Palaeobiodiversity and Palaeoenvironments
https://doi.org/10.1007/s12549-020-00440-5

SENCKENBERG

ORIGINAL PAPER

The Devonian–Carboniferous boundary in Belgium and surrounding areas

Julien Denayer[1] · **Cyrille Prestianni**[1,2] · **Bernard Mottequin**[2] · **Luc Hance**[3] · **Edouard Poty**[1]

Received: 6 June 2019 / Revised: 28 April 2020 / Accepted: 8 July 2020

Abstract

The Devonian–Carboniferous boundary is associated with a major extinction event of the Phanerozoic. It was also a time marked by a rapid but short-lasting change in deposition called Hangenberg Event. In the Namur–Dinant Basin the uppermost Devonian (‘Strunian’) deposits recorded a third-order transgression that produced a progressive switch from coastal siliciclastic to proximal mixed deposits with an increase of the carbonate production on the ramp. Hence, the Comblain-au-Pont and lower Hastière formations are considered as the transgressive system tract, whereas the middle member of the Hastière Formation is interpreted as the highstand system tract, capped by an erosion surface corresponding to the third-order sequence boundary. Superimposed on these third-order sequences are well-marked orbitally forced precession cycles (wet–dry climate alternations) of c. 18.6 ka, appearing as irregular c. 30–80-cm-thick couplets of limestone and calcareous shale beds. The Hangenberg Black Shale Event is locally present as dark shales that likely spread over the shelf, marking the maximum flooding surface of the sequence. Before and after this event, carbonate facies rich in benthic macrofauna and microfauna continued to develop. The Hangenberg Sandstone Event, appearing as a sandstone bed in pelagic sections, is variously recorded at the base of the Hastière Formation, either as a sandy siltstone bed in proximal sections or as a horizon with limestone clasts and reworked fossils in more distal settings. The Hangenberg Sandstone Event beds occur sharply in the stratigraphic record and do not correspond to the long sea level fall of a third-order sequence boundary, but most probably to a short out-of-sequence event. The revision of the stratigraphic distribution of major fossil groups pleads for a continuous biostratigraphic succession with no obvious hiatus. The variable development of some micropalaeontological zones at the end of the Devonian is the result of complex eco-biostratigraphic interactions with the environment rather than the reflection of true hiatuses. It is marked by extinctions of Devonian taxa, concomitantly with the end of the reworking produced by the Hangenberg Sandstone Event, most probably immediately below the entry of the conodont *Protognathodus kockeli*. It is also coincident with the boundary between the foraminiferal zones DFZ7–MFZ1, rugose coral zones RC0–RC1 and between the palynozones LE–VI. After the short-lasting regressive phase of the Hangenberg Sandstone Event, normal depositional settings returned with the deposition of the Hastière Formation. Hence, the end of the Hangenberg Sandstone Event is proposed as the most natural proxy to pinpoint the Devonian–Carboniferous boundary.

Keywords Neritic facies · Carbonate · Hiatus · Eco-biostratigraphy · Hangenberg Event · Extinction · Crisis

---

This article is a contribution to the special issue *Global review of the Devonian-Carboniferous Boundary*

✉ Julien Denayer
julien.denayer@ulg.ac.be; julien.denayer@uliege.be

Cyrille Prestianni
cyrille.prestianni@naturalsciences.be

Bernard Mottequin
bmottequin@naturalsciences.be

Luc Hance
luc.hance@carmeuse.com

Edouard Poty
e.poty@uliege.be

[1] Evolution & Diversity Lab, Université de Liège, Allée du Six-Août, B18, Sart Tilman, 4000 Liège, Belgium

[2] D.O. Terre et Histoire de la Vie, Institut royal des Sciences naturelles de Belgique, Rue Vautier 29, 1000 Brussels, Belgium

[3] Carmeuse Research and Technology, Boulevard de Lauzelle, 65, 1348 Louvain-la-Neuve, Belgium

Introduction

The Devonian–Carboniferous boundary (DCB) was the first chronostratigraphic boundary to be defined officially and globally at the Heerlen Congress in 1935 (Paeckelmann and Schindewolf 1937). It was originally defined by the appearance of the goniatite *Gattendorfia subinvoluta*, but it was soon acknowledged that the boundary was chosen in a condensed deep-water section that accumulated more hiatuses than sediments (e.g. Alberti et al. 1974; Bless et al. 1987). The search for a new type section documenting a new marker for the DCB occupied the stratigraphers during almost 20 years and resulted in the selection of the La Serre trench E' in Southern France where the DCB was placed at the first appearance of the conodont *Siphonodella sulcata* in the lineage *Siphonodella praesulcata*–*S. sulcata* (Feist and Flajs 1987; Paproth et al. 1991). This decision revealed not to be adequate for several reasons including the presence of unfavourable facies, reworking of conodont faunas, difficult correlations and poor taxonomy of the guide taxon (see Kaiser et al. (2009) and Corradini et al. (2017) for a recent synopsis). Most of these issues were already known at that time by the International Working Group on the DCB, who chose the La Serre trench E' as the Global Boundary Stratotype Section and Point (GSSP). Moreover, the GSSP was established with an apparent ignorance of three major issues: (1) the natural aspect of a boundary based on major biotic changes and extinction, (2) the unnatural idea that the specific evolution of a conodont taxa would happen chronostratigraphically worldwide and would be facies-independent and (3) the rejection of neritic sections as they were—incorrectly—considered as incomplete compared to the pelagic ones. Indeed, it is now largely acknowledged—but often forgotten (e.g. Corradini and Spalletta 2018)—that pelagic sections also display hiatuses. Moreover, the impact of the palaeoenvironment on the conodont associations was underestimated (e.g. Sandberg and Dreesen 1984).

More recent views on sedimentology, biostratigraphy—indeed eco-biostratigraphy—and processes involved in biotic and environmental crises allow reconsidering the definition of the DCB in terms of natural boundary and correlativity in various depositional settings. The recent workshop of the International Working Group on the DCB witnessed the will to move forward by using multi-proxy stratigraphic markers and by looking for a new GSSP for the DCB (Aretz 2014).

Devonian–Carboniferous boundary and Hangenberg Event(s)

The original idea of Walliser's (1984) 'natural boundary' was to associate the chronostratigraphic boundary with the events and extinctions that took place at the end of the Devonian period. However, commonly merged with the late Frasnian crisis as the 'Late Devonian extinction event'—one of Sepkowski's 'Big Five Mass Extinctions', regardless of the meaning now attributed to this concept (see e.g. McGhee et al. 2004, 2012)—the Hangenberg Biocrisis stands alone. The late Frasnian extinctions took place over a very long period of slowly degrading environmental conditions spread over c. 5 Ma, starting with the middle–late Frasnian boundary and culminating with the upper Kellwasser Event in the late Frasnian (Mottequin and Poty 2016). On the contrary, the late Famennian extinctions occurred during a period of recovery: they were relatively sudden and short-lasting (one to several 100 ka, Kaiser et al. 2016) and occurred within a depleted biosphere. Kaiser et al. (2016) recently summarised the effects of the Hangenberg Biocrisis on fauna and flora, and their main conclusion shows the various extent and diachronism of extinction within pelagic ecosystems. The deep-water and pelagic fauna were stroked early during the crisis (e.g. ammonoids, conodonts), whereas shallow-water benthic assemblages (corals, stromatoporoids, foraminifers, etc.) persisted until the end of the Hangenberg Biocrisis. Moreover, the effect of the crisis in continental settings seems to have been overestimated in the past. The timing of the events on the continent is still poorly constrained, but data on plants (Decombeix et al. 2011a, b; Prestianni et al. 2015, 2016) tend to show that continental ecosystems, even if affected by the crisis, were more resilient.

In the pelagic sections of the Rhenish Mountains where the Hangenberg Event was defined originally, the stratigraphical succession is typically as follows (Krebs 1979; Paproth et al. 1986; Bless et al. 1987): (1) the Drewer Sandstone covering the Wocklum Limestone and recording the first extinctions among pelagic biota; (2) the Hangenberg Black Shale (HBS) recording anoxia; (3) the Hangenberg Shale (HS), depleted in fauna but not anoxic; (4) the Hangenberg Sandstone (HSS) most probably regressive; and (5) the Stockum Limestone that includes conodonts of Carboniferous affinity in its upper part (Clausen et al. 1989; Bless et al. 1993). The Hangenberg Black Shale mostly corresponds to the 'lower Hangenberg Crisis' and coincides with the lower part of the Middle *praesulcata* conodont Zone (~ lower part of the *costatus*–*kockeli* Interregnum after Kaiser et al. (2009), ~ upper part of the *Bispathodus ultimus* Zone sensu Corradini et al. (2017)); the Hangenberg Shale and Hangenberg Sandstone form the *middle crisis* in the upper part of the Middle *praesulcata* Zone; the Stockum Limestone corresponds to the *upper crisis* in the Upper *praesulcata* Zone (= *kockeli* Zone sensu Kaiser et al. (2009); lower part of the *kockeli* Zone sensu Spalletta et al. (2017)). In the type section, the Hangenberg Biocrisis corresponds to a few metres of sediments (c. 7 m in Oberrödinghausen section, c. 2 m in Drewer section; e.g. Clausen et al. 1989) or even less in extremely condensed sections (< 0.2 m in Grünen Schneide section, Carnic Alps; e.g. Spalletta et al. in press, this issue).

In contrast with the pelagic—i.e. bathyal condensed—sections commonly used to study global boundaries, the succession across the DCB in southern Belgium consists of a relatively thick series (> 50 m) of shallow-water siliciclastics evolving to transgressive carbonate deposits (*Strunian transgression*). This rather thick succession allows a good understanding of the Famennian and Tournaisian transition and of the crisis affecting the marine ecosystems across this boundary. Being thicker and more complete for the record of local and global sea level and/or facies changes, the neritic sections provide a better suited understanding than their deeper, so-called condensed—i.e. discontinuous and hiatus-rich (Paproth and Streel 1971, 1984; Walliser 1996; Strasser 2015; Lucas 2018)—equivalents that have long been overindulged by biostratigraphers for their higher conodont content. The sequence of events that marks the DCB transition and the diversity crisis is spread over 25 m of sediments in Belgium whereas, in classic pelagic sections, the events are condensed in a few metre-thick succession where they appear superimposed to each other.

Settings and stratigraphy

Southern Belgium (‘the Ardenne(s)’ of the foreign authors) is part of the Rhenohercynian fold and thrust belt, resulting from the Variscan orogeny, that extends across Europe from southern Portugal through Southern England, northern France, Belgium and Germany, into Poland. Devonian and lower Carboniferous rocks crop out in southern Belgium on both sides of the major Midi–Eifel thrust fault, notably in the Brabant Parautochton and the Dinant Synclinorium (for more details, see Hance et al. 1999; Belanger et al. 2012). Several sedimentation areas are distributed in the Namur–Dinant Basin that developed along the southeastern margin of Laurussia during Devonian and Carboniferous times. In the course of the Late Devonian and early Carboniferous, the Namur–Dinant Basin (NDB, Fig. 1) of southern Belgium and surrounding areas recorded proximal facies in its northern part, whereas its southern part acted as a shallow basin with deeper facies (Poty 2016). The basin was probably connected to the southwest British Province and Ireland and northward, to the Campine Basin (Fig. 1). However, during most of the Lower Carboniferous, the NDB was separated from the Campine Basin by the Booze–Le Val-Dieu ridge (Poty and Delculée 2011). Eastward, the NDB was probably connected to the German Kulm Basin but a land barrier probably acted discontinuously in the Aachen area where depositional gaps are known in the Devonian and Carboniferous (Poty 2016). Unlike displayed by the traditional reconstructions (e.g. Van Steenwinkel 1990), the NDB was not connected southward to the Rhenohercynian (Cornwall–Rhenish) Kulm Basin, from which it was separated by the first stage of the Variscan emersion of the Ardenne Massif (Poty et al. 2011). Conversely, the presence of proximal carbonate facies in the southern Avesnois suggests a local or regional platform area southwards rather than a basin (Conil in Mansy et al. 1988; Poty et al. 2006).

The NDB was subdivided into six sedimentation areas by Poty (1997), emended by Poty (2016); (Fig. 1): they correspond to different tectono-sedimentary units with distinct lithostratigraphic and faunal succession during the Carboniferous. However, only five of them expose upper Famennian–Tournaisian deposits. The Namur sedimentation area (NSA) and the Vesdre–Aachen area (VASA), both located on the southern margin of the London–Brabant Massif, display an incomplete succession of proximal facies, often dolomitised and bearing hiatuses. The Condroz sedimentation area (CSA) exposes proximal facies grading southwards into deeper facies of the Dinant sedimentation area (DSA). The southern Avesnois sedimentation area (ASA) exposes peculiar facies that change laterally over short distances. The lithostratigraphy of these areas is described below, each area displaying distinct and typical facies at the DCB transition (Fig. 2).

Quite widely used to qualify the end of the Famennian worldwide, the Strunian regional substage received increased attention after the proposition of division of the Famennian into four substages instead of three and the establishment of the uppermost Famennian substage (Streel et al. 1998; Streel 2005). This substage is still waiting for a formal definition, but its base is commonly correlated with the base of the *Bispathodus ultimus* conodont Zone sensu Hartenfels and Becker (2018) (former Upper *expansa* conodont Zone), it is also marked by the First Appearance Datum (FAD) of the foraminifer *Quasiendothyra kobeitusana* (Conil and Lys 1970). The FAD of the miospore *Retispora lepidophyta* (Streel et al. 1998, 2006) once proposed as the base of the Strunian (Conil et al. 1977) is, however, too low in the upper Famennian (Streel et al. 2006; Marynowski et al. 2012).

In the type section of the Strunian regional substage—the Avesnelles railway section near Avesnes-sur-Helpe in northern France (Conil 1964; Mamet et al. 1965; Conil and Lys 1980)—the FAD of *Q. kobeitusana* is situated at the very base of unit ‘n’ of Conil (1964) (Conil and Groessens 1975), 25 m above the sequence boundary (between the shallow-water limestone of unit ‘k’ and the calcareous shale of unit ‘l’). The base of the Strunian as a substage is therefore positioned at the base of this unit ‘n’, but it should be noted that no foraminifers were recognised in the shale of units ‘l’ and ‘m’, so again, the entry of the guide taxon is cryptic. However, the first quasiendothyrid foraminifers and stromatoporoids were recovered from the units ‘j’ and ‘k’ (Conil and Lys 1980; Conil and Groessens 1975) together with the conodonts *Polygnathus communis* and *Spathognatodus costatus* (Conil et al. 1974). The type

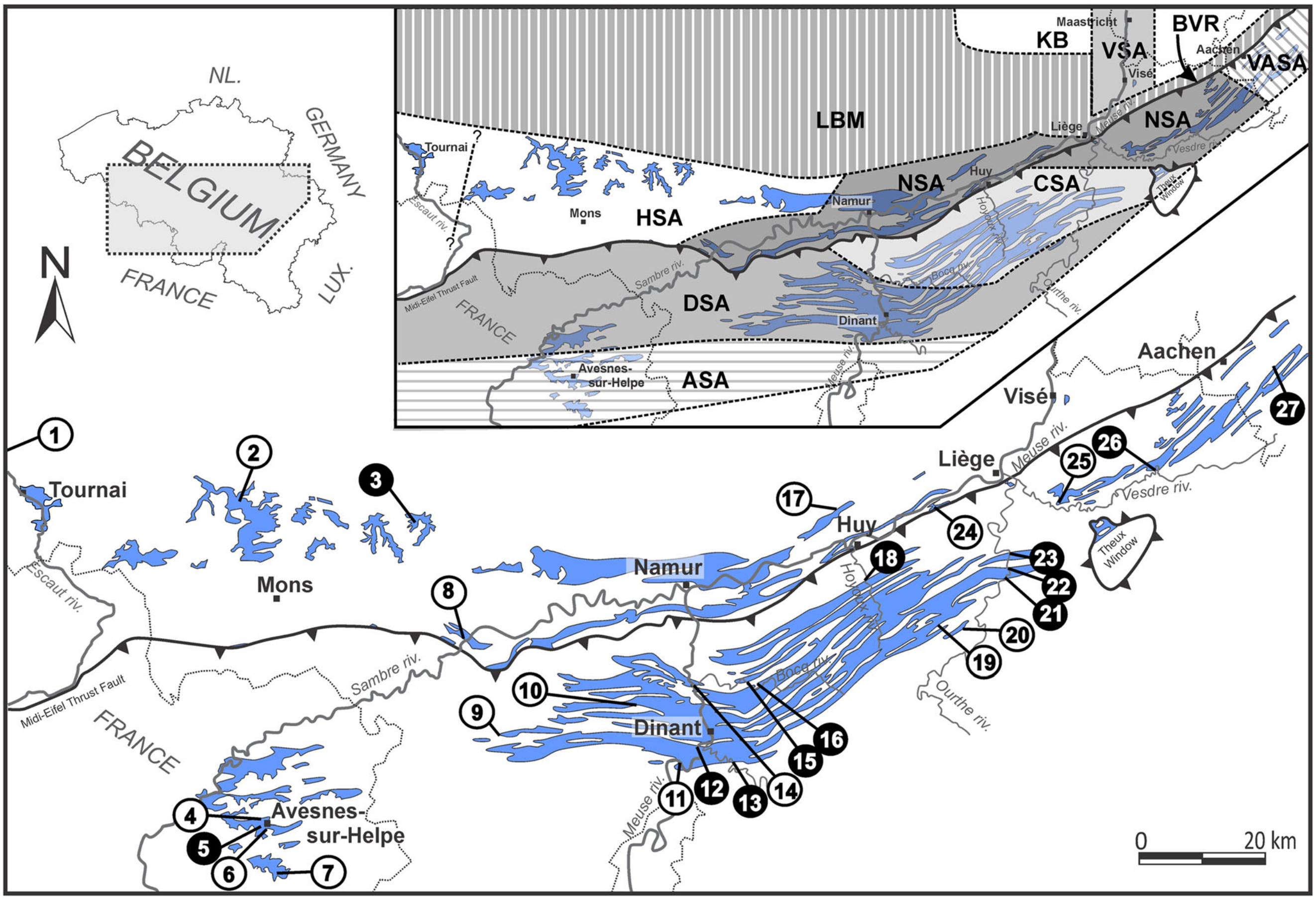


Fig. 1 Dinantian sedimentation areas in the Namur–Dinant Basin and location map of the main sections cited (white circles) and described (black circles) in the text. Blue areas correspond to the outcrop zone of the lower Carboniferous strata. Abbreviations: *ASA* South Avesnois sedimentation area; *BVR* Booze–Le-Val-Dieu ridge; *CSA* Condroz sedimentation area; *DSA* Dinant sedimentation area; *HSA* Hainaut sedimentation area; *KB* Campine Basin; *LBM* London–Brabant Massif; *NSA* Namur sedimentation area; *VASA* Vesdre–Aachen sedimentation area; *VSA* Visé–Maastricht sedimentation area (modified after Poty 2016). Sections: *1* Menen borehole; *2* Mévergnies; *3* Feluy; *4* Saint-Hilaire; *5* Godin quarry (Avesnes-sur-Helpe); *6* Avesnelles; *7* Etrœungt (du Parcq quarry); *8* Landelies; *9* Walcourt; *10* Maredsous; *11* Hastière; *12* Anseremme; *13* Gendron-Celles; *14* Yvoir; *15* Chansin (section and quarry); *16* Spontin; *17* Huccorgne; *18* Royseux; *19* Jenneret; *20* Tohogne borehole; *21* Martinrive; *22* Rivage and Pont-de-Scay; *23* Chanxhe; *24* Engis; *25* Chaudfontaine; *26* Dolhain; *27* Stolberg

localities are in need of revision to solve the problem of the base of the Strunian therein.

In the NDB, the Strunian almost coincides with the Comblain-au-Pont Formation (Fm) (Fig. 3), defined by its first marine limestone bed—first to yield the biostratigraphic marker of the substage (Dreesen et al. 1986), which suggest either a cryptic entrance of the markers or a hiatus at the base of the transgressive deposits forming the Comblain-au-Pont Fm (typical hiatuses associated with sequence boundary are c. 0.67 Ma, Poty 2016).

Along the NDB, the mixed siliciclastic–carbonate sedimentation typical of the Strunian follows the dominantly siliciclastic succession of the Famennian. The facies indicate an inner-to-median ramp environment close to the base of the fair-weather wave zone, commonly enclosing storm deposits and showing both detrital and marine influences (Thorez and Dreesen 1986; Paproth et al. 1986; Van Steenwinkel 1990). In the DSA and CSA, the Strunian corresponds to the Comblain-au-Pont Fm, that is composed of alternating carbonate and fine-grained siliciclastic sediments, showing a proximal–distal gradient along a north–south transect. In the VASA, the Strunian typically includes stromatoporoid biostromes within a more shaly sequence (Dolhain Fm). In the ASA, the type area of the Strunian, it is represented by the Etrœungt Fm that comprises stromatoporoid- and coral-rich carbonate beds within a dominantly shaly succession (Figs. 2 and 3). Note that in the old literature, these Strunian formations were designated as 'Tn1a', a purely lithostratigraphic acronym introduced by Maillieux and Demanet (1928) and used by the Belgian geologists until the 1960s but without any chronostratigraphic value (Conil 1968; Hance et al. 2001). This acronym which causes confusion between lithostratigraphy and chronostratigraphy can no longer be accepted. Furthermore, Conil et al. (1977) introduced the Hastarian (lower Tournaisian) substage in order to include the former—and very short—'Tn1b' and 'Tn2' units, whereas the Ivorian

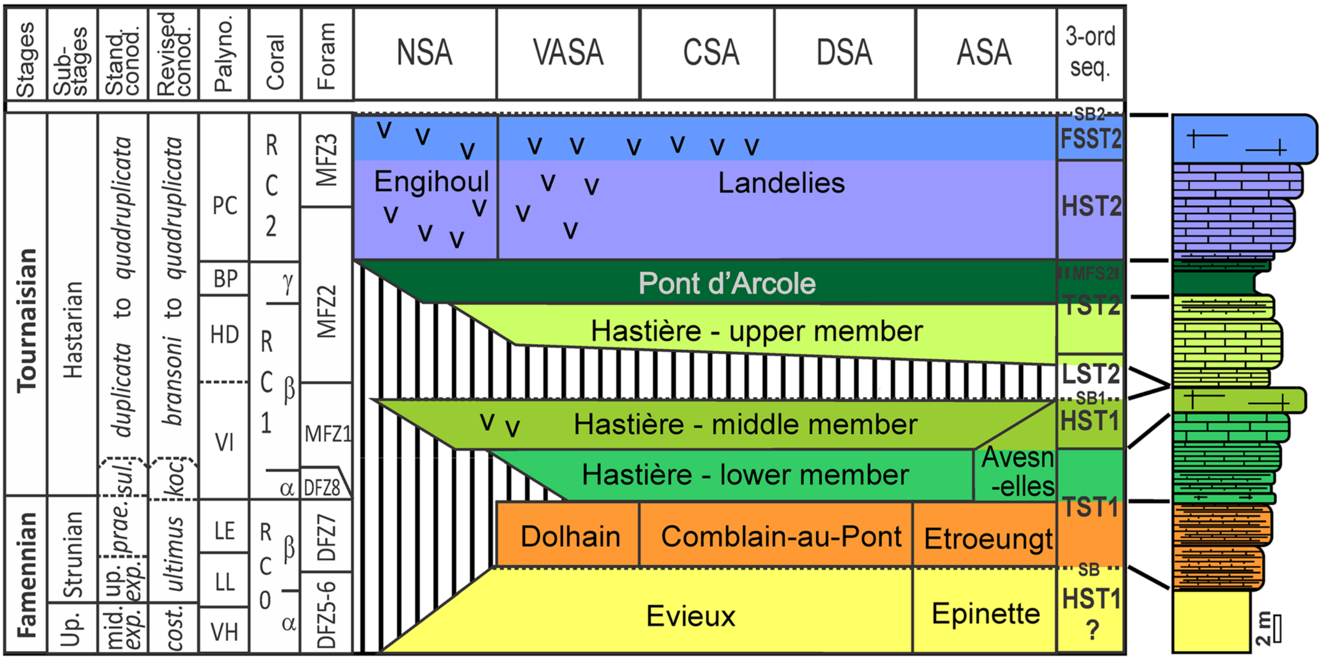


Fig. 2 Emended lithostratigraphic and biostratigraphic patterns of the Late Devonian and early Carboniferous in southeastern Belgium and surrounding areas with indication of the third-order sequences (modified from Poty et al. (2006, 2011) and Poty (2016)). Abbreviations: *ASA* South Avesnois sedimentation area; *CSA* Condroz sedimentation area; *DSA* Dinant sedimentation area; *NSA* Namur sedimentation area; *VASA* Vesdre–Aachen sedimentation area; 3-ord seq., third-order sequences; up., upper Famennian; Stand. conod., standard conodont zones (Ziegler and Sandberg 1984, 1990); Mid. *exp*., Middle *expansa*; Up. *exp*., Upper *expansa*; *prae*, *praesulcata* (undistinguished); *sul*., *sulcata*; Revised conod., revised conodont zonation (Corradini et al. 2016; undistinguished in the NDB); *cost*., *costatus*; *kock*., *kockeli*. Palyno, palynozones (Higgs et al. 1988). Coral, rugose coral zones (Poty et al. 2006). Foram, foraminiferan biozones (Poty et al. 2006; emended by Poty 2016). *LST* lowstand system tract; *TST* transgressive system tract; *HST* highstand system tract; *MFS* maximum flooding 'surface'; *SB* sequence boundary. Depositional hiatuses are indicated by striped pattern. Legend in Fig. 15

(upper Tournaisian) substage includes the former 'Tn3' and a part of the 'V1a' units (Poty et al. 2014). Consequently, the name 'Middle Tournaisian' that some authors still use under the former 'Tn2' assumption is no longer valid and it should be rejected in order to avoid further confusion.

Based on zircon age published by Trapp et al. (2004), Streel et al. (2006) inferred a duration of 3 My for the Strunian (covering the latest Famennian *S. praesulcata* Zone to earliest Tournaisian *S. sulcata* Zone). This age appears now to be overestimated for the duration of only a single transgressive system tract within the Comblain-au-Pont Fm and its lateral equivalents in the type area. Based on the counting of 45 to 48 (some uncertainties remain) precession cycles (18.6 ky in rough estimation, Poty et al. 2013), the Strunian substage has a duration of only 0.84–0.89 My. With the same method, the duration of the Hastarian substage is estimated as 4.22 My, 0.57 my for the Hastière Fm only (Poty 2016). The base of the Strunian (base of the Upper *expansa* Zone sensu Streel 2000; i.e. *B. ultimus* Zone, see "Conodonts") is situated in the upper part of the so-called 'Strunien gréseux' (Conil 1964) in the Anseremme section (bed 38), recording the FAD of *Quasiendothyra kobeitusana* (Bouckaert et al. 1974) and *B. ultimus* (Dreesen and Thorez 1994), and in the Chanxhe section where the FAD of *Q. kobeitusana* (bed 115, Bouckaert et al. 1970) follows that of *B. ultimus* (bed 97, Dreesen et al. 1993) overlying the sequence boundary (bed 93). Note that the base of the Strunian proposed by Maziane-Serraj et al. (2007) in bed 110 of the Chanxhe section is only based on graphic correlation with the Refrath borehole of western Germany (Streel et al., 2004) and therefore should not be taken into account.

The Comblain-au-Pont, Dolhain and Etrœungt formations are overlain by the carbonate-richer Hastière Fm, the first deposit of the Carboniferous succession in the NDB. The Hastière Fm exposes at its base one bed including Devonian faunas. The reworked nature of these faunas is debated (Van Steenwinkel 1988; Casier et al. 2004 and discussion below). The rest of the formation has clearly post-Devonian faunas and includes both post-disaster faunas (Lazarus and Liliput taxa, generalists, ubiquists) and a few long-ranging taxa, as well as the first typically Carboniferous biota. The lower member of the Hastière Fm is a lateral equivalent of the Binsfeldhammer Mbr in the VASA and partly to the Stockum Limestone. The Avesnelles Fm ('Calcaire noir d'Avesnelles') is also a lateral equivalent of the lower and middle members of the Hastière Fm to which it passes

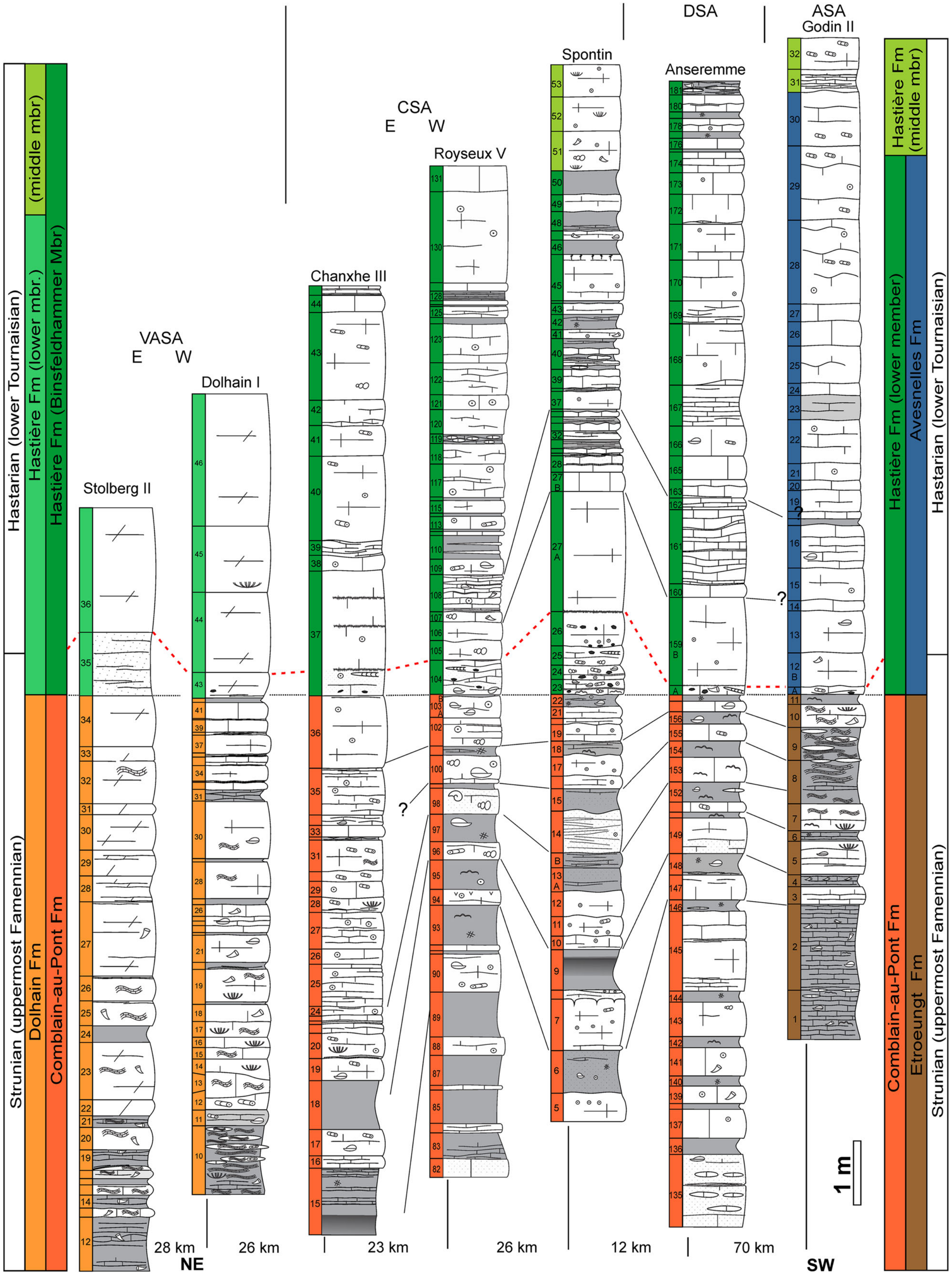


Fig. 3 Correlation of the presented sections. Abbreviations: *ASA* South Avesnois sedimentation area; *CSA* Condroz sedimentation area; *DSA* Dinant sedimentation area; *VASA* Vesdre–Aachen sedimentation area. Legend in Fig. 15

laterally over a few hundred metres as demonstrated in the Godin quarry in Avesnes-sur-Helpe (see below for biostratigraphic correlations).

From a sequence-stratigraphical point of view, the third-order sequence no. 1 of Hance et al. (2001, 2002; Fig. 2) straddles the DCB. Its transgressive system tract (TST) starts on an erosional surface (Conil 1968) capping a sandstone unit (possibly the lowstand system tract) referred as Epinette Fm or Strunien gréseux by Conil (1964). It covers the laterally equivalent Etrœungt/Comblain-au-Pont/Dolhain formations and the lower member of the Hastière Fm. The Strunian part of this TST includes 45–48 cycles of 18.6 ky whereas the Hastarian part includes 31 cycles (plus the unknown time corresponding to the 1.75-m-thick unit at the base, see Denayer et al. 2019), i.e. a duration of c. 1.45 My. Comparable duration is obtained for the TSTs of other Tournaisian sequences (Poty 2016). The highstand system tract (HST) is represented by the middle member of the Hastière Fm. However, several authors (e.g. Van Steenwinkel 1988; Muchez 1996; Smeesters et al. 2000; Kumpan et al. 2014) favour another interpretation. They consider the Etrœungt Fm as a HST, and the Hastière Fm is the succeeding TST. The Hangenberg Event would thus represent the sequence boundary. However, as already noted by Hance et al. (2001), the facies across the DCB are almost identical and can hardly be representative of different system tracts. In addition, the very homogeneous composition of the middle member of the Hastière Fm and its wide extension in the basin is rather typical of a HST. A unequivocal third-order sequence boundary is located higher, between the middle and upper members of the Hastière Fm (Poty et al. 2006; Poty 2016), which can be traced at a global scale (South China (Hance et al. 1993, 2011), Poland (Poty et al. 2003), NW Turkey (Denayer 2014)). The latter upper member starts with an erosive surface and is clearly transgressive with a maximum flooding 'surface' (in fact a zone rather than a surface) corresponding to the shaly Pont d'Arcole Fm and a highstand system tract corresponding to the carbonate Landelies Fm (Denayer et al. 2015; Poty 2016; Fig. 2).

Several sections were explored with geochemical and geophysical aspects (e.g. Azmy et al. 2009; Kumpan et al. 2014, 2019; Bábek et al. 2016), but none yielded significant results.

Biostratigraphy and biotic assemblages across the DCB

The NDB is a classical area for the Devonian–Carboniferous transition and has been studied for almost a century (see summary in Groessens 2006). As stated earlier, a much thicker and complete succession is recorded within these neritic settings as compared with the time-equivalent deeper facies (e.g. Conil and Lys 1970, 1980; Conil et al. 1986). However, due to the absence of a good record of the *Siphonodella* lineage within neritic settings, the DCB was traditionally placed above the last conodonts of the *praesulcata* Zone (Webster and Groessens 1991), hence, above the horizon, recording the extinction of the Devonian fauna such as the quasiendothyrid foraminifers, cryptophyllid ostracods, Strunian rugose corals, brachiopods and trilobites (Conil et al. 1977, 1986; Paproth et al. 1983; see below). Although not matching the ICS standards, this highly pragmatic criterion is based on the recognition of the abundant last occurrences of Devonian fauna and flora in shallow-water sections and has proven to be very efficient (Fig. 2). Moreover, the *Montpellier criterion* has been successfully applied and allows precise correlation between sections inside and outside the NDB. As currently accepted by the palaeontological community, the scarcity or even the lack of conodonts around the DCB everywhere in shallow-water facies—and sometimes in deeper facies as well (Corradini et al. 2017)—hampers their effective use for the recognition of a precise boundary. However, conodonts characteristic of shallow-water conodont biofacies are present in these neritic facies but their study remained preliminary (Austin et al. 1970; Bouckaert and Groessens 1976; Dreesen et al. 1986), possibly because it was traditionally/dogmatically admitted that they had less utility for international correlations. A review of the main fossil groups occurring in the Devonian–Carboniferous transitional beds in Belgium and surrounding areas is proposed, with a focus on their utility and efficiency as biostratigraphic markers.

Unless specified, all illustrated specimens are housed in the palaeontological collection of the University of Liège under prefix PA.ULg.

Plant macrofossils and microfossils

Spores are particularly abundant in the upper Famennian–Strunian succession of the NDB. Conversely, the dominantly carbonate Hastarian deposits are particularly poor and only a few levels have yielded spores. Due to the particular depositional settings of the Strunian in Belgium (alternating marine limestone beds and fine-grained proximal siliciclastics), biostratigraphic zonations combining both continental and marine organisms can be proposed. However, their occurrence in separated beds prevents precise correlations at a scale lower than bed thickness, i.e. 10–30 cm.

The abundant and widely distributed miospore *Retispora lepidophyta* (Fig. 4a, b) was very early identified as a key marker of the Strunian (Streel 1966; Conil and Lys 1970). Recorded in many parts of the world, it is characterised by a narrow stratigraphic range and a strong morphological variation (Streel 1966; Owens and Streel 1967). Conil and Lys (1980) placed the base of the Strunian at its FAD and proposed the Avesnelles and Saint-Hilaire (France) sections as stratotypes. The precise first occurrence of *R. lepidophyta*, however, rises some correlation problems due to facies influence. In the NDB, *R. lepidophyta* is found near the base of the

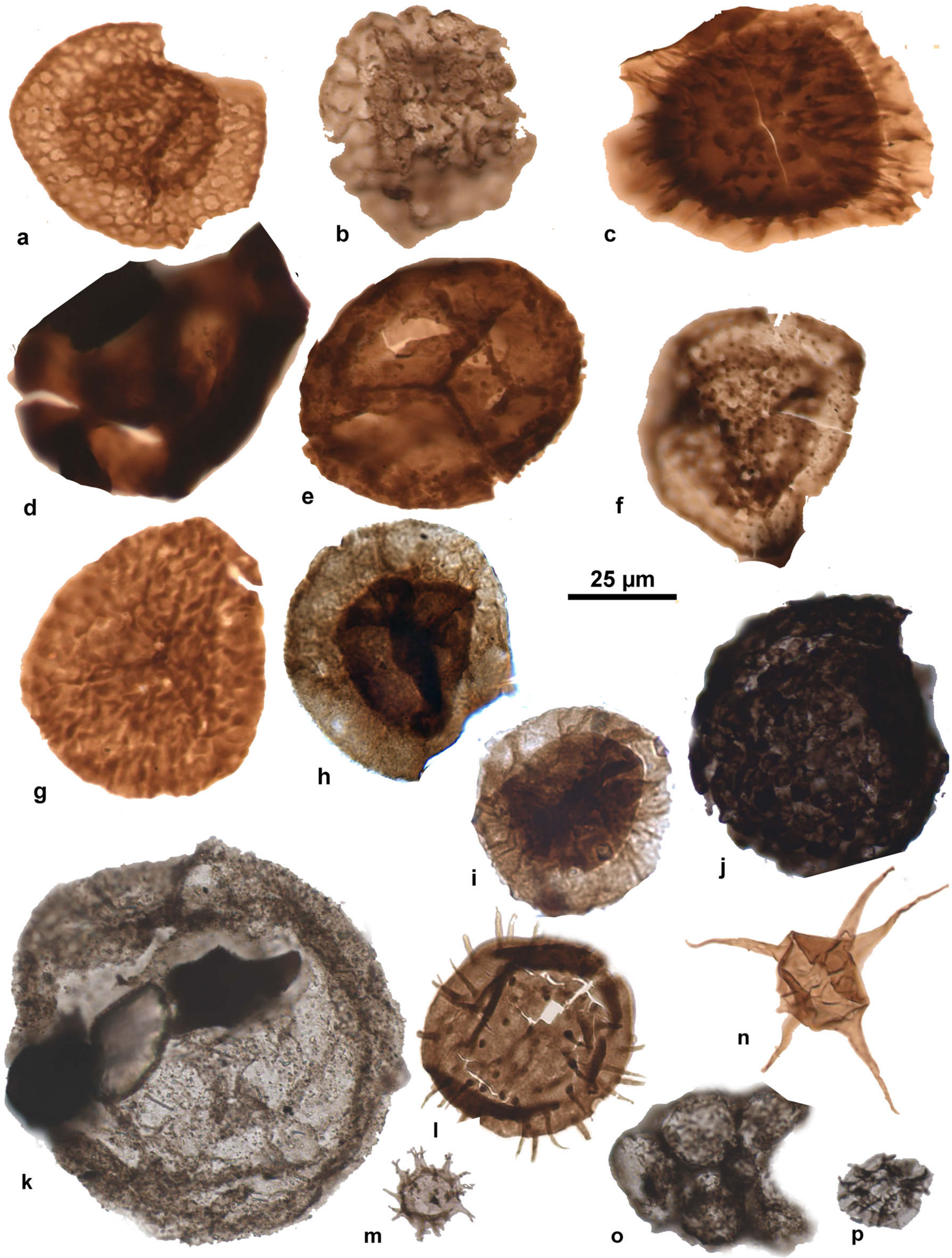


Fig. 4 **a**–**p** Selected miospore and acritarch guide taxa across the DCB. **a** *Retispora lepidophyta*, specimen ULg 72237/I. Pont-de-Scay section bed 73. **b** *Retispora lepidophyta* var. *tener*, specimen ULg 72242 B. 87, Pont-de-Scay section. **c** *Vallatisporites hystricosus*, specimen ULg 72237/II, Pont-de-Scay section bed 73. **d** *Knoxisporites literatus*, specimen ULg 72208, Pont-de-Scay section bed 65. **e** *Apiculiretusispora verrucosa*, specimen ULg 72214, Pont-de-Scay section bed 75. **f** *Indotriradites explanatus*, specimen ULg 72242, Pont-de-Scay section bed 87. **g** *Rugospora radiata*, specimen ULg 72235, Pont-de-Scay bed 69. **h** *Diducites plicabilis*, specimen ULg 62464, E42/2, Strud. **i** *Diducites versabilis*, specimen ULg 62464, M42, Strud. **j** *Verrucosisporites nitidus*, specimen ULg 77831, Chansin. **k** *Maranhites stockmansii*, specimen ULg 77837, Chansin section. **l** *Gorgonisphaeridium winslowiae*, specimen ULg 72207 R48, Pont-de-Scay section. **m** *Multisphaeridium anastomosis*, specimen ULg 72207, Pont-de-Scay section. **n** *Micrhystridium ampliatum*, specimen ULg 72207 K48, Pont-de-Scay Section. **o** *Synsphaeridium* sp., specimen ULg 77837, Chansin section. **p** *Cymatiosphaera* sp., specimen ULg 77837, Chansin section

Comblain-au-Pont Fm (top of the Strunien gréseux of Conil (1964)) or its lateral equivalent in the ASA (upper part of the Epinette Fm, Conil and Lys 1970, 1980; Fig. 2). Unfortunately, in the latter type area, conodonts are lacking at the base of the Strunian. Streel (2005) proposed the well-studied Chanxhe section as a stratotype for the uppermost Famennian because of the co-occurrence of spores and conodonts. However, in this section, *R. lepidophyta* is found 12.5 m (bed 93, Fig. 3) below the first limestone bed (bed 97) containing conodonts of the *B. ultimus* conodont Zone, suggesting a FAD of *R. lepidophyta* older than the base of the Strunian (Dreesen et al. 1993; Maziane et al. 1999). A similar situation is encountered in the Hastière section (Bouckaert et al. 1974). These doubts are confirmed by data coming from the Refrath borehole in Germany that record the spore in layers attributed to the *Bispathodus costatus* conodont Zone (upper part of the former Middle *expansa* Zone) (Hartkopf-Fröder 2004; Piecha 2004). Hence, the definition of the base of the Strunian at smaller scale remains problematic, mainly due to facies issues.

In a first approach, the Strunian has been subdivided by means of a biometrically based zonation using *R. lepidophyta* only. Six successive *zones* have been established (A to F in Streel 1966). However, though being of great importance for regional correlations, these biometrical zones are obviously biased by the grain size and sorting of the spore-bearing sediments and should therefore be used with caution. This was already suggested by Streel (1969) and Maziane et al. (2002), who both showed that the size sorting is not restricted to *Retispora* but affects all spores.

In parallel, a biozonation combining several palynological criteria was established (Bouckaert et al. 1968, 1969, 1970). The latter biozones were either interval zones, Oppel zones or assemblage zones. Four zones and twelve subzones were established for the Famennian by Bouckaert et al. (1970). The Strunian was entirely included within the same *Pusilites–Lepidophyta* (PL) (PLm to PLs) Florizone, characterised by the co-occurrence of *R. lepidophyta* and *Vallatisporites pusillites* (now *Vallatisporites hystricosus*). The base of the Carboniferous was, according to this zonation scheme, characterised by the *trivialis–explanatus* (TE) Florizone (Paproth and Streel 1971). The biozonation revised by Higgs et al. (1988) based on the Irish succession was successfully applied in the German Rhenish Mts and led firstly to a subdivision of the PL Zone in three to four subzones that are *R. lepidophyta–Apiculiretusispora verrucosa* (LV), *R. lepidophyta–Knoxisporites literatus* (LL), *R. lepidophyta–Indotriradites explanatus* (LE) and *R. lepidophyta–Verrucosisporites nitidus* (LN) (Paproth et al. 1986). A confusion, however, remained concerning the statuses of the LV and LL subzones that were never found in stratigraphical succession in any section. In 1984, a new revision of the zonation led to the upgrade of the LL, LE and LN subzones to a full biozonal status referring for a formal definition of each of them to Higgs et al. (1988) that apparently remained in press for a long time.

Maziane and Vanguestaine (1997) and Maziane et al. (1999, 2002) presented the biometric evolution of the spore *Retispora lepidophyta* below the DCB, showing a significant decrease of size through the LL and LE palynozones, as already observed by Streel (1966). In parallel, spores attributed to ‘coal swamp’ plants (such as *Diducites* spp., i.e. group II in Maziane et al. 2002) decrease in abundance upwards. It is interpreted by these authors as the progressive replacement of the 'coal swamp' ecosystem by the ‘swamp margin’ vegetation and thus witnessing a probable drying of the continental margin during the Strunian.

Streel et al. (1987), in fact, summarised and defined most of the biozones that have been used subsequently. The Strunian is thereby divided into six interval zones: *Retispora lepidophyta* (Lep.), *Apiculiretusispora verrucosa* (Ver., Fig. 4e), *Grandispora echinata* (Ech.), LL, LE and LN. The Lep., Ver. and Ech. zones correspond to the *Retispora lepidophyta–Apiculiretusispora verrucosa* (LV) Oppel Zone. The same issue of the relationship between the LV Oppel Zone and LL interval Zone however remained. The latter was considered either younger or equivalent to the Ech. interval Zone part of the LV Oppel Zone. This problem was solved by Maziane et al. (1999) that showed the presence of *Knoxisporites literatus* (Fig. 4d), the marker of the LL interval Zone just after the *Apiculiretusispora verrucosa–Vallatisporites hystricosus* (VH) interval Zone proving the LV and LL biozones to be equivalent.

Maziane et al. (1999) highlighted the problem of the absence of *Verrucosisporites nitidus* in most Belgian sections and suggested that the change to continuous limestone succession towards the top of the Comblain-au-Pont Fm and the base of the Hastière Fm would preclude the possibility of recognising this biozone. This question was addressed by Prestianni et al. (2016) while documenting beds closer to the DCB in the CSA. They suggest the absence of *Verrucosisporites nitidus* in Belgium, for ecological and palaeogeographical reasons. The latter authors argue that the absence of this spore alone is not sufficient to prove the presence of a hiatus at the end of the uppermost Famennian, as suggested earlier by Van Steenwinkel (1993) and should be regarded as an ecozone characterising the upper part of the LE Zone. The recent discovery of a single specimen of *V. nitidus* (Fig. 4j) in the Chansin section reinforces the hypothesis of the rarity and, most probably, ecologically influenced distribution of the *V. nitidus* bearing plant. The hypothesis of a gap at the end of the uppermost Famennian in Belgium based on this absence (e.g. Van Steenwinkel 1993; Casier et al. 2004) has consequently to be dismissed. Another argument reinforcing this statement is the record of the *tener* Event in Belgium (Prestianni et al. 2016). In most regions, where the levels immediately preceding the DCB could be observed in detail, a disrupted and/or abnormal palynological assemblage has been observed. Named 'LCr' in Ireland (Van Veen 1981) and 'LN transitional' in Sauerland (Higgs et al. 1992; Streel and Hartkopf-Fröder 2005) and also identified in Poland (Filipiak and Racki 2010), it corresponds to zone F in Streel (1966). It is characterised by a depauperate assemblage dominated by *R. lepidophyta* var. *tener* and presenting a high percentage of abnormally shaped spores (Fig. 4b).

The basal Carboniferous VI Palynozone, defined in the British Isles by Neves et al. (1972), was hardly correlated with the DCB because conodonts lack in the British successions (Higgs et al. 1986). In Belgium, the TE (*trivialis–explanatus*) Zone introduced by Streel (1966) has the same definition than the VI Zone. The latter was therefore used instead of TE in the Belgian Tournaisian, again with a base roughly correlated with the DCB by the lack of marker conodonts and the lack of facies suitable for palynology immediately around the supposed DCB. Paproth and Streel (1971), however, recognised the base of the VI Zone in the German Hasselbachtal section, c. 18 cm below the first *Siphonodella sulcata* conodont-yielding bed (Higgs and Streel 1984). This 18-cm delay between spores and conodonts obviously reflects lithological differences and Signor–Lipps effect (Signor and Lipps 1982) rather than any significant stratigraphical discrepancy.

In the subsequent literature, the base of the VI Zone was placed in the Strunian. In Belgium, however, the last shaly horizon of the Devonian, immediately below the HSS Event (e.g. bed 22 in the Spontin section, 1.2 m below the DCB, see "Mid-shelf: the Spontin and Chansin sections (southern CSA)" and Fig. 3) still yields Devonian spores such as *Retispora lepidophyta*, typical of the last Famennian Zone LE, whereas a thin silty layer within the HSS Event equivalent beds (1-cm-thick interbeds 107–108 in Chansin) yielded the Devonian spore *V. nitidus* (Fig. 4j). The first shaly horizon in the Tournaisian (bed 30 in Spontin, 2 m above the DCB) recorded spores of the VI Zone. A similar situation is known in the classical Yvoir section (Paproth and Streel 1971). The boundary between the LE and VI zones therefore should be placed in this c. 3-m limestone interval. It has to be noted that the VI Zone is defined by the disappearance of the emblematic Late Devonian spores *Retispora lepidophyta* (Fig. 4a), *Vallatisporites hystricosus* (Fig. 4c), *Rugospora radiate* (Fig. 4g), *Diducites versabilis* (Fig. 4i) and *Diducites plicabilis* (Fig. 4h) (Streel 2015). It seems therefore logical and legitimate to correlate these disappearances—and consequently the base of the VI Zone—with the extinctions of marine fauna at the top of the HSS Event equivalents, hence with the DCB.

As floral macroremains are lacking in the NDB, spores are the only reliable proxies of the Strunian continental plant cover and its dynamics. The Strunian palynological assemblages diverge slowly from the upper Famennian VCo and VH assemblages with several new taxa appearing. The top of the LL interval Zone is marked by the highest spore diversity of the whole Famennian. The LE Zone, in contrast, is marked by a progressive decrease in diversity that seems to happen as a step-by-step process (Streel 1996). The *tener* Event represents the last scene of this process with low specific diversity, a lower number of specimens and the occurrence of abnormal, deformed spores that suggest an environmental disruption on the continent margins (Fig. 4).

Many studies have been focusing on the Late Devonian plant diversity in Belgium (Stockmans 1948; Fairon-Demaret 1996; Prestianni and Gerrienne 2015). It is mainly represented by the upper (not uppermost) Famennian Evieux flora (Fairon-Demaret 1986; Thorez et al. 2006). The Strunian is marked in the NDB by an increasing marine influence on the facies, the plant preservation is therefore less favourable and most fossils are unidentifiable drifted laciniate fragments. No plants have up to now been reported in Belgium between the upper Famennian and the lower Viséan (Mottequin et al. 2015).

Conodonts

Conodonts are quite rare microfossils in the upper and uppermost Famennian deposits of the NDB, where they generally tend to be concentrated in thin carbonate deposits within dominant siliciclastic formations. The upper part of the upper Famennian Evieux Fm was attributed to the *Bispathodus costatus* Zone by Dreesen et al. (1993). The occurrence of *Bispathodus ultimus ultimus* in the first limestone bed of the Comblain-au-Pont Fm in the Chanxhe and Anseremme sections (Dreesen et al. 1993; Dreesen and Thorez 1994) allows to include the entire formation in the uppermost Famennian *B. ultimus* zone (former Upper *expansa* standard conodont Zone, Fig. 2), hence to pinpoint the lower boundary of the uppermost Famennian and of the Strunian substage, as proposed by Streel et al. (1998) and Streel (2005).

The conodont assemblages across the DCB received little attention, as they were supposedly poor (< 10 specimens/kg), less diverse and dominated by neritic and/or endemic species. Seen through the prism of the conodont standard zones of Ziegler and Sandberg (1984, 1990) and subsequent zonations (e.g. Corradini et al. 2017; Spalletta et al. 2017), these assemblages were considered of less interest for international biostratigraphic correlations (Dreesen et al. 1986, 1993). They are, nowadays, reconsidered as they bear an important eco-biostratigraphical signal (Sandberg and Dreesen 1984). Nevertheless, several identifications were performed by Austin et al. (1970), Bouckaert and Groessens (1976), Paproth and Streel (1971), Van Steenwinkel (1980, 1988) and Sandberg (in Casier et al. 2004). Apparently, most (deeper-water) biostratigraphic markers or index conodonts are lacking, especially the fully marine siphonodellids. However, some species characteristic of—or restricted to—shallower-water biofacies are useful for intrabasinal correlations and with other shallow-water depositional settings (e.g. with Poland, Paproth and Streel 1971). Van Steenwinkel (1988) summarised the occurrences of conodont faunas in the Anseremme section across the DCB. *Icriodus* sp., *Pelekysgnathus* sp., *Bispathodus costatus*, *Pseudopolygnathus graulichi* and *Clydagnathus cavusformis* occur in the Strunian Comblain-au-Pont Fm; *Pseudopolygnathus conili* (now junior synonym of *Pseudopolygnathus primus*), *Pseudopolygnathus vogesi* (= *P. primus primus* M2 sensu Hartenfels and Becker 2018), *Neopolygnathus communis communis*, *Bispathodus aculeatus aculeatus*, *Bispathodus stabilis* and *Polygnathus inornatus* occur in both the Comblain-au-Pont and the Hastière Fm; *Polygnathus paprothae*, *Siphonodella duplicata*, *Siphonodella quadruplicata*, *Polygnathus parapetus*, *Bispathodus sculderus* (now junior synonym of *Clydagnathus plumulus*), *Bispathodus aculeatus anteposicornis*, *Protognathodus meischneri* and *Pseudopolygnathus expansus* (= *P. primus primus* M2 to M3 sensu Hartenfels and Becker 2018) are only known from the lower member of the Hastière Fm—note that the last three taxa were identified in the upper part of Strunian strata in the Walcourt section (Dreesen et al. 1976) and the Tohogne borehole (Bouckaert et al. 1977). Additional occurrences in the Strunian and Hastarian can be found in Bouckaert and Groessens (1976). However, none of these latter taxa is indicative of the DCB. The presence of *Protognathodus kockeli* in the basal bed of the Hastière Fm in the Anseremme, Hastière and Gendron-Celles sections (Bouckaert and Groessens 1976); in the Gendron section (Hulsonniaux road, a few hundred metres W of the classical section; Bouckaert et al. 1974); in the Yvoir section (Paproth and Streel 1971); and in the basal bed of the Avesnelles Fm in Avesnes-sur-Helpe (Paproth and Streel 1971) allows a correlation of the two formations as lateral time-equivalent deposits (see discussion below). The specimens determined as *P. kockeli* by Bouckaert and Groessens (1976, plate 1, Figs. 8 and 10) from Anseremme are possibly transitional forms between *Protognathodus collinsoni* and *P. kockeli* (Corradini, written com., February 2020).

Foraminifers

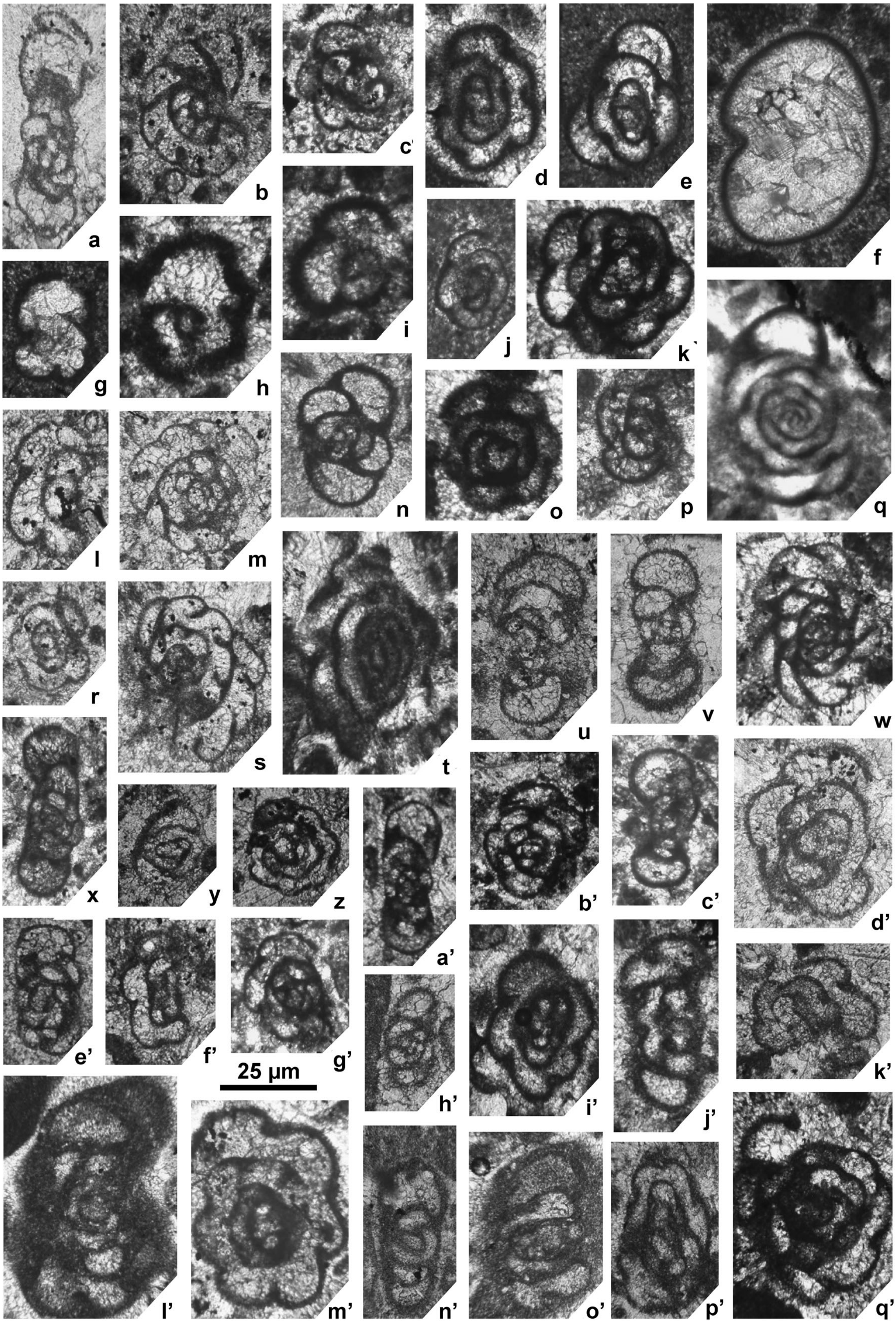
Strunian and Hastarian foraminifer associations were reported from the NDB in numerous papers (e.g. Conil 1964, 1980; Conil and Lys 1970; Conil et al. 1991; Mamet 1986). As for other faunas, the foraminifer associations differ significantly in different parts of the basin, reflecting particular sedimentary environmental conditions along a proximal–distal gradient. Therefore, the stratigraphic entries are sometimes cryptic and facies-controlled, just as it is the case for other macrofossils (brachiopods, rugose corals, stromatoporoids). However, the lithostratigraphic constraints help to discriminate environmentally controlled associations which could be assigned to an older stratigraphic position or interpreted as diagnostic for a hiatus (e.g. Van Steenwinkel 1988).

Calcareous foraminifers began to diversify during the Late Devonian and were sufficiently abundant and diverse from the base of the Strunian onwards to become stratigraphically useful (Conil 1980). Conil et al. (1977) introduced the biozone Df3 to characterise this particular interval, with subzones α to ε corresponding to successive foraminifer associations. The youngest Df3ε subzone (renamed DFZ7 by Poty et al. 2006) covers the Etrœungt, Dolhain and Comblain-au-Pont formations, with a rich association dominated by *Quasiendothyra kobeitusana* (Fig. 5a), *Quasiendothyra konensis*, *Klubovella* sp., *Septatournayella* ex. gr. *rauserae* (Fig. 5o, l'), *Laxoendothyra parakosvensis*, *Septaglomospiranella* spp. (Fig. 5r, t, b', h', i'), *Septabrunsiina* spp. (Fig. 5u, v, d'), *Glomospiranella* spp. (Fig. 5y) and abundant *Paracaligelloides* spp.

In some areas (central CSA), the very large and evolved *Quasiendothyra* (*Q. kobeitusana*, *Q. dentata*, *Q. konensis*) and *Klubovella* seem to be very scarce and only a few specimens of *Quasiendothyra regularis* with a doubtful incipient inner fibrous layer (forma '*radiata*') have been found so far. The HSS Event equivalent beds yield a slightly more diverse foraminifer association with, in addition to the previously cited genera, cf. *Klubovella* and *Chernyshinella* spp. (Fig. 5c, e').

However, those large quasiendothyrids are reported from the upper part of the Etrœungt Fm in the ASA (Conil and Lys 1970) and from the upper part of the Comblain-au-Pont Fm in the eastern part of the CSA, allowing the identification of the DFZ6–DFZ7 zones. Lipina (1961) stated that the large quasiendothyrid forms are often confined to strong hydrodynamic facies. In the ASA and VASA, they are often associated with the reefal facies (Conil 1968, 'faciès récifaux de l'ouest' and 'faciès récifaux de l'est'). As very rare stromatoporoids and corals occur in the upper Strunian of the 'central' CSA (Spontin and Royseux sections), the large *Quasiendothyra* also seem to be lacking for the same reason of hydrodynamics. The impact of rapid facies changes and siliciclastic influxes on the Upper Devonian microfaunal distribution in the central NDB was also pointed by Conil (1968). Reitlinger (1961) indicated that the last and very large quasiendothyrids seem to be lacking or that they are very rare in most parts of Western Europe. The HSS Event equivalent beds yield a slightly more diverse foraminifer association with, in addition to the previously cited genera, cf. *Klubovella* and *Chernyshinella* spp. (Fig. 5p').

Poty et al. (2006) defined the MFZ1 interzone from Conil et al.'s (1991) 'Cf1α' zone, covering the Hastière lower and middle members above the HSS Event equivalent. It contains simple forms such as *Bisphaera irregularis*, *Earlandia minima*, *Earlandia moderata* and parathuramminids. Small tournayellids are rare due to the crinoidal grainstone–rudstone facies of the Hastière Fm, not suitable for plurilocular foraminifers (Conil et al. 1991; Brenckle and Hance 2005).


a
b
c
d
e
f
g
h
i
j
k`
l
m
n
o
p
q
r
s
t
u
v
w
x
y
z
a'
b'
c'
d'
e'
f'
g'
25 µm
h'
i'
j'
k'
l'
m'
n'
o'
p'
q'

◀ **Fig. 5** **a–q'** Selected foraminifers across the DCB in southern Belgium. **a–c**, **m** From the Strunian Comblain-au-Pont Fm. **r–g'**, **j'**, **l'** From the HSS Event equivalent horizon, below the DCB. **d–g**, **j**, **k**, **n–q** From the basal Tournaisian Avesnelles Fm. **h'–j'**, **m'–q'** From the lower Tournaisian lower member of the Hastière Fm. **a**, **b** *Quasiendothyra kobeitusana substricta*, specimens Spontin 19 and 16. **c** *Chernyshinella* sp., specimen Spontin 18. **d**, **e** *Septabrunsiina* sp., specimens Godin 28 and 24. **f** *Bisphaera malvkensis*, specimen Godin 24/I. **g–i** *Tournayellina pseudobeata*, specimens Godin 15, 23/I and 24/II. **j** *Prochernyshinella* sp., specimen Godin 24/IV. **k** *Septabrunsiina* sp., specimen Godin 23/II. **l** *Chernyshinella* sp., specimen Chansin 108/II. **m** *Quasiendothyra communis*, specimen 25A/I. **n** *Prochernyshinella* sp., specimen Godin 14. **o** *Septatournayella* ex gr. *rauserae*, specimen Godin 23/IV. **p** *Prochernyshinella* sp., specimen Godin 23/III. **q** *Septatournayella* sp., specimen Godin 29. **r** *Septaglomospiranella* sp., specimen Chansin bed 108/I. **s** *Quasiendothyra regularis*, specimen Spontin 25A/II. **t** *Septatournayella* aff. *potensa*, specimen Spontin 26. **u**, **v** *Septabrunsiina kingirica*, specimens Spontin 24/II and Chansin 109A. **w**, **x** *Quasiendothyra regularis*, specimens Spontin Chansin 107 and Spontin 24 top. **y** *Glomospiranella* aff. *rara*, specimen Spontin 25/II. **z** *Septatournayella* ex gr. *rauserae*, specimen Chansin 108/III. **a'** *Quasiendothyra regularis*, specimen Spontin 25/I. **b'** *Septaglomospiranella* sp., specimen Spontin bed 25A/II. **c'** *Septabrunsiina* sp., specimen Spontin bed 23A/I. **d'** *Septabrunsiina kingirica*, specimen Spontin 24/III. **e'** *Chernyshinella* sp., specimen Spontin 24. **f'**, **g'** *Septatournayella* sp., specimens Spontin 24/IV and 23A/II. **h'** *Septaglomospiranella* aff. *bouckaerti*, specimen Chansin 115/IV. **i'** *Septabrunsiina kingirica*, specimen Chansin 115/II. **j'** *Septaglomospiranella rudis*, specimen Chansin 114/II. **k'** *Chernyshinella* sp., specimen Spontin 25/II. **l'** *Septatournayella* ex gr. *rauserae*, specimen Chansin 114/I. **m'** *Septabrunsiina kingirica*, specimen Chansin bed 108/IV. **n'** *Septaglomospiranella* aff. *bouckaerti*, specimen Chansin 116. **o'** *Chernyshinella* aff. *paucicamerata*, specimen Chansin 115/V. **p'** *Chernyshinella* sp., specimen Chansin 115/III. **q'** *Septabrunsiina kingirica*, specimen Chansin 114/IV

Richer and more diverse plurilocular associations occur locally where palaeoenvironmental conditions where less defavourable (Conil and Pirlet 1970). It is the case in the ASA, 2 to 5 m above the base of the Calcaire noir d'Avesnelles (Avesnelles Fm; Conil et al. 1986). Typical taxa include *Chernyshinella* spp., *Earlandia moderata*, *Laxoendothyra parakosvensis nigra*, *Septabrunsiina* spp., *Septaglomospiranella* spp. and abundant representatives of the index *Tournayellina pseudobeata* (Fig. 5g–i). They define the DFZ8 *Tournayellina pseudobeata* foraminifer Zone of Poty et al. (2006), which was initially assigned to the Devonian. Conil et al. (1986) considered that the associated conodont fauna had Devonian affinities with '*preasulcata*-age' elements—notably *P. kockeli* reported by Paproth and Streel (1971) and Paproth et al. (1979). However, the foraminifers were more indicative of a Hastarian age. This interpretation is followed by Kumpan et al. (2014) who place it even higher, in the MFZ3 foraminifer zone, i.e. in the Ivorian substage, based on the occurrence of evolved chernyshinellids (identified as *Chernyshinella glomiformis* and *Chernyshinella paucicamerata*), but *Chernyshinella* species are usually misidentified because of an imprecise taxonomy (Brenckle and Hance 2005). Kumpan et al. (2014) admitted that both species are known from Eastern Europe in the lower Tournaisian Upin Horizon (*Prochernyshinella disputabilis* Zone, Makhlina et al. 1993). Hence, their occurrence in the Avesnelles Fm is not evidence of an age younger than Hastarian. As the HSS Event is recognised at its base (see discussion below), the Avesnelles Fm can be correlated with the Hastière Fm (hypothesis no. 1 in Conil et al. 1986). Consequently, the DFZ8 zone would be coeval of the depleted MZF1, which is characterised by an impoverished foraminifer association, most probably for facies reasons.

According to Vevel (2009), *T. pseudobeata* occurs in peloidal packstone-to-grainstone facies of the lower Tournaisian of Timan–Pechora (Urals). Similar carbonate microfacies characterise the upper half of the Avesnelles Fm (i.e. beds 22–31 in the Saint-Hilaire section, Conil et al. 1986). However, the predominant wackestone facies of the lower half of the Avesnelles Fm also contains numerous *T. pseudobeata* (beds 13–21 in Saint-Hilaire). This suggests that this species prefers low-energy shallow-marine environments, conditions that are not met with the coarse crinoidal–peloidal grainstones of the Hastière Fm, characteristic of a strong hydrodynamic environment (Conil and Lys 1970; Poty 2016). Conil and Lys (in Mansy et al. 1988) suggest, however, that the lower member of the Hastière Fm which locally displays some finer-grained facies in the NSA localities of Engis and Landelies could yield *T. pseudobeata* but recent search failed to confirm this hypothesis.

The guide taxa *T. pseudobeata* has a very short stratigraphical range and quickly disappears after the DCB (Kulagina et al. 2016; Hance et al. 2011). Kulagina et al. (2003) use it to define the Gumerovian Horizon that straddles the DCB and covers only a few tens of centimetres of sediments in the western Urals section. Hence, it seems obvious to correlate the Avesnelles Fm (bearing the 'DFZ8' association) with the upper part of the type Gumerovian Horizon (Kulagina 2013; Kulagina et al. in press, this issue). It is post-dating the HSS Event but could be older than the unilocular association (Malevkian) of MFZ1.

Another plurilocular association occurs in the 0.5–2.5-m-thick oolitic limestone directly overlying the HSS Event equivalent beds in several sections: Spontin, Chansin and Jenneret (eastern CSA, unpublished and Lentz 1985); Maredsous (northwestern DSA, Conil 1968); and Anseremme (southern DSA, unpublished). This association shares many taxa with DFZ8, but *T. pseudobeata* is lacking as well as *Septatournayella* ex. gr. *rauserae*. New elements include *Septaglomospiranella* aff. *bouckaerti* and large *Septabrunsiina* species with triangular septa (Fig. 5h', i').

It is conceivable that during the recovery phase immediately after the Hangenberg Crisis, small unilocular or bilocular forms—possibly ecological generalists or ubiquists—colonised hostile environments whereas more specialised forms developed in suitable environments such as shallow oolitic shoal and protected back-shoal facies. These forms can also be seen as the evidence of a Lilliput effect, affecting faunas after the crisis (Aretz et al. 2014), and especially in harsh environments such as crinoidal meadows. The recovery phase is recorded in the zone MFZ2 still yielding a poorly diverse fauna comprising *Tournayellina beata*, Chernyshinella spp., *Septabrunsiina* spp., *Septaglomospiranella* spp. and *Inflatoendothyra* sp. (Conil et al. 1977; Poty et al. 2006), but it is not before the next MFZ3 that the foraminifer faunas become really diversified again (Brenckle and Hance 2005; Poty et al. 2006).

Calcified algae and microbionts

As a global tendency, the Strunian algal microflora was dominated by long-ranging taxa and it remained scarce and poorly diverse throughout the whole Tournaisian (Mamet 1986). In Belgium, the Strunian formations yield only a few umbellinids, kamaeninids, issinellids, *Sphaerinvia*, *Bevocastria* and rare *Parachaetetes* (Herbig and Weber 1996; Casier et al. 2004; Herbig and Mamet 2006). The incertae sedis *Menselina* and *Bisphaera* can be abundant in the upper part of the Strunian limestone (Herbig and Mamet 2006). The Hastarian is not richer, comprising the same elements, locally associated with abundant calcimicrobes (*Girvanella duccii* and *Girvanella wetheredi*, Conil 1964) and moravaminids.

Acritarchs

Although locally relatively abundant, Strunian acritarchs have only hardly been studied in Belgium. Streel (in Becker et al. 1974) provided a first overview of the general acritarch content of the middle to uppermost Famenn ey (eastern CSA). He pinpointed that the Strunian is characterised by the abundance of specimens of *Gorgonipshaeridium winslowiae*. Since then, only three sections reaching the DCB have been studied in detail for their acritarch content: the Tohogne borehole (Vanguestaine 1978; Maziane 1999), the Chanxhe section I (Maziane 1999; Maziane-Serraj et al. 2007) and the Spontin source section (Di Clemente 1985). However, none of these has yielded Tournaisian acritarchs. Vanguestaine (1978) provided a detailed account on the acritarch content of the Tohogne borehole. Unfortunately, this work only documents the lower part of the borehole corresponding to the LL Palynozone (Maziane et al. 2002). That interval is characterised by a very high diversity of acritarchs with up to 50 identified taxa. A tentative biostratigraphic interpretation was proposed, suggesting a correlation with the upper part of the *Cymatiosphaera labyrinthica* Zone established by Wicander (1975) in Ohio. The study of the Tohogne borehole was revised and completed by Maziane et al. (1999). This work confirms the earlier observations for the first part of the interval (− 174 to − 85.3 m deep: a relatively stable and very diverse assemblage with up to 57 identified taxa. In contrast, the last 20 m of the borehole was characterised by very poor acritarch assemblages. Similar results were published by Maziane et al. (1999) for the Chanxhe section I. Maziane-Serraj et al. (2007) gave a very detailed quantitative account of this section. The basal part of the Comblain-au-Pont Fm (beds 94–111), corresponding to the LL biozone, is marked by a significant diversification of acritarch taxa, with the notable occurrence of small spiny acritarchs like *Veryachium* and *Micrhystridium* (Fig. 4n), large acritarchs such as *Solisphaeridium* and *Stellinium*, small *Leiosphaeridia*, large and small *Gorgonosphaeridium* (Fig. 4l) as well as prasinophytes like *Cymatiosphaera* (Fig. 4p), *Synsphaeridium* (Fig. 4o) and *Petrospermella*. Nonetheless, the diversity in acritarchs tends to remain stable, whereas the end of the LL Palynozone (beds 111–147) is marked by a progressive loss of abundance and a higher proportion of prasinophytes. The top of the section corresponding to the LE Palynozone (beds 147–162) records a very depauperate acritarch assemblage dominated by *Leiospheridia* and *Gorgonisphaeridium*. Furthermore, Maziane et al. (1999) identified two acritarch zones in the Strunian of Belgium: the *Gorgonisphaeridium ohioense*–*Gorgonisphaeridium absitum* and *G. winslowiae*–*G. ohioense* biozones. The change in diversity observed throughout the Strunian in the Chanxhe section by Maziane-Serraj et al. (2007) can probably be explained by changing depositional conditions (ongoing transgression) although the influence of climatic change cannot be ruled out.

Corals

Corals are among the most common macrofaunal elements in the Strunian and in the basal Hastarian. Whereas the corals are rather uncommon in the Famennian of Belgium (Denayer et al. 2012), they became more abundant and diversified in the Strunian, where two successive assemblages have been defined (Poty 1999; Poty et al. 2006). The first one rugose coral zone—subzone RC0α—is characterised by the occurrence of ‘clisiophyllids’ and *Campophyllum* ssp. It is only known from the Epinette Fm in the ASA. The second assemblage—subzone RC0β—is more diverse (at least 11 species after Denayer et al. 2011) and characterised by the occurrence of *Campophyllum flexuosum* (Fig. 6a), *Campophyllum gosseleti* (Fig. 6e), ‘*Clisiophyllum*’ *omaliusi* (Fig. 6d), *Bounophyllum praecursor* (Fig. 6b) and ‘*Palaeosmilia*’ *aquisgranensis* (homeomorphic with the Carboniferous *Palaeosmilia*, see Poty 2010) (Fig. 6f). However, almost all sections yield a different assemblage, suggesting strong relationship of these corals to environment. Tabulate corals are not uncommon but require a taxonomic revision. *Yavorskia* spp. (Fig. 6c) and syringoporids are the most common (Tourneur et al. 1989). The RC0β subzone covers the Etrœungt (ASA), Comblain-au-Pont (DSA, CSA)

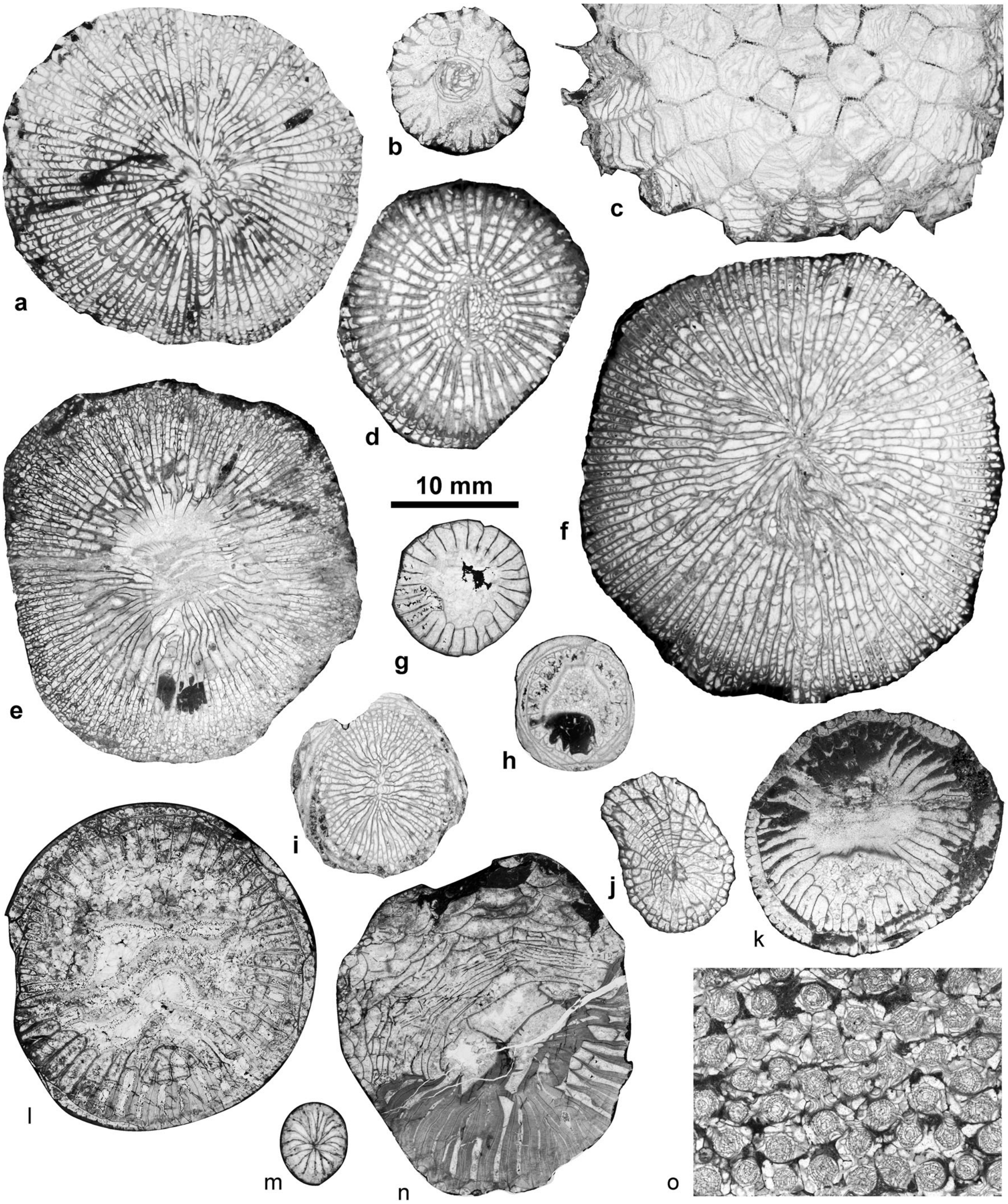


Fig. 6 **a**–**k** Selected typical guide taxa across the DCB among corals. **a** *Campophyllum flexuosum*, specimen Stol. II.21-91g; Stolberg II section, Dolhain Fm. **b** *Bounophyllum praecursor*, specimen Stol. II.141; Stolberg II section, Dolhain Fm. **c** *Yavorskia* sp., specimen God.25-82b, Godin section, Etroeungt Fm. **d** '*Clisiophyllum*' *omaliusi*, specimen Aves.69-92, Avesnelles section, Etroeungt Fm. **e** *Campophyllum gosseleti*, specimen Ans.146-12; Anseremme section, Comblain-au-Pont Fm. **f** '*Palaeosmilia*' *aquisgranensis*, specimen Dol.16-69e, Dolhain section, Dolhain Fm. **g** *Conilophyllum priscum*, specimen Ans.169-24a, Anseremme section, lower member of the Hastière Fm. **h** '*Hebukophyllum priscum*', specimen 13d.5292, Drewer section, Hangenberg Fm (courtesy D. Weyer). **i** *Kizilia kremersi*, specimen Roy.108-X, Royseux section, lower member of the Hastière Fm. **j** *Eostrotion* sp. specimen Spon.47-2b, Spontin section, middle member of the Hastière Fm. **k** *Conilophyllum streeli*, specimen Spon.47-12a, Spontin section, middle member of the Hastière Fm. **l** *Siphonophyllia hastariensis*, specimen GC.1, Gendron-Celles section, Landelies Fm. **m** *Saleelasma delepinei*, specimen Roy.V.33-V, Royseux section, Landelies Fm. **n** *Uralinia lobata*, specimen Chan.I.13, Chanxhe section, Landelies Fm. **o** *Groessensia* (= *Verolites*?) *ambigua*, specimen Nut.X, Chansin quarry, upper member of the Hastière Fm

and Dolhain (VSA) formations. All rugose corals became extinct at the end of the Strunian in the NDB (Poty 1999), and the last *Campophyllum* occurs in the beds corresponding to the HSS Event. The tabulate corals, however, persist in the

Tournaisian, although the stratigraphic distribution at species level is unknown.

The rugose corals re-appeared rapidly after the extinction of the Strunian corals at the DCB extinction event. The diversity of the first Tournaisian zone RC1 (*Conilophyllum* interval Zone of Poty et al. 2006) is rather low. The RC1α subzone, corresponding only to the lowermost beds of the lower member of the Hastière Fm, yields only *Conilophyllum priscum* (Fig. 6g) and *Kizilia kremersi* (Fig. 6i), a Lazarus taxon (Denayer et al. 2015). The RC1β subzone corresponds to the entrance of *Conilophyllum streeli* (Fig. 6k), *Siphonophyllia hastariensis* (Fig. 6l) and *Eostrotion* sp. (Fig. 6j) in the lower member of the Hastière Fm. The appearance of *Uralinia lobata* (Fig. 6n) and *Saleelasma delepinei* (Fig. 6m) defines the base of the subzone RC1γ in the Pont d'Arcole Fm. The tabulate corals include syringoporids, cleistoporids (*Yavorskia*) and the enigmatic *Groessensia* (= *Verolites*?) *ambigua* (Fig. 6o) recorded from the upper member of the Hastière Fm (Tourneur et al. 1989). The Hastarian was a period of recovery for the corals with a low diversity. The coral taxa share characteristics of so-called post-disaster faunas (Denayer and Webb 2017). Their origin is rarely recorded with the exception of *Kizilia* and *Conilophyllum*, which are known in the Famennian of Omolon (Poty 1999), the later possibly evolved from *Hebukophyllum* known from the Strunian–Hastarian deep-water deposits in western Germany (Weyer 2000; Fig. 6h). Furthermore, they apparently disappeared with no obvious descendants (or as Lazarus taxa such as *Kizilia* re-appearing in the Viséan). Their morphology is rather simple but with high morphological plasticity. Hence, this ability witnesses their ability to colonise wide areas (and typically, several empty niches) after the faunal extinction associated with the DCB (Poty 2010).

Stromatoporoids

Strunian stromatoporoids are regarded as a Lazarus group re-appearing late in the Famennian after their complete disappearance during the late Frasnian Kellwasser extinction Event (Stearn et al. 1987; Herbig and Weber 1996). Most of them are representatives of genera already present in the Givetian–Frasnian strata (Mistiaen and Weyer 1999). The Etrœungt (ASA) and Dolhain (VASA) formations are both characterised by the development of stromatoporoid-rich facies, including biostromes alternating with siliciclastic units. In the CSA and DSA, no real biostrome developed, but stromatoporoids are not uncommon (Conil and Vandenven 1972). The horizons, named '*premier biostrome*' and '*second biostrome*' by Conil (1961) and subsequent workers, are not genuine reefs as the stromatoporoids are scattered and often broken and/or not in living position (Poty 2007). The last *'biostrome principal'* is locally a reefal construction. In the CSA, the genera *Actinostroma*, *Atelodictyon*, *Amphipora*, *Clathrodictyon* and *Stromatoporella* were reported by Conil (1961) and Mistiaen and Weyer (1999). In the Aachen area (VASA), the biostromes are dominantly built by *Clathrodictyon* spp. and *Actinostroma* spp. (Weber 1999). Other components are *Amphipora*, *Anostylostroma*, *Atelodictyon*, *Clathrostroma*, *Hammatostroma*, *Pseudostromatoporella* and *Stromatoporella* (Conil 1961; Flügel and Flügel-Kahler 1975; Mistiaen and Weyer 1999; Weber 1999). A few specimens of the labechiid genus *Stylostroma* were reported from the Aachen area by Weber and Mistiaen (2001), witnessing of the Eastern European influence on this zone.

In the ASA, Le Maître (1933), Mistiaen (1997), Mistiaen et al. (1998) and Mistiaen and Weyer (1999) reported several species attributed to the genera *Actinostroma*, *Amphipora*, *Clathrodictyon*, *Stromatopora* and *Stromatoporella*. In the Godin quarry section (Avesnes-sur-Helpe), the last stromatoporoids occur in the youngest limestone bed of the Etrœungt Fm, 15 cm below the HSS equivalent. They became thus extinct immediately before the event or during its early phase. Up to now, no stromatoporoid reworked in, or that lived during the deposition of the HSS beds has been recorded.

Bryozoans

Bryozoans are very common in the Strunian and in Hastarian beds, but they attracted very few attention. Belgian and German occurrences in the Strunian were described by Ernst and Herbig (2010) and Tolokonnikova et al. (2015), whereas Ernst et al. (2017) reported some long-ranging genera in the basal Tournaisian.

Brachiopods

The uppermost Famennian is characterised by radiations among several brachiopod orders, notably within the productides, the rhynchonellides, the spiriferides and the spiriferinides, which developed morphological features heralding the Carboniferous brachiopod faunas (Conil et al. 1986; Simakov 1990). These are very useful for correlations in neritic environments near the DCB, in conjunction with foraminifers and rugose corals (Mottequin et al. 2014).

According to Conil et al. (1986), at least three brachiopod species can be considered as good guides for the Strunian in the Belgian part of the NDB, namely the rhynchonellide *Araratella moresnetensis* (Fig. 7a–d), and the spiriferides *Prospira struniana* (Fig. 7e–i) and *Sphenospira julii* (Fig. 7j–l); the authors also mentioned a fourth species, namely the productidine *Whidbornella caperata*, but the specimens identified as such need to be revised (Legrand-Blain 1995). According to Sartenaer and Plodowski (1975), *A. moresnetensis* is occurring in the NDB, from the base of the Strunian (DFZ7) onwards (see

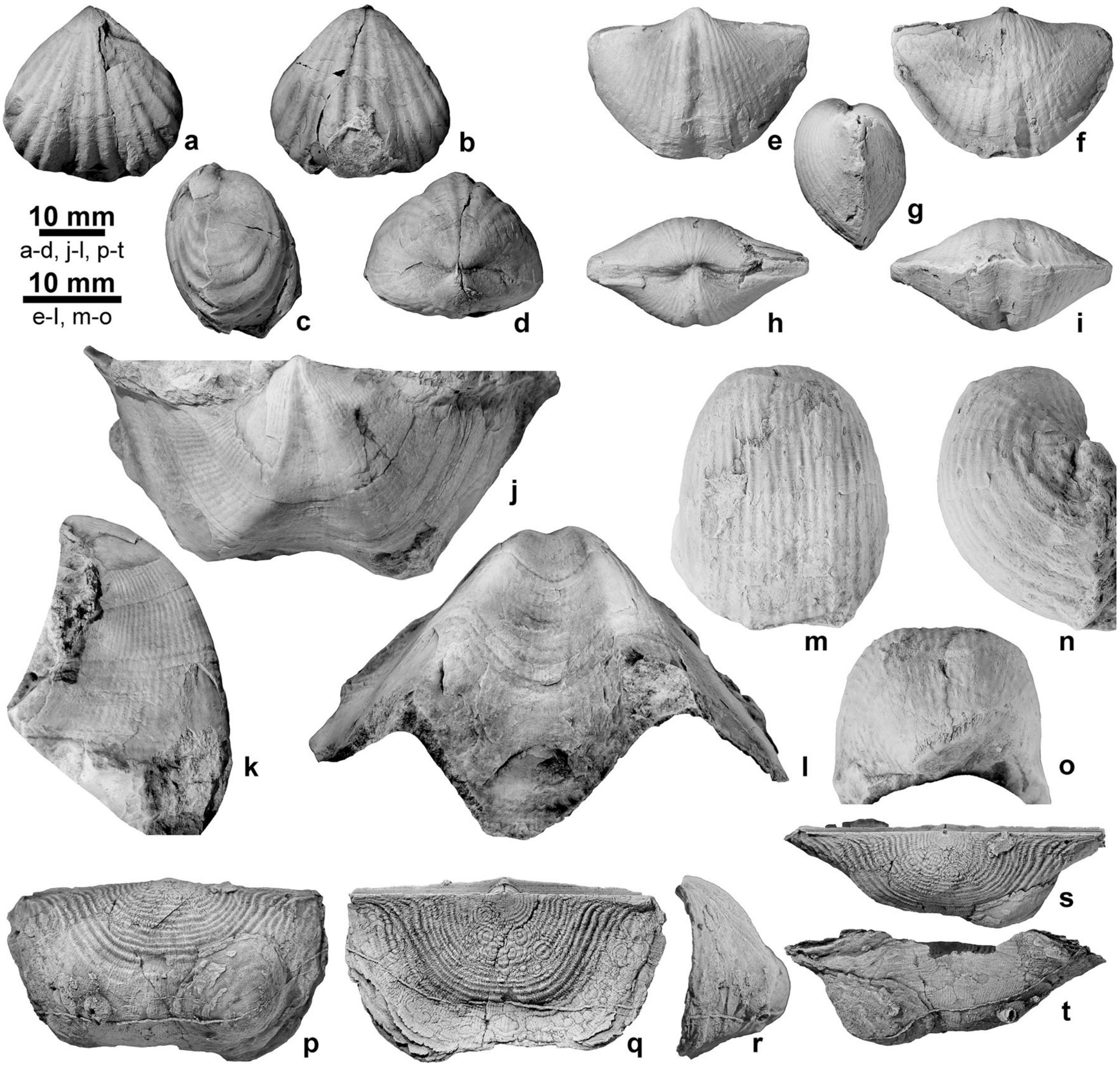


Fig. 7 Selected typical guide taxa (**a**–**l**) across the Devonian–Carboniferous boundary among brachiopods (rhynchonellide, spiriferides, productidine) (partly modified from Mottequin and Brice 2016) and Ivorian strophomenide (**p**–**t**) (Mottequin and Simon 2017). **a**–**d** *Araratella moresnetensis*, PA.ULg 3501/2, almost complete specimen in ventral, dorsal, lateral and posterior views, Comblain-au-Pont Formation, Chanxhe (Belgium). **e**–**i** *Prospira struniana*, MGL 1591 (lectotype; Musée d'Histoire naturelle de Lille), slightly flattened articulated specimen in ventral, dorsal, lateral, posterior and anterior views, Etrœungt Formation, Etrœungt (France). **j**–**l** *Sphenospira julii*, MGL 1579 (lectotype; Musée d'Histoire naturelle de Lille), ventral valve in plan, lateral and anterior views, Etrœungt Formation, Flaumont (France). **m**–**o** *Spinocarinifera nigra*, MGL 1538 (lectotype; Musée d'Histoire naturelle de Lille), almost complete ventral valve in plan, lateral and posterior views, Avesnelles Formation, Avesnelles (France). **p**–**t** *Leptagonia franca*, RBINS a5895 (Institut royal des Sciences naturelles de Belgique), complete articulated specimen in ventral, dorsal, lateral, posterior and anterior views, Tournai Formation, Tournai

also Mottequin 2019). Although the first occurrences of *P. struniana* and *S. julii* need to be precisely located within the Belgian Strunian, the last occurrence of these three guide species is recorded within the first metre of the Hastière Fm (Conil et al. 1986). The material reported from the base of the Hastière Fm by these authors most probably includes reworked specimens, as it is the case for some rugose corals (see further under discussion) and others that genuinely lived on the reworked substrate. Whereas *P. struniana* and *S. julii* are abundant in the Etrœungt Fm in the ASA (Mottequin and Brice 2016), the absence of *A. moresnetensis* in this area is noteworthy (Sartenaer and Plodowski 1975), although some poorly preserved specimens assigned to *Araratella* were reported by Brice (in Milhau et al. 1997) and Mottequin and Brice (2016). Note that Legrand-Blain's (1995) report of *S. julii* within the Avesnelles Fm remains dubious in the absence of illustration. The productidine *Spinocarinifera nigra* (Fig. 7m–o) is reported in great abundance in the Avesnelles Fm (Legrand-Blain 1991), but this species has never been recognised so far in the basal member of the Hastière Fm in Belgium. The distribution of *S. nigra* was obviously facies-controlled; thus, its assumed preference for calm muddy environments may explain its absence from the base of the Hastière Fm, which is characterised by more turbulent environmental conditions. As stated by Legrand-Blain (1991), the '*Productus niger*' listed by Demanet (1958) and the '*Nigeroplica nigra*' reported by Conil et al. (1986) in several Belgian localities of the NDB do not belong to this species but to other unspecified productidines. Besides the three guide species cited above, the Strunian brachiopod fauna of the NDB includes productides (chonetidines, productidines), orthotetides, orthides, rhynchonellides and spire-bearers (athyridides, spiriferides, spiriferinides) (e.g. Legrand-Blain 1991, 1995; Brice et al. 2013; Mottequin and Brice 2016) that are partly recognised in the Velbert Anticline (Rhenish Mts, Germany) (Paeckelmann 1931; Paul 1937, 1939; Legrand-Blain 1995). Furthermore, the NDB brachiopod diversity is lower than that reported in other contemporaneous shallow-water environments (e.g. Afghanistan (Mottequin and Brice 2019) and South China (Sun and Baliński 2011)). In the Holy Cross Mountains (Poland), Halamski and Baliński (2009) described Strunian brachiopod assemblages comprising species known from the NDB (e.g. *S. julii*) and others that are characteristic from deep-water settings (e.g. *Rozmanaria equitans*). In Thuringia (Germany), Strunian brachiopod faunas evolving in deep-water environments (cephalopod limestones, entomozoid ostracod shales) are markedly different from those recognised in the NDB. They are poorly diversified and clearly dominated by smooth to poorly ornamented rhynchonellides (rozmanariids) that became extinct during the Hangenberg Crisis (Mottequin et al. 2019).

The dysoxic shaly facies recognised below the DCB within the Comblain-au-Pont Fm (identified as equivalent to the HBS) yielded some lingulides associated to bivalves, but they need to be investigated further.

Brachiopod assemblages from the basal Hastarian in southern Belgium are still poorly known, and they seem to be less diverse, according to Demanet's (1958) lists of species, which were partly revised and completed by Conil et al. (1986) and Legrand-Blain (1991, 1995). Orders recognised in the Strunian are still present at the base of the Hastarian (Mottequin et al. 2014), but as reported by Mottequin and Simon (2017), one of the striking features of the Hastarian and Ivorian brachiopod assemblage of the NDB is the reappearance of Leptaeninae (Rafinesquinidae) belonging to the genus *Leptagonia* (Fig. 7p–t) after their absence during almost, if not, all of the Late Devonian in this area (see these authors for a detailed discussion); these brachiopods proliferated in some Tournaisian argillaceous and carbonate environments post-dating the Hangenberg Crisis. Leptaeninae were reported in the uppermost Famennian of the ASA by Dehée (1929) and Brice et al. (2013), and in the DSA and CSA by Demanet (1958), but these occurrences have been challenged by Mottequin and Brice (2016).

Molluscs

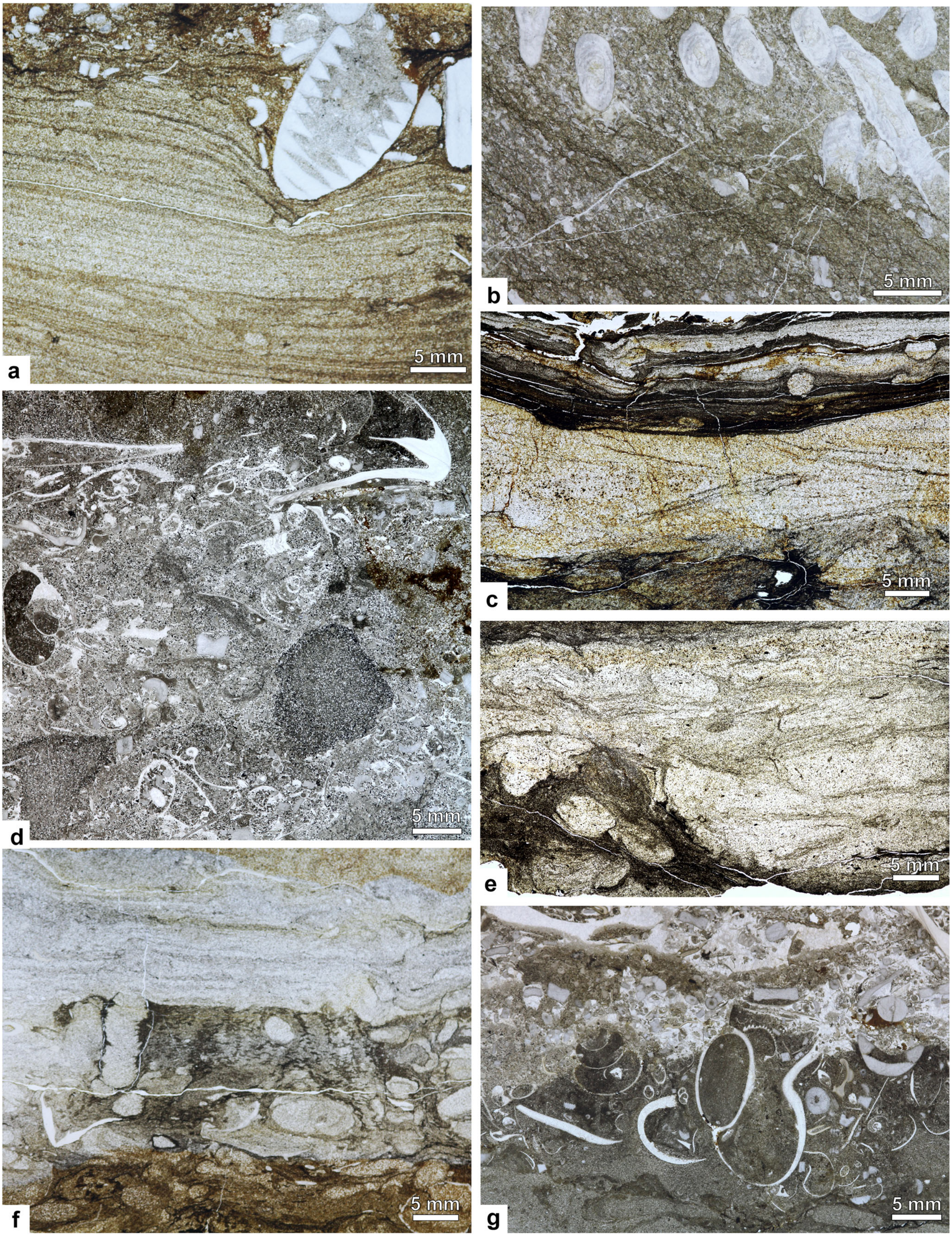
Strunian and Hastarian cephalopods were seldomly reported, mostly in faunal lists. A single occurrence of the goniatite *Striatoclymenia euryomphala* (synonym to *Postclymenia evoluta* according to Korn and Klug (2002)) was reported by Demanet (1958) from the Hastière section, but Demanet's specimens stored at the Royal Belgian Institute of Natural Sciences in Brussels correspond to poorly preserved gastropods. In the ASA, Delépine (1929) illustrated one specimen referred to as *Cymaclymenia camerata* from the 'Etrœungt Zone' and later identified as *P. evoluta* by Delépine (1940). Goniatites are very rare in the Belgian Strunian, but some fragments have been noticed in the Royseux section c. 1.5 m below the HSS equivalent.

Orthoconic nautiloids and actinoceratoids are rare as well, except in the HSS equivalent in most sections, and some display respectable sizes.

Similarly, rostroconchids and gastropods are only known from the name lists in Dehée (1929) and Demanet (1958), with the exception of recent reviews by Amler (2016) of the rostroconchids from the Velbert Anticline and by Amler and Heidelberger (2003) of the gastropods of the Pilton Beds (UK) and equivalent strata.

Bivalves are quite diverse and locally abundant within pelagic facies of the Strunian and Hastarian, where their stratigraphical value was demonstrated by Amler (1992, 2004, 2014). However, in shallower facies such as those developed in the NDB, besides the faunal lists of Dehée (1929) and Demanet (1958), only few recent data are available. Amler (1992) documented the distribution of several taxa among the Palaeotaxodonta, Pteriacea, Pterinopectinidae, Aviculopectinidae, Heteroconchia, Isofilibranchia and Anomalodesmata (the last three being more diverse in shallow facies) from siliciclastic facies of the Velbert Anticline. In the Spontin and Chansin sections (CSA), gastropods and bivalves (Eupteriomorphia with a dominance of the genus *Pernopecten*, M. Amler, written com., January 2019) are typically abundant and diverse in the HSS equivalent beds.

Fig. 8 **a**–**g** Selected facies across the DCB in the proximal areas. **a** ▶ Laminated micaceous sandstone passing upwards to coarse badly washed crinoidal rudstone (Royseux section bed 104, basal bed of the Hastière Fm equivalent to the HSS). **b** Coarse dolomitic grainstone with syringoporid tabulate corals (Dolhain section, bed 46, lower part of the dolomitised Hastière Fm = Binsfeldhammer Mbr). **c**, **e** Cross-laminated siltstone with sandstone layers and bioturbation (Stolberg II section, bed 35, basal bed of the Hastière Fm equivalent to the HSS). **d** Floatstone to rudstone with intraclasts and reworked elements (cf. gastropod shell with filling different from the sedimentary matrix) (Royseux section, upper part of bed 104, basal bed of the Hastière Fm and equivalent to the HSS). **f** Intensively bioturbated laminated siltstone–sandstone (Royseux section, bed 104, basal bed of the Hastière Fm equivalent to the HSS). **g** Bioclastic floatstone to rudstone with large gastropod shells (Royseux section, bed 103, top Comblain-au-Pont Fm)


5 mm
a
5 mm
b
5 mm
c
5 mm
d
5 mm
e
5 mm
f
5 mm
g

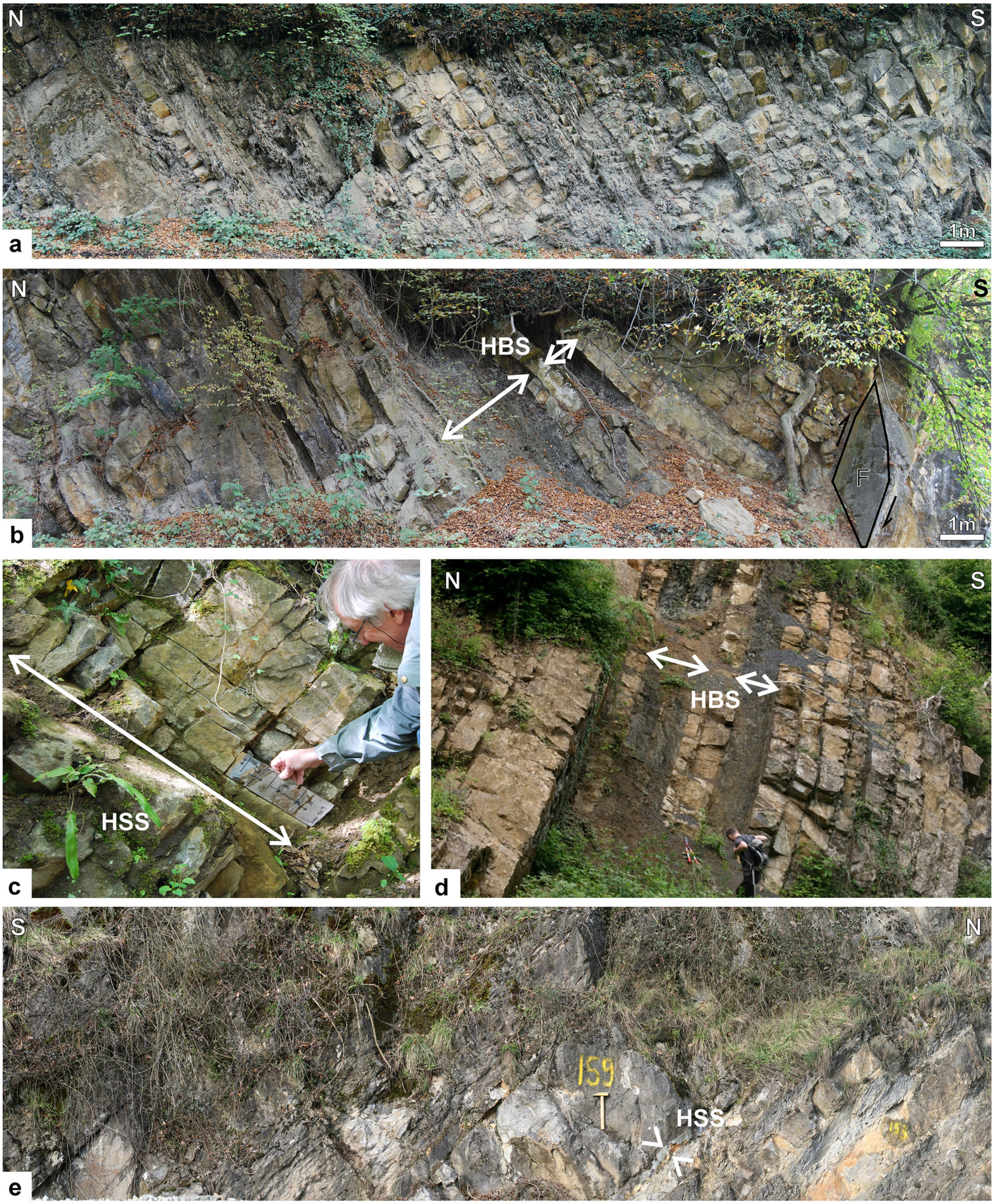


Fig. 9 **a**–**e** Field pictures of the investigated sections at the DCB. **a** Chanxhe I section exposing the cyclic aspect of the lower part of the Comblain-au-Pont Fm. **b** Upper part of the Chanxhe I section exposing the two dark shale beds interpreted as an HBS equivalent (F, fault eliminating the DCB). **c** Royseux V section with close-up view of the basal bed of the Hastière Fm interpreted as the HSS equivalent. **d** Martinrive section exposing the c. 30-cm-thick beds of dark shale interpreted as the HBS equivalent in the Comblain-au-Pont Fm. **e** Anseremme section showing the top of the cyclic succession of the Comblain-au-Pont Fm, the basal bed of the Hastière Fm (bed 159) and the lower part of the Hastière Fm

Ostracods

Strunian ostracods were first described by Rome and Goreux (1964) and by Becker and Bless (1974) from the Anseremme section and by Lethiers (1974a, b, 1975) in the ASA, whereas Bless (1983, 1993) and Coen (1995) reported ostracods from the Hastière Fm. Recently, Casier et al. (2004, 2005) revised the systematics and distributions of ostracods in the Anseremme and Chanxhe sections. The Strunian and Hastarian assemblages are dominantly composed of genera belonging to the Podocopina, Paraparchiticopina, Platycopina, Palaeocopine and Eridostraca in various proportions, the latter two being restricted to the Strunian strata. In the ASA, a similar distribution is documented (Casier and Préat 2003) with notable rarefication of the ostracods in the lower and uppermost beds of the Avesnelles Fm. The eridostracean ostracod *Cryptophyllus* locally disappears at the base of the Hastière and Avesnelles Fm, together with the other typically Strunian fauna, but does not become extinct as scarce occurrences are known from the Hastarian in this section (Conil and Lys 1970; Casier and Préat 2003). Moreover, the group reappears in the Viséan of Gondwana (Bless and Groos-Uffernorde 1984). *Pseudoleperditia* gr. *venulosa* (= '*Bernix*' *venulosa*) was considered to be restricted to the lower part of the Hastière Fm by Bless et al. (1993), but its occurrence in the Comblain-au-Pont Fm in Chanxhe (Casier et al. 2004) indicates that the species is not diagnostic.

Trilobites

Trilobites are abundant in some levels of the Strunian Comblain-au-Pont and Etrœungt formations. Since the classical works by Richter and Richter (1933) and Struve (1976), the Strunian trilobites of Belgium were almost not studied and are only cited in more recent works (e.g. Brauckmann and Hahn 1984; Weber 2000). The most common trilobites are species of the *Omegops accipitrinus* group (Brauckmann et al. 1992), whereas other taxa have virtually not been studied. *Omegops accipitrinus* and *Omegops maretiolensis* are particularly abundant in HSS equivalent beds (e.g. Spontin, Chansin and Royseux sections): these are indeed the youngest known phacopids that disappeared at the end of the HSS Event. Although much rarer, the Hastarian trilobites are better documented. Very rare specimens of *Moschoglossis rhiannon* and *Piltonia* (*Piltonia*) *balor* were reported from the Hastière Fm, and a single cranidium of *Archegonus* (*Phillibole*) *artaios* was reported from the Avesnelles Fm by Hahn and Hahn (1988). A fourth species, recently collected in the lower member of the Hastière Fm in the Spontin section, was provisionally identified as *Liobolina* sp. (R. Feist, written com., September 2018).

Vertebrates

The DCB corresponds to a significant faunal overturn for the vertebrates, with the extinction of placoderms and allied groups and the subsequent radiation of osteichthyans and chondrichthyans during the early Carboniferous (Janvier 1996). Although vertebrate remains are not uncommon in the Strunian of southern Belgium, they only have attracted minor attention. *Bothriolepis* and *Phyllolepsis*, though very rare, were reported from the Strunian (Fourmarier 1899; Lelièvre and Goujet 1986). Derycke-Khatir (2005) described the microremains from residues after dissolution of carbonates for conodont extraction. However, she sampled only one horizon in the upper Famennian (Ciney Fm, distal equivalent of the Evieux Fm) and another one in the upper Tournaisian (Waulsort Fm). Hence, a fine-scale analysis of the extinction, survival and recovery of the vertebrate fauna is not possible. Macroremains (mainly chondrichthyans) are known from the Strunian and Hastarian, but they have not been analysed yet.

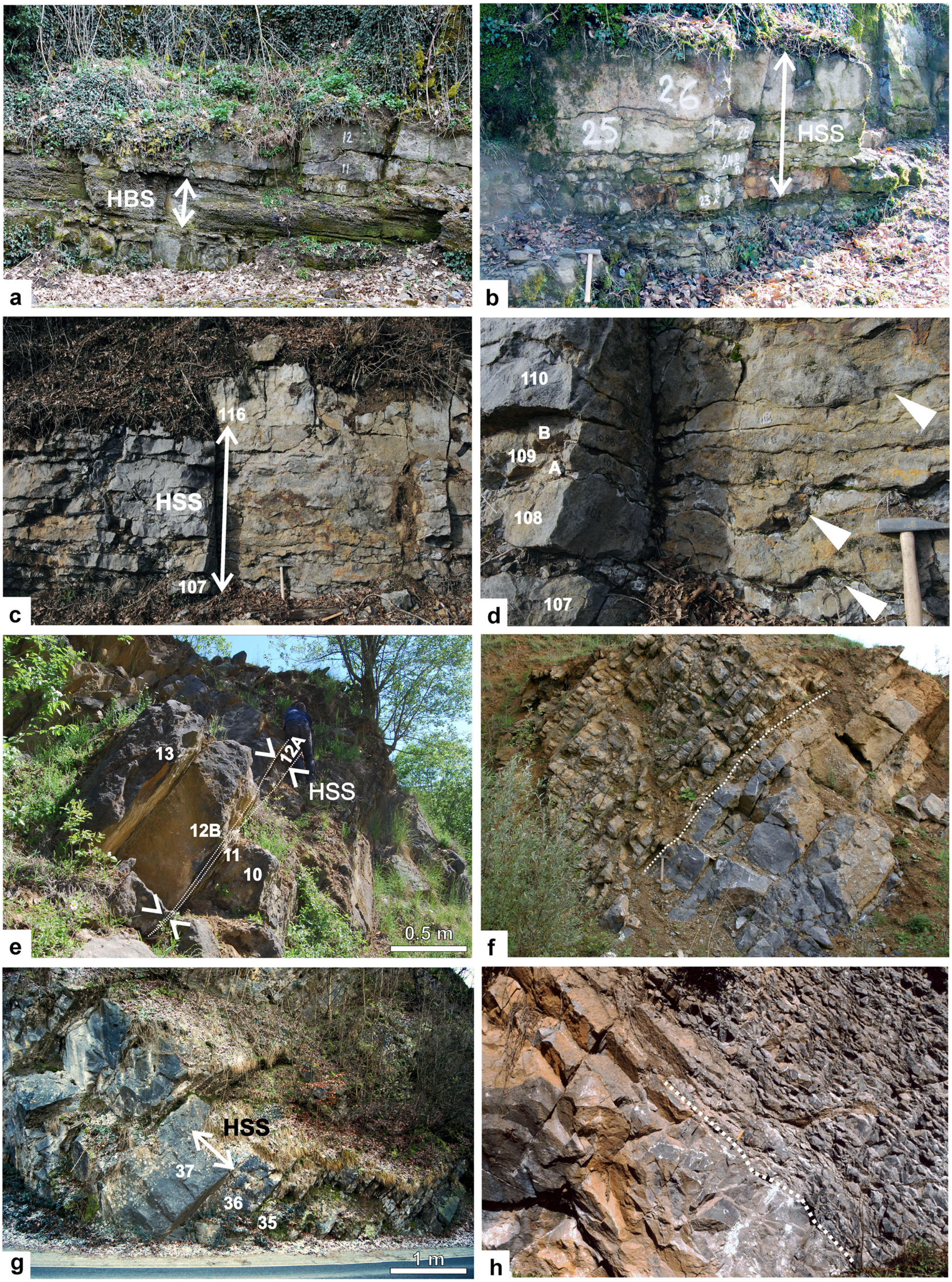
Description of the local lithostratigraphical successions

Rather than describing all sections individually as it was done previously in the literature, we present here key sections documenting the lithological succession for each of the known depositional settings.

Proximal settings: the Feluy section (HSA)

Sections situated on or very close to the London-Brabant Massif (e.g. Feluy, Mévergnies, Menen borehole in the HAS, Huccorgne in the NSA; Streel 1977; Higgs et al. 1992; Loboziak et al. 1994; Fig. 1) display successions with a very incomplete Famennian (almost entirely lacking in Huccorgne) and lower Tournaisian deposits with proximal

Fig. 10 **a**–**h** Field pictures of the investigated sections at the DCB. **a** Dark shale horizon (bed 9) in the upper part of the Comblain-au-Pont Fm in the Spontin section, interpreted as equivalent to the HBS. **b** Interval with reworked material in the basal part of the Hastière Fm in the Spontin section, interpreted as the HSS equivalent. **c** The same interval in the Chansin section. **d** Closer view of the base of the Hastière Fm displaying basal erosion associated with the reworking of the HSS equivalent (arrows). **e** Boundary between the Etrœungt Fm (Strunian, below) and the Avesnelles Fm (above) with its basal bed recording the reworking associated with the HSS Event, Godin quarry. **f** The same section exposing the third-order sequence boundary (dotted line) between the top of the Avesnelles Fm (= middle member of the Hastière Fm, top of sequence 1) and the base of the upper member of the Hastière Fm (base of sequence 2), Godin quarry. **g** Boundary between the Comblain-au-Pont Fm (right) and the Hastière Fm (left), Chanxhe III section. **h** Third-order sequence boundary (dotted line) between the middle and upper members of the Hastière Fm, Chanxhe I section ▶


a
HBS
12
11
10
b
26
25
HSS
c
116
HSS
107
d
110
B
109
A
108
107
e
13
12A
HSS
12B
11
10
0.5 m
f
g
HSS
37
36
35
1 m
h

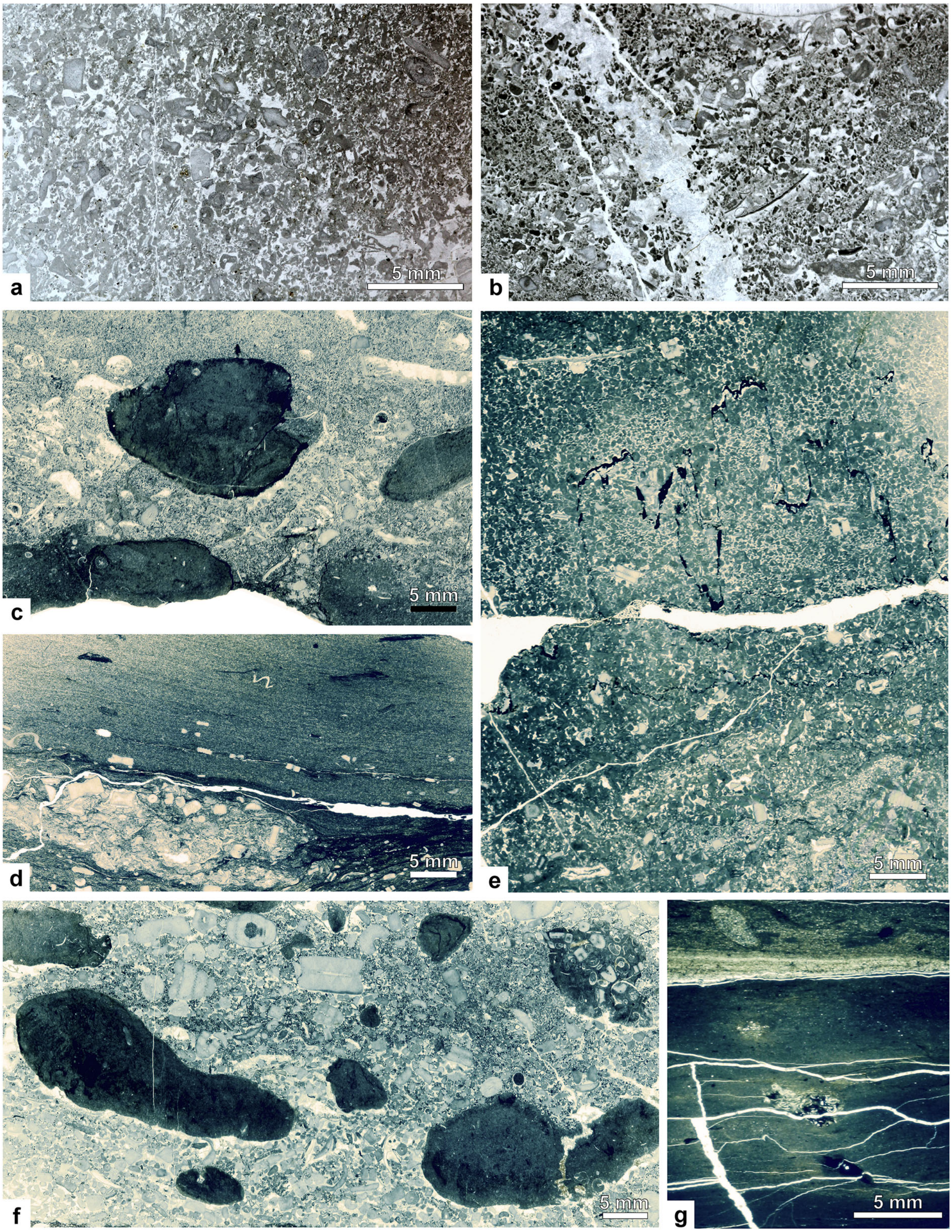
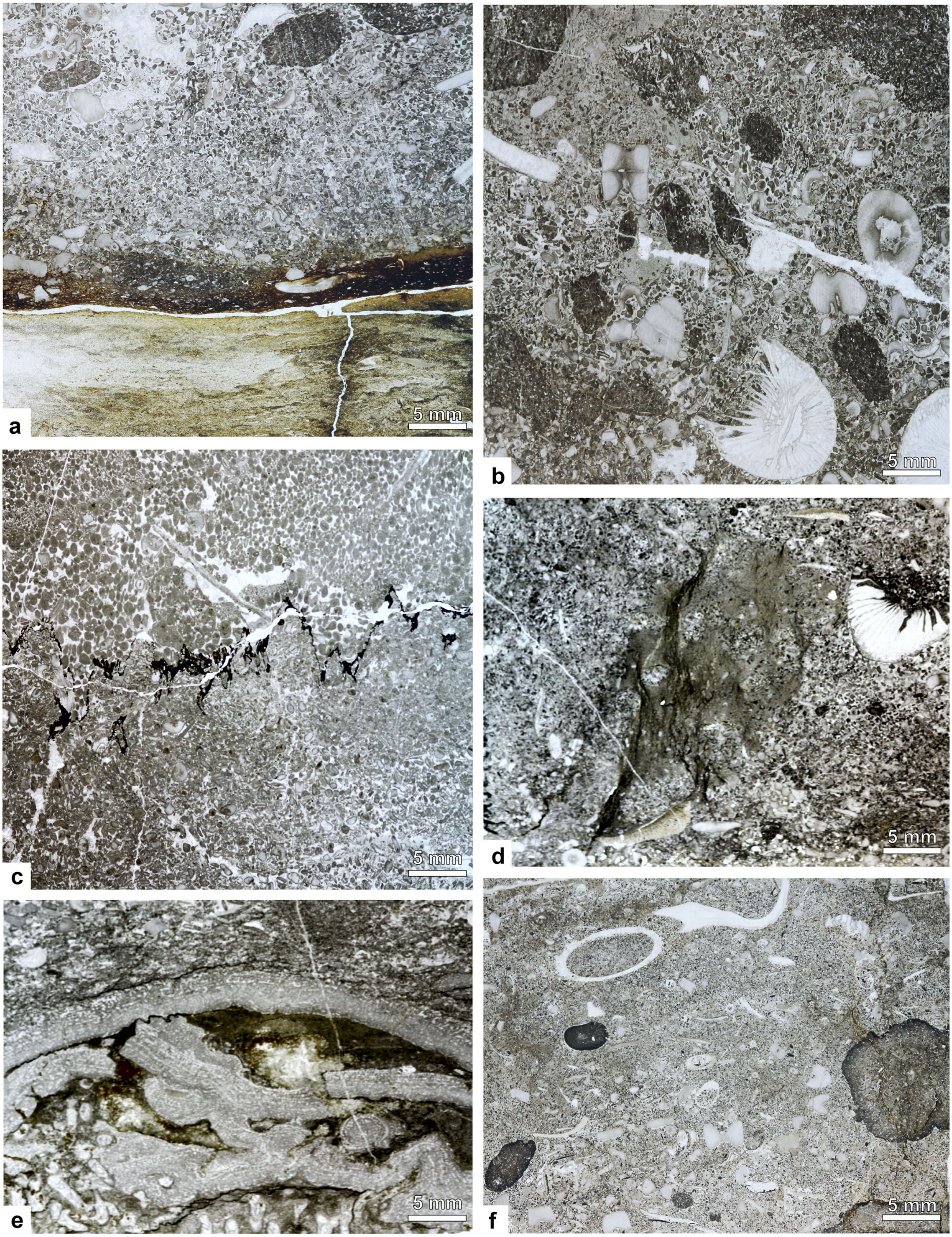


Fig. 11 **a**–**g** Selected microfacies across the DCB. **a** Crinoidal–peloidal grainstone, typical of the middle member of the Hastière Fm (bed 54), Spontin section. **b** bioclastic–peloidal grainstone, lower part of the lower member of the Hastière Fm (bed 28A, immediately above the DCB), Spontin section. **c** Reworked ichnoclasts in a bioclastic rudstone at the base of the Hastière basal bed interpreted as the HSS equivalent (bed 107), Chansin section. **d** Uppermost silty shale bed of the Comblain-au-Pont Fm (bed 22), Spontin section. **e** Stylolithic boundary between the bioclastic–peloidal grainstone of bed 115 (top HSS equivalent) and the oolitic grainstone of bed 116 (base of Carboniferous, Hastière Fm), Chansin section. **f** Intraclasts and ichnoclasts in bioclastic rudstone in the basal Hastière Fm interpreted as equivalent to HSS (bed 110), Chansin section. **g** Dark laminated (below) and bioturbated (top) shale equivalent to HBS (bed 9), Spontin section


5 mm
a
5 mm
b
5 mm
c
5 mm
d
5 mm
e
5 mm
f

◀ **Fig. 12** **a**–**f** Selected microfacies across the DCB. **a** Boundary between the topmost silty shale horizon of the Strunian Comblain-au-Pont Fm (bed 158) and the bioclastic grainstone–rudstone with intraclasts in the basal bed of the Hastière Fm (bed 159A), Anseremme section. **b** Bioclastic–peloidal grainstone–rudstone with intraclasts, large crinoid columnals and *Campophyllum* rugose corals in the basal bed of the Hastière Fm (bed 159A), Anseremme section. **c** Stylolithic boundary between the bioclastic–peloidal grainstone of bed 159A (top of the HSS equivalent) and the oolitic grainstone of bed 159B (base of Carboniferous, Hastière Fm), Anseremme section. **d** Bioclastic–peloidal grainstone with reworked coral with mud-coated margin (compare with **b** where margin is clear) and holocephalian dental plates (arrows), basal bed of the Hastière Fm interpreted as equivalent to HSS (bed 159A), Anseremme section. **e** Typical bioclastic grainstone with tabulate corals and stromatoporoid coverstone in the Strunian Dolhain Fm (bed 17), Dolhain I section. **f** Reworked ichnoclasts in bioclastic–peloidal grainstone, basal bed of the Hastière Fm interpreted as equivalent to HSS (bed 53), Chanxhe II section

siliciclastic facies (the so-called 'basal clastic complex' of Higgs et al. 1992), where the Hangenberg Event is usually not recorded (Poty 2016) or incorrectly reported (Bouckaert and Conil 1970). These sections have not been investigated recently. In the central NSA (e.g. in Engis), the middle member of the Hastière Fm rests directly on the Famennian sandstones, the Strunian and the lower part of the Hastarian deposits being entirely lacking because the Strunian transgression did not reach this area (Hance et al. 2001).

Proximal settings: the Stolberg and Dolhain sections (VASA)

The German locality of Stolberg in the Aachen vicinity belongs to the Vesdre–Aachen sedimentation area (Fig. 1) and displays very proximal facies. In Stolberg, the Strunian Dolhain Fm is composed of stromatoporoid–coral biostromes embedded in a locally dolomitised carbonate shaly matrix relatively rich in macrofauna (Fig. 8b). The top is capped by a 2-m-thick bed of bioturbated sandstone and siltstone that probably represents a time-equivalent deposit of the HSS Event (Fig. 8c, e). The subsequent Hastarian is intensively dolomitised and has been assigned to the local Binsfeldhammer Mbr of the Hastière Fm (Amler and Herbig 2006). In the Binsfeldhammer section, c. 600 m NE of the Stolberg section, the sandstone bed is missing (Becker and Weber 2016), suggesting that the siliciclastics filled palaeotopographic lows.

In the Dolhain section ('Dolhain–Limbourg' in Conil 1964), the Strunian succession is analogous to the stromatoporoid biostromes that are characteristic of the VASA. It is c. 50 m thick and starts with a 10-m-thick series of mainly shaly beds with calcareous siltstone interbeds. A first horizon with corals and stromatoporoids (c. 4 m) is relatively sandy and shaly in its middle part. It then passes to an alternation of bioclastic calcareous shale and coarse crinoidal limestone capped by a c. 1-m-thick parabiostrome composed of small lamellar stromatoporoids. Conil's (1964) '*biostrome principal*' is a 4.2-m-thick biostrome composed of large lenticular lamellar stromatoporoids in a sandy and argillaceous matrix produced by stylolitic joints. Corals, crinoids and foraminifers are abundant in this unit. It is overlain by 7 m of bioclastic limestone beds with few corals and stromatoporoids alternating with siliciclastic interbeds. The overlying unit is a massive crinoidal limestone, often dolomitised, with poor microfauna and macrofauna that already represents the Hastière Fm. The top of the Strunian is positioned at the top of bed no. 43 that yielded the last quasiendothyrids. No sedimentary evidence of the HSS Event is recorded here. The upper massive limestone could represent the middle member of the Hastière Fm as known from other localities such as the Chaudfontaine (see Conil 1964) and Stolberg ('lower dolomite' of Kasig 1980) sections but without biostratigraphic evidence (Poty 2016).

Proximal settings: the Royseux section (CSA)

The Royseux station section (= 'Huy 15' in Conil 1964 and Austin et al. 1970), located in the Hoyoux River valley, corresponds to a disused railway cutting exposing almost continuously the upper Famennian–Yvorian succession. This section displays the most proximal facies in the Dinant Synclinorium, as it is located along its northern limb. The Comblain-au-Pont Fm (c. 15 m thick) displays an alternation of shale–siltstone, occasionally enclosing crinoidal grainstone to rudstone that are commonly sandy, in 25- to 40-cm-thick beds (Fig. 8a). Both the shale and limestone contain centimetre-thick horizons of coarse coquina (crinoids and brachiopods) interpreted as tempestites.

The DCB interval is an 85-cm-thick accumulation of calcareous siltstone lenses, sandy and silty at the base, interrupted by thin irregular shaly layers. The boundary with the overlying shale bed is wavy but not erosive, and there is no evidence for any sedimentation break (Denayer et al. 2015). Centimetric lithoclasts occur in the lower half, together with coarse coquinas (brachiopod *Sphenospira julii*, gastropods and phacopid trilobites) (Fig. 8d, g). Although similar in facies from the base to the top, this bed seems to have recorded several siliciclastic influxes and/or several hydrodynamic phases developed as several fining-upwards sequences, commonly displaying hummocky cross-stratifications and pervasive bioturbations (Fig. 8f). This level (beds 104 and 105, Fig. 9c) has been interpreted as resulting from the HSS Event (Mottequin and Poty 2014; Denayer et al. 2015; Poty 2016). This first bed forms the base of the Hastière Fm.

The rest of the Hastière Fm (above bed 105) consists of crinoidal grainstone to packstone rich in large crinoidal stems and brachiopod shells, interrupted by millimetre-thick argillaceous layers producing undulating beds. There is no trace of any discontinuity with the previous bed. It grades upwards into a nodular bed of argillaceous crinoidal packstone with

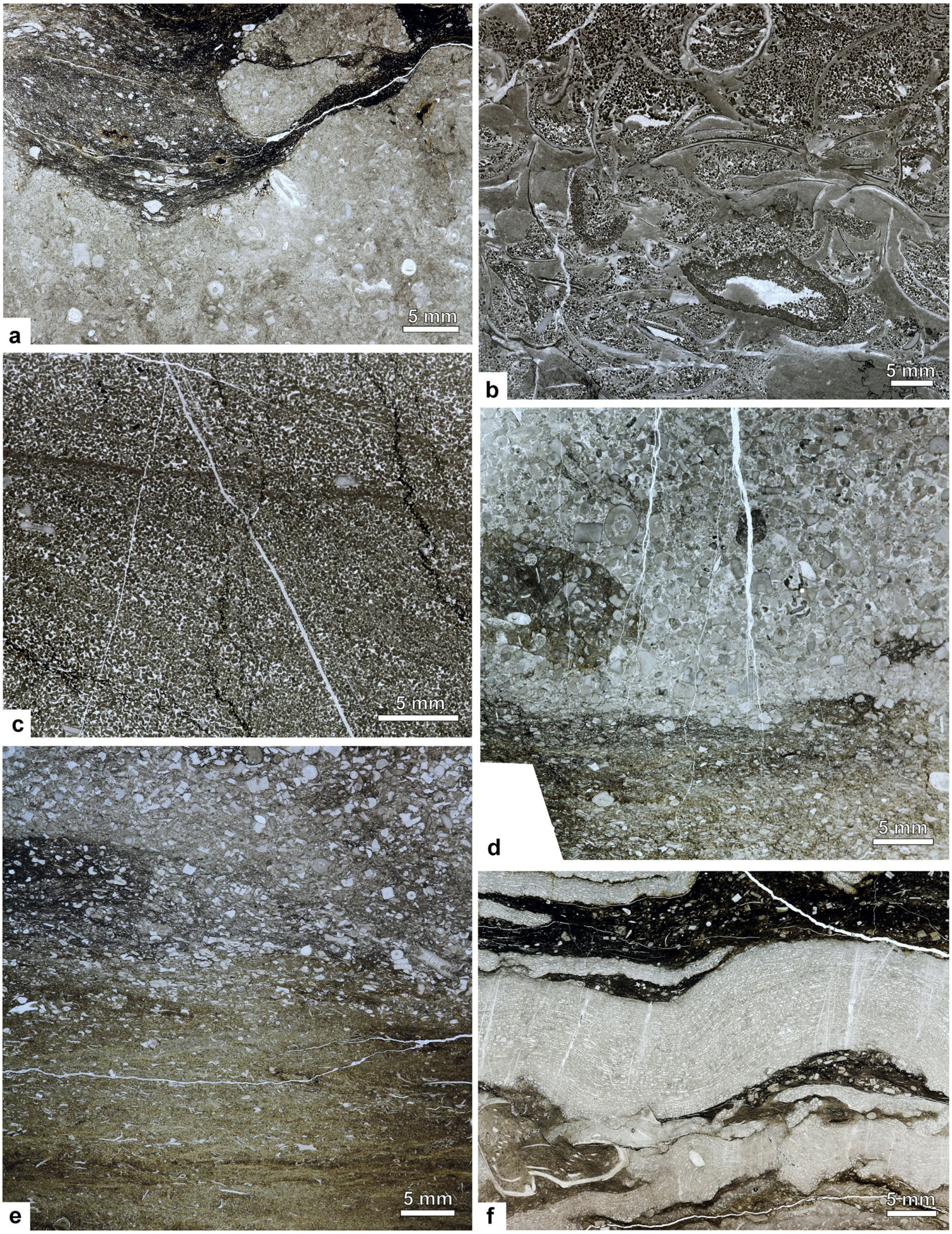


Fig. 13 **a**–**f** Selected microfacies across the DCB in the Godin section. **a** Sequence boundary between the crinoidal grainstone of top of the Avesnelles Fm (= middle member of the Hastière Fm, bed 34B) and the upper member of the Hastière Fm (bed 35). **b** Peloidal and bioclastic grainstone with pendular cement below brachiopod shells in the upper part of the Avesnelles Fm (= middle Mbr of the Hastière Fm, bed 30). **c** Typical peloidal grainstone with mud-coated grains and oblique stratifications, upper part of the Avesnelles Fm (bed 26). **d**, **e** Boundary between the topmost shaly horizon of the Strunian Etrœungt Fm (bed 11) and the crinoidal grainstone with intraclasts in the basal bed of the Avesnelles Fm (bed 12A). **f** Typical biostromal stromatoporoid coverstone with argillaceous matrix in the Etrœungt Fm (bed 8)

numerous *Kizilia kremersi* and *Conilophyllum priscum* (beds 106 to 108). The clay content increases upwards. Above this level, the lower member of the Hastière Fm displays the typical cyclic alternation of calcareous shale with bioclastic layers and crinoidal packstone to grainstone with brachiopods and bryozoans. The fauna, however, is poorly diverse.

Inner shelf: the Martinrive and Chanxhe sections (CSA)

In the Ourthe valley (eastern CSA, Fig. 1), numerous sections expose the DCB transitional beds, many of which have been previously described (e.g. Conil 1964, 1968; Bouckaert et al. 1970; Bless et al. 1974; Thorez and Dreesen 1986). The renowned Chanxhe section (Chanxhe I, Fig. 9a, b) exposes the transition from littoral siliciclastic deposits of the upper Famennian Evieux Fm to mixed littoral–marine sediments of the Strunian Comblain-au-Pont Fm. However, the uppermost 3 m of the latter formation and the basal 2 m of the Hastière Fm do not crop out because of fault activity. The middle and upper members of the Hastière Fm are also well exposed. A second, so far, unpublished section (Chanxhe III, Fig. 10g), situated 400 m east of the classical one and located within the same syncline, allows the observation of the DCB, as this section is not affected by faults. The Chanxhe II and Rivage sections are badly accessible, whereas the Pont-de-Scay section seems to be affected by a fault near the DCB as well. The Martinrive road section exposes the top of the Comblain-au-Pont and Hastière formations.

The Comblain-au-Pont Fm as exposed in Chanxhe I is typically made of an alternation of 30–50-cm-thick crinoidal and bioclastic grainstone–packstone beds with rather abundant macrofauna (brachiopod, corals) and decimetre-thick beds of shale and siltstone, usually calcareous, also rich in fossils commonly forming coquina beds. Quartz grains are common, even in grainstone facies, witnessing a continuous detrital influence (Thorez and Dreesen 1986). Upsection, the cyclic alternations become more and more calcareous as a result of the increasing carbonate content of the shale and of the increasing thickness of the limestone beds. However, this overall increase is interrupted by a 3-m-thick shale unit interbedded with thin argillaceous limestone (Fig. 9b, d). The shale is dark—not black—and several horizons are rich in small flat bivalves probably indicating dysoxic conditions. This particular facies most likely corresponds to the HBS Event. The overlying beds are composed of crinoidal–peloidal grainstone including a still diverse fauna (foraminifers, brachiopods, ostracods, fragments of corals and stromatoporoids, etc.), showing that carbonate facies rich in benthic fauna continued to develop after the dysoxic episode. As a general tendency, the carbonate–shale cycles become increasingly calcareous up to the top of the Comblain-au-Pont Fm, where the last 10-cm-thick, slightly argillaceous limestone intercalation is overlain by a massive c. 1-m-thick bed of crinoidal grainstone containing quartz grains and intraclasts (bed 37 in Chanxhe III section, Fig. 3). Compared to other sections, the clasts are small (rarely exceeding 2 cm) and their margins are often affected by stylolites. Detrital quartz grains are abundant. They are witnesses of the HSS Event. As in other sections, the clast-bearing bed also contains Devonian faunal elements such as quasiendothyrid foraminifers that are contemporary of the reworking.

After this first bed assigned to the Hastière Fm, the limestone facies remains the same (crinoidal–peloidal grainstone with bioclasts) but without any traces of reworking and without Devonian fauna elements. The rest of this lithostratigraphic unit is post-dating the HSS Event.

The lower member of the Hastière Fm comprises thick beds of crinoidal grainstone with stylolitic imprints and very few argillaceous intervals, so that the climatic cyclicity is less obvious. The middle member is a massive 7-m-thick unit of the same grainstone with pendulous cement; it is capped by an erosive surface interpreted as a third-order sequence boundary (Fig. 10h). The upper member corresponds to a stylonodular limestone starting slightly argillaceous at its base, then passing upsection to thicker beds of peloidal and crinoidal packstone to grainstone with conspicuous 50–80-cm-thick cyclic alternations (Fig. 3).

Mid-shelf: the Spontin and Chansin sections (southern CSA)

The Strunian Comblain-au-Pont Fm and (mostly) Tournaisian Hastière Fm are well exposed in these two sections, on each side of an anticline and located about 2 km from each other (Fig. 1). Both units present the classical cyclic pattern of orbitally forced climatic cycles, except at the Devonian–Carboniferous transition, where they are not expressed. In the Comblain-au-Pont Fm, the cycles are 75–130-cm-thick and quite irregular. The carbonate part is usually a bioturbated peloidal and bioclastic packstone–grainstone grading upwards into wackestone, with various amounts of quartz grains. The poorly sorted skeletal elements are dominantly crinoids, brachiopods, gastropods, bryozoans, foraminifers, ostracods and trilobites. The carbonate episodes display characteristics of tempestites (hummocky stratifications, shelter structure of cement under shells). The siliciclastic part of the cycles is commonly represented by bioclastic and bioturbated siltstone or shale commonly with more calcareous lenses near the base (Fig. 11d). Some of these levels are micaceous and yield fragments of floated plants.

One c. 30-cm-thick horizon, 4 m below the base of the Hastière Fm, is composed of dark siltstone shales with a poorly diverse fauna, including small bivalves that reflect dysoxic conditions. It possibly corresponds to the local expression of the HBS (Figs. 10a and 11g).

The DCB interval is a 4-m-thick unit, starting with a 120-cm-thick atypical unit of bioturbated, very bioclastic

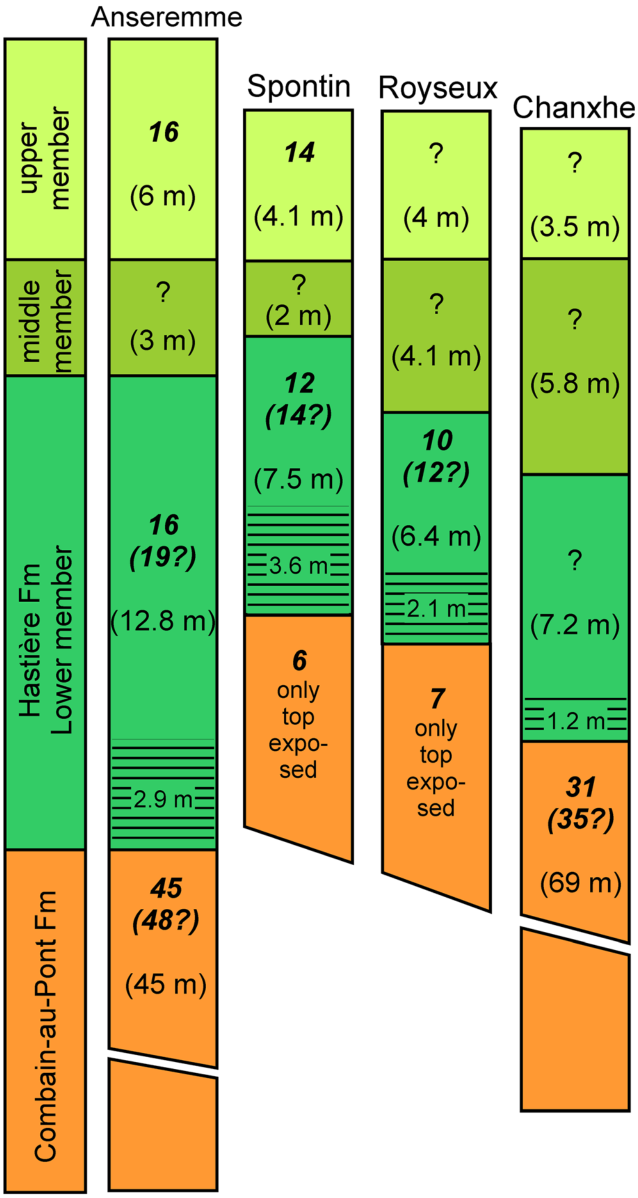


Fig. 14 Schematic representation of the c. 18.6-ky precession cycles in the Devonian–Carboniferous transition in selected sections. The sequence boundary capping sequence 1 of Hance et al. (2001) is taken as horizontal level. Numbers in italic are numbers of counted cycles, and values between square brackets are thickness of each unit. Striped areas represent non-cyclic deposits at the base of the Hastière Fm with indication of their relative thickness. Note that in the Chanxhe section, the upper c. 4 m of the Comblain-au-Pont Fm is massive and displays no cyclicity; the actual number of cycles could be higher than 31(− 35?)

grainstone and rudstone with an uncommonly very abundant fauna (crinoids, brachiopods, bivalves, gastropods, trilobites, cephalopods, bryozoans and uncommon chondrichthyan dental plates) and centimetre-sized limestone clasts of various facies (Fig. 10b–d). The coarse layers consist of crinoidal and bioclastic rudstone with centimetre-sized limestone clasts either of similar facies (i.e. peloidal packstone to grainstone) or of carbonate microfacies that are known only in the underlying beds (Fig. 11b, c, f). Geopetal structures within the clasts and in the larger fossils point to different directions, suggesting reworking during or just after cementation. The repetition of clastic layers within the bioclastic matrix suggests a repeated phenomenon. Five such layers are observed in the Chansin section, and five (or six) are observed in the Spontin section. Note that a 1.5-cm-thick lens of laminated siltstone occurs in the fine-grained part of one of these layers. It yielded a typically late Famennian spore assemblage and a single *Verrucosisporites nitidus* spore (Fig. 4j). This productive horizon is the closest to the DCB ever analysed palynologically in Belgium up to now (Fig. 3).

The fauna within this unit is particularly abundant and quite diverse. The brachiopods are dominated by *Sphenospira julii* (sometimes encrusted by auloporid tabulate corals) and *Araratella moresnetensis*. Most of these are represented by dissociated valves, but as is the case of the former species, delicate structures such as the mucronate cardinal extremities are still preserved, reflecting limited transport and disarticulation. This unit also yielded numerous gastropods (euomphalids, loxonemids), bivalves and phacopid trilobites and very rare orthoconic cephalopods.

This particular facies is overlain by a 200-cm-thick unit of cross-bedded oolitic grainstone, more or less bioclastic and crinoidal at the base then rich in bahamites, mud-coated grains and grapestones in the upper part. The transition with the overlying facies is stylolitic (Fig. 11e). Nevertheless, some oolites are observed in some beds below the oolitic bar, and thus, their occurrence suggests a progressive change of facies.

The reworking of older rocks is restricted to these five (six?) layers and suggests five pulses during the deposition of the 1.2-m-thick HSS equivalent. The oolitic unit is tentatively considered as representing the Stockum Limestone equivalent. Above, the sedimentation returns to its cyclic pattern with facies most similar to those known below the HSS and SL equivalent, except that the fauna is very depleted with almost only crinoids and brachiopods.

The Hastière Fm displays thinner 25–80-cm-thick cycles, starting with crinoid-bearing peloidal wackestone to packstone passing to a more or less calcareous and sandy siltstone. Nodules and lenses made of badly washed peloidal packstone with crinoids, ostracods and brachiopods are common in the siliciclastic parts. There are 13 such cycles in the lower member of the Hastière Fm. The middle member corresponds to a 250-cm-thick unit of coarse bioclastic and crinoidal packstone to grainstone with brachiopods, corals, foraminifers, peloids and mud-coated grains (Fig. 11a). The upper member of the Hastière Fm is not exposed in the Spontin and Chansin sections, but a temporary exposure in the nearby Chansin quarry (Poty et al. 2011) allows us to complete our observations. This upper member appears as an irregular alternation of limestone and shale, quite similar to the lower member (Denayer et al. 2015).

Distal settings: the Anseremme and Gendron-Celles sections (DSA)

Both sections are located in the southern part of the Dinant Synclinorium, i.e. in the DSA (Fig. 1), along the Namur–Bertrix railway, south of Dinant. The Anseremme section serves as the neostratotypes of the Hastarian substage and thus as the Belgian stratotype of the DCB (Hance and Poty 2006) (Fig. 9e). The Gendron-Celles section is the most distal one of southern Belgium and records a relatively deeper environment. The Anseremme section displays similar facies. Both sections are here described together (see also Bouckaert et al. 1974; Conil et al. 1977; Paproth et al. 1986; Van Steenwinkel 1988).

The Strunian is represented by the Comblain-au-Pont Fm, which shows more argillaceous facies than the corresponding stratotype of the formation in the Ourthe valley (eastern CSA), although it was often described as the Etrœungt Fm (see description of Godin section). However, in the actual sections, it appears as a regular alternation of 40–100-cm-thick beds of bioturbated bioclastic and crinoidal limestone, usually fossiliferous (brachiopods, solitary rugose corals, ostracods). The coral *Campophyllum gosseleti* is particularly abundant. The cyclic alternations are very obvious in the Anseremme section, where the boundary between shale and limestone is commonly condensed by stylonodularisation. Van Steenwinkel (1984) interpreted these alternations as periodites (sensu Einsele 1982) deposited under the wave base in a topographically uniform ramp. The base of the Hastière Fm is defined by the occurrence of the first massive limestone bed resting on the last shaly interbed (Figs. 9e and 12a).

The DCB interval is present in the lower bed of the Hastière Fm as thoroughly described by Van Steenwinkel (1988, 1990). The lower 25 cm of the bed (159A in Anseremme, 52A in Gendron-Celles, Fig. 3) records a hydrodynamic event that was responsible for the reworking of the sediment. Centimetric lithoclasts (and ichnoclasts?) are common, displaying a facies similar to that of the host rock but slightly darker: argillaceous packstone with clear margin, in a bioturbated crinoidal and bioclastic grainstone (Fig. 12a, b, d). Microfauna and macrofauna are abundant within the reworked material. Among the latter, some elements are clearly reworked such as upside-down colonies of the tabulate coral *Syringopora* and *Campophyllum* with perforations filled with micritic matrix, suggesting a position on the sea floor for a certain amount of time (Poty 2016). However, other fossils show no obvious reworking such as corals and brachiopods that are even not abraded. Chondrichthyan dental plates with a limited pitting of the osteon (Fig. 12d) indicate a very limited erosion, as does the fine ornamentation preserved on thin-shelled ostracods (Casier et al. 2004). Hence, it is rather obvious that these last Devonian organisms lived within the reworked material on the sea floor, most probably during the reworking phase. This first unit is separated from the rest of the bed by a stylolite of regional extension, as it is always found at the same level of facies change in all sections of the DSA (Van Steenwinkel 1990) (Fig. 12c). Contrary to this author, who interpreted the clasts as a ‘relict deposit’ witnessing of a large-scale erosion followed by a transgression, the faunal and facies succession rather indicate a rapid and short-term reworking, contemporary with the deposition. However, there is no evidence of a reworking of older deposits (lower in the Strunian) nor a mix of Devonian and Tournaisian faunas.

The upper part of the lower bed of the Hastière Fm is a monotonous bioturbated oolitic grainstone with mud-coated grains, lumps, grapestones and irregular often flattened ooids. This facies witnesses the development of an oolitic bar in the shelf (probably close to Spontin, where it reaches its maximal thickness) during the transgressive pulse following the HSS regression. As in other sections, a set of thinly bedded and nodular beds of peloidal and crinoidal packstone with few macrofaunal elements lays above the basal bed of the Hastière Fm. Next, it grades vertically into cyclic alternations of crinoidal packstone and centimetre-thick shale beds, very similar to the alternations known in the Strunian. The limestone beds are still crinoidal and badly sorted, commonly graded. Van Steenwinkel (1984) interpreted the latter limestone beds as amalgamated tempestites. The middle member of the Hastière Fm is a massive metre-thick unit of crinoidal grainstone showing a shallowing-upwards trend (Van Steenwinkel 1984) and topped by an erosive surface interpreted as the sequence boundary of the third-order sequence 1 of Hance et al. (2001).

Offshore high: the Godin section in Avesnes-sur-Helpe (ASA)

During the Strunian, the southern Avesnois sedimentation area was characterised by the deposition of the Etrœungt Fm overlying the shaly Epinette Fm (Figs. 1 and 2). The Etrœungt Fm varies laterally in composition from massive beds of stromatoporoid coverstone with a bioclastic and argillaceous matrix (e.g. Parcq quarry in Etrœungt and southern trench of the Godin quarry in Avesnes-sur-Helpe, Fig. 13f) to an alternation of smaller stromatoporoid beds and marly interbeds with an abundant coral and brachiopod fauna (e.g. northern trench of the Godin quarry and Saint-Hilaire section, Conil and Lys 1980). The microfauna and macrofauna of these units were abundantly described in nearby classical sections (Avesnelles, Saint-Hilaire and Godin South; see e.g. Conil and Lys 1970, 1980; Mistiaen 1997; Mistiaen et al. 2013; Casier and Préat 2003; Mottequin and Brice 2016). The youngest shaly bed of the Etrœungt Fm is overlain by the first 1-m-thick limestone bed of the Avesnelles Fm ('*Calcaire noir d'Avesnelles*'). The base of this formation is a lenticular bed 0–25-cm-thick (bed 12A) of crinoidal and bioclastic rudstone with small intraclasts (few centimetres in diameter), that is slightly darker than the surrounding sediment (Fig. 13d, e). The upper part of this lenticular bed is slightly finer and argillaceous, and locally, a reverse grading appears. The clasts are only observed locally, and the clast-bearing facies passes laterally to the above-described rudstone with no trace of reworking. This lenticular morphology might point to the filling of channel or gullies (Fig. 10e). The following bed (12B) is more regular in thickness and displays a microfacies very similar to that known in the Hastière Fm in other sections, i.e. badly washed crinoidal grainstone or rudstone–floatstone. The typical facies of the *'Calcaire noir d'Avesnelles'* appears in bed 13, i.e. 2 m above the base of the formation, and corresponds to a roughly bedded, finely bioclastic dark limestone with coquinas. The microfacies varies from mudstone to wackestone with small bioclasts, foraminifers and ostracods (including *Cryptophyllus* in the lower 2 m) to bioclastic packstone–grainstone with peloids and crinoids, in which small accumulations of brachiopod shells probably represent tempestites. The brachiopod *Spinocarinifera nigra* is locally abundant in this facies. Six metres above the base of the Avesnelles Fm (from bed 28 to 31), the limestone is still dark but thicker-bedded and coarser. The dominant microfacies is a bioclastic and peloidal packstone to grainstone with abundant mud-coated grains, crinoids and brachiopod shells (Fig. 13c). Pendent cement under the large bioclasts is very common (Fig. 13b). A latter thick-bedded unit, often included in the Avesnelles Fm (Conil et al. 1986), is seemingly the local facies of the middle member of the Hastière Fm (Fig. 13a). A very irregular surface caps this member and is overlain by thinly bedded, stylonodular, badly washed, finely bioclastic packstone–grainstone with small crinoids, ostracods and numerous moravaminids (Conil and Lys 1970) (Fig. 10f). The former irregular surface is interpreted as the sequence boundary of Hance et al.'s (2001) sequence 1, and the overlying unit represents the upper member of the Hastière Fm.

The age of the Avesnelles Fm and its geometrical and stratigraphical relationships with the Hastière Fm are discussed below ("Biostratigraphic misconceptions and incorrect correlations").

Cycles and correlation of the sections

As shown before, most of the Strunian and Hastarian deposits display a strong cyclicity that was already recognised by Conil (1964), who used some of these cycles for intrabasinal correlation (e.g. Conil 1968).

In the Strunian Comblain-au-Pont Fm, such as exposed in the Anseremme section (DSA), the typical cycles correspond to limestone/shale alternations, in which the basal limestone part is 30–60 cm thick and the shale varies from a few centimetres up to 40 cm. The contact between the argillaceous and carbonate facies is irregular, with a gradual transition from one facies to the other, as already observed by Van Steenwinkel (1988). In the lower part of the Comblain-au-Pont Fm, where the limestone beds are replaced by nodular and calcareous sandstone beds, the cycles are less clear cut. In the Spontin and Royseux sections (CSA), the cycles show similar lithologies but most of the limestone beds are tempestites whereas the shale beds often include more proximal elements such as small plant fragments. In the Chanxhe sections (CSA), the Comblain-au-Pont Fm displays very typical cycles in its lower part, but in the upper part, the dominant lithology is a more massive, although bedded, limestone with only thin and discontinuous shaly layers, making the identification of cycles more difficult (see uncertainty regarding the exact number of cycles in Fig. 14). In the Dolhain and Stolberg sections (VASA), where the Strunian deposits of the Dolhain Fm include stromatoporoid biostromes, the cycles are not well developed and the upper part is dolomitised, hampering their recognition. In the ASA, only a few individual cycles are obvious but the monotony of some units renders the cyclicity unrecognisable (see Fig. 3).

However, at the Devonian–Carboniferous transition, the cyclicity is not developed/expressed in the HSS Event equivalent deposits. The lower member of the Hastière Fm (and Avesnelles Fm in the ASA) is usually monotonous crinoidal grainstone with few shaly intercalations. However, in the Spontin and Royseux sections, good outcrops and weathering conditions allow the recognition of 12(− 14?) and 10(− 12?) cycles, respectively. The middle member of the Hastière Fm is a massive unit without any trace of cyclicity in any of the sections (Fig. 14). The upper member displays 15 shale and limestone alternations in the Anseremme section, 15 in the Gendron-Celles section and 15 in a quarry close to the Chansin section (Denayer et al. 2015).

Correlations between sections are possible by using individual cycles, with some restrictions due to their difficult recognition in the field. It appears that sections located in proximal areas possibly recorded fewer cycles compared to the distal ones during the transgressive phase. As summarised in Fig. 14, the Comblain-au-Pont Fm contains 45(− 48?) cycles in Anseremme and 31(− 35?) in Chanxhe, but in the latter, the upper c. 4 m that displays no cycles corresponds to the thickness of 10 individual cycles. Similarly, the lower member of the Hastière Fm includes 28(− 31?) cycles in Gendron-Celles, 28(− 34?) cycles in Anseremme, 23(− 26?) in Spontin and 17(− 23?) in Royseux. These differences might result from the weakest individualisation of the cycles and/or from the retrograding trend of the transgressive system tract as

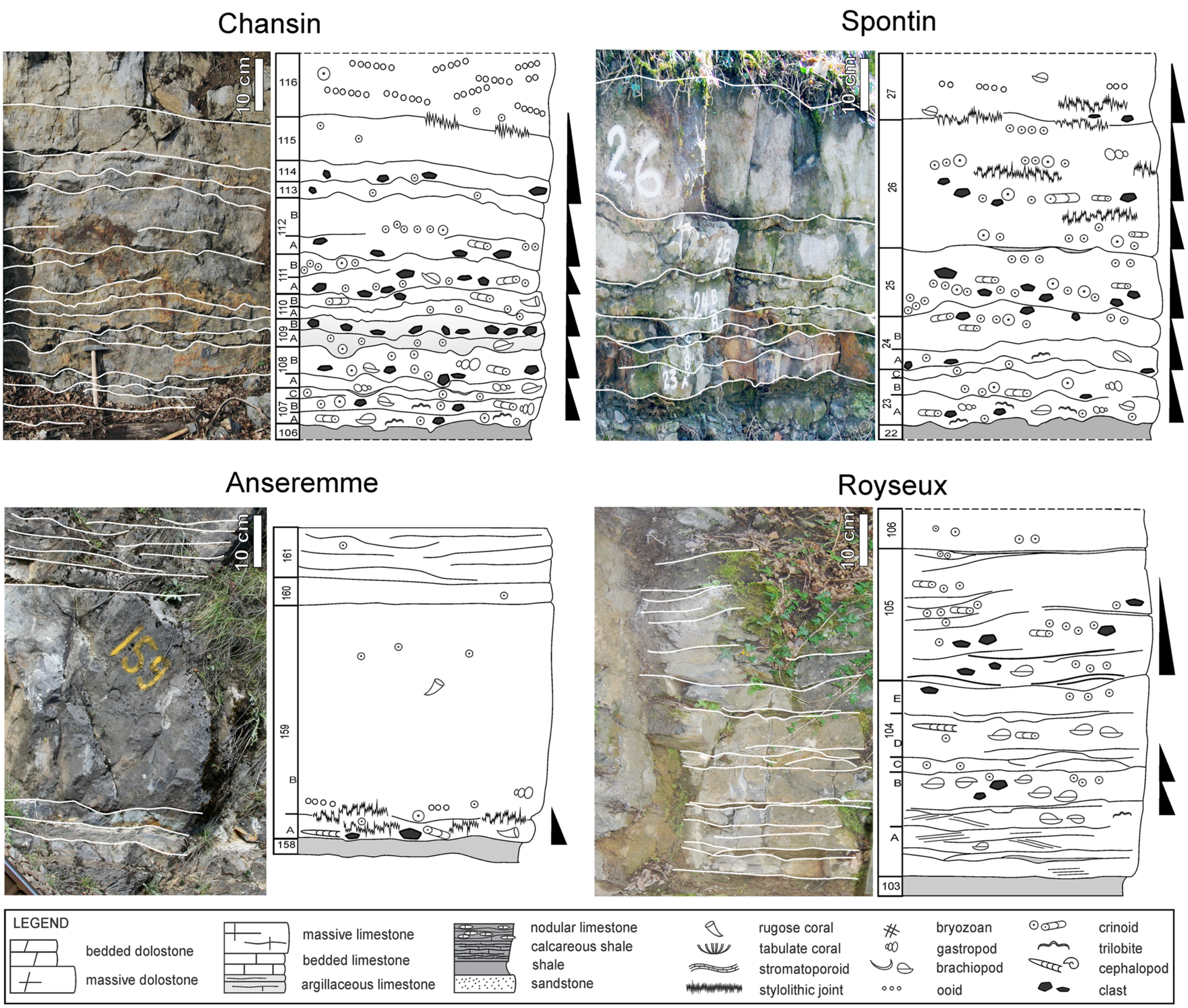


Fig. 15 Detailed stratigraphy and sedimentological events in the basal bed of the Hastière Fm interpreted as equivalent to the HSS in the Chansin and Spontin sections. Here, at least five (possibly six) fining-upwards horizons with intraclasts and contemporary rich and diverse fauna are recorded (black triangles). In the Anseremme section, the reworking event is represented as a 10–15-cm-thick horizon. In the Royseux V section, the c. 1-m-thick basal bed of the Hastière Fm recorded the reworking event as a sandy deposit with clasts

suggested earlier by Van Steenwinkel (1990) but probably did not produce any stratigraphically detectable hiatus other than slightly condensed FADs in proximal successions (see "Plant macrofossils and microfossils").

Discussion

Traditional views and misconceptions of the DCB in southern Belgium

As explained above, the research concerning the DCB in Belgium is a long-running (and still-running) process. Following a historically purely lithostratigraphical definition ('Fa2d'/'Tn1a'/'Tn1b'), international correlations led to the erection of an increasing precise biostratigraphy based on relatively abundant faunal and floral elements, notably foraminifers and spores. Modern approaches started in the 1960s, and numerous data have been accumulated since then. During the last 70 years, ideas and concepts continuously evolved. Meanwhile, new methods were applied (e.g. sequence stratigraphy, geochemical analysis), and at the same time, new questions arose, leading to several paradigm changes. Today, many original data are not accessible anymore for various reasons and the only sources of information are to be found in the abundant literature consisting too often of summarised views of hypothesis-driven interpretations. Since there were only few revisions of the original data, the literature kept citing itself, progressing in some ideas, but also repeating and transmitting obsolete views. As a result, recent publications still contain many misconceptions that require new explanations or interpretations. The present paper does not judge the published interpretations but aims to integer old and new data in a revised model in order to withdraw these misconceptions.

Depositional hiatus

The HBS is supposed to be missing in the NDB. This is true if one expects a thick unit of black shales. Hence, this absence was interpreted as a stratigraphic gap due to a sea level drop by Van Steenwinkel (1990), relying on the non-recognition of biozones (e.g. LN Palynozone, siphonodellid conodonts, see "Biostratigraphic misconceptions and incorrect correlations") and consequently reported in the literature (Bless et al. 1993; Casier et al. 2004; Kumpan et al. 2014; Becker et al. 2016). Similarly, the non-development of black shale facies was reported from neritic sections of Pomerania by Matyja et al. (2015), where the LN (eco-) Palynozone was yet recognised. In other settings without any sedimentary development of anoxic facies, the anoxic event is still detectable with the help of geochemistry (Carmichael et al. 2016; Bábek et al. 2016). The presence of dark (not black) shale is long known from the Belgian Strunian (Conil 1964) but only as decimetre- to metre-thick (after compaction and diagenesis) intercalations in the shaly beds of the Comblain-au-Pont Fm (e.g. two or three beds in the Chanxhe and Martinrive sections, one in the Spontin section; see descriptions of the sections, Fig. 9b, d). Besides an unsupported assumption, there is no evidence whatsoever for a hiatus and the most logical explanation would be that the anoxic facies did not spread into the shallow-water environments and remained confined to the deeper-water areas, where true black shales developed. Dysaerobic waters have occasionally reached the shelf, possibly during transgressive pulses, corresponding to dark shale horizons with impoverished marine faunas, such as dysoxic-water pelecypods and lingulide brachiopods (Mottequin and Poty 2014). In the NDB, carbonate facies rich in benthic fossils continued to develop during the HBS interval. Where the dark shale facies is not detected, geochemical proxies allow tracing the anoxia, i.e. in the Gendron-Celles section, where it occurs in bed 45 (Kumpan et al. 2019). No significant extinction is observed during this particular time interval span, nor linked to the dark shale horizons, as the biotas recorded below and above those horizons are identical.

Reworked fauna

In the basal bed of the Hastière Fm, the fauna is typically Devonian: quasiendothyrid foraminifers, campophyllid rugose corals, sphenospirid brachiopods and phacopid trilobites. These fossils were long considered as reworked by a transgressive pulse that followed the so-called hiatus between the Comblain-au-Pont and Hastière formations (Conil et al. 1986; Van Steenwinkel 1988) and strongly overestimated in the subsequent literature (e.g. Casier et al. 2004; Kumpan et al. 2014; Becker et al. 2016; Kulagina et al. 2016). There are indeed fossils that seem to have been reworked at the base of the Hastière Fm (25-cm-thick basal horizon in the classical Anseremme section, not in the entire metre-thick basal bed!). But besides them, most of the fossils show no evidence of reworking, fragmentation, abrasion or microbial coating (Fig. 12a, b, d). It is therefore suggested that the organisms were contemporary with the reworking but not all reworked themselves. As explained above, the reworked material is autochthonous (intraclasts) and points to rapid reworking due to short-living hydrodynamic event(s). A long-term subaerial exposure with erosion, as suggested by some authors (e.g. Sandberg et al. 2002; Casier et al. 2004), is not supported by sedimentological or stratigraphical arguments. Geochemical proxies show no switch of value nor change in trends across this so-called unconformity (i.e. Azmy et al. 2009; Kumpan et al. 2014), adding a final argument indicating that there is no rupture in the sedimentological record as previously suggested (Conil et al. 1991; Poty et al. 2006).

Biostratigraphic misconceptions and incorrect correlations

The revision of the palynostratigraphic succession of the Strunian in the NDB by Prestianni et al. (2016) demonstrated that the LN Palynozone, only characterised by the appearance of the single-spore *Verrucosisporites nitidus*, is an ecozone rather than a true biozone and that the LE Oppel Zone has to be extended up to the DCB with a decrease of diversity as well as a progressive disappearance of *heavier* spore genera such as *Lophozonotriletes*, *Tumulispora* or *Verrucosisporites*. Both observations can be explained by the disappearance of the ecosystem inhabited by the plant producing *V. nitidus* and the progressive marine character of the sediments towards the end of the Devonian, both produced by the Strunian transgression (Poty 2016). In consequence, the LN Palynozone, seen as an ecozone, can no longer be used as a stratigraphic biozone characterising the upper part of the Strunian due to the rarity of the spore *V. nitidus*, even if locally recorded very high in the Strunian. Furthermore, it can no longer be used as an argument for suggesting a hiatus at this particular moment in time.

As explained above, the foraminiferal zone DFZ8 was defined in the ASA to cover a part of the Avesnelles Fm and was never found outside this area in the NDB. Its guide taxon (*Tournayellina pseudobeata*) serves as a marker for the metre-thick Gumerov Horizon of Urals (Kulagina et al. 2016). Following Poty (2016), this zone is here re-assigned to the early Hastarian as it is included between the HSS Event and the upper member of the Hastière Fm. Hence, the

Avesnelles Fm is a lateral equivalent of the lower and middle members of the Hastière Fm. The conodonts found in the Avesnelles Fm (Conil et al. 1986) are not useful as biostratigraphic markers, because they occur in both the Famennian and the Tournaisian (*Polygnathus inornatus*, *P. communis*, *Pseudopolygnathus graulichi*). *Pelekysgnathus inclinatus* and *Protognathodus kockeli* were both first considered as Devonian in age, when Conil et al. (1986) described the assemblage, but they are nowadays considered as post-HSS Event. Only two conodont specimens tentatively assigned to the species *Siphonodella praesulcata* might have a Devonian affinity, but this particular species also occurs in the early Tournaisian (e.g. Kaiser 2009). Moreover, it is now admitted that the taxonomy of the siphonodellids is highly questionable (Kaiser and Corradini 2011), so that their occurrence in the Avesnelles Fm should be considered with some reserves. Poty et al. (2006) stated that no rugose coral was known from the Avesnelles Fm. However, some specimens of *Conilophyllum priscum* were found since. These corals are indicative of the lower Hastarian RC1α Zone of Poty et al. (2006).

Conil et al. (1986) proposed two hypotheses for the age of the Avesnelles Fm: (1) a Tournaisian age based on foraminifers with a few reworked Famennian conodonts and (2) a Famennian age based on conodonts with the very early appearance of the Tournaisian foraminifers. As explained above, these conodonts are now considered as Tournaisian. Therefore, the age of the '*Calcaire noir d'Avesnelles*' is definitively lower Hastarian, as suggested by the foraminifers, conodonts and corals. At the base of the Avesnelles Fm, the presence of the HSS Event, here consisting of a < 10-cm-thick horizon with lithoclasts, would constrain the rest of the formation to a post-Hangenberg age. However, the upper part of the formation consists of a more massive peloidal grainstone (matching the facies of the middle member of the Hastière Fm) and is capped by an emersion surface, interpreted as the sequence boundary of the third-order sequence no. 1 of Hance et al. (2001) and by the upper member of the Hastière Fm (Conil et al. 1986). Hence, the Avesnelles Fm is lithostratigraphically, biostratigraphically and sequence-stratigraphically constrained as a lateral equivalent of the lower and middle members of the Hastière Fm, as developed elsewhere in the NDB (Figs. 2 and 3). In consequence, the DFZ8 zone should be regarded as the lateral equivalent or part of the MFZ1 foraminiferal biozone of Poty et al. (2006), and as explained above, the difference in facies is the most persuasive explanation for the differences in fauna. The foraminifer assemblage found in the oolitic lower beds of the Hastière Fm is also considered as a time-restricted ecozone (see detailed argumentation in "Foraminifers"). Once again, zones regarded as successive biozones should be considered rather as ecobiozones, laterally present and time-equivalent to each other at the scale of the biozone. The second consequence is the lack of evidence for the presence of any hiatus either in the ASA or in the rest of the basin.

Sedimentary identity of the events and correlation

The Strunian transgression, at the top of the Devonian, marks the transgression of the first third-order sequence 1 of Hance et al. (2001), and therefore, the first transgression of the Carboniferous. The DCB falls within the transgressive system tract of this first third-order eustatic sequence. Because of all the aspects explained previously, the regressive event at the DCB is out of sequence—i.e. not related to any third-order eustatic fluctuation—and therefore does not correspond to a third-order sequence boundary (Poty 2016) (Fig. 15).

Besides the HSS regressive event, the other events can be explained by eustasy. The HBS, with its diachronous base (Higgs and Streel 1984; Streel 1999; Kaiser et al. 2011), its retrograding pattern and proximal thinning, seems to correspond to the maximum flooding *zone* of the TST1. In the NDB, the dysoxic facies occurs as dark horizons only within shaly intervals c. 5 m below the DCB (i.e. Chanxhe, Martinrive and Spontin). In more proximal and/or more agitated settings, the water seems to have stayed well oxygenated during this time interval and a rich benthic fauna continued to develop, with no record of a major extinction. In deeper-water facies, where most of the deposited sediments were anoxic, the HBS facies developed during a longer period of time, with a duration according to its relative position within the basin. Therefore, it can be hardly considered an 'event'! According to Van Steenwinkel (1993), the HBS recorded the condensed starved sedimentation corresponding to the maximum rate of sea level rise, i.e. the maximum flooding interval. Conversely, Bábek et al. (2016), estimating a high rate of accumulation during the HBS Event, concluded that the black shale in pelagic settings would correspond to an increase in terrigenous flux into the marine basin due to a regression pulse rather than a transgressive one as traditionally accepted. Nonetheless, Kumpan et al. (2019) supported this interpretation and considered that the HBS Event, bringing anoxic water onto shelves, was typically transgressive. This latter view is much more supported now by stratigraphical and sedimentological evidence.

The fine-grained siliciclastics of the HS, traditionally seen as *regressive* deposits following the *transgressive* black shale, possibly corresponds to the background noise of sedimentation, where anoxic facies locally developed, producing the HBS. Alternatively, the deposition of the HS could be the effect of a reduced accommodation above the maximum flooding zone with a sedimentary catch-up, a correlative decreasing bathymetry and therefore a false impression of regression during the TST (see also Bábek et al.'s (2016) discussion, suggesting also a possible confusion between HBS and HS). In the proximal areas, this episode corresponds to the deposition of the limestone unit between the HBS equivalent and that of the HSS, e.g. in the Chanxhe section (Fig. 9). The better preservation of vegetal palaeodebris in these facies argues for a quicker

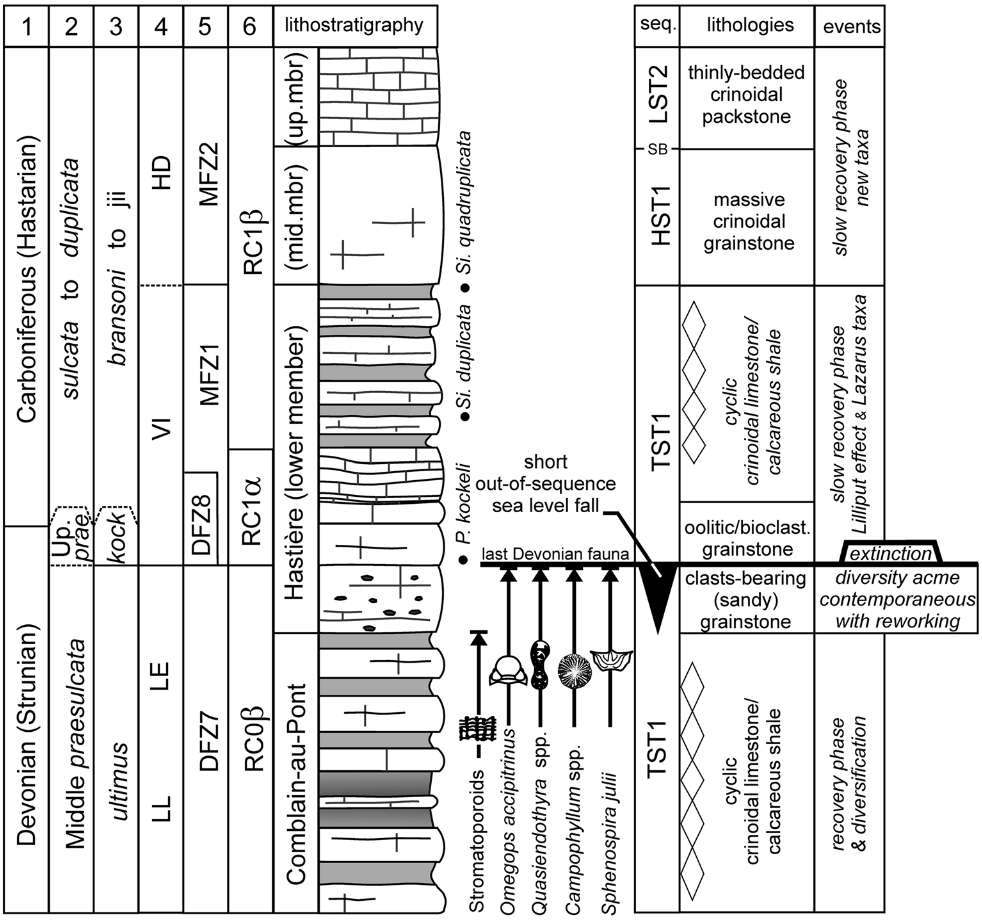


Fig. 16 Synoptic succession of sedimentological and biotic events across the DCB in the Namur–Dinant Basin. 1, Chronostratigraphy. 2, Standard conodont zones of Ziegler and Sandberg (1990). 3, Revised conodont zones sensu Corradini et al. (2017). 4, Miospore palynozones from Streel et al. (1987), emended by Prestianni et al. (2016), see also discussion in "Conodonts". 5, Foraminifer zones according to Poty et al. (2006), emended by Poty (2016). 6, Rugose coral zones according to Poty et al. (2006). Abbreviations: *kock.*, *kockeli*; *P.*, *Protognathodus*; *Si.*, *Siphonodella*. Legend in Fig. 15

deposition (Streel and Marshall 2006) in a sediment catching-up phase. The upper part of the HS might have also recorded the rapid and short-living sea level fall of the HSS Event, as the shale locally replaces the sandstone, e.g. in Wocklum (Luppold et al. 1994).

The HSS clearly corresponds to a sea level fall that is well documented in many locations and settings (for a recent review, see Becker et al. 2016). The regressive pulse characterised by the deposition of the regressive unit is biostratigraphically correlated with high-latitude glaciation by Becker et al. (2016), who argued for a glacio-eustatic origin of the HSS Event and who suggested a sea level amplitude of c. 100 m. This sea level drop seems, however, quite high as it would have exhumed the whole NDB. Although it is clear that reworking of sediments has occurred, it is also clear that this reworking was contemporary with new sedimentation and with the development of a rich benthic fauna. The latter observations are not compatible with the occurrence of such a huge sea level drop, even a very short one (tens of ky?). Streel and Marshall (2006) interpreted the HSS as the peak of a eustatic fall (their 'event 17') followed by rapid deglaciation. The subsequent transgression is most probably recorded within the oolitic unit above the DCB, in the lower member of the Hastière Fm, but also in the Laupen Member (Velbert Anticline, Herbig et al. 2013) and in the La Serre section (Kaiser 2009) among other localities. Note that there is no clear evidence of other glaciation before (in the Strunian) or after (in the Tournaisian) in the NDB.

While the sea level continued to increase with a slower rate, the facies became shallower and thus calcareous sediments started to deposit again, with the deposition of e.g. the Stockum Limestone in the Rhenish domain and that of the Hangenberg Limestone and its nearshore equivalent, the Hastière Fm, interpreted as the HST of the sequence. The erosive surface at the top of the middle member of the Hastière Fm corresponds to the sequence boundary, on top of which the next transgression started with the deposition of the upper member of the Hastière Fm and its equivalent beds in the Hangenberg Limestone. This second transgressive pulse reached a maximum depth when the sedimentation was not strong enough to catch-up the rising sea level. The resulting deposits correspond to the Pont-d'Arcole Fm reflecting deeper facies. The latter formation is considered as a time-equivalent deposit of the lower Alum Shale of the German successions, but without the development of anoxic conditions (see Herbig 2016 and references therein).

It has to be noted that both the HSS regressive event and the sequence boundary at the top of sequence 1 are of global extension, at least within the Palaeotethys Ocean realm, demonstrating their eustatic origin. On the contrary, local- to regional-scale unconformities in the upper (uppermost) Famennian of Northern and Southern America were apparently tectonically induced by various orogenies (Streel and Marshall 2006 and references therein).

As a preliminary conclusion, the Devonian–Carboniferous transition should be regarded as a period of global transgression (third-order sequence) starting in the Strunian and culminating within the Hastière Fm. Most of the ‘events’ of the Rhenish standard succession can be explained by sequence stratigraphy, and they correlate rather well with the neritic succession of Belgium. The Wocklum Limestone records the onset of the TST. The HBS is typically the expression of the starved sedimentation around the maximum flooding zone. The Hangenberg Shale and equivalent recorded the catch-up of the sedimentation when accommodation decreased before the end of the transgression, where it passed to the Stockum Limestone. The HST is recorded in the Hangenberg Limestone and in the massive middle member of the Hastière Fm, with the sequence boundary laying at the top of the latter. This first sequence is typically glacio-eustatic in origin (Poty et al. 2006). The HSS regressive event, which is superimposed to this transgressive sequence, occurs during the transgression and is seemingly not related to the third-order glacio-eustatic sequence. As an out-of-sequence event, it recorded a short-lived but likely strong sea level drop followed by a rapid sea level rise. Neither the sea level fall nor the rise had any consequence on the third-order sequence as the sediments and cyclicity before and after the event are perfectly identical (Fig. 14). Herbig (2016), however, proposed an alternative sequential model in which the HBS corresponds to the HST whereas the HSS corresponds to the next LST, the sequence boundary therefore being situated within the Hangenberg Event s.l., and a hiatus should be considered between HBS and HSS.

Origin and duration of the regression

In the southern CSA (e.g. Spontin and Chansin), where the HSS Event is recorded with the thickest deposits, the HSS regressive deposits are 1.2 m thick + 2 m of oolites formed during the subsequent sea level rise. Although this sedimentation is not *normal*, the above 3.2-m-thick deposit has the thickness equivalence of three c. 1-m-thick precession cycles in the same sections. If we consider the average duration of a cycles at about 18.6 ky, the 3.2-m-thick unit might have lasted at most c. 55 ky, with roughly c. 20 ky for the regressive part and c. 35 ky for the transgressive part (or even less as oolites are known to accumulate rapidly). The origin of the sea level fall is highly hypothetical as it seems to represent a very short and intense event, even more rapid than the Pleistocene glaciations that lasted between 40 and 100 ky each. A unique orbitally driven glaciation might therefore not be a satisfactory explanation by itself.

In the Spontin and Chansin sections, the regressive event is recorded in the above-described 1.2 m of coarse and fossiliferous grainstone–rudstone with intraclasts and ichnoclasts. The clasts are arranged in five (possibly six) horizons separated by similar facies without large clasts. Hence, it is suggestive of a stepped regression separated by small breaks in reworking (Fig. 15). Could it be diagnostic for five (or more?) progressive phases in the glaciation? Or is it only the effect of storms (tempestites) producing a grading in the sediment? In the Royseux section in the proximal CSA, the HSS is recorded within a c. 1-m-thick bed of calcareous sandstone with clasts, fossils and bioturbations but without any trace of erosive horizons (Fig. 15). Similarly, in the Stolberg II section (VASA), the event is represented by a c. 2-m-thick unit of bioturbated sandy siltstones. The sudden influx of siliciclastic sediments in the carbonate environment dominating the DCB transition is resembling the sedimentary consequences of the upper Triassic Carnian Pluvial Event. Indeed, during the Carnian, localities around the Neotethys Ocean recorded the massive influx of coarse siliciclastics intercalated within a thick evaporitic or carbonate sequence (Simms et al. 1995). These deposits and associated biotic crisis have been interpreted as the result of a major increase in rainfall (Simms and Ruffle 1989, 1990). The scale and duration (> tens to hundreds of metres of rock, > 5 Ma) are not comparable to the short-living HSS Event, and if increased rainfall explains the influx of siliciclastics in proximal areas, it still fails to explain the accumulation of clasts in more distal areas. Throughout the NDB, the HSS Event started in the last shaly part of the last Devonian precession cycle, i.e. during the wet climate phase. The contemporaneity of the onset of the regression is thus demonstrated as no 18.6-ky cycle is missing in any section. The end of the regression is marked by the end of the reworking and/or siliciclastic input and by the return to normal sedimentation (oolitic or bioclastic). The end of the regression is thus thought to be isochronous and is marked by the disappearance of the last Devonian taxa (trilobites, corals, brachiopods, foraminifers, spores), immediately followed by the development of the Carboniferous faunal and floral assemblages.

If regression was the probable proximal killing mechanism, the concluding question remains of what phenomenon could trigger such a rapid, intense and short-living regression. Short and strong glaciations cannot be excluded, but again, which phenomenon could produce such a rapid, intense and short-living glaciation? Glacial sediments such as diamictites are known in Gondwana (Brezinski et al. 2010; Wicander et al. 2011; Lakin et al. 2016), but most of them are dated by palynology as of late–latest Famennian age—i.e. during the transgressive phase—and do not seem to have recorded a peak at the DCB or immediately below. Intense volcanism releasing massive SO_2 aerosols in the atmosphere could have produced a strong cooling that persisted during several thousands of years, depending on the intensity of the volcanic activity (Bond and Grasby 2017; Soreghan et al. 2019). Large igneous province (LIP)-induced volcanism such as in that of the Pripyat–Dnieper–Donets rift system (not radio-isotopically dated but estimated to be of Famennian age, Wilson and Lyashkevich 1996) could have triggered a cooling, leading to a rapid and short-living glaciation. A significant mercury enrichment, possibly due to distal but intense volcanic, was identified at the top of the HSS equivalent in Vietnam (Paschall et al. 2019). Cosmic phenomena reducing the illumination of Earth during several thousands of years (variation in solar activity? Cosmic clouds? Bolid lowering the solar activity?) cannot be excluded here, but they are—up to now—not verifiable and thus in the field of science fiction. Let us remember that a bolide impact triggering extinctions was also in the field of science fiction before Alvarez's theory in the 1980s.

Conclusions (Fig. 16)

Unlike previous publications (e.g. Sandberg et al. 2002), an increasing amount of data suggests that the Hangenberg Biocrisis near the DCB certainly belongs to the 'Big Six Extinction Events'. This is indeed proved not only by its severity (Droser et al. 2000; McGhee et al. 2013) but also and mainly by the variety of ecosystems that were driven to extinction (Flügel and Kiessling 2002; McGhee et al. 2013; Bond and Grasby 2017) and by the disparity reboot triggered by the extinctions (Poty 1986, 1999; Denayer and Webb 2017). Contrary to most of the other Big Five, the Hangenberg Crisis occurred during the recovery phase that followed the extinctions associated with the Kellwasser Biocrisis at the end of the Frasnian. Hence, the ecosystems were hit during their rebuilding phase when the diversity and disparity were increasing. It was not an event affecting ecosystems already diminished by long-term environmental degradation as for the end-Frasnian, end-Permian or end-Cretaceous. The impact of the Hangenberg Biocrisis was double, triggering first a major crisis in the nektonic and planktonic domains during the transgressive Hangenberg Black Shale anoxic phase and then the benthic domain during the sudden regressive Hangenberg Sandstone Event.

The succession of sedimentary and biotic events is well developed and particularly well documented in the neritic facies of the Namur–Dinant Basin in southern Belgium, where the Devonian–Carboniferous transition is represented by c. 25 m of shallow-water sediments. This includes fossiliferous bioclastic limestones and shales, dark dysoxic shales of the HBS equivalent, a horizon with clasts that corresponds to the reworking associated with the HSS regressive event. The Belgian succession was often excluded from the discussion on the DCB because it was supposedly suffering from major stratigraphical imperfections: e.g. the lack of index conodonts and the occurrence of hiatuses. However, a re-assessment of these so-called imperfections tends to demonstrate that these disorders are no longer true and that, on the contrary, the neritic succession of the NDB is probably one of the most continuous successions for studying the DCB saga.

The occurrence of hiatuses, long spread in the literature, was based on the non-recognition of the Hangenberg Black Shale in Belgium and the absence of biozones (foraminiferan DFZ8 and palynozone LN) that were considered as supporting arguments for the existence of a non-deposition/erosion event in the Devonian–Carboniferous transitional deposits. The presence of dark dysoxic shale c. 5 m below the level of extinction of the Devonian fauna in several Belgian sections demonstrated the local spread of dysoxic water on the shelf and the local development of the HBS equivalent. On the other hand, it is demonstrated now that the absence of the DFZ8 Zone, only developed in the fine-grained facies of the Avesnelles Fm, is a local equivalent of the depleted MFZ1 Zone. Both zones bracket the HSS Event at the base and the sequence boundary of the third-order sequence 1 at the top (Hance et al. 2001). Moreover, the only argument pleading for a Devonian age of the DFZ8 Zone in the Avesnois area was the occurrence of conodonts, including *P. kockeli*, however actually regarded as the post-Hangenberg Sandstone Event. The extreme rarity or quasi-absence of the LN Palynozone, due to the almost general absence of its index spore *V. nitidus* in most facies, is now considered as related to the absence of the *V. nitidus*-producing plant in most environments. The LN Palynozone is therefore regarded as an ecozone rather than a biozone. Consequently, its absence is not an argument for any hiatus.

The HSS regressive event is recorded in various facies (bioclastic limestone with clasts, sandy limestone, sandstone beds) varying from some tens of centimetres up to 1.2-m-thick beds, depending on the position along the proximo-distal gradient. It recorded the last Devonian fauna that was seemingly contemporary with the reworking. These easily recognisable facies allow pragmatic section-to-section and intrabasinal and interbasinal correlations. Although often interpreted as a sequence boundary in the literature, the careful examination of several sections led to the conclusion that the HSS is not the sequence boundary of a third-order glacio-eustatic sequence but an out-of-sequence regressive pulse that was intense, sudden and short-living. This dramatic sea level fall was recorded during the global transgressive phase (sequence 1, Strunian transgression), and the sequence boundary is indeed located c. 10–15 m above the DCB, between the middle and upper members of the Hastière Fm.

During the DCB working group meeting in Montpellier in 2016, a new criterion for the definition of the DCB was selected to being tested (Aretz and the working group 2016). The working group on the redefinition of the Devonian–Carboniferous boundary voted to test the suitability of a timeline recognised by “the base of the *Pr. kockeli* Zone, beginning of radiation and top of major regression (top of HSS), and end of mass extinction” as the level of the newly defined boundary. The criterion relies on a timeline recognised and established by the end of the extinctions and reworking associated to the HSS regressive event, immediately below the FAD of the index conodont species *P. kockeli* (Spalletta et al. 2017; Corradini et al. in press, this issue). Following this criterion, the DCB can be officially recognised in Belgium at the top of the basal bed of the Hastière Fm, between the reworked horizon corresponding to the HSS and the overlying deposits that record the sea level rise after the HSS regression. The correlation potential is maximal for this criterion as it corresponds to a global, facies-wide, geochemically and sedimentologically traceable, almost synchronous event bracketed by excellent biostratigraphic markers (conodonts, spores, foraminifers, corals). Moreover and eventually, it also corresponds to a natural boundary as pleaded by Walliser (1984) since it now coincides with the disappearance of the Upper Devonian biotas.

Acknowledgements For the help in identifying some biota, we would like to thank Michael Amler (Cologne), Carlo Corradini (Trieste), Raimund Feist (Montpellier) and Catherine Crônier (Lille). We also thank Roland Dreesen (Brussels) for the inspiring discussions and for the review of the early version of the manuscript and Markus Aretz, Denise Brice, Hans-Georg Herbig, Jean-Marc Marion, John Marshall, Georges Sevastopoulo, Philippe Steemans and Maurice Streel for the interesting and inspiring discussion. Thierry Oudoire is thanked for lending the specimens curated at the Musée d’Histoire naturelle de Lille. The manuscript benefited from a careful review by Sven Hartenfels (Cologne), Carlo Corradini (Trieste) and Markus Aretz (Toulouse).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Alberti, H., Groos-Uffenorde, H., Streel, M., Uffendorde, H., & Walliser, O. H. (1974). The stratigraphical significance of the *Protognathodus* fauna from Stockum (Devonian/Carboniferous boundary, Rhenish Schiefergebirge). *Newsletters on Stratigraphy, 3*, 263–276.

Amler, M. R. (1992). Shallow marine bivalves at the Devonian/Carboniferous boundary from the Velbert Anticline (Rheinisches Schiefergebirge). In M. Streel, G. Sevastopulo, & E. Paproth (Eds.) *Devonian–Carboniferous boundary*, *Annales de la Société Géologique de Belgique 115*, 405–423.

Amler, M. R. (2004). Late Famennian bivalve, gastropod and bellerophontid molluscs from the Refrath 1 borehole (Bergisch Gladbach-Paffrath Syncline; Ardennes-Rhenish Massif, Germany). *Courier Forschungsinstitut Senckenberg, 251*, 151–173.

Amler, M. R. (2014). Bivalves in Upper Devonian to lower Mississippian biostratigraphy. In R. Rocha, J. Pais, J. Kullberg, & S. Finney (Eds.) *STRATI 2013* (pp. 1021–1025). Cham: Springer Geology.

Amler, M. R. (2016). Shallow marine Rostroconchia (Mollusca) from the Latest Devonian (Strunian) and their significance for rostroconch life style and evolution. In J. Denayer & M. Aretz (Eds.) *Devonian and Carboniferous research: homage to Prof. Edouard Poty*, *Geologica Belgica 19*, 111–120.

Amler, M. R., & Heidelberger, D. (2003). Late Famennian gastropoda from South-West England. *Palaeontology, 46*, 1151–1211.

Amler, M. R., & Herbig, H.-G. (2006). Ostrand der Kohlenkalk-Plattform und Übergang in das Kulm-Becken im westlichen Deutschland zwischen Aachen und Wuppertal. *Schriftenreihe der Deutschen Gesellschaft für Geowissenschaften, 41*, 441–477.

Aretz, M. (2014). Redefining the Devonian–Carboniferous boundary: an overview of problems and possible solutions. In R. Rocha, J. Pais, J. Kullberg, & S. Finney (Eds.) *STRATI 2013* (pp. 227–231). Cham: Springer Geology.

Aretz, M., & the working group. (2016). *A new look at the Devonian–Carboniferous boundary – atatements of participants and task group members*. Montpellier, France: International Workshop of the joined SDS/SCCS Task group 29 pp.

Aretz, M., Nardin, E., Vachard, D., Wang, Y., & Liu, M. (2014). Diversity patterns and palaeobiogeographical relationships of latest Devonian–Lower Carboniferous foraminifers from South China: what is global, what is local? *Journal of Palaeogeography, 3*, 35–59.

Austin, R., Conil, R., Rhodes, F., & Streel, M. (1970). Conodontes, Spores et Foraminifères du Tournaisien Inferieur dans la Vallée du Hoyoux. *Annales de la Société Géologique de Belgique, 93*, 305–315.

Azmy, K., Poty, E., & Brand, U. (2009). High-resolution isotope stratigraphy of the Devonian–Carboniferous boundary in the Namur–Dinant Basin, Belgium. *Sedimentary Geology, 216*, 117–124.

Bábek, O., Kumpan, T., Kalvoda, J., & Grygar, T. M. (2016). Devonian/Carboniferous boundary glacioeustatic fluctuation in a platform-to-basin direction: a geochemical approach of sequence stratigraphy in pelagic settings. *Sedimentary Geology, 337*, 81–99.

Becker, G., & Bless, M. J. M. (1974). Ostracode stratigraphy of the Ardenno-Rhenish Devonian and Dinantian. In J. Bouckaert & M. Streel (Eds.) *Publication of the international symposium on Belgian micropaleontological limits from Emsian to Visean, Namur* (pp. 1–52).

Becker, G., Bless, M. J., Streel, M., & Thorez, J. (1974). Palynology and ostracode distribution in the Upper Devonian and basal Dinantian of Belgium and their dependence on sedimentary facies. *Mededelingen Rijks Geologische Dienst, 25*, 9–99.

Becker, R. T., & Weber, M. (2016). Review of the Devonian–Carboniferous transition in the Aachen region (western Rhenish Massif). *Münstersche Forschungen zur Geologie und Paläontologie, 108*, 29–35.

Becker, R. T., Kaiser, A. I., & Aretz, M. (2016). Review of the chrono-, litho- and biostratigraphy across the global Hangenberg Crisis and Devonian–Carboniferous boundary. In R. T. Becker, P. Königshof, & C. E. Brett (Eds.) *Devonian climate, sea level and evolutionary events*, *Geological Society, London, Special Publications 423*, 355–386.

Belanger, I., Delaby, S., Delcambre, B., Ghysel, P., Hennebert, M., Laloux, M., Marion, J.-M., Mottequin, B., & Pingot, J.-L. (2012). Redéfinition des unités structurales du front varisque utilisées dans le cadre de la nouvelle Carte géologique de Wallonie (Belgique). *Geologica Belgica, 15*, 169–175.

Bless, M. J. M. (1983). Late Devonian and Carboniferous ostracode assemblages and their relationship to the depositional environment. *Bulletin de la société belge de Géologie, 92*, 31–53.

Bless, M. J. M. (1993). Comparison between eustatic T-R cycles around the Devonian-Carboniferous boundary and the distribution of the ostracode taxon *Pseudoleperditia* gr. *venulosa*. In M. Streel, G. Sevastopulo, & E. Paproth (Eds.) *Devonian–Carboniferous* *boundary*, *Annales de la Société Géologique de Belgique 115*, 475–482.

Bless, M. J. M., & Groos-Uffenorde, H. (1984). Ostracods at the Devonian–Carboniferous. In E. Paproth & M. Streel (Eds.) *The Devonian–Carboniferous boundary*, *Courier Forschungsinstitut Senckenberg 67*, 23–28.

Bless, M. J. M., Bouckaert, J., Conil, R., Dreesen, R., Groessens, E., Streel, M., & Thorez, J. (1974). Guidebook excursion D. In J. Bouckaert & M. Streel (Eds.) *International symposium on Belgian micropalaeontological limits, Namur September 1974, guidebooks* 41 pp.

Bless, M. J. M., Streel, M., & Becker, G. (1987). Distribution and paleoenvironment of Devonian to Permian ostracode assemblages in Belgium with reference to some late Famennian to Permian marine nearshore to «brackish-water» assemblages dated by miospores. *Annales de la Société Géologique de Belgique, 110*, 347–362.

Bless, M. J. M., Becker, R. T., Higgs, K., Paproth, E., & Streel, M. (1993). Eustatic cycles around the Devonian–Carboniferous boundary and the sedimentary and fossil record in Sauerland (Federal Republic of Germany). *Annales de la Société Géologique de Belgique, 115*, 689–702.

Bond, D. P., & Grasby, S. E. (2017). On the causes of mass extinctions. *Palaeogeography, Palaeoclimatology, Palaeoecology, 478*, 3–29.

Bouckaert, J., & Conil, R. (1970). Les couches de passage du Dévonien au Carbonifère dans la vallée de la Dendre; découverte de conodontes à Brugelette. *Bulletin de la Société belge de Géologie, 79*, 1–4.

Bouckaert, J., & Groessens, E. (1976). *Polygnathus paprothae*, *Pseudopolygnathus conili*, *Pseudopolygnathus graulichi*: espèces nouvelles à la limite Dévonien–Carbonifère. *Annales de la Société Géologique de Belgique, 99*, 587–599.

Bouckaert, J., Streel, M., & Thorez, J. (1968). Schéma biostratigraphique et coupes de référence du Famennien belge. *Annales de la Société Géologique de Belgique, 91*, 317–336.

Bouckaert, J., Streel, M., Thorez, J., & Mound, M. C. (1969). Biostratigraphic chart of the Famennian stage (Upper Devonian) in the type localities of Belgium: a preliminary report. *Journal of Paleontology, 43*, 727–734.

Bouckaert, J., Streel, M., & Thorez, J. (1970). Le Famennien et les couches de transition Dévonien–Carbonifère dans la vallée de l'Ourthe (sud de Liège, Synclinorium de Dinant). In M. Streel & R. Wagner (Eds.) *Compte-rendus de la 8e réunion de la Commission internationale de Microflore du Paléozoïque et de l'Assemblée générale de l'IUGS, Liège, 1970 Subcommission on Carboniferous Stratigraphy*, *Les Congrès et Colloques de l'Université de Liège 55*, 25–46.

Bouckaert, J., Conil, R., Groessens, E., Streel, M., & Sandberg, C. (1974). Guidebook excursion C. In J. Bouckaert & M. Streel (Eds.) *International symposium on Belgian micropalaeontological limits, Namur September 1974, guidebooks* 18 pp.

Bouckaert, J., Conil, R., Dusar, M., & Streel, M. (1977). Stratigraphic interpretation of the Tohogne borehole (province of Luxembourg), Devonian–Carboniferous transition. *Annales de la Société Géologique de Belgique, 100*, 87–101.

Brauckmann, C., & Hahn, G. (1984). Trilobites as index fossils at the Devonian–Carboniferous boundary. *Courier Forschungsinstitut Senckenberg, 67*, 11–14.

Brauckmann, C., Chlupáč, I., & Feist, R. (1992). Trilobites at the Devonian–Carboniferous boundary. *Annales de la Société Géologique de Belgique, 115*, 507–518.

Brenckle, P. L., & Hance, L. (2005). New and revised Tournaisian (Early Mississippian) foraminiferal taxa from Belgium. *Rivista Italiana di Paleontologia e Stratigrafia, 111*, 199–216.

Brezinski, D. K., Cecil, C. B., & Skema, V. W. (2010). Late Devonian glacigenic and associated facies from the central Appalachian Basin, Eastern United States. *Geological Society of America Bulletin, 122*, 265–281.

Brice, D., Nicollin, J.-P., & Mottequin, B. (2013). Diversity of strophomenid, orthotetid and orthid brachiopods in the uppermost Famennian ('Strunian'; Upper Devonian) of the Avesnois (northern France), *Annales de la Société géologique du Nord, 2ème série 20*, 53–63.

Carmichael, S. K., Waters, J. A., Batchelor, C. J., Coleman, D. M., Suttner, T. J., Kido, E., Moore, L. M., & Chadimová, L. (2016). Climate instability and tipping points in the Late Devonian: detection of the Hangenberg Event in an open oceanic island arc in the Central Asian Orogenic Belt. *Gondwana Research, 32*, 213–231.

Casier, J.-G., & Préat, A. (2003). Ostracods and lithofacies of the Devonian–Carboniferous boundary beds in the Avesnois, north of France. *Bulletin de l'Institut Royal des Sciences Naturelles de Belgique. Sciences de la Terre, 73*, 83–107.

Casier, J.-G., Mamet, B., Préat, A., & Sandberg, C. A. (2004). Sedimentology, conodonts and ostracods of the Devonian–Carboniferous strata of the Anseremme railway bridge section, Dinant Basin, Belgium. *Bulletin de l'Institut Royal des Sciences Naturelles de Belgique, Sciences de la Terre, 74*, 45–68.

Casier, J.-G., Lebon, A., Mamet, B., & Préat, A. (2005). Ostracods and lithofacies close to the Devonian–Carboniferous boundary in the Chanxhe and Rivage sections, northeastern part of the Dinant Basin, Belgium. *Bulletin de l'Institut Royal des Sciences naturelles de Belgique, Sciences de la Terre, 75*, 95–126.

Clausen, C.-D., Leuteritz, K., Ziegler, W., & Korn, D. (1989). Ausgewählte Profile an der Devon/KarbonGrenze im Sauerland (Rheinisches Schiefergebirge). *Fortschritte in der Geologie von Rheinland und Westfalen, 35*, 161–226.

Coen, M. (1995). On *Amicus complanatus* (Kummerow 1939) and related ostracode species. *Mémoires de l'Institut géologique de l'Université de Louvain, 35*, 177–180.

Conil, R. (1961). Les gîtes à stromatopores du Strunien de la Belgique. *Mémoires de l'Institut géologique de l'Université de Louvain, 22*, 335–369.

Conil, R. (1964). Localités et coupes types pour l'étude du Tournaisien inférieur – révision des limites sous l'aspect micropaléontologique, Mémoires de l'Académie royale de Belgique*, Classe des Sciences, 2e série 15*, 1–87.

Conil, R. (1968). Le calcaire carbonifère depuis le Tn1a jusqu'au V2a. *Annales de la Société Géologique de Belgique, 90*, 687–726.

Conil, R. (1980). Note sur quelques foraminifères du Strunien et du Dinantien d'Europe occidentale. *Annales de la Société Géologique de Belgique, 103*, 43–53.

Conil, R., & Groessens, E. (1975). Introduction à la stratigraphie et aux phénomènes récifaux du Dinantien. In R. Conil, E. Groessens, M. Lejeune-Carpentier, J. Pel, & H. H. Tsien (Eds.) *Livret-guide du second symposium international sur les coraux et récifs coralliens fossiles, Paris, Septembre 1975, excursion C (Nord de la France et Belgique)*. Service géologique de Belgique 39 pp.

Conil, R., & Lys, M. (1970). Données nouvelles sur les Foraminifères du Tournaisien inférieur et des couches de passage du Famennien au Tournaisien dans l'Avesnois. In M. Streel & R. Wagner (Eds.) *Comptes rendus de la 8e réunion de la Commission internationale de Microflore du Paléozoïque et de l'Assemblée générale de l'IUGS, Liège, 1970. Subcommission on Carboniferous Stratigraphy*, *Les Congrès et Colloques de l'Université de Liège 55*, 241–265.

Conil, R., & Lys, M. (1980). Strunien. In C. Cavelier & J. Roger (Eds.) *Les étages français et leurs stratotypes*, *Mémoires du Bureau de Recherches géologiques et minières 109*, 26–35.

Conil, R., & Pirlet, H. (1970). Le calcaire Carbonifère du Synclinorium de Dinant et le sommet du Famennien. In M. Streel & R. Wagner (Eds.) *Comptes rendus de la 8e réunion de la Commission internationale de Microflore du Paléozoïque et de l'Assemblée générale de l'IUGS, Liège, 1970. Subcommission on*

Carboniferous Stratigraphy, *Les Congrès et Colloques de l'Université de Liège 55*, 47–63.

Conil, R., & Vandenven, G. (1972). Le Tournaisien des sondages de Saint-Aubain, Chaumont et Silenrieux. *Service géologique de Belgique, Professional paper, 1972*(1), 1–20.

Conil, R., Groessens, E., & Streel, M. (1974). Guidebook excursion H. In J. Bouckaert & M. Streel (Eds.) *International symposium on Belgian micropalaeontological limits, Namur September 1974, guidebooks* 13 pp.

Conil, R., Groessens, E., & Pirlet, H. (1977). Nouvelle charte stratigraphique du Dinantien type de la Belgique. *Annales de la Société géologique du Nord, 96*, 363–371.

Conil, R., Dreesen, R., Lentz, M. A., Lys, M., & Plodowski, G. (1986). The Devono-Carboniferous transition in the Franco-Belgian basin with reference to foraminifera and brachiopods. In M. J. M. Bless & M. Streel (Eds.) *Late Devonian events around the Old Red Continent*, *Annales de la Société Géologique de Belgique 109*, 19–26.

Conil, R., Groessens, E., Laloux, M., Poty, E., & Tourneur, F. (1991). Carboniferous guide foraminifera, corals and conodonts in the Franco-Belgian and Campine basins: their potential for widespread correlation. *Courier Forschungsinstitut Senckenberg, 130*, 15–30.

Corradini, C., & Spalletta, C. (2018). Continuity of fossil record and biozonation schemes: an example across the Devonian/Carboniferous boundary. In *5th International Palaeontological Congress, Paris, 2018 July, 9-13th, Abstract book* (p. 789).

Corradini, C., Spalletta, C., Mossoni, A., Matyja, H., & Over, D. J. (2017). Conodonts across the Devonian/Carboniferous boundary: a review and implication for the redefinition of the boundary and a proposal for an updated conodont zonation. *Geological Magazine, 154*, 888–902.

Corradini, C., Mossoni, A., Corriga, M. G., & Spalletta, C. (in press). The Devonian/Carboniferous boundary in Sardinia (Italy). In M. Aretz & C. Corradini (Eds.) *Global review of the Devonian-Carboniferous boundary. Palaeobiodiversity and Palaeoenvironments*. https://doi.org/10.1007/s12549-019-00411-5. [this issue]

Decombeix, A.-L., Meyer-Berthaud, B., Galtier, J., Talent, J. A., & Mawson, R. (2011). Arborescent lignophytes in the Tournaisian vegetation of Queensland (Australia): palaeoecological and palaeogeographical significance. *Palaeogeography, Palaeoclimatology, Palaeoecology, 301*, 39–55.

Decombeix, A.-L., Meyer-Berthaud, B., & Galtier, J. (2011b). Transitional changes in arborescent lignophytes at the Devonian–Carboniferous boundary. *Journal of the Geological Society, 168*, 547–557.

Dehée, R. (1929). Description de la faune d'Etrœungt – Faune de passage du Dévonien au Carbonifère. *Mémoires de la Société géologique de France, nouvelle série, 5*, 1–62.

Delépine, G. (1929). Sur Ja présence de *Cymaclymenia camerata* Schindewolf dans la zone d'Etrœungt à Sémeries (Nord de la France). *Annales de la Société géologique du Nord, 54*, 99–103.

Delépine, G. (1940). Les Goniatites du Dinantien de la Belgique. *Mémoires du Musée royal d'Histoire naturelle de Belgique, 91*, 1–91.

Demanet, F. (1958). Contribution à l'étude du Dinantien de la Belgique. *Mémoires de l'Institut royal des Sciences naturelles de Belgique, 141*, 1–152.

Denayer, J. (2014). Rugose corals across the Devonian–Carboniferous boundary in NW Turkey. *Acta Palaeontologica Polonica, 6*, 51–71.

Denayer, J., & Webb, G.E. (2017). Earliest Mississippian rugose corals of eastern Australia: post-disaster fauna across the Devonian–Carboniferous boundary? In B. Mottequin, L. Slavík, P. Königshof (Eds.) *Climate change and biodiversity patterns in the mid-Palaeozoic. Palaeobiodiversity and Palaeoenvironments 97*(3), 655–667.

Denayer, J., Poty, E., & Aretz, M. (2011). Uppermost Devonian and Dinantian rugose corals from southern Belgium and surrounding areas. In M. Aretz & E. Poty (Eds.) *11th international symposium on Fossil Cnidaria and Porifera - Liège, 19-29 August, 2011, Field-Guides; Kolner Forum für Geologie und Paläontologie 20*, 151–201.

Denayer, J., Poty, E., Marion, J.-M., & Mottequin, B. (2012). Lower and Middle Famennian (Upper Devonian) rugose corals from southern Belgium and northern France. In J. Denayer, M. Aretz, & E. Poty (Eds.) *Proceedings of the XIth international symposium on fossil cnidaria and porifera, Liège, Belgium, August 19-29, 2011*, *Geologica Belgica 15*, 273–283.

Denayer, J., Prestianni, C., Sautois, M., Poty, E., & Mottequin, B. (2015). The Devonian–Carboniferous boundary and the Lower Carboniferous in the type area. In J. Denayer, B. Mottequin, & C. Prestianni (Eds.) *IGCP596-SDS Symposium, Climate Change and Biodiversity patterns in the Mid-Palaeozoic, Brussels, September 2015, Field guidebooks*. *STRATA. 17*, 59–81.

Denayer, J., Prestianni, C., Mottequin, B., & Poty, E. (2019). Field trip A1: the uppermost Devonian and Lower Carboniferous in the type area of southern Belgium. In M. Aretz, H.-G. Herbig, S. Hartsenfelds, & M. Amler (Eds.) *19th international congress on the Carboniferous and Permian, Cologne 2019, field guidebooks*, *Kölner Forum für Geologie und Paläontologie 24*, 5–41.

Derycke-Khatir, C. (2005). Microrestes de vertébrés du paléozoïque supérieur de la Manche au Rhin. *Publication de la Société géologique de Nord, 33*, 1–261.

Di Clemente C. (1985), Biostratigraphie et Palynofaciès de la transgression du Famennien supérieur dans la région du Bocq. Unpublished master thesis, Université de Liège, 79 pp.

Dreesen, R., & Thorez, J. (1994). Parautochtonous – allochtonous carbonates and conodont mixing in the late Famennian (uppermost Devonian) Condroz Sandstones of Belgium. *Courier Forschungsinstitut Senckenberg, 168*, 159–182.

Dreesen, R., Dusar, M., & Groessens, E. (1976). Biostratigrahy of the Yves-Gomezée road section. *Service Géologique de Belgique, Professional Papers, 1976-6*, 1–20.

Dreesen, R., Sandberg, C. A., & Ziegler, W. (1986). Review of Late Devonian and Early Carboniferous conodont biostratigraphy and biofacies models as applied to the Ardenne shelf. *Annales de la Société Géologique de Belgique, 109*, 27–42.

Dreesen, R., Poty, E., Streel, M., & Thorez, J. (1993). *Late Famennian to Namurian in the eastern Ardenne, Belgium. IUGS, Subcommission on Carboniferous Stratigraphy Guidebook. Liège* (pp. 1–60).

Droser, M. L., Bottjer, D. J., Sheehan, P. M., & McGhee, G. R. (2000). Decoupling of taxonomic and ecologic severity of Phanerozoic marine mass extinctions. *Geology, 28*, 675–678.

Einsele, G. (1982). Limestone-marl cycles (periodites): diagnosis, significance, causes–a review. In G. Einsele & A. Seilacher (Eds.) *Cyclic and event stratification* (pp. 8–53). Berlin: Springer.

Ernst, A., & Herbig, H. G. (2010). Stenolaemate bryozoans from the Latest Devonian (uppermost Famennian) of western Germany. *Geologica Belgica, 13*, 173–182.

Ernst, A., Tolokonnikova, Z., Poty, E., & Mottequin, B. (2017). A bryozoan fauna from the Mississippian (Tournaisian and Viséan) of Belgium. *Geobios, 50*, 105–121.

Fairon-Demaret, M. (1986). Some uppermost Devonian megafloras: a stratigraphical review. *Annales de la Société Géologique de Belgique, 109*, 43–48.

Fairon-Demaret, M. (1996). *Dorinnotheca streelii* Fairon-Demaret, gen. et sp. nov., a new early seed plant from the upper Famennian of Belgium. *Review of Palaeobotany and Palynology, 93*, 217–233.

Feist, R., & Flajs, G. (1987). La limite Dévonien–Carbonifère dans la Montagne Noire (France). Biostratigraphie et environnement. *Comptes rendus de l'Académie des sciences. Série 2, Mécanique,* *Physique, Chimie, Sciences de l'Univers, Sciences de la Terre, 305*, 1537–1544.

Filipiak, P., & Racki, G. (2010). Proliferation of abnormal palynoflora during the end-Devonian biotic crisis. *Geological Quarterly, 54*, 1–14.

Flügel, E., & Flügel-Kahler, E. (1975). Stromatoporen aus dem Unteren Kohlenkalk (Tn1b, Strunium) von Aachen. *Neues Jahrbuch für Geologie und Paläontologie Abhandlungen, 149*, 1–38.

Flügel, E., & Kiessling, W. (2002). Patterns of Phanerozoic reef crises. In W. Kiessling, E. Flügel, & J. Golonka (Eds.) *Phanerozoic reef patterns*, *SEPM Special Publication 72*, 691–733.

Fourmarier, P. (1899). Découverte d'un Dipterus à Bilstain. *Annales de la Société Géologique de Belgique, 26*, 63.

Groessens, E. (2006). Dinantian. *Geologica Belgica, 9*, 157–162.

Hahn, G., & Hahn, R. (1988). The biostratigraphical distribution of Carboniferous limestone trilobites in Belgium and adjacent areas. *Bulletin de la Société belge de géologie, 97*, 77–93.

Hahn, G., Hahn, R., & Brauckmann, C. (1988). Die Trilobieten des belgischen Kohlenkalkes (Unter-Karbon). Part 10: Biostratigraphie. *Geologica et Palaeontologica, 22*, 55–72.

Halamski, A. T., & Baliński, A. (2009). Latest Famennian brachiopods from Kowala, Holy Cross Mountains, Poland. *Acta Palaeontologica Polonica, 54*, 289–306.

Hance, L., & Poty, E. (2006). Hastarian. *Geologica Belgica, 9*, 111–116.

Hance, L., Muchez, P., Coen, M., Fang, X. S., Groessens, E., Hou, H.-F., Poty, E., Steemans, P., Streel, M., Tan, Z., Tourneur, F., Van Steenwinkel, M., & Xu, S.-C. (1993). Biostratigraphy and sequence stratigraphy at the Devonian–Carboniferous transition in southern China (Hunan Province); comparison with southern Belgium. *Annales de la Société Géologique de Belgique, 116*, 359–378.

Hance, L., Dejonghe, L., Ghysel, P., Laloux, M., & Mansy, J.-L. (1999). Influence of heterogeneous lithostructural layering on orogenic deformation in the Variscan Front Zone (eastern Belgium). *Tectonophysics, 309*, 161–177.

Hance, L., Poty, E., & Devuyst, F.-X. (2001). Stratigraphie séquentielle du Dinantien type (Belgique) et corrélation avec le Nord de la France (Boulonnais, Avesnois). *Bulletin de la Société géologique de France, 172*, 411–426.

Hance, L., Poty, E., & Devuyst, F.-X. (2002). Sequence stratigraphy of the Belgian Lower Carboniferous – tentative correlation with the British Isles. In L. V. Hills, C. M. Henderson, & E. W. Bamber (Eds.) *Carboniferous and Permian of the world*, *Canadian Society of Petroleum Geologists Memoir 19*, 41–51.

Hance, L., Hou, H., & Vachard, D. (2011). *Upper Famennian to Viséan foraminifers and some carbonate microproblematica from South China - Hunan, Guangxi and Guizhou*. Beijing: Geological Publishing House 359 pp.

Hartenfels, S., & Becker, R. T. (2018). Age and correlation of the transgressive *Gonioclymenia* limestone (Famennian, Tafilalt, eastern Anti-Atlas, Morocco). *Geological Magazine, 155*, 586–629.

Hartkopf-Fröder, C. (2004). Palynostratigraphy of upper Famennian sediments from the Refrath 1 borehole (Bergish Gladbach-Paffrath Syncline; Ardennes-Rhenish Massif, Germany). *Courier Forschungsinstitut Senckenberg, 251*, 77–87.

Herbig, H.-G. (2016). Mississippian (Early Carboniferous) sequence stratigraphy of the Rhenish Kulm Basin, Germany. In J. Denayer & M. Aretz (Eds.) *Devonian and Carboniferous research: homage to Professor Edouard Poty*, *Geologica Belgica 19*, 81–110.

Herbig, H. G., & Mamet, B. (2006). A muddy to clear carbonate ramp, latest Devonian, Velbert Anticline (Rheinisches Schiefergebirge, Germany). *Geologica et Palaeontologica, 40*, 1–25.

Herbig, H.-G., & Weber, H. M. (1996). Facies and stromatoporoid biostromes in the Strunian (Latest Devonian) of the Aachen region, Germany. In J. Reitner, F. Neuweiler, & F. Gunkel (Eds.) *Global and regional controls on biogenic sedimentation. I: Reef evolution, research reports*, *Göttinger Arbeiten zur Geologie und Paläontologie 2*, 359–364.

Herbig, H.-G., Lobova, D., & Seekamp, V. (2013). Tales of a core: sea-level history, global crises and changing depositional architecture - the Famennian-Viséan of 'Velbert 4', westernmost Rhenish Massif, Germany. In J. Žák, G. Zulauf, & H. G. Röhling (Eds.) *Crustal evolution and geodynamic processes in Central Europe. Proceedings of the joint conference of the Czech and German geological societies held in Plzeň (Pilsen), September 16–18, 2013*, *Schriftenreihe der Deutschen Gesellschaft für Geowissenschaften 82*, 49.

Higgs, K., & Streel, M. (1984). Spore stratigraphy at the Devonian–Carboniferous boundary in the northern «Rheinisches Schiefergebirge», Germany. *Courier Forschungsinstitut Senckenberg, 67*, 157–179.

Higgs, K. T., Clayton, G., & Keegan, J. B. (1986). Stratigraphy and systematic palynology of the Tournaisian rocks of Ireland. *Special Paper of the Geological Survey of Ireland, 7*, 1–93.

Higgs, K. T., McPhilemy, B., Keegan, J. B., & Clayton, G. (1988). New data on palynological boundaries within the Irish Dinantian. *Review of Palaeobotany and Palynology, 56*, 61–68.

Higgs, K. T., Dreesen, R., Dusar, M., & Streel, M. (1992). Palynostratigraphy of the Tournaisian (Hastarian) rocks in the Namur Synclinorium, West Flanders, Belgium. *Review of Palaeobotany and Palynology, 72*, 149–158.

Janvier, P. (1996). *Early vertebrates. Oxford monographs on geology and geophysics, 33*. Oxford: Clarendon Press 393 p.

Kaiser, S. I. (2009). The Devonian/Carboniferous boundary stratotype section (La Serre, France) revisited. *Newsletters on Stratigraphy, 43*, 195–205.

Kaiser, S. I., & Corradini, C. (2011). The early siphonodellids (Conodonta, Late Devonian–Early Carboniferous): overview and taxonomic state. *Neues Jahrbuch für Geologie und Paläontologie-Abhandlungen, 261*, 19–35.

Kaiser, S. I., Becker, R. T., Spalletta, C., & Steuber, T. (2009). High-resolution conodont stratigraphy, biofacies, and extinctions around the Hangenberg Event in pelagic successions from Austria, Italy, and France. *Palaeontolographica Americana, 63*, 97–139.

Kaiser, S. I., Becker, R. T., Steuber, T., & Aboussalam, Z. S. (2011). Climate-controlled mass extinctions, facies, and sea-level changes around the Devonian–Carboniferous boundary in the eastern Anti-Atlas (SE Morocco). *Palaeogeography, Palaeoclimatology, Palaeoecology, 310*, 340–364.

Kaiser, S. I., Aretz, M., & Becker, R. T. (2016). The global Hangenberg Crisis (Devonian–Carboniferous transition): review of a first-order mass extinction. In R. T. Becker, P. Königshof, & C. E. Brett (Eds.) *Devonian climate, sea level and evolutionary events*, *Geological Society, London, Special Publications 423*, 387–437.

Kasig, W. (1980). Dinantian carbonates in the Aachen region, F.R.G. *Mededelingen Rijks Geologische Dienst, 32*, 44–52.

Korn, D., & Klug, C. (2002). Ammoneaea Devonicae. *Fossilium Catalogus Animalia, 138,* 375 p.

Krebs, W. (1979). Devonian basinal facies. In M. R. House, C. T. Scrutton, & M. G. Bassett (Eds.) *The Devonian system*, *Special Papers in Palaeontology 23*, 125–139.

Kulagina, E. I. (2013). Taxonomic diversity of foraminifers of the Devonian–Carboniferous boundary interval in the south Urals. *Bulletin of Geosciences, 88*, 265–282.

Kulagina, E. I., Gibshman, N. B., & Pazukhin, V. N. (2003). Foraminiferal zonal standard for Lower Carboniferous of Russia and its correlation with conodont zonation. *Rivista Italiana di Paleontologia e Stratigrafia, 109*, 173–185.

Kulagina, E. I., Vevel, Y. A., Stepanova, T. I., & Zaytseva, E. L. (2016). Foraminifers of the genus *Tournayellina* Lipina, 1955. *Paleontological Journal, 50*, 557–572.

Kulagina, E. I., Zaytseva, E. L., Vevel, Y. A., Stephanova, T. I., Gibshman, N. B., Nikolaeva, S. V., Kononova, L. I., & Plotitsyn, A. N. (in press). The foraminiferal zonal scale of the Devonian–Carboniferous boundary beds in Russia and Western Kazakhstan and its correlation with ammonoid and conodont scales. In M. Aretz & C. Corradini (Eds.) *Global review of the Devonian-Carboniferous boundary*, *Palaeobiodiversity and Palaeoenvironments* https://doi.org/10.1007/s12549-020-00439-y. [this issue]

Kumpan, T., Bábek, O., Kalvoda, J., Grygar, T. M., & Frýda, J. (2014). Sea-level and environmental changes around the Devonian–Carboniferous boundary in the Namur–Dinant Basin (S Belgium, NE France): a multi-proxy stratigraphic analysis of carbonate ramp archives and its use in regional and interregional correlations. *Sedimentary Geology, 311*, 43–59.

Kumpan, T., Kalvoda, J., Bábek, O., Holá, M., & Kanický, V. (2019). Tracing paleoredox conditions across the Devonian–Carboniferous boundary event: a case study from carbonate-dominated settings of Belgium, the Czech Republic, and northern France. *Sedimentary Geology, 380*, 143–157.

Lakin, J. A., Marshall, J. E. A., Troth, I., & Harding, I. C. (2016). Greenhouse to icehouse: a biostratigraphic review of latest Devonian–Mississippian glaciations and their global effects. In R. T. Becker, P. Königshof, & C. E. Brett (Eds.) *Devonian climate, sea level and evolutionary events*, *Geological Society, London, Special Publications 423*, 439–464.

Le Maître, D. (1933). Description des stromatoporoides de l'Assise d'Etrœungt. *Mémoires de la Société géologique de France, 20*, 6–31.

Legrand-Blain, M. (1991). Les Brachiopodes Productacés Spinocarinifera nigra (Gosselet, 1888) et formes voisines dans le Dévono-Dinantien du Nord de la France et de la Belgique, Annales de la Société géologique du Nord*, 2ème série*, *1*, 29–52.

Legrand-Blain, M. (1995). Relations entre les domaines d'Europe occidentale, d'Europe méridionale (Montagne Noire) et d'Afrique du Nord à la limite Dévonien–Carbonifère: les données des brachiopodes. *Bulletin de la Société belge de Géologie, 103*, 77–97.

Lelièvre, H., & Goujet, D. (1986). Biostratigraphic significance of some uppermost Devonian placoderms. *Annales de la Société Géologique de Belgique, 109*, 55–59.

Lentz M.-A. (1985). *Les couches de passage du Dévonien au Carbonifère dans le bassin franco-belge (révision micropaléontologique)*. Unpublished master thesis, Université Catholique Louvain, pp. 105.

Lethiers, F. (1974a). Ostracodes de la limite Dévonien–Carbonifère dans l'Avesnois. *Comptes rendus de l'Académie des Sciences, Paris, Série D, 278*, 1015–1017.

Lethiers, F. (1974b). Nouveaux ostracodes du passage Dévonien–Carbonifère de la région-type. *Comptes rendus de l'Académie des Sciences, Paris, Série D, 279*, 1613–1616.

Lethiers, F. (1975). Révision de l'espèce *Bairdia* (*Orthobairdia*?) *hypsela* Rome, 1971 (Ostracoda) du Strunien ardennais. *Annales de la Société géologique du Nord, 95*, 71–77.

Lipina, O. A. (1961). Relationship between foraminifers and facies in the Famennian and Tournaisian deposits of western Ural. *Voprosy Mikropaleontologii, 5*, 147–161. [in Russian]

Loboziak, S., Streel, M., Dusar, M., Boulvain, F., & De Geyter, G. (1994). Late Devonian-Early Carboniferous miospores from the Menen borehole, Namur Synclinorium, Belgium. *Review of Palaeobotany and Palynology, 80*, 55–63.

Lucas, S. G. (2018). The GSSP method of chronostratigraphy: a critical review. *Frontiers in Earth Science, 6*, 191–209.

Luppold, F.-W., Clausen, C.-D., Korn, D., & Stoppel, D. (1994). Devon/Karbon-Grenzprofile im Bereich von Remscheid-Altenaer Sattel, Warsteiner Sattel, Briloner Sattel und Attendorn-Elsper Doppelmulde (Rheinisches Schiefergebirge). *Geologie und Paläontologie in Westfalen, 29*, 7–69.

Maillieux, E., & Demanet, F. (1928). L'échelle stratigraphique des terrains primaires de la Belgique. *Bulletin de la Société belge de Géologie, 38*, 124–131.

Makhlina, M. K., Vdovenko, M. V., Alekseev, A. S., Byvsheva, T. V., Donakova, L. M., Zhulitova, V. E., Kononova, L. I., Umnova, N. I., & Shik, E. M. (1993). Lower Carboniferous of the Moscow sineclise and Voronezh anteclise. *Rossiyskaya Akademiya Nauk, Moskva* 224 p. (in Russian).

Mamet, B. (1986). Marine calcareous algae from the Devonian–Carboniferous transition beds. *Annales de la Société Géologique de Belgique, 109*, 61–64.

Mamet, B., Mortelmans, G., & Sartenaer, P. (1965). Réflexions à propos du Calcaire d'Etroeungt. *Bulletin de la Société belge de Géologie, 74*, 41–53.

Mansy, J.-L., Conil, R., Meilliez, F., Khatir, A., Delcambre, B., Groessens, E., Lys, M., Poty, E., Swennen, R., Trentesaux, A., & Weynant, M. (1988). Nouvelles données stratigraphiques et structurales sur le Dinantien dans l'Avesnois. *Annales de la Société géologique du Nord, 108*, 125–142.

Marynowski, L., Záton, M., Rakocinski, M., Filipiak, P., Kurkiewicz, S., & Pearce, T. J. (2012). Deciphering the upper Famennian Hangenberg Black Shale depositional environments based on multi-proxy record. *Palaeogeography, Palaeoclimatology, Palaeoecology, 346–347*, 66–86.

Matyja, H., Sobień, K., Marynowski, L., Stempień-Sałak, M. A. R., & Małkowski, K. (2015). The expression of the Hangenberg Event (latest Devonian) in a relatively shallow-marine succession (Pomeranian Basin, Poland): the results of a multi-proxy investigation. *Geological Magazine, 15*, 400–428.

Maziane, N. (1999). *Biostratigraphie et palynofacies du Famennien supérieur en Belgique et au sud de l'Irlande*. Unpublished PhD thesis, Université de Liège, pp. 165.

Maziane, N., & Vanguestaine, M. (1997). Acritarchs from the uppermost Famennian at Chanxhe and Tohogne (eastern Belgium). In O. Fatka & T. Servais (Eds.) *Acritarcha in Praha*, *Acta Universitatis Carolinae, Geologica 40*, 527–530.

Maziane, N., Higgs, K. T., & Streel, M. (1999). Revision of the late Famennian miospore zonation scheme in eastern Belgium. *Journal of Micropalaeontology, 18*, 17–25.

Maziane, N., Higgs, K. T., & Streel, M. (2002). Biometry and paleoenvironment of *Retispora lepidophyta* (Kedo) Playford 1976 and associated miospores in the latest Famennian nearshore marine facies, eastern Ardenne (Belgium). *Review of Palaeobotany and Palynology, 118*, 211–226.

Maziane-Serraj, N., Hartkopf-Fröder, C., Streel, M., & Thorez, J. (2007). Palynomorph distribution and bathymetry in the Chanxhe section (eastern Belgium), reference for the neritic Late to Latest Famennian transition (Late Devonian). *Geologica Belgica, 10*, 170–175.

McGhee, G. R., Sheehan, P. M., Bottjer, D. J., & Droser, M. L. (2004). Ecological ranking of Phanerozoic biodiversity crises: ecological and taxonomic severities are decoupled. *Palaeogeography Palaeoclimatology Palaeoecology, 211*, 289–297.

McGhee, G. R., Sheehan, P. M., Bottjer, D. J., & Droser, M. L. (2012). Ecological ranking of Phanerozoic biodiversity crises: the Serpukhovian (early Carboniferous) crisis had a greater ecological impact than the end-Ordovician. *Geology, 40*, 147–150.

McGhee, G. R., Clapham, M. E., Sheehan, P. M., Bottjer, D. J., & Droser, M. L. (2013). A new ecological-severity ranking of major Phanerozoic biodiversity crises. *Palaeogeography Palaeoclimatology Palaeoecology, 370,* 260–270.

Milhau, B., Mistiaen, B., Brice, D., Degardin, J.-M., Derycke, C., Hou, H., Rohart, J.-C., Vachard, D., & Wu, X. (1997). Comparative faunal content of Strunian (Devonian) between Etaoucun (Guilin, Guangwi, South China) and the stratotype area (Etrœungt, Avesnois, north of France). In Y.-G. Jin & D. Dineley (Eds.)

Palaeontology and historical geology. Proceedings of the 30th International Geological Congress 12, 79–94.

Mistiaen, B. (1997). Découverte du genre *Amphipora* Schülz, 1883, dans le Famennien terminal 'Strunien', de la carrière du Parcq, à Etrœungt, stratotype du Calcaire d'Etrœungt et ailleurs en Avesnois (Nord de la France). *Compte Rendu de l'Académie des Sciences, Paris, 324*, 665–662.

Mistiaen, B., & Weyer, D. (1999). Late Devonian stromatoporoid from the Sudetes Mountains (Poland), and endemicity of the upper Famennian to uppermost Famennian (= "Strunian") stromatoporoid fauna in Western Europe. *Senckenbergiana lethaea, 79*, 51–61.

Mistiaen, B., Milhau, B., Dégardin, J.-M., Derycke, C., Hou, H., Rohart, J.-C., Vachard, D., & Wu, X. (1998). Famennien terminal (Strunien) d'Etrœungt (Avesnois, Nord de la France) et d'Etaoucun (Guanxi, Chine du Sud). Incidences paléogéographiques des données relatives aux stromatopores et ostracodes. *Annales de la Société géologique du Nord, 6*, 97–104.

Mistiaen, B., Brice, D., Devleeschouwer, X., Hubert, B. L., Khatir, A., Mottequin, B., & Poty, E. (2013). Le 'Calcaire d'Etrœungt' dans les coupes historiques d'Etrœungt et d'Avesnelles (Avesnois, Nord, France). *Annales de la Société géologique du Nord, 2*, 43–51.

Mottequin, B. (2019). An annotated catalogue of types of Silurian–Devonian brachiopod species from southern Belgium and northern France in the Royal Belgian Institute of Natural Sciences (1870–1945), with notes on those curated in other Belgian and foreign institutions. *Geologica Belgica, 22*, 47–89.

Mottequin, B., & Brice, D. (2016). Upper and uppermost Famennian (Devonian) brachiopods from North-Western France (Avesnois) and southern Belgium. In J. Denayer & M. Aretz (Eds.) *Devonian and Carboniferous research: homage to Professor Edouard Poty*, *Geologica Belgica 19*, 121–134.

Mottequin, B., & Brice, D. (2019). Reappraisal of some Upper Devonian (Famennian) spiriferide brachiopods from the Band-e Bayan Domain (Afghanistan). *Geobios, 52*, 47–65.

Mottequin, B., & Poty, E. (2014). The uppermost Famennian Hangenberg Event in the Namur–Dinant Basin (South Belgium). *Berichte des Institutes für Erdwissenschaften, Karl-Franzens-Universität Graz, 19*, 36–37.

Mottequin, B., & Poty, E. (2016). Kellwasser horizons, sea-level changes and brachiopod–coral crises during the late Frasnian in the Namur–Dinant Basin (southern Belgium): a synopsis. In R. T. Becker, P. Königshof, & C. E. Brett (Eds.) *Devonian climate, sea level and evolutionary events*, *Geological Society, London, Special Publications 423*, 235–250.

Mottequin, B., & Simon, E. (2017). New insights on Tournaisian–Visean (Carboniferous, Mississippian) athyridide, orthotetide, rhynchonellide, and strophomenide brachiopods from southern Belgium. *Palaeontologia Electronica, 20.2*(28A), 1–45.

Mottequin, B., Brice, D., & Legrand-Blain, M. (2014). Biostratigraphic significance of brachiopods near the Devonian–Carboniferous boundary. *Geological Magazine, 151*, 216–228.

Mottequin, B., Poty, E., & Prestianni, C. (2015). Catalogue of the types and illustrated specimens recovered from the 'black marble' of Denée, a marine conservation-Lagerstätte from the Mississippian of southern Belgium. *Geologica Belgica, 18*, 1–14.

Mottequin, B., Bartzsch, K., Simon, E., & Weyer, D. (2019). Brachiopod faunas from the basinal facies of southeastern Thuringia (Germany) before and after the Hangenberg Crisis (Devonian–Carboniferous boundary). *Palaeontologia Electronica, 22.1*(16A), 1–54.

Muchez, P. (1996). Sequence stratigraphy at the Devonian–Carboniferous transition in southern China. *Mémoires de l'Institut Géologique de l'Université de Louvain, 36*, 193–202.

Neves, R., Gueinn, K. J., Clayton, G., Ioannides, N., & Neville, R. S. (1972). *A scheme of miospore zones for the British Dinantian. Compte Rendu du 7ème Congrès International de Stratigraphie et de Géologie du Carbonifère, Krefeld, 1979*, *1*, 347–353.

Owens, B., & Streel, M. (1967). *Hymenozonotriletes lepidophytus* Kedo, its distribution and significance in relation to the Devonian–Carboniferous boundary. *Review of Palaeobotany and Palynology, 1*, 141–150.

Paeckelmann, W. (1931). Die Fauna des deutschen Unterkarbons, II: Die Brachiopoden des deutschen Unterkarbons. Part 2. Die Productinae und *Productus*-ahnlichen Chonetinae. *Abhandlungen der Preussischen Geologischen Landesanstalt, Neue Folge, 136*, 1–440.

Paeckelmann, W., & Schindewolf, O. H. (1937). Die Devon–Karbon-Grenze. In W. J. Jongmans (Ed.) *Deuxième Congrès pour l'avancement des études de stratigraphie carbonifère, Heerlen, Septembre 1935*, *2*, 703–714.

Paproth, E., & Streel, M. (1971). Corrélations biostratigraphiques près de la limite Dévonien/Carbonifère entre les faciès littoraux ardennais et les faciès bathyaux rhénans. In M. Streel & R. Wagner (Eds.) *Compte-rendus de la 8e réunion de la Commission internationale de Microflore du Paléozoïque et de l'Assemblée générale de l'IUGS, Liège, 1970. Subcommission on Carboniferous Stratigraphy*, *Les Congrès et Colloques de l'Université de Liège 55*, 365–398.

Paproth, E., & Streel, M. (1984). Precision and practicability: on the definition of the Devonian–Carboniferous boundary. *Courier Forschungsinstitut Senckenberg, 67*, 255–258.

Paproth, E., Streel, M., & Ziegler, W. (1979). Present data on the Devonian–Carboniferous boundary in Western Europe. In *Compte Rendu du 8ème Congrès international de Stratigraphie et de Géologie du Carbonifère, Moscou, 1975*, *3*, 6–9).

Paproth, E., Dreesen, R., & Thorez, J. (1986). Famennian paleogeography and event stratigraphy of Northwestern Europe. *Annales de la Société Géologique de Belgique, 109*, 175–186.

Paproth, E., Feist, R., & Flajs, G. (1991). Decision on the Devonian–Carboniferous boundary stratotype. *Episodes, 14*, 331–336.

Paschall, O., Carmichael, S. K., Königshof, P., Waters, J. A., Ta, P. H., Komatsu, T., & Dombrowsk, A. (2019). The Devonian–Carboniferous boundary in Vietnam: sustained ocean anoxia with a volcanic trigger for the Hangenberg Crisis? *Global and Planetary Change, 175*, 64–81.

Paul, H. (1937). Die Transgression der Viséstufe am Nordrande des Rheinischen Schiefergebirges. *Abhandlungen der Preussischen Geologischen Landesanstalt, Neue Folge, 179*, 5–117.

Paul, H. (1939). Die Etrœungt-Schichten des Bergischen Landes. *Jahrbuch der Preussischen Geologischen Landesanstalt, 59*, 647–726.

Piecha, M. (2004). Late Famennian conodonts from the Refrath 1 borehole (Bergish Gladbach-Paffrath Syncline; Ardennes-Rhenish Massif, Germany). *Courier Forschungsinstitut Senckenberg, 251*, 253–265.

Poty, E. (1986). Late Devonian to early Tournaisian rugose corals. *Annales de la Société Géologique de Belgique, 109*, 65–74.

Poty, E. (1997). Devonian and Carboniferous tectonics in the eastern and southeastern parts of the Brabant Massif (Belgium). In T. Camelbeeck, M. Sintubin, & S. Vandycke (Eds.) *Belgian Symposium on structural Geology and Tectonics, Leuven 1997*, *Aardkundige Mededelingen 8*, 143–144.

Poty, E. (1999). Famennian and Tournaisian recoveries of shallow water Rugosa following late Frasnian and late Strunian major crises, southern Belgium and surrounding areas, Hunan (South China) and the Omolon region (NE Siberia). *Palaeogeography, Palaeoclimatology, Palaeoecology, 154*, 11–26.

Poty, E. (2007). Latest Famennian (Strunian) stromatoporoid biostromes. In J. J. Alvaro, E. Vennin, A. Munnecke, F. Boulvain, D. Vachard, & M. Aretz (Eds.) *Catalogue of facies from palaeozoic reefs and bioaccumulations*, *Museum national d'Histoire naturelle, Paris, Mémoires 195*, 221–223.

Poty, E. (2010). Morphological limits to diversification of the rugose and tabulate corals. *Palaeoworld, 19*, 389–400.

Poty, E. (2016). The Dinantian (Mississippian) succession of southern Belgium and surrounding areas: stratigraphy improvement and inferred climate reconstruction. In J. Denayer & M. Aretz (Eds.) *Devonian and Carboniferous research: homage to Professor Edouard Poty*, *Geologica Belgica 19*, 177–200.

Poty, E., & Delculée, S. (2011). Interaction between eustacy and bloc-faulting in the Carboniferous of the Visé-Maastricht area (Belgium, The Netherlands). *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 162*, 117–126.

Poty, E., Berkowski, B., Chevalier, E., & Hance, L. (2003). Biostratigraphic and sequence stratigraphic correlations between the Dinantian deposits of Belgium and southern Poland (Krakow area). In T. E. Wang (Ed.) *Proceedings of the XVth International Congress on Carboniferous and Permian Stratigraphy, Utrecht, the Netherlands 10*, 97–107.

Poty, E., Devuyst, F.-X., & Hance, L. (2006). Upper Devonian and Mississippian foraminiferal and rugose coral zonations of Belgium and northern France: a tool for Eurasian correlations. *Geological Magazine, 143*, 829–857.

Poty, E., Denayer, J., & Aretz, M. (2011). Field trip 3: uppermost Devonian and Lower Carboniferous of Southern Belgium. In M. Aretz & E. Poty (Eds.) *11th international symposium on Fossil Cnidaria and Porifera, Liège, 2011, field guides*, *Kölner Forum für Geologie und Paläontologie 20*, 99–150.

Poty, E., Mottequin, B., & Denayer, J. (2013). An attempt of time calibration of the lower Tournaisian (Hastarian substage) based on orbitally forced sequences. *Document de l'Institut Scientifique, Rabat, 26*, 105–107.

Poty, E., Aretz, M., & Hance, L. (2014). Belgian substages as a basis for an international chronostratigraphic division of the Tournaisian and Viséan. *Geological Magazine, 151*, 229–243.

Prestianni, C., & Gerrienne, P. (2015). *Thorezia vezerensis* gen. et sp. nov., a new seed plant with multiovulate cupules from the Late Devonian of Belgium. *Historical Biology, 27*, 316–324.

Prestianni, C., Rustán, J. J., Balseiro, D., Vaccari, E., Sterren, A. F., Steemans, P., Rubinstein, C., & Astini, R. A. (2015). Early seed plants from Western Gondwana: paleobiogeographical and ecological implications based on Tournaisian (Lower Carboniferous) records from Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology, 417*, 210–219.

Prestianni, C., Sautois, M., & Denayer, J. (2016). Disrupted continental environments around the Devonian–Carboniferous boundary: introduction of the *tener* event. In J. Denayer & M. Aretz (Eds.) *Devonian and Carboniferous research: homage to Professor Edouard Poty*, *Geologica Belgica 19*, 135–145.

Reitlinger, E. A. (1961). Some questions of the systematics of the *Quasiendothyra*. *Voprosy mikropaleontologii, 5*, 31–68 (in Russian).

Richter, R., & Richter, E. (1933). Die letzten Phacopidae. *Bulletin du Musée royal d'Histoire naturelle de Belgique, 9*, 1–19.

Rome, R., & Goreux, J. (1964). *Cryptophyllus* (ostracodes) du Strunien de la Belgique. *Mémoires de l'Institut géologique de l'Université de Louvain, 21*, 184–203.

Sandberg, C. A., & Dreesen, R. (1984). Late Devonian icriodontid biofacies models and alternate shallow-water conodont zonation. *Geological Society of America Special Paper, 196*, 143–178.

Sandberg, C. A., Morrow, J. R., & Ziegler, W. (2002). Late Devonian sea-level changes, catastrophic events, and mass extinctions. In C. Koeberl & K. G. MacLeod (Eds.) *Catastrophic events and mass extinctions: impacts and beyond*, *Special Papers of the Geological Society of America 356*, 473–488.

Sartenaer, P., & Plodowski, G. (1975). Importance stratigraphique et répartition géographique du genre rhynchonellide *Araratella* n. gen. du Famennien supérieur. *Bulletin de l'Institut royal des Sciences naturelles de Belgique, Sciences de la Terre, 51*, 1–34.

Signor, P. W., & Lipps, J. H. (1982). Sampling bias, gradual extinction patterns, and catastrophes in the fossil record. In L. T. Silver & P. H. Schultz (Eds.) *Geological implications of impacts of large asteroids and comets on the Earth*, *Geological Society of America Special Paper 190*, 291–296.

Simakov, K. V. (1990). Major evolutionary events among spiriferids at the Devonian–Carboniferous boundary. In E. G. Kauffman & O. H. Walliser (Eds.) *Extinction events in earth history*, *Lecture Notes in Earth Sciences 30*, 189–198.

Simms, M. J., & Ruffle, A. H. (1989). Synchronicity of climatic change and extinctions in the Late Triassic. *Geology, 17*, 265–268.

Simms, M. J., & Ruffle, A. H. (1990). Climate and biologic change in the Late Triassic. *Journal of the Geological Society of London, 147*, 321–327.

Simms, M. J., Ruffle, A. H., & Johnson, A. L. A. (1995). Biotic and climatic changes in the Carnian (Triassic) of Europe and adjacent areas. In N. C. Fraser & H. D. Sues (Eds.) *In the shadow of the dinosaurs: Early Mesozoic tetrapods* (pp. 352–365). Cambridge University Press.

Smeesters, A., Muchez, P., & Hance, L. (2000). Sequence stratigraphical study of the Tournaisian strata in Belgium and southern China. *Geologica Belgica, 3*, 285–307.

Soreghan, G. S., Soreghan, M. J., & Heavens, N. G. (2019). Explosive volcanism as a key driver of the late Paleozoic ice age. *Geology, 47*, 600–604.

Spalletta, C., Perri, M. C., Over, D. J., & Corradini, C. (2017). Famennian (Upper Devonian) conodont zonation: revised global standard. *Bulletin of Geosciences, 92*, 31–57.

Spalletta, C., Corradini, C., Feist, R., Korn, D., Kumpan, T., Perri, M. C., Pondrelli, M., & Venturrini, C. (in press). The Devonian–Carboniferous boundary in the Carnic Alps (Austria and Italy). In M. Aretz & C. Corradini (Eds.) *Global review of the Devonian-Carboniferous boundary*, *Palaeobiodiversity and Palaeoenvironments*. https://doi.org/10.1007/s12549-019-00413-3. [this issue]

Stearn, C. W., Halim-Dihardja, M. K., & Nishida, D. K. (1987). An oil-producing stromatoporoid patch reef in the Famennian (Devonian) Wabamun Formation, Normandville Field, Alberta. *Palaios, 2*, 560–570.

Steenwinkel, M. van (1980). Sedimentation and conodont stratigraphy of the Hastière Limestone, lowermost Dinantian, Anseremme, Belgium. *Mededelingen Rijks Geologische Dienst, 32*, 30–33.

Steenwinkel, M. van (1984). The Devonian–Carboniferous boundary in the vicinity of Dinant, Belgium. *Courier Forschungsinstitut Senckenberg, 67*, 57–69.

Steenwinkel, M. van (1988). *The sedimentary history of the Dinant platform during the Devonian-Carboniferous transition*. Unpublished PhD Thesis, Katholieke Universiteit Leuven, Belgium, 177 p.

Steenwinkel, M. van (1990). Sequence stratigraphy from 'spot' outcrops – example from a carbonate-dominated setting: Devonian–Carboniferous transition, Dinant synclinorium (Belgium). *Sedimentary Geology, 69*, 259–280.

Steenwinkel, M. van (1993). The Devonian–Carboniferous boundary in southern Belgium: biostratigraphic identification criteria of sequence boundaries. In H. W. Posamentier, C. P. Summerhayes, B. U. Haq, & G. P. Allen (Eds.) *Sequence stratigraphy and facies associations*, *IAS Special Publication 18*, 237–246.

Stockmans, F. (1948). Végétaux du Dévonien Supérieur de la Belgique. *Mémoires du Musée royal d'Histoire Naturelle de Belgique, 110*, 1–85.

Strasser, A. (2015). Hiatuses and condensation: an estimation of time lost on a shallow carbonate platform. *The Depositional Record, 1*, 91–117.

Streel, M. (1966). Critères palynologiques pour une stratigraphie détaillée du Tn1a dans les bassins Ardenno-Rhénans. *Annales de la Société Géologique de Belgique, 89*, 65–96.

Streel, M. (1969). *Corrélations palynologiques entre les sédiments de transition Dévonien-Dinantien dans les bassins Ardenno-Rhénans, Compte Rendu Sixième Congrès International de Stratigraphie et de Géologie du Carbonifère, 11–16 September 1967, Sheffield*, *1*, 3–18.

Streel, M. (1977). Corrélations palynologiques dans le Tournaisien du Synclinorium de Namur. *Bulletin de la Société Belge de Géologie, 82*, 397–415.

Streel, M. (1996). Miospore ranges near the D/C boundary and extinction events. *IUGS Subcommision of Devonian Stratigraphy Newsletter, 12*, 62–64.

Streel, M. (1999). Quantitative palynology of Famennian events in the Ardenne-Rhine regions. *Abhandlungen der geologischen Bundesanstalt, 54*, 201–212.

Streel, M. (2000). The uppermost Famennian around the World (definition, biostratigraphical and sedimentological context). *Subcommission on Devonian Stratigraphy Newsletter, 18,* 55–61.

Streel, M. (2005). Subdivision of the Famennian stage into four substages and correlation with the neritic and continental miospore zonation. *IUGS Subcommission of Devonian Stratigraphy Newsletter, 21*, 53–57.

Streel, M. (2015). Palynomorphs (miospores, acritarchs, prasinophytes) before and during the Hangenberg Crisis. In B. Mottequin, J. Denayer, P. Königshof, C. Prestianni, & S. Olive (Eds.) *IGCP596-SDS symposium, climate change and biodiversity patterns in the Mid-Palaeozoic, Brussels, September 2015, Abstracts*, *STRATA 16*, 140–143.

Streel, M., & Hartkopf-Fröder, C. (2005). Late Famennian correlation by miospores between the Refrath 1 borehole (Bergisch Gladbach-Paffrath Syncline, Germany) and the reference section of Chanxhe (Dinant Syncline, Belgium). *Carnets de Géologie / Notebooks on Geology, 2005*(02), 57–60.

Streel, M., & Marshall, J. E. A. (2006). Devonian–Carboniferous boundary global correlation and their paleogeograhic implications for the assembly of Pangea. In T. E. Wang (Ed.) *Proceedings of the XVth International Congress on Carboniferous and Permian Stratigraphy, Utrecht, the Netherlands 10*, 481–496.

Streel, M., Higgs, K., Loboziak, S., Riegel, W., & Steemans, P. (1987). Spore stratigraphy and correlation with faunas and floras in the type marine Devonian of the Ardenne-Rhenish regions. *Review of Palaeobotany and Palynology, 50*, 211–229.

Streel, M., Brice, D., Degardin, J.-M., Derycke, C., Dreesen, R., Groessens, E., Hance, L., Legrand-Blain, M., Lethiers, F., Loboziak, S., Maziane, N., Milhau, B., Mistiaen, B., Poty, E., Rohart, J.-C., Sartenaer, P., Thorez, J., Vachard, D., & Blieck, A. (1998). Proposal for a Strunian substage and a subdivision of the Famennian stage into four substages. *IUGS Subcommission of Devonian Stratigraphy Newsletter, 15*, 47–52.

Streel, M., Belka, Z., Dreesen, R., Durkina, A. V., Groos-Uffenorde, H., Hance, L., Hartkopf-Fröder, C., Haydukiewicz, J., Korn, D., Perri, M. C., Piecha, M., & Spalletta, C. (2004). *Relation of the neritic microfaunas and continental microfloras with the conodont and other pelagic faunas within the latest part of the Famennian, with a few, new additional data and a synthetic correlation chart. SDS Business Meeting Florence, August 23, 2004, abstracts* (pp. 17–18).

Streel, M., Brice, D., & Mistiaen, B. (2006). Strunian. *Geologica Belgica, 9*, 105–109.

Struve, W. (1976). *Phacops* (*Omegops*) n. sg. (Trilobita; Ober-Devon). *Senckenbergiana lethaea, 56*, 429–451.

Sun, Y.-L., & Baliński, A. (2011). Silicified Mississippian brachiopods from Muhua, southern China: rhynchonellides, athyridides, spiriferides, spiriferinides, and terebratulides. *Acta Palaeontologica Polonica, 56*, 793–842.

Thorez, J., & Dreesen, R. (1986). A model of a regressive depositional system around the Old Red Continent as exemplified by a field trip in the upper Famennian 'Psammites du Condroz' in Belgium. *Annales de la Société Géologique de Belgique, 109*, 285–323.

Thorez, J., Dreesen, R., & Streel, M. (2006). Famennian. *Geologica Belgica, 9*, 27–45.

Tolokonnikova, Z., Ernst, A., Poty, E., & Mottequin, B. (2015). Middle and uppermost Famennian (Upper Devonian) bryozoans from southern Belgium. *Bulletin of Geosciences, 90*, 33–49.

Tourneur, F., Conil, R., & Poty, E. (1989). Données préliminaires sur les tabulés et les chaetetidés du Dinantien de la Belgique. *Bulletin de la Société belge de Géologie, 98*, 401–442.

Trapp, E., Kaufmann, B., Mezger, K., Korn, D., & Weyer, D. (2004). Numerical calibration of the Devonian–Carboniferous boundary: Two new U-Pb isotope dilution–thermal ionization mass spectrometry single-zircon ages from Hasselbachtal (Sauerland, Germany). *Geology, 32*, 857–860.

Veen, P. M. van (1981). Aspects of Late Devonian and Early Carboniferous palynology of southern Ireland. V. The change in composition of palynological assemblages at the Devonian-Carboniferous boundary. *Review of Palaeobotany and Palynology, 34*, 67–94.

Vanguestaine, M. (1978). Late Devonian and Carboniferous acritarch stratigraphy and paleogeography. *Annales de la Société Géologique de Belgique, 109*, 93–102.

Vevel, Y. A. A. (2009). Nakhodka foraminifer *Tournayellina beata pseudobeata* Reitlinger et Kulagina v nizhnem karbone Pechorskoy gryady. *Neftegazovaya geologiya, Teoriya i praktika, 4*, 2–15 (in Russian).

Walliser, O. H. (1984). Pleading for a natural D/C boundary. *Courier Forschungsinstitut Senckenberg, 67*, 241–246.

Walliser, O. H. (1996). Global events in the Devonian and Carboniferous. In O. H. Walliser (Ed.) *Global events and event stratigraphy in the Phanerozoic* (pp. 225–250). Berlin: Springer.

Weber, H. M. (1999). *Die karbonatischen Flachwasserschelfe im europäischen Oberfamennium (Strunium) Fazies, Mikrobiota und Stromatoporen-Faunen*. Unpublilshed PhD thesis, Universität zu Köln, 192 p.

Weber, H. M. (2000). Neufund von *Omegops cornelius* Richter & Richter, 1933 (Arthropoda, Trilobita) aus dem hichsten Oberdevon ('Strunium') von Kornelimünster bei Aachen, Deutschland. *Senckenbergiana lethaea, 79*, 541–546.

Weber, H. M., & Mistiaen, B. (2001). First evidence of labechiids (Stromatoporoidea) in the Strunian (uppermost Devonian) of Western Europe. In 15th annual Senckenberg conference, joint meeting IGCP 421/SDS, Frankfurt am Main, 2001. *Senckenbergische Naturforschende Gesellschaft, 102*, 48–50.

Webster, G. D., & Groessens, E. (1991). Conodont subdivision of the Lower Carboniferous. *Courier Forschungsinstitut Senckenberg, 130*, 31–40.

Weyer, D. (2000). Korallen im Unterkarbon Deutschlands. *Abhandlungen und Berichte für Naturkunde, 23*, 57–91.

Wicander, E. R. (1975). Fluctuations in a Late Devonian Early Mississippian phytoplankton flora of Ohio, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology, 17*, 89–108.

Wicander, R., Clayton, G., Marshall, J. E. A., Troth, I., & Racey, A. (2011). Was the latest Devonian glaciation a multiple event? New palynological evidence from Bolivia. *Palaeogeography, Palaeoclimatology, Palaeoecology, 305*, 75–83.

Wilson, M., & Lyashkevich, Z. M. (1996). Magmatism and the geodynamics or rifting of the Pripyat-Dnieper-Donets rift, East European Platform. *Tectonophysics, 268*, 65–81.

Ziegler, W., & Sandberg, C. A. (1984). *Palmatolepis*-based revision of upper part of standard Late Devonian conodont zonation. *Geological Society of America Special Paper, 196*, 179–194.

Ziegler, W., & Sandberg, C. A. (1990). The Late Devonian standard conodont zonation. *Courier Forschungsinstitut Senckenberg, 121*, 2–115.