. The east to west circulation may be partly blocked because of the development of the emerging Variscan mountains between Laurussia and Gondwana. Based on faunal evidence it is likely that surface ocean water could freely circulate between the western and eastern part of Laurussia. Caspian bioherms at the edge of the Russian Platform share a seaway with the area north of the London-Brabant Massif. Caspian bioherms at the edge of the Russian Platform indicated with (C) share a seaway with the area north of the London-Brabant Massif (L). An arrow indicates the dominant trade wind direction at the Russian Platform that may effect circulation around this Massif. This figure is available in colour online at www.interscience.wiley.com/journal/gj

It is interesting to note, that the Caspian bioherms like Tengiz are positioned close to the same seaway, albeit at a slightly higher latitude. This means that some of the conclusions of the Caspian reservoir studies may be of importance and relevance in the Netherlands.

In the UK many detailed palaeogeographic reconstructions have been made for the area north of the London-Brabant Massif. It is generally accepted that a progradational limestone wedge developed from several Caledonian nuclei. Such a carbonate platform area is also called a block. In the lows between blocks a starved basin with thin sequences of shale, cherts and minor limestones developed. The palaeogeographical maps were mainly focused on the UK part. The Dutch sector is mostly schematic on these maps and there is certainly no consensus as to how to extrapolate features into the Netherlands (Ziegler 1990; Glennie 2005; Wong *et al*. 2007).

One of the reasons that there is no agreement on the Dinantian palaeogeography is the lack of seismic interpretation of the deep horizons in the Netherlands. In order to establish a palaeogeographical pattern, a different method has been used here. The pre-Permian subcrop pattern (Figure 6), formed by the Variscan (Saalian) deformation phase (Van Adrichem Boogaert and Kouwe 1997), has been interpreted to predict the location of Dinantian blocks and basins. It is assumed that the Variscan deformation on this map is only a secondary effect and that the Dinantian topographic pattern is the primary cause of the subcrop pattern (Van Hulten 2005). Assuming excessive shale compaction in the basins, a pattern of blocks and basins can be deduced from this subcrop map. It is proposed that Dinantian highs are indicated by the subcrop of the early Westphalian units like the Westphalian A or B. The Dinantian basins are positioned where the younger Westphalian C and D units or even Stephanian can be found.

Based on the subcrop map, it is now possible to distinguish a number of highs that appear to play an important role in the tectonic history of the Netherlands (Van Adrichem Boogaert and Kouwe 1997):

1. The Winterton High
2. The Maasbommel-Krefeld High
3. The Achterhoek High
4. The Texel-IJsselmeer High
5. The Friesland Platform
6. The Groningen High

Plotted on a map, these highs seem to fit in with the arc-shaped UK pattern of Dinantian platforms (Figure 9). Analysis of the UK examples has discerned that the internal structural configuration of the blocks may be very complex with tilting and complex aggradation. This map is therefore only a simplification.

To the east and north of the Netherlands, the onset of the German Kulm shale basin is present. In the German wells Isselburg-3 (ISSB, Figure 2) and Münsterland-1, Kulm facies have been found (Wolburg 1963; Wong *et al*. 2007). The magnetotelluric method, which relies on measurement of long-period natural electric and magnetic field variations, indicates a highly conductive zone from the Ringkøbing-Fyn High in the north, to the very deep Münsterland-1 well in the south (Hoffmann *et al*. 2001, 2005). This confirms the presence of a black shale basin, which probably extends to the northern part of the Netherlands. Contrary to the published subcrop map (Van Adrichem Boogaert and Kouwe 1997) new well information in the Cleaver Bank High area makes it likely that a subcrop of Westphalian C and D is present there (lower D and E quadrants, Figure 2) comparable with the bordering UK (Cameron *et al*. 2005; Wong *et al*. 2007). The subcrop suggests that the Cleaver Bank High and in all likelihood also the hypothetical Schill Grund High (Palaeogeographic sketch map of the Early Carboniferous in Wong *et al*. 2007) do not exist during the Lower Carboniferous. The Cleaver Bank High was partly a high during the Permian because Westphalian B and C contain sandy layers which were relatively hard to erode. The East Friesland Black Shale Basin of Hoffmann *et al*. (2005) probably extended into the southern part of the Dutch E and F quadrants of the northerly Dutch offshore and may even have reached the UK in the west. Further to the east into Germany the extension of the basin is obscured by the Variscan thrust sheets. The northern boundary of the basin is situated just south of the Mid North Sea High and the Ringkøbing-Fyn High (Figures 5 and 9). Wells in that area drilled into the Dinantian display the influence of Yoredale-type (Farne Group) clastics. During the Mississippian, clastic sediments derived from the Caledonian highlands in the North are deposited at the northern edge of the basin (Van Adrichem Boogaert and Kouwe 1997; Wong *et al*. 2007), but did not reach the southern carbonate platforms.

From this palaeogeography a clearer picture emerges of the play area. The targets for exploration, the bioherms, will be mainly positioned in the southern part of the country. This was already partly suggested based on limited well data (Bless *et al*. 1976). The platform areas probably extend slightly further to the north than was predicted 30 years ago. It is likely that the build-ups developed on the windward (east) side of the platforms and benefited from strong East to West currents (see Gursky 2006, figure 1). Reservoir studies in the Caspian area showed that a dominant trade wind direction (from the East-North East) determined the primary reservoir facies of bioherms. The presence of a dominant wind direction is therefore important for the prediction of the reservoir architecture of the blocks. The equatorial setting of the Netherlands during the Dinantian makes the trade wind issue complicated. It is debatable if a dominant trade wind or monsoon was present and if such trade winds could reach these equatorial latitudes. Palaeoclimate studies have shown that a large landmass like Gondwana can create a strong monsoon circulation (Rowley *et al*. 1985). It has also been suggested (Streel and Marshall 2007) that the emerging Variscan mountains intercept trade winds from the south. If this is the case, such North–East winds could create strong currents in the relatively narrow (palaeo) strait, just south of the Scandinavian craton, connecting the Netherlands with the shelf sea of the Russian Platform. With such dominant wind directions the presence of significant build-ups at E–NE margins are likely. In the Belgian Campine Basin and also in the UK, Upper Viséan bioherms are developed on rimmed margins on the windward side, consistent with an E–NE wave direction (Muchez *et al*. 1990; Aretz and Chevalier 2007). The steep slope of the UK Derbyshire platforms on the east side is also explained by microbialite build-ups on the windward side (Gutteridge 1995).

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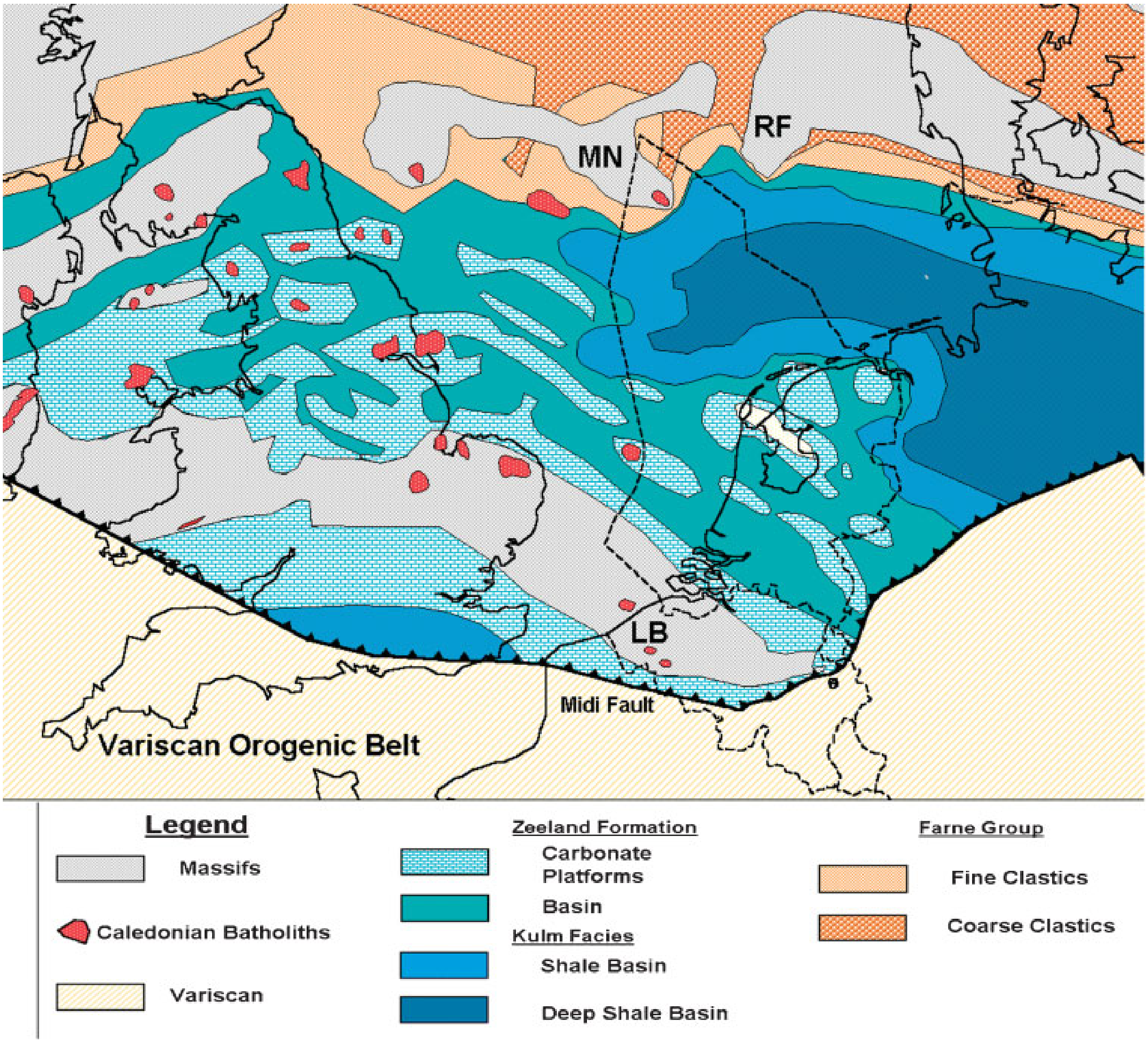

Figure 9. Palaeogeography of the Netherlands and adjacent countries during the Lower Carboniferous with the focus on the area north of the London-Brabant Massif. A progradational limestone wedge developed from several Caledonian nuclei. (Batholiths indicated in red, Palaeozoic Massifs indicated in grey). A pattern of carbonate platforms (blocks) and basins are draped around the London-Brabant Massif (Glennie 2005). Based on the subcrop pattern at the base of the Permian (after the Variscan deformation) a pattern of blocks and basins can be predicted for the Netherlands. To the north and in Germany a black shale basin is present based on Hoffmann *et al*. (2005) on the map this is indicated with darker shades of blue. The carbonate blocks are indicated in light blue, deeper parts darker. From the north, clastic sediments derived from the Caledonian highlands are deposited into the basin (Farne Group) indicated in brown. RF = Ringkøbing-Fyn High; MN = Mid North Sea High; LB = London-Brabant Massif.

5. DINANTIAN OF SOUTHERN BELGIUM

The data from the Netherlands is too limited to conclude on a realistic geological model for these biohermal reservoirs. Other areas with a comparable geological setting have to be incorporated. The UK literature has been used extensively for Dinantian reservoir concepts (Fraser *et al*. 1990). Many examples there are invaluable because subsurface information can be combined with outcrop descriptions of the UK Midlands. Dinantian outcrops, closest

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to the Netherlands, are situated in southern Belgium (Figures 10 and 11). In that area Dinantian-aged rocks are exposed in many quarries and (rail) road cuts and have been intensively studied (Bouckaert and Streel 1974; Devuyst *et al*. 2005).

This wealth of detailed Dinantian information can be compared with information from the model developed for the north side of the London-Brabant Massif. Unfortunately, the southern Belgium area has been affected by the Variscan Orogeny, which sometimes obscures the comparison. The southern Belgium area can be split into autochthonous and allochthonous parts. South of the Variscan deformation front there occurs an area with intense telescoping. In order to understand more clearly the associations of Dinantian rocks, geographic sedimentation areas have been proposed (Poty *et al*. 2002b). Using this concept a transition can be found from shallow-marine carbonates in the Namur Sedimentation Area to deeper marine shales and carbonates in the Dinant Sedimentation Area.

During the Dinantian the overall depositional setting of the area south of the London-Brabant Massif can be characterized as a platform slope. In the Tournaisian, the succession starts on a homoclinal ramp. In the Viséan the succession develops into a southward prograding platform. Despite marked differences in the various sedimentological cycles, the overall setting remains in agreement with deposition on the lee side of the London-Brabant Massif. Dominant off-land winds can explain poor reef growth and explains why southern Belgium is not a good model for the bioherms postulated for the area north of the London-Brabant Massif.

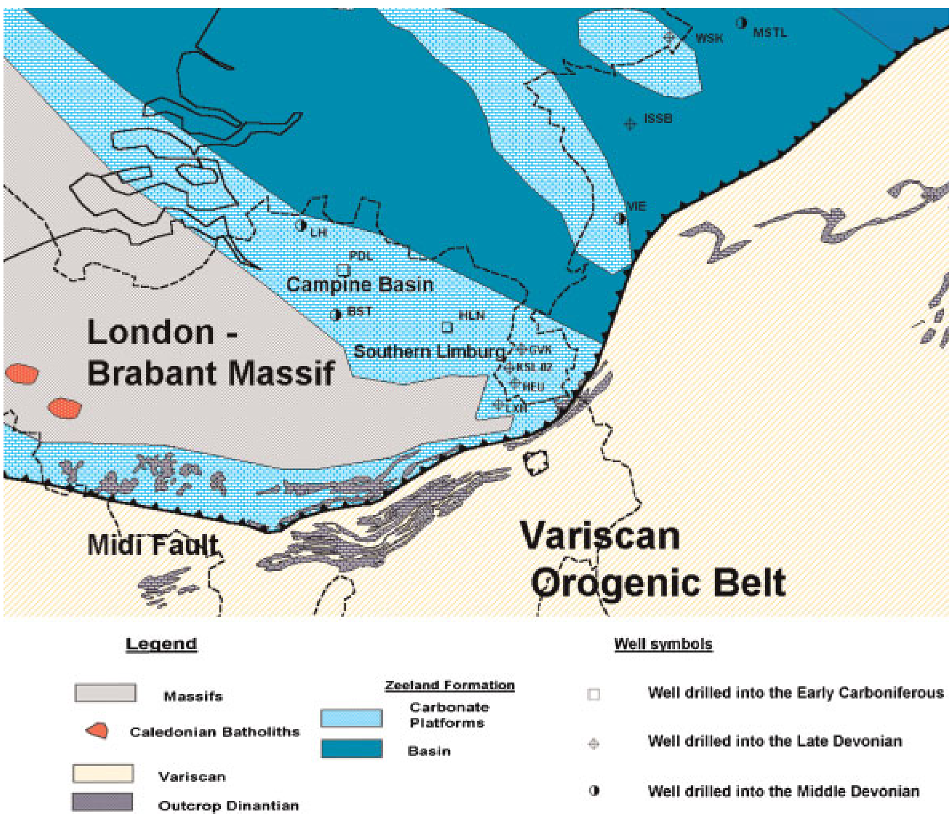

Figure 10. Geological map of southern Belgium with the outcrop of the Dinantian-aged rocks compared with the more hypothetical outline of the carbonate platform facies. Dinantian rocks are exposed in many quarries and road cuts. The area can be divided into an autochthonous (north of the Midi- (Eifelian) thrust) and allochthonous part. South of this Variscan deformation front, there occurs an area with intense telescoping. The locations of referred wells in the vicinity of Maastricht are indicated: GVK = Geverik-1, KSL-02 = Kastanjelaan, HEU = Heugem, LXH = Lixhe B. The other wells are BST = Booischot (KB-132), HLN = Halen (KB-131), ISSB = Isselburg-3, LH = Loenhout/Heibaart (DzH-1), MSTL= Münsterland-1, PDL = Poederlee, VIE = Viersen-1001, WSK = Winterswijk-01. This figure is available in colour online at www.interscience.wiley.com/journal/gj

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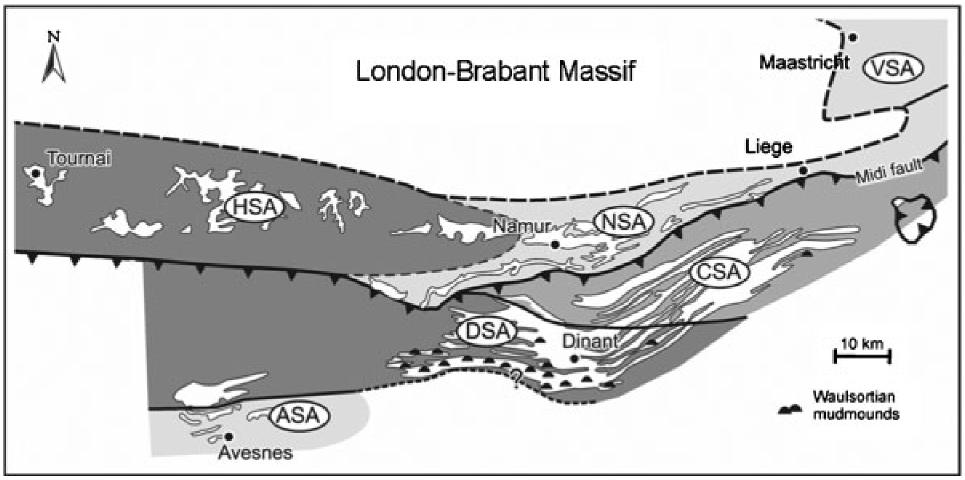

Figure 11. Geological map of southern Belgium with the sedimentation areas of the Dinantian. The area has been divided (Poty *et al*. 2002b) in 5–6 Sedimentation Areas (SA). ASA = Avesnes sedimentation area; DSA = Dinant sedimentation area; CSA = Condroz sedimentation area; NSA = Namur sedimentation area; HAS = Hainaut sedimentation area; VSA = Visé sedimentation area. Deep-water facies with Waulsortian mud-mounds occur towards the south.

This is not to say that no small reefs will be present on the south side of the Massif. In fact, in the southern part of Belgium, the well-known Waulsortian reefs (Lees 1988) and some small patch reefs (Aretz and Chevalier 2007) can be found. The latter, cannot be confused with the reefal build-ups expected north of the London-Brabant Massif or the Waulsortian mounds.

5.1. Waulsortian mounds

A restricted fauna characterizes these well-known carbonate build-ups (Figure 11), named after the small town of Waulsort in the southern part of Belgium (Lees and Miller 1995). Their development, in a more ramp-type depositional setting and relatively deep water, makes them incomparable to high-energy reefs, expected north of the Brabant Massif. This is not to preclude these well-known build-ups with their restricted fauna from being present in the Netherlands, but the lenticular Waulsortian mounds are unlikely candidates for a good reservoir. They cannot develop the grainstone layers, as described from Tengiz (Weber *et al*. 2003), that make those platforms so attractive as a reservoir.

5.2. Correlatable cycles and accommodation space

Useful information for the reservoir model north of the London-Brabant Massif is the nature of the basin-wide correlatable cycles. Nine third-order cycles have been described in detail (Hance *et al.* 2001). The well-documented lithostratigraphic correlations in the Dinantian show that the formations related to these cycles thin to the north and are overstepped by the next cycle (Poty *et al*. 2002b). This suggests that increased accommodation space away from the Massif is present, something that may happen north of the Massif as well (see Figure 12). This means that further to the north, in the Netherlands, reefs may be thicker than those in the vicinity of the London-Brabant Massif.

5.3. Sea-level changes, source rock development, karstification and erosion

The third-order cycles are linked to major sea-level changes (Hance *et al.* 2001). The relative sea-level changes, during the nine cycles, provide an important model for the area north of the London-Brabant Massif. Erosion, leaching, karstification and dolomitization, induced by major low stands, will enhance reservoir potential.

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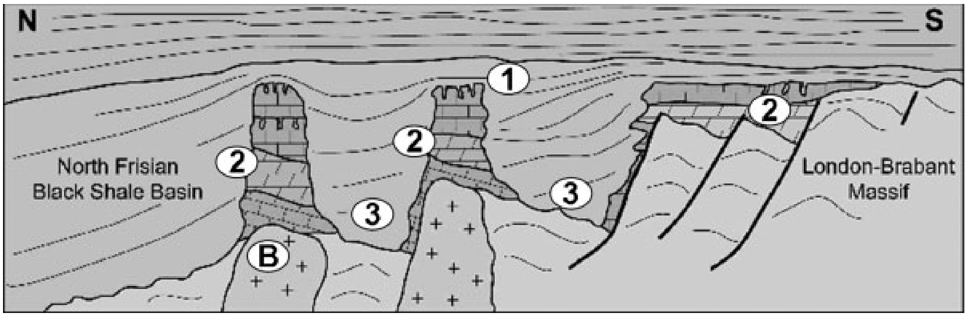

Figure 12. Geological model of Dinantian platform carbonates north of the London-Brabant Massif (partly after Mossop and Shetsen 1994). Caledonian batholiths (B) form the nuclei of Dinantian carbonate build-ups. Part of the basins are formed by half grabens. The carbonates are covered by kilometre-thick shales in the early Namurian. Karstification (1) and the dolomitization process is related to major sea-level low stands (2). Hot shales can develop in the restricted basins of that period (3) or directly after the reef building phase in the early Namurian.

Basin-wide events linked to major sea-level changes can generate source rocks that may be present north of the London-Brabant Massif:

– Black shales develop in the Upper Frasnian and correspond to the lower and upper Kellwasser events.
– The Pont d'Arcole Formation and its equivalent (Alaunschiefer) in the third-order sequence 2 (lower Tournaisian) is characterized by black shales and is widespread in southern Belgium. Its equivalent is probably present in the Netherlands.
– The third-order sequence 5 (lower part of Lower Viséan) is characterized by lower relative sea-levels. Deposition occurs in the deeper parts of basins, sometimes restricted, such as in the Dinant area where the slightly bituminous Black Marble can be found (Mottequin 2008).
– During the Upper Viséan bituminous silty-argillaceous limestones developed in deep parts of the Visé-Maastricht graben. Two chemical analysis have given organic percentages (TOC) ranging between 3.24% and 14.54%. These limestones were found in the Lixhe B Distrigaz Borehole (Liétart 2003, unpublished; LXH, Figure 10), but are also known from other places. Similar bituminous limestones can be developed in areas in the Netherlands affected by block faulting.

Porosity can be enhanced by weathering and fracturing of limestone during a sea-level low stand. In relation to third-order low-stands emersion of carbonate platforms are relatively common during the Dinantian.

In the Kastanjelaan-2 and Heugem-1 wells porosity and permeability have been studied in the Dinantian section (KSL-02 and HEU, Figure 10). Some remarkably high porosities are linked to karstification of the top of the Dinantian (Bless *et al*. 1981).

A hiatus is described directly at the Dinantian/Namurian boundary in wells close to the London-Brabant Massif. On the Massif, the gap lasts until the Pendleian/Serpukhovian and locally until the Kinderscoutian/(Early-) Bashkirian (Bless *et al*. 1976). It is not entirely clear if this is a local phenomenon related to Variscan movements of the Massif, or if this has a regional significance. In the Geverik-1 well (GVK, Figure 10), no hiatus has been found. Also, the mapping of the hiatus (Bless *et al*. 1976) indicates that it may be a local phenomenon. The fall of the sea-level at the Viséan-Namurian boundary gave rise to an important karstification event at the top of the Viséan limestone. This karst is well known in the Namur-Dinant and Campine basins, and is also described in the Montagne Noire in southern France (Poty *et al*. 2002a). The cavities are usually filled with Namurian deposits, but they are sometimes reactivated during the Mesozoic or Cenozoic. On the northern side of the London-Brabant Massif the karst developed in the Upper Viséan of Loenhout-Heibaart (LH, Figures 2 and 10) and is used as a gas storage reservoir.

A special case of the effects of the sea-level fall is solution collapse. The fall in the sea level created, locally, solution collapse breccias from Lower Viséan evaporites, for example in the Condroz area (Belle Roche breccia see: Swennen *et al*. 1990), or from middle Viséan evaporites (Grande Brèche viséenne; Mamet *et al*. 1986).

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5.4. Dolomite

The Belgium area provides a good model for the understanding of the dolomite diagenesis of the Dinantian-aged carbonates. Dolomitization is one of the more important factors that can provide a good reservoir in carbonate rock. In southern Belgium a major low stand is documented during sequence 3 (lower Upper Tournaisian) and sequence 5 (Lower Viséan), giving rise to dolomitization of the coarse-grained limestones of the high-stands of the underlying sequences 2 and 4. Such dolomites are well developed in the Lower Carboniferous-aged carbonates of the Namur-Dinant Basin, but also in the Mississippi area, in the West Canadian Basin, in southern China and in the English Midlands. For Canadian Dinantian petroleum reservoirs, dolomitization is an important factor providing reservoir quality (Mossop and Shetsen 1994). These could also be present in the Netherlands and may form prospective reservoirs (see Figure 12).

The dolomitization process in Belgium is related to major sea-level low stands. The timing of dolomitization is difficult to determine. South of the London-Brabant Massif shallow-marine limestones of Tournaisian and early Viséan age have been dolomitized (Nielsen *et al*. 1994). Dolomitization is limited to carbonates stratigraphically positioned below a low stand in the Late Viséan (Muchez 2001). An important evaporitic collapse breccia is present between the dolomite and Early Viséan peritidal limestone (Swennen *et al*. 1990). A palaeosol dated as Early Viséan also indicates that there was occasional sub-aerial exposure at least up to that time. The low stands that occurred up to the Early Viséan, allowed meteoric water to migrate into the subsurface. Petrographic studies (Muchez and Viaene 1994) indicate a dolomitization process, related to fluid flow near a coastal mixing zone of sea- and meteoric water, during major low stands in the Halen well (HLN, Figure 10). From this information it can be concluded that widespread dolomitization can be expected over large areas in the shallower early Dinantian rocks, as a consequence of some of these major low stands. Dolomitization is not observed in deep water facies. In the Campine Basin dolomitization is also observed up to the Early Viséan low stand (Bless *et al*. 1976; Muchez and Viaene 1994; Laenen 2003). Similar dolomitization must therefore have affected Dutch areas on the north side of the London-Brabant Massif during the early Dinantian and may be a major factor to create a good reservoir in shallow-marine carbonate facies.

5.5. Weathering

After the Dinantian the diagenetic history of large parts of the southern Belgian carbonates is strongly affected by the Variscan uplift (Muchez 2001) and provides no good model for the Dinantian carbonates of the Dutch subsurface. An important fracture system, pressure solution and cements supplied by meteoric water, created in Belgium a porosity system not very representative for the situation in the north. This is not unlike the situation in the UK Midlands. There, poor porosity in some of the outcrops of bioherms has been explained as being caused by local diagenesis and not necessarily condemning reservoir potential of all Dinantian bioherms (Walkden and Williams 1991).

5.6. A model for the Dinantian north of the London-Brabant Massif

For build-ups north of the London-Brabant Massif the Belgian outcrops provide a number of important elements. They are shown in Figure 12. The bioherms will likely be thicker away from the Massif. The major third-order cycles will be of importance as in southern Belgium. Porosity can be enhanced by weathering and fracturing of limestone during a sea-level low stand. Dolomitization is also expected to be important for reservoir development. In the deeper parts of the basin hot shales may have developed.

6. CONCLUSIONS

For the Netherlands it is time-critical to investigate all remaining exploration potential including pre-Silesian plays. Based on recent information from the Caspian Sea area thick carbonate biohermal build-ups of Dinantian age may

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have developed on the north side of the London-Brabant Massif. The overlying Namurian shales may have acted as a source and seal. These bioherms developed along a pre-Variscan fault pattern with a strong NW–SE direction. Locally, batholiths or even Devonian reefs may form the nuclei for the reefal platform. The Dinantian platform facies can be deduced from the subcrop pattern at the Variscan (Saalian) unconformity. At least five platform areas are outlined in the Netherlands, which show a good fit with the pattern of Dinantian platforms in the UK. The Dinantian-aged rocks of southern Belgium provide a good model for the understanding of the frequency of the major depositional cycles, the evaporite deposits and their solution collapse, the dolomitization process and erosion and onlap, during the Dinantian. A dominant trade wind may be the explanation for poor reef growth on the south side of the London-Brabant Massif, contrary to the windward setting that is favourable for reef growth and can provide good primary reservoir facies in grainstone shoal deposits.

In southern Belgium more accommodation space is available away from the Massif. Thick build-ups, or even reefs, can be expected in the Dutch Dinantian fringe, if this is also the case, north of the Massif. The best primary facies, the grainstones, are expected on the east north-east side of the platforms. Dolomite formation is restricted to the section older than the early Viséan and may be one of the more important factors that provide reservoir quality on a more regional scale.

Based on these findings, the reservoir risk of Dinantian carbonate plays has been diminished. It is expected that with these results and improved resolution of modern seismic, the interest in this play will increase.

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