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Palynological indications for Silurian – earliest Devonian age strata in the Netherlands

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Geo(im)pulse

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Abstract

Knowledge of the stratigraphic development of pre-Carboniferous strata in the subsurface of the Netherlands is very limited, leaving the lithostratigraphic nomenclature for this time interval informal. In two wells from the southwestern Netherlands, Silurian strata have repeatedly been reported, suggesting that these are the oldest ever recovered in the Netherlands. The hypothesised presence of Silurian-aged strata has not been tested by biostratigraphic analysis. A similar lack of biostratigraphic control applies to the overlying Devonian succession. We present the results of a palynological study of core material from wells KTG-01 and S05-01. Relatively low-diversity and poorly preserved miospore associations were recorded. These, nonetheless, provide new insights into the regional stratigraphic development of the pre-Carboniferous of the SW Netherlands. The lower two cores from well KTG-01 are of a late Silurian (Ludlow–Pridoli Epoch) to earliest Devonian (Lochkovian) age, confirming that these are the oldest sedimentary strata ever recovered in the Netherlands. The results from the upper cored section from the pre-Carboniferous succession in well KTG-01 and the cored sections from the pre-Carboniferous succession in well S05-01 are more ambiguous. This inferred Devonian succession is, in the current informal lithostratigraphy of the Netherlands, assigned to the Banjaard group and its subordinate Bollen Claystone formation, of presumed Frasnian (i.e. early Late Devonian) age. Age-indicative Middle to Late Devonian palynomorphs were, however, not recorded, and the overall character of the poorly preserved palynological associations in wells KTG-01 and S05-01 may also suggest an Early Devonian age. In terms of lithofacies, however, the cores in well S05-01 can be correlated to the upper Frasnian – lower Famennian Falisolle Formation in the Campine Basin in Belgium. Hence, it remains plausible that an unconformity separates Silurian to Lower Devonian strata from Upper Devonian (Frasnian–Famennian) strata in the SW Netherlands. In general, the abundance of miospore associations points to the presence of a vegetated hinterland and a relatively proximal yet relatively deep marine setting during late Silurian and Early Devonian times. This differs markedly from the open marine depositional settings reported from the Brabant Massif area to the south in present-day Belgium, suggesting a sediment source to the north. The episodic presence of reworked (marine) acritarchs of Ordovician age suggests the influx of sedimentary material from uplifted elements on the present-day Brabant Massif to the south, possibly in relation to the activation of a Brabant Arch system.

Introduction

The stratigraphic relationships of pre-Carboniferous strata in the Netherlands are poorly understood. The lithostratigraphic nomenclature of the Netherlands accounts merely informally for Devonian strata by means of the Banjaard group (TNO–GDN, 2020). Somewhat of an exception is the northern offshore sectors where the Upper Devonian Old Red Group is formally established, largely in analogy to the nearby and extensively studied United Kingdom (UK) offshore. For older than Devonian strata, not even an informal lithostratigraphic nomenclature is available.

In well Kortgene-01 (KTG-01; Fig. 1) and in a well from the adjacent southwestern offshore (O18-01; Fig. 1), both located on the northern flank of the Brabant Massif, Silurian strata have repeatedly been described close to these wells' total depths (TDs). This 'interpretation' is mainly based on facies correlation to wells in the UK (e.g. well 53/16-1; Pharaoh, 1999; Fig. 1) and Belgium (Verniers & Van Grootel, 1991). Independent biostratigraphic evidence for Silurian age strata in the Netherlands is lacking. A similar situation is observed for the overlying Devonian succession in these wells. According to Van Adrichem Boogaert & Kouwe (1994), the Lower Devonian sediments were eroded or were not deposited, an interpretation that is based on the inferred timing of the Brabantian inversion phase related to the onset of the Variscan Orogeny (Herbosch & Debacker, 2018; Pharaoh, 2018).

The informal Devonian Banjaard group consists of the Bollen Claystone formation, which was assigned a tentative Frasnian (early Late Devonian) age, and the Bosscheveld formation of

Fig. 1. Geographical locations where Silurian and/or Devonian strata have been reported in the Netherlands; including relevant wells in the UK and Belgium.

Famennian (late Late Devonian) to Tournaisian (earliest Carboniferous) age. Strata that are undifferentiated on the formation level are claimed to be as old as Middle Devonian (Givetian; see TNO-NITG, 1999). However, the age of the sediments straddling the interval between the metamorphic basement and the conspicuous Lower Carboniferous platform and ramp limestones of the Zeeland Formation (see e.g. Reijmer et al., 2017) remains elusive.

We conducted a palynological study on core material from two key wells penetrating the inferred Silurian and Devonian strata in the southwestern part of the Netherlands: wells KTG-01 and S05-01 (Fig. 1). The resultant stratigraphic relationships, combined with palynologically derived interpretations of the depositional environment, help to elucidate palaeogeographic patterns of the northern fringe of the Brabant Massif.

Geological setting

During Ordovician to Devonian times, the present-day area of NW Europe was affected by major collisions (see Franke et al., 2017 for an overview). Over the course of the Cambrian and Ordovician, Avalonia rifted from Gondwana, drifted northwards and joined Baltica, thereby progressively closing the Tornquist and Iapetus Oceans (Fig. 2A–C). This major tectonic reorganisation is often referred to as the Caledonian Orogeny. As the Avalonia–Baltica continent progressively collided with Laurentia in the late Silurian (Fig. 2C), the large continent Laurussia was formed in the Early Devonian (Fig. 2D). Coeval large-scale compression and rifting of the Rheic Ocean between Armorica and Gondwana and clockwise rotation of Laurussia led to a complex tectonic regime south of the present-day location of the Netherlands, with the establishment of the Rheno-Hercynic Ocean, which comprises a steep foredeep trough, the Brabant Trough, by latest Silurian – earliest Devonian times (Fig. 2C and D). In Belgium, the last phase of the Caledonian orogeny is referred to as the Brabantian inversion phase (Verniers et al., 2002), which set the stage for the progressive uplift of the Late Palaeozoic – Mesozoic Brabant Massif.

The present-day Brabant Massif is completely covered by Mesozoic–Cenozoic deposits. However, the nature and timing of its genesis remain poorly understood. Early Palaeozoic deposition

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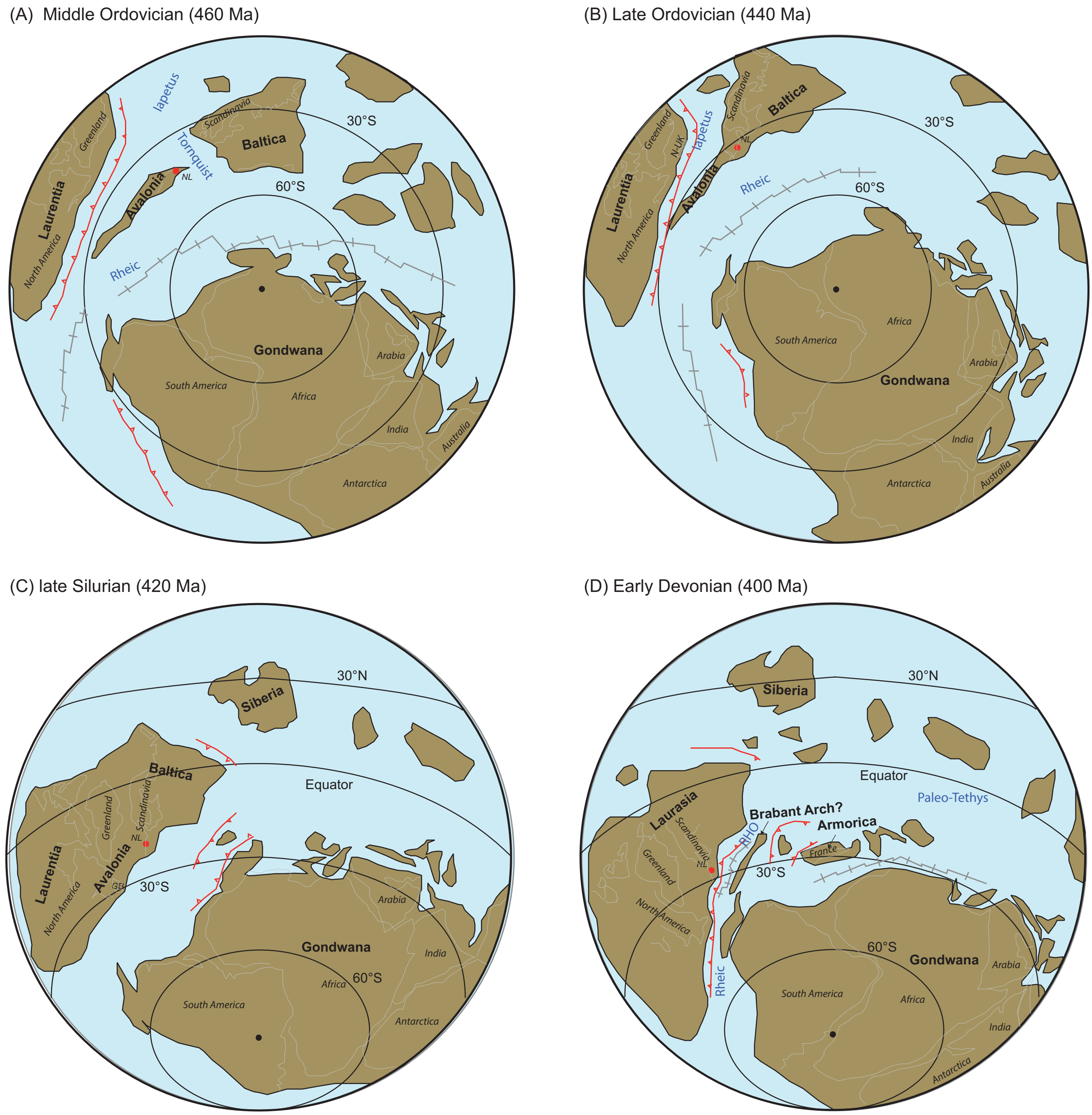

Fig. 2. Palaeogeographic reconstructions displaying the palaeoposition of the Netherlands (red dot) from the Ordovician to the Early Carboniferous. These maps were modified after Franke et al. (2017). Bold annotations refer to ancient land masses, whereas the annotations in italic indicate the position of present-day geographical areas. RHO refers to Rheno-Hercynic Ocean.

in the present-day Brabant Massif area comprises a siliciclastic, often turbiditic succession, ranging from the lower Cambrian in the core to the lowermost Devonian along the southern rims. Evidence exists for a compressional deformation event, likely relating to the Brabantian inversion phase (Debacker, 2002, 2012; Verniers et al., 2002; Sintubin et al., 2009). To the south, southwest and southeast of the Brabant Massif area, the lower Palaeozoic succession is truncated by a major unconformity, with deformed strata overlying relatively undeformed Devonian to Carboniferous deposits (Herbosch & Debacker, 2018). Based on the youngest deformed basement rocks in boreholes on the Brabant Massif (Pridoli to Lochkovian, latest Silurian to earliest Devonian; Verniers & Van Grootel, 1991) and the oldest cover sediments above the Brabantian unconformity (Givetian, Middle Devonian; De Vos et al., 1993), deformation along the southern rim of the Brabant Massif is thought to have taken place between the latest Silurian and the Middle Devonian (Herbosch & Debacker, 2018).

The stratigraphic and depositional context of the northern edge of the Brabant Massif, into the current Dutch study area, remains largely unknown. In the Campine Basin in Belgium, about 50–100 km to the southeast of the current study area. Lagrou &

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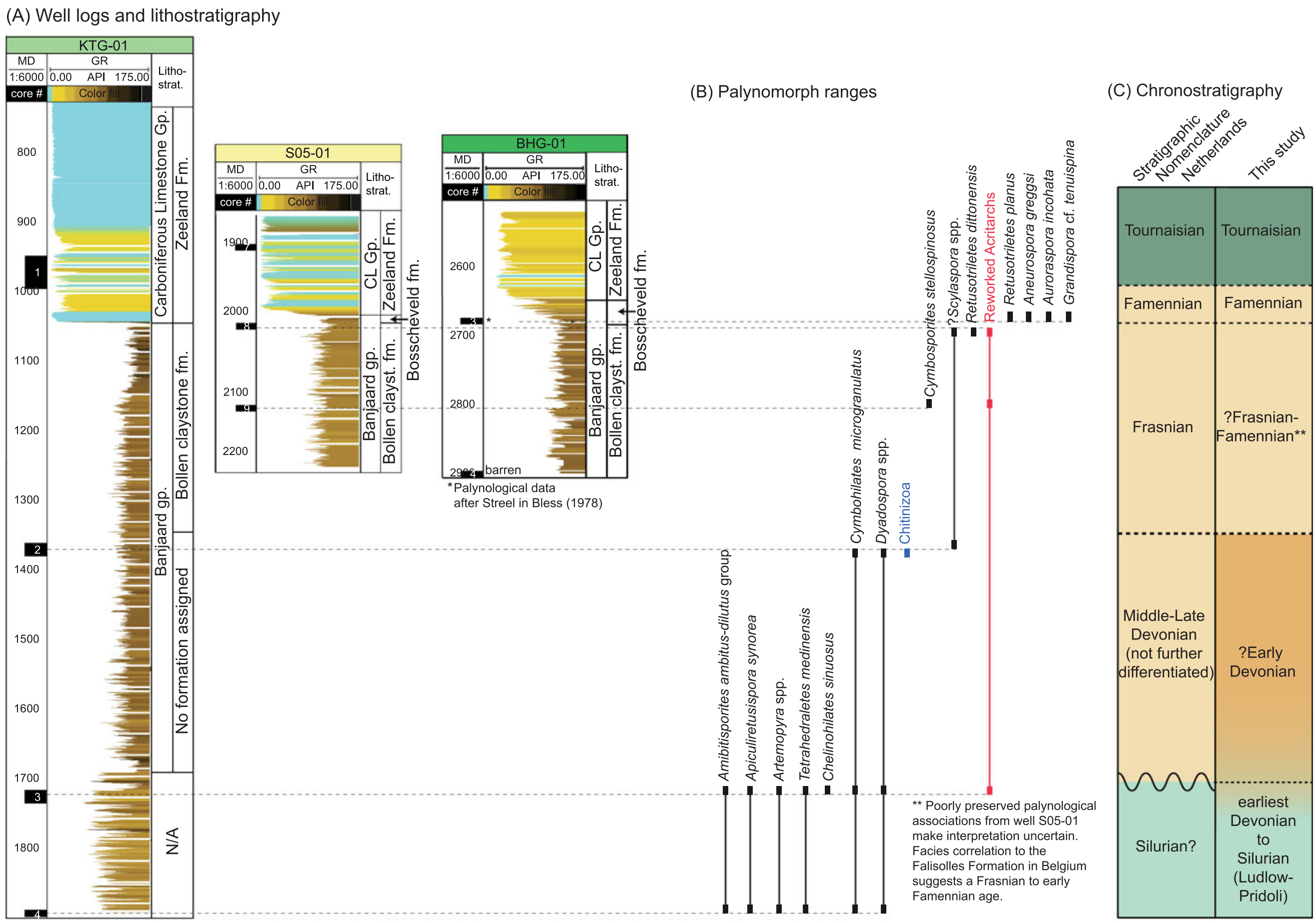

Fig. 3. Results and interpretation of the inferred Silurian–Carboniferous succession as sampled in wells KTG-01, S05-01 and BHG-01. The palynological data of wells KTG-01 and S05-01 were generated in this study. The data for BHG-01 are after Bless (1978). (A) Gamma-ray log patterns for the wells and the lithostratigraphic interpretation according to TNO-GDN (2020). Note that the sections are aligned at the top of the interpreted Bollen Claystone formation. (B) Stratigraphic ranges of palynomorphs. Details on the sampling and palynological observations can be found in the Supplementary Material available online at https://doi.org/10.1017/njg.2020.20. (C) Resulting chronostratigraphic interpretations following from the Stratigraphic Nomenclature of the Netherlands (TNO-GDN, 2020) and the proposed interpretation following from this study.

Coen-Aubert (2017) illustrate, on the basis of two critical wells, that the Caledonian basement of the Brabant Massif, which is of Silurian age, is overlain by a Middle–Late Devonian succession. Details of this stratigraphic section are provided in the next section.

Van Adrichem Boogaert & Kouwe (1994) suggest the presence of a similar truncation in the southwestern part of the Netherlands. In essence, they state that inferred Silurian strata are unconformably overlain by Upper Devonian shales that are in turn overlain by unequivocal lower Carboniferous limestones of the Zeeland Formation (Fig. 3A).

Wells penetrating pre-Carboniferous strata in the Netherlands and the Campine Basin (Belgium)

Southwestern Netherlands

Wells O18-01, S02-02, S05-01, Kortgene-01 (KTG-01) and Brouwershavensegat-01 (BHG-01) have penetrated sediments of the Banjaard group. These sediments comprise dark-coloured shaly and occasionally carbonate-containing mudstones and intercalations of white to greenish-grey, fine-grained sandstones (TNO–GDN, 2020). Wells O18-01 and KTG-01 are supposed to penetrate older, supposed Silurian strata.

Attempts to biostratigraphically constrain the Banjaard group deposits in the SW Netherlands have been unsuccessful (Krans et al., 1983), or compromised by contamination (Abbink & Van de Laar, 2000).

(South)eastern Netherlands

Directly east of the Brabant Massif, in well Kastanjelaan-02 (KSL-02; Fig. 1), in the city of Maastricht, South Limburg, *c.*120 m of Banjaard group sedimentary rocks were continuously cored, all assigned to the Bosschieveld formation. The succession at KSL-02 has been successfully dated using miospores (Bless et al., 1981) as latest Devonian (Upper Famennian) to earliest Carboniferous (Tournaisian). The Bosscheveld formation at KSL-02 comprises from base to top a micaceous sandstone interval, an uppermost Famennian bioclastic limestone interval and a lower Tournaisian dark-coloured shale interval (Bless et al., 1981). Respectively, these intervals can be correlated to the Evieux Formation, the Hastière Formation and the Pont d'Arcole Formation in the Walloon Region in Belgium (Bultynck & Dejonghe, 2001).

Well Winterswijk-01 (WSK-01) has recovered almost 550 m of Banjaard group sedimentary rocks (4460–5010 m). A short

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(0.25 m) core was retrieved close to the well's terminal depth, recovering a non-fossiliferous arcosic sandstone that could not be biostratigraphically dated. However, based on its mineral content, it was considered to be analogous to the Lower Devonian of Germany and Belgium (Bless, 1978).

Northeastern Netherlands

Well Luttelgeest-01 (LTG-01; Fig. 1) recovered *c.*40 m of sediments assigned to the Banjaard group just above its terminal depth of 5162 m. Similarly, in well Uithuizermeeden-02 (UHM-02; Fig. 1), *c.*90 m of sedimentary rock were recovered immediately above the terminal depth of 5432 m and underneath characteristic limestones of the Zeeland Formation. Based on their stratigraphic position in the well, these sediments were assigned to the Devonian and consequently the Banjaard group.

Campine Basin (Belgium)

In the Campine Basin of Belgium, two key wells (Heibaart and Booischot; Fig. 1) penetrate pre-Carboniferous strata that rest on Silurian basement. Lagrou & Coen-Aubert (2017) describe the stratigraphy of this interval in detail. A nearly 400 m thick continental conglomeratic succession is intersected close to the base of the Booischot borehole. These strata are formally described as the Booischot Formation by Lagrou & Coen-Aubert (2017). The upper part of the Booischot Formation is tentatively dated as late Givetian to late Frasnian in age. In the Booischot borehole, the Booischot Formation is overlain by the Upper Devonian marine sediments of the Aisemont and Falisolle formations which are capped by Famennian sandstones assigned to the Evieux Formation. These latter three lithostratigraphic units are also present in the Heibaart borehole, above a few metres of shale and nodular limestone that is attributed to the Middle Frasnian Huccorgne Formation which rests directly on the Caledonian basement of the Brabant Massif (Lagrou & Coen-Aubert, 2017). In both boreholes a succession of richly fossiliferous nodular limestones and shales is assigned to the Aisemont Formation. Based on corals and lithofacies correlation to the type area for this unit in the Ardennes (Bultynck & Dejonghe, 2001), an upper Frasnian age is inferred. The Aisemont Formation is overlain by green-grey shales with micaceous sand intercalations that are assigned to the Falisolle Formation. According to Lagrou & Coen-Aubert (2017), the Falisolle Formation straddles the Frasnian–Famennian boundary in terms of age, largely based on legacy acritarch and conodont interpretations (Kimpe et al., 1978; Vanguestaine et al., 1983). On top of this shaly succession, green and red alluvial sandstones are recorded in both boreholes in the Campine Basin. Streel (1965) presents a typical Famennian palynoflora for these sandstones, supporting their correlation to the Evieux Formation. These Famennian sandstones are overlain by Lower Carboniferous carbonates.

Recent developments

Wells drilled between 2012 and 2016 for geothermal energy near Venlo (CAL-GT-01 to CAL-GT-05; Fig. 1) have all encountered Devonian sediments near their terminal depths (Bosscheveld formation). Two wells drilled near the Belgian border in 2017 and 2019 (Terziet-1 (B62D1112) and 2 (B62D1113); Fig. 1) also encountered Devonian micaceous sandstones. Near the Belgian town of Mol in the Campine Basin (Fig. 1), a well drilled for a geothermal plant encountered 150 m of Late Devonian (Famennian) sandstones (VITO, 2018).

Material and methods

Material

Wells O18-01, S05-01, KTG-01 and BHG-01 all contain cored sections through the interval of interest. Core material from wells KTG-01, S05-01 and BHG-01 is curated in the core storage of both the TNO – Geological Survey of the Netherlands (Zeist) and Nederlandse Aardolie Maatschappij (NAM, Assen). For well O18-01, only polymer slabs, unsuited for palynological sampling, are curated at the TNO – Geological Survey of the Netherlands in Zeist. The remainder of the core could not be traced. For the purpose of this study, we sampled the cores from KTG-01 and S05-01.Published palynological data from BHG-01 exist (Bless, 1978) and were used for correlation in this study.

Well Kortgene-01 (KTG-01)

Vertical well KTG-01 was drilled in 1982 as an exploration well by NAM near the town of Kortgene (Fig. 1). The slightly deviated well recovered a 945 m thick Cenozoic–Cretaceous succession which is unconformably underlain by a 100 m thick lower Carboniferous limestone succession (Beveland Member of the Zeeland Formation). Below 1043 m depth, a *c.*900 m thick fine-grained succession was recovered up to the well's terminal depth at 1900 m. In terms of the gamma-ray log (Fig. 3A), the interval below 1690 m is distinct from the overlying succession in having more prominent low-gamma-ray beds. This is the position at which, according to current insight, strata of the Devonian Banjaard group are separated from underlying Silurian strata.

A total of four cored intervals were retrieved from the well, three of which are below the Carboniferous limestone succession. Both core 4 (1891–1900 m depth) and core 3 (1720–1735 m depth) contain dark laminated silty claystones, with relatively small-scale erosional scours overlain by slightly coarser-grained, lighter-coloured sediment. The depositional setting is interpreted as turbiditic. Core 2 (1351–1363 m depth) consists of dark shaly mudstones and intercalated fine-grained sandstones. Throughout, calcareous and dolomitic veins are recorded. The Geological Survey of the Netherlands has carried out a biostratigraphic study on these cores (Krans et al., 1983), without success. Based on sediment petrographical comparison to outcrops in the Ardennes, the entire interval underlying the lower Carboniferous limestones was inferred to be Middle to Upper Devonian (Givetian–Frasnian; Krans et al., 1983). Abbink & Van de Laar (2000) palynologically analysed one sample from 1351.8 m depth. They only report on two remarkably light-coloured spores which were assigned to *Discernisporites micromanifestus* and *Rotaspora knoxii* and on this basis suggest a Late Devonian to early Carboniferous (Visean) age. In the light of the palynological associations found in this study, these two specimens are regarded as contamination.

Well S05-01

Vertical well S05-01 was drilled as an exploration well by NAM, *c.*20 km offshore (Fig. 1). The stratigraphic succession is similar to that of well KTG-01. At 1187 m depth the unconformable contact between the Cretaceous Ommelanden Formation (Chalk Group) and the underlying Lower Carboniferous Zeeland Formation was reached. Below this 800 m thick section at 1997

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m depth, 233 m of deposits assigned to the Banjaard group were recovered.

The upper 8 m are ascribed to the Bosscheveld formation (Fig. 3) and comprise alternations of dark-grey clay-, silt- and sandstones and nodular limestones. The lower section is ascribed to the Bollen Claystone formation and consists of dark-grey to green clayey siltstones with intercalated sandstones with hummocky cross-stratification. Based on this observation, a shallower water depth, likely above storm wave-base, may be inferred compared to the sediments recovered in well KTG-01. Two sections were cored in the Bollen Claystone formation between 2130–2148 m and 2015–2019 m.

Sampling

The cores were sampled from the core repository of TNO – Geological Survey of the Netherlands. Although the complete cores were no longer present, large (>100 cm^3) representative core samples were curated for every metre. These were subsampled using a hammer and/or saw and the surface was cleaned with a brush and water. In the Supplementary Material available online at https://doi.org/10.1017/njg.2020.20, an Excel file with the sampling and palynological observations is provided.

Methodology

Rock samples were processed at Palynological Laboratory Services (PLS), Holyhead, UK. Samples were first treated with dilute hydrochloric acid to remove calcium carbonate, and subsequently macerated by leaving the sample in 75% hydrofluoric acid overnight. The organic residue was sieved over a 53 µm and subsequently a 10 µm mesh. The resultant kerogens of these size classes were visually examined for their degree of brown colouration and the presence of dark macerals, upon which a specific oxidation step was applied. This involves the addition of Schulze reagents, fuming nitric acid and/or warm nitric acid. Both the unoxidised kerogens and the oxidised kerogens were transferred to a glass slide in epoxy resin and covered by a cover slip. Typically, the unoxidised kerogen did not yield discernible palynomorph associations. The slides with oxidised kerogen were microscopically examined using a transmissive light Leica DM-LB2 microscope fitted with a Leica MC170 digital camera on 787.5× magnification. Each slide was fully scanned and the presence of palynomorph taxa and palynodebris clasts was scored qualitatively. The palynological slides and macerated residues are in the Geological Survey of the Netherlands sample archive.

Results and interpretation

The abundance and quality of the palynological associations in the studied material is variable and ranges from barren to moderate. Many specimens are substantially affected by thermal alteration, oxic degradation and/or the imprint of diagenetic pyrite-growth structures (Fig. 4: **6**). This caused many miospore specimens to be unidentifiable and some samples to be very scarce in determinable palynomorphs. Palynomorphs are consistently dark-coloured (values of 7 to 9 on the Spore Coloration Index of Fisher et al., 1980). In addition, a majority of the recorded miospore specimens are remarkably affected by tension gashes. According to Arai & Melo (2003), similar phenomena indicate the effects of severe faulting. In terms of palynomorph assemblages, terrestrial palynomorphs are clearly dominant. In some samples acritarchs are recorded. Although a special 53 µm mesh sieving was performed for the concentration of chitinozoans, only two specimens of the latter palynomorph category were observed in the residue sieved over a 10 µm mesh from 1351 m MD in well KTG-01 (Fig. 4: **9**).

Stratigraphic interpretation of phytodebris associations

A classification for early Palaeozoic phytodebris clasts is laid out by Burgess & Edwards (1991) and Wellman (1995). According to these authors, phytodebris assemblages comprise tubular structures ascribed to *Porcatitubilus* and *Constrictitubulus* (Fig. 4: **2** and **3**). In addition, septate filamentous cuticle-like structures resembling *Nematothallus* are recorded in low abundance. These tubular structures and filaments remain difficult to link to unambiguous biological entities. One hypothesis is that these structures stem from nematophytes, a group of probable land plants of uncertain affinity which have a tubular anatomy. Burgess & Edwards (1991) considered the stratigraphical distribution of these phytodebris groups in the uppermost Ordovician to Lower Devonian of the Anglo-Welsh basin. They recognised essentially two assemblages, with the oldest (Ordovician to early Silurian) having low diversity and dominance of smooth forms ascribed to *Laevitubulus*. A more diverse assemblage appears in the middle Silurian and ranges into the Lower Devonian. The latter is similar to that that recorded in the lower two cores of well KTG-01, suggesting a middle Silurian to Early Devonian age for these cores. The phytodebris associations in the upper core from KTG-01 and the cores from S05-01 are not distinctly dominated by these associations.

Stratigraphic interpretation of palynological associations

Out of four samples from the lowermost cored section from well KTG-01 (1890–1910 m), two have sufficient palynological recovery. It is often very difficult to identify specimens to the species level or even generic level. Therefore we have grouped specimens into morphological groups. Identifiable miospore taxa include those of the *Ambitisporites avitus–dilutus* group, *Apiculiretusispora synorea*, *Artemopyra* spp., *Cymbohilates microgranulatus* and *Tetrahedraletes* spp. The latter taxon is confined to this interval. The presence of the *Ambitisporites avitus–dilutus* group has biostratigraphic significance. This taxon is the oldest laevigate trilete miospore and is generally known to first occur in the late Aeronian Stage (middle of the early Silurian Llandovery Epoch; see Richardson, 1996 and references therein). However, recently in extremely well-preserved palynological associations from Saudi Arabia, reminiscent spores have also been found in Upper Ordovician strata (Wellman et al., 2015). *Apiculiretusispora synorea* first occurs in the Ludfordian Stage of the late Silurian Ludlow Epoch (Richardson, 1974; Richardson et al., 1981) and is thought to range up to the base of the Devonian (reported as the British regional Downtonian stage, which is roughly equivalent to the latest Silurian Pridoli Epoch). The alete monads ascribed to *Artemopyra* spp. are considered to originate in the Homerian Stage (upper part of the middle Silurian Wenlock Epoch); their range top is poorly constrained (Richardson, 1996).

The *Ambitisporites avitus–dilutus* group, *Apiculiretusispora synorea*, *Artemopyra* spp., *Cymbohilates microgranulatus* and *Tetrahedraletes* spp. continue stratigraphically into the overlying cored section of KTG-01 (1736–1722 m). This section yielded sufficient recovery in two out of the five processed samples. In this section, *Chelinohilates sinuosus* appears. Some authors reported this taxon to first occur in the uppermost Silurian to lowermost

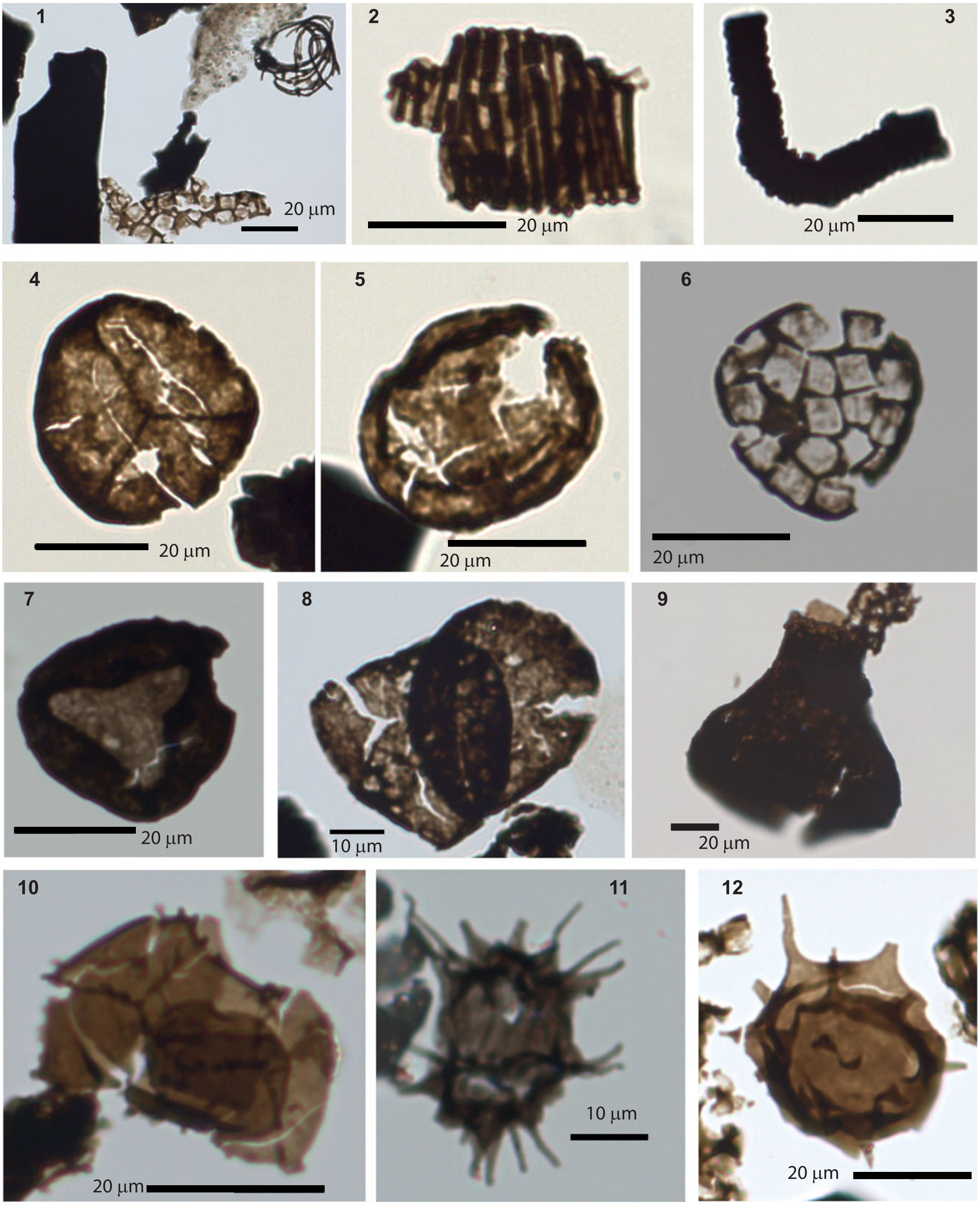

Fig. 4. Photomicrographs of illustrative phytodebris clasts and palynomorphs encountered in this study. Photomicrographs 1–3 display different types of phytoclasts, 4–8 display miospores, 9 is a chitinozoan and 10–12 display reworked Ordovician acritarchs.

1: Overview of palynodebris associations in a sample 1898.5 m from well KTG-01. **2**: Specimen of phytodebris class assigned to the genus *Porcatitubulus* (well KTG-01, 1898.5 m). **3**: Specimen of phytodebris class assigned to genus *Constrictitubulus* (well KTG-01, 1898.5 m). **4**: *Ambitisporites ambitus–dilutus* group (sample KTG-01, 1910.4 m, EF-coordinate E38-3). **5**: *Artemopyra* spp. (sample KTG-01, 1898.5 m, EF coordinate F25-4). **6**: Degraded rounded–subtriangular miospore, affected by pyrite grains (sample KTG-01, 1730.3 m, EF coordinate E35-1). **7**: ?*Scylaspora* spp. (sample KTG-01, 1351.9 m, EF-coordinate D41-2). **8**: *Dyadospora* spp. (sample KTG-01, 1351.9 m, EF coordinate F2-5). **9**: Chitinozoan resembling the genus *Fungochitina* (sample KTG-01, 1351.9 m, EF coordinate E8-4). **10**: Genus *Cymatiogalea* (sample KTG-01, 1722.43 m). **11**: Genus *Acanthodiacrodium* (sample KTG-01, 1722.42 m). **12**: Genus *Multiplicisphaeridium* (sample S05-01, 2022 m).

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Devonian (Richardson & Lister, 1969; Barclay et al., 1994; Wellman et al., 2000). Remarkably, this interval is also characterised by the abundance of acritarchs resembling *Micrhystridium stellatum*, the *Cymatiogalea* group, *Diexallophasis remota*, the *Gorgonisphaeridium* group and the *Multiplicisphaeridium* group. Except for the *M. stellatum*, which is a stratigraphically very long-ranging taxon (see e.g. Wall, 1965), these are restricted to the Early Ordovician (Tremadocian) of the Brabant Massif (Servais and Maletz, 1992; Servais et al., 1993) and are therefore considered to be reworked. Although some of the above-mentioned miospore taxa range well into the Devonian, the presence of *A. synorea* and the alete monads together with the absence of taxa specifically appearing during Early Devonian times leads us to surmise that the section below 1722 m depth in well KTG-01 was deposited during late Silurian (Ludlow–Pridoli) to Earliest Devonian (Lochkovian) times. These observations are in line with those on cores from similar-looking deposits in the UK (well 53/16-1, 919-1151 m; Church et al., 1968). According to these authors, 'The spores encountered here are of a very simple organisation; they are generally small and belong to a very restricted variety of types. These assemblages consist almost exclusively of the genera *Leiotriletes* and *Retusotriletes*, which exhibit a marked dominance throughout.' It is likely that these simple trilete forms in fact resemble the Silurian – Early Devonian forms associated with *Ambitisporites* and *Retusotriletes*. Interestingly, these authors record such associations immediately below Lower Carboniferous limestones, an observation that points towards the absence of Middle to Upper Devonian strata in the adjacent UK sector.

Successively, there is a clear distinction in miospore-assemblage composition in the overlying cored section (1350–1367 m) which yielded two productive samples out of five processed in total. The *Ambitisporites avitus–dilutus* group, *Apiculiretusispora synorea*, *Artemopyra* spp., *Chelinohilates sinuousus* and *Tetrahedraletes* spp. are no longer recorded. Morphologically distinct taxa that would suggest a substantially younger Middle–Late Devonian age such as *Geminospora lemurata*, *Auroraspora greggsi*, *Grandispora famennensis* and/or *Retispora lepidophyta* are not recorded. The poorly preserved associations contain miospores tentatively identified as ?*Scylaspora* spp. and *Cymbohilates microgranulatus*, which would fit with a Silurian to earliest Devonian age.

In the cores from well S05-01, preservation is generally very poor. The identification of *Cymbosporites stellospinosus* may indicate the Early Devonian (Lockhovian) is reached (Steemans, 1989; Breuer & Steemans, 2013), but this can also be assigned to reworking. In addition, we note the appearance of *Retusotriletes dittonensis*, which is reported to first occur in the Lochkovian (e.g. Wellman & Richardson, 1996; Wellman et al., 2000). However, this taxon ranges substantially longer into the Late Devonian. Reworked acritarchs, including the *Multiplicisphaeridium* group and the *Gorgonisphaeridium* group, are also recorded in this interval.

On the basis of absence of marker species, the intervals between 1367 and 1351 m in well KTG-01 and 2145.9-2018.4 m in well S05-01 may be interpreted as older than Middle Devonian. Since this is no more than a tentative indication, the age of the sediments assigned to the Bollen Claystone formation and the undifferentiated Banjaard group essentially remains elusive. In the Campine Basin, a relatively well-dated Frasnian to Famennian sedimentary succession is developed (Lagrou & Coen-Aubert, 2017). In particular, the sediments in the cores from well S05-01 are quite similar to those reported for the Falisolle Formation. Hence, it cannot be excluded that a correlative upper Frasnian – lower Famennian succession is developed in the SW Netherlands (Fig. 3C). However, other aspects of the stratigraphy of the Campine Basin (e.g. the Booischot conglomerate and/or the nodular limestones of the Aisemont Formation) have not been recognised in the Netherlands.

The only evidence for Upper Devonian strata in the study area comes from well BHG-01. Here, two cores were taken below the Lower Carboniferous Zeeland Formation. According to M. Streel in Bless (1978), the lower core (2902–2906.8 m in the Bollen Claystone formation) did not contain any miospores. The upper core (2672–2681 m in the Bosscheveld formation) contains the miospore taxa *Retusotriletes planus*, *Rugospora versabilis*, *Aneurospora greggsi*, *Aneurospora incohata* and *Grandispora* cf. *tenuispina*. The presence of these taxa unambiguously indicates a Late Devonian (early late Famennian) age. The type section for this Bosscheveld formation is in well KSL-02 in Maastricht, about 170 km to the southeast of well BHG-01. In the Maastricht–Visé area, the Bosscheveld formation is underlain by a Frasnian–Famennian sandstone-dominated succession which is analogous to the Evieux Formation of the Walloon Region (see Bultynck & Dejonghe, 2001). This contrasts with the general clay- and silt-dominated lithologies currently described for the Bollen Claystone formation. and thus points to complications in adopting the informal lithostratigraphic concepts of the Banjaard group in different parts of the Netherlands.

Summary and conclusions

In spite of the relatively low-diversity and poorly preserved miospore associations, we arrive at new insights for the regional stratigraphic development of the southwestern part of the Netherlands. The sediments of the lower two cores from well KTG-01 are of a late Silurian (Ludlow–Pridoli Epoch) to earliest Devonian (Lochkovian) age (Fig. 3C), making these the oldest sedimentary strata ever recovered in the Netherlands.

Van Adrichem Boogaert & Kouwe (1994) suggest the presence of an unconformity (i.e. the Brabantian Unconformity) in the study area and that the Silurian strata are separated from Middle–Upper Devonian shales that underlie unequivocal Lower Carboniferous limestones of the Zeeland Formation. The palynological results do not unambiguously support the existence of such a major unconformity between the now confirmed Silurian – earliest Devonian strata and the Lower Carboniferous limestones of the Zeeland Formation. In terms of lithological facies, the sediments assigned to the Bollen Claystone formation in well S05-01 resemble the upper Frasnian – lower Famennian Falisolle Formation of the Campine Basin (Lagrou & Coen-Aubert, 2017).

Since the strata discussed here are the basis of the informal Banjaard group, their age, genesis and depositional context need to be revisited, which will be part of the ensuing efforts of the Geological Survey of the Netherlands. Since this area is characterised by a different stratigraphic architecture than observed in the southeast of the Netherlands (Limburg), where the Middle and Upper Devonian are well developed (e.g. in well Kastanjelaan-2), we advise against interchangeable use of the lithostratigraphic nomenclature between these areas, including the use of the Bosscheveld formation.

The Silurian and lowermost Devonian of the SW Netherlands is characterised by the abundance of miospores, which points to the presence of a vegetated hinterland and relatively proximal setting during late Silurian and Devonian times. This differs markedly from the open marine depositional settings reported from the

Brabant Massif area in Belgium (Verniers et al., 2001, 2002 and references therein). Woodcock & Pharaoh (1993) report Silurian lithofacies types in the East Anglian Basin (UK) resembling those recorded in our study area. Based on facies variation patterns, they suggest the presence of an eastward-deepening basin with a wide progradational shelf in the west. The recorded abundance of miospores suggests that Laurasia-sourced terrestrial material from the north eventually reached a relatively distal basin in the SW Netherlands. The episodic presence of reworked (marine) acritarchs of Ordovician age also suggests the influx of sedimentary material from uplifted elements on the present-day Brabant Massif to the south, possibly related to the inception of the Brabant Arch (Fig. 2D), a phenomenon also noted in the Ardennes Region (Steemans, 1989).

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/njg.2020.20

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References

Abbink, O.A. & Van de Laar, H., 2000. Devonian–Carboniferous palynology of 8 NAM/BEB Wells. LPP Project-0004. Laboratory for Palaeobotany and Palynology Report for Nederlandse Aardolie Maatschappij (Assen): 20 pp.

Arai, M. & Melo, J., 2003. The occurrence of shear-torn palynomacerals in Middle to Early Late Devonian strata of Southern Subandean Bolivia: their geological significance. *In*: 8th Simposio Bolivariano – Exploracion Petrolera en las Cuencas Subandinas. European Association of Geoscientists & Engineers (Houten): p. cp-33-00002.

Barclay, W.J., Rathbone, P.A., White, D.E. & Richardson, J.B., 1994. Brackish water faunas from the St Maughans Formation: the Old Red Sandstone section at Ammons Hill, Hereford and Worcester, UK, re-examined. Geological Journal **29**: 369–379.

Bless, M.J.M., 1978. Het Paleozoïcum van diepboring Winterswijk-1 (N.A.M.) tussen 1300 en 5009.5 m. Rijksgeologische Dienst Geologisch Bureau van het Mijngebied (Heerlen). Rapport GB1601: 4 pp.

Bless, M.J.M., Boonen, P., Bouckaert, J. & 25 others, 1981. Preliminary report on Lower Tertiary–Upper Cretaceous and Dinantian–Famennian rocks in the boreholes Heugem-1, 1a and Kastanjelaan2 (Maastricht, the Netherlands). Mededelingen Rijks Geologische Dienst **35**(15): 333–415.

Breuer, P. & Steemans, P., 2013. Devonian miospores from northwestern Gondwana. Special Papers in Palaeontology **89**: 1–163.

Bultynck, P. & Dejonghe, L., 2001. Devonian lithostratigraphic units (Belgium). Geologica Belgica **4**(1–2): 39–69.

Burgess, N.D. & Edwards, D., 1991. Classification of uppermost Ordovician to Lower Devonian tubular and filamentous macerals from the Anglo-Welsh Basin. Botanical Journal of the Linnean Society **106**(1): 41–66.

Church, J.W., Fryer, K. & Greenwood, R.J., 1968. The palynology and stratigraphy of the Interval 2540′–3779′ of the Arpet 53/16-1 North Sea Well. Robertson Research Oil Fields Report No. 166: 1–11.

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.

Debacker, T., 2002. Cleavage/fold relationship in the Silurian of the Mehaigne-Burdinale area, southeastern Brabant Massif, Belgium. Geologica Belgica **5**: 3–15.

Debacker, T.N., 2012. Folds and cleavage/fold relationships in the Brabant Massif, southeastern Anglo-Brabant Deformation Belt. Geologica Belgica **15**: 81–95.

Fisher, M.J., Barnard, P.C. & Cooper, B.S., 1980. Organic maturation and hydrocarbon generation in the Mesozoic sediments of the Sverdrup Basin, Arctic Canada. Proceedings IV International Palynological Conference, Lucknow, India (1976–1977), vol. 2: 581–588.

Franke, W., Cocks, L.R. M. & Torsvik, T.H., 2017. The Palaeozoic Variscan oceans revisited. Gondwana Research **48**: 257–284.

Herbosch, A. & Debacker T., 2018. A new geological map of the outcrop areas of the Brabant Massif (Belgium). Geologica Belgica **21**: 41–58.

Kimpe, W.F.M., Bless, M.J.M., Bouckaert, J., Concil, R., Groessens, E., Meessen, J.P.M., Poty, E., Streel, M., Thorez, J. & Vanguestaine, M., 1978. Paleozoic deposits east of the Brabant Massif in Belgium and the Netherlands. Mededelingen van de Rijks Geologische Dienst **30**(2): 37–103.

Krans, T., Fermont, W.J.J., Van de Laar, H., Meessen, J. & Pagnier, H., 1983. Onderzoek monsters NAM-boring Kortgene-1; Kerntrajecten 946.9-995.6, 1351-1365.10, 1720.33-1735 en 1891.5-1900 m. Rijks Geologische Dienst Rapport GB1888 (Heerlen): 7 pp.

Lagrou, D. & Coen-Aubert, M., 2017. Update of the Devonian lithostratigraphic subdivision in the subsurface of the Campine Basin (northern Belgium). Geologica Belgica **20**(1–2): 1–13.

Pharaoh, T., 1999. Palaeozoic terranes and their lithospheric boundaries within the Trans-European Suture Zone (TESZ): a review. Tectonophysics **314**(1–3): 17–41.

Pharaoh, T., 2018. The Anglo-Brabant Massif: persistent but enigmatic palaeo-relief at the heart of western Europe. Proceedings of the Geologists' Association **129**(3): 278–328.

Reijmer, J.G., Ten Veen, J.H., Jaarsma, B. & Boots, R., 2017. Seismic stratigraphy of Dinantian carbonates in the southern Netherlands and northern Belgium. Netherlands Journal of Geosciences **96**(4): 353–379.

Richardson, J.B., 1974. The stratigraphic utilization of some Silurian and Devonian miospore species in the northern hemisphere: an attempt at a synthesis. International Symposium on Belgian Micropaleontological Limits **9**: 1–13.

Richardson, J.B., 1996. Lower and middle Palaeozoic records of terrestrial palynomorphs. *In*: Jansonius, J. & McGregor, D.C. (eds.): Palynology: principles and applications, vol. 2. Association of Stratigraphic Palynologists Foundation (College Station, TX): 555–574.

Richardson, J.B. & Lister, T.R., 1969. Upper Silurian and lower Devonian spore assemblages from the Welsh borderland and south Wales. Palaeontology **12**(2): 201–245.

Richardson, J.B., Rasul, S.M. & Al-Ameri, T., 1981. Acritarchs, miospores and correlation of the Ludlovian-Downtonian and Silurian-Devonian boundaries. Review of Palaeobotany and Palynology **34**(2): 209–224.

Servais, T. & Maletz, J., 1992. Lower Llanvirn (Ordovician) graptolites and acritarchs from the "Assise de Huy", Bande de Sambre-et-Meuse, Belgium. Annales de la Société géologique de Belgique **115**: 265–285.

Servais, T., Vanguestaine, M. & Herbosch, A., 1993. Review of the stratigraphy of the Ordovician in the Brabant Massif, Belgium. Geological Magazine **130**(5): 699–710.

Sintubin, M., Debacker, T.N., & Van Baelen, H., 2009. Early Palaeozoic orogenic events north of the Rheic suture (Brabant, Ardenne): a review. Comptes Rendus Geoscience **341**(2–3), 156–173.

Steemans, P., 1989. Paléogeographie de l'Eodevonien Ardennais et des Régions limitrophes. Annales de la Société Géologique de Belgique **112**: 103–119.

Streel, M., 1965. Etude palynologique du Dévonien du sondage de Booischot (Belgique). Bulletin de la Société Belge de Géologie **73**(2): 159–175.

TNO–GDN, 2020. Banjaard groep. *In*: Stratigrafische nomenclator van Nederland, TNO – Geologische Dienst Nederland. Available at www.dinoloket.nl/stratigrafische-nomenclator/banjaard-groep, last accessed 17 November 2020.

TNO–NITG, 1999. Explanation to map sheet XV: Sittard-Maastricht + Map Sheet XV. Geological atlas of the subsurface of the Netherlands (1 : 250 000). Netherlands Institute of Applied Geoscience TNO – Geological Survey of the Netherlands (Utrecht): 127 pp.

Van Adrichem Boogaert, H.A. & Kouwe, W.F.P., 1994. Stratigraphic nomenclature of the Netherlands; revision and update by RGD and NOGEPA, Section B, Devonian and Dinantian. Mededelingen Rijks Geologische Dienst **50**: 1–20.

Vanguestaine, M., Declairfayt, T., Rouhart, A. & Smeesters, A., 1983. Zonation par acritarches du Frasnien superieur-Famennien inferieur dans les bassins de Dinant, Namur, Hervé et Campine (Dévonien supérieur de Belgique). Société Géologique de Belgique, Annales **106**: 121–171.

Verniers, J. & Van Grootel, G., 1991. Review of the Silurian in the Brabant Massif, Belgium. Annales de la Société Géologique de Belgique **114**: 163–193.

Verniers, J., Herbosch, A., Vanguestaine, M., Geukens, F., Delcambre, B., Pingot, J.L., Belanger, I., Hennebert, M., Debacker, T., Sintubin, M. & De Vos, W., 2001. Cambrian–Ordovician–Silurian lithostratigraphical units (Belgium). *In*: Bultynck, P. & Dejonghe, L. (eds): Lithostratigraphical scale of Belgium. Geologica Belgica 4: 5–38.

Verniers, J., Pharaoh, T., André, L., Debacker, T.N., De Vos, W., Everaerts, M., Herbosch, A., Samuelsson, 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*: Geological Society of London, Special Publication 201(1): 47–93.

VITO, 2018. VITO (Flemish Institute for Technological Research) website, https://vito.be/nl/nieuws/vito-boort-naar-ongekende-diepten.

Wall, D., 1965. Microplankton, pollen, and spores from the Lower Jurassic in Britain. Micropaleontology **11**(2): 151–190.

Wellman, C. H., 1995. "Phytodebris" from Scottish Silurian and Lower Devonian continental deposits. Review of Palaeobotany and Palynology, **84**(3–4): 255–279.

Wellman, C.H., & Richardson, J.B., 1996. Sporomorph assemblages from the Lower Old Red Sandstone of Lorne, Scotland. Special Papers in Palaeontology **55**, 41–102.

Wellman, C.H., Habgood, K., Jenkins, G. & Richardson, J.B., 2000. A new plant assemblage (microfossil and megafossil) from the Lower Old Red Sandstone of the Anglo-Welsh Basin: its implications for the palaeoecology of early terrestrial ecosystems. Review of Palaeobotany and Palynology **109**: 161–196.

Wellman, C.H., Steemans, P. & Miller, M.A., 2015. Spore assemblages from Upper Ordovician and lowermost Silurian sediments recovered from the Qusaiba-1 shallow core hole, Qasim region, central Saudi Arabia. Review of Palaeobotany and Palynology **212**: 111–126.

Woodcock, N.H. & Pharaoh, T.C., 1993. Silurian facies beneath East Anglia. Geological Magazine **130**(5): 681–690.

Taxonomic appendix

Miospores

Ambitisporites avitus/dilutus group Steemans, LeHérissé and Bozdogan, 1996

Apiculiretusispora synorea Richardson and Lister, 1969

Artemopyra spp. This represents a group of simple emphanoid miospores. Preservation is not sufficient to differentiate specimens to species level.

Chelinohilates sinuosus Wellman and Richardson, 1996

Cymbohilates microgranulatus Wellman and Richardson, 1996

Cymbosporites stellospinosus Steemans, 1986

Dyadospora spp. This represents a group of miospores occurring in dyads. Preservation is not sufficient to differentiate specimens to species level.

Retusotriletes dittonensis Richardson and Lister, 1969

?*Scylaspora* sp. Wellman, 1999

Tetrahedraletes medinensis Strother and Traverse, 1979

Phytodebris clasts

Genus *Constrictitubulus* Burgess and Edwards, 1991

Genus *Porcatitubulus* Burgess and Edwards, 1991

Genus *Laevitubulus* Burgess and Edwards, 1991

Genus *Nematothallus* Lang, 1937

Acritarchs

Acanthodiacrodium spp.

Cymatiogalea cristata (Downie) Rauscher, 1973

Diexallophasis remota (Deunff) Playford, 1977

Goniosphaeridium spp.

Gorgonisphaeridium spp.

Multiplicisphaeridium spp.

Mychristridium stellatum Deflandre, 1937

Polygonium spp.

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