

Conodonts across the Devonian/Carboniferous boundary: a review and implication for the redefinition of the boundary and a proposal for an updated conodont zonation

CARLO CORRADINI*†, CLAUDIA SPALLETTA‡, ANGELO MOSSONI*,
HANNA MATYJA§ & D. JEFFREY OVER¶

*Dipartimento di Scienze Chimiche e Geologiche, Università di Cagliari, via Trentino 51, I-09129 Cagliari, Italy

‡Dipartimento di Scienze Biologiche, Geologiche e Ambientali, Alma Mater Studiorum Università di Bologna, via Zamboni 67, I-40126 Bologna, Italy

§Polish Geological Institute - National Research Institute, Rakowiecka 4, PL-00-975 Warsaw, Poland

¶Department of Geological Sciences, State University of New York College at Geneseo, Geneseo, NY 14454, USA

(Received 15 July 2015; accepted 22 April 2016; first published online 15 June 2016)

Abstract – This paper is a contribution to the redefinition of the base of Carboniferous system. At present the criterion for the definition of the Devonian–Carboniferous boundary is the first occurrence of a conodont species. In order to evaluate the stratigraphic potential for new criteria for the definition of the Devonian–Carboniferous boundary, the distribution of conodont species of *Bispathodus*, *Branmehla*, *Palmatolepis*, *Polygnathus*, *Protognathodus*, *Pseudopolygnathus* and *Siphonodella* across the boundary is presented and discussed. An updated biozonation scheme across the boundary based on the First Appearance of *Bispathodus ac. aculeatus*, *Bispathodus costatus*, *Bispathodus ultimus*, *Protognathodus kockeli*, *Siphonodella bransoni* and *Siphonodella duplicata* is proposed, and it is suggested that the new criterion for the definition of the base of the Carboniferous system be the First Appearance Datum of *Pr. kockeli* or *Si. bransoni*.

Keywords: conodonts, Devonian–Carboniferous boundary, biostratigraphy, biozonation.

1. Introduction

The criterion for defining the base of the Carboniferous system is placed to coincide with the First Appearance Datum (FAD) of the conodont species *Siphonodella sulcata*; the GSSP (Global Stratotype Section and Point) is located in La Serre Trench E' section (Paproth, Feist & Flajs, 1991). Problems in discrimination of *Si. sulcata* from the supposed ancestor *Si. praesulcata* were already known when the GSSP was established (e.g. Wang & Yin, 1984; Ji, 1987). Flajs & Feist (1988) published a biometric study of *S. praesulcata* and *S. sulcata* based on the La Serre faunas, demonstrating that transitional forms are very common. Despite these taxonomical uncertainties, the FAD of *Si. sulcata* was chosen to define the base of the Tournaisian. Further studies on the stratotype section have revealed other problems, such as lack of other important stratigraphic guides and the existence of reworking (e.g. Ziegler & Sandberg, 1996; Casier, Lethiers & Pr at, 2002; Kaiser, 2009).

A redefinition of the Devonian–Carboniferous boundary (DCB) was determined necessary, and in 2008 the International Commission on Stratigraphy established a working group with the goal of proposing a new criterion for defining the boundary and finding a new GSSP. For that purpose several sections are under investigation around the world, including

already-known localities (Mossoni, Corradini & Spalletta, 2013; Kumpan *et al.* 2014b; Malec, 2014) and new locations (Bahrami, Corradini & Yazdi, 2011; Becker *et al.* 2013; Girard *et al.* 2014; Komatsu *et al.* 2014; Kumpan *et al.* 2014b; Kalvoda, Kumpan & Babek, 2015; Mossoni *et al.* 2015; Qie *et al.* 2015), and main fossil groups are subject to revision. Multiproxy studies including isotope stratigraphy, gamma-ray and magnetic susceptibility are also in progress (Kumpan *et al.* 2014a; Matyja *et al.* 2015).

This paper is a contribution to the activities of the working group, presenting a summary of the distribution of important uppermost Devonian and lowermost Carboniferous conodont species.

The interval from the Middle *expansa* Zone to the Lower *duplicata* Zone is considered in this paper, spanning a time interval of about 4 Ma across the present boundary according to more recent geochronologic calibration (Becker, Gradstein & Hammer, 2012; Davydov, Korn & Schmitz, 2012). Possible new positions of the DCB in terms of conodont stratigraphy are presented and discussed and a new biozonation for the uppermost Devonian and lowermost Carboniferous is proposed.

2. Conodont taxa across the DCB

The distribution of the stratigraphically most important species of *Bispathodus*, *Branmehla*, *Palmatolepis*,

†Author for correspondence: corradin@unica.it

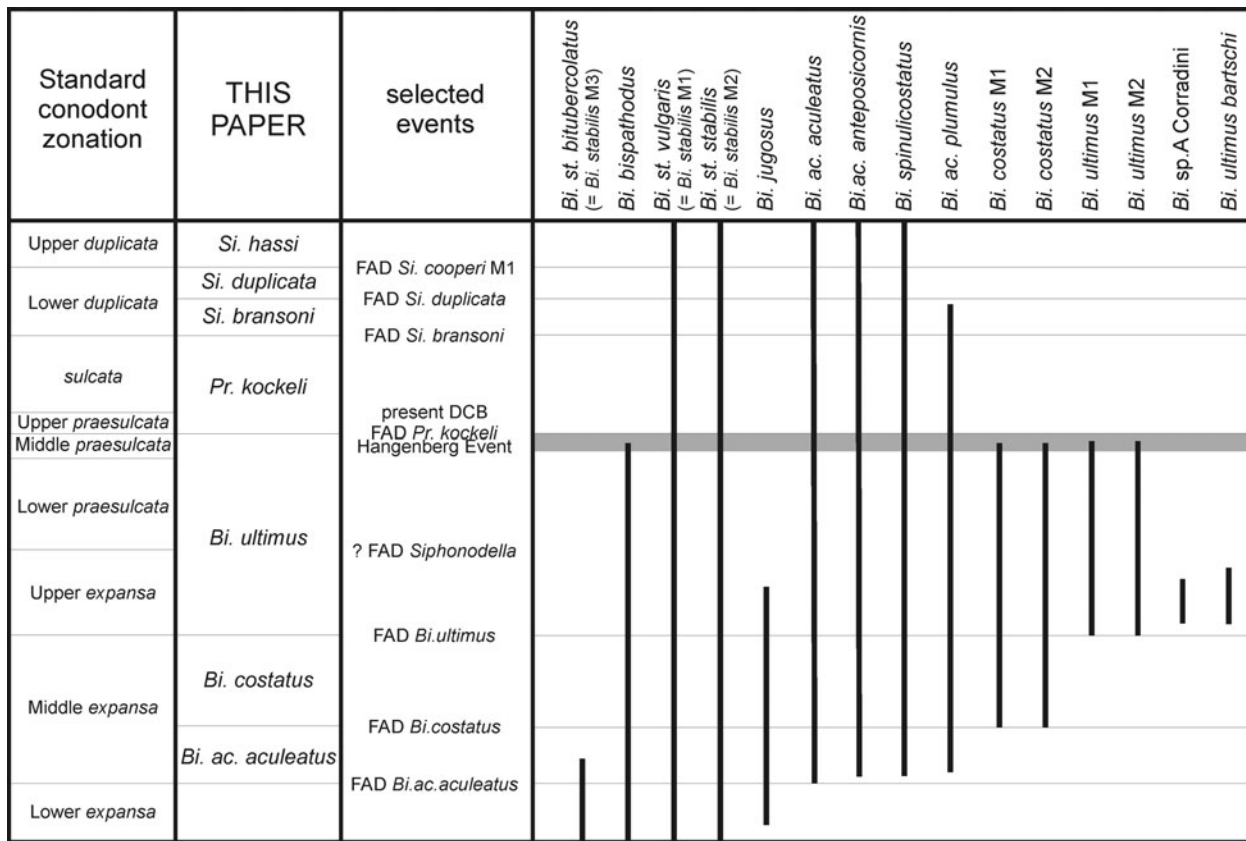


Figure 1. Distribution of *Bispathodus* across the Devonian–Carboniferous Boundary (data after Ziegler, Sandberg & Austin, 1974; Sandberg *et al.* 1978; Ziegler & Sandberg, 1984; Corradini, 2003; S. I. Kaiser, PhD Thesis, Ruhr-University Bochum, 2005; Kaiser *et al.* 2009; Kononova & Weyer, 2013).

Polygnathus, *Protognathodus*, *Pseudopolygnathus* and *Siphonodella* and other genera were investigated, in order to analyse their potential for biostratigraphy across the DCB (Figs 1–4). All data available in literature were considered and integrated with unpublished data from our collections, mainly from the Carnic Alps and Sardinia.

It should be noted that some other genera have been proposed recently (e.g. *Bizignathus* Gatovsky, 2009; *Neopolygnathus* Voronova, 1991 (in Barskov *et al.* 1991) and *Polynodosus* Vorontsova, 1993), detaching part of the species from another genus, mostly from the ‘mega-genus’ *Polygnathus*. This paper is not based on supraspecific taxonomy, and we do not want to enter into systematic discussions here even if, in our opinion, a single morphological variation is not sufficient to establish a new genus. We therefore maintain the classical generic attribution for the species claimed to belong to *Bizignathus*, dubitatively included in *Pseudopolygnathus*; those of *Neopolygnathus* and *Polynodosus* are maintained in *Polygnathus*. These new genera are not widely accepted. Finally, it is important to note that most of the species included in *Neopolygnathus* are not widely distributed and are likely endemic forms, so their stratigraphic potential for a new criterion for the definition of the Devonian–Carboniferous boundary is rather limited.

The ranges of the taxa are presented on the basis of present standard zonations for the uppermost Devonian (Ziegler & Sandberg, 1984) and lowermost Carboniferous (Sandberg *et al.* 1978). For comments on the zonation and discussion of the new zonation scheme depicted in Figures 1–4, see Section 3.

2.a. *Bispathodus*

Bispathodus is a genus widely distributed in the Famennian and Tournaisian strata and is represented by several species (Fig. 1), most of which have a broad geographical distribution. In first approximation the genus can be subdivided into two stocks, one characterized by taxa with a relatively small basal cavity (‘aculeatus branch’ of Ziegler, Sandberg & Austin, 1974) and the second with a wide basal cavity that extends to the posterior end (‘bispathodus branch’ of Ziegler, Sandberg & Austin, 1974).

The genus was revised first by Ziegler, Sandberg & Austin (1974), and later the ‘ultimus Group’ by Ziegler & Sandberg (1984). Hartenfels (2011) elevated the morphotypes of *Bi. stabilis* to subspecies rank, and introduced a new subspecies. More recently Kononova & Weyer (2013) approached the ‘ultimus Group’ in a different way, partly refusing the revision by

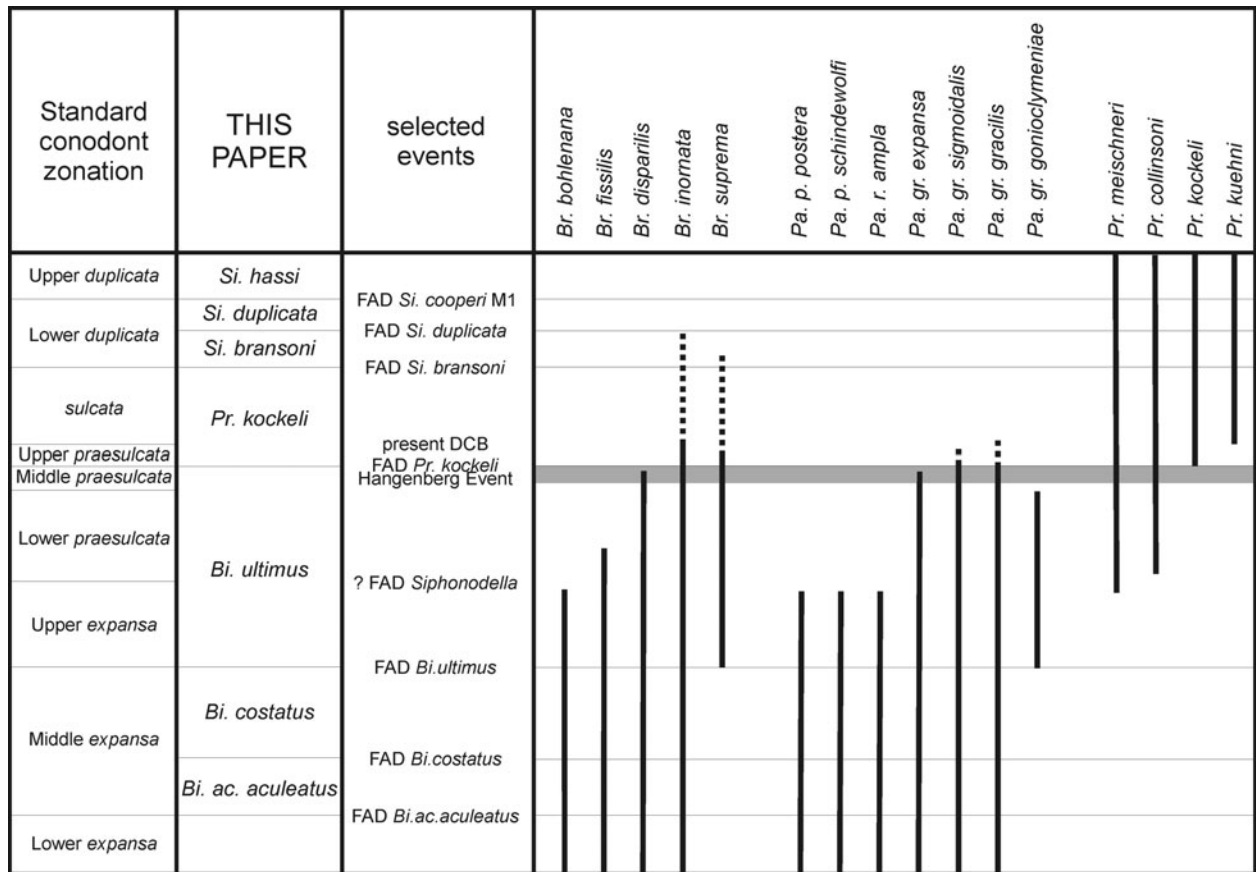


Figure 2. Distribution of *Branmehla*, *Palmatolepis* and *Protognathodus* across the Devonian–Carboniferous Boundary (data after Ziegler & Sandberg, 1984; Ji & Ziegler, 1993; Corradini, 2008; Kaiser *et al.* 2009; Corradini *et al.* 2011; and unpublished data).

Ziegler & Sandberg (1984), but their revision needs to be carefully evaluated and is not followed here.

Bispathodus represents an important genus for the uppermost Famennian biostratigraphy. Ziegler (1962) named the last pre-Hangenberg Event zone after *Bi. costatus* (Branson) and Ziegler & Sandberg (1984) selected *Bi. aculeatus aculeatus* (Branson & Mehl) and *Bi. ultimus* (Bischoff) as markers of the Middle and Upper *expansa* zones, respectively.

A large radiation of species of *Bispathodus* occurred during latest Famennian time: 11 taxa have their first appearance between the Lower and the Upper *expansa* zones. *Bi. stabilis stabilis* (Branson & Mehl) (= *Bi. stabilis* Morphotype 2 of Ziegler, Sandberg & Austin, 1974) is often documented from the base of the Lower *expansa* Zone. The taxon was used by Hartenfels (2011) to approximate the base of the Lower *expansa* Zone, renamed *stabilis* Zone in his ‘Overregional Zonation’, because the marker *Pa. gracilis expansa* is not present in Central Europe and Morocco. However, it should be noted that the species has an early first occurrence in the Carnic Alps and Thuringia, where it enters within the Upper *trachytera* Zone (Spalletta & Perri, unpubl. data; Girard *et al.* unpubl. data). *Bi. jugosus* branched from *Bi. st. stabilis* in the upper part of the Lower *expansa* Zone.

The early part of the Middle *expansa* Chron represented a period of wide radiation of *Bispathodus*: as

already mentioned *Bi. ac. aculeatus* is the marker of the base of the zone, and *Bi. ac. anteposicornis* (Scott) and *Bi. ac. plumulus* (Rhodes *at al.*) appeared slightly later. The latter taxon was moved to *Clydagnathus* by Hartenfels (2011), but this change of generic attribution should be carefully evaluated. Both the morphotypes of *Bi. costatus* (Branson) enter in the central part of the zone. The last radiation of *Bispathodus* happened in the Late *expansa* Chron, and involved the ‘ultimus Group’: the two morphotypes of *Bi. ultimus* have an almost simultaneous first appearance at the base of the zone, and related taxa have been reported regionally in slightly higher levels: *Bi. ultimus bartschi* Kononova & Weyer in Thuringia and *Bispathodus* sp. A Corradini in Sardinia. No species of *Bispathodus* originated after the Upper *expansa* Zone (Fig. 1).

Bispathodus bispathodus Ziegler *et al.*, *Bispathodus costatus* and *Bispathodus ultimus* did not survive the Hangenberg Event (Ziegler & Sandberg, 1984), whereas *Bispathodus stabilis*, *Bi. spinulicostatus* and *Bi. aculeatus* are reported in the lower Carboniferous at least up to the Lower *crenulata* Zone (Sandberg *et al.* 1978).

2.b. *Branmehla* and *Mehlina*

Branmehla and *Mehlina* are ozarkodinids characterized by a single row of denticles on the processes. In

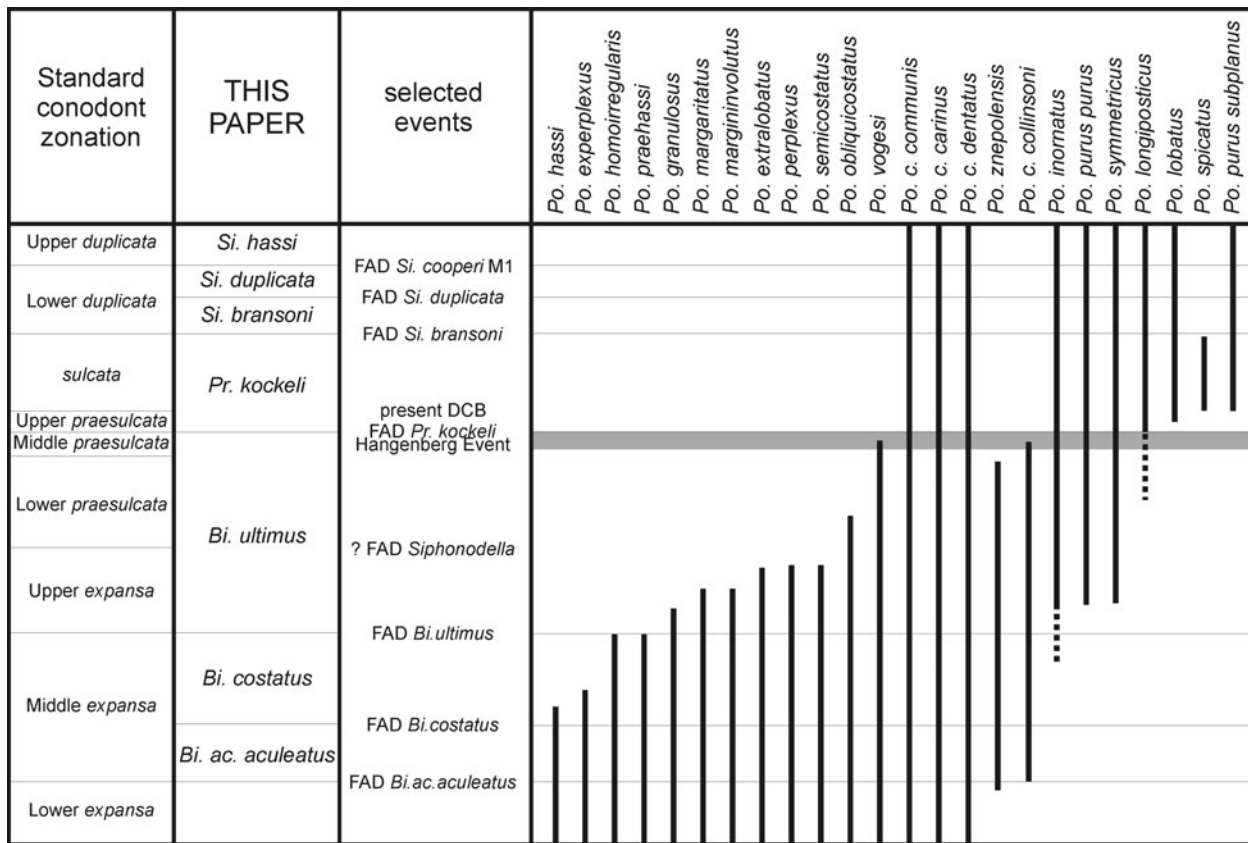


Figure 3. Distribution of selected taxa of *Polygnathus* across the Devonian–Carboniferous Boundary (data after Sandberg *et al.* 1978; Ziegler & Sandberg, 1984; Wang & Yin, 1988; Perri & Spalletta, 1991, 2000a; Ji & Ziegler, 1993; Corradini, Barca & Spalletta, 2003; Corradini, 2008; Hartenfels 2011; Qie *et al.* 2014; and unpublished data).

general they do not represent a major component of the conodont association, even if some species are quite abundant in some levels.

The distribution of *Branmehla* is limited to the uppermost Devonian and lowermost Carboniferous strata (Fig. 2). *Branmehla bohlenana* (Helms) ranges up to the Upper *expansa* Zone, while *Br. fissilis* (Branson & Mehl) enters in the Lower *praesulcata* Zone. *Branmehla suprema* (Ziegler), with a wide asymmetrical basal cavity, is a characteristic species of the Upper *expansa* and Lower *praesulcata* zones, but is tentatively recorded also from the lowermost Tournaisian strata of the Graz Palaeozoic and French Pyrenees (Kaiser *et al.* 2009). The report (not figured) of *Br. fissilis* from the Tournaisian of China (Hou *et al.* 1985) should be confirmed and possible reworking should be excluded before considering these unusually high occurrences; the presence of *Br. weneri* in the Carboniferous of Dapoushang section (Wang & Yin, 1988) is disregarded because the figured specimens belong to another taxon.

Branmehla inornata (Branson & Mehl) is a long-ranging taxon that survived the Hangenberg Event (Ziegler & Sandberg, 1984) and entered the Carboniferous system (Over, 1992; Kaiser *et al.* 2009; Bahrami, Corradini & Yazdi, 2011). *Mehlina strigosa* (Branson & Mehl) was once considered extinct at the DCB, but recently it has been documented together with

definitely Carboniferous associations (Kaiser *et al.* 2009; Bahrami, Corradini & Yazdi, 2011).

2.c. *Palmatolepis*

Palmatolepis is the dominant genus of the Upper Devonian pelagic environment. Numerous species and subspecies have been established in the Frasnian and Famennian strata, but the diversity decreases within the upper Famennian and only a few taxa are documented in the uppermost Famennian deposits (Fig. 2).

The most common taxon in that stratigraphic interval is *Pa. gracilis*, represented by several subspecies. *Pa. gr. expansa* Sandberg & Ziegler ranges from the base of the Lower *expansa* Zone up to the level of the Hangenberg Event, but in some parts of the world it is a rare taxon (i.e. central Europe). *Palmatolepis gr. gonioclymeniae* Müller is documented from the Upper *expansa* Zone to just below the Hangenberg Event; its LAD was chosen by Ziegler & Sandberg (1984) to indicate the base of their Middle *praesulcata* Zone, but this definition is often not applicable because the taxon is very rare or absent (Corradini, 2008; Kaiser *et al.* 2009). The most successful taxa of this stock are the nominal species, *Pa. gr. gracilis* Branson & Mehl and *Pa. gracilis sigmoidalis* Ziegler, which ranged for most

of the Famennian age and became extinct within the Hangenberg Event, or slightly later.

Beside *Pa. gracilis*, only a few taxa of *Palmatolepis* belonging to the ‘perlobata’ and ‘rugosa’ groups occur up to the Upper *expansa* Zone: *Pa. perlobata postera* Ziegler; *Pa. p. schindewolfi* Müller; and *Pa. rugosa ampla* Müller (Fig. 2).

2.d. *Polygnathus*

Polygnathus is the most abundant and differentiated conodont genus of the Devonian and Carboniferous strata: Becker (2012, 2013) listed hundreds of names of species (and subspecies) attributed to *Polygnathus*. About 40 taxa are documented in the uppermost Devonian and lowermost Carboniferous strata (Fig. 3), but few have an important stratigraphic value either due to a long range or a restricted regional distribution.

Many species became extinct within the Middle and Upper *expansa* zones (Fig. 3). *Polygnathus znepolensis* Spassov is documented up to the top of the Middle *praesulcata* Zone, and *Po. vogesi* Ziegler ranges up to the Hangenberg Event. It should be noted that the latter taxon was reported from Tournaisian deposits after a Lazarus phase (see Kaiser *et al.* 2009, p. 124), but these occurrences should be confirmed in order to exclude homeomorphism or taxonomic confusion with *Po. c. carinus*, which is quite similar in upper view.

The most common polygnathid species across the DCB is *Polygnathus communis* Branson and Mehl (= *Neopolygnathus* Vorontsova), which has been subdivided into several subspecies. Some of the subspecies have a wide geographical distribution, such as *Po. c. communis*, *Po. c. carinus* Hass and *Po. c. dentatus* Druce, but are documented from the Famennian into the Tournaisian strata, whereas *Po. c. collinsoni* Druce is limited to the uppermost Famennian deposits. Other subspecies (e.g. *Po. c. quadratus* Wang, *Po. c. renatae* Corradini & Spalletta, *Po. c. shangmiaobeiensis* Qin *et al.* and others) have shorter ranges but are geographically limited.

Polygnathus purus purus, which Voges (1959) indicated as an index of the basal Carboniferous, have been reported from Upper Devonian strata before the entry of *Siphonodella* in several North Gondwana regions (Corradini, Barca & Spalletta, 2003; Bahrami, Corradini & Yazdi, 2011; Girard *et al.* 2014). *Polygnathus purus subplanus* enters more or less around the present DCB (Kaiser *et al.* 2009), but it is not a common taxon; this also applies for *Po. spicatus* Hinde, which has a range limited to the present *sulcata* Zone (Sandberg *et al.* 1978; Qie *et al.* 2014).

Other species such as *Polygnathus inornatus* and *P. symmetricus* originate in the upper Famennian and range well into the Tournaisian strata (Sanz López *et al.* 1999; Corradini, 2008; Bahrami, Corradini & Yazdi, 2011). *Polygnathus longiposticus* have been reported before the Hangenberg Event only in China (Wang & Yin, 1988).

2.e. *Protognathodus*

Protognathodus is a short-ranging genus, known from the uppermost Famennian to the Tournaisian strata. Its stratigraphic potential around the DCB is well known since Ziegler (1969) introduced the ‘*Protognathodus* fauna’ to define the uppermost Devonian strata, and later Ziegler & Sandberg (1984) defined the base of the last Devonian zone, the ‘Upper *praesulcata* Zone’, by the entry of *Pr. kockeli*. However, it should be noted that in some regions such as in Poland the genus is very rare.

The genus has been revised by Corradini *et al.* (2011). Four species of *Protognathodus* are known in the time frame across the DCB (Fig. 2): *Pr. meischneri* Ziegler; *Pr. collinsoni* Ziegler; *Pr. kockeli* (Bischoff); and *Pr. kuehni* Ziegler & Leuteritz. Two more species occur in the middle Tournaisian: *Pr. praedelicatus* Lane *et al.* and *Pr. cordiformis* Lane *et al.*

Protognathodus meischneri, the oldest species of the genus, evolved from *Bispathodus stabilis* (Ziegler, 1969) during late Famennian time by a variation in the position and shape of the basal cavity (cup). In *Protognathodus* the basal cavity extends to the posterior end of the element and is more rounded and inflated; *Pr. meischneri* has an almost symmetrical and unornamented cup. The first occurrence of *Pr. meischneri* is reported from the Upper *expansa* Zone (Corradini, Barca & Spalletta, 2003; Corradini *et al.* 2011). In the very early part of its range *Pr. meischneri* gave rise to *Pr. collinsoni*, characterized by the occurrence of scattered nodes on the upper surface of the slightly asymmetrical cup. Both these species range to within the Upper *duplicata* Zone (Over, 1992).

Protognathodus kockeli, characterized by an asymmetrical cup covered by at least one longitudinal row of nodes, evolved from *Pr. collinsoni* just after the Hangenberg Event. It ranges up to the lower part of the Lower *crenulata* Zone in North America (Sandberg *et al.* 1978), whereas elsewhere it is limited to the *sandbergi* Zone. *Protognathodus kockeli* is the marker of the Upper *praesulcata* Zone (= *kockeli* Zone after Kaiser *et al.* 2009, the last Devonian biozone) and is the most abundant and widely documented species of *Protognathodus*. It has a wide geographic distribution, but in many regions it occurs only in Carboniferous strata (Corradini *et al.* 2011). However, it should be noted that a hiatus occurs above the Hangenberg Shales equivalents in several sections around the world, and the older part of the range of *Pr. kockeli* is therefore often not documented.

Protognathodus kuehni is distinguished by robust transverse ridges on the upper surface of the cup running radially from the margins to the carina, which can be suppressed. It evolved from *Pr. kockeli* and ranges from at or just above the present DCB to the *sandbergi* Zone (Lane, Sandberg & Ziegler, 1980). The first occurrence of *Pr. kuehni* was used by Kaiser *et al.* (2009) to approximate the DCB in sections where siphonodellids are absent. However, it is in general an extremely

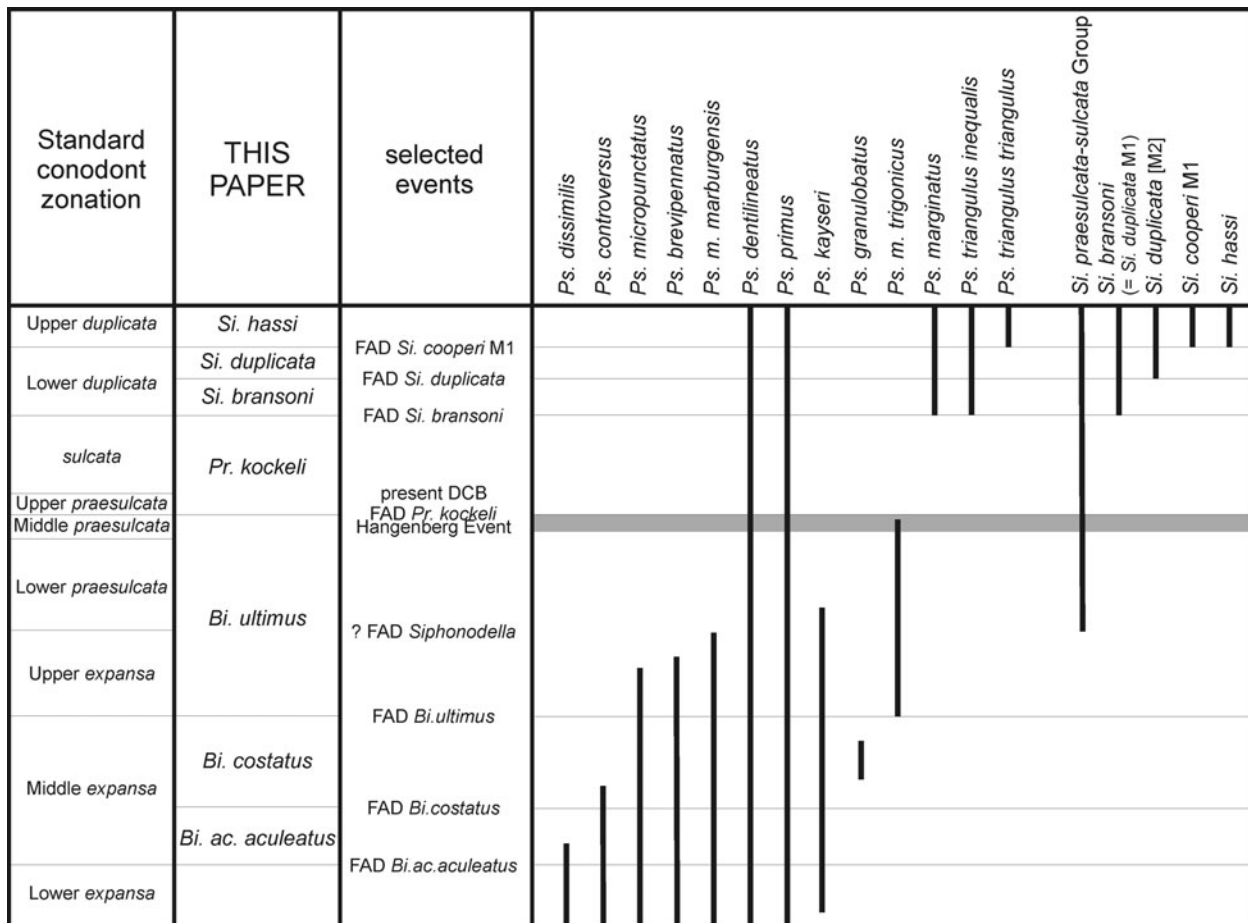


Figure 4. Distribution of *Pseudopolygnathus* and *Siphonodella* across the Devonian–Carboniferous Boundary (data after Sandberg *et al.* 1978; Klapper in Ziegler, 1981; Ziegler & Sandberg, 1984; Perri & Spalletta, 1991; Ji & Ziegler, 1993; Corradini, Barca & Spalletta, 2003; Corradini, 2003, 2008; Kaiser *et al.* 2009; Hartenfels, 2011; and unpublished data).

rare taxon with a restricted range in many sections and, outside the type area, it often occurs only in higher stratigraphic levels (Corradini *et al.* 2011).

2.f. *Pseudopolygnathus*

Pseudopolygnathus is a relatively abundant and widely distributed genus in the uppermost Famennian and lowermost Tournaisian strata (Fig. 4). However, the genus underwent a crisis during the Middle and Late *expansa* chrons, when several Devonian species became extinct: *Ps. brevipennatus* Ziegler; *Ps. controversus* Sandberg & Ziegler; *Ps. dissimilis* (Helms & Wolska); *Ps. marburgensis marburgensis* Bischoff & Ziegler; and *Ps. micropunctatus* Bischoff & Ziegler. *Pseudopolygnathus? kayseri* Bischoff & Ziegler entered into the Lower *praesulcata* Zone. It should be noted that *Ps.? kayseri* and *Ps. dissimilis* were moved to the new genus *Bizignathus* by Gatovsky (2009) and Hartenfels (2011), respectively.

Only a few taxa are documented around the Devonian–Carboniferous boundary: *Ps. dentilineatus* Branson; *Ps. marburgensis trigonicus* Ziegler; *Ps. multistriatus* Mehl & Thomas; and *Ps. primus* Branson & Mehl. None of these seem to have a strong stratigraphic importance.

Pseudopolygnathus marburgensis trigonicus became extinct during the Hangenberg crisis (Ziegler & Sandberg, 1984). *Pseudopolygnathus dentilineatus*, once reputed to have its first occurrence together with *Protognathodus kockeli* above the Hangenberg Event (Voges, 1959), has been reported from the Middle *expansa* Zone in Devonian strata (Klapper in Ziegler, 1981). *Pseudopolygnathus primus* and *Ps. dentilineatus* have long ranges, at least from the Lower *expansa* Zone (Klapper in Ziegler, 1981) to the Lower *crenulata* Zone (Sandberg *et al.* 1978).

Pseudopolygnathus multistriatus enters at the base of Carboniferous system, but it is a rare taxon. A larger radiation of *Pseudopolygnathus* took place during the Tournaisian age, when several species have their first appearance within the Lower *duplicata* Zone and in higher levels.

2.g. *Siphonodella*

Two taxa have been established within the early range of the genus *Siphonodella* lineage: *Siphonodella praesulcata* Sandberg and *Siphonodella sulcata* (Huddle). Although problems in discrimination of *S. praesulcata* from *S. sulcata* were evidenced by numerous authors in several parts of the world (Ji, 1987; Flajs & Feist,

1988; Wang & Yin, 1988), the base of the Carboniferous system was defined by the First Occurrence of *Siphonodella sulcata* within the claimed *S. praesulcata* – *S. sulcata* lineage (Paproth, Feist & Flajs, 1991).

The diagnoses of the two taxa are not clear and they overlap each other (Kaiser & Corradini, 2011). According to the original diagnosis (Sandberg, *in* Sandberg, Strel & Scott, 1972), *Siphonodella praesulcata* has a slightly arched, narrow platform ornamented on both sides by weak to obsolescent transverse ridges, separated from the straight to slightly curved carina by wide adcarinal troughs; the basal cavity is straight to slightly curved. The author reports that the species can be distinguished from *S. sulcata* from the fact that the latter has a more asymmetrical, slightly curved, platform with a stronger ornamentation and, mainly, a strongly curved pseudokeel. In fact, the emended diagnosis (Sandberg, *in* Sandberg, Strel & Scott, 1972) of *Si. sulcata* reads: ‘slightly asymmetrical arched platform is ornamented on both sides by transverse ridges, which are separated from the strongly curved nodose carina by narrow adcarinal grooves. The strongly curved basal cavity . . .’

However, as demonstrated by Kaiser & Corradini (2011), only a few specimens fit one or the other definition well; the great majority of specimens show features intermediate between those listed for the two taxa. Furthermore, the claimed phylogenetic transition from *S. praesulcata* to *S. sulcata* is not recorded in the DCB GSSP section at La Serre, where the supposed *S. praesulcata* – *S. sulcata* lineage was based on reworked elements found in sediments derived from different source areas (Ziegler & Sandberg, 1996; Kaiser, 2009).

It should also be noted that specimens assignable to *Siphonodella praesulcata-sulcata* group, both with straight and curved shape of the carina and basal cavity, have been illustrated and described as species of *Polygnathus* in the literature (e.g. some of the specimens of *Polygnathus* sp. D and *Polygnathus* sp. E of Kononova & Weyer, 2013). Often these specimens came from levels yielding an uppermost Famennian association.

It is worthwhile mentioning that the lost holotype of *S. sulcata* was from a level likely yielding Carboniferous conodonts at least referable to the *duplicata* Zone (Evans *et al.* 2013), therefore representing a late morphotype. However, after a complete revision of the early siphonodellids, it cannot be excluded that other species of *Siphonodella* may be discriminated within the early part of the lineage.

In higher levels a very good datum point is represented by the FAD of *Si. bransoni* Ji (= *Si. duplicata* M1) (Fig. 4), a well-known, easy to identify and relatively abundant species with a wide geographical distribution. Establishing the species, Ji (1985) reported the description of *Si. duplicata* M1 of Sandberg *et al.* (1978), but did not indicate a holotype. The designation of a type is needed, possibly reconsidering the collections by Canis (1968), mentioned by Sandberg *et al.* (1978) and Ji (1985). According to Sandberg *et al.* (1978, p. 105), *Si. bransoni* ‘evolved from *Si. sulcata* by development of

a complete rostrum on both side of the anterior end of the platform’.

A different group of species of *Siphonodella* are represented by the so-called ‘naked Siphonodellas’, regarded by several authors as typical of shallow-water facies. These forms are documented at the base of the Carboniferous system, mainly in China and Russia (Ji & Ziegler, 1992; Qie *et al.* 2014) and are rare elsewhere. *Siphonodella homosimplex* Ji & Ziegler is the oldest representative of the group and has its FAD close to the present DCB. Shortly after, *Si. levis* (Ni), *Si. semichatovae* Kononova & Lipnjagov and *Si. bella* Kononova & Migdisova first appear; *Si. sinensis* Ji and *Si. quasinuda* Gagiev, Kononova & Pazukin enter at the base of the Lower *duplicata* Zone. Other taxa, such as *Si. dasaibaensis* Ji *et al.* and *Si. eurylobata* Ji, are documented higher in the Tournaisian strata.

Ji & Ziegler (1992) proposed an alternate zonation scheme for the shallow-water facies of the lower and middle Tournaisian strata, defining six zones based on the entries of species of naked siphonodellas: *homosimplex* Zone; *levis* Zone; *sinensis* Zone; *dasaibaensis* Zone; Early *eurylobata* Zone; and Late *eurylobata* Zone.

3. Conodont zonation across the DCB

The conodont zonation scheme in use for the Upper Devonian and lower Tournaisian strata is a combination of the ‘Late Devonian Standard Conodont Zonation’ (Ziegler & Sandberg, 1990), and the Late Devonian – early Carboniferous zonation of Sandberg *et al.* (1978). Variations and improvements to these schemes were proposed by Ji (1985), Corradini (2008), Kaiser *et al.* (2009) and Hartenfels (2011), but these modifications have not been widely used up to now. Some of these proposals are accepted here.

The taxonomic revision of taxa and the updating of their stratigraphic and geographic distribution imply a reconsideration of the zonation scheme for uppermost Famennian and lower Tournaisian strata, in order to achieve a new, global, zonation. Before focusing on open problems in the zonation schemes in use, it is necessary to briefly summarize the history of the conodont zonation across the Devonian–Carboniferous Boundary.

3.a. Review of former zonation schemes

The first zonation scheme for the Upper Devonian strata was provided by Ziegler (1962) who discriminated 24 conodont zones before the Hangenberg Event, mainly based on sections in Germany. In the uppermost Famennian strata *Po. styriacus* and *Spathognathodus costatus* (now *Bi. costatus*) were chosen as index taxa for two zonal groups, both subdivided into a Lower, a Middle and an Upper part. The time frame of interest of this paper includes the Upper *styriacus*, the Lower *costatus*, the Middle *costatus* and the Upper *costatus* zones *sensu* Ziegler (1962) (Fig. 5). The Upper *styriacus* Zone cor-

Ziegler (1962, 1969)	Sandberg et al. (1978)	Ziegler & Sandberg (1990)	Corradini (2003)	Kaiser et al. (2009)	Hartenfels (2011)	THIS PAPER	selected events
<i>S. duplicata</i> - <i>Ps. triangulus</i> <i>inequalis</i>	Upper <i>duplicata</i>		Upper <i>duplicata</i>	<i>hassi</i>		<i>Si. hassi</i>	◀ FAD <i>Si. hassi</i> , <i>Si. cooperi</i> M1 ◀ FAD <i>Si. duplicata</i> ◀ FAD <i>Si. bransoni</i>
	Lower <i>duplicata</i>		Lower <i>duplicata</i>	<i>duplicata</i>		<i>Si. duplicata</i>	
				<i>bransoni</i>		<i>Si. bransoni</i>	
<i>S. sulcata</i> - <i>Pr. kockeli</i>	<i>sulcata</i>	<i>sulcata</i>	<i>sulcata</i>	<i>sulcata/kuehni</i>		<i>Pr. kockeli</i>	◀ FAD <i>Pr. kuehni</i> ▲ FAD <i>Pr. kockeli</i>
Lower Prot. fauna	<i>praesulcata</i>	Up. <i>praesulcata</i>	Up. <i>praesulcata</i>	<i>kockeli</i>			▲ FAD <i>Pr. collinsoni</i> ▲ ? FAD <i>Siphonodella</i> ▼ FAD <i>Pr. meischneri</i>
Upper <i>costatus</i>		Mid. <i>praesulcata</i>	Low. <i>praesulcata</i>	<i>cost.-kock. int.</i>			
Middle <i>costatus</i>		Low. <i>praesulcata</i>		<i>praesulcata</i>			
	Lower <i>costatus</i>	Upper <i>expansa</i>	Upper <i>expansa</i>	Upper <i>expansa</i>			
Upper <i>styriacus</i>		Middle <i>expansa</i>	Middle <i>expansa</i>	Middle <i>expansa</i>	<i>Bi. ac. aculeatus</i>	<i>Bi. ultimus</i>	◀ FAD <i>Bi. ultimus</i> ◀ FAD <i>Bi. costatus</i>
	Middle <i>styriacus</i>	Lower <i>expansa</i>	Lower <i>expansa</i>	Lower <i>expansa</i>	<i>Bi. st. stabilis</i>	<i>Bi. ac. aculeatus</i>	◀ FAD <i>Bi. ac. aculeatus</i> ◀ FAD <i>Bi. jugosus</i>

Figure 5. Main conodont zonation schemes across the Devonian–Carboniferous boundary, with indication of the main bioevents useful for stratigraphy. Thickness of zone is calibrated according to their length, as estimated in the Devonian and Carboniferous chapters of *The Geologic Time Scale 2012* (Becker, Gradstein & Hammer, 2012; Davydov, Korn & Schmitz, 2012).

responded to the upper part of the range of *Po. styriacus*, above the entry of *Ps. brevipennatus*, *Ps. dentilineatus* and *Sp. jugosus* (now *Bi. jugosus*). The base of Lower *costatus* Zone was indicated by the FAD of the nominal species; the Middle *costatus* Zone fell in the central part of the range of *Bi. costatus* together with *Pa. gr. gonioclymeniae* and *Bi. ultimus*; and the Upper *costatus* Zone was defined as the upper part of the range of *Bi. costatus* and *Bi. ultimus* after the extinction of *Pa. gr. gonioclymeniae*. This zonation was confirmed by Ziegler (1971, 1979), with the addition of the Lower *Protognathodus* Fauna that Ziegler (1969) documented from the uppermost part of the *Wöcklumeria*-Stufe.

Voges (1959, 1960) introduced a zonation scheme for the lowermost Carboniferous in Germany. In the ‘*Gattendorfia* Stufe’ he distinguished three zones: the *kockeli-dentilineata* Zone; the *Siphonodella-triangulus inequalis* Zone; and the *Siphonodella-triangulus triangulus* Zone. Ziegler (1969) updated this zonation renaming the oldest zones *Siphonodella sulcata* – *Protognathodus kockeli* Zone and *Siphonodella duplicata-triangulus inequalis* Zone, and proposed the equivalence of these zones with the *Siphonodella sulcata* and *Siphonodella duplicata* zones described in North America by Klapper (in Sandberg & Klapper, 1967).

Sandberg et al. (1978) introduced a zonation scheme for the uppermost Famennian and most of the Tournaisian strata based on the evolution of genus *Siphonodella*. In this scheme the entry of *Si. praesulcata* discriminates the last Devonian zone and that of *Si. sulcata* marks the base of the Carboniferous. The sub-

sequent Lower *duplicata* Zone is distinguished by the FAD of *Si. duplicata*, and the Upper *duplicata* Zone by the entry of *Si. cooperi* Morphotype 1.

Ziegler & Sandberg (1984) revised the upper part of the Upper Devonian zonation, naming all the zones before the entry of *Si. praesulcata* after species of genus *Palmatolepis*. The *styriacus* and *costatus* zonal groups of Ziegler (1962) were replaced by the *postera* and *expansa* zonal groups. The former Upper *styriacus* Zone was replaced by the Lower *expansa* Zone, the base of which is indicated by the FAD of *Pa. gr. expansa*; the Middle *expansa* Zone is marked by the entry of *Bi. ac. aculeatus*; and the Upper *expansa* Zone is marked by those of *Bi. ultimus*. *Siphonodella praesulcata* was chosen to name the last group of zones of the Devonian, in order to connect the Upper Devonian zonation based on *Palmatolepis* with the lower Carboniferous zonation based on *Siphonodella*. The Lower *praesulcata* Zone is marked by the FAD of the nominal species, the Middle *praesulcata* Zone by the extinction of *Pa. gr. gonioclymeniae* and the Upper *praesulcata* Zone by the entry of *Pr. kockeli*. Surprisingly, even though some of the boundaries of the new zones are defined exactly as those of the former zones, in both the text and figures of Ziegler & Sandberg (1984) there are some discrepancies in the correlation and definition of the old and the new zonal schemes. The LAD of *Pa. gr. gonioclymeniae* in Ziegler (1962) defines the base of the Upper *costatus* Zone, whereas in Ziegler & Sandberg (1984) it indicates the base of the Middle *praesulcata* Zone. Further, the bases of the biozones do not correspond

(see Ziegler & Sandberg, 1984, p. 184, figs 1–4) although they are supposed to be defined with the same criterion. Only the equivalence between the Lower *Protognathodus* fauna and the Upper *praesulcata* Zone was correctly indicated.

Later the same authors (Ziegler & Sandberg, 1990) updated the Upper Devonian zonation without making any variation in the uppermost Famennian strata, and renamed the scheme the ‘Late Devonian Standard Conodont Zonation’. In addition, Ziegler & Sandberg (1994) claimed this zonation as a ‘phylogenetic zonation’, where zones are ‘defined from the first occurrences of an ancestral species to the first occurrence of the next younger descendant species’ (Sandberg & Ziegler, 1996, p. 261). This definition was strongly criticized (Corradini, 2008; Kononova & Weyer, 2013) because that scheme is based on both first occurrences and extinction within several genera and therefore, apart from a few short intervals, was not a phylogenetic zonation. The taxonomic concept on which the so-called standard zonation is based had already been rejected by Klapper & Foster (1993) for Frasnian species.

The Ziegler & Sandberg (1990) scheme was widely used in the last decades, even if some problems arose. In the uppermost Famennian strata the main concern was with the definition of the Middle *praesulcata* Zone, defined by the extinction of *Pa. gr. gonioclymeniae*, a taxon that is not common outside Germany. Problems in discrimination of that zone were evidenced by Over (1992), Perri & Spalletta (2000a) and Corradini (2008). S. I. Kaiser (PhD Thesis, Ruhr-University Bochum, 2005) reported that ‘the base of the Middle *praesulcata* cannot be regarded as the approximation of an isochronous level, and its recognition does not allow reliable biostratigraphical and geochemical correlations’. On the basis of these considerations, Corradini (2008) proposed to expand the Lower *praesulcata* Zone up to the entry of *Pr. kockeli*, essentially eliminating the Middle *praesulcata* Zone.

Kaiser *et al.* (2009) accepted the proposal to abandon the Middle *praesulcata* Zone and introduced a new interval zone, the ‘*costatus-kockeli* Interregnum (CKI)’, corresponding to the Hangenberg conodont extinction event. This interval is equivalent to the uppermost part of the former Middle *praesulcata* Zone. In addition these authors renamed the zones across the Devonian–Carboniferous boundary by the name of the index taxon, and adopted for the Tournaisian strata proposal by Ji (1985) based on *Siphonodella: sulcata* Zone, *bransoni* Zone, *duplicata* Zone, *hassi* Zone, etc. (Fig. 5). All these zones, as well as several middle and upper Famennian zones renamed by Hartenfels (2011), are named after the index taxon where the first appearance indicates the base of the zone. Kaiser *et al.* (2009) also renamed the *sulcata* Zone as *sulcata/kuehni* Zone, suggesting the use of the FAD of *Pr. kuehni* as an index when *Si. sulcata* was not present.

Finally, a chronologic calibration of the zones was attempted in the Geological Time Scale 2012 (Devonian: Becker, Gradstein & Hammer, 2012; Carbonifer-

ous: Davydov, Korn & Schmitz, 2012). The biozones in Figure 5 are calibrated according to these results where a few zones, such as the Middle *praesulcata* and the *kockeli* zones, were very short and others definitely longer (i.e. Middle *expansa* Zone).

3.b. Proposal of a new zonation

A zonation that can be used globally should be based on index taxa easy to recognize, with a well-known stratigraphic range and a broad geographic distribution. Taxa whose taxonomic attribution is not clear and/or need taxonomic revision should be avoided. In the majority of cases candidate species do not have a wide geographical distribution or their first occurrence is not simultaneous in different regions, or in some areas are rare.

Zonation schemes can also be developed for limited geographic areas only. These regional zonations can be based on endemic taxa, or on taxa with a wide and limited geographic distribution, and may allow more detailed correlation within the region than the standard zonation.

In the uppermost Devonian and lowermost Carboniferous strata only a few taxa have the characteristics to define the zones of a possible global zonation. As an example, species of *Siphonodella* in the upper part of the range of the genus (the entry of *Si. bransoni* and above) may be very good markers, but it is better to avoid the use of the early representatives because of significant taxonomic uncertainties. Some species of *Bispathodus* can be good markers in the uppermost Famennian strata. Among *Protognathodus* only *Pr. kockeli* can be used, while the other representatives of the genus have a very low stratigraphic potential due to their rarity (Corradini *et al.* 2011).

A new zonation for the uppermost Famennian and lowermost Tournaisian strata is presented in the following (Fig. 5). The stratigraphic interval considered is equivalent to the former Middle *expansa* to the Lower *duplicata* zones. All the zones are defined by First Appearance Datum (FAD) of well-known taxa and are named after the index species. Taxonomic references of the index taxa are indicated, and the type specimens (or reference specimens) are illustrated in Figure 6.

3.c. The *Bispathodus ac. aculeatus* Zone

Lower limit: FAD of *Bispathodus aculeatus aculeatus*

Upper limit: FAD of *Bispathodus costatus*

Remarks: The *Bi. aculeatus* Zone is equivalent to the lower part of the Middle *expansa* Zone of Ziegler & Sandberg (1984) and to the upper part of the Upper *styriacus* Zone of Ziegler (1962). Hartenfels (2011) proposed a *Bi. aculeatus* Zone in his ‘Overregional Zonation’, but extended the upper boundary up to the FAD of *Bi. ultimus*, therefore also including the *Bi. costatus* Zone which he considered as a subzone.

Notes on the index taxon: The holotype was not indicated by Branson & Mehl (1934a) when the species

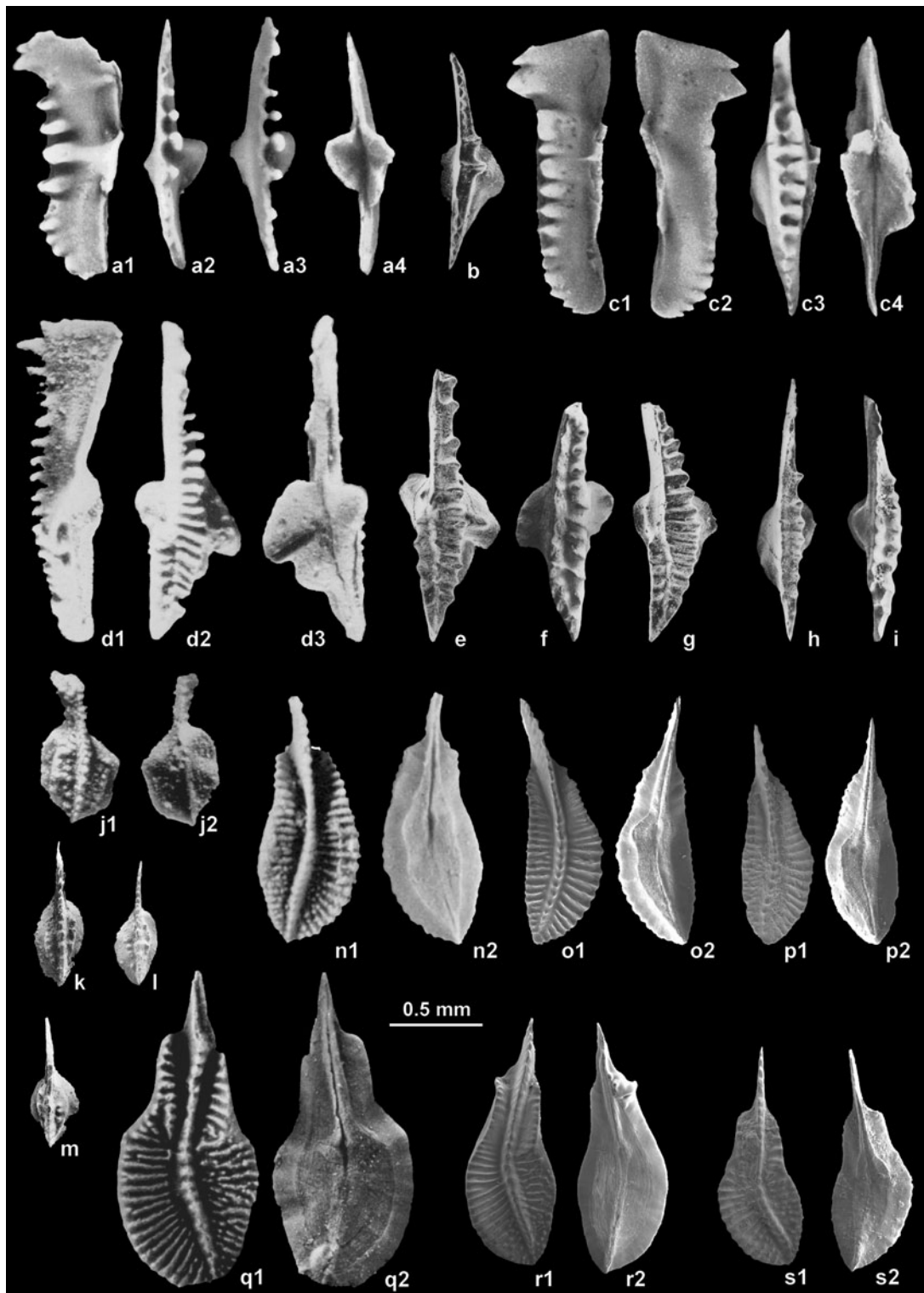


Figure 6. (a) *Bispathodus aculeatus aculeatus* (Branson & Mehl). Lectotype, lateral (a1), upper (a2), upper-lateral (a3) and lower (a4) views. Tributary of South Fork of North River, Marion County, Missouri. Refigured after Ziegler, Sandberg & Austin (1974). (b) *Bispathodus aculeatus aculeatus* (Branson & Mehl), upper view. Corona Mizziu section, Sardinia, sample CM I 25 of Corradini (2003). (c) *Bispathodus costatus* (Branson). Holotype, inner-lateral (c1), outer-lateral (c2), upper (c3) and lower (c4) views. Hannibal Shale, section at Lovers Leap. refigured after Ziegler (in Ziegler, 1975). (d) *Bispathodus ultimus* (Bischoff). Holotype, lateral (d1), upper (d2) and lower (d3) views. Abandoned quarry between the villages of Wocklum and Mellen, SW slope of Burg-Berg, Rhenish Slate Mountain. Refigured, after Bischoff (1957, pl. 4, fig. 24a–c). (e) *Bispathodus ultimus* (Bischoff). Morph 1 of Ziegler & Sandberg (1984), upper view. Corona Mizziu section, Sardinia, sample CM I 24 of Corradini (2003). (f) *Bispathodus ultimus* (Bischoff). Morph 2 of Ziegler & Sandberg (1984), upper view. NW Poland (Pomerania), borehole section Rzeczenica-1, depth 3002.5 m. (g) *Bispathodus ultimus* (Bischoff). Morph 2 of Ziegler & Sandberg (1984), upper view. Corona Mizziu section, Sardinia, sample CM I 26 of Corradini (2003). (h) *Bispathodus costatus* (Branson), upper view. Corona Mizziu section, Sardinia, sample CM I 25B of Corradini (2003). (i) *Bispathodus costatus* (Branson), upper view. NW Poland (Pomerania), borehole section Rzeczenica-1, depth 3002.5 m. (j) *Protognathodus kockeli* Bischoff. Holotype, upper (j1) and lower (j2) views. Abandoned quarry between the villages of Wocklum

was erected; Ziegler (1962) chose the lectotype as the element figured by Branson & Mehl (1934a) in plate 17, figure 11. The lectotype was refigured by Ziegler, Sandberg & Austin (1974, pl. 2, fig. 1) and Ziegler (in Ziegler 1975, *Bispathodus* pl. 1, fig. 1). For a revised diagnosis and description refer to Ziegler *et al.* (1974).

3.d The *Bispathodus costatus* Zone

Lower limit: FAD of *Bispathodus costatus*

Upper limit: FAD of *Bispathodus ultimus*

Remarks: The *Bi. costatus* Zone is equivalent to the upper part of the Middle *expansa* Zone of Ziegler & Sandberg (1984) and to the Lower *costatus* Zone of Ziegler (1962). Hartenfels (2011) proposed a *Bi. costatus* subzone in Germany and Poland, to discriminate the upper part of the *Bi. aculeatus* Zone.

Notes on the index taxon: The species was erected by Branson (1934) who illustrated the holotype in plate 27, figure 13. For a revised diagnosis and description refer to Ziegler, Sandberg & Austin (1974).

3.e. The *Bispathodus ultimus* Zone

Lower limit: FAD of *Bispathodus ultimus*

Upper limit: FAD of *Protognathodus kockeli*

Remarks: The *Bi. ultimus* Zone is equivalent to the Upper *expansa*, Lower and Middle *praesulcata* zones of Ziegler & Sandberg (1984), to the Middle and Upper *costatus* zones of Ziegler (1962) and to the Upper *expansa* and *praesulcata* zones and the *costatus-kockeli* Interregnum by Kaiser (2009). This zone extends for a quite long time frame compared to the adjacent zones in the uppermost Famennian strata, up to the Hangenberg Extinction Event. However, at present, there are no definite markers for a possible subdivision: the entry of *Si. praesulcata* was used for subdividing this interval, but this is not suitable due to the problems on the taxonomy of early siphonodellids. *Protognathodus meischneri* and *Pr. collinsoni* enter in the central part of this zone, but are rare and in many regions only documented above the Hangenberg Event (Corradini *et al.*

2011). *Polygnathus purus* and *Po. symmetricus* enter in the lower part of the Zone, but their first occurrence looks to be asynchronous worldwide.

The *Bispathodus ultimus* Zone can be roughly subdivided into two parts, the lower characterized by a more diverse fauna. In the central part of the zone, approximately in correspondence to the entry of protognathodids, conodonts actually experience a severe crisis marked by the extinction of several taxa (*Pa. perlobata*, *Pa. rugosa*, *Ps. m. marburgensis* and *Ps. brevipennatus*) and several polygnathids became extinct. It is possible that a more precise zonation can be proposed after a complete revision of the early species of *Siphonodella*.

In the upper part of the *Bi. ultimus* Zone the Hangenberg extinction took place: according to Kaiser *et al.* (2009) up to 70% of conodont taxa disappeared in a short interval represented by the '*costatus-kockeli* Interregnum'. However, uncertainties of contemporaneous extinctions among conodonts may result in problems of long-distance correlations. Also, this interval cannot be discriminated in places due to sedimentological features connected to the Hangenberg Event. However, where present it is a useful tool to discriminate the upper part of the *Bi. ultimus* Zone.

Notes on the index taxon: The species was erected by Bischoff (1957) who illustrated the holotype in plate 4, figure 24. The species was first revised by Ziegler, Sandberg & Austin (1974), and later by Ziegler & Sandberg (1984). In the latter paper the species was expanded to include *Bi. zieglerei* Rhodes *et al.* For a revised diagnosis and description refer to Ziegler & Sandberg (1984).

3.f. The *Protognathodus kockeli* Zone

Lower limit: FAD of *Protognathodus kockeli*

Upper limit: FAD of *Siphonodella bransoni*

Remarks: The *Pr. kockeli* Zone is equivalent to the Upper *praesulcata* and *sulcata* zones of Ziegler & Sandberg (1984) and to the *kockeli* and *sulcata/kuehni* zones of Kaiser *et al.* (2009).

and Melien, SW slope of Burg-Berg, Rhenish Slate Mountains. Refigured after Bischoff (1957, pl. 3, fig. 27a–b). (k) *Protognathodus kockeli* Bischoff, upper view. Plan di Zermula A section, Carnic Alps, sample PZA 2a1 of Perri & Spalletta (2000b). (l) *Protognathodus kockeli* Bischoff, upper view. Plan di Zermula C section, Carnic Alps, sample PZC 4 of Perri & Spalletta (2000b). (m) *Protognathodus kockeli* Bischoff, upper view. Passo di Monte Croce Carnico section, Carnic Alps, sample PMC 1. (n) *Siphonodella bransoni* Ji (= *Siphonodella duplicata* Morph 1 of Sandberg *et al.* 1978), upper (n1) and lower (n2) views. Element figured by Canis (1968, pl. 72, figs 22, 23) as *Si. sulcata* and indicated by Sandberg *et al.* (1978) as example of typical specimen of *Si. duplicata* Morph 1. (o) *Siphonodella bransoni* Ji (= *Siphonodella duplicata* Morph 1 of Sandberg *et al.* 1978). Hannibal Shale, 1.7 m above base, exposure on Grassy Creek, Cuivre Township, Pike County, Missouri (type Cuivre Shale Member). (p) *Siphonodella bransoni* Ji (= *Siphonodella duplicata* Morph 1 of Sandberg *et al.* 1978), upper (p1) and lower (p2) views. Woodford Shale, E110 at Ebey Dam, locality of Over (1992). (q) *Siphonodella duplicata* (Branson and Mehl) (= *Siphonodella duplicata* Morph 2 of Sandberg *et al.* 1978). Lectotype, upper (q1) and lower (q2) views. Bushberg Sandstone, exposure at Brickeys on the Mississippi River, Ste. Genevieve County, Missouri. Refigured after Klapper (in Ziegler, 1975). (r) *Siphonodella duplicata* (Branson and Mehl) (= *Siphonodella duplicata* Morph 2 of Sandberg *et al.* 1978), upper (r1) and lower (r2) views. Hannibal Shale, 1.7 m above base, exposure on Grassy Creek, Cuivre Township, Pike County, Missouri (type Cuivre Shale Member). (s) *Siphonodella hassi* Ji (= *Siphonodella duplicata* sensu Hass of Sandberg *et al.* 1978), upper (s1) and lower (s2) views. Woodford Shale, Hass G-1 locality of Over (1992).

The marker *Pr. kockeli* is the only species that has its FAD just above the Hangenberg Event, and its validity for stratigraphic correlations is well known. *Protognathodus kuehni*, *Ps. multistriatus* and *Po. purus subplanus* enter in the lower part of the zone, more or less around the present DCB, but none is a good marker taxon.

Notes on the index taxon: The species was erected by Bischoff (1957) who illustrated the holotype in plate 4, figure 24. For a revised diagnosis and description refer to Corradini *et al.* (2011).

3.g. The *Siphonodella bransoni* Zone

Lower limit: FAD of *Siphonodella bransoni* (= *Si. duplicata* M1)

Upper limit: FAD of *Siphonodella duplicata* (= *Si. duplicata* M2)

Remarks: The *Si. bransoni* Zone was introduced by Ji (1985) and newly proposed by Kaiser *et al.* (2009). It is equivalent to the lower part of the Lower *duplicata* Zone of Sandberg *et al.* (1978).

Notes on the index taxon: The species was erected by Ji (1985), but a holotype was not indicated. The species is equivalent to *Si. duplicata* M1 sensu Sandberg *et al.* (1978), who referred to the specimen figured by Canis (1968, pl. 72, figs 22, 23) as a typical specimen. For a description of the taxon refer to the account of *Si. duplicata* M1 by Sandberg *et al.* (1978). However, the designation of a type is needed, possibly reconsidering the collections by Canis (1968) mentioned by Sandberg *et al.* (1978) and/or Ji (1985).

3.h. The *Siphonodella duplicata* Zone

Lower limit: FAD of *Siphonodella duplicata* (= *Si. duplicata* M2)

Upper limit: FAD of *Siphonodella hassi* (= *Si. duplicata* sensu Hass)

Remarks: This definition of the *Si. duplicata* Zone, here accepted, was introduced by Ji (1985) and newly proposed by Kaiser *et al.* (2009). It is equivalent to the upper part of the Lower *duplicata* Zone of Sandberg *et al.* (1978).

Notes on the index taxon: The species was erected by Branson & Mehl (1934b), but a holotype was not indicated. Klapper (*in* Ziegler, 1975) choose a lectotype and illustrated it *Siphonodella*-plate 2, figure 6. For a description of the taxon refer to the account of *Si. duplicata* M2 by Sandberg *et al.* (1978).

4. Possible DCB position based on conodonts

In order to redefine the Devonian–Carboniferous boundary, it is necessary to find a criterion that guarantees stability in the future and does not significantly

change the present stratigraphic position. As stated in Section 2, the few conodont species that appear close to the present boundary do not have the characteristics of a stratigraphic index taxon since all are quite rare.

For the new definition of the boundary other fossil groups could be considered and checked for use as index fossils, but if the DCB working group decides to remain on conodonts there are two possible solutions: the FAD of *Protognathodus kockeli* and the FAD of *Siphonodella bransoni*. Both of these possible positions of DCB boundary have advantages and problems, briefly discussed in the following sections.

4.a. FAD of *Protognathodus kockeli*

Protognathodus kockeli is the most abundant and widely distributed species of *Protognathodus* and has long been used as an index taxon where the FAD is just above the Hangenberg Event but, as evidenced by Corradini *et al.* (2011), in many regions it only occurs above the present DCB. However, this can be related to the post-Hangenberg evolution of sedimentary basins that at places caused hiatuses above the Hangenberg shale equivalents (e.g. Sardinia: Corradini, Barca & Spalletta, 2003; Mossoni, Corradini & Spalletta, 2013; Mossoni *et al.* 2015).

Aretz (2014, p. 230) stated that placing the ‘boundary at the Hangenberg level (biostratigraphically defined) offers the advantage that, in many cases, the DCB can be placed with sufficient accuracy without specific knowledge of the taxonomy of a specific fossil group’. The entry of *Pr. kockeli* respects this criterion, even if its local first occurrence is just above a facies break.

4.b. FAD of *Siphonodella bransoni*

Siphonodella bransoni (= *Si. duplicata* M1) is a well-known, abundant and widely distributed species. The species is probably the best index taxon in the whole time frame around the DCB where the FAD is already used to define the base of the *Si. bransoni* Zone (= Lower *duplicata* Zone), which has long been considered the second zone of the Carboniferous. However, as pointed out by Aretz (2014), the FAD of *Si. bransoni* occurs well above the entry of *Gattendorfia*; it therefore does not respect the historical dimension of the boundary criterion, because *Gattendorfia* and other historically lowermost Carboniferous taxa would then become Devonian.

4.c. Discussion of the new DCB criterion

The new criterion for the definition of the DCB will be proposed by the working group and later voted on by the International Commission on Stratigraphy. In this article we can only give some advice.

If we consider the matter only from the view of conodont biostratigraphy, the FAD of *Siphonodella bransoni* would be the best choice: *Si. bransoni* is distributed

worldwide and is quite easy to identify. However, the choice of *Si. bransoni* as criterion for the DCB would create problems regarding the historical position of the boundary; if the FAD of *Si. bransoni* was chosen, the historical first part of the Carboniferous system will be included in the Devonian system.

The FAD of *Protognathodus kockeli* corresponds more or less, or is exactly equivalent, to the historical Devonian–Carboniferous boundary, much better than the supposed FAD of *Si. sulcata*. It enters just above the Hangenberg Event, which is recognizable around the world in most marine strata and is a more natural boundary (Walliser, 1985) between the two systems.

A boundary placed just after the Hangenberg Event has the advantage that it will be possible to indicate an approximate position of DCB even in sections where *Pr. kockeli* is not present. We therefore support this criterion as preferable.

5. Conclusion

Recent studies show that a different level should be used to define the DC boundary. Rarity of some important stratigraphic guides in the uppermost Famennian strata and close to the DCB, as well as inconsistency in the taxonomic concept of early siphonodellids, compel us to propose a new zonation scheme for this stratigraphic interval.

The distribution of the most important conodont species have been investigated in order to evaluate their stratigraphic potential for a revised zonation of the uppermost Famennian and lowermost Tournaisian strata and for the redefinition of the Devonian–Carboniferous boundary. In this stratigraphic interval only a few conodont taxa meet the requirements of global index taxa: easy to recognize, a well-documented stratigraphic range and a broad geographic distribution. Some species of *Bispathodus* are good markers in the uppermost Famennian strata. Among *Protognathodus* only *Pr. kockeli* could be used, while the other representatives of the genus have a very low stratigraphic potential due to their rarity. Species of *Siphonodella* in the Tournaisian part of the range of the genus, the entry of *Si. bransoni* and above, may be very good markers, but it is better to avoid the use of the early representatives because of significant taxonomic uncertainties in the identification of *Si. sulcata* from the supposed ancestor *Si. praesulcata*.

The proposed revised part of the conodont scheme comprises seven zones. In ascending order, these are: *Bispathodus aculeatus* Zone; *Bispathodus costatus* Zone; *Bispathodus ultimus* Zone; *Protognathodus kockeli* Zone; *Siphonodella bransoni* Zone; *Siphonodella duplicata* Zone; and *Siphonodella hassi* Zone. The bases of these zones are defined by FADs of conodont species of the nominative taxa.

As for the new definition of the DCB, we propose the FAD of *Si. bransoni* or the FAD of *Pr. kockeli*. The latter is preferable, because it is very close to the historical position of the base of the Carboniferous system

and, placed just above the Hangenberg Event, has the advantage that it can be recognized in localities where the taxon is not present.

Acknowledgements. This study was partly supported by RAS (grants LR7/07 - 2010, resp. C. Corradini). This study is a contribution to PGI-NRI Project 61.2908.1304.00.0 (HM). We acknowledge the useful comments, corrections and suggestions by Jed Day and an anonymous reviewer. This paper is a contribution to IGCP 596 ‘Mid Palaeozoic climate and biodiversity’.

References

- ARETZ, M. 2014. Redefining the Devonian-Carboniferous Boundary: an overview of problems and possible solutions. In *Strati 2013* (eds R. Rocha, J. Pais, J. C. Kullberg, S. Finney), pp. 227–31. Switzerland: Springer.
- BAHRAMI, A., CORRADINI, C. & YAZDI, M. 2011. Conodont biostratigraphy across the Devonian-Carboniferous boundary in the Shotori Range, Tabas area, central east Iran Microplate. *Bollettino della Società Paleontologica Italiana* **50**, 35–53.
- BARSKOV, I. S., VORONTSOVA, T. N., KONONOVA, L. I. & KUZMIN, A. V. 1991. *Index conodonts of the Devonian and Early Carboniferous*. Moscow: Moscow University, 183 pp.
- BECKER, R. T. 2012. The uncounted species of *Polygnathus* - Plea for clear tracks through a taxonomic jungle. *SDS Newsletter* **27**, 42–8.
- BECKER, R. T. 2013. Species list of *Polygnathus* - corrections and additions. *SDS Newsletter* **28**, 29–31.
- BECKER, R. T., GRADSTEIN, F. M. & HAMMER, O. 2012. The Devonian Period. In *The Geologic Time Scale 2012* (eds F. M. Gradstein, J. G. Ogg, M. Schmitz & G. Ogg), pp. 559–601. Oxford: Elsevier.
- BECKER, R. T., HARTENFELS, S., ABOUSSALAM, Z. S., TRAGELEHN, H., BRICE, D. & EL HASSANI, A. 2013. The Devonian-Carboniferous boundary at Lalla Mimouna (Northern Maider) - A progress report. In *International Field Symposium ‘The Devonian and Lower Carboniferous of northern Gondwana’ - Field Guidebook* (eds R. T. Becker, A. El Hassani & A. Tahiri), pp. 109–20. Document de l’Institut Scientifique, Rabat 27.
- BISCHOFF, G. 1957. Die Conodonten-Stratigraphie des rhenohertzynischen Unterkarbons mit Berücksichtigung der Wocklumeria-Stufe und der Devon/Karbon-Grenze. *Abhandlungen hessisches Landesamt für Bodenforschung* **19**, 1–64.
- BRANSON, E. B. 1934. Conodonts from the Hannibal Formation of Missouri. *Missouri University Studies* **8**, 301–43.
- BRANSON, E. B. & MEHL, M. G. 1934a. Conodonts from the Grassy Creek shale of Missouri. *Missouri University Studies* **8**, 171–259.
- BRANSON, E. B. & MEHL, M. G. 1934b. Conodonts from the Bushberg sandstone and equivalent formations of Missouri. *Missouri University Studies* **4**, 265–300.
- CANIS, W. F. 1968. Conodonts and biostratigraphy of the Lower Mississippian of Missouri. *Journal of Paleontology* **42**, 525–55.
- CASIER, J.-G., LETHIERS, F. & PRÉAT, A. 2002. Ostracods and sedimentology of the Devonian-Carboniferous stratotype section (La Serre, Montagne Noire, France). *Bulletin de l’Institut Royal des Sciences Naturelles de Belgique, Science de la Terre* **72**, 43–68.

- CORRADINI, C. 2003. Late Devonian (Famennian) conodonts from the Corona Mizziu sections near Villasalto (Sardinia, Italy). *Palaeontographia Italica* **98**, 65–116.
- CORRADINI, C. 2008. Revision of Famennian–Tournaisian (Late Devonian–Early Carboniferous) conodont biostratigraphy of Sardinia, Italy. *Revue de Micropaléontologie* **51**, 123–32.
- CORRADINI, C., BARCA, S. & SPALLETTA, C. 2003. Late Devonian–Early Carboniferous conodonts from the “Clymeniae limestones” of SE Sardinia (Italy). *Courier Forschungs-Institut Senckenberg* **245**, 227–53.
- CORRADINI, C., KAISER, S. I., PERRI, M. C. & SPALLETTA, C. 2011. *Protognathodus* (Conodonta) and its potential as a tool for defining the Devonian/Carboniferous boundary. *Rivista Italiana di Paleontologia e Stratigrafia* **117**, 15–28.
- DAVYDOV, V. I., KORN, D. & SCHMITZ, M. D. 2012. *The Carboniferous Period*. In *The Geologic Time Scale 2012* (eds F. M. Gradstein, J. G. Ogg, M. Schmitz & G. Ogg), pp. 603–649. Oxford: Elsevier.
- EVANS, S. D., OVER, D. J., DAY, J. E. & HASENMUELLER, N. R. 2013. The Devonian/Carboniferous boundary and the holotype of *Siphonodella sulcata* (Huddle, 1934) in the upper New Albany Shale, Illinois Basin, southern Indiana. In *International Field Symposium ‘The Devonian and Lower Carboniferous of northern Gondwana’ - Field Guidebook* (eds A. El Hassani, R. T. Becker, A. Tahiri), pp. 42–3. Document de l’Institut Scientifique, Rabat **26**.
- FLAJS, G. & FEIST, R. 1988. Index conodonts, trilobites and environment of the Devonian–Carboniferous boundary beds at La Serre (Montagne Noire, France). *Courier Forschungs-Institut Senckenberg* **100**, 53–107.
- GATOVSKY, Y. A. 2009. New Genera *Barskovella* and *Bizignathus* (Conodonts) from the Famennian of Southern Kazakhstan. *Paleontological Journal* **43**, 550–7.
- GIRARD, C., CORNÉE, J.-J., CORRADINI, C., FRAVALO, A. & FEIST, R. 2014. Paleoenvironmental changes at Col des Tribes (Montagne Noire, France), a reference section for the Famennian of north Gondwana-related areas. *Geological Magazine* **151**, 864–84.
- HARTENFELS, S. 2011. Die globalen Annulata-Events und die Dasberg-Krise (Famennium, Oberdevon) in Europa und Nord-Afrika: hochauflösende Conodonten-Stratigraphie, Karbonat-Mikrofazies, Paläoökologie und Paläodiversität. *Münstersche Forschungen zur Geologie und Paläontologie* **105**, 17–527.
- HOU, H. F., JI, Q., WU, X. H., XIONG, J., WANG, S., GAO, L., SHENG, H., WIE, J. & TURNER, S. 1985. *Muhua Section of Devonian–Carboniferous Boundary Beds*. Geological Publishing House, Beijing, China, 226 pp.
- Ji, Q. 1985. Study on the phylogeny, taxonomy, zonation and biofacies of *Siphonodella* (Conodonta). *Bulletin of the Institute of Geology* **11**, 51–75.
- Ji, Q. 1987. New results from Devonian–Carboniferous boundary beds in South China. *Newsletters on Stratigraphy* **17**, 155–67.
- Ji, Q. & ZIEGLER, W. 1992. Phylogeny, speciation and Zonation of *Siphonodella* of shallow water facies (Conodonta, Early Carboniferous). *Courier Forschungs-Institut Senckenberg* **154**, 149–77.
- Ji, Q. & ZIEGLER, W. 1993. The Lali section: an excellent reference section for Late Devonian in south China. *Courier Forschungsinstitut Senckenberg* **157**, 1–183.
- KAISER, S. I. 2009. The Devonian/Carboniferous stratotype section La Serre (Montagne Noire) revisited. *Newsletters on Stratigraphy* **43**, 195–205.
- KAISER, S. I., BECKER, R. T., SPALLETTA, C. & STEUBER, T. 2009. High-resolution conodont stratigraphy, biofacies and extinctions around the Hangenberg Event in pelagic successions from Austria, Italy and France. *Palaeontographica Americana* **63**, 97–139.
- KAISER, S. I. & CORRADINI, C. 2011. The early Siphonodelids (Conodonta, Late Devonian–Early Carboniferous): overview and taxonomic state. *Neues Jahrbuch für Geologie und Paläontologie Abhandlungen* **261**, 19–35.
- KALVODA, J., KUMPAN, T. & BABEK, O. 2015. Upper Famennian and Lower Tournaisian sections of the Moravian Karst (Moravo-Silesian Zone, Czech Republic): a proposed key area for correlation of the conodont and foraminiferal zonations. *Geological Journal* **50**, 17–38.
- KLAPPER, G. & FOSTER, C. T., JR. 1993. Shape analysis of Frasnian species on the Late Devonian conodont Genus *Palmatolepis*. *Paleontological Society Memoir* **32**, 1–35.
- KOMATSU, T., KATO, S., HIRATA, K., TAKASHIMA, R., OGATA, Y., OBA, M., NARUSE, H., TA, P. H., NGUYEN, P. D., DANG, H. T., DOAN, T. N., NGUYEN, H. H., SAKATA, S., KAIHO, K. & KÖNIGSHOF, P. 2014. Devonian–Carboniferous transition containing a Hangenberg Black Shale equivalent in the Pho Han Formation on Cat Ba Island, northeastern Vietnam. *Palaeogeography, Palaeoclimatology, Palaeoecology* **404**, 30–43.
- KONONOVA, L. I. & WEYER, D. 2013. Upper Famennian conodonts from the Breternitz Member (Upper Clymenioid Beds) of the Saalfeld region, Thuringia (Germany). *Freiberger Forschungshefte C* **545**, 15–97.
- KUMPAN, T., BABEK, O., KALVODA, J., FRYDA, J. & GRYGAR, T. M. 2014a. A high-resolution, multiproxy stratigraphic analysis of the Devonian–Carboniferous boundary sections in the Moravian Karst (Czech Republic) and a correlation with the Carnic Alps (Austria). *Geological Magazine* **151**, 201–15.
- KUMPAN, T., BABEK, O., KALVODA, J., GRYGAR, T. M. & FRYDA, J. 2014b. Sea-level and environmental changes around the Devonian–Carboniferous boundary in the Namur–Dinant Basin (S Belgium, NE France): A multiproxy stratigraphic analysis of carbonate ramp archives and its use in regional and interregional correlations. *Sedimentary Geology* **311**, 43–59.
- LANE, H. R., SANDBERG, C. A. & ZIEGLER, W. 1980. Taxonomy and phylogeny of some Lower Carboniferous conodonts and preliminary standard post-*Siphonodella* zonation. *Geologica et Palaeontologica* **14**, 117–64.
- MALEC, J. 2014. The Devonian/Carboniferous boundary in the Holy Cross Mountains (Poland). *Geological Quarterly* **58**, 217–34.
- MATYJA, H., SOBIEN, K., MARYNOWSKI, L., STEMPIEN- SALEK, M. & MAŁKOWSKI, K. 2015. The expression of the Hangenberg Event (latest Devonian) in a relatively shallow-marine succession (Pomeranian Basin, Poland): the results of a multi-proxy investigation. *Geological Magazine* **152**, 400–28.
- MOSSONI, A., CARTA, N., CORRADINI, C. & SPALLETTA, C. 2015. Conodonts across the Devonian/Carboniferous boundary in SE Sardinia (Italy). *Bulletin of Geosciences* **90**, 371–88.
- MOSSONI, A., CORRADINI, C. & SPALLETTA, C. 2013. Conodonts from the Monte Taccu section (Famennian–Tournaisian, Sardinia, Italy). *Asociación Paleontológica Argentina, Publicación Especial* **13**, 85–90.
- OVER, D. J. 1992. Conodonts and the Devonian–Carboniferous boundary in the Upper Woodford Shale, Arbuckle Mountains, South-Central Oklahoma. *Journal of Paleontology* **66**, 293–311.

- PAPROTH, E., FEIST, R. & FLAJS, G. 1991. Decision on the Devonian–Carboniferous boundary stratotype. *Episodes* **14**, 331–6.
- PERRI, M. C. & SPALLETTA, C. 1991. Famennian conodonts from Cava Cantoniera and Malpasso sections, Carnic Alps, Italy. *Bollettino della Società Paleontologica Italiana* **30**, 47–78.
- PERRI, M. C. & SPALLETTA, C. 2000a. Devonian–Early Carboniferous transgressions and regressions in the Carnic Alps (Italy). *Record of the Western Australian Museum* **58**(Suppl), 305–19.
- PERRI, M. C. & SPALLETTA, C. 2001b. Hangenberg Event al limite Devoniano/Carbonifero al Monte Zermula, Alpi Carniche, Italia. *Giornale di Geologia*, ser. 3° **62**(Suppl), 31–40.
- QIE, W., ZHANG, X., DU, Y., YANG, B., JI, W. & LUO, G. 2014. Conodont biostratigraphy of Tournaisian shallow water carbonates in central Guangxi, South China. *Geobios* **47**, 389–401.
- QIE, W., WANG, X., ZHANG, X., JI, W., GROSSMAN, E.L., HUANG, X., LIU, J. & LUO, G. 2015. Latest Devonian to earliest Carboniferous conodont and carbon isotope stratigraphy of a shallow-water sequence in South China. *Geological Journal*, published online 11 August 2015, doi: [10.1002/gj.2710](https://doi.org/10.1002/gj.2710).
- SANDBERG, C. A. & KLAPPER, G. 1967. Stratigraphy, age, and paleotectonic significance of the Cottonwood Canyon Member of the Madison Limestone in Wyoming and Montana. *United States Geological Survey Bulletin* **1251-B**, 1–70.
- SANDBERG, C. A., STREEL, M. & SCOTT, R. A. 1972. Comparison between conodont zonation and spore assemblages in the Devonian–Carboniferous boundary in the western and central United States and in Europe. In *Septième Congrès Internationale de Stratigraphie Géologie di Carbonifère*, Krefeld, 23–28 August 1971, *Compte Rendu* **1**, 179–203.
- SANDBERG, C. A. & ZIEGLER, W. 1996. Devonian conodont biochronology in geologic time calibration. *Senckenbergiana Lethaea* **76**, 259–65.
- SANDBERG, C. A., ZIEGLER, W., LEUTERITZ, K. & BRILL, S. M. 1978. Phylogeny, speciation and zonation of *Siphonodella* (Conodonta, Upper Devonian and Lower Carboniferous). *Newsletters on Stratigraphy* **7**, 102–20.
- SANZ LÓPEZ, J., GARCÍA LÓPEZ, S., MONTESINOS, J. R. & ARBIZU, M. 1999. Biostratigraphy and sedimentation of the Vidrieros Formation (middle Famennian–lower Tournaisian) in the Gildar-Montó unit (northwest Spain). *Bollettino della Società Paleontologica Italiana* **37**, 393–406.
- VOGES, A. 1959. Conodonten aus dem Unterkarbon I und II (*Gattendorfia* und *Pericyclus*-Stufe) des Sauerlandes. *Paläontologische Zeitschrift* **3**, 266–314.
- VOGES, A. 1960. Die Bedeutung der Conodonten für die Stratigraphie des Unterkarbon I und II (*Gattendorfia*- und *Pericyclus*-Stufe) im Sauerland. *Fortschritte in der Geologie von Rheinland und Westfalen* **3**, 197–228.
- VORONTSOVA, T. N. 1993. The genus *Polygnathus* sensu lato (Conodonta): phylogeny and systematics. *Palaeontological Journal* **27**, 83–99.
- WALLISER, O. H. 1985. Natural boundaries and commission boundaries in the Devonian. *Courier Forschungs-Institut Senckenberg* **75**, 401–7.
- WANG, C. Y. & YIN, B. A. 1984. Conodont zonation of early Lower Carboniferous and Devonian–Carboniferous boundary in pelagic facies, South China. *Acta Palaeontologica Sinica* **23**, 224–38.
- WANG, C. Y. & YIN, B. A. 1988. Conodonts. In *Devonian–Carboniferous Boundary in Nanbiancun Guilin* (ed. C. M. Yu), pp. 105–48. Beijing: Science Press.
- ZIEGLER, W. 1962. Taxonomie und Phylogenie Oberdevonischer Conodonten und ihre stratigraphische Bedeutung. *Abhandlungen des Hessisches Landesamt für Bodenforschung* **38**, 1–166.
- ZIEGLER, W. 1969. Eine neue Conodontenfauna aus dem höchsten Oberdevon. *Fortschritte Geologie von Rheinland und Westfalen* **17**, 179–91.
- ZIEGLER, W. 1971. Conodont stratigraphy of the European Devonian. *Geological Society of America Memoirs* **127**, 67–99.
- ZIEGLER, W. (ed.) 1975. *Catalogue of Conodonts*, 3. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 404 pp.
- ZIEGLER, W. 1979. Historical subdivisions of the Devonian. *Special Papers in Paleontology* **23**, 23–47.
- ZIEGLER, W. (ed.) 1981. *Catalogue of Conodonts*, 4. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 445 pp.
- ZIEGLER, W. & SANDBERG, C. A. 1984. *Palmatolepis*-based revision of upper part of standard Late Devonian conodont zonation. *Geological Society of America Special Paper* **196**, 179–94.
- ZIEGLER, W. & SANDBERG, C. A. 1990. The Late Devonian Standard Conodont Zonation. *Courier Forschungs-Institut Senckenberg* **121**, 1–115.
- ZIEGLER, W. & SANDBERG, C. A. 1994. Conodont phylogenetic-Zone concept. *Newsletters on Stratigraphy* **30**, 105–23.
- ZIEGLER, W. & SANDBERG, C. A. 1996. Reflexions on Frasnian and Famennian Stage boundary decisions as a guide to future deliberations. *Newsletters on Stratigraphy* **33**, 157–80.
- ZIEGLER, W., SANDBERG, C. A. & AUSTIN, R. L. 1974. Revision of *Bispathodus* group (Conodonta) in the Upper Devonian and Lower Carboniferous. *Geologica et Palaeontologica* **8**, 97–112.