The Devonian-Carboniferous transition at Borkewehr near Wocklum (northern Rhenish Massif, Germany) – a potential GSSP section

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Abstract
The Borkewehr section near Balve at the southeastern end of the Remscheid-Altena Anticline is currently the best and most complete Devonian/Carboniferous Boundary (DCB) succession of the Rhenish Massif, Germany. Based on a multidisciplinary approach, focusing on refined conodont and ammonoid biostratigraphy, microfacies analyses, sequence stratigraphy, carbon isotopes (Corg and Ccarb), trace element geochemistry, including REE data, and cyclostratigraphy, the section is proposed as a candidate for the new basal Carboniferous GSSP. The succession represents a pelagic “seamount” setting. It spans the upper Famennian to lower Viséan, with a condensed development of most Rhenish lithostratigraphic units and sedimentary sequences. It is the type-section of the oxic and strongly cyclic, fossiliferous Wocklum Limestone and of important uppermost Famennian and basal Carboniferous index species. The First Appearance Datum (FAD) of Protognathodus kockeli s.str., in a phylogenetic succession from the ancestral Pr. semikockeli n. sp., is proposed as future GSSP level. This FAD is sandwiched between many other marker levels for global correlation. Below are, from base to top, the transgressive base of the at least partly anoxic Hangenberg Black Shale (base Lower Hangenberg Crisis Interval), the Hangenberg Regression (onset of siltstones of the basal Middle Crisis Interval), the level of maximum regression, indicated by maximum Zr/Al values, and the initial transgression of the basal Upper Crisis Interval, marked by the re-onset of carbonate deposition. Above follow the locally cryptogenic FAD of Siphonodella (Eosiphonodella) sulcata s.l. at the base of the post-Crisis Interval (Hangenberg Limestone), associated with a conodont biofacies shift, the FAD of Si. (Eo.) bransoni, and, much higher, the sharp...
Lower Alum Shale Event at the base of the classical middle Touraisian. The significance of the section is greatly enlarged by its precise correlation with numerous other Rhenish DCB sections that provide important additional data on faunas, geochemistry, geochronological ages, and magnetic susceptibility. The new Borkewehr data suggest changes of weathering intensity, based on Rb/K and K/Al trends, and Milankovitch cyclicity associated with the climate changes of the Hangenberg Crisis. The local conodont extinction rate at the top of the Wocklum Limestone lies at 57% while there are no survivors in ammonoids, trilobites, or deep-water corals. Positive carbon isotopic shifts of carbonate in the Upper Crisis Interval and of Corg in the Middle Crisis Interval are decoupled, which suggests complex underlying processes that are not yet understood.

Keywords Devonian/Carboniferous Boundary · Hangenberg Crisis · Conodonts · Stratigraphy · Geochemistry · Rhenish Massif

Introduction

The Devonian/Carboniferous Boundary (DCB) was the first chronostratigraphic level to be designated at the Second Heerlen Congress in 1935 (Paeckelmann and Schindewolf 1937), using the entry of the index goniatite *Gattendorfia subinvoluta* in the Oberrödinghausen Railway Cut (Hönne Valley, Rhenish Massif, GPS 51°23′45.5″N, 007°50′23.8″E, ca. 7 km northwest of the Borkewehr section, Fig. 1). Subsequent studies (e.g. Alberti et al. 1974) proved that the selected stratotype section contains a hiatus at the boundary level, corresponding to the interval of the main Stockum Limestone. This resulted in more than 15 years of intensive search for a new DCB definition and stratotype. Finally, the entry of the conodont *Siphonodella (Eosiphonodella) sulcata*, in a supposed phylogenetic lineage from *Si. (Eo.) praesulcata*, was chosen as the...
Carboniferous index fossil and, following the proposal of Feist and Flajs (1988), the new GSSP was placed at the base of Bed 89 in an oolithic succession at La Serre Trench E', Montagne Noire, southern France (Paproth et al. 1991). This decision was controversially discussed and especially criticised by Ji et al. (1989) as well as by Ziegler and Sandberg (1996). Based on different views regarding their taxonomic position, intermediates within the supposed phylogenetic lineage from ancestral Si. (Eo.) praesulcata to Si. (Eo.) sulcata had been recorded from below the GSSP level (Feist and Flajs 1988). In the course of geochemical studies, and using the same morphological species definition as Feist and Flajs (1988), Kaiser (2005, 2009) discovered that the index conodont occurs at La Serre Trench E’ as early as in Bed 84b in the section log in Feist et al. (2020 online). This is well below the GSSP at the base of Bed 89, in the basalmost part of the upper calcoolitic unit and just above a facies break (compare Feist et al. 2000, 2020 online; Kaiser et al. 2007; Spalletta et al. 2011; Aretz et al. 2016). This confirmed the most important point of criticism by Ziegler and Sandberg (1996), who mentioned that “… the whole sequence containing the supposed Si. praesulcata-Si. sulcata lineage is an artifact created by reworked sediments derived from different source areas …”. Since there are no other criteria to correlate the GSSP level with precision, another revision became necessary (e.g. Kaiser and Becker 2007; Kaiser and Corradini 2008; Aretz and Corradini 2021). For this, an International Devonian/Carboniferous Task group was founded in 2008 by Philip H. Heckel (then chairman of SCCS = Subcommission on Carboniferous Stratigraphy) and R. Thomas Becker (then chairmen of SDS = Subcommission on Devonian Stratigraphy; compare Heckel 2008). Markus Aretz (chairman) and Carlo Corradini (vice-chairman) were appointed as the task group leaders at the International Commission of Stratigraphy workshop in 2010 that was held in Prague (Richards and Task group 2010).

In the meantime and the following years, progress was made by the task group and accompanying scientists. Results and new ideas were presented and discussed at several symposia, congresses, and workshops (e.g. 2nd International Conodont Symposium, ICOS 2009, Calgary; 3rd International Palaeontological Congress, IPC3, London 2010; International Field Symposium “The Devonian and Lower Carboniferous of northern Gondwana”, Erfoud 2013; IGCP 596 – SDS Symposium, Brussels 2015). New papers/documents critically scrutinized and forwarded taxonomic problems within the supposed phylogenetic lineage of Si. (Eo.) praesulcata - Si. (Eo.) sulcata and within the genus Protognathodus (e.g. Traegerleh 2010; Corradini et al. 2011, 2013, 2016 online, 2017; Kaiser and Corradini 2011; Evans et al. 2013; Hartenfels and Becker 2018, 2019; Kaiser et al. 2019a online, b; Becker et al. 2021). During a workshop in Montpellier (2016), the task group agreed to test a proposal combining several criteria for a DCB re-definition (for advantages and disadvantages of these criteria compare Becker et al. 2016a): (1) main extinction level and base of the Hangenberg Black Shale Event, (2) “top of the major regression (top of the Hangenberg Sandstone)”, end of the mass extinction, and base of the Pr. kockeli Zone, as well as (3) base of the Si. (Eo.) sulcata/Pr. kuehni Zone and lowland plant extinction. Therefore, the search for suitable successions has become crucial. A final vote by the working group on the suitability of the Montpellier criteria in the frame of the XIX ICCP 2019 (= International Congress on the Carboniferous and Permian, Cologne, compare Aretz and Corradini 2019a), did not lead to a decision. However, a majority of more than 60 % voted for the criterion “top of the major regression (top of the Hangenberg Sandstone), end of the mass extinction, and base of the Pr. kockeli Zone” and, therefore, for a new DCB definition and GSSP level, which will be situated below the current First Appearance Datum (FAD) of Si. (Eo.) sulcata sensu Flajs and Feist (1988; = Si. (Eo.) sulcata s.l. sensu Becker et al. 2021). A precise understanding of sea level changes and of the early post-extinction radiation of Protognathodus and other faunal groups will be crucial. The advantage of this new timeline will be its position near the current GSSP level, which will maintain stratigraphic stability (Aretz and Corradini 2019b, 2021).

A new terminology and subdivision of an extended Hangenberg Crisis Interval was introduced by Kaiser et al. (2015) and Becker et al. (2016a, 2021). It uses lithostratigraphic units of the northern Rhenish Massif as reference levels and includes from the base to the top the following steps (see Becker et al. 2021, fig. 1, compare Aretz and Corradini 2021, fig. 2):

**Crisis Prelude:** initial regressive interval (top Wocklum Limestone, locally with the Drewer Sandstone)

**Lower Crisis Interval:** hypoxic to anoxic, transgressive, and climatic warming interval, with the main pelagic extinction event at the base (Hangenberg Black Shale = HBS)

**Middle Crisis Interval:** glacially induced regressive interval; subdivided locally by a sequence boundary into two units (Hangenberg Shale and Hangenberg Sandstone = HS and HSS)

**Upper Crisis Interval:** initial post-glacial transgressive interval; subdivided by conodont biostratigraphy into three units (Stockum Limestone: basal part = top part of B. costatus-Pr. kockeli Interregnum; lower part = Pr. kockeli Zone; upper part = Si. (Eo.) sulcata s.l./Pr. kuehni Zone); in some sections partly represented by black shales/marls (Stockum Level Black Shale = SLBS)

**post-Crisis Interval:** lies above the Si. (Eo.) sulcata s.l. FAD (Hangenberg Limestone)

The recent review of thirty Rhenish DCB sections by Becker et al. (2021), based on a wealth of data published by many other authors, showed that there is a limited number of...
regional sections that could meet the criteria outlined above. Within the pelagic realm of the northern and eastern Rhenish Massif, numerous sections are now covered or poorly accessible (e.g. Hasselbachtal, Seiler region, Apricke, Müsennberg, Hangenberg, Stockum, Eulenspiegel, Scharfenberg). Others have gaps (Oberrödinghausen Railway Cut, Reigern Quarry, easily accessible successions at Drewer) or are too condensed (Effenburg, Kattensiepen). At Oese, the basal limestones overlaying the regressive, locally thick Hangenberg Sandstone are too poor in conodonts to establish firm ranges in the critical interval. This problem was also encountered when Drewer was recently re-sampled. This leaves a single section, the Borkewehr near Wocklum, which we re-sampled bed-by-bed. Its revised litho-, bio-, cyclo-, and chemostratigraphy as well as a sequence stratigraphic overview are presented. We regard it as the prime Rhenish DCB stratotype candidate, especially since it is an easily accessible section that is not in danger of destruction and which can be investigated using all modern stratigraphic techniques.

Abbreviations and repository

Conodont genera: B. = Bispathodus, Br. = Branmehla, D. = Dasbergina, M. = Mehлина, Neo. = Neopolygnathus, Pa. = Palmatolepis, Po. = Polygnathus, Pr. = Protognathodus, Ps. = Pseudopolygnathus, Sc. = Scaliognathus, Si. = Siphonodella (Eosiphonodella), Si. (St.) = Siphonodella (Siphonodellla).

Ammonoid genera: Ac. = Acutimitoceras (Stockunites), Cyma. = Cymacyclamena, Epiw. = Epiwocklumeria, Fini. = Finicyclamenia, G. = Gattendorfia, Kallo. = Kalloyclamenia, Ken. = Kenseycoceras, L. = Lissoclymenia, May. = Mayneoceras, Mim. = Mimimitoceras, Paravo. = Parawocklumeria, Postgl. = Postglaziella, Wo. = Wocklumeria. Zonal keys of ammonoid zones follow Becker and House (2000).

Repository: All specimens (if not stated otherwise) are stored in the Geomuseum of the Westfälische Wilhelms University Münster (GMM), figured conodonts under GMM B9A.11-1 to GMM B9A.11-71, unfigured paratypes of Pr. semikockeli n. sp. under GMM B9A.11-72 to GMM B9A.11-78, figured ammonoids under GMM B6C.52-1 to GMM B6C.52-7, and a single coral under GMM B2C.55-1. Mentioned MB.K. numbers for corals refer to the collection of the Museum für Naturkunde, Berlin.

Locality and access

The Borkewehr section (=an der Borke, Borke, Burg bei Wocklum, südlich Wocklumer Hammer, or Burgberg near Balve) is situated approximately 1 km east-southeast of the town centre of Balve. It crops out along a forest track and in a small old quarry at the southwestern slope of the Burgberg near Wocklumber Mell (GPS 51°19'34.0"N, 007°52'48.8"E, map sheet 4613 Balve, Fig. 1). Access is from Balve downtown, taking the B229 to the southeast towards Langenholthausen and then, following the Mellener Straße to the left, towards Mellen. After approximately 2.5 km, an unpaved road heads towards the left to a small parking site for hikers at the edge of the forest. One has to follow the forest track to the west-northwest, which leads after 250 m to the section.

The Borkewehr is a typical pelagic section with reduced sedimentation rates but without evidence for gaps and reworking in the critical DCB interval. It is the so far insufficiently studied type section of the Wocklum Limestone (Denckmann 1901, 1902; compare discussion in Lange 1929). It is the type locality of important uppermost Famennian index conodonts, including B. ultimus ultimus (Bischoff, 1957) and Pr. kockeli (Bischoff, 1957), index clymeniids, Cyma. involvens Lange, 1929, Epis. applanata (Wedekind, 1918), Fini. wocklumensis (Lange, 1929), Paravo. paradoxa (Wedekind, 1918), and Wo. denckmanni Wedekind, 1918, as well as of two agglutinating foraminifera, Hyperammina aperta Eickhoff, 1970 and ?Moravamina constricta Eickhoff, 1970. Exposed is a strongly cyclic pelagic succession, which reaches from the middle Famennian Palmatolepis marginifera utahensis Zone – based on the co-occurrence of Pa. marginifera marginifera, Pa. glabra pectinata M2, Pa. glabra prima M3, Pa. perlobata grossi, and Po. glaber bilobatus – to the lower Tourmainsian Si. (Si.) lobata M1 Subzone of the Si. (Si.) sandbergi Zone (compare new zonal scheme of Becker et al. 2021). The section contains all lithological units of the “Rhenish Standard Succession” sensu Kaiser et al. (2015) and Becker et al. (2016a). These are the top of the Wocklum Limestone, the Hangenberg Black Shale, equivalents of the Hangenberg Sand/Shale, as well as the Stockum and Hangenberg limestones. As in other sections of the Rhenish Massif, these units have been explained in terms of sea level changes and sequence stratigraphy (e.g. van Steenwinkel 1993b; Bless et al. 1993; Herbig 2016; Becker et al. 2021). A correlation with neritic successions of the Namur-Dinant Basin, Belgium, to the west is possible and was discussed by Denayer et al. (2020 online). At the top of the Hangenberg Limestone follows in the old adjacent quarry a strongly condensed succession of the middle Tourmainsian Lower Alum Shale (Kahlenberg Formation), above an hiatus uppermost Tourmainsian Erdbach Limestone equivalents, and lower Viséan siliceous shales with few calciturbidite beds (Hillershausen Formation; Herbig et al. 2019).

Research history

The Borkewehr section was first mentioned by Denckmann (1901, 1902) in the frame of stratigraphic investigations.

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during the initial geological mapping by the Prussian Geological Survey. Subsequent work by Wedekind (1914a, b, 1918) focused on the ammonoid fauna and installed the succession as an important type locality. Based on a more extensive geological survey in association with a renewed mapping campaign, Paekelmann (1924) provided further descriptions, regarding the lithology of the upper/uppermost Famennian Dasberg and Wocklum limestones, Hangenberg beds, as well as overlying Tournaisian and Viséan strata. The light-coloured Viséan “lydites” are nowadays mostly covered. A first brief section log of the complete succession and few faunal records (e.g., “Posidonia venusta” from the Hangenberg Black Shale) were given in Schmidt (1924), followed by Devonian trilobite data in Richter and Richter (1926), and ostracod records in Matern (1929). Lange (1929) provided further ammonoid data, including two new species from the Wocklum Limestone. He discussed Schmidt’s rejection of the term “Wocklumer Schichten” (= Wocklum Limestone), which was based on an apparent co-occurrence of ammonoids from the Wocklum Limestone (= Dasberg Limestone of Schmidt 1924) and the younger Hangenberg Limestone. Lange (1929) pointed out that Schmidt’s specimens were mostly collected from the scree at the northern wall of the quarry. Based on the limited stratigraphic benefit of such material, Lange (1929) declared that the term “Wocklumer Schichten” is valid. Rabien (1954) added Upper Devonian ostracod records.

The first conodont data from the Wocklum and Gattendorfia stages (for further details on Rhenish regional chrono- and lithostratigraphy see the summary of Becker et al. 2021) of the Borkewehr section were published by Bischoff (1957), who described three new (sub)species, Tripodellus robustus, B. ultimus ultimus (as Spathognathodus spinulicostatus ultimus), and Pr. kockeli (as Gnathodus kockeli), the potential index conodont for the future base of the Carboniferous. Additional conodont records were provided by Voges (1959, 1960), who indicated in higher parts the upper Tournaisian Sc. anchoralis Zone, amongst others. Within their geological field guide to the “Sauerland”, Schmidt and Pfeßmann (1961) mentioned briefly the DCB and showed a simplified geological map/figure of the outcrop area. An attempt by Streel (1969) to find spores from the Devonian-Carboniferous transition failed. Eickhoff (1970) described agglutinating foraminifera from the Wocklum Limestone, including two new species, Hyperammina aperta and ?Moravamina constricta. A new section log was illustrated in a field guide by Ziegler (1971), who provided a conodont biostratigraphy from the “Upper costatus Zone” to the Sc. anchoralis Zone.

Upper Devonian ammonoids from Borkewehr were treated in several papers, such as Korn (1981, 1994), Korn and Price (1987, 2019), and Price and Korn (1989). Luppold et al. (1994) studied a few DCB conodont faunas and gave a new log of the section called “Wocklum”. A sample from the uppermost 10 cm of the Wocklum Limestone yielded a typical pre-crisis fauna, including Si. (Eo.) praesulcata and the last B. muessenbergensis, B. ultimus ultimus, as well as representatives of the Pa. gracilis Group. A younger sample from the base of the assumed Hangenberg Limestone, actually from the Upper Stockum Limestone sensu Becker et al. (2021), contained Pr. kuehni, Pr. kockeli, Pr. collinsoni, as well as Neo. communis communis. Based on indifferent conodont faunas without siphonodellids, it was supposedly not possible to locate the DCB (“Si. (Eo.) sulcata Boundary”) with precision. Becker (1996) illustrated a well-preserved “Mim.” lentum, which originally was identified by H. Schmidt as “Aganides quadripartitus”. The local record of Wocklumieridae was revised by Becker (2000) and Ebbighausen and Korn (2007). Whilst it was possible to select lectotypes for Wo. denckmanni and Parawo. paradoxa, Wedekind’s (1918) single original of Epiwo. annulata has been lost. Korn (2002) listed the Borkewehr section in his compilation of important localities for the late Middle Devonian to Late Devonian ammonoid zonation in the northern Rhenish Massif.

Großhäusser (2014) studied the Tournaisian to Viséan succession but did not address the strongly condensed middle Tournaisian to lower Viséan lithological units correctly since thicknesses and facies developments deviate quite strongly from the standard of the Rhenish Kulm Basin. A new detailed bed-by-bed section log for the top Wocklum Limestone to the top of the Hangenberg Limestone, with some macrofauna records (bivalves, trilobites, but mainly ammonoids), was provided by Becker et al. (2016a). Becker and Hartenfels (2017) summarised the existing Borkewehr data in the context of the ongoing DCB revision. A new survey and re-sampling by Hartenfels et al. (2017a,b) made new geochemical and conodont data available. It was pointed out that the phylogenetic change from ancestral Pr. collinsoni to Pr. kockeli is recognisable in the first few transgressive limestones immediately after the siliciclastics of the glacioeustatic Hangenberg Regression. Hartenfels and Becker (2018, 2019) proposed the Borkewehr as a DCB stratotype candidate section and gave preliminary insights into the transition from Pr. collinsoni to Pr. kockeli. Herbig et al. (2019) summarised the Borkewehr data and reported that, according to new conodont data, the interval of the Stockum Limestone is thicker than previously shown in Becker et al. (2016a). Preliminary remarks concerning sequence stratigraphy, biofacies of agglutinating foraminifera, and the middle Tournaisian to lower Viséan succession were added. Basse and Lemke (2020) began to revise all Rhenish trilobites of the Wocklum Limestone. From the Borkewehr section, they recorded nine species of phacopids and proetids, with new material collected mostly from the top 10 cm below the Hangenberg Black Shale. Due to the parallel preparations
for this paper, the Borkewehr section was only briefly treated in the review of Rhenish DCB sections by Becker et al. (2021).

**Tectonic and palaeogeographic setting**

Famennian and Mississippian strata of the northern Rhenish Massif belong to a narrow outcrop belt along the northwestern to southeastern axial ramps of the 1st order Remscheid-Altena Anticline (Fig. 1). The latter shows the typical Variscan strike direction, extends from the Remscheid-Wuppertal region in the southwest towards the Hönne Valley region in the northeast, and disappears with the plunging fold axis to the north and northeast of Balve. Further to the northeast, the Famennian re-appears on the top of horst structures, such as the Effenberg Quarry (e.g. Hartenfels 2011; Hartenfels and Becker 2016c), which are surrounded by Mississippian strata. The Borkewehr section is situated on the southeastern flank of the Remscheid-Altena Anticline. The southeastern continuation of the anticline is the Lüdenscheid Syncline, which separates the western end of the “Ostauerländer Hauptsattel”. Amongst others, regional review papers were provided by Stoppel et al. (2006), Langenstrassen (2008), and Clausen and Korn (2008).

In the Upper Devonian, the drowned Hönne Valley Reef Complex at the eastern end of the Remscheid-Altena Anticline created a subphotic palaeohigh (e.g. Becker et al. 2016b), which descended gently from the Oberrödinghausen region to the south (e.g. Wedekind 1914b). There, Frasnian submarine volcanoes resulted in a more complex “seamount” pattern around Balve (Domsiepen 1973; Becker et al. 2016b). The Borkewehr section is positioned on the southeastern slope of the overall palaeohigh.

**Material and methods**

This study is based on a new, continuous bed-by-bed logging, with new records of conodonts, ammonoids, and geochemistry. For orientation, one conodont sample was taken from the middle Famennian base of the succession. Dieter Weyer collected ammonoids and solitary rugose corals from the last 21 nodules of the Wocklum Limestone, which was supplemented by collections of R. T. Becker and S. Hartenfels from the last five layers and from the first limestones above the HS/HSS equivalents. We took 12 conodont samples from the top Wocklum Limestone and sampled 26 of 29 possible micritic beds of the Stockum and Hangenberg limestones for conodonts, other microfauna, and carbonate microfacies. In the critical DCB interval, beds were re-sampled up to six times in order to establish full taxon ranges and to evaluate the initial conodont radiation with high-resolution. A medium weight of three kilograms for each sample was dissolved by a 10 % solution of formic acid. Washed residues were separated into 0.100, 0.315, and 0.630 mm fractions. If necessary, the smallest one was treated before picking by heavy liquid separation, using diluted sodium polytungstate (3Na2WO4 × 9WO3 × H2O). As it is common practice in high-resolution biostratigraphic conodont studies, only the Pa element taxonomy has been utilised, because many Famennian and Mississippian multi-element reconstructions are still doubtful. Ramiform elements were picked but not identified. The samples provided sparse to rich conodont faunas, which enabled the location of almost all zonal boundaries and, most importantly, of the evolutionary succession within the genus Protophanerodus. Results are used to improve the regional bio- and event stratigraphy.

Using 50 × 50 and/or 100 × 75 mm thin sections, carbonate microfacies analysis and classification follow the nomenclature by Dunham (1962) as well as the modified microfacies types of Hartenfels (2011). The latter were introduced, because the standard microfacies types sensu Wilson (1975), developed for Upper Triassic reefal carbonates, do not permit a differentiated classification of (hemi)pelagic carbonates. Even the refined model by Flügel (2004) is too rough (compare discussion in Hartenfels 2011). It should be stressed that the local microfacies of all Wocklum, Stockum, and Hangenberg Limestone beds give no hints for any reworking processes (Becker et al. 2016a; Hartenfels et al. 2017a; Herbig et al. 2019).

Calcite powders were drilled from 42 freshly cut carbonate rock samples of Wocklum, Stockum, and Hangenberg limestones for carbon and oxygen isotope analyses. Powders were reacted with phosphoric acid at 70 °C and the generated CO2 gas was analysed using a MAT 253 mass spectrometer at the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences. For δ13Corg studies, a total of 65 samples, including carbonate rock samples mentioned above, and 23 more samples from the HBS and HS/HSS intervals were ultrasonicated in deionized water to remove surficial organic contaminants. The dried samples were crushed to 200 mesh and acidified using 3N HCl. Insoluble residues were repeatedly rinsed in ultrapure water, dried at 60 °C, and then loaded into tin capsules. Samples were measured using a MAT 253 mass spectrometer, coupled to a high-temperature element analyser at the Nanjing Institute of Geology and Mineral Resources. All isotope ratios presented here are expressed by δ notation as per mill (‰) relative to the Vienna Pee Dee Belemnite standard (VPDB). Accuracy and precision were controlled by replicate measurements of Chinese National Standard GBW-04405 (δ13C = +0.57 ‰, δ18O = -8.49 ‰) and international standard IAEA-600 (δ13C = -27.8 ‰), respectively, and were better than 0.04 ‰ for δ13Ccarb, 0.08 ‰ for δ18Ocarb, and 0.1 ‰ for δ13Corg.
Element composition of powdered samples was determined by inductively coupled plasma optical emission spectrometry/mass spectrometry (ICP-OES/MS; n = 35), commercial laboratory ACME, Bureau Veritas Commodities Canada Ltd laboratories, Vancouver; details of the procedures used are available at [http://acmelab.com](http://acmelab.com) and by energy-dispersive X-ray fluorescence spectrometry [ED-XRF; n = 184; MiniPal 4.0 (PANalytical, Netherlands) and a Rh lamp and Peltier cooled Si-PIN detector at the Institute of Inorganic Chemistry, Czech Academy of Sciences, Prague]. Powders for ICP-OES/MS and ED-XRF analyses were not prepared from the same parts of the samples. ICP-OES/MS provided data on concentrations of a wide spectrum of elements with high accuracy and low limits of detection (Online Resource 1), which were used for the calculation of various geochemical proxies. ED-XRF was used to get high-resolution data on selected major and trace elements, expressed in the counts per second (c. p. s.) unit (Online Resource 1).

Framboid pyrite diameters were measured by a JEOL 6490 LV scanning electron microscope at the Department of Geological Sciences, Masaryk University, Brno, Czech Republic. Only one polished thin section taken from the Hangenberg Black Shale contained altered framboid pyrites, which were analysed in backscattered electron mode. Based on Wignall and Newton (1998), more than 100 framboid pyrites were measured (n = 102). Basic statistics of min, max, mean, standard deviation, and plots were carried out using the software Statistica 12 (Statsoft; Online Resource 1).

The cyclostratigraphic interpretation in this study is based on the frequency of alternations between shales/marls and nodular limestones. To obtain insight into the frequency composition of the Borkewehr lithological rhythms, the periodogram of a lithological depth-series was calculated. This quantified litholog was constructed by assigning a code “1” to shales/marls and “2” to (nodular) limestone beds. Frequency-selective bandpass filters with rectangular windows were used to isolate and extract specific frequency-components from the litholog that we associate with either precession or obliquity. All time-series analyses were carried out using the freely-available R-library astrochron (Meyers 2014).

**Upper Famennian to lower Touraisian conodont zonation**

The upper to uppermost Famennian pelagic conodont zonation was introduced by Ziegler (1962) and revised by Ziegler and Sandberg (1984, 1990), Kaiser et al. (2009), Hartenfels (2011), Hartenfels and Becker (2016 online), Spalletta et al. (2017, 2020 online), and Corradini et al. (2020 online). Based on a phylogenetic reconstruction of the genus Siphonodella, Sandberg et al. (1978) established the lower Touraisian siphonodellid zonation. Significant changes were introduced by Ji (1985) – which were followed by Kom and Weyer (2003) – and by Becker et al. (2021). A compilation and correlation of the different Touraisian zonal schemes was given in Esteban Lopez (2021).

Becker et al. (2016a) gave an overview of the DCB conodont stratigraphy, including references to shallow-water successions. These are relevant for wide regions outside Germany. Subsequently, Corradini et al. (2016 online) and Spalletta et al. (2017) installed a new zonal scheme, which is strictly based on the FADs of taxa. They decided against the Si. (Eo.) praesulcata Zone and created an expanded B. ultimus Zone, based on uncertainties stemming from the thorough analysis of the Si. (Eo.) praesulcata - Si. (Eo.) sulcata Group in Kaiser and Corradini (2011). As an upper subdivision of their B. ultimus Zone, Spalletta et al. (2020 online, following the suggestion of Corradini et al. 2020 online) introduced a Pr. meischneri Subzone in the Carnic Alps. However, in many other regions the species is very rare in the uppermost Famennian and commonly shows a delayed entry. In general, the FAD of Pr. meischneri is not a reliable biostratigraphic tool. If the index taxon is absent or enters at a higher level, they proposed to mark the base of the subzone approximately by the first occurrences of Pr. collinsoni or Si. (Eo.) praesulcata. But the FAD of Pr. collinsoni lies significantly above the FAD of Pr. meischneri. Despite the taxonomic complexity of early Siphonodella and its relatives – see the concept of early Siphonodella-type conodonts by Tragethek (2010; called siphonodellids in Becker et al. 2013) – the Si. (Eo.) praesulcata Zone has been recorded around the world. Consequently, Söte et al. (2017) proposed to keep the Si. (Eo.) praesulcata Zone. Becker et al. (2021) recognised the current nomenclatorial uncertainty by referring to a Si. (Eo.) praesulcata s.l. Zone, especially since the Montana Si. (Eo.) praesulcata holotype is not from Wocklum Limestone time equivalents but from a level well above the Hangenberg extinction (Rice et al. 2017).

Corradini et al. (2016 online) as well as Spalletta et al. (2017) decided also against the costatus-kockeli Interregnum (ckI) sensu Kaiser et al. (2009), which base marks the main conodont extinction at the base of the Lower Crisis Interval. As pointed out by Kaiser et al. (2009), the main victims include important index taxa as well as dominant and “cosmopolitan” forms, such as B. bispalodosus, both morphotypes of B. costatus and B. ultimus ultimus, Br. disparilis, Neo. communis collinsoni, subspecies of the Pa. gracilis Group, Po. vogesi, and Ps. marburgensis trigonics (compare range charts in Hartenfels 2011 and Spalletta et al. 2017). Thus, it is important to mark the main extinction level and the base of the Hangenberg Black Shale Event and its equivalents (Kaiser et al. 2015 online) in the conodont scale. Söte et al. (2017) emphasised that no biostratigraphic rule discourages the use of Last Appearance Datum (LAD)-defined conodont zones. Therefore, they proposed to keep both intervals, the Si. (Eo.) praesulcata Zone as well as the ckI, but other authors may
prefer to recognise these only as subzones within the expended *B. ultimus* Zone sensu Corradini et al. (2016). It has to be emphasised that the global conodont record from the Lower Crisis Interval is extremely poor. In the Rhenish Massif, attempts to find conodonts on bedding surfaces or by physical/chemical cracking of the Hangenberg Black Shale failed, so far. The hypoxic to anoxic environment was apparently hostile to conodonts. However, as discussed by Corradini and Spalletta (2018), the current record gap may mask the true details of extinction and short-term survival of taxa.

Through the DCB interval, the genus *Prognathodus* is represented by four species: *Pr. meischneri*, *Pr. collinsoni*, *Pr. kockeli*, and *Pr. kuehni*. The biostratigraphic potential of these protognathids has been recognised by Bischoff (1957), Collinson et al. (1962), Weyer (1965), Ziegler (1969), and Alberti et al. (1974). Subsequently, Ziegler and Sandberg (1984) defined their Upper *praesulcata* Zone by the FAD of *Pr. kockeli*. This led to a re-naming as *Pr. kockeli* Zone by Kaiser et al. (2009). Corradini et al. (2011) pointed out that the latter is the most abundant species amongst the protognathids, with a wide geographic distribution, but in many regions with an alleged variation of the First Occurrence Datum (FOD). Consequently, they concluded that “none of the four *Prognathodus* species has a high potential as a tool for redefining the D/C boundary interval”. In the following years, detailed (re-)investigations of DCB sections throughout the world improved the knowledge and provided new insights into the global distribution and regional first occurrences of protognathids (e.g. Becker et al. 2013, 2021; Corradini et al. 2013, 2016 online; 2020; Mossonni et al. 2015; Arezt et al. 2016, 2021; Narkiewicz et al. 2017; Hartenfels et al. 2017a, b; Kumpan et al. 2018, 2019b, 2020 online; Feist et al. 2019, 2020; Hartenfels and Becker 2019; Kaiser et al. 2019a, b; Qie 2019; Spalletta et al. 2020 online; Over 2020 online; Denayer et al. 2020 online; Matyja et al. 2020 online; Kulagina et al. 2021), especially of *Pr. kockeli*. Partly based on these new datasets, Corradini et al. (2016) and Spalletta et al. (2017) changed their point of view and installed an expanded *Pr. kockeli* Zone, which includes both the *Pr. kockeli* Zone sensu Kaiser et al. (2009) and the following *Si. (Eo.) sulcata* Zone. It is more than unfortunate that different authors will mean a different time interval hidden under a single zonal name, which has been used since many years. The *Pr. kockeli* Zone sensu Kaiser et al. (2009) refers strictly to the “classical interval” (Upper *praesulcata* Zone) between the FADs of *Pr. kockeli* and *Si. (Eo.) sulcata* s.l. The expanded *Pr. kockeli* Zone sensu Corradini et al. (2016 online) and Spalletta et al. (2017) also embraces the Upper Stockum Limestone and lower portions of the Hangenberg Limestone, reaching upwards until the entry of *Si. (Eo.) bransoni*.

The transition from *Pr. collinsoni* to *Pr. kockeli* is more complex than previously thought (compare Hartenfels and Becker 2018, 2019; Kaiser et al. 2019a online). *Prognathodus collinsoni* is characterised by one or a few irregularly distributed nodes on the upper surface of the cup. The emended (expanded) *Pr. kockeli* diagnosis of Corradini et al. (2011: “The coarse, nodose, ornamentation and the presence of at least one row of nodes parallel to the carina on one half of the cup...”) contains also intermediates between *Pr. collinsoni* and *Pr. kockeli* sensu Bischoff (1957, whose original diagnosis translates as: “... with one or two lines of coarse nodes parallel to the carina on the inner AND outer side of the cup”). Investigations of the Borkewehr section and other localities (e.g. Puech de la Suque, Montagne Noire, France; locality description and access in Kaiser 2005 and Feist et al. 2020 online) prove that “intermediate *kockeli*” types with a row of nodes on only one side – herein designated as *Pr. semikockeli* n. sp. (see taxonomic chapter) – may occur in the first limestone bed immediately above the conodont-free Hangenberg Shale/Sandstone. Feist et al. (2020) illustrated a specimen from the Middle Crisis Interval of the Montagne Noire. If it would be included in *Pr. kockeli*, using the Corradini et al. (2011) re-definition, the *Pr. kockeli* range would have to be significantly expanded downwards, into a level that has very few conodont faunas on a global scale. The holotype and originally illustrated paratypes of *Pr. kockeli* have two rows of nodes (second outer rows partly initially developed) on one or both sides of the cup (however, one row of nodes occurs in any case on each side). In this sense, *Pr. kockeli* s.str. enters in the third Stockum Limestone bed (Bed 4b) at Borkewehr (Hartenfels and Becker 2019).

Apart from the past inconsistencies in discriminating *Si. (Eo.) sulcata* from its supposed ancestor *Si. (Eo.) praesulcata* (compare Kaiser and Corradini 2011), we think that *Si. (Eo.) sulcata* is a useful zonal marker, if it is used in the sense of the lost type specimen sensu Huddlle (1934). The latter came from the basal Tourmaisian Henryville Bed within the Ellsworth Member of the upper New Albany Shale (Illinois Basin, southern Indiana; Evans et al. 2013). Kaiser et al. (2019a online) emphasised that it is Morphotype 5 sensu Kaiser and Corradini (2011) that should be used for the definition of a *Si. (Eo.) sulcata* Zone. It is long known that *Siphonodella* is almost lacking in the Stockum Limestone, where the FAD of *Pr. kuehni* provided a distinction of Lower and Upper *Prognathodus* faunas (Alberti et al. 1974). Later it was shown, that the FADs of *Pr. kuehni* and *Si. (Eo.) sulcata* coincide (e.g. Clausen et al. 1989a). Further support based on Austrian sections led Kaiser et al. (2019a online) to advocate a combined *Si. (Eo.) sulcata/Pr. kuehni* Zone. The taxonomic uncertainty of *Si. (Eo.) sulcata* led Becker et al. (2021) to apply a *Si. (Eo.) sulcata* s.1./*Pr. kuehni* Zone until revisions have been completed.

The subsequent Tourmaisian conodont zonation of Sandberg et al. (1978) has been refined by Ji (1985) and discussed by Becker et al. (2016a). The latter re-named and designated accidently two specimens of *Si. (Si.) hassi* Ji, 1985,
using the originals of *Si. duplicata* sensu Hass (1959: pl. 49, figs. 17–18) as the types of *Si. (Si.) jii*, because Ji (1985) overlooked that the species name *hassi* was already occupied by *Si. cooperi hassi* Thompson and Fellows, 1970. Consequently, they re-named the *Si. (Si.) hassi* Zone sensu Ji (1985 = former Upper *Si. duplicata* Zone) as *Si. (Si.) jii* Zone. Zhuravlev and Plotitsyn (2018) re-illustrated the type material of *Si. (Si.) jii* and described initial second rostral ridges, at least on the inner anterior platform. Therefore, they assigned the types of *Si. (Si.) jii* to *Si. (Si.) quadruplicata* (compare taxonomic assignment by Klapper 1966). Referring to the emended *quadruplicata* diagnosis by Klapper (1971), the number of rostral ridges of the latter varies from three to five. Becker et al. (2021) selected the adult material of *Si. (Si.) mehli*, because Ji (1985) as an upper subdivision of the *Si. quadruplicata*-type encrusta-

*Sedimentary succession*

The used lithostratigraphic terminology follows the Stratigraphic Table of Germany 2016 (Deutsche Stratigraphische Kommission 2016; Herbig et al. 2017). The succession from the base of the Hangenberg Black Shale to the top of the Hangenberg Limestone forms subunits of the Hangenberg Formation, previously known as “Hangenberg Schichten”.

At Borkewehr, there is a bed-by-bed record, which spans the higher part of the uppermost Famennian Wocklum Limestone to the lower Viséan top of the succession (Großhäuser 2014; Hartenfels et al. 2017a, b; Hartenfels and Becker 2018; Herbig et al. 2019). Becker et al. (2016a: fig. 3) provided a detailed section log, showing the position of the main Hangenberg Event and the strongly cyclic deposition of the Wocklum and Hangenberg limestones, interrupted by the siliciclastic Hangenberg Black Shale and Hangenberg Shale/Sandstone equivalents.

**Wocklum Limestone**

The Wocklum Limestone at Borkewehr consists of a cyclic alternation of greenish-grey shales/marls and grey nodular limestones or nodular shales (Figs. 2a–b, 3). Reddish nodular shales and limestones occur below, but are a part of a folded and faulted interval. Typical for the Wocklum Limestone is a pelagic fauna yielding entomozoan ostracods, ammonoids, orthocnomic cephalopods, agglutinating foraminifera, thin-shelled bivalves, small-sized gastropods, bellerophontid gastropods, small chonetids, blind and occulated trilobites, solitary rugose corals, as well as conodonts. Bioturbation is evident in the micritic and matrix-rich limestones, which consist of microsparitic mud-wackestones to wackestones through the entire interval (Fig. 4a–d, f). Occasionally, reddish-brown cauliflower structures encrusted skeletal remains (e.g. in beds -9b, -7b, and -3b). They resemble *Frutexites*-type encrustations sensu Böhmer and Brachert (1993) and were previously mentioned from the upper to uppermost Famennian (e.g. Hartenfels 2003, 2011; Prétat et al. 2008; Hartenfels and Becker 2016a, b). Like the benthic foraminifera, they indicate very slow sedimentation rates. Thus, the Wocklum Limestone accumulated under oxic conditions, below the photic zone, and below the influence of storm waves. A single thin layer of small-sized fragmented crinoid packstone intercalated within a mud-wackestone facies indicates an episode of increased
Fig. 2 Field photos showing the uppermost Famennian to basal middle Tournaisian Borkewehr succession. a Overview of the main section at the forest track. b Details of the top Wocklum Limestone and sharply overlying Hangenberg Black Shale. c Details of the interval from the Hangenberg Black Shale to the Hangenberg Shale/Sandstone equivalents. d Details of the interval from the Hangenberg Shale/Sandstone equivalents to the lower part of the Hangenberg Limestone.

e Lower Alum Shale Event (sharp base of Kahleberg Formation) in the quarry behind the main section and upper Tournaisian to Viséan succession to the right. Abbreviations: WL Wocklum Limestone, HBS Hangenberg Black Shale (Lower Crisis Interval), HSS Hangenberg Shale/Sandstone equivalents (Middle Crisis Interval), SL Stockum Limestone (Upper Crisis Interval), HL Hangenberg Limestone, LAS Lower Alum Shale.
bottom turbulence (Bed -12b, Fig. 4e). The crinoid debris must have been derived from more elevated parts of the drowned seamount. The increase in pyrite content and the simultaneous decrease in bioturbation within the last five limestone beds (-4b to -1b, Fig. 4c to 4a), immediately below the Hangenberg Black Shale, argues for a successive deterioration of oxygen availability and, therefore, of the ecological conditions for benthos on the sea-floor. Especially within Bed -1b (Fig. 4a), the content of dispersed pyrite increased rapidly. Thus, the facies change between the cyclic sedimentation and the overlying Lower Crisis Interval was somewhat gradual, as at Drewer (Becker et al. 2016c). In this respect, the Crisis Prelude of Borkewehr shows analogies with the older, smaller-scale *Annulata* Events and Dasberg Crisis in the Rhenish Massif (compare Hartenfels and Becker 2009, 2016b, c; Hartenfels 2011).

Based on shallowing upwards, strong condensation, and non-deposition, upper to uppermost portions of the Wocklum Limestone are lacking in some neighbouring sections of the northern Rhenish Massif. At the mostly overgrown Reigern Quarry (GPS 51° 23' 15.77" N, 007° 59' 25.20" E) near Hachen, type locality of the conodont *B. ultimus corradianii* Söte, Hartenfels, and Becker, 2017 and famous for its rich Famennian ammonoid fauna, Söte et al. (2017) mentioned a major hiatus, which spans from the topmost Famennian to the upper Tournaisian. There, the middle parts of the Wocklum Limestone are disconformably overlain by laminated radiolarites and a thin metabentonite of the Mississippian Hardt Formation.

Hangenberg Black Shale and Hangenberg Shale/Sandstone equivalents

In the two lateral Borkewehr successions, the Wocklum Limestone is sharply overlain by 20 cm of very fissile, Hangenberg Black Shale (Bed 0, Figs. 2a–c, 3). The base marks the pelagic mass-extinction level and Lower Crisis Interval I sensu Becker et al. (2021). The fine lamination suggests the lack of bioturbation due to anoxic sea-floor conditions. For a review of extinction patterns and interpretation of associated palaeoclimatic and palaeoceanographic changes see Kaiser et al. (2015).

The Hangenberg Black Shale enabled a spread of pelagic facies westwards into neritic environments of the Vélbert region (Becker et al. 2021) and further to the Ardennes (e.g. supposed Hangenberg Black Shale equivalent at Spontin, southeast of Namur, Denayer et al. 2020 online).

The Hangenberg Black Shale is followed by approximately 80 cm of moderately solid, greenish-grey, silty, unenriched, and micaceous Hangenberg Shale/Sandstone equivalents (beds 1a–b, combined Middle Crisis Interval I–II sensu Becker et al. 2021, Figs. 2a, c, 3). In contrast to DCB localities to the northwest (e.g. Oese), north, and east, the Hangenberg Sandstone is inconspicuous and indistinguishable from the underlying Hangenberg Shale. This may reflect the increasing distance from the depocentre and northern clastic source (Becker et al. 2016a; Koltonik et al. 2018, 2019). This implies that the siliciclastics of Stockum, which lies to the southeast, derived from a different shedding path. The Middle Hangenberg Crisis Interval covers the major, glacio-eustatic sea level fall, which is indicated by increasing Zr/Al values (see below). An absolute peak value lies approximately 45 cm below the top of this unit and is correlated by us with the base of the Hangenberg Sandstone.

Stockum and Hangenberg limestones

The overlying top 3 cm (Bed 1c) are dark-grey, marly, and represent a renewed short episode of limited oxygenation. This interval may correlate with the “Stockum Level Black Shale” (Becker et al. 2021) above the top of the Hangenberg Sandstone, described by Korn (1991) and Korn et al. (1994) from the poorly accessible western quarry wall at Drewer. It marks the gradual, initial postglacial transgression, the base of the Upper Crisis Interval.

The 11 cm thick beds 2–3 represent locally the main Upper Crisis Interval I and Basal Stockum Limestone sensu Becker et al. (2021, Figs. 2a, d, 3). In comparison with other Sauerland sections, it is a somewhat unusual interval of platy, thin-bedded (“laminated”), dark-grey limestones with squashed goniatite impressions on bedding planes. Microsparitic mudstones are intercalated by darker layers, enriched in C<sub>org</sub> and interrupted by thin-bedded siltstones of lighter colour (Fig. 5e–f). Whereas the darker layers indicate an increased deposition of fine clay and organic matter, probably due to episodes of higher primary production, the siltstones probably resulted from distal turbidites and, therefore, final minor pulses of Hangenberg Sandstone sedimentation. In contrast to the conodont-free Bed 2, Bed 3 contains a low-diversity conodont fauna, a few ostracods, and thin-shelled bivalves.

The first nodular limestone (Bed 4b) represents locally the lower Stockum Limestone (Upper Crisis Interval II sensu Becker et al. 2021, Figs. 2a, d, 3). It is a microsparitic mudstone (Fig. 5d) with ostracods, thin-shelled bivalves, and trilobites. Clausen in Luppold et al. (1994, p. 56) mentioned silt-sized quartz grains and calcispheres. Bioturbation indicates the return to better oxygenated conditions. The microfacies of Bed 5b is similar to the preceding Bed 4b.

The Hangenberg Limestone (beds 6b–30, Figs. 2a, d, 3) consists of strongly cyclic, alternating, greenish-grey marls and micritic nodular limestones that are rather poor in macrofauna. There is no obvious microfacies distinction between Lower and Upper Stockum (beds 4b, 5b) and post-crisis Hangenberg Limestone levels; the distinction follows the conodont biofacies (see below). The pelagic fauna mostly consists of rare ammonoids (Fig. 6e), orthoconic cephalopods,
Middle Touraisian to Viséan

The uppermost carbonate layers of the Hangenberg Limestone are overlain by the middle Touraisian Kahlenberg Formation ("Liegende Alauschiefer", "Lower Alum Shales"). The fissile, laminated, un fissi l i s t, dark-grey to blackish shales, exposed at the right (southeastern) side of the quarry, show a very sharp base (Figs. 2e, 7a, b). The strongly condensed, only 56 cm thick formation (Bed 31, Fig. 8), which in most sections along the northern margin of the Rhenish Massif measures about ten metres, is also somewhat lighter coloured than in standard facies; the intensively black-coloured alun shales are missing.

Most interestingly, the conspicuous black bedded cherts and siliceous shales of the upper Touraisian Hardt Formation ("Schwarze Kiesel schiefer") are missing due to a hiatus. This is also observed in sections at the western basin margin and on intrabasinal swells, for example in the Drewer Quarry in the northeastern Rhenish Massif (Herbig 2016; Herbig et al. 2019).

Above, a 51.5 cm thick, unnamed unit crops out (beds 32a–35), which is a stratigraphic equivalent of the Erdbach Limestone II of Krebs (1966, 1968) and of two other formations in the Rhenish Massif (Kohleiche Formation, Korn 2005a; Kattensiepen Formation, Korn 2005b) as mentioned by Herbig et al. (2019, Fig. 7a). At the base, a 15 cm thick dark shale horizon (Bed 32a) enriched in phosphorite nodules and up to 8 cm thick and up to few decimetres long limestone lenses contain phosphorite pebbles, as already indicated by Voges (1959: fig.1; 1960: fig. 2; Fig. 7c). The phosphorite nodule horizon indicates reworking. Therefore, despite of the lithological similarity, it cannot be included in the dark shales of the underlying Kahlenberg Formation. This is also shown by its younger, uppermost Touraisian conodont fauna (see below). The upper 36.5 cm of the unit are a true lithological equivalent of the Erdbach Limestone II. Already Schmidt (1924, p. 105, horizon f of the described section) and later Voges (1959, 1960) attributed this unit to the “Erdbacher Schichten”, respectively “Erdbach Horizon”. It consists of two decimetric limestone beds (beds 32b and 34b = beds K1 and K2 in Großhäuser 2014) separated by a 5 cm thick shale interval (beds 33a to 34a) that includes an intervening 2 cm thick limestone veneer (Bed 33b, Fig. 8). Beds 32b and 34b are moderately bioturbated microbioclastic-microintraclastic wackestones/packstones (Fig. 9a). Only the intervening limestone veneer (Bed 33b) shows laminations. Besides differing packing density of the components and bioturbation, differences are faint. Fossils are restricted to some conodonts, ostracods, diminuitive echinoderm debris, and spheres, which at least in part, are radiolarian ghost structures. Extremely rare are the calcareous microbiota Archaeasphaera, Radiosphaera, Diplosphaera, and Eotuberitina. Multichambered foraminifera and calcareous algae are missing. Small calcite crystals occur, which in part are dissolved bioclasts, in part recrystallized matrix. The 17 cm thick upper bed (Bed 34b) is bipartite. A siltitic mudstone at its base is bored (Fig. 9b).

A renewed sedimentation and bottom currents caused erosion of some well-rounded clasts that float in identical siltitic mudstone as at the base of the bed (Fig. 9b). In general, microfacies indicates deposition in deeper water below storm wave base. Sedimentation processes, however, remain unclear. Involvement of gravitational turbiditic re-deposition, indicated by dense packing, strong grain diminution and sorting, as well as by relictic lamination seems reasonable. Components indicate a deeper water source. The 2.5 cm thick top (Bed 35) of the upper limestone presumably is a nodular, light-weathering hardground (Herbig et al. 2019).

All overlying strata belong to the Hillershausen Formation (“Helle Kieselschiefer und Kieselkalke”) that has an exposed thickness of 7.5 m (beds 36a–45, Fig. 8). In general, the formation consists of intercalated siliceous shales and calciturbidite beds that are quite unique due to the diagenetically
Fig. 4 Microfacies from the Wocklum Limestone of Borkewehr, Si (Eo.) praesulcata s.l. Zone. a Microsparitic mud-wackestone facies with few ammonoids (1), ostracods (2), and thin-shelled bivalves. The increase in pyrite (white arrows) content and the simultaneous decrease in bioturbation (3, compare Fig. 4b–c) documents a deterioration of oxygen availability. Bed -1b, first nodular limestone bed immediately below the Hangenberg Black Shale. b Authigenetic pyrite within a bioturbated (1), microsparitic mud-wackestone facies documents slightly dyserobic conditions. The faunal assemblage consists of rare deep-water rugose corals (2), trilobites, thin-shelled bivalves, ammonoids (3), and ostracods (4), Bed -2b. c Well-bioturbated (1), microsparitic mud-wackestone facies, yielding sporadic small-sized ammonoids (2), ostracods (3), trilobites (4), and thin-shelled bivalves, proving good living conditions for the benthos, Bed -4b. d Microsparitic wackestone with fragmented, thin-shelled bivalves, ostracods, trilobites (1), Finiclymenia sp. (2) and other fragmented ammonoids, partly with geopetal fabrics, small-sized gastropods, echinoderm debris (3), probably crinoids, and bioturbation structures, Bed -10b. e Thin layer of small-sized, fragmented crinoid packstone intercalated within a microsparitic mud-wackestone facies, indicating bottom currents, Bed -12b. f Perforated wall (white arrows) of an skeletal remain encrusting microproblematica, Bed -12b.
Fig. 5 Microfacies from the Upper Crisis Interval and the Hangenberg Limestone of Borkewehr. a Bioturbated, microsparitic mudstone; sparse faunal assemblage consists of ostracods (1), skeletal remains (2), probably bivalves, and echinoderm fragments (3), Bed 12b, Si. (Sz.) duplicata Zone. b Detailed view of black to reddish-brown, cauliflower-shaped Frutexites-type encrustations (white arrows) of a skeletal remain within a microsparitic mudstone facies (compare Fig. 5c), Bed 6b, Si. (Eo.) sulcata s.l./Pr. kuehni Zone. c Microsparitic mudstone, yielding rare ostracods, trilobites, and thin-shelled bivalves, Bed 6b, Si. (Eo.) sulcata s.l./Pr. kuehni Zone. d Microsparitic mudstone facies with very few ostracods and thin-shelled bivalves, Bed 4b, first solid nodular limestone bed above the Hangenberg Shale/Sandstone equivalents, Pr. kockeli Zone. e Microsparitic mudstones intercalated by darker layers; the latter are enriched in Corg, indicating an increased deposition of fine clay, Bed 3, upper part of the “laminated” limestones above the Hangenberg Shale/Sandstone equivalents, costatus-kockeli Interregnum. f Microsparitic mudstones interrupted by thin-bedded siltstone layers (white arrows) of lighter colour, partially broken up into individual pieces (1), probably indicating distal turbidites, Bed 2, lower part of the “laminated” limestones just above the Hangenberg Shale/Sandstone equivalents, costatus-kockeli Interregnum.
Fig. 6 Microfacies from the Hangenberg Limestone of Borkewehr. a Microsparitic wackestone, containing ostracods (1), echinoderm fragments (2), bivalves (3), trilobites (4), and authigenetic calcite (5). Bed 30, topmost nodular limestone bed of the Hangenberg Limestone, Si. (Si.) lobata M1 Subzone of the Si. (Si.) sandbergi Zone. b Agglutinating foraminifera Tolypammina sp. (white arrows), Bed 30, Si. (Si.) lobata M1 Subzone of the Si. (Si.) sandbergi Zone. c Cross section of the deep-water rugose coral Cyathaxonia sp. B, GMM B2C.55-1, Bed 27, Si. (Si.) sandbergi Zone. d Microsparitic wackestone with selective enrichments of skeletal remains: echinoderm fragments (1), ostracods (2), and bivalves (3). In contrast to the Wocklum Limestone (compare Fig. 4c), the reduced benthos led to a weaker bioturbation (4), Bed 25, Si. (Si.) sandbergi Zone. e Ribbed goniatite, ?Paprothites sp. (1), and widely evolute juvenile goniatite, probably an Eocanites of the nodosus Group (2), Bed 21b, Si. (Si.) melhi Zone. f Microsparitic mud-wackestone facies with large bioturbation structures, Bed 20, Si. (Si.) duplicata Zone.
Fig. 7  Field aspects of the middle Tournaisian–lower Viséan condensed succession in the Borkewehr section.  

a  General overview of the succession showing the top of the Hangenberg Limestone (lower Tournaisian, Sequence 1), Kahlenberg Formation (middle Tournaisian, Sequence 2), equivalents of Erdbach Limestone II (uppermost Tournaisian, Sequence 4, HST), including dark basal horizon with enriched phosphorite nodules (Sequence 4, LST/TST), and the lowermost part of the Hillershausen Formation (lower Viséan, Sequence 5, TST). Note the absence of the Hardt Formation (Sequence 3) above the Kahlenberg Formation. 

b  Sharp basal contact of the Kahlenberg Formation (Bed 31, Sequence 2) above slightly nodular bedding plane of the Hangenberg Limestone (Bed 30). 

c  Enriched phosphorite nodules at the base of uppermost Tournaisian Sequence 4 (LST/TST), above homogeneous dark grey shales of the Kahlenberg Formation (Sequence 2); diameter of coin 16 mm. 

d  Lower, very fine-grained and inconspicuous calciturbidite set within the Hillershausen Formation. Bed 37 (= BE1) and Bed 39 (= BE3/BE4) are two calciturbidite beds separated by the calcareous, strongly siliceous interbed Bed 38 (= BE2; modified from Großhäuser 2014). 

e  Monotonous dark-grey siliceous shales form most of the exposed part of the Hillershausen Formation. 

f  Upper calciturbidite set of the Hillershausen Formation close to the top of the section, consisting of three beds, 41–44 (= X1–X3). Note bentonite layers (asterisks, left: Bed 40b, right: Bed 40d) and typically brown weathering calcareo-siliceous shale (Bed 40e) below Bed 41 (= X1).
silicified matrix. However, in the Borkewehr section, calciturbidite intercalations are extraordinarily rare. The basal 0.80 m of the formation (beds 36a–36e) consist of dark-grey to blackish, slightly calcareous, and only faintly siliceous shales that strongly resemble the Kahlenberg Formation below (Fig. 7a); two conspicuous yellowish, silicified tuffitic horizons (bentonites, beds 36b and d), each about 1 cm thick, are intercalated. Above, a first set of two medium-grey, dense to very fine-grained siliceous calciturbidite beds, 5 cm (Bed 37 = Bed BE1 in Großhäuser 2014) and 9 cm (Bed 39 = beds BE3–BE4 in Großhäuser 2014) thick, occur. They are separated by an 8 cm thick calcareous, strongly siliceous interbed (Bed 38 = Bed BE2 in Großhäuser 2014, Fig. 7d). The microfacies from the lower part of the calciturbidite beds shows a peloidal mudstone with some detrital quartz silt, pyrite grains, and isolated calcified radiolarian ghost structures (Fig. 9c); abundant yellowish streaks are regarded as radiolarians, filled with clayey-ferruginous calcite, which were almost completely flattened due to pressure solution. The upper part of the beds consists of radiolarian packstone with some sponge spicules (Fig. 9d). The siliceous interbed is finely laminated and has similar facies as the lower part of the calciturbidite beds. As a conclusion, the lower part of the calciturbidite beds is interpreted to represent the diagenetic prephase of the proper radiolarian turbidite. They preserve only slightly compacted autochthonous basinal sediment due to impregnation by carbonate-rich fluids delivered by the turbidite (Meischner 1964; Eder 1970, 1982; Herbig and Mamet 1994).

On top, ca. 4.4 m of monotonous, dark-grey, siliceous shales follow (beds 40a–e, Figs. 7e, 8). Two further conspicuous bentonitic tuffite layers, 2 cm (Bed 40b) and 3 cm (Bed 40d) thick, occur in the topmost part. The upper bentonite layer is overlain by 9 cm of calcareo-siliceous shales (Bed 40e) preluding a second siliceous calciturbidite set (beds 41–44 = beds X1–X3 in Großhäuser 2014, Fig. 7f). It consists of three beds, altogether 41 cm thick, and macroscopically identical to the lower calciturbidite set. Above, a few decimetres of siliceous shales (Bed 45) form the top of the section.

The microfacies of these calciturbidite beds is a predominantly fine-grained, diagenetically flasered peloidal-bioclastic packstone as a result of intense pressure solution. Therefore, in many cases only small stringers and lenses of the primary facies were preserved, which on first sight are easily confused with intraclasts (Fig. 9e). Calcispheres predominate. Well-preserved primary facies within an early diagenetic nodule shows peloidal-bioclastic grainstone with some foraminifers, echinoderm debris, and brachiopod shells. Algae are missing except for rare kamaenids. Peloids have been derived from small intraclasts, micritized bioclasts, and some ooids. Thus, in contrast to the lower calciturbidite set that was derived from a pelagic deeper water source, these calciturbidites reworked shallow-water platform material. Besides Radiosphaera sp. (Fig. 9e), Calcsphaera pachysphaerica (Pronina, 1963), Priscella cf. priscia (Rauser-Chernousova and Reitlinger in Rauser-Chernousova et al. 1936; Fig. 9f), and Pseudotaxis sp., only Uralidiscus rotundus (Chernysheva, 1948, Fig. 9g) were determined with confidence. An oblique section of an archeodiscid might belong to either Glomodiscus sp. or ‘Archaediscus’ at involutes stage (Fig. 9f). In general, the assemblage suggests the middle Moliniacian MFZ 11α or MFZ 11β Zone of Cózar et al. (2020), respectively the top of Cf4β or Cf4γ (Conil et al. 1991). In the review of Herbig (2006), oldest foraminifera from the Hillershausen Formation (“Kieselkalk and equivalents”) were mentioned from the Cf4γ. Thus, this might be the oldest foraminiferan fauna hitherto recorded from the Hillershausen Formation, which correlates well with the sample position from the basal part of the formation.

Sequence stratigraphy

The sequence stratigraphic interpretation of the section follows Herbig (2016), who first established sequences for the uppermost Devonian and Mississippian of the Rhenish Kulm Basin and correlated them with the sequences of the Northwest European shallow water platform (Hance et al. 2001, 2002; Poty et al. 2014; see also Poty 2016).

The lowermost sequence boundary in the Rhenish Kulm Basins discussed by Herbig (2016) coincides with the top of the Wocklum Limestone. The uppermost part is considered to record a falling systems stage tract (FSST) due to condensation and concomitant thinning of calcareous beds, increased faunal content as described in many sections by Korn (1995), Becker (1996), Korn and Weyer (2003), and Becker et al. (2016a, 2021) and by increased Zr/Al values (Kumpan et al. 2015, and herein). In the Borkewehr section, the in conspicuous FSST could be tentatively related to the interval above Bed 9b (Figs. 2b, 3). It has to be stressed that the gradual deterioration of ecological conditions in the uppermost beds of the Wocklum Limestone that are interpreted to be a prelude of the overlying Hangenberg Black Shale, point to an extraordinary complete sedimentary succession.

A relictic sequence is recorded by the Hangenberg Black Shale (Bed 0, transgressive systems tract/maximum flooding surface, TST/mfs) and the lower part of the overlying Hangenberg Shale/Sandstone equivalents that record the highstand systems tract (HST, Fig. 2c) or initial regression (Kaiser et al. 2015 online; Becker et al. 2016a; references therein). Considerable non-deposition or even erosion, as seen elsewhere by incised valley fills, e.g. some 20 km further
northwest by the famous Seiler conglomerate, have to be assumed for this sequence. This is stressed by the fact that Kaiser et al. (2015) estimated in southern Morocco a relative sea level fall in the scale of more than 100 m before deposition of Hangenberg Sandstone equivalents. The continuous fine-grained siliciclastic facies development of the Borkewehr section does not show any macroscopic impact of such a change.

However, Zr/Al values indicate an absolute peak some centimetres above the base of Bed 1b (see below). In comparison with other sections, this level is correlated with the base of the Hangenberg Sandstone, which was addressed as the lowstand systems tract (LST) of Sequence 1 in the Rhenish Kulm Basin by Herbig (2016). In the Borkewehr section, the onset of the TST is seen in the dark grey marly Bed 1c at the
top of the Hangenberg Shale/Sandstone equivalents (Fig. 3), which might be an equivalent of the “Stockum Level Black Shale” of Becker et al. (2021; see above). The following Stockum and Hangenberg limestones are regarded as the undifferentiated TST/HST of Sequence 1 (Fig. 2d).

In regions not reached by sandstone shedding, Herbig (2016) placed the base of Sequence 1 at the base of the Hangenberg Shale. Though this is a pragmatic approach, geochemical results from the Borkewehr section show that the sequence boundary has to be sought inside the Hangenberg Shale succession. However, in general Herbig (2016) followed the earlier model of van Steenwinkel (1993b) that was developed by comparison with the Belgian Namur-Dinant Basin (van Steenwinkel 1990, 1993a) and similar models for the latter by Kumpan et al. (2014) and Bábek et al. (2016a). On the contrary, Hance et al. (2001, 2002) and later publications of the Liège working group placed the base of the Belgian Sequence 1 below, at the base of the mixed siliciclastic-carbonate succession of the Etrouengt Formation and its lateral equivalents (Comblain-au-Pont and Dollhain formations). Poty (2016), who also gave a thorough review of the development of Dinantian sequence stratigraphy in Northwest Europe, and particularly in the Namur-Dinant Basin, interpreted the Hangenberg Sandstone interval and the concomitant sea level fall not as a third-order sequence boundary close to the DCB, but as an “out-of-sequence event”. This was based on the identical pattern of precession cycles below and above the Hangenberg Sandstone interval, and further arguments forwarded by Hance et al. (2001) and Denayer et al. (2015, 2019, 2020 online), i.e. very similar facies across the DCB, which hinders separation into different system tracts, and homogeneous facies and wide extension of the middle Hastière Formation, which typify a HST.

The dark-grey to blackish shales of the Kahlenberg Formation correspond to the TST of Sequence 2 (Figs. 7a, 8). By means of facies and biostratigraphy, the formation is well correlated with the Belgian Pont d’Arcole Formation, which corresponds to the same sequence stratigraphic tract. For the Rhenish Massif, Herbig (2016) showed the unconformable contact at the base and disproved earlier interpretations of a single sequence consisting of the Hangenberg beds below (LST) and the Kahlenberg Formation above (TST; van Steenwinkel 1993b) or of a sequence even continuing into the uppermost Tournaisian, including the Richrath Limestone (HST; Siggmund et al. 2002). In the Borkewehr section, a hiatus at the base of the Kahlenberg Formation is clearly shown by the sharp contact with the underlying Hangenberg Limestone (Figs. 2e, 7a). Like elsewhere in the Rhenish Massif, the LST of Sequence 2 is not recognised.

The upper Hastarian-lower Ivorian Sequence 3, elsewhere in the Rhenish Massif represented by the black siliceous shales and bedded cherts of the Hardt Formation, is missing. This corresponds to the development in the Velbert Anticline at the western margin of the Kulm Basin (Herbig 2016). Also, on the intrabasinal deep Drewer Swell the Hardt Formation is missing, though a very thin Sequence 3 was postulated by Herbig (2016).

The LST/TST of Sequence 4 is well documented by a thin, dark horizon with enriched phosphorite nodules and phosphorite pebbles (Bed 32a) at the base of the thin limestone package (beds 32b–35, Figs. 7a, c, 8), which are equivalents of the Erdbach Limestone II. The limestones represent the HST of Sequence 4, which ends with a questionable hardground. However, condensation and omission are already indicated by a bored horizon in the limestone bed below (Fig. 9b). Again, the succession is closely comparable to the western reaches of the Rhenish Kulm Basin. In the Herzkamp Syncline sections at Kohleiche and Riescheid, the Kohleiche Formation starts with a thin horizon bearing detrital quartz, phosphorite nodules, and phosphorite clasts that is overlain by a limestone horizon. Similar limestones are also known from other intrabasinal swells in the Kulm Basin, e.g. from the Warstein and Belecke anticlines (Kattensiepen Formation) or from the southernmost Dill Syncline (Erdbach Limestone II on top of the drowned Givetian-Frasnian Langenaubach-Breitscheid Reef).

Above, the TST of Sequence 5 is documented by the dark-grey to blackish, slightly calcareous, and only faintly siliceous shales at the base of the Hillershausen Formation (beds 36a–e, Figs. 7a, 8). Similar dark, in places also phosphorite-bearing shales are recorded from other intrabasinal swells in the Kulm Basin, for example in the Riescheid and Drewer sections (Herbig 2016). The lower calciturbidite set still records...
reworking of deeper water, slope-derived material and, thus, still relatively low sea levels (Fig. 9c–d). This is a corroboration of preliminary observations by Herbig et al. (2013, 2014) from the Zippenhaus Member of the Heiligenhaus Formation, which is a lateral equivalent of the Hillershausen Formation, and also observations from other depositional systems (Reijmer and Everaars 1991; Reijmer et al. 1991). Reworking of platform material – this means further rising sea level and initial flooding of the platform – is first documented in the upper calciturbidite set close to the top of the Borkewehr section (Fig. 9e–g).

**Depositional setting**

The regional geological context, lithofacies, lithostratigraphy, and sequence stratigraphic interpretation enable a characterisation of the depositional setting of the extraordinary Borkewehr section. In general, the section is situated on the southeastern slope of an overall palaeo-high related to the drowned lower Givetian-lower/middle Frasnian Hönne Valley Reef Complex. Volcanic activity (“Schalstein volcanism”) occurred during the uppermost Givetian in the surroundings of Balve, resulting in a 250 m thick, mostly tuffitic succession at the Husenberg, directly north of the Givetian in the surroundings of Balve, resulting in a 250 m thick, submarine relief (“seamount topography”) that was influenced later sedimentation (Dornsiepen 1973; Becker et al. 2016b). The complex palaeotopography of the region caused variously extended sedimentary breaks (e.g. Oberrödinghausen Railway Cut, Reigern Quarry, Becker et al. 2021) and special facies developments of the Fammennian to Viséan successions (Schäfer 1975, 1978).

For the Borkewehr section, sedimentation on a submarine high is evident by the well-developed Wocklum, Stockum, and Hangenberg limestones (Fig. 3). Continuous pelagic carbonate input (“pelagic rain”) resulted in a remarkably complete carbonate sequence, as demonstrated by the in conspicu-ous FSST and missing hiatus at the top of the Wocklum Limestone and – most important – by the complete conodont succession. Vice versa, the topographic high almost completely prevented coarse-grained clastic influx and suppressed the development of the Hangenberg Sandstone. Since the source of the sand was in the north (Koltonik et al. 2018, 2019), the Borkewehr section was in a more distal position than the typical Hangenberg Sandstone localities, such as Oese (compare Becker et al. 2021). Another phase of condensation started in the middle Tourinaisan (Herbig et al. 2019). Already Paeckelmann (1938) described the presence of a lower Carboniferous swell facies. The Kahlenberg Formation is locally extremely thin (Fig. 8) and deviates from the typical black alum shale facies observed elsewhere in the Rhenish Massif. The upper Tourinaisan siliceous shales and bedded cherts of the Hardt Formation are missing and typical deep swell limestones of the Erdbach type overlie the hiatus, but only as a thin veneer. Above, the exposed part of the Viséan Hillershausen Formation is remarkably poor in calciturbidites. This indicates either a missing well-developed source area on top of the Hönne Valley Reef Complex or, alternatively, turbidite currents that by-passed the swell according to the model first sketched by Bender et al. (1977) for Frasnian calciturbidites in the northeastern Rhenish Massif.

**Conodont faunas and stratigraphy**

Bed -12b of the Wocklum Limestone yielded our first conodont fauna (Fig. 3), which was extraordinary rich in juveniles. The bed yielded B. aculeatus aculeatus, both morphotypes of B. costatus and B. ultimus ultimus, B. ultimus corradinii M1, Pa. gracilis gracilis, Pa. gracilis expansa M1, Pa. gracilis semisigmoidalis, Pa. gracilis sigmoidalis, Ps. marburgensis trigosinus, the siphonodelloid N. Gen. 2 n. sp. sensu Becker et al. (2013, Fig. 10o–r), and intermediates between Br. inornata and Br. suprema (for taxonomic remarks compare Hartenfels 2011), amongst others. Although we did not obtain Si. (Eo.) praesulcata s.l., the ammonoid faunas (see below) and well-established ammonoid-conodont correlation (e.g. Becker 1996; Becker et al. 2016a, 2021) indicate that the

![Fig. 10 Conodonts from the Wocklum Limestone of Borkewehr.](image-url)
fauna falls in the Si. (Eo.) praesulcata s.l. Zone. The next younger carbonate layer (Bed -11b) provided, again, uppermost Famennian index taxa. In addition to B. aculeatus aculeatus, B. costatus M2, B. ultimus ultimus M2, and Ps. marburgensis trigonicus occur. The name-giving zonal marker conodont of the Si. (Eo.) praesulcata s.l. Zone enters delayed in Bed -10b. As a special feature, Famennian representatives of the rare genus Caenodontus were extracted from beds -8b and -4b (Fig. 10m), amongst others. Söte et al. (2017) described Caenodontus sp. from the basal part of the Si. (Eo.) praesulcata s.l. Zone at Reigern Quarry. Therefore, the new specimens are currently the youngest Famennian records. The genus is normally known from Permian (Behnken 1975; Dzik 2009) and Triassic (Kozur and Mostler 1976) strata but first occur locally as Lazarus events and range at least into the post-Crisis Interval. They are known especially higher level than the base of the former Zone, which was defined by the extinction of Pa. gracilis semisigmoidalis, Pa. gracilis expansa M1 (Fig. 10e), both morphotypes of B. costatus (Fig. 10a) and B. ultimus ultimus (Fig. 10d), B. bispathodus (Fig. 10b), B. muessenbergensis, Br. suprema (Fig. 10c), Ps. marburgensis trigonicus, and N. Gen. 2 n. sp. sensu Becker et al. (2013) have their LAD or Last Occurrence Datum (LOD), B. stabilis stabilis, B. stabilis vulgaris, B. aculeatus aculeatus, B. spinulicostatus M1, Br. inornata, M. strigosa, Neo. communis communis, Po. inornatus, and Si. (Eo.) praesulcata s.l. cross the main extinction event and range at least into the post-Crisis Interval. Protognathodus meischneri, Pr. collinsoni, Po. restrictus, all three morphotypes of Ps. primus primus (morphotypes introduced in Hartenfels and Becker 2016b online, compare taxonomic notes), Neo. communis phaphaensis, and Ps. inordinatus show locally delayed entries. They are known from upper to uppermost Famennian strata below the Hangenberg Black Shale, but first occur locally as Lazarus taxa in the earliest Stockum Limestone beds. Luppold et al. (1994) recorded, in addition, Po. inornatus (not figured) from the top Wocklum Limestone, but it could not be found in our samples. The extinction of B. costatus at the top of Bed -1b, the base of the Hangenberg Black Shale, defines the base of the ck1. It is a slightly higher level than the base of the former Middle praesulcata Zone, which was defined by the extinction of Pa. gracilis gonioicymeniae. Since the subspecies is lacking in our Wocklum Limestone samples at Borkewehr, the level of the former Middle praesulcata Zone is not recognisable locally. The Hangenberg Black Shale at Borkewehr is too fissile to search for bedding plane conodonts. We did not observe any specimens on partings of the Hangenberg Shale/Sandstone equivalents (beds 1a-b, Fig. 3).

As typical for pelagic settings, a Crisis Prelude Palmatolepid-Bispathodid Biofacies shifted locally into an Upper Crisis Interval Neopolygnathid-Protognathid Biofacies. Conodont samples from Bed 2, the basal Upper Crisis Interval I, were all barren. Bed 3 yielded Pr. meischneri, Pr. collinsoni, as well as Pr. semikockeli n. sp. (Fig. 11p). It documents the conodont radiation with continuing transgression in higher parts of Upper Crisis Interval I. Associated is Neo. communis communis (Fig. 11q), an opportunistic taxon (Söte et al. 2017). This assemblage marks the top of the costatus-kockeli Interregnum.

Bed 4b contains a joint Pr. collinsoni-Pr. kockeli assemblage of the Pr. kockeli Zone and Upper Crisis Interval II (Lower Stockum Limestone, Fig. 3). In concert with Pr. collinsoni (Fig. 11m) and Pr. semikockeli n. sp. (Fig. 11l), all three new morphotypes (M1:1, Fig. 11i-k; M1:2, Fig. 11h; M2:2) of Pr. kockeli enter together with kockeli relatives, which show incipient transversal ridges or transversally elongated nodes. The latter may be considered to be transitional between Pr. kockeli and Pr. kuehni. Therefore, the FAD of Pr. kockeli s.str., the index species

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*Fig. 11* Conodonts from the Upper Crisis Interval of Borkewehr (beds 3–5b). a Protognathodus kockeli (Bischoff, 1957) transitional to Pr. kuehni, GMM B9A.11-17, Bed 5b, Pr. kockeli Zone, oral view, ornament transitional between Pr. kockeli and Pr. kuehni. b Protognathodus kockeli (Bischoff, 1957) transitional to Pr. kuehni, GMM B9A.11-18, Bed 5b, Pr. kockeli Zone, oral view, ornament transitional between Pr. kockeli and Pr. kuehni. e Protognathodus kockeli (Bischoff, 1957) transitional to Pr. kuehni, GMM B9A.11-19, Bed 5b, Pr. kockeli Zone, oral view, ornament transitional between Pr. kockeli and Pr. kuehni. d Protognathodus kockeli (Bischoff, 1957) Morphotype 1:2, GMM B9A.11-20, Bed 5b, Pr. kockeli Zone, oral view. e Protognathodus kockeli (Bischoff, 1957) Morphotype 1:1, GMM B9A.11-21, Bed 5b, Pr. kockeli Zone, oral view. g Neopolygnathus communis phaphaensis (Savage, 2013), GMM B9A.11-23, Bed 5b, Pr. kockeli Zone, oral view. j Protognathodus kockeli (Bischoff, 1957) Morphotype 1:2, GMM B9A.11-24, Bed 4b, Pr. kockeli Zone, oral view, i Protognathodus kockeli (Bischoff, 1957) Morphotype 1:1, GMM B9A.11-25, Bed 4b, Pr. kockeli Zone, oral view, h Protognathodus kockeli (Bischoff, 1957) Morphotype 1:1, GMM B9A.11-26, Bed 4b, Pr. kockeli Zone, oral view, f Protognathodus kockeli (Bischoff, 1957) Morphotype 1:1, GMM B9A.11-27, Bed 4b, Pr. kockeli Zone, oral view. i Protognathodus semikockeli n. sp., paratype, GMM B9A.11-28, Bed 4b, Pr. kockeli Zone, oral view, g Protognathodus kockeli (Bischoff, 1957) Morphotype 1:2, GMM B9A.11-29, Bed 4b, Pr. kockeli Zone, oral view. n Protognathodus meischneri Ziegler, 1969, GMM B9A.11-30, Bed 4b, Pr. kockeli Zone, oral view. o Protognathodus meischneri Ziegler, 1969, GMM B9A.11-31, Bed 4b, Pr. kockeli Zone, oral view. p Protognathodus semikockeli n. sp., paratype, GMM B9A.11-32, Bed 3, costatus-kockeli Interregnum, oral view. q Neopolygnathus communis communis (Branson and Meeh, 1934b), GMM B9A.11-33, Bed 3, costatus-kockeli Interregnum, oral view.
of the former Upper prausulcata Zone, provides a suitable base for a revised, new Devonian/Carboniferous Boundary (compare discussion above) at the base of Bed 4b. The finding of Po. restrictus in Bed 4b give first-time evidence that its range has to be extended from the top of the Si. (Eo.) prausulcata s.l. Zone (compare range chart in Hartenfels 2011) into the Pr. kockeli Zone.

Prognathodus kockeli s.str. (Fig. 11d–e) also occurs in the subsequent Bed 5b in concert with B. aculeatus aculeatus, B. stabilis vulgaris, M. strigosa, Neo. communis communis, Po. purus purus (Fig. 11f), Si. (Eo.) prausulcata s.l., and, again, Pr. collinsoni. Unusual is a record of Neo. communis phaphaensis (Fig. 11g), which was first described by Savage (2013) from the upper Famennian postera zones (= Polygonatus styriacus to Pa. gracilis marco Zone) of north-west Thailand. The FOD of Po. purus purus is typical for Upper Crisis Interval faunas but Kaiser (2009) extended the range of this taxon downwards into the costatus-kockeli Interregnum of the La Serre stratotype (compare range discussion in Becker et al. 2016b). Since Becker et al. (2013) illustrated a related but distinguishable form as Po. cf. purus purus from the upper clk of Morocco, it is regrettable that the French early form has not yet been illustrated.

Our samples do not provide a local distinction of Lower (with Pr. kockeli) and Upper (with Pr. kuehni) Prognathodus faunas (Lower and Upper Stockham limestones/levels; compare Alberti et al. 1974; Clausen et al. 1989a; Bless et al. 1993; Becker et al. 2016a, 2021). Apart from intermediates between Pr. kockeli and Pr. kuehni (Fig. 11a–c), there is a delayed entry of Pr. kuehni s.str. in Bed 11b at the top of the Si. (Eo.) bransoni Zone, so far. However, Luppold et al. (1994, p. 39, not figured) recorded both Pr. kockeli and Pr. kuehni and, therefore, an “Upper Prognathodus Fauna”, from their “base of the Hangenberg Limestone”, which equals our Bed 4b/5b interval (Fig. 3).

Based on the entry of Si. (Eo.) sulcata s.l. M5 and of a transitional form between morphotypes 4 and 5 (Fig. 12m, lacking the Morphotype 4 typical constriction in the anterior part of the platform, compare Kaiser and Corradini 2011), Bed 6b marks the base of the Si. (Eo.) sulcata s.l./Pr. kuehni Zone and, thus, the currently valid base of the Devonian/Carboniferous Boundary. Associated are Neo. communis aff. dentatus sensu Luppold et al. (1984, Fig. 12s–t), Po. purus purus (Fig. 12q–r), and Ps. primus primus M2 (Fig. 11n–p). Bed 6b coincides locally with the base of the post-Crisis Interval and the base of the strongly cyclic Hangenberg Limestone. In terms of conodont biofacies, the local Upper Crisis Interval Neopolygonathid-Proagnosthathid Biofacies shifted to a post-Crisis Siphonodella Biofacies. Two carbonate-marl cycles above, Po. purus subplanus first occurs, with a local delay, in Bed 8b, together with Ps. primus primus M3. The latter was recorded by Hartenfels and Becker (2016b online) from the Famennian of the Tafiltat, SE Morocco, where it links Ps. primus primus with the more weakly ornamented Ps. controversus.

Upsection, the base of the Si. (Eo.) bransoni Zone is drawn at the base of Bed 10 (FAD of Si. (Eo.) bransoni, Fig. 3). It yielded a diverse and rich conodont fauna, with the LODs of B. aculeatus aculeatus (Fig. 12), B. stabilis stabilis, Neo. carina, Pr. meischneri, Pr. collinsoni (Fig. 12i), Pr. semikockeli n. sp. (Fig. 12e), and, therefore, an “Upper Prognathodus Fauna”, from their “base of the Hangenberg Limestone”, which equals our Bed 6b/10 interval (Fig. 3).

Fig. 12 Conodonts from the post-Crisis Hangenberg Limestone of Borkewehr (beds 6b–10). a Prognathodus kockeli (Bischoff, 1957) transitional to Pr. kuehni, GMM B9A.11-34, Bed 10, Si. (Eo.) bransoni Zone, oral view, ornament transitional between Pr. kockeli and Pr. kuehni. b Prognathodus kockeli (Bischoff, 1957) Morphotype 1:2, GMM B9A.11-35, Bed 10, Si. (Eo.) bransoni Zone, oral view. c Protognathodus kockeli (Bischoff, 1957) ?Morphotype 1:2, GMM B9A.11-36, Bed 10, Si. (Eo.) bransoni Zone, oral view. d Protognathodus kockeli (Bischoff, 1957) Morphotype 1:1, GMM B9A.11-37, Bed 10, Si. (Eo.) bransoni Zone, oral view. e Protognathodus semikockeli n. sp., paratype, GMM B9A.11-38, Bed 10, Si. (Eo.) bransoni Zone, oral view, advanced specimen with two rows of nodes parallel to the carina on the right side of the cup and two nodes on the left side. f Protognathodus semikockeli n. sp., paratype, GMM B9A.11-39, Bed 10, Si. (Eo.) bransoni Zone, oral view. g Protognathodus semikockeli n. sp., holotype, GMM B9A.11-40, Bed 10, Si. (Eo.) bransoni Zone, oral view. h Protognathodus collaris GMM B9A.11-41, Bed 10, Si. (Eo.) bransoni Zone, oral view. i Protognathodus collaris GMM B9A.11-42, Bed 10, Si. (Eo.) bransoni Zone, oral view. j Bispathodus aculeatus aculeatus (Branson and Mehli, 1934a), GMM B9A.11-43, Bed 10, Si. (Eo.) bransoni Zone, oral view. k Siphonodella (Eo.) sulcata Sandberg, 1972 (in Sandberg et al. s.l.), GMM B9A.11-44, Bed 10, Si. (Eo.) bransoni Zone, oral view. l Siphonodella (Eo.) sulcata (Huddle, 1934), Morphotype 5 sensu Kaiser and Corradini (2011), GMM B9A.11-45, Bed 10, Si. (Eo.) bransoni Zone, oral view. m Siphonodella (Eo.) sulcata (Huddle, 1934), transition-al form between morphotypes 4 and 5 (compare Kaiser and Corradini 2011), GMM B9A.11-46, Bed 6b, Si. (Eo.) sulcata s.l./Pr. kuehni Zone, oral view. n Pseudopolygnathus primus primus Branson and Mehli, 1934b Morphotype 2, GMM B9A.11-47, Bed 6b, Si. (Eo.) sulcata s.l./Pr. kuehni Zone, oral view. o–p Pseudopolygnathus primus primus Branson and Mehli, 1934b Morphotype 2, GMM B9A.11-48, Bed 6b, Si. (Eo.) sulcata s.l./Pr. kuehni Zone, oral view. q–r Polygnathus purus purus Voges, 1959, GMM B9A.11-49, Bed 6b, Si. (Eo.) sulcata s.l./Pr. kuehni Zone, oral view. s–t Neopolygnathus aff. dentatus sensu Luppold et al. (1984), GMM B9A.11-50, Bed 6b, Si. (Eo.) sulcata s.l./Pr. kuehni Zone, oral view. (t) lateral view.
slightly delayed, two carbonate layers higher in Bed 14 (Fig. 13m–n). Becker et al. (2021) emphasised that the lowest range of *Ps. triangulus inaequalis* requires further investigation. For example, Ziegler (1971) placed the base of the “*Ps. triangulus inaequalis Zone*” at Oese between his beds F and G, which is well below the locally oldest *Si. (Si.) mehli* Zone in Bed J. Represented by Morphotype 1:1, youngest local *Pr. kockeli* were recorded from Bed 15b, from the middle part of the *Si. (Si.) duplicata Zone*. We are aware that *Pr. kockeli* may show younger blooms in other sections (e.g. Flajs and Feist 1988; Becker et al. 2013).

Based on the absence of *Si. (Si.) mehli*, the base of the *Si. (Si.) mehli* Zone (= base of the former “Upper duplicata Zone”, Becker et al. 2021) is recognised by the entries of the alternative index conodonts *Si. (Si.) carinthiaca* (Fig. 13j) and *Si. (Si.) cooperi* in Bed 21b. Sandberg et al. (1978) suggested that *Si. (Si.) carinthiaca* as well as *Si. (Si.) cooperi* s.str. (= Morphotype 2) enter slightly later than *Si. (Si.) mehli* (= *Si. (Si.) cooperi* M1). As pointed out by Becker et al. (2021), published faunas from Rhenish successions do not provide support. The range of *Ps. inordinatus* Tragelehn and Hartenfels, 2012, introduced by Tragelehn and Hartenfels (2011) as *Ps. irregularis* (younger homonym of *Ps. irregularis* Branson, 1934) from the *Pa. gracilis expansa* Zone of Franconia, is extended at Borkewehr into the *Si. (Si.) mehli* Zone and, therefore, into the Mississippian.
Conodont diversity trends

Within the Wocklum Limestone, Bed -4b yields the most diverse fauna, with a total of 18 different taxa, including four morphotypes and the transitional form between Br. inornata and Br. suprema. The main conodont extinction took place at the base of the Hangenberg Black Shale, followed by the clastic interval without faunas. This local extinction rate of 57.1 % for the main Hangenberg Event lies in the lower range (55–72 %) of rates known from sections around the globe (Kaiser et al. 2009). However, it lies above the total pelagic extinction rate, which is at 38 % (compare discussion in Hartenfels 2020).

The onset of the new conodont radiation is locally recorded in the second limestone bed (= upper part of the “laminated” limestones) above the Hangenberg Shale/Sandstone equivalents, at the top of the cKL (Fig. 3). Beds 2 and 3 are lithologically similar. Although sampling was repeated, Bed 2 remained barren. The first conodont-bearing Bed 3 yielded four taxa, including the entry of Pr. semikockeli n. sp. (Fig. 11p). Intensive re-sampling, six successive attempts based on comparable sample sizes, did not change the result. The temporary disappearance of eight taxa known from the Wocklum Limestone marks an episodic regional diversity reduction (Lazarus phase), triggered by the ecological changes of the Hangenberg Crisis. With continuing transgression in the basal Pr. kockeli Zone, the overlying Bed 4b (which was also re-sampled several times) provided 12 different taxa, including four FODs of species and subspecies, and four local Lazarus taxa ranged through. This tendency culminates in Bed 10 at the base of the Si. (Eo.) bransoni Zone. The contrast between 16 proven (sub)species versus three Lazarus taxa shows that the ecological conditions were now favourable for many conodont taxa. Nevertheless, it represents a turning point in the local conodont diversity.

Starting from the immediately overlying Bed 11b at the top of the Si. (Eo.) bransoni Zone, the diversity decreases significantly. In contrast to the locally delayed entry of Pr. kuehni in our samples, there is a (local) loss of seven taxa. A total of six (sub)species is recorded, excluding seven local Lazarus taxa. Apart from some FODs and LODs and changes in the number of Lazarus taxa, the local palaeodiversity (between 14 and ten different taxa, including Lazarus taxa) remains fairly consistent until Bed 26b of the Si. (Si.) sandbergi Zone. At that level, there are seven (sub)species, excluding five Lazarus taxa. The conodont record in the subsequent carbonate layers decreases strongly. Whereas Bed 28b at the base of the Si. (Si.) lobata M1 Subzone yielded four conodont (sub)species and six Lazarus taxa, seven (sub)species are known from the topmost Hangenberg Limestone, Bed 30 (Fig. 3). This suggests a sudden local degradation of palaeoenvironmental conditions for conodonts, as a prelude to the subsequent Lower Alum Shale Event.

Ammonoid faunas and stratigraphy

From the beginning of regional research, the Borkewehr section has been recognised as an important locality for topmost Devonian ammonoids (Fig. 15). The top of the Wocklum Limestone is most fossiliferous. It yielded Wedekind (1914a, 1918) and Lange (1929) the types of Wo. denckmanni, Paraw. paradoxa, Epiwo. planulata, Fini. wocklumensis, Ken. tetragonum, and Cyma involvens. Overviews of the complete fauna can be found in Schmidt (1924) and Lange (1929), but later studies and new bed-by-bed collections, mostly by D. Weyer, added further records. Noteworthy are the contributions by Schindewold (1923, 1926, 1937), Korn (1981, 1994), Price (1982), Korn and Price (1987, 2019), Price and Korn (1989, Becker (1996, 2000), Ebbighausen and Korn (2007), and Becker et al. (2016a). The preservation of material is often poor due to diagenetic dissolution processes. Evolute clymeniids are mostly preserved as whorl fragments. Small-sized specimens recovered from within limestone nodules still may have shell and display growth ornament (Fig. 16). The following 19 (sub)species are known from the upper Wocklum Limestone of Borkewehr (Fig. 17):

Prionoceratoidea

Mayneoceras nucleus
Kenseyoceras rostratum (= biforme; new record, Fig. 15.g–h)
Kenseyoceras tetratum (new generic assignment based on the type illustration in Korn 1994)
“Mimimitoceras” lentum (some specimens could also belong to the closely related “Mm. ” geminum)
“Mimimitoceras” liratum (new record)
Mimimitoceras trizonatum (new record)

Sporadoceratoidea

Sporadoceras muensteri orbiculare (record of Schmidt 1924)

Tornoceratoidea

Ebbighausenites seidlitzi (= Sporadoceras posthumum of Lange 1929, Fig. 15a–b)

Wocklumerioidea

Wocklumeria denckmanni (including previous records of Wo. sphaeroides)
Epiwocklumeria planulata
Parawocklumeria paradoxa (Fig. 15c–d)
Parawocklumeria paprothae (see Becker 2000)
Parawocklumeria ?distorta (new record, poorly preserved)

Glatzielloidea

Postglaziella carinata (new record, Fig. 15i–l, a third specimen leg. H. Kaufmann)
Cyrtoclymenioidea
Cyrtoclymenia lateseptata (= Cyrt. angustiseptata of Schindewolf 1923)
Cymaclymenia involvens (Fig. 15e–f)
Cymaclymenia cf. sudetica (new record)

Clymenioidea
Lissoclymenia wocklumeri (probably including Oxyclymenia linearis of Lange 1929; reaching 12 cm diameter)
Lissoclymenia aff. wocklumeri (new record, with almost 60 % umbilical width)
Linguaclymenia sp. juv. (new record)

Gonioclymenioidea
Finiclymenia wocklumensis (including Sellaclymenia cf. angusta of Wedekind 1914a and Gonioclymenia plana of Schmidt 1924)

The faunal composition fits closely the well-known assemblages from the contemporaneous Parawo. paradoxa Subzone (UD VI-C2) to Wo. denckmanni Zone (UD VI-D) of adjacent sections, such as Oese, the Oberrödinghausen Railway Cut, Müssenberg, Dasberg, and Effenberg (e.g. Schindewolf 1937; Korn and Luppold 1987; Luppold et al. 1994; Klein and Korn 2015 online; Becker et al. 2021). Finiclymenia wocklumensis may be slightly more common than in other sections; associated are orthoconic cephalopods (e.g. “Orthoceras” cinctum).

The lower part of the Wocklum Limestone is locally strongly affected by folding and faulting. Underlying variably reddish and greenish nodular limestones (“Foßley”) yielded Wedekind (1914a, 1914b) Clymenia laevigata, an index clymeniid of the Dasbergian (UD V). We found a large, poorly preserved Kalloclymenia in the last reddish interval, which indicates the lower Wocklumian (UD VI-A/B). It confirms a former record of Kallo. subarmata by Wedekind (1914a). The collection of H. Kaufmann includes a well-preserved specimen of Kallo. pessoides, with whorls that are slightly wider than high, but its precise level is not known.

Table 1 Ranges of ammonoids in the upper part of the Wocklum Limestone at Borkewehr.

| Taxon                  | -19b | -17b | -16a/b | -15a/b | -14b | -6b | -5b | -4b | -3b | -2c |
|------------------------|------|------|--------|--------|------|-----|-----|-----|-----|-----|
| L. wocklumeri          |      |      | x      | x      |      |     |     |     |     |     |
| Fint. wocklumensis     |      |      | x      | x      |      |     |     |     |     |     |
| Parawo. paradoxa       |      |      | x      | x      |      |     |     |     |     |     |
| Parawo. ?distorta      |      |      |        |        |      |     |     |     |     |     |
| May. nucleus           |      |      |        |        |      | x   |     |     |     |     |
| Ken. rostratum         |      |      |        |        |      |     | x   |     |     |     |
| Postgl. carinata       |      |      |        |        |      |     |     | x   |     |     |
| “Mim.” lentum          |      |      |        |        |      |     |     |     | x   |     |
| Mim. trizonatum        |      |      |        |        |      |     |     |     |     | x   |
| Cyma. cf. sudetica     |      |      | x      |        |     |     |     |     |     |     |
| Wo. denckmanni         |      |      | x      |        |     |     |     |     |     |     |
| L. aff. wocklumeri     |      |      |        |        |      |     |     |     |     | x   |
| Cyma. involvens        |      |      |        |        |      |     |     |     |     |     |
| “Mim.” libratum        |      |      | x      |        |     |     |     |     |     |     |
| Linguaclymenia sp.     |      |      |        |        |      |     |     |     |     |     |
| Ebb. seidlitzi         |      |      | x      |        |     |     |     |     |     |     |

The Hangenberg Black Shale at Borkewehr is very fissile and disintegrates in the field. This is probably the reason why the post-extinction Postclymenia evoluta Zone (UD VI-E) has not yet been recognised. Schmidt (1924) recorded three prionoceratid species that indicate the Ac. (St.) prorsum Zone (UD VI-F to LC A1) – “Aganides infracarbonicus”, “Ag. guerichi”, and Ac. (Streeliceras) carinatum. Lange (1929) added Imitoceras subbilobatum, Im. cf. intermedium, and Im. substriatum. Without a re-examination of the types, it is
Fig. 15 Some small-sized ammonoids from the upper Wocklum Limestone of Borkewehr. a–b Ebbighauzenites seidlitzi (Schindewolf, 1924), GMM B6C.52-1, Bed -4b, juvenile showing very high whorls (whorl expansion rate near 3.0) and sutures, especially ventral saddles that become slightly subrectangular. (a) lateral view, (b) ventral view, x 2.5. c–d Parawocklumeria paradoxa (Wedekind, 1918), topotype, GMM B6C.52-2. Bed -15a/b, (c) lateral view, (d) adoral view, x 2.5. e–f Cymachymentia involvens Lange, 1929, GMM B6C.52-3, Bed -5b, juvenile topotype with shell, showing the lack of growth lines, (e) lateral view, (f) adoral view, x 4. g–h Kentseyoceras rostratum Selwood, 1960, GMM B6C.52-4, Bed -16a/b, typical micromorphic representative showing the sudden onset of a parabolic constriction and pronounced ventral keel, with an openly coiled Tolypammina in the body chamber, (g) lateral view, (h) ventral view, x 4. i–j Postglatziella carinata Schindewolf, 1937, GMM B6C.52-5, Bed -15a/b, whorl fragment showing the typical, concave flank ribbing and incipient ventral keel, (i) lateral view, (j) ventral view, x 4. k–l Postglatziella carinata Schindewolf, 1937, GMM B6C.52-6, Bed -16a/b, juvenile still without ribbing but showing sutures with a lingulate A-lobe on the flanks (unlike as in Schindewolf’s figures), incipient E-lobes, and a wide, low ventral saddle, (k) lateral view, (l) ventral view, x 5.
difficult to translate most of the old identifications into modern taxonomy. In addition, there are unsolved uncertainties whether Rhenish specimens are really conspecific with Acutimitoceras taxa described from Franconia (Kirchhattenhof), as it has been assumed in the past (e.g. Schmidt 1924; Vöhringer 1960; Korn 1984, 1994), but without sufficient knowledge of the ontogenetic morphometry of populations. New poorly preserved specimens of Acutimitoceras (Stockumites) sp. were recovered from beds 2, 3, and 4b, which fall in the upper part of the Ac. (St.) prorsum Zone that lies above the Hangenberg Sandstone equivalent (Upper Crisis Interval sensu Becker et al. 2021). One fragment originally had rather thick whorls, resembling Ac. (St.) kleinerae. Small-sized Ac. (St.) prorsum (Fig. 16), with typical, markedly biconvex growth lirae, constrictions, and relatively wide umbilicus, and a form close to Ac. (St.) intermedium were collected by H. Kaufmann from Bed 5b. The combination of old and new records shows that the Borkewehr section includes index goniatites around the revised DCB.

Schmidt (1924) mentioned a juvenile G. subinvoluta. This is sparse evidence for the post-Crisis G. subinvoluta Zone and for the occurrence of goniatites in the Hangenberg Limestone. We found one poorly preserved Acutimitoceras (Stockumites) sp. in Bed 7b (compare Becker et al. 2016a). The thin section of Bed 21b cuts through a widely evolute juvenile goniatite, probably an Eocanites of the nodosus Group (Fig. 6e), and a ribbed goniatite, which points to a member of the Pseudarieititinae, according to the conodont level (basal Si. (Si.) mehli Zone; Fig. 3), possibly Paprothites. In the Rhenish Massif, there is practically no ammonoid record from the middle Tourmaisian and only very few, poorly preserved specimens are known from the upper Kahlenberg Formation. Therefore, the discovery of a fragmentary, involute goniatite impression from dark-grey to blackish, slightly calcareous shales at the base of the Lower Alum Shale (Bed 31, Fig. 8) is exceptional. Seven, widely-spaced, convexly arches “ribs” may be the remnants of septa (wide dorsolateral saddles). A generic identification is not possible.

**Coral faunas**

Corals are extremely rare in the DCB beds of the Borkewehr section, as usual in sediments of the dysphotic/aphotic cephalopod facies, where rich anthozoan communities occur only exceptionally. Besides, they are usually ignored and remain uncолlected. A special one-day-search (collection K. Bartzsch and D. Weyer 1992) resulted in 13 determinable Rugosa and two Heterocorallia – mostly of dwarfish growth – from the upper 0.85 m of the Wocklum Limestone (Fig. 17).

This uppermost Famennian fauna is characterised by Neaxon regulus (Richter, 1848, Bed -19, Fig. 18b–c), the best index fossil among corals, ranging from the Clymenia laevigata Zone to the Wocklumeria sphaeroides Zone, up to the Hangenberg extinction Event, in Thuringia (Korn and Weyer 2003: fig. 19). It is known from Europe and the Holy Cross Mountains (central Poland) through Germany to the Montagne Noire (southern France) and has also been discovered at five localities in the Anti-Atlas (southern Morocco).

The tiny Neaxon n. sp. A (Bed -5b, Fig. 18d) indicates that more species of this genus existed in Wocklumian times than hitherto described. Other species from Poland and Germany are: Neaxon subcylindricum Różkowska, 1969, Neaxon bartzschii Weyer, 1978, Neaxon muensteri Weyer, 1989, Neaxon n. sp. sensu Korn and Weyer (2003), but not Neaxon teniseptatum Różkowska, 1969, which meanwhile was transferred to the unrelated Petraiia Münster, 1839.

*Laccophyllum rozkowskiae* (Fodorowski, 2003) was found in the upper Famennian of the Holy Cross Mountains and at Dasberg near Hövel in the Rhenish Massif. Better preserved and analysed material is needed for a revision of this species, which might include *Laccophyllum aff. rozkowskiae* (Bed -5b, Fig. 18a) from the Wocklum Stufe as the hitherto unknown juvenile stages. Unpublished upper/uppermost Famennian
and lower Tournaisian collections yield many new species of the genus and of related Laccophyllinae.

A questionable Famennelasma sp. indet is represented by a crushed specimen of normal, large size (calice diameter ca. 20 mm, Bed -19, Fig. 17). This upper/uppermost Famennian genus was recorded from the Rhenish Massif and Thuringia and occurs also in Morocco. In Poland, it was described as *Amplexizaphrentis conus* Rózkowska, 1969. Its relationship to the problematical genus *Friedbergia* Rózkowska, 1969 remains unclear (Weyer 1973b; Berkowski 2002; Korn and Weyer 2003).

The two small fragments of the heterocoral *Oligophylloides* sp. indet (diameter 0.6–0.9 mm) are now usually interpreted as parts of destroyed colonies, indicated by budding in one specimen, determinable only at the generic level (Bed -4b, Fig. 18e). Middle to uppermost Famennian *Oligophylloides* are widely distributed in Poland, Germany, France, and especially in Morocco, with only one fragmentary specimen as questionable survivor of the global Hangenberg Crisis in the higher part of the *Si. (Eo.) sulcata s.l./Pr. kuehni* Zone at La Serre (Bed 93, Montagne Noire, Vachard 1988: pl. 2, fig. 1; Weyer 1995: fig. 5).

Lower Tournaisian corals from the ca. 1.2 m thick Hangenberg Limestone (Fig. 17) are rare and were never systematically collected at Borkewehr. We know only two specimens. One small coral, *Drewerelasma?* n. sp. B (length 18 mm), was stored undetermined in the former Prussian Geological Survey in Berlin (H. Schmidt collection 1923, not mentioned in his publication 1924, without precise bed data) and is now intensively sectioned. This lower Tournaisian genus (Weyer 1973a, 1994; Korn and Weyer 2003) is typical for the German Hangenberg Limestone (Rhenish Massif) and the equivalent Pfaffenberg Member of the Saalfeld region (Thuringia). It occurs in synchronous beds at Dalnia (Holy Cross Mountains); “*Saleelasma sp.*” (Rózkowska in Szulczewski 1973: p. 12, tab. 1). Asiatic records come from the Berchogur section (Mugodzhary region, Kazakhstan, unpublished specimen, “*Imitoceras* bed” of Kuzina in Barskov et al. 1984, “Upper praesulcata Zone”) and from NW China (Hoboksar section, northern Xinjiang). There, the youngest uppermost Famennian coral zone of Liao and Cai (1987) is characterised by *Metriophyllum omhaense* Liao and Cai, 1987 and *Metriophyllum curvipectatum* Liao and Cai, 1987. These species might be transferred to *Drewerelasma* Weyer, 1973a and are younger according to conodont data in Sartenaer and Xu (1990: p. 39, *Protagonathodus* fauna of the “Upper praesulcata Zone”). The unique specimen from Wocklum differs from typical
Drewerelasma in the absence of an antiseptal triad. This might be interpreted as an only juvenile feature or as a sign for a separate genus; similar in the situation in the tabulacarian Devonian ancestor 
*Metriophyllum* Milne-Edwards and Haimé, 1850.

The second rugose coral was found in a thin section (Bed 27, collection S. Hartenfels, Figs. 6c, 17). It is the typical Cyathaxonia Hasselbachtal and Oberrödinghausen Railway Cut (Rhenish Massif). For the moment, a final specific determination seems impossible due to the problematical taxonomic situation within the genus Cyathaxonia Michelin, 1847 (see Weyer 1994: p. 184). Throughout its lifespan (lower Famennian–Cisuralian), species are extremely similar and difficult to diagnose. In the literature, there are “lumpers” (e.g. Schindewolf 1951) and “splitters” (e.g. Fomichev 1953); the latter taxonomic practice is preferred here. A dominating species Cyathaxonia cornu Michelin, 1847, ranging through the complete Mississippian, is not acceptable. Populations of a short time interval, such as the lower Hastarian (Gattendorfia Stufe), and from different, mainly German regions, lead to recognition of four morphotypes, which could be named as separate species. One of them is Cyathaxonia n. sp. A from Drewer (Schindewolf 1951: p. 101, Cyathaxonia cornu n. ssp.; Weyer 1994: p. 184, fig. 2), which occurs also in Asia (Berchogur section, Mugodzhary, Kazakhstan). The true upper Tournaisian Cyathaxonia cornu Michelin, 1847 was studied for comparisons (collections from the Baltic Sea island of Rügen, borehole Dranske 1/1968, Weyer 1993: fig. 3).

The genera Drewerelasma and Cyathaxonia are typical and dominant elements in the richer German coral faunas of the Gattendorfia Stufe (Saalfeld in Thuringia, Oberrödinghausen Railway Cut and Drewer in the Rhenish Massif).

**Geochemistry**

Carbon isotopes

The Devonian-Carboniferous transition was associated with a significant perturbation to the global marine carbon cycle, as indicated by distinct positive excursions of both $\delta^{13}C_{\text{carb}}$ and $\delta^{13}C_{\text{org}}$ in the Hangenberg Crisis Interval worldwide (Brand et al. 2004; Kaiser et al. 2006, 2015; Cramer et al. 2008; Kump et al. 2015, 2020; Qie et al. 2015, 2021). The Hangenberg carbon isotope excursion was generally attributed to either abundant organic carbon burial during the Lower Crisis Interval (HBS and equivalents) or enhanced primary productivity in the Upper Crisis Interval (initial post-glacial transgressive interval), although the precise timing, pattern, and controlling mechanism remain debatable (see discussions in Kaiser et al. 2015 online and Qie et al. 2015). At Borkewehr, high-resolution $\delta^{13}C_{\text{carb}}$ records (n = 42) were obtained from the Wocklum, Stockum, and Hangenberg limestones at intervals between 1 to 12.5 cm, whereas the 103 cm-thick HBS (Bed 0), HS/HSS (beds 1a–1b), and possible basal Stockum Level Black Shale (Bed 1c) equivalents yielded no $\delta^{13}C_{\text{carb}}$ data (Fig. 19). Meanwhile, two samples from beds -6a and 27 show low $\delta^{13}C_{\text{carb}}$ values of -0.3 ‰ and -2.5 ‰, respectively, which are best explained by diagenetic alteration, evidenced by abnormal $\delta^{18}O_{\text{carb}}$ values (Fig. 19). In the pre-Crisis Interval, the Wocklum Limestone records baseline $\delta^{13}C_{\text{carb}}$ values of 1.7 ‰ that decrease slightly to 1.4 ‰ at the top of the Si. (Eo.) praeusculata s.l. Zone (Fig. 19). Above the HBS and fine-grained siliciclastic successions, $\delta^{13}C_{\text{carb}}$ drifted toward higher values in the Upper Crisis Interval I and II (beds 2 to 6a), reaching a peak value of 2.2 ‰ in the Pr. kockeli Zone (Bed 4b), and representing the Hangenberg Crisis carbon isotope excursion in the Rhenish Massif. Upsection, a long-term gradual decrease to lower value (~0.2 ‰) in the lower to middle Tournaisian is observed, except for two minor positive shifts in the Si. (Eo.) bransoni Zone and basal Si. (Si.) sandbergi Zone (Fig. 19). A similar pattern of $\delta^{13}C_{\text{carb}}$ records was observed from other pelagic DCB successions in the Rhenish Massif (Hasselbachtal), Carnic Alps (Grüne Schneid, Kronhofgraben), and South China (Muhua II, Gedongguan, Daposhang), characterised by relatively constant $\delta^{13}C_{\text{carb}}$ values in the pre-Crisis Interval, a minor positive shift (generally < 1 ‰) in the Pr. kockeli Zone, and gradual decrease to ~0 ‰ in the aftermath of the Hangenberg Crisis (Kaiser 2005; Qie et al. 2021). Global time-varying signals of $\delta^{13}C_{\text{carb}}$ allow for high-resolution regional and intercontinental correlation of the DCB intervals.

Unlike the widely studied $\delta^{13}C_{\text{carb}}$ excursion in the DCB successions, $\delta^{13}C_{\text{org}}$ records were merely reported in several localities from Canada, the Rhenish Massif, Carnic Alps, Poland, and Vietnam (Caplan et al. 1996; Kaiser 2005; De Vleeschouwer et al. 2013; Paschall et al. 2019). A global $\delta^{13}C_{\text{org}}$ trend has not been well established due to complex isotopic fractionation between dissolved CO$_2$ and primary biomass, organic matter source variation, secondary biological fractionation (e.g. heterotrophy), widespread sedimentary gaps, and lack of precise biostratigraphic control. In the Rhenish Massif and Carnic Alps, Kaiser et al. (2006, 2015) reported peak $\delta^{13}C_{\text{org}}$ values within the Hangenberg Crisis Interval, mainly in the Lower and Upper Crisis intervals and their equivalents, and suggested that the shifts of $\delta^{13}C_{\text{org}}$ values reflect enhanced burial of organic carbon during the major climate and environment perturbations around the Devonian-Carboniferous transition. At Borkewehr, $\delta^{13}C_{\text{org}}$ values range from -22.7 to -28.3 ‰, and the profile exhibits a major positive excursion from -25.4 ‰ to -22.8 ‰ in the HS/HSS equivalents (beds 1a and 1b) rather than in the Lower and Upper Crisis intervals (Fig. 19). $\delta^{13}C_{\text{org}}$ values decrease to -26.6 ‰ near the basal Upper Crisis Interval I (Bed 2), stay stable around -26.9 ‰ in the Upper Crisis Interval (top clk to
lower *Si. (Eo.) sulcata* s.l./*Pr. kuehni* Zone), then return to -25.1 ‰ in the *Si. (Eo.) bransoni* Zone, before recording a gradual decrease to -28.2 ‰ at the top of the Hangenberg Limestone. At Borkewehr, the $\delta^{13}C_{\text{org}}$ profile of the Hangenberg Crisis Interval is markedly different from trends in $\delta^{13}C_{\text{carb}}$ and the previous description of Kaiser et al. (2015) in this region, an indication that other factors (e.g. changes of organic matter compositions and atmospheric $pCO_2$) rather than changes of $\delta^{13}C$ of oceanic dissolved inorganic carbon (DIC) are responsible for the decoupling of $\delta^{13}C_{\text{org}}$ and $\delta^{13}C_{\text{carb}}$. High-resolution studies of paired $\delta^{13}C_{\text{carb}}$ and $\delta^{13}C_{\text{org}}$ records in widely separated regions are needed to
reveal controlling factors of major carbon cycling perturbations during the Devonian-Carboniferous transition.

Inorganic geochemistry

Concentrations of the elements used in the present study are shown in the supplementary material (Online Resource 1). The principal component analysis of ICP-OES/MS dataset revealed common relationships among measured elements and discriminated groups of elements with similar geochemical behaviour. The principal components PC1 and PC2 explain 69.52 % and 16.39 % of dataset variance, respectively. The PC3 explains 4.16 % of the total variability (Online Resource 3). Group 1 comprises Ca, Sr, and Mn, elements with affinity to carbonates, which have a strong positive score on PC1 and low negative score on PC2. Group 2 involves mainly lithophile elements (e.g. Al, Si, Fe, Zr, Ti, K, Rb) and Rare Earth Elements (REEs), with strong negative score on PC1 and low positive score on PC2. Group 3 is represented by Zn, Cu, Pb, Co, U, as well as Ni and is characterised by positive scores on PC1 and negative scores on PC2 (Online Resource 3.1). The main majority of the groups 1 and 2 can be explained by carbonate dilution of siliciclastic detritus (PC1). Group 3 consists of elements, typically related to autigenic phases or organic matter, deposited in reducing or high-productivity conditions (Craigie 2018). The main lithologic types can be categorised by CaCO₃ content to carbonate composition during the Devonian-Carboniferous transition. REEs concentrations have been normalized to the REEs composition of average upper continental crust (UCC, McLennan 2001), where N stands for REEs normalized to UCC:

\[
REE_N = \frac{REE_{sample}}{REE_{UCC}}
\]

Detrital input

The terrigenous elements, namely K, Rb, and Ti, have high statistic correlation with Al (\(r_s = >0.9, n = 35, p < 0.05\)), indicating their affinity to clay minerals. Faintly lower correlation between Al and Si (\(r_s = 0.83, n = 35, p < 0.05\)) is probably influenced by presence of biogenic silica. Average content of Al is 1.2 % in carbonate facies, 4.1 % in mixed facies, and 7.9 % in siliciclastic facies. The Al/Ti ratio is between 14 and 22 (mean 18.8), which is close to the UCC values (Al UCC/Ti UCC = 19.6; McLennan 2001) or Post Archaean Australian Shale (Al PAAS/Ti PAAS = 17; Taylor and McLennan 1985), and thus indicates detrital Al and Ti source (Murray and Leinen 1996). Also, an average Zr/Al ratio (0.0029) is similar to the Zr/Al of UCC (0.0024; McLennan 2001), revealing a detrital origin of Zr. Zr/Al is used as a proxy for tracing the variations in grain size of detrital particles in fine grained sediments, as Zr is enriched in the silty and sandy fraction, whereas Al is carried mainly by clay minerals (e.g. Ganeshram et al. 1999; Calvert and Pederson 2007). Correlation between Al and Zr is strong (\(r_s = 0.83, n = 35, p < 0.05\)) but slightly lower compared to other terrigenous elements. This can be explained by the combination of carbonate dilution and the effect of sorting in the siliciclastic facies (Online Resource 3.2). The Zr/Al curve displays a well-marked cyclic pattern through the section, especially in the Wocklum Limestone. These cycles correlate well among northern Rhenish Massif DCB sections (e.g. Oberrodinghausen Railway Cut, Oese, Drewer; compare Kumpan et al. 2015). Zr/Al values drop in the lower portion of the studied Wocklum Limestone (Fig. 20a) as a record of fining of detrital grain size, probably related to the deepening of the depositional environment. Up section, Zr/Al values increase in the cyclic pattern indicating coarsening, which matches with the shallowing trend inferred from facies analysis (see above). The decreasing Zr/Al pattern in the Hangenberg Black Shale (Fig. 20a) supports a transgressive nature of the unit. The overlying Hangenberg Shale/Sandstone equivalents start with a sharp Zr/Al increase reaching the highest values of the dataset approximately 45 cm below the top of this unit (Fig. 20a) and is correlated by us with the base of the Hangenberg Sandstone. It reflects the presence of the coarsest clastic material and records the maximal regression. Zr/Al values decrease from the upper part of the Hangenberg Sandstone equivalent to the dark-grey platy limestones of the Upper...
In general, Zr/Al values increase in cyclic manner from the Wocklum Limestone up to the top of the Hangenberg Limestone. Higher Zr/Al ratio and Al content distinguish the Hangenberg Limestone from the Wocklum Limestone and reveal more proximal depositional setting of the former. Rb/K and K/Al ratios are proxies for weathering intensity related to mobilisation of K during chemical weathering, although K/Al is partly controlled by grain size (Bábek et al. 2016a). Rb/K values are lower and K/Al values are higher in the studied limestones than in siltstones, revealing the more dominant role of a mechanical weathering during deposition of limestones. The highest K/Al values are below the top of the Wocklum Limestone (Bed -4b), followed by K/Al decrease toward the top of the Hangenberg Crisis interval (Fig. 20a). A change in weathering character took place at the base of the Lower Crisis Interval, where low K/Al and high Rb/K ratios indicate the deposition of products of more weathered clastic material. Higher Rb/K ratios indicate deposition of chemical weathering products, both in the Hangenberg Shale/Sandstone equivalents and in the overlying dark-grey platy limestones. A decreasing K/Al trend demonstrates the combined influence of increased weathering and grain size fining upward. K/Al increases and Rb/K decreases again in the Stockum and Hangenberg limestones (Fig. 20a).

Crisis Interval (beds 2 and 3). The redox-sensitive trace elements V, Cr, Ni, and U revealed strong affinity to the detrital component, as they show good statistical correlations with Al (rs = > 0.8, p < 0.05) and low enrichment factors, which complicates their application as redox proxies. Moderate correlation with Al is shown by Mo and P (rs = 0.7, p < 0.05). Weak correlation with Al has As (rs = 0.3, n = 35, p < 0.05) and Pb, Cu, and Sb have no statistically significant correlation with Al (Online Resource 2). These elements have higher enrichment factors in several samples. Their enrichments can be considered as a product of authigenic accumulation in oxygen deficient conditions (Tribovillard et al. 2006).

Redox and palaeoproductivity

The redox-sensitive trace elements V, Cr, Ni, and U revealed strong affinity to the detrital component, as they show good statistical correlations with Al (rs = > 0.8, p < 0.05) and low enrichment factors, which complicates their application as redox proxies. Moderate correlation with Al is shown by Mo and P (rs = 0.7, p < 0.05). Weak correlation with Al has As (rs = 0.3, n = 35, p < 0.05) and Pb, Cu, and Sb have no statistically significant correlation with Al (Online Resource 2). These elements have higher enrichment factors in several samples. Their enrichments can be considered as a product of authigenic accumulation in oxygen deficient conditions (Tribovillard et al. 2006).

Wocklum Limestone: The enrichments of Cu (EF up to 13) and Sb (EF = 5) first occur in the upper part of the Wocklum Limestone (4 to 5 m of the section thickness, Fig. 20a) and are followed by enrichments of Cu (EF = 5.7), Sb (EF = 21.8), Pb (EF = 6.7), As (EF = 134.0) (Fig. 20a), and P (EF = 4.6, Online Resource 3.3) in the uppermost part of the limestone unit. The enrichment of redox-sensitive trace elements is interpreted as a record of the iron shuttle process and episodic oxygen-deficient conditions (Tribovillard et al. 2013, 2015). The oxic-anoxic fluctuations are also supported by the REE...
(see section REE geochemistry). Oxygen-deficient conditions are also evidenced by the presence of pyrite and decreased bioturbation in the uppermost part of the Wocklum Limestone (see above). However, Cu, Sb, Pb, and As enrichments do not correspond with low Mo$_{EF}$ and U$_{EF}$ (Online Resource 3.3) and thus exhibit differential responses to weathering or high-frequency redox fluctuations (Jin et al. 2018). Low Mo$_{EF}$ and U$_{EF}$ may indicate the loss of Mo and U during weathering. This may be supported by a high Co/Mo ratio (Online Resource 1), which may reflect more intense dissolution of the original metal enrichment as Co is preferentially retained in the original sediment layer because of the high insolubility of Co(II)oxyhydroxides and the slow reaction kinetics of Co(III) (Märtz et al. 2011). Another factor influencing low Mo is caused by the distinct hydrological restriction of the basin indicated by low Mo/TOC ratios ranging between 4.3 and 21.3 (Fig. 20a, Online Resource 1; Algeo 2004; Algeo and Rowe 2012). A slightly lesser basin restriction is apparent at the top of the Famennian with no restriction at the Hangenberg Black Shale Event (Mo/TOC = 121, Fig. 20a), regarded as transgressive by many authors (e.g. Kaiser et al. 2015 online). These data are similar to those obtained in the Namur-Dinant Basin (Kumpan et al. 2019a, b).

Hangenberg Black Shale and Hangenberg Shale/Sandstone equivalents: The lower part of the Hangenberg Black Shale has higher Cu$_{EF}$ (7.5) and As$_{EF}$ (16.5), which increase together with EFs of other trace elements (Cu$_{EF}$ = 4.1, Zn$_{EF}$ = 4.7, As$_{EF}$ = 91.9, U$_{EF}$ = 4.8, Pb$_{EF}$ = 20.2, Sb$_{EF}$ = 14.0, Fig. 20a) and contents of S, Hg, and Mo (Online Resource 3.3) in the uppermost part of the black shale, revealing deposition in anoxic conditions. The calculated redox proxies suggest a conflicting redox interpretation of the lower part of the Hangenberg Black Shale with redox conditions between ferruginous andoxic conditions. The U/Al, V/Al, and Mo/Al proxies of Bennett and Canfield (2020) show an oxic or seasonal oxygen minimum zone (OMZ) in the lower part of the Hangenberg Black Shale and a seasonal OMZ in the upper part (Online Resource 3.4). High As$_{EF}$ and medium Sb$_{EF}$ may indicate the iron shuttle process and the lack of significant Mo$_{EF}$ may suggest the release of Mo during weathering, supported again by the high Co/Mo ratio (Märtz et al. 2011). The U/Th ratio reaches the value 1.25 in the uppermost part of the Hangenberg Black Shale (Fig. 20a), indicating the transition from suboxic to anoxic conditions (Jones and Manning 1994). The low content of all redox-sensitive trace elements may indicate oxic conditions for the overlying Hangenberg Shale/Sandstone equivalents (Fig. 20a).

Stockum and Hangenberg limestones: The low content of redox-sensitive trace elements may indicate prevailing oxic conditions in the Stockum and Hangenberg limestones. The only exceptions are the enrichments of As (EF = 37) and Sb (EF = 9), accompanied by higher Mo/Al at 7.9 m of the section thickness (Fig. 20a, Online Resource 3.4). The enrichment indicates the role of the Fe and Mn oxyhydroxide shuttle, which may have been connected with suboxic conditions. Increased U/Al and V/Al ratios at 8.5 m of the section thickness (Fig. 20a) correspond to oxic to seasonal OMZ in the model of Bennett and Canfield (2020; Online Resource 3.4). Pyrite occurrences restricted to beds 15b (~ 7.9 m) and 29 (~ 8.5 m, see above) may support this interpretation.

REE geochemistry

There is no systematic change of REE patterns through the Crisis interval (Fig. 20) but the REE distribution develops two characteristics through the section: (1) a ‘flat distribution’ signifying predominantly terrigenous siliciclastic influence supported by a very good correlation of REEs and Al (rs = 0.82, n = 35, p < 0.05, Fig. 20b, Online Resource 3.5), (2) a ‘middle-REE bulge’ (Fig. 20b, Online Resource 3.5) due to adsorption of light and heavy REEs to Mn and Fe oxyhydroxides, respectively, documented by a positive MREE/MREE* anomaly and supported by a relatively high content of Fe and Mn, high Al/(Al+Fe+Mn) ratios, and a low Y/Ho ratio (Online Resource 4). The MREE bulge represents an early diagenetic signature associated with suboxic to anoxic conditions, possibly related to diagenetic dissolution of Mn and Fe oxyhydroxides (Haley et al. 2004; Himmler et al. 2010; Chen et al. 2015; Fig. 20b). The early diagenetic REE enrichment appears to vary as a function of the influence of the Fe-Mn oxyhydroxide shuttle and redox cycling and the content of clay minerals and phosphates (Abbott et al. 2015; Chen et al. 2015; Yang et al. 2017).

The (La/Yb)$_N$ and (La/Sm)$_N$ proxy (Reynard et al. 1999; Lécuyer et al. 2004; Fazio et al. 2007) shows the influence of early diagenesis and adsorption (Online Resource 3.6). The role of diagenesis is supported also by (La/Nd)$_N$ and Y$_{anom}$ crossplots, by a weak positive correlation between (La/Sm)$_N$ and Ce anomaly (Ce/Ce* = 0.5 x (La$_N$ + Pr$_N$)), weak negative correlation between Eu (Eu/Eu* = Eu$_N$ / (Sm$_N$ / (Sm$_N$ / Tb$_N$)^1/3)) and Ce anomalies, and weak negative correlation between the Dy/Sm$_N$ ratio and Ce anomalies, which also implies that Ce/Ce* values have been affected by MREE arching (Shields and Stille 2001; Fazio et al. 2007; Online Resource 4).

Positive Eu anomalies seem to indicate a hydrothermal source (Bau 1991; Fitzgerald and Gillis 2006; Jiang et al. 2007). Relatively low Ba/Sm and Ba/Nd ratios and a negative correlation between Ba/Sm and Eu/Eu* indicate that the anomaly is not influenced by Ba interference (Jiang et al. 2007; Online Resource 3.6). Positive Eu anomalies have been distinguished in the uppermost Devonian of different parts of the Rhenohercynian Zone (Kalvoda et al. 2018; Kumpan et al. 2019a).
The oxic-anoxic fluctuations, inferred from the redox sensitive trace element enrichments for the upper part of the Wocklum Limestone, are supported by the MREE bulge (Fig. 20b; Reynard et al. 1999; Shields and Webb 2004; Lécuyer et al. 2004; Gu et al. 2019) and a changing Ce anomaly ranging between 0.46 and 1.02 (Online Resource 4). The role of REE in redox interpretation is obscured in shale samples from the Lower and Middle Crisis intervals. The samples with a strong correlation between Al/ΣREE indicate a modification of the original ‘seawater’ REE signal and Ce anomaly by detrital input (Fig. 20b; e.g. Frimmel 2009; Tostevin et al. 2016). The MREE bulge supports episodic suboxic to anoxic conditions interpreted in the Hangenberg Limestone (7.9 m, Fig. 20b, Online Resource 4).

Pyrite framboids

Pyrite framboids, altered by weathering to Fe-oxyhydroxides, were only observed in the uppermost part of the Hangenberg Black Shale, where diameters of 102 pyrite framboids were measured. The minimum diameter was 1.3 μm, the maximum diameter was 16.2 μm, the mean 3.9 μm, and the standard deviation 2.1 μm (Online Resource 1). In the sample, small framboids predominate (< 5 μm, n = 88), whereas large framboids (> 10 μm) were rare (n = 3). The size distribution of pyrite framboids (Fig. 20c) indicates anoxic conditions (Wignall and Newton 1998) during deposition of the uppermost part of the Hangenberg Black Shale and supports the geochemical interpretation based on the high trace metals enrichment.

Cyclostratigraphy

The Borkewehr section is particularly well-suited for cyclostratigraphy across the DCB for two reasons. First, based on the microfacies survey, there is no evidence for sedimentary hiatuses or major reworking events. Second, the section exhibits a steady lithological rhythm between marls/shales and limestones at the centimetre scale, prior to, as well as after, the Hangenberg Crisis. A typical cycle starts with a thin-bedded marly or shaly layer, followed by a slightly thicker (nodular) limestone bed. However, prior to a cyclostratigraphic assessment of the lithological rhythms, the primary nature of the limestone/marl alternations needs to be assessed. This is because differential diagenesis may produce secondary limestone/marl alternations that mimic astronomical signals. Here, we adopt a technique first suggested by Westphal et al. (2010) and later refined by Nohl et al. (2021), which considers the ratio of diagenetically inert elements such as Al and Ti. The marls and limestones of the Wocklum Formation at the Borkewehr section exhibit two separate trend lines in the Al vs. Ti cross-plot, indicating a bimodal chemical composition of the non-carbonate fraction. This is a clear indication of varying environmental conditions, notably of changes in the hinterland weathering regime, and is a strong indication that the observed marl/limestone rhythms are of primary origin (Nohl et al. 2021). Titanium in soils is less soluble than aluminium. Hence, the relatively low Al/Ti ratios in the Borkewehr marls and shales (~0.54 for limestone layers) indicate that these lithologies were formed under a more intense weathering regime compared to the interbedded limestone layers (Fig. 21).

The thicknesses of lithologic couplets range between 3 and 10 cm. This relatively large range can be explained with three scenarios, of which the third is advocated in this study.

- In a first scenario, all lithological cycles are the result of the same forcing factor with a quasi-constant periodicity. The changing thickness of lithological couplets can be ascribed to changes in accumulation rate. We consider this scenario unlikely, as the section was deposited below the photic zone and storm wave base. Sedimentation rate variability, with two-fold or three-fold changes over relatively short periods of time, are not in line with expectations for such a calm sedimentary environment, without major reworking.

- In a second scenario, a relatively steady sedimentation rate is assumed and all lithological cycles are the result of the same forcing factor with a quasi-constant periodicity. In this

![Fig. 21 Diagenetically inert element ratios (Al/Ti; ED-XRF dataset, Online Resource 1) from the Wocklum Limestone (limestones black squares, marls/shales grey triangles). Two separate trend lines reveal differences in the non-carbonate fraction between limestones and marls, indicating significantly different weathering regimes in the hinterland during the deposition of either lithology. The bimodal composition of the non-carbonate fraction reflects varying environmental conditions and thus proves the primary origin of the lithologic rhythmicity (see Fig. 20a for stratigraphic variations in Ti/Al).](image-url)
scenario, the variations in couplet thickness are explained by the sedimentary system, occasionally failing to develop a thin-bedded marl/shale during a forcing extreme. In other words, the sedimentary system sometimes misses a beat, but sedimentation rates are more or less constant. We also deem this scenario unlikely because a random distribution of thicker cycles throughout the lithological column would be expected. This is not the case in Borkewehr.

**Fig. 22** Cyclostratigraphic interpretation of the lithologic couplets at the Borkewehr sections. Thinner cycles (3.5–5.5 cm) are interpreted to reflect precession cycles (green), whereas somewhat thicker cycles (7–12.5 cm) are associated with obliquity (blue). The lithological cyclicity is used as a geologic metronome by applying the theoretical periodicities of precession (18.5 kyr) and obliquity (33 kyr), as calculated by Berger et al. (1992). Whereas the lower power spectrum refers to the cyclic succession (Wocklum Limestone) below the siliciclastics of the Hangenberg Black Shale and Hangenberg Shale/Sandstone equivalents, the upper power spectrum refers to the cyclic succession (Stockum and Hangenberg limestones) above.
- In a third scenario, relatively steady sedimentation rates and lithological cycles with different thicknesses reflecting the sedimentary response to different astronomical forcing factors are assumed. In this scenario, the thinner cycles, spectral peaks with a periodicity around 4 cm (Fig. 22) are attributed to precession, as previously suggested by Becker et al. (2012). The thicker cycles that have spectral peaks with a periodicity of ~8.3 cm in the Hangenberg Limestone (Fig. 22) are ascribed to obliquity. Considering an 18.5 kyr and 33 kyr periodicity for precession and obliquity, respectively (Berger et al. 1992), the suggested relationship between astronomical parameters and lithological couplets implies a sedimentation rate of ~0.23 cm/kyr (after compaction). This value chiefly complies with the first-order chronologic constraints from biostratigraphy.

Here, we advocate the third scenario because the Borkewehr section exhibits interesting stacking and amplitude modulation patterns. In the Wocklum Limestone as well as in the Hangenberg Limestone series of four to six thinner cycles are interrupted on both sides by a thicker cycle. As the thinner cycles are thought to be of precessional origin, it is expected to see indications of amplitude-modulation of those cycles by orbital eccentricity with 100-kyr and 405-kyr periods. This is because precession cannot exert any influence on insolation patterns when Earth’s orbit is perfectly circular and has zero eccentricity. However, with increasing eccentricity, the imprint of precession on insolation patterns worldwide rises. In other words, when eccentricity decreases, obliquity gains in relative importance as eccentricity-modulation precession lessens its control on insolation patterns. In the studied section, we interpret the disruption of a series of thinner cycles by a thicker cycle as such a shift from a precession-dominated insolation regime (green intervals on Fig. 22) to an obliquity-dominated regime (blue intervals on Fig. 22).

The five successive obliquity cycles at the top of the studied interval, however, no longer fit into this eccentricity-paced pattern. There seems to be a permanent transition from a mainly precession-sensitive climate and sedimentary environment to a more obliquity-sensitive system in the lower Tournaisian. However, this palaeoclimate interpretation needs scrutinization by future work, e.g., by means of a cm-resolution, geochemistry-based cyclostratigraphy throughout the section. Future work will also include cyclostratigraphic studies of other lower Tournaisian sections to lay out the global or regional nature of the proposed shift in Earth System response to Milankovitch forcing. A multi-section approach is also a prerequisite for adopting cyclostratigraphy as a tool to estimate absolute durations of successive conodont and/or ammonoid zones by means of cycle-counting. In addition, large sedimentation rate changes within the Crisis Interval are suspected, but these have yet to be determined.

**Taxonomic notes**

**Conodonts**

*Protognathodus* Ziegler, 1969

Representatives of the genus *Protognathodus* are well known in uppermost Famennian and Tournaisian strata. They are widely distributed and were studied by various authors in the last decades (compare synonymy lists given below). As suggested by Ziegler (1973) and Corradini et al. (2011), the ornamentation on the oral surface and the shape of the cup indicate a phylogenetetic lineage within early protognathids. Herein we concentrate on the evolution from ancestral *Pr. collinsoni* to *Pr. kockeli*, because this transition is rather complex (e.g. Luppold et al. 1994; Hartenfels and Becker 2018, 2019; Kaiser et al. 2019a online).

As outlined by Kaiser et al. (2019b), “almost all diagnostic features regarding the typical shape of cup of one taxon can be applied to all other ornamentation-types” in early protognathids. Nevertheless, general trends exist. Therefore, we focused mainly on the arrangement of cup ornamentation, which allows a clear distinction of species within the genus (Fig. 23). However, atypical characteristics, especially in transitional forms, result in a significant morphological complexity.

With the introduction of *Pr. semikockeli* n. sp. (Figs. 12g, 23c) we ensure the use of *Pr. kockeli* s.str. as a biostratigraphic tool for defining a future Devonian/Carboniferous Boundary, within the frame of successive other stratigraphic markers. It avoids the problem that the siliciclastic intercalation of Hangenberg Black Shale, Hangenberg Shale, and/or Hangenberg Sandstone normally lacks a conodont record. It would be difficult to place a future GSSP directly above such a facies break, since any defining conodont could have existed in the record gap. Furthermore, within *Pr. kockeli*, three new morphotypes (Fig. 23d–f) are defined.

The three considered species are discussed in an evolutionary order – *Pr. collinsoni*, *Pr. semikockeli* n. sp., and *Pr. kockeli*. Our review of their geographic distributions is grouped in figured and not figured records (Tabs. 2–4). Not figured quotations of *Pr. collinsoni* as well as *Pr. kockeli* may possibly include the transitional *Pr. semikockeli* n. sp. The evolution from *Pr. kockeli* to *Pr. kuehni* was investigated conscientiously by Kaiser et al. (2019a online) but it will be helpful to designate in future clearly defined morphotypes along the transition.

As pointed out by Sanz-López et al. (2018), the genus *Protognathodus* is homeomorphic with the younger *Pseudognathodus*, which ranges from the upper Tournaisian to the upper Viséan.

**Synonymy lists, abbreviations:** * = introduction of a new taxon, ? = the allocation to a taxon is questionable, e.p. = *ex parte*, only a specified part of the material of a publication belongs to the discussed taxon, non = the specimen does not belong to the taxon.
**Protognathodus collinsoni** Ziegler, 1969 (Figs. 11m, 12h

Protognathus collinsoni Ziegler, 1969, GMM B9A.11-66, Bed 10A1, Pr. kockeli Zone, oral view. b Protognathus collinsoni Ziegler, 1969, GMM B9A.11-66, Bed 10A1, Pr. kockeli Zone, oral view, two isolated nodes on both sides of the cup surface (red circles). c Protognathus semikockeli n. sp., GMM B9A.11-67, Bed 10A1, Pr. kockeli Zone, oral view, one node on the left cup surface (red circle) and a row of three nodes parallel to the carina on the right side of the cup (red line). d Protognathus kockeli (Bischoff, 1957) Morphotype 1:1, GMM B9A.11-68, Bed 10A2, Pr. kockeli Zone, oral view, one row of nodes (consisting of at least three nodes) parallel to the carina on each side of the cup (red lines, Morphotype 1:1 already occurs in Bed 10A1). e Protognathus kockeli (Bischoff, 1957) Morphotype 1:2, GMM B9A.11-69, Bed 10A1, Pr. kockeli Zone, oral view, one row of nodes parallel to the carina on the right side and two rows of nodes on the left side of the cup (red lines). The row of nodes on the right side is accompanied by an additional node (red circle). f Protognathus kockeli (Bischoff, 1957) Morphotype 2:2, GMM B9A.11-70, Bed 10A2, Pr. kockeli Zone, oral view, two rows of nodes run on both cup sides parallel to the carina (red lines).

Protognathodus collinsoni Ziegler, 1969

1969 Gnathodus kockeli – Gedik, p. 232, pl. 7, fig. 6 [only].
1969 Protognathodus collinsoni n. sp. – Ziegler, p. 353–354, pl. 1, figs. 14–18.
1973 Protognathodus collinsoni – Ziegler in Ziegler, p. 415–416, Schmidtognathus pl. 2, fig. 4.
1973 Protognathodus collinsoni – Szulczewski, p. 42–43, pl. 2, figs. 9–10.
1974 Gnathodus kockeli – Gedik, p. 13, pl. 7, fig. 6 [only].
1975 Protognathodus collinsoni – Nössing, p. 89, pl. 1, Fig. 8.
1976 Protognathodus cf. collinsoni – Chlupač and Zikmundová, pl. 4, figs. 12, 15.
1980 Protognathodus collinsoni – Ebner, pl. 16, figs. 3, 5.
1982 Protognathodus collinsoni – Bartzsch and Weyer, pl. 3, figs. 1–2.
1983 Protognathodus collinsoni – Wang and Ziegler, pl. 8, fig. 16.
1984 Protognathodus collinsoni – Wang and Yin, pl. 3, fig. 16.
1984 Protognathodus collinsoni – Luppold et al., p. 104, pl. 4, fig. 1 [only].
1984 Protognathodus collinsoni – Hou et al., pl. 4, fig. 12.
1985 Protognathodus collinsoni – Austin et al., pl. 4, fig. 20.
1985 Protognathodus collinsoni – Ji et al. in Hou et al., p. 120–121, fig. 37, pl. 28, figs. 14–18.
1985 Protognathodus kockeli – Ji et al. in Hou et al., p. 121–122, pl. 28, figs. 21–22, ?25 [only].

e.p. 1987 Protognathodus collinsoni – Kalvoda and Kukal, pl. 4, fig. 4 [only].
1988 Protognathodus collinsoni – Flajs and Feist, pl. 9, fig. 6.
1988 Protognathodus collinsoni – Wang and Yin, p. 130, pl. 22, figs. 5–7.
e.p. 1988 Protognathodus kockeli – Wang and Yin, p. 130, pl. 22, figs. 9, 11, 13, ?17 [only].
e.p. 1988 Protognathodus kockeli – Qiu, p. 290–291, pl. 1, fig. 20 [only].
e.p. 1989 Protognathodus collinsoni – Ji et al., p. 90–91, pl. 18, figs. 8–9 [only].
1989 Protognathodus collinsoni – Wang, p. 126, pl. 40, fig. 7.
e.p. 1990 Protognathodus kockeli – Gagiev and Kononova, pl. 3, figs. 29–30 [only].
1990 Protognathodus collinsoni – Gagiev and Kononova, pl. 4, fig. 4.
1992 Protognathodus collinsoni – Over, fig. 7.15.
1992 Protognathodus collinsoni – Ji and Ziegler, pl. 3, fig. 22.
e.p. 1992 Protognathodus kockeli – Nemirovskaya et al., pl. 2, fig. 21 [only].
1992 Protognathodus collinsoni – Nemirovskaya et al., pl. 2, fig. 20.
e.p. 1993 Protognathodus collinsoni – Perret, p. 314, pl. C VIII, fig. 4 [only].
e.p. 1993 transitional form from Protognathodus collinsoni to Protognathodus kockeli [formes intermédiaires entre Pr. collinsoni et Pr. kockeli] – Perret, pl. C VIII, fig. 7 [only].
2020 Protognathodus collinsoni – Chauffe and Nichols, p. 178, pl. 2, figs. 30–32, ?38.

e.p. 1993 Protognathodus kockeli – Perret, p. 314–315, pl. C VIII, fig. 8 [only].

1995 Protognathodus cf. P. collinsoni – Chauffe and Nichols, p. 178, pl. 2, figs. 30–32, ?38.

2000b Protognathodus collinsoni – Perri and Spalletta, pl. 1, fig. 4.

2003 Protognathodus collinsoni – Corradini et al., p. 235, pl. 1, fig. 3.

2009 Protognathodus collinsoni (-kockeli) – Kaiser, pl. 1, fig. 1.

2011 Protognathodus collinsoni – Corradini et al., p. 17–18, pl. 1, figs. 4–8.

2013 Protognathodus collinsoni – Becker et al., pl. 3, fig. 7.

2016 Protognathodus collinsoni – Sacher, p. 56, pl. 9, fig. 13.

e.p. 2016 Protognathodus collinsoni – Cifer, pl. 25, pl. 8, fig. 12 [only].

2018 Protognathodus collinsoni – Plotitsyn and Gruzdov, fig. 4.4.

e.p. 2019a Protognathodus cf. collinsoni – Kaiser et al., pl. 1, fig. 4 [only, broken specimen].

2019a Protognathodus collinsoni (collinsoni-kockeli) – Kaiser et al., pl. 1, figs. 6, 9.

2019a Protognathodus collinsoni (kockeli) – Kaiser et al., pl. 1, fig. 7.

2019a Protognathodus collinsoni – Kaiser et al., pl. 1, fig. 11, pl. 2, fig. 4, pl. 3, figs. 10–11.

2019 Protognathodus collinsoni – Plotitsyn and Gruzdov, fig. 4.4.

e.p. 2020 Protognathodus collinsoni – Feist et al., fig. 6g [only].

2020 Protognathodus collinsoni – Kumpan et al., fig. 5.8.

2020 Protognathodus collinsoni – Corradini et al., fig. 4.d.

2020 Protognathodus collinsoni – Hartenfels, fig. 4.2.

2020 Protognathodus collinsoni – Qie et al., pl. 5-1-30, figs. 5a-b.

2021 Protognathodus collinsoni – Sattari et al., fig. 7.1

2021 Protognathodus collinsoni – Becker et al., fig. 2b–d.

Material: Twelve Borkewehr and two Puech de la Suque (Montagne Noire, southern France) specimens; additional elements from other Rhenish sections, Franconia, and Montagne Noire.

Diagnosis (emended): A species of Protognathodus with a single or several nodes on one or both sides of the carina that do not form rows that consist of at least three nodes, parallel to the carina.

Discussion: The longitudinal axis of Pr. collinsoni is straight to slightly curved laterally. The latter leads to a slightly asymmetrical shape of the cup and a more expanded outer side. In many specimens, the anterior part of the inner portion and the posterior part of the outer side show convexities of the cup margins (e.g. Fig. 12i; Bartsch and Weyer 1982: pl. 3, figs. 1–2; Kaiser et al. 2019a online: pl. 3, fig. 10; Plotitsyn and Gruzdov 2019: fig. 4.4). However, more or less symmetrical forms occur, too (e.g. Fig. 23b; Hou et al. 1984: pl. 4, fig. 12; Ji et al. 1989: pl. 18, fig. 9; Corradini et al. 2011: pl. 1, fig. 4). The cup, which extends to the posterior tip, bears one node or more scattered nodes on one or both sides of the surface. The nodes are situated at variable distances to the carina (e.g. Perri and Spalletta 2000b: pl. 1, fig. 4; Feist et al. 2020 online: fig. 6g) or further away and closer to the cup margins (e.g. Bartsch and Weyer 1982: pl. 3, fig. 1). In the majority, the anterior cup margins begin directly opposite at the blade (e.g. Figs. 12h, 23b), but there are also specimens in which the anterior terminations show an offset (e.g. Kaiser et al. 2019a: pl. 1, fig. 6; Plotitsyn and Gruzdov 2019: fig. 4.4).

The free blade is about one third to one half of the element length. It consists of laterally compressed, fused denticles with free tips, slightly decreasing in height towards the cup. The blade extends to the posterior end as a carina. In some specimens, the denticles of the carina get broader, thickened laterally (e.g. Szulczewski 1973: pl. 2, fig. 10; Corradini et al. 2011: pl. 1, fig. 5).

At Borkewehr, well-preserved specimens are available in various growth stages (additional elements from other Rhenish sections, Franconia, and Montagne Noire). No variation in cup shape can be recognised depending on the size. The ancestral Pr. meischneri (Figs. 11n–o, 23a) can be distinguished easily from Pr. collinsoni in the absence of cup ornamentation. In some Pr. collinsoni specimens, two nodes are arranged in parallel to the carina (e.g. Fig. 12h; Flajs and Feist 1988: pl. 9, fig. 6; Becker et al. 2013: pl. 3, fig. 7; Corradini et al. 2003: pl. 4, fig. 3, re-illustrated in Corradini et al. 2011: pl. 1, fig. 7; Kaiser et al. 2019a online: pl. 1, fig. 6). Such morphotypes are intermediate towards Pr. semikockeli n. sp., but were part of the original Pr. collinsoni type series (Ziegler 1969: pl. 1, fig. 14). Specimens with three or more nodes arranged in a diagnostic line parallel to the carina on only one side are assigned to Pr. semikockeli n. sp., specimens with at least one row of nodes on both sides of the carina to Pr. kockeli. Advanced forms of Pr. collinsoni display numerous nodes without any regular orientation (Fig. 11m) and may be recognised as a distinctive morphotype. Previously, they may have been identified as Pr. kockeli (e.g. Gedik 1969: pl. 7, fig. 6, re-illustrated in Gedik 1974: pl. 7, fig. 6; Luppold et al. 1984: pl. 4, fig. 1; compare remarks by Corradini et al. 2011: p. 18). The distinction of such advanced Pr. collinsoni from the younger (middle to upper Tournaisian) Pr. praedelicatus Lane, Sandberg, and Ziegler, 1980 with randomly distributed nodes requires further revision.

Stratigraphic range: From the lower part of the Si. (Eo) praesulcata s.l. (= Lower praesulcata) Zone (Ziegler and Sandberg 1984; Clausen et al. 1989a) to the Si. (Si.) mehli (= Upper duplicata) Zone (Over 1992; compare Corradini et al. 2011 and Spalletta et al. 2017).
| Region (in alphabetic order) | References with figs. | References without figs. (possibly including Pr. semikockeli n. sp.) |
|-----------------------------|-----------------------|---------------------------------------------------------------|
| Arbuckle Mountains, Oklahoma, USA | Over 1992 | Raven 1983, cf. identification
| Cantabrian Mountains, Spain | Gedik 1969, 1974, Perri and Spalletta 2000b, Corradini et al. 2011, Kaiser et al. 2019a | Schönlaub 1993, 2018
|   | | Perri and Spalletta 2000a, Kaiser et al. 2006, 2009, Corradini 2016, Spalletta et al. 2020 |
| Carnic Alps, Austria/Italy | Gedik 1969, 1974, Perri and Spalletta 2000b, Corradini et al. 2011, Kaiser et al. 2019a | Schönlaub 1993, 2018
|   | | Perri and Spalletta 2000a, Kaiser et al. 2006, 2009, Corradini 2016, Spalletta et al. 2020 |
| Central Iran | Sattari et al. 2021 | Königshof et al. 2020 |
| Chernyshev Swell, northern Russia | Plotitsyn and Gruzdev 2019 | |
| Cornwall, United Kingdom | Austin et al. 1985, Austin and Armstrong 1985 | Ausin and Armstrong 1985 |
| East Bohemia, Czech Republic | Chlupáč and Zikmundová 1976 | |
| Graz Palaeozoic, Austria | Nössing 1975, Ebner 1980, Kaiser et al. 2019a | |
| Franconia, Germany | Hartenfels collection, unpubl. | |
| Guangxi, China | Wang and Ziegler 1983, Wang and Yin 1988, Wang 1989, Ji and Ziegler 1992 | Li et al. 1988
|   | | |
| Guizhou, China | Wang and Yin 1984, Hou et al. 1984, Ji et al. in Hou et al. 1985, Ji et al. 1989, Qie et al. 2020 | Ji 1987
| Holy Cross Mountains, Poland | Szuklewski 1973 | Malec 2014
|   | | Davydov 2020 |
| Illinois, USA | Chauffe and Nichols 1995 | |
| Jungar Basin, Xinjiang, China | Gagiev and Kononova 1990 | Xu et al. 1990 |
| Kolyma River Basin, NE Russia | | |
| Maider, Morocco | Becker et al. 2013 | Aretz et al. 2021 |
| Missouri, USA | Chauffe and Nichols 1995 | |
| Montagne Noire, France | Flajs and Feist 1988, Kaiser 2009, Corradini et al. 2011, Cifer 2016, Feist et al. 2020, Hartenfels 2020 | Feist and Flajs 1987
|   | | Klapper in Feist 1990, Kaiser et al. 2009, Becker et al. 2012, Davydov et al. 2012, Aretz et al. 2016 |
| Moravian Karst, Czech Republic | Kalvoda and Kukal 1987, Kalvoda et al. 2013 | Bábek et al. 2016b |
| Pyrenees, France/Spain | Kumpa et al. 2020, Perret 1993 | Perret 1988
|   | | Cygan and Perret 2002, Kaiser et al. 2009, Aretz et al. 2021 |
| Rhenish Massif, Germany | Ziegler 1969, 1973, Luppold et al. 1984, Sacher 2016, Becker et al. 2021 | Ziegler et Leuteritz in Koch et al. 1970
|   | | Becker et al. 1984, Ziegler et al. 1988, Clausen et al. 1989a, 1994, Claué-Long et al. 1993, Kürschner et al. 1993, Luppold et al. 1994, Becker et al. 2009, Kaiser et al. 2006, 2017, Herbig and Stoppel 2006, Streel and Korn 2016b, Becker and Hartenfels 2017, Hartenfels et al. 2017a, b |
Protognathodus semikockeli n. sp.
(Figs. 11l, p, 12e–g, 23c, Tab. 3)

e.p. 1969 Protognathodus kockeli („stratigraphische Frühformen”) – Ziegler, p. 354–355, pl. 1, figs. 21–25 [only].
e.p. 1973 Protognathodus kockeli – Szulczewski, p. 43–44, pl. 2, fig. 11 [only].
? 1976 Protognathodus cf. kockeli – Chlupáč and Zikmundová, pl. 4, figs. 20, 25.
e.p. 1976 Protognathodus kockeli – Bouckaert and Groessens, pl. 1, fig. 8 [only].
1979 Protognathodus collinsoni – Buchroithner, pl. 1, fig. 9.
1981 Protognathodus – Clark et al., p. W162, fig. 109.6.
1982 Protognathodus cf. collinsoni – Bartzsch and Weyer, pl. 3, fig. 3.
e.p. 1984 Protognathodus kockeli – Wang and Yin, pl. 3, fig. 15 [only].
1984 Protognathodus kockeli – Qiu, pl. 5, fig. 3.
? 1985 Protognathodus kockeli – Austin et al., pl. 4.9, fig. 13 [incrusted specimen].
1988 Protognathodus collinsoni – Flajs and Feist, pl. 9, fig. 7 [transitional to Pr. kockeli].
1988 Protognathodus kockeli – Weyant, pl. 2, fig. 10.
e.p. 1988 Protognathodus kockeli – Wang and Yin, p. 130, pl. 22, figs. 10, 14 [only].
e.p. 1988 Protognathodus kockeli – Qiu, 290–291, “P. kockeli” fig. on p. 291, pl. 2, fig. 7 [only].
e.p. 1989 Protognathodus collinsoni – Ji et al., p. 90–91, pl. 18, fig. 7 [only].
e.p. 1992 Protognathodus kockeli – Nemirovskaya et al., pl. 2, fig. 16 [only].

? e.p. 1993 transitional form from Protognathodus collinsoni to Protognathodus kockeli [formes intermédiaires entre Pr. collinsoni et Pr. kockeli] – Perret, pl. C VIII, fig. 5 [only].
? 1994 Protognathodus sp. aff. Protognathodus kockeli – Luppold in Luppold et al., p. 45, pl. 4, fig. 11.
? 1994 Protognathodus sp. 1 – Luppold in Luppold et al., p. 45, pl. 4, fig. 12.
e.p. 1995 Protognathodus kockeli – Chauffe and Nichols, p. 178, pl. 2, fig. 29 [only].
1999 Protognathodus cf. kockeli – Sanz-López et al., pl. 2, fig. 1 [incrusted specimen].
e.p. 2003 Protognathodus kockeli – Corradini et al., p. 235, pl. 4, fig. 1 [only].
2008 Protognathodus kockeli – Habibi et al., p. 772, fig. 4.6.
2009 Protognathodus collinsoni – Kaiser, pl. 1, fig. 3.
e.p. 2011 Protognathodus kockeli – Corradini et al., p. 18–19, pl. 1, figs. 9, 15–16 [only].
2015 Protognathodus collinsoni – Mossoni et al., fig. 7X.
e.p. 2016 Protognathodus collinsoni – Cifer, p. 25, pl. 8, fig. 13 [only].
2018 Protognathodus kockeli – Zhang et al., fig. 2e.
2019a Protognathodus kockeli “one-row” morphotype – Kaiser et al., pl. 1, figs. 12, 14, pl. 3.
2019a Protognathodus aff. Pr. kockeli “one-row” morphotype – Kaiser et al., pl. 3, figs. 2, 3 [specimen with an initial transversal ridge], 4 [broken specimen], 6.
2019a Protognathodus kockeli cf. “one-row” morphotype – Kaiser et al., pl. 3, fig. 7.
e.p. 2019a Protognathodus kockeli “two-rows” morphotype – Kaiser et al., pl. 3, fig. 9 [only].
2019 Protognathodus collinsoni-Protognathodus kockeli – Plotitsyn and Gruzdev, fig. 4.5.

### Table 2 (continued)

| Region (in alphabetic order) | References with figs. | References without figs. |
|------------------------------|-----------------------|--------------------------|
| Sardinia, Italy              | Corradini et al. 2003, 2011, 2020 | Herbig et al. 2019 |
| (Sub)Polar Urals, northern Russia | Nemirovskaya et al. 1992, Plotitsyn et al. 2018 | Mossoni et al. 2013 |
| Thailand                     | Bartzsch and Weyer 1982 | ? Savage 2013 |
| Thuringia, Germany           |                       | Weyer 1977 |
| Tien Shan, Tajikistan        |                       | Bardasheva et al. 2004 |
| Utah, USA                    |                       | Over 2020 |
| Xizang, Tibet, China         | Qiu 1988              |                       |

? e.p. 1993 transitional form from Protognathodus collinsoni to Protognathodus kockeli [formes intermédiaires entre Pr. collinsoni et Pr. kockeli] – Perret, pl. C VIII, fig. 5 [only].
? 1994 Protognathodus sp. aff. Protognathodus kockeli – Luppold in Luppold et al., p. 45, pl. 4, fig. 11.
? 1994 Protognathodus sp. 1 – Luppold in Luppold et al., p. 45, pl. 4, fig. 12.
e.p. 1995 Protognathodus kockeli – Chauffe and Nichols, p. 178, pl. 2, fig. 29 [only].
1999 Protognathodus cf. kockeli – Sanz-López et al., pl. 2, fig. 1 [incrusted specimen].
e.p. 2003 Protognathodus kockeli – Corradini et al., p. 235, pl. 4, fig. 1 [only].
2008 Protognathodus kockeli – Habibi et al., p. 772, fig. 4.6.
2009 Protognathodus collinsoni – Kaiser, pl. 1, fig. 3.
e.p. 2011 Protognathodus kockeli – Corradini et al., p. 18–19, pl. 1, figs. 9, 15–16 [only].
2015 Protognathodus collinsoni – Mossoni et al., fig. 7X.
e.p. 2016 Protognathodus collinsoni – Cifer, p. 25, pl. 8, fig. 13 [only].
2018 Protognathodus kockeli – Zhang et al., fig. 2e.
2019a Protognathodus kockeli “one-row” morphotype – Kaiser et al., pl. 1, figs. 12, 14, pl. 3.
2019a Protognathodus aff. Pr. kockeli “one-row” morphotype – Kaiser et al., pl. 3, figs. 2, 3 [specimen with an initial transversal ridge], 4 [broken specimen], 6.
2019a Protognathodus kockeli cf. “one-row” morphotype – Kaiser et al., pl. 3, fig. 7.
e.p. 2019a Protognathodus kockeli “two-rows” morphotype – Kaiser et al., pl. 3, fig. 9 [only].
2019 Protognathodus collinsoni-Protognathodus kockeli – Plotitsyn and Gruzdev, fig. 4.5.
2019 Protognathodus kockeli – Plotitsyn and Gruzdev, fig. 4.6. e.p. 2020 Protognathodus kockeli – Feist et al., fig. 6a [only]. e.p. 2020 Protognathodus collinsoni transitional form to *Pr. kockeli* – Feist et al., fig. 6h [only]. 2020 Protognathodus kockeli – Königshof et al., fig. 3.

**Derivation of name:** From *semi* = partial; because the *Pr. kockeli*-type ornamentation is developed only on one side of the cup.

**Material:** Eleven Borkewehr specimens – holotype GMM B9A.11-40 (Fig. 12g), figured paratypes GMM B9A.11-28 (Fig. 11l), GMM B9A.11-32 (Fig. 11p), GMM B9A.11-38 (Fig. 12e), GMM B9A.11-39 (Fig. 12f), as well as six unfigured paratypes GMM B9A.11-72, GMM B9A.11-73, GMM B9A.11-74, GMM B9A.11-75, GMM B9A.11-76, and GMM B9A.11-77; two Puech de la Suque (Montagne Noire, southern France) specimens – figured paratype GMM B9A.11-67 (Fig. 23c) and unfigured paratype GMM B9A.11-78.

**Type locality and level:** Borkewehr, Bed 10, grey nodular limestone, lower Tourmaisian, *Si. (Eo.) bransoni* Zone, post-Crisis Interval sensu Becker et al. (2021).

**Diagnosis:** A species of *Protognathodus* with a row consisting of at least three nodes, or a ridge of fused nodes, parallel to the carina only on one side of the cup.

**Description:** In oral view, the longitudinal axis of *Pr. semikockeli* n. sp. is straight or slightly curved laterally. The free blade is about one third to one half of the length of the element and consists of laterally compressed fused denticles with free tips. With slightly decreasing height towards the posterior end, the edge of the free blade is marked by a narrow, sharp median groove. Rare juveniles, as well as abundant medium sized and adult specimens, are available from the literature and our collections. No variation in cup shape and ornamentation can be recognised depending on growth stages.

**Discussion:** *Protognathodus semikockeli* n. sp. is introduced to ensure the biostratigraphical use of *Pr. kockeli* s.str. as a potential marker for defining a future Devonian/Carboniferous Boundary. It falls outside the original definitions of both *Pr. collarisoni* and *Pr. kockeli*. Intermediates between *Pr. collarisoni* and *Pr. kockeli* are well known but they were assigned to *Pr. collarisoni*, expanding the original diagnosis sensu Ziegler (1969), or to *Pr. kockeli*, in the sense of the emended diagnosis sensu Corradini et al. (2011). At Borkewehr and in other sections (e.g. Puech de la Suque, Montagne Noire, France), *Pr. semikockeli* n. sp. occurs in the first limestone bed immediately above the conodont-free Hangenberg Shale/Sandstone. Therefore, its entry is not useful for a future boundary definition. The oldest Borkewehr specimens are not preserved well enough to select a holotype.

*Protognathodus semikockeli* n. sp. differs from its ancestor *Pr. collarisoni* in the row arrangement of cup nodes on one side. A row is defined by at least three nodes (Fig. 12g). In some specimens the nodes are arranged in a rather more or less symmetrical cup outline (e.g. Figs. 11i, with left cup partly broken; Mossoni et al. 2015: fig. 7Y). A nodose cup ornamentation and the restriction of a row of nodes that consist of at least three nodes, parallel to the carina on only the inner or outer side, characterises *Pr. semikockeli* n. sp. In some specimens the nodes are fused to a ridge (Fig. 11i). One or two additional node(s) may occur beside the row of nodes/ridge, closer to the cup margin (Fig. 12e). On the other side of the carina the nodes are scattered and unarranged (e.g. Corradini et al. 2011: pl. 1, fig. 16) or only one or two node(s) are developed (e.g. Figs. 11i, p. 12e, 23c; Ziegler 1969: pl. 1, figs. 21–25; Bartzsch and Weyer 1982: pl. 3, fig. 3; Zhang et al. 2018: fig. 2e; Plotitsyn and Gruzdev 2019: fig. 4.5). In some specimens, one cup side remains unornamented (e.g. Fig. 12g; Flajs and Feist 1988: pl. 9, fig. 7; Ji et al. 1989: pl. 18, fig. 7).
were recorded by Corradini et al. (2003; pl. 4, fig. 1, re-figured in Corradini et al. 2011: pl. 1, fig. 15) from the Monte Taccu North A section, Sardinia, Italy and by Habibi et al. (2008: fig. 4.6) from the Shahmirzad section, central Elburz Mountains, Iran. Both specimens show nodes arranged in a line on one side of the cup and a cluster of irregularly distributed nodes on the upper cup surface of the other side. Especially the Italian specimen shows additional scattered nodes between the carina and the parallel running row of nodes. On both elements further nodes occur closer to the cup margin.

In addition, it is possible that a record of “Pr. kockeli early form” in Conil et al. (1986) from the French side of the Ardennes refers to Pr. semikockeli n. sp.

Since our new species overlaps only partially in time with its ancestor (Pr. collinsoni) and descendent (Pr. kockeli s.str.), it does not represent a simple intermediate stage (“chronomorphotype”) of a single taxon that changes gradually. Due to its shorter time range (see below) it cannot be simply regarded as an intraspecific variant. However, in a more conservative approach, authors may prefer to recognise it at subspecies level only, which has no affect on its biostratigraphic value.

**Stratigraphic range:** Unlikely Pr. collinsoni, the new species is not known from pre-crisis levels, such as the Wocklum Limestone. It enters at Borkewehr at the top of the costatus-kockeli Interregnum, in the upper part of the “laminated” limestones, just above the Hangenberg Shale/Sandstone equivalents, which were divided into the lithologically similar beds 2 and 3. An equal FAD was indirectly reported by Kaiser et al. (2019a online) from the Graz Palaeozoico, Austria. At Trolp, Pr. semikockeli n. sp. enters in the first limestone bed immediately below the FAD of Pr. kockeli s.str. Sanz-López et al. (1999) described the first specimens assigned by us to Pr. semikockeli n. sp. from the second nodular limestone bed above the extinction of B. ultimus, within an interval of darker interbeds, interpreted as Hangenberg Crisis Interval. There is a lack of Pr. kockeli in the subsequent layers and Si. (Eo.) sulcata s.l. enters in the twelfth (nodular) limestone bed above. In the absence of illustrations, it cannot be ruled out that the oldest Pr. kockeli reported from Stockum Trench II (Clausen et al. 1994, Bed 108) and Drewer (Korn et al. 1994, Bed 100) belong to Pr. semikockeli n. sp. The oldest known Pr. semikockeli n. sp. record is from Bed 21 at La Serre, Trench F (Feist et al. 2020 online, their fig. 6h), the top of shallow-water limestones (lower carbonate unit) that fall in the top of Middle Crisis Interval I.

At Borkewehr, the last occurrence of Pr. semikockeli n. sp. is in the basal part of the Si. (Eo.) bransoni Zone. However, the atypical specimen of Corradini et al. (2003) occurs in the Si. (Si.) mehli (= Upper duplicata) Zone, whereas the one of Habibi et al. (2008) was extracted from a limestone bed at the top of an interval, which was dated as sandbergi to Lower crenulata Zone.

To the right of the table:

**Table 3** Geographic distribution of Pr. semikockeli n. sp.

| Region (in alphabetic order)     | References with figs. |
|----------------------------------|-----------------------|
| Ardennes, Belgium                | Bouckaert and Grossens 1976 |
| Bechar Basin, Algeria            | Weyant 1988 |
| Cantabrian Mountains, Spain      | Sanz-López et al. 1999 |
| Carnic Alps, Austria/Italy       | Corradini et al. 2011, Kaiser et al. 2019a |
| Chernyshev Swell, northern Russia| Plotitsyn and Gruzdev 2019 |
| Cornwall, United Kingdom         | ?Austen et al. 1985 |
| ?East Bohemia, Czech Republic    | Chlupač and Zikmundová 1976 |
| Elburz Mountains, northern Iran  | Habibi et al. 2008 |
| Graz Palaeozoico, Austria        | Kaiser et al. 2019a |
| Guangxi, China                   | Wang and Yin 1988, Ji et al. 1989, Zhang et al. 2018 |
| Guizhou, China                   | Wang and Yin 1984 |
| Holy Cross Mountains, Poland     | Szulczewski 1973 |
| Illinois, USA                    | Chauffe and Nichols 1995 |
| Northern Iran                    | Königshof et al. 2020 |
| Montagne Noire, France           | Flajs and Feist 1988, Kaiser 2009, Cifer 2016, Feist et al. 2020 |
| (Sub)Polar Urals, northern Russia| Nemirovskaya et al. 1992 |
| Pyrenees, France/Spain           | Buchroithner 1979, ?Perret 1993 |
| Rhenish Massif, Germany          | Ziegler 1969, ?Luppold et al. 1994 |
| Sardinia, Italy                  | Corradini et al. 2003, 2011, Mossoni et al. 2015 |
| Thuringia, Germany               | Bartzsch and Weyer 1982 |
| Xizang, Tibet, China             | Qiu 1984, 1988 |

* 1957 Gnathodus kockeli n. sp. – Bischoff, p. 25, pl. 3, figs. 27–29, ?30, 31–32.
* 1957 Gnathodus kockeli n. sp. – Voges, p. 281–282, pl. 33, fig. 27 [only].
* 1967 Gnathodus kockeli – van Adrichem Boogaert, p. 179, pl. 2, figs. 17–18.
* 1968 Gnathodus kockeli – Canis, p. 538, pl. 74, figs. 11, 22, e.p. 1969 Gnathodus kockeli – Gedik, p. 232, pl. 7, figs. 5, 7 [only].
* 1969 Gnathodus kockeli – Schönlaub, p. 330, pl. 1, figs. 1–2, e.p. 1969 Protognathodus kockeli – Ziegler, p. 354–355, pl. 1, figs. 19, ?20 [unclear number of nodes on the left side of the cup, possibly two fused nodes in the posterior part], pl. 2, figs. 1–5 [only].
1970 *Protognathodus kockeli* – Ziegler and Leuteritz in Koch et al., pl. 8, figs. 1-3, 5.
*e.p.* 1970 *Protognathodus kuehni* n. sp. – Ziegler and Leuteritz in Koch et al., p. 715, pl. 8, fig. 4 [only, non figs. 6–7, 9–13, non figs. 14–16 = holotype of *Pr. kuehni*].
1973 *Protognathodus kockeli* – Ziegler in Ziegler, p. 417–418, Schmidtognathus pl. 2, fig. 5.
*e.p.* 1973 *Protognathodus kockeli* – Szulczewski, p. 43–44, pl. 2, figs. 12–13 [only].
1974 *Gnathodus kockeli* – Gdik, p. 13, pl. 7, figs. 5, 7 [only].
1975 *Protognathodus kockeli* – Nössing, p. 89, pl. 1, fig. 10.
1976 *Protognathodus kockeli* – Weyer, pl. 1, figs. 3–6 [transitional to *Pr. kuehni*].
1977 *Protognathodus kockeli* – Weyer, pl. 3, figs. 3-4, 6 [only].
1979 *Protognathodus kockeli* – Buchroither, pl. 1, fig. 4.
1980 *Protognathodus kockeli* – Ebner, pl. 16, figs. 4, 6.
1980 *Protognathodus kockeli* – Lane et al., pl. 3, fig. 1.
1982 *Protognathodus kockeli* – Bartzsch and Weyer, pl. 3, figs. 4–7 [4–5 transitional to *Pr. kuehni*, 6–7 slightly transitional to *Pr. kuehni*].
1984 *Protognathodus kockeli* – Wang and Yin, pl. 3, fig. 14 [only].
1984 *Protognathodus kockeli* – Luppold et al., p. 104, pl. 4, fig. 2, pl. 6, fig. 4 [only].
1984 *Protognathodus kockeli* – Hou et al., pl. 4, fig. 10.
1985 *Protognathodus kockeli* – Ji et al. in Hou et al., p. 121–122, fig. 38, pl. 28, figs. 19–20, 23–24, 26–28 [only].
1986 *Gnathodus kockeli* – Zhao, p. 95, pl. 3, fig. 7.
1987 *Protognathodus kockeli* – Kalvoda and Kukal, pl. 4, figs. 2–3 [only].
1988 *Protognathodus kockeli* – García-Alcalde and Menéndez-Alvarez, pl. 1, fig. 7.
1988 *Protognathodus kockeli* – Flajs and Feist, pl. 9, figs. 8–10.
1988 *Protognathodus kockeli* – Schönlaub et al., p. 155, pl. 4, figs. 1–2, 5.
1988 *Protognathodus praedicatus* – Schönlaub et al., p. 155, pl. 4, fig. 9 [only, slightly transitional to *Pr. kuehni*].
1988 *Protognathodus kockeli* – Wang and Yin, p. 130, pl. 22, figs. 8, 15 [only].
1988 *Protognathodus kuehni* – Wang and Yin, p. 130–131, pl. 22, fig. 19.
1989 *Protognathodus kockeli* – Ji et al., p. 91, pl. 18, figs. 3–4, 5 [only].
1989b *Protognathodus kockeli* – Clausen et al., pl. 5, figs. 3, 5 [fig. 3 slightly transitional to *Pr. kuehni*].
1990 *Protognathodus kockeli* – Gagiev and Kononova, pl. 4, figs. 5–6 [only].
1992 *Protognathodus kockeli* – Over, fig. 7.16.
1992 *Protognathodus kockeli* – Nemirovskaya et al., pl. 2, fig. 15 [only].
1993 *Protognathodus kuehni* – Nemirovskaya et al., pl. 2, fig. 19 [transitional to *Pr. kuehni*].
1993 *Protognathodus kockeli* – Kürschner et al. 1993, pl. 1, fig. 12, pl. 3, fig. 12.
1993 *Protognathodus kockeli* – Perret, p. 314, pl. C VIII, fig. 3 [only].
1993 *Protognathodus kockeli* – Perret, p. 314–315, pl. C VIII, figs. 9, 11 [only].
1993 *Protognathodus kockeli* – Perret, p. 313–315, pl. C VIII, figs. 9, 11 [only].
1994 *Protognathodus kockeli* – Luppold in Luppold et al., p. 45, pl. 4, figs. 14, 18 [both transitional to *Pr. kuehni*].
1994 *Protognathodus kockeli* – Belka in Korn et al., pl. 5, figs. 4–11 [fig. 10 transitional to *Pr. kuehni*], pl. 7, figs. 8, 10 [only].
1995 *Protognathodus kockeli* – Chauffe and Nichols, p. 178, pl. 2, fig. 34 [only, transitional to *Pr. kuehni*].
1997 *Protognathodus kockeli* – Chauffe and Guzman, p. 232, pl. 2, figs. 7, 15.
1997 *Protognathodus kockeli* – Dzik, p. 72, figs. 8A–B, 8D–I [only].
2000b *Protognathodus kockeli* – Perri and Spalletta, pl. 1, fig. 5.
2000 *Protognathodus kockeli* – Wang et al., pl. 1, fig. 11.
2002 *Protognathodus kockeli* – Buggisch and Michl, pl. 4, figs. 125, 127.
2003 *Protognathodus kockeli* – Corradini et al., p. 235, pl. 4, fig. 2 [only].
2005 *Protognathodus kockeli* – Kaiser, p. 15–16, pl. 2, figs. 13–14.
? e.p. 2006 *Protognathodus kockeli* – Dzik, p. 157, figs. 116M, 138.
2007 *Protognathodus kockeli* – Kaiser, pl. 2, figs. 3, 5–6.
2009 *Protognathodus kockeli* – Kaiser, pl. 1, fig. 2. [poorly illustrated].
2009 *Protognathodus kockeli* – Kaiser et al., p. 128, pl. 1, figs. 10, 11 [specimens with atypical narrow cup], pl. 2, fig. 16.
2011 *Protognathodus kockeli* – Corradini et al., p. 18–19, pl. 1, figs. 10–14, 17–19, 21 [only; fig. 13 transitional to *Pr. kuehni*].
2013 *Protognathodus kockeli* – Becker et al., pl. 3, figs. 8–9 [poorly preserved].
2013 *Protognathodus kockeli* – Kalvoda et al., fig. 5.16–5.17.

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Protognathodus kockeli – Mossoni et al., fig. 7X.
2016 Protognathodus kockeli – Corradini et al., fig. 6j–m.
2016 Protognathodus kockeli – Sacher, p. 56, pl. 9, figs. 15–16 [fig. 16 slightly transitional to Pr. kuehni].
2016 Protognathodus kockeli – Ciferri, p. 25, pl. 8, fig. 16.
2017 Pr. kockeli (transitional to Pr. kuehni) – Kaiser et al., pl. 2, fig. 19–20, fig. 10.9 [transitional to Pr. kuehni].
2018 Protognathodus kockeli – Plotitsyn et al., pl. 1, fig. 9.
2019 Protognathodus kockeli – Schönlaub, fig. 6 [left specimen].
cp. 2019a Protognathodus kockeli “two-rows” morphotype – Kaiser et al., pl. 1, figs. 1–2, 8, pl. 2, fig. 2 [only].
2019a Protognathodus kockeli – Kaiser et al., pl. 1, fig. 13 [broken specimen].
2019a Protognathodus kockeli (kockeli-kuehni) – Kaiser et al., pl. 1, fig. 15, pl. 2, figs. 10–11.
? 2019a Protognathodus kockeli-kuehni – Kaiser et al., pl. 1, fig. 16 [transitional to Pr. kuehni].
2019a Protognathodus kockeli advanced form – Kaiser et al., pl. 2, figs. 5, 13.
2019a Protognathodus aff. Pr. kockeli (kockeli-kuehni) – Kaiser et al., pl. 2, fig. 79, pl. 3, figs. 22–23, 24, 25 [figs. 23–25, specimens with atypical narrow cup].
cp. 2019a Protognathodus cf. collinsoni – Kaiser et al., pl. 2, fig. 15 [only, broken specimen].
2019a Protognathodus aff. Pr. kockeli advanced morphotype – Kaiser et al., pl. 3, fig. 26.
2019a Protognathodus aff. Pr. kockeli “two-rows” morphotype – Kaiser et al., pl. 3, fig. 29.
cp. 2020 Protognathodus kockeli – Feist et al., fig. 6b [only, transitional to Pr. kuehni].
2020 Protognathodus kockeli – Kumpfan et al., fig. 5.9.
2020 Protognathodus kockeli – Spalletta et al., fig. 10e [transitional to Pr. kuehni].
2020 Protognathodus collinsoni transitional to Pr. kockeli – Corradini et al., fig. 4a.
2020 Protognathodus kockeli – Corradini et al., fig. 4c, e [fig. 4c transitional to Pr. kuehni].
2020 Protognathodus kockeli – Hartenfels, figs. 3.1, 4.4–6. non 2020 Protognathodus kockeli – Davlatov et al., tab. 2, fig. 13.
2020 Protognathodus kockeli – Qie et al., pl. 5-1-30, figs. 6a–b.
cp. 2021 Protognathodus sp. – Becker et al., fig. 2f [only, specimen with atypical ornament transitional between Pr. kockeli and Pr. kuehni].
2021 Pr. kockeli transitional towards Pr. kuehni – Becker et al., fig. 2h [transitional to Pr. kuehni].

Material: 26 Borkewehr specimens, seven specimens transitional towards Pr. kuehni; four Puech de la Suque (Montagne Noire, southern France) specimens.

Diagnosis (emended): A species of Protognathodus with at least one row of nodes that consists of at least three nodes, or a ridge of fused nodes, parallel to the carina on both sides of the cup.

Description and discussion: The holotype of Pr. kockeli (Bischoff, 1957: pl. 3, fig. 27) has two rows of nodes on both sides of the cup parallel to the carina. The originally illustrated paratypes show at least one row of nodes on each cup side. Additional nodes closer to the cup margins initiate second outer rows (Bischoff 1957: pl. 3, figs. 28–29, 31–32). This excludes specimens separated by us as Pr. semikockeli n. sp. from the variability of the type series. It seems that the number of rows increases in some specimens ontogenetically. This fact has already been mentioned by Bischoff (1957), who recognised that adults could develop a second row of nodes on both sides of the cup. Corradini et al. (2011) pointed out that “some large specimens bear one row of nodes on both sides of the cup, sometimes together with other scattered nodes”. Juveniles with two rows of nodes on one or both sides of the cup are not known, neither in our collections nor in the literature.

With respect to ontogeny and variability, we propose an emended diagnosis that enables an easy identification independent of size and an easy distinction from Pr. semikockeli n. sp. The holotype is clearly an adult and morphologically advanced form. Based on past taxonomic uncertainties and discrepancies, a new synonymy list is supplied. As pointed out by Ziegler (1973), the cup ornamentation is closer to or at the level of carina denticles. The longitudinal axis can be straight (Fig. 11e, j), but in the majority of specimens it is (slightly) curved laterally (Figs. 11d, 12b–c). This results in an asymmetrical cup, with an outer half more strongly expanded than the inner one. As in its ancestors, two convexities of the cup margins are developed, one at the inner anterior and one at the outer posterior sector (Fig. 11d). However, specimens with a more or less symmetrical cup shape also exist.

In aboral view, Pr. kockeli equals Pr. semikockeli n. sp. A moderately deep cup reaches the posterior tip and the edge of the free blade shows a narrow, sharp median groove.

We recognise three Pr. kockeli morphotypes based on the number of rows of nodes or ridges of fused nodes on each side of the cup. They can be distinguished easily and strictly. At least three nodes arranged in a line parallel to the carina are necessary to build a row. Morphotype 1:1 (Figs. 11e, i–k, 12d, 23d), the most common form, bears one row of nodes/ridge on both cup sides and equals the “Pr. kockeli “two-rows” morphotype” sensu Kaiser et al. (2019a online). Morphotype 1:2 (Figs. 11d, h, 12b–c, 23e) has one row of nodes/ridge on one side and two rows of nodes/ridges on the other side. It does not matter if the two rows/ridges are developed on the inner or the outer side of the cup. In Morphotype 2:2 (Fig. 23f), which includes the holotype, two rows of nodes/ridges run on both cup sides parallel to the carina. However, these rows of nodes/ridges can be accompanied by additional node(s) (e.g. Fig. 23e) in each of the three morphotypes.
## Table 4  Geographic distribution of *Pr. kockeli*.

| Region (in alphabetic order) | References with figs. | References without figs. (possibly including *Pr. semikockeli* n. sp.) |
|------------------------------|-----------------------|----------------------------------------------------------------------------|
| Aachen region, Belgian-German border | Reißner 1990 | |
| Arbuckle Mountains, Oklahoma, USA | Over 1992 | Groessens 1974, van Steenwinkel 1980, 1984, Dreesen et al. 1986, Casier et al. 2004, Denayer et al. 2020 |
| Ardennes, Belgium | van Steenwinkel 1980, 1984, Dreesen et al. 1986, Casier et al. 2004, Denayer et al. 2020 | |
| Cantabrian Mountains, Spain | Garcia-Alcalde and Menéndez-Alvarez 1988 | Higgins and Wagner-Gentis 1982, Raven 1983, García-López and Sanz-López 2002, Aretz et al. 2021 |
| Carnic Alps, Austria/Italy | Gedik 1969, 1974, Schönlaub 1969, 2018, Schönlaub et al. 1988, Perri and Spalletta 2000b, Kaiser 2005, 2007, Corradini et al. 2011, 2016, 2020, Kaiser et al. 2019a, Spalletta et al. 2020, Schönlaub 1993, Perri and Spalletta 2000a, Kaiser et al. 2006, 2009, Corradini 2016, Rakociński et al. 2020 | |
| Cornwall, United Kingdom | Austin and Armstrong 1985 | |
| Franconia, Germany | Hartenfels 2020 | Wurm 1958 |
| Graz Palaeozoic, Austria | Nössing 1975, Ebner 1980, Kaiser et al. 2009, 2019a, Corradini et al. 2011 | Ziegler et al. 1988, Li et al. 1988, Wang 1989, 1993 |
| Guangxi, China | Wang and Yin 1988 | Ziegler et al. 1988 |
| Guizhou, China | Wang and Yin 1984, Hou et al. 1984, Ji et al. in Hou et al. 1985, Ji et al. 1989, Qie et al. 2020 | Ji 1987, Ziegler et al. 1988 |
| Holy Cross Mountains, Poland | Szulczewski 1973, Dzik 1997, 2006 | ?Davydov 2020 |
| Illinois, USA | Chauffe and Nichols 1995 | Over 2020 |
| Kitab, Uzbekistan | | Narkiewicz et al. 2017 |
| Kolyma River Basin, NE Russia | Gagiev and Kononova 1990 | |
| Maider, Morocco | Becker et al. 2013 | Aretz et al. 2021 |
| Manitoba, Canada | | Nicolas 2008 |
| Middle Ural, Russia | | |
| Missouri, USA | Canis 1968, Chauffe and Guzman 1997 | Ziegler 1959, Boyer et al. 1968, Feist and Flajs 1987, Klapper in Feist 1990, Feist 2002, Becker and Weyer 2004, Aretz et al. 2016 |
| Montagne Noire, France | Flajs and Feist 1988, ?Kaiser 2009, Kaiser et al. 2009, Corradini et al. 2011, Cifer 2016, Feist et al. 2020, Hartenfels 2020 | Ziegler 1959, Boyer et al. 1968, Feist and Flajs 1987, Klapper in Feist 1990, Feist 2002, Becker and Weyer 2004, Aretz et al. 2016 |
| Moravian Karst, Czech Republic | Kalvoda and Kukal 1987, Kalvoda et al. 2013, Kumpan et al. 2020 | Bäbek et al. 2016, Kaiser et al. 2017, Kumpan et al. 2019b |
| Oklahoma, USA | | Over 2020 |
| Pyrenees, France/Spain | Buchroithner 1979, Perret 1993 | Ziegler 1959, Bouquet and Stoppel 1975, Perret 1988 |
It may be argued to separate other morphological extremes as additional Pr. kockeli morphotypes. For example, specimens with strongly expanded cups were figured by Ebner (1980: pl. 16, figs. 4, 6) and Corradini et al. (2011: pl. 1, fig. 17, re-illustrated in Kaiser et al. 2019a online as “Protognathodus aff. Pr. kockeli advanced morphotype”; pl. 3, fig. 26) from the Trolp section, Graz Palaeozoic, Austria. The same locality yielded an atypical form with a narrow cup (Kaiser et al. 2009: pl. 1, figs. 10–11, both specimens re-illustrated in Kaiser et al. 2019a online as “Protognathodus aff. Pr. kockeli (kockeli-kuehni)”; pl. 3, figs. 24–25). Corradini et al. (2003: pl. 4, fig. 2, re-illustrated in Corradini et al. 2011: pl. 1, fig. 14) recorded a narrow specimen from the Monte Taccu North B section, Sardinia, Italy.

Protognathodus kockeli s.str. differs from Pr. semikockeli n. sp. in the development of at least one row of nodes/ridge parallel to the carina on both sides of the cup. The descendant Pr. kuehni Ziegler and Leuteritz in Koch et al. (1970) can be distinguished by the fusing of nodes to transverse ridges. However, intermediates between Pr. kockeli s.str. and Pr. kuehni are well known (Figs. 11a–e, 12a) and bear rounded nodes, transversally elongated nodes, as well as incipient transverse ridges. These transitional forms were discussed conscientiously in Corradini et al. (2011) and Kaiser et al. (2019a online) and may be recognised as additional, distinctive morphotype(s). The distinction of Pr. kockeli s.str. from the younger Pr. praedelicatus, characterised by indistinct longitudinal rows (e.g. type material of Lane et al. 1980: pl. 3, figs. 5–6), requires further revision. Kalvoda et al. (2013 online: fig. 5.16, re-illustrated in Kumpan et al. 2020 online: fig. 5.9) as well as Kaiser et al. (2019a: pl. 1, fig. 8) figured Pr. kockeli specimens, which have not directly opposed anterior cup margins.

**Stratigraphic range:** After the current DCB definition, the species enters in the uppermost Famennian and defines the base of the eponymous Pr. kockeli (= Upper praesulcata) Zone (compare Ziegler and Sandberg 1984). We propose to use the FAD of Pr. kockeli s.str. to define in the future the Carboniferous base. It ranges at least into the Lower crenulata Zone (= crenulata/isostichia zones; Sandberg et al. 1978, North America; compare Corradini et al. 2011 and Spalletta et al. 2017). Kaiser et al. (2009, Puech de la Suque, Montagne Noire) described the youngest specimens from the Si. (Si.)
Conclusions

Becker et al. (2021) reviewed thirty DCB sections of the Rhenish Massif. In order to appreciate the quality of the Borkewehr section, comparisons of the immediate DCB interval of the best-known Rhenish sections is helpful. These are Hasselbachtal, Oese, Oberrödinghausen Railway Cut, Stockum Trench II, and Drewer (especially the poorly accessible sections WI and WJ of Korn et al. 1994; Fig. 24). For the extensive literature on the named sections see Becker et al. (2021). The lateral DCB sections provide important additional data on faunas, especially on lower Tournaisian ammonoids and trilobites, pelagic-neritic correlation, cyclostratigraphy, element and isotope geochemistry, magnetic susceptibility, the provenance of the siliciclastics, and the geochronological dating of bentonites.

Our proposal of the Borkewehr section as a DCB GSSP section should be viewed in the context of the enormous regional package of information. The Borkewehr is currently the only section with a record of the Pr. semikockeli n. sp.—Pr. kockeli s.str. sequence, which we propose to use for a new DCB definition. In many other sections, with a slightly later onset of carbonate deposition after the Hangenberg Regression, the FOD of Pr. kockeli, in its original sense, enables an unequivocal recognition of the Carboniferous base. At Borkewehr, conodont faunas of the Upper Hangenberg Crisis Interval are not very rich but ranges were confirmed by several rounds of re-sampling. The base of the Si. (Eo.) sulcata s.l./Pr. kuehni Zone can be recognised in the sixth limestone bed above the Hangenberg Shale/Sandstone equivalents, which coincides with a marked shift of conodont biofacies, as it is typical for the base of the Hangenberg Limestone. Borkewehr is the type section of the Wocklum Limestone, of several important topmost Devonian ammonoids, and both of Pr. semikockeli n. sp. and Pr. kockeli s.str. Other important faunal groups with stratigraphical significance, such as ostracods, trilobites, and deep-water bentonite; St = Ac. (Stockumites), Str = Ac. (Streeliceras), Post = Postclymenia, Ga = Gattendorfia, coll = Pr. collinsoni, semi = Pr. semikockeli n. sp., kock = Pr. kockeli s.str., kue = Pr. kuehni, su = Si. (Eo.) sulcata s.l.; LN and VI = miospore zones. For further details of sections, their bed numbers, and full references see Becker et al. (2021).
corals, are present. In the critical interval, there is no evidence for sedimentary gaps or reworking events. As further important tie points for global correlation, the Hangenberg Black Shale is well-developed as a transgressive and at least partly anoxic interval and Zr/Al ratios show the precise level of maximum regression within the locally undivided Hangenberg Shale/Hangenberg Sandstone unit. There is evidence for a change of Milankovitch cyclicity by climatic developments associated with the Hangenberg Crisis. Above the DCB interval, the middle Tourmainsian Lower Alum Shale Event is sharp, but remarkably thin, followed by a condensed Tourmainsian–Viséan succession that is exceptional for the missing upper Tourmainsian bedded cherts (Hardt Formation) and development of equivalents of the Erdbach Limestone II. The Borkewehr is very easily accessible, not in danger of destruction, and suitable for the application of numerous modern stratigraphic techniques, as demonstrated by us for element chemostratigraphy, carbon isotope stratigraphy, cyclostratigraphy, and sequence stratigraphy. The proposal of the Borkewehr section as a new GSSP candidate ensures its return to the type region of the first Devonian/Carboniferous Boundary GSSP.

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Data availability All data generated or analysed during this study are included in this published article [and its supplementary information files]. All specimens (if not stated otherwise) are stored in the Geomuseum of the Westfälische Wilhelms University Münster (GMM).

Declarations

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

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