



Global review of the Devonian-Carboniferous Boundary: an introduction

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The stability of our stratigraphic schemes is an important task for the geoscience community in order to provide a solid temporal framework and calendar for the description and reconstruction of Earth's history and geological processes. The International Commission on Stratigraphy (ICS) via its subcommissions has and continues to put a large effort into this task in defining *Global Boundary Stratotype Sections and Points* (GSSPs) as global references. This results in an impressive and globally accepted chronostratigraphic zonation for the Phanerozoic and Precambrian (see the charts on [stratigraphy.org](https://www.stratigraphy.org)). So, we can assume that once the long process of establishing a GSSP has been closed, stratigraphic stability for this boundary has been achieved and that a powerful stratigraphic instrument has become available for the geoscience community.

Although the golden spike is a powerful symbol for finality and stability, a GSSP is not set in stone. Stratigraphy and also its timescales are only summarising the current state of knowledge, and since this knowledge is continuously progressing and new techniques and concepts become available, we have to adapt and integrate these new data in our schemes. The Devonian-Carboniferous Boundary (DCB), corresponding to the base of the Carboniferous Period, is a good example for such a scenario.

In fact, the definition of the base of the Carboniferous Period at the Second Heerlen Congress in 1935 (Jongmans and Gothan, 1937) is the first internationally and widely recognised chronostratigraphic boundary, hence the first GSSP in our modern understanding. In the deeper-water cephalopod facies of the Rhenish Mountains (Germany), a section

— Ober-Röddinghausen in the Hönne Valley — and a point — the base of the *Gattendorfia* Zone represented by the FAD of the goniatite *Gattendorfia subinvoluta* — were selected to define the base of the Carboniferous by an international board, what was later to become the Commission on Carboniferous Stratigraphy (ICS was not existing at this time).

The Ober-Röddinghausen stratotype already highlighted the importance of the sections in the Rhenish Mountains for the stratigraphic division and subsequent discussions of the latest Devonian–earliest Carboniferous time. This is the consequence of a long tradition of studying the DCB in that region and resulting in a very detailed knowledge. This perception is highlighted in ideas like “time-specific facies” (e.g. Walliser, 1984) and “Rhenish Standard Succession” (e.g. Becker et al., 2016), which emphasise the importance of the Rhenish sections for global correlation. Today, the local lithostratigraphic units of the northern Rhenish Mountains have often lost their original lithostratigraphic connotation and they have become chronostratigraphic time markers. Thus, names like Hangenberg Sandstone (or strata named as equivalents of the Hangenberg Sandstone) have not only been used around the globe, but they are thought to set distinctive time markers.

In the 1960s and 1970s, the arrival of fine-scaled biostratigraphy using conodonts brought to light a hiatus at the boundary level in the Ober-Röddinghausen section (Alberti et al. 1974). Hence, the Ober-Röddinghausen stratotype was abandoned and the search for a new stratotype started. The IUGS working group responsible for the new stratotype used as stratigraphic marker the first occurrence of the conodont *Siphonodella sulcata*, which immediately precedes the entry of *Gattendorfia* in the Hönne Valley (Paproth and Streel, 1984).

The GSSP (Paproth et al., 1991) for the base of the Tournaisian Stage, hence the base of the Carboniferous System, was defined in the La Serre E' section (Montagne Noire, southern France) (Fig. 1). According to a morphometric study of the supposedly preserved *Si. praesulcata*–*Si. sulcata*

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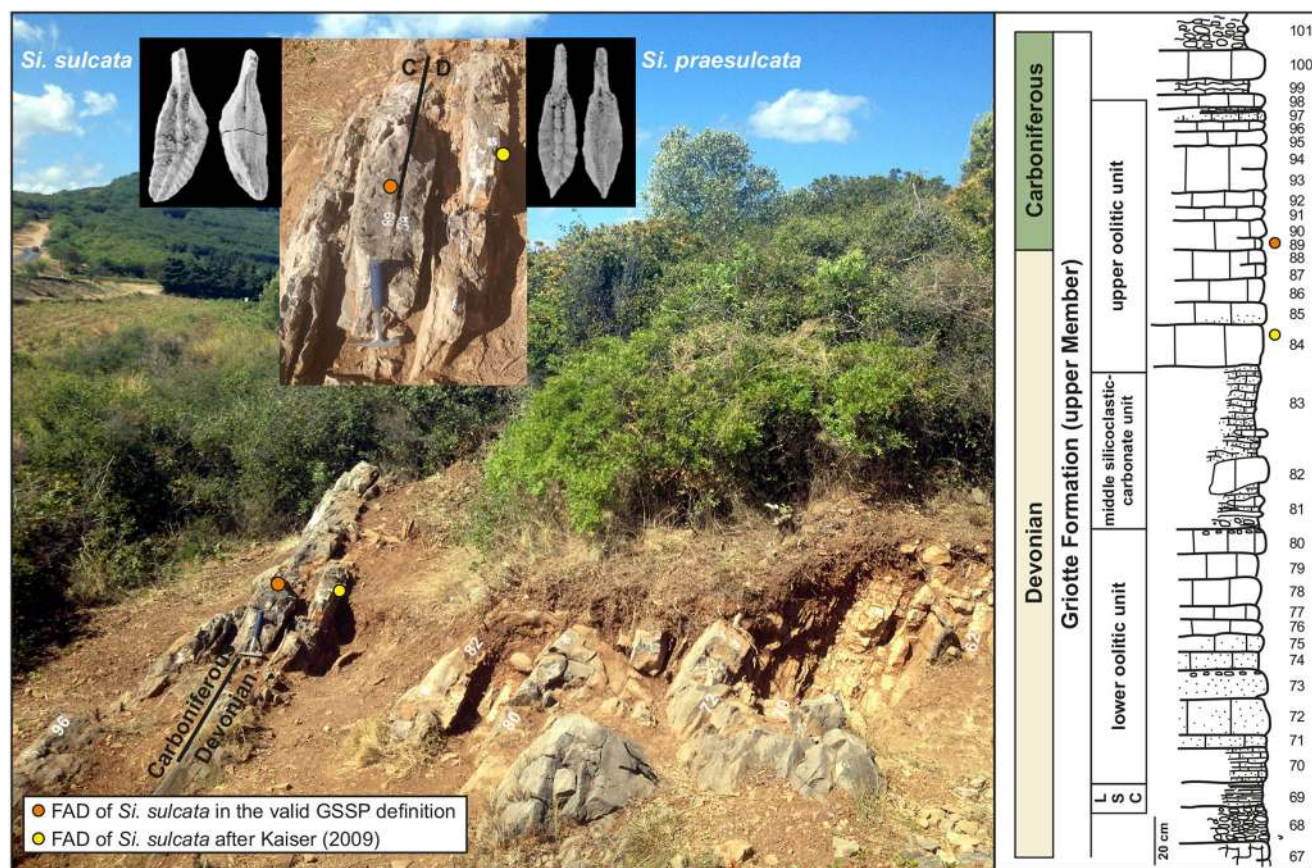


Fig. 1 Graphical mosaic summarizing the important information of the valid GSSP at La Serre, southern France: photo of the section (cleaned in 2016), close-up on the boundary interval, photos of the critical conodont species, position of the biostratigraphic index, and the section log modified from Paproth et al. (1991)

lineage (Flajs and Feist 1988), the FAD of *Si. sulcata* in bed 89 of this section indicates the base of the Carboniferous (Fig. 1). The strata straddling the DCB is a 3.7-m thick unit composed of well-bedded, graded biodetrital limestones. This unit is divided into two oolitic intervals (beds 70–80, 84–98) separated by a clay-rich level (beds 81–83) with reworked blocks and pebbles. Many of the limestone beds show variations in bed thicknesses and restricted lateral traceability pointing to channelised deposits in a high-energy environment.

Already during the selection process of the new GSSP, the section had been criticised (e.g. Ji, 1987; Ziegler and Sandberg, 1996) for its shallow-water nature including reworked fauna and strata, and especially the possible presence of *Si. sulcata* below bed 89. Ziegler and Sandberg (1996) already formally identified *Si. sulcata* in bed 85. Later, Kaiser (2009) found the index species several centimetres lower in bed 84b (upper part of bed 84). Hence, with the occurrence of the marker fossil below the GSSP just above a lithological change, the definition of the base of the Carboniferous came back on the agendas of the Devonian and Carboniferous subcommissions. At the same time, difficulties in discriminating the marker from its ancestor *Si. praesulcata* and from the several morphs of early

siphonodellids were evidenced (Kaiser and Corradini, 2011), and studies on other conodont taxa important for the stratigraphy across the boundary levels were enhanced (e.g. *Protognathodus*, Corradini et al., 2011). It is evident that profound and widely accepted understandings of the morphological variability of the biological markers is the only possible solid base for a successful global boundary, since otherwise the (bio)stratigraphic information becomes too dependent from the taxonomical concept of an individual researcher.

A joined SDS/SCCS task group was established in 2009 to redefine the base of the Carboniferous and thus to regain stratigraphic stability in this critical interval of Earth's history. Task group members and other researchers have been active in various aspects related to the boundary definition, and a huge amount of new data has become available (e.g. Corradini et al., 2017; Davydov, 2020; Kaiser et al., 2015; Marshall et al., 2020; Prestianni et al., 2016). Characteristic for many studies are multi-disciplinary approaches, which combine palaeontological, sedimentological, geochemical and petrophysical methods and data (e.g. Bábek et al., 2016; Kumpan et al., 2014; Matyja et al., 2015).

The past and present boundary stratotypes have given a lot of attention to the deeper water facies (slope and basinal

settings) and its faunal elements, which have been judged to represent the best potential for undisturbed continuous successions and nektonic faunal elements ensuring a wide palaeobiogeographical distribution of marker taxa. This focus has at least two pitfalls. The first is conceptual. It directs the focus of the DCB discussion to a particular facies (deep water “pelagic” facies) and faunal groups (conodonts, ammonoids), and the data coming from elsewhere gain less attention or are completely put aside. This renders global correlation more difficult if not impossible. The second pitfall is the supposed continuous sedimentary record, and hence a complete stratigraphic record. This seems to be a rather obvious simplification, because low sedimentation rates invariably resulted in condensation, hardgrounds and/or (cryptic) hiatuses. It also points to the problem that sampling strategies may not be adequate to achieve the predicted temporal resolution and precision, because a single bed can represent a rather long time. Hence, the discussions of the DCB and its stratotype have to take into consideration very different facies realms, if possible from at least the majority of the palaeocontinents and palaeoclimatic belts, in order to approach the very ambitious aim of a truly global applicable approach and definition. In this respect, it might sometimes be necessary to take a step back and to put the practicability of the boundary for the wide geoscience community on the forefront of the discussion.

The Devonian-Carboniferous transition is marked by major perturbations in the geosphere (palaeoclimate, geochemical cycles, relative sea-level changes) and biosphere (extinctions and radiations) (e.g. Carmichael et al., 2016; Kaiser et al., 2015; Kalvoda et al., 2019; Marshall et al., 2020; Rakociński et al., 2020, 2021). The name Hangenberg Crisis has been coined for this time of major changes. Hence, a good understanding of the dynamics of the crisis is important for any definition of the DCB, but most importantly for the definition of the DCB, the geoscience community has to agree when this crisis starts and when it ends.

The Hangenberg Crisis is equalled with important turnovers in the faunal and flora records, and Kaiser et al. (2015) qualified it as a 1st-order mass extinction. However, it must be stressed that the Hangenberg extinction is not a single short event, which would mark a perfect point in time. It corresponds to a timespan starting in the very latest Devonian and reaching (slightly) into the earliest Carboniferous. The crisis is multi-phased, and it contains not only several marked extinctions, but also radiations of particular taxa. Any definition of the boundary has to ensure that the major extinction levels in the marine realm remain in the Devonian to avoid that taxa traditionally restricted to the Devonian would become extinct in the Carboniferous. Hence, the lowest possible datum is theoretically set. This datum excludes the proposal of Davydov (2020) to use as GSSP a very accurately dated ashlayer below the Hangenberg Black Shale in the Kowala Quarry in Poland. The upper datum is similarly set, since the

Carboniferous radiation of most taxa should not start in the Devonian. This indicates that the DCB should be best placed within the later stages of the Hangenberg Crisis. Kaiser et al. (2015) divided the crises into three intervals, which are precised further in the detailed calendar of Becker et al. (2021, this issue).

One consistent problem in the interpretation of the Hangenberg Crisis is related to the completeness of fossil records and timing of extinctions due to different ideas on sea-level fluctuations and resulting sequence stratigraphic interpretations (Aretz, 2020). In the Rhenish standard succession (e.g. Kaiser et al., 2015), the lower crisis interval starts with a minor regression (top Wocklum Limestone) followed by a rapid transgressive pulse, which resulted in the deposition of the Hangenberg Black Shale, which also contains the maximum flooding surface. The following regression is documented in the middle crisis interval, corresponding to the Hangenberg Shale and Sandstone. The maximum regression is reached near or at the top of the Hangenberg Sandstone. The upper crisis interval corresponds to the following sea-level rise resulting in the deposition of the Stockum Limestone. The sea-level drop in the middle crisis interval is interpreted as a third-order sequence boundary (e.g. Herbig, 2016; Kaiser et al., 2015), which may have reached up to 100 m deduced from incised valleys. This important drop in sea-level is then put forward to conclude important stratigraphic gaps in the shallow-water realm due to subaerial exposure and inferred erosion during most of the time represented by the Hangenberg Sandstone in the Rhenish Massif (e.g. Van Steenwinkel, 1990).

However, growing evidences arising from modern sedimentological and biostratigraphic work show much more complete records in the shallow water realm (Poty, 2016; Denayer et al., 2021, this issue). The entire pre-extinction to post-extinction succession in Belgium belongs to a single third-order sequence. This highlights the unique, sudden and disruptive nature of the Hangenberg Crises as an out-of-sequence event of the general relative sea-level history in the Devonian-Carboniferous transition. It also points to a distinct temporal offset between the major extinctions in the deeper and shallow water marine facies. Most of the “pelagic” fauna disappeared with the onset of the anoxic to dysoxic conditions in the lower crisis interval, whereas the shallow water fauna survived until the major regression at the top of the middle crisis interval.

In consequences, the Hangenberg Crisis as the “Natural Devonian Carboniferous Boundary” (Walliser, 1984) offers a very good tool to approximately place the DCB based on sedimentological, geochemical, petrophysical and palaeontological data in very different facies realms. This approximation is sufficient for many geological questions, but when high-precision data are required, its timespan is far too long. However, as developed further down, timelines and events in

SYSTEM	STAGE	CONODONTS		AMMONOIDS	SPORES	FORAMINIFERS		RUGOSE CORALS	HANGENBERG CRISIS	
		Corradini et al. 2017, 2021	Becker et al. 2016, 2021	Becker et al. 2016	Streel et al. 1987 Prestianni et al. 2016	Kulagina et al. 2021	Poty et al. 2006 Denayer et al. 2021	Poty et al. 2006 Denayer et al. 2021	Becker et al. 2021	
CARBONIFEROUS	Tournaisian	<i>Si. sandbergi</i>	<i>Si. (Si) sandbergi</i>	<i>Zadelsdorfia</i>	HD	<i>Chernyshinella disputabilis</i>	MFZ 2	RC 1β	post-crisis Interval	
				<i>Pseudarietites</i>						
		<i>Si. jii</i>	<i>Si.(Si.) mehli</i>							<i>Earlandia minima</i>
		<i>Si. duplicata</i>	<i>Si.(Si.) duplicata</i>	<i>Paprothites</i>						
		<i>Si. bransoni</i>	<i>Si.(Eosi.) bransoni</i>							
	Famennian	<i>Pr. meischneri</i> SZ	<i>Pr. kockeli</i>	<i>Si. (Eosi.) sulcata</i> s.l./ <i>Pr. kuehni</i>	<i>Gattendorfia</i>	VI	<i>Tournayelina pseudobeata</i> - remnant <i>Quasiendotyhra</i>	MFZ 1		RC 1α
				<i>Pr. kockeli</i>	<i>Acumitoceras (Stockumites)</i>			DFZ 8		
				<i>Bi. costatus-Pr. kockeli</i> Interregnum	<i>Postclymenia</i>					
				<i>Si.(Eosi.) praesulcata</i>	<i>Wocklumeria</i>			LE		
					<i>Parawocklumeria</i>					
<i>Bi. ultimus</i>	<i>Bi. ultimus ultimus</i>	<i>M. bisulcata</i>	LL							
<i>Bi. costatus</i>	<i>Bi. costatus</i>	<i>Kalloclymenia</i>								
								Upper III		
								Middle II		
								Lower II		
								Prelude II		
								pre-crisis Interval		

Fig. 2 Correlation scheme of biostratigraphic important fossils groups and calendar of the different phases of the Hangenberg Crises. The dotted red line indicates the timeline for a revised DCB currently discussed by the working group

the latest Devonian and basal Carboniferous inevitably fall into the dynamics of the Hangenberg Crisis, but the establishment of a detailed calendar will provide a very useful fine-scaled stratigraphic framework (Fig. 2). As different contributions in this issue show, the next challenge for the stratigraphic community is to produce an applicable, universal calendar.

In the last 10 years, the task group met several times in connection with international congresses, and special sessions on the DCB, or formal discussions were held at the 3rd International Palaeontological Congress in London (July 2010), at the SDS/ISCS field symposium in Morocco (March 2013), at the 2nd International Congress on Stratigraphy (Strati 2015) in July 2015 in Graz, at the Congress on Carboniferous and Permian in Kazan (August 2015), at the IGCP 596 final meeting in Brussels (September 2015) and at the Congress on Carboniferous and Permian in Köln (August 2019). Furthermore, a dedicated workshop with 2 days of discussions and a field trip to the classical sections in Montagne Noire, where the present GSSP is located, was organised in Montpellier in September 2016 (Fig. 3). On that occasion, it was decided to test a possible position of the Devonian/Carboniferous Boundary

based on a timeline defined by “the base of the *Protognathodus kockeli* conodont Zone, the end of the Devonian mass extinction and beginning of the Carboniferous radiation, and the top of a major regression (top of Hangenberg Sandstone)”. It has to be stressed that this timeline is based on different criteria, which should increase the potential of placing the boundary in different facies realms and palaeobiogeographical provinces, and increase the practicability of global correlations. The proposed timeline is in accordance to the approach of the task group to reduce the dependence of the boundary definition based on the presence or absence of a single marker (chronostratigraphic units have to be separated from biostratigraphic units!). Hence, the new boundary should be placed not only by characterising the boundary timeline by different criteria, but also by the development of a robust calendar of well-defined timelines slightly below and above the new DCB. Thus, it is not the presence or absence of a single criterion, which may be “too early” or “delayed” in a particular section, but a sequence of arguments for placing the boundary.

The onset of dysoxic and anoxic facies and subsequent extinction of the pelagic and nektonic fauna (often correlated with the base or the Hangenberg Black Shale) is an important timeline in



Fig. 3 Group photo of the participants of the DCB workshop in Montpellier (Sept. 2016) taken in the current GSSP section at La Serre. Photo courtesy of F. Lübbecke (Münster)

the latest Devonian and below the proposed new DCB timeline. It is interesting to note that this timeline should be younger than 359.0 Ma according to the data in Davydov (2020), which changes the widely accepted age for the DCB of 359.2 or 359.3 (e.g. Aretz et al., 2020). A timeline characterised by the floral turnover (e.g. extinction of *R. lepidophyta*) in the continental realm and the income of *Si. sulcata* (if taxonomic agreement could be reached) and *Pr. kuehni* in the marine pelagic facies would be a timeline slightly higher above the proposed new boundary level. This timeline fits relatively well to the current GSSP level.

Hence, in constructing a calendar including these and other timelines, we do not only increase chances for precise global correlation, but also offer a powerful tool for the entire geoscience community, and not only the experienced stratigrapher. The proposed boundary level is in accordance to the theoretical lower and upper datum set by our traditional understanding of the geological and biological history around the boundary between the Devonian and Carboniferous systems. Finally, such a boundary would help to maintain stratigraphic stability (Becker et al., 2016).

To avoid any stratigraphic chaos and ambiguity where and how the DCB should be placed in the light of the current ongoing discussions, it has to be stressed that the GSSP at La Serre is still valid and our current reference (Aretz et al., 2020). This would only change in the future if ICS ratifies a different proposal. Hence, the discussions and proposals in the working group are important for our understanding of the latest Devonian–earliest Carboniferous time, and the position of the DCB may change in the future, but nothing has yet been formalised. In any case, in many sections, the proposed criteria by the working group would only slightly lower the boundary.

Before a formal vote on the new position of the DCB, task group members and other scientists were asked to (i) provide regional overviews on the DCB and (ii) check the suitability of the proposed boundary level in their working regions all over the world. This special issue is the result of these studies, and data from various regions are presented in 14 thematic papers authored by a total of 55 experts from all over the world (Fig. 4).

The first contribution by Feist et al. (2021, this issue) is dedicated to the **Montagne Noire**. Naturally, with the DCB

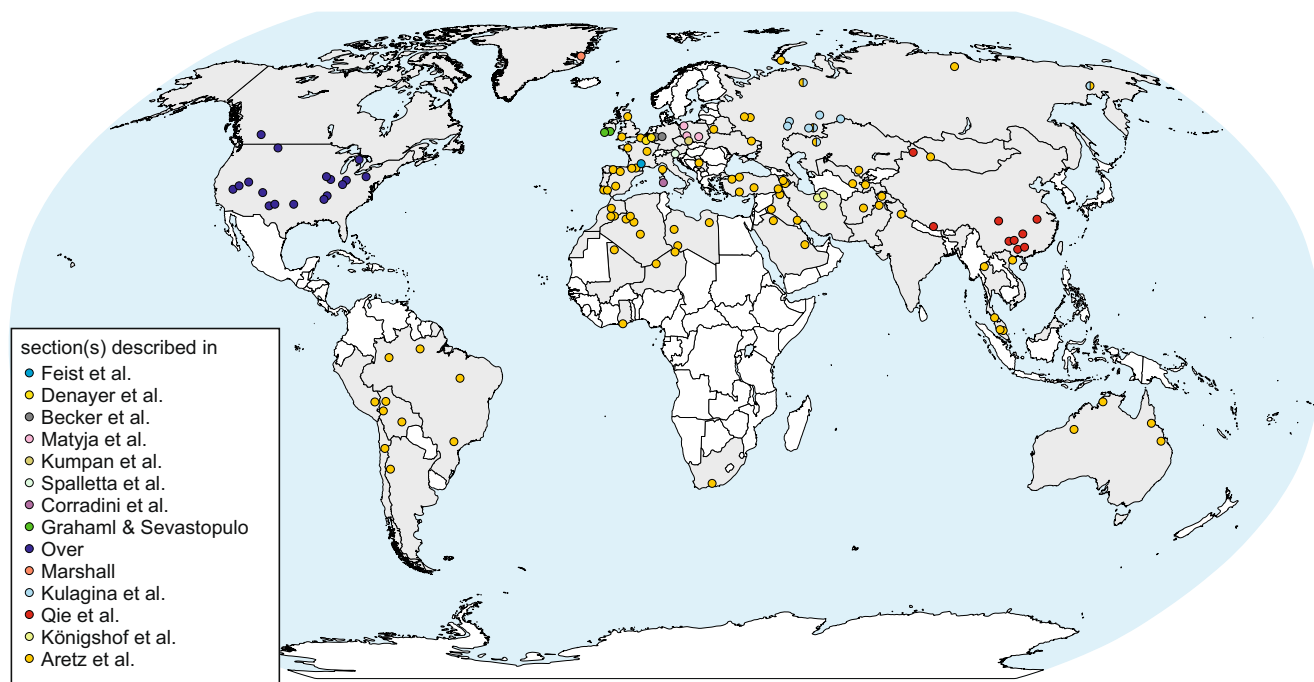


Fig. 4 Geographic distribution of the studied DCB sections on a modern world geography: the countries dealt within this issue are in grey. A dot indicates the approximate position of one or several nearby DCB sections

GSSP situated at La Serre, many papers have already dealt with this region, and a wealth of data is available in the existing literature. However, this study includes new sedimentological interpretation and correlations between the shallow and deeper water sections of the Montagne Noire. (*Palaeobiodiversity and Palaeoenvironments* 101(2) <https://doi.org/10.1007/s12549-019-00402-6>)

Denayer et al. (2021, this issue) deal with the sections in **Belgium and the Avesnois**. It provides a lot of new and revised data for this classical region for the DCB in mainly shallow marine facies. As already mentioned above, this study provides new lines of evidences for the completeness of the records, and thus underlines the importance for a holistic approach for the understanding and definition of the DCB (*Palaeobiodiversity and Palaeoenvironments* 101(2) <https://doi.org/10.1007/s12549-020-00440-5>).

Another classical region, the **Rhenish Mountains**, where numerous DCB sections in deeper water (“pelagic”) facies crop out, is dealt with by **Becker et al. (2021, this issue)**. Overall 30 sections are reviewed in detail in terms of litho-, event, conodont, ammonoid, sequence, and chemostratigraphy. A by-product of this is the refinement of the nomenclature and calendar of the Hangenberg Crisis (*Palaeobiodiversity and Palaeoenvironments* 101(2) <https://doi.org/10.1007/s12549-020-00469-6>).

Matyja et al. (2021, this issue) described the DCB in **Poland**. This multidisciplinary study summarises astonishingly detailed data from ramp environments known from the subsurface of Pomerania (western Poland) and the pelagic successions of the

Holy Cross Mountains and Sudetes, where the DCB is found in surface outcrops (*Palaeobiodiversity and Palaeoenvironments* 101(2) <https://doi.org/10.1007/s12549-020-00442-3>).

The DCB interval of the **Moravian Karst** is presented by **Kumpan et al. (2021, this issue)**. Their study presents well-studied sections, with almost continuous carbonate sedimentation, characterised by carbonate turbidites and hemipelagic successions. From a stratigraphic point of view, the intermixing of faunal markers from the pelagic and neritic realms (conodonts, calcareous foraminifers) provides interesting perspectives (*Palaeobiodiversity and Palaeoenvironments* 101(2) <https://doi.org/10.1007/s12549-019-00409-z>).

The review of the DCB sections in the **Carnic Alps** provided by **Spalletta et al. (2021, this issue)** showcases a rather unique situation in 2 sections, including the well-known Grüne Schneid. There, a fully carbonated and highly condensed deeper water succession crosses the boundary, and the typical lithological changes related to the Hangenberg Crisis the “pelagic” facies are absent. However, a black shale interval is present in two other sections in the area (*Palaeobiodiversity and Palaeoenvironments* 101(2) <https://doi.org/10.1007/s12549-019-00413-3>).

Corradini et al. (2021, this issue) provide a short overview on the two DCB sections, which are exposed on **Sardinia**. Both sections show a lithological change in the boundary interval, and detailed data on conodonts and magnetic susceptibility suggest a hiatus just above the black shale interval (*Palaeobiodiversity and Palaeoenvironments* 101(2) <https://doi.org/10.1007/s12549-019-00411-5>).

The DCB interval in **southern Ireland** is presented by **Graham and Sevastopulo (2021, this issue)**. In this area, thick successions of siliciclastic rocks are well-exposed in numerous coastal sections with the Old Kinsale Head section being the most famous one. This study shows that the fluvial coastal plain environments of the latest Devonian are replaced by shallow marine strata of earliest Carboniferous age (*Palaeobiodiversity and Palaeoenvironments* 101(2) <https://doi.org/10.1007/s12549-020-00455-y>).

Over (2021, this issue) documents the DCB from various basin with marine strata in **North America** using conodonts, brachiopods, miospores, carbon isotope data, and magnetic susceptibility data. The boundary is well-constrained and conformable in the Illinois Basin and Oklahoma. It is less well-constrained in the Appalachian Basin, Antler Foreland, western platform, and the Alberta Platform, and often developed on an unconformity (*Palaeobiodiversity and Palaeoenvironments* 101(2) <https://doi.org/10.1007/s12549-020-00428-1>).

In his contribution on **Greenland, Marshall (2021, this issue)** describes sections straddling the DCB in a terrestrial (lacustrine) setting hundreds of kilometres away from the palaeocoastlines of Laurussia. Information provided for the extinction sequences of the terrestrial microflora are important for the discussions on the correlation between the marine and terrestrial realms (*Palaeobiodiversity and Palaeoenvironments* 101(2) <https://doi.org/10.1007/s12549-020-00448-x>).

Kulagina et al. (2021, this issue) review the foraminiferal biostratigraphy of the DCD beds in shallow water carbonated facies in **Russia and Western Kazakhstan**. The DCB is situated within the *Tournayellina pseudobeata*–remnant *Quasiendothyra* Zone. Correlations to ammonoid-based and conodont-based faunal schemes are provided and ensure the correlation in to deeper marine facies (*Palaeobiodiversity and Palaeoenvironments* 101(2) <https://doi.org/10.1007/s12549-020-00439-y>).

Sections straddling the DCB in southern **China** have been reviewed by **Qie et al. (2021, this issue)**. Their multidisciplinary study uses integrated biostratigraphic, event-stratigraphic, and geochemical approaches along a proximal to basinal transect. It provides detailed insights into the Hangenberg Crisis in the different palaeoenvironmental settings, and results in a robust stratigraphic framework for the DCB interval (*Palaeobiodiversity and Palaeoenvironments* 101(2) <https://doi.org/10.1007/s12549-021-00494-z>).

Königshof et al. (2021, this issue) provide an interesting insight into the shallow water settings in which most of the **Iranian** DCB sections are situated. Biostratigraphic uncertainties in most sections and/or hiatuses in the DCB interval make difficult the correlation of those sections to the standards developed in pelagic/hemipelagic palaeoenvironments (*Palaeobiodiversity and Palaeoenvironments* 101(2) <https://doi.org/10.1007/s12549-020-00438-z>).

The last contribution of this issue by **Aretz et al. (2021, this issue)** compiles data on the Devonian-Carboniferous Boundary

successions from countries and regions, which have not been dealt with separately in this special issue. These necessarily shorter and less detailed compilations than the detailed studies in the other contributions cover a wide geographic range from **South America, Africa, Arabia, Asia, Australia, to Europe** (*Palaeobiodiversity and Palaeoenvironments* 101(2) <https://doi.org/10.1007/s12549-021-00495-y>).

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