Boletín de la Sociedad Geológica Mexicana / 76 (3) / A210524/ 2024 / 1

The Devonian-Carboniferous boundary in the Graz Paleozoic (Eastern Alps, Austria) and its global significance

El límite Devónico-Carbonífero en el Paleozoico de Graz (Alpes orientales, Austria) y su importancia global

Sandra I. **Kaiser**[1,*], Bernhard **Hubmann**[2]

[1] State Museum of Natural History Stuttgart, Germany, Rosenstein 1, 70372 Stuttgart, Germany

[2] Karl-Franzens University of Graz, Institute of Earth Sciences, Universitaetsplatz 3 8010 Graz, Austria.

* Corresponding author: (S.I. Kaiser)
dr.sandra.kaiser@gmail.com

How to cite this article:
Kaiser, S.I., Hubmann, B., 2024, The Devonian-Carboniferous boundary in the Graz Paleozoic (Eastern Alps, Austria) and its global significance: Boletín de la Sociedad Geológica Mexicana, 76 (3), A210524. http://dx.doi.org/10.18268/BSGM2024v76n3a210524

Manuscript received: April 7, 2024
Corrected manuscript received: April 28, 2024
Manuscript accepted: May 12, 2024

Peer Reviewing under the responsibility of Universidad Nacional Autónoma de México.

ABSTRACT

Pelagic, outer-shelf sedimentary successions across the Devonian-Carboniferous boundary (DCB) in the western Graz Paleozoic at Trolp (Eastern Alps, Austria) display exceptional, continuous limestone facies of the Hangenberg Crisis interval. These enable the study of conodont successions, lithofacies, and geochemistry without noteworthy interruptions by siliciclastic intervals, which are equivalents of the Hangenberg Black Shale and Hangenberg Sandstone. The *praesulcata*, *kockeli*, and *sulcata/kuehni* conodont Zones are recognized by stratigraphically significant markers in the early siphonodellids and early protognathodids within thin-bedded limestones. The major conodont biofacies change and initial mass extinction phase (*costatus-kockeli* Interregnum) of the Hangenberg Crisis is succeeded by radiations among conodonts in the *kockeli* and *sulcata/kuehni* Zones. Carbon isotopes ($\delta^{13}C_{carb}$) record positive excursions and enhanced C_{org} burial episodes; the characteristic signals can be used as chemo-indicators of the early, middle and late phases of the Hangenberg Crisis.

The global common *Siphonodella sulcata* Morphotype 5 and *Protognathodus kuehni* have their first occurrence at the base of the Tournaisian at Trolp and elsewhere in Europe, Asia and North Africa, and thus can be used to define the base of the *sulcata/kuehni* Zone and the current DCB level. `*Protognathodus*´ faunas with a high morphological variability are recorded in the *praesulcata* and *kockeli* Zones, but spread mainly in the *sulcata/kuehni* Zone, or even later in the lower Tournaisian. Therefore, the extended *kockeli* Zone suggested recently, and even leaves the current DCB level undivided, as well as the use of *Protognathodus kockeli* as index fossil for the DCB, are not applicable as suggested herein.

A precise biozonation concept as well as multidisciplinary approaches used at Trolp are needed for understanding ultimate causes of the 1st order Hangenberg mass extinctions and major environmental changes at the DCB. Multidisciplinary approaches comprise taxonomically significant index conodonts, extinctions and radiations, as well as lithofacies and isotopic analyses. These markers at Trolp can be well correlated with those from many other settings worldwide, reflecting the global significance of the Graz Paleozoic.

Keywords: Hangenberg Crisis, conodont mass extinctions, sta*ble isotopes, Trolp quarry, Protognathodus fauna, kockeli Zone, sulcata/kuehni Zone.*

RESUMEN

Las sucesiones sedimentarias pelágicas de la plataforma exterior a lo largo del límite Devónico-Carbonífero (DCB) en el Paleozoico occidental de Graz en Trolp (Alpes orientales, Austria) muestran facies de piedra caliza continuas y excepcionales en el intervalo de la crisis de Hangenberg. Estos permiten el estudio de sucesiones de conodontes, litofacies y geoquímica sin interrupciones notables por intervalos siliciclásticos, que son equivalentes de Hangenberg Black Shale y Hangenberg Sandstone. Las zonas de conodontes praesulcata, kockeli y sulcata/kuehni se reconocen mediante marcadores estratigráficamente significativos en los primeros sifonodélidos y los primeros protognatódidos dentro de calizas de estrato delgado. El cambio de biofacies de conodontes principales y la fase inicial de extinción masiva (interregno costatus-kockeli) de la crisis de Hangenberg es seguida por radiaciones entre conodontes en las zonas de kockeli y sulcata/kuehni. Los isótopos de carbono ($\delta^{13}C_{carb}$) registran excursiones positivas y episodios de entierro de C_{org} mejorados; las señales características pueden utilizarse como quimioindicadores de las fases temprana, media y tardía de la crisis de Hangenberg.

El morfotipo 5 de Siphonodella sulcata, común a nivel mundial y Protognathodus kuehni tienen su primera aparición en la base del Tournaisiano en Trolp y en otras partes de Europa, Asia y el norte de África y por lo tanto, pueden usarse para definir la base de la zona sulcata/kuehni y el nivel DCB actual. En las zonas praesulcata y kockeli se registran faunas de 'Protognathodus' con una alta variabilidad morfológica, pero se extendieron principalmente en la zona sulcata/kuehni, o incluso más tarde en el Tournaisiano inferior. Por lo tanto, la zona de kockeli extendida sugerida recientemente, e incluso deja indiviso el nivel actual de DCB, así como el uso de Protognathodus kockeli como fósil índice para el DCB, no son aplicables como se sugiere en este documento.

Se necesita un concepto de biozonificación preciso, así como enfoques multidisciplinarios utilizados en Trolp, para comprender las causas últimas de las extinciones masivas de primer orden del Hangenberg y los principales cambios ambientales en el DCB. Los enfoques multidisciplinarios comprenden conodontos índice taxonómicamente significativos, extinciones y radiaciones, así como litofacies y análisis isotópicos. Estos marcadores pueden correlacionarse bien con los de muchos otros entornos en todo el mundo, lo que refleja la importancia global del Paleozoico de Graz.

Palabras clave: Crisis de Hangenberg, extinciones masivas de conodontes, isótopos estables, cantera Trolp, fauna de Protognathodus, zona kockeli, zona sulcata/kuehni

1. Introduction

The Graz Paleozoic belongs to the Upper Austroalpine Nappe System (Schmid *et al.*, 2004) of the Eastern Alps and consists of Silurian to Carboniferous sedimentary rocks which crop out in the surroundings of Graz (Styria, southeastern Austria, Figure 1). In general terms, the internal tectonic architecture of the Graz Paleozoic has a structure consisting of a lower, tectonically, and metamorphically more stressed nappe system and an upper one comprising less metamorphic sequences (Gasser *et al.*, 2010; Figure 2). The slightly metamorphic and in places very fossiliferous sequence of the upper nappe system has been the subject of numerous paleontological and sedimentological studies (*e.g.*, Histon *et al.*, 2010; Ebner and Hubmann, 2012). In particular, biostratigraphic and geochemical studies of the stratigraphic younger parts (*e.g.*, Nössing, 1974a, 1974 b; Ebner, 1976b, 1980a; Kaiser, 2005; Bojar *et al.*, 2013; Kaiser *et al.*, 2020) have provided important new data on environmental dynamics during the 1st order mass extinctions of the multiphase Hangenberg Crisis at the Devonian-Carboniferous boundary (DCB; Kaiser *et al.*, 2016; Becker *et al.*, 2016a).

Worldwide the DCB is characterized by either transgressive Hangenberg black shales and regressive Hangenberg sandstone deposits, or by unconformities with stratigraphic gaps (Kaiser *et al.*, 2016). The latter phenomenon is also known from the Graz Paleozoic east of the Mur River (Figure 3). In contrast, stratigraphically comparable sections west of the Mur River show exceptionally continuous limestone sequences. The best outcrop is located in the abandoned Trolp quarry (Figures 2 and 3) and was examined with regard to high resolution biostratigraphy, lithostratigraphy and chemostratigraphy.

The Trolp section focused on herein, consists of pelagic cephalopod limestones of the upper

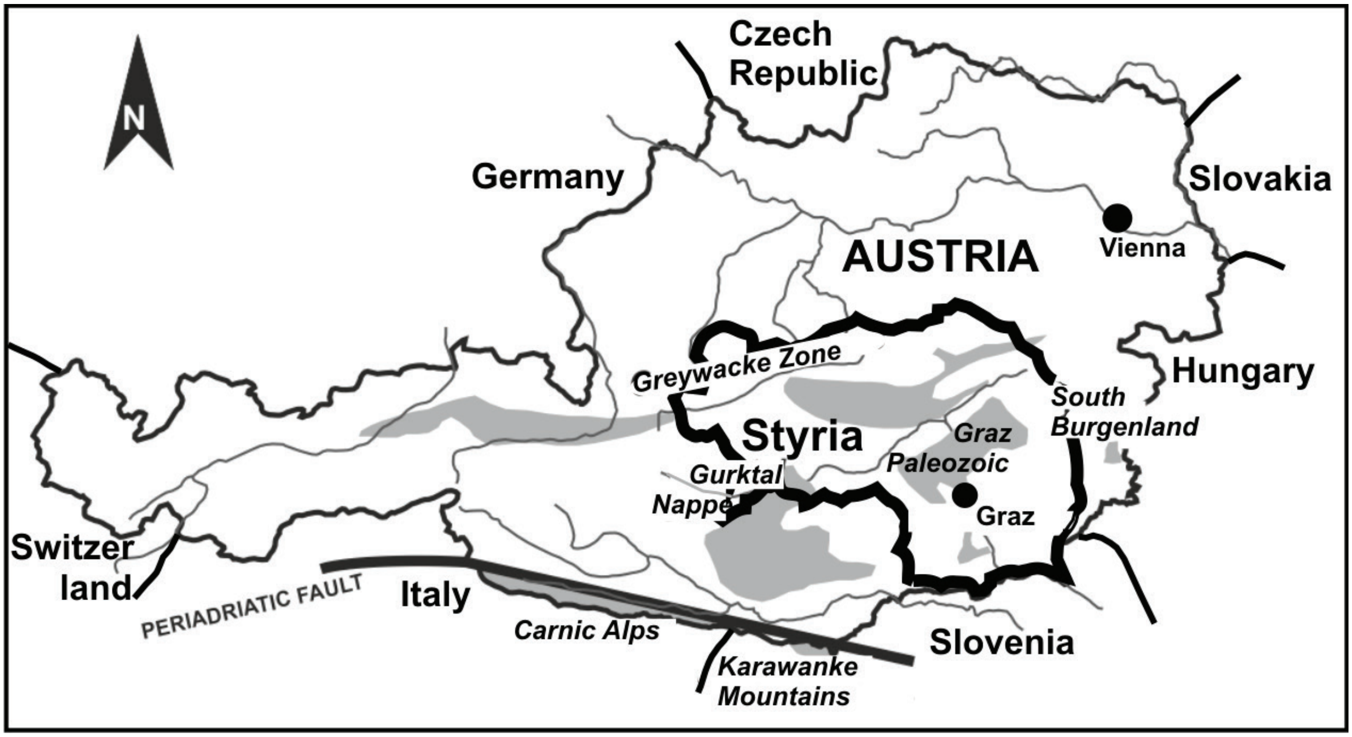

Figure 1 Disconnected Paleozoic units in Austria. The Paleozoic units belong to the Eastern Alps (Graz Paleozoic, Greywacke Zone, Gurktal Nappe, South Burgenland) and the Southern Alps (Carnic Alps, South Karawanken Mts.) which are separated by the Periadriatic Fault, modified from Hubmann *et al.* (2003).

Famennian Steinberg Formation and Tournaisian Sanzenkogel Formation. The DCB is located between both units (Figures 4-8). A positive carbon isotope excursion ($\delta^{13}C_{carb}$) measured previously in thin-bedded limestones coincides with the major change in conodont biofacies and the initial mass extinction episode of the Hangenberg Crisis (Figure 9-11). After Kaiser *et al.* (2020), recent high-resolution geochemical and biostratigraphic studies at Trolp, and the correlation with the Grüne Schneid section in the Carnic Alps (see reviews by Schönlaub, 2018; Spalletta *et al.*, 2021), reveal the utility of the joint *sulcata/kuehni* Zone, as well as uncertainties in the taxonomy of the *Protognathodus* fauna (Figures 12-14).

During the 1980s, the DCB working group at the time initially considered the base of the *kockeli* (upper *praesulcata*) Zone as a DCB position. However, this idea with the first occurrence (FO) of *Protognathodus kockeli* was rejected after intensive studies that included visits to relevant sections worldwide (*pers. comm.* C. Sandberg, 2019). The current DCB, based on the FO of *Siphonodella sulcata*, was established by the Heerlen Congress in 1935, confirmed by the DCB Working Group in 1988, and since has been applied worldwide. However, the current GSSP at La Serre E´ (Montagne Noire, France) was reconsidered by Kaiser (2009) due to former uncertainties in the identification of early siphonodellids (Kaiser and Corradini, 2011; Spalletta *et al.*, 2017; see summary in Becker *et al.*, 2016a; Kaiser *et al.*, 2020; Hartenfels *et al.*, 2022). Also, according to Ziegler and Sandberg (1996), the current GSSP position at La Serre É - between Bed 88 and 89 - was chosen hastily and despite the objections of conodont specialists in the DCB working group. Kaiser´s studies in 2005 and 2009 reveal an older FO of the first morphotype (M5) of the index fossil *Siphonodella sulcata* at La Serre É in Bed 84 (not in Bed 86 as shown in figure 1, Aretz and Corradini, 2021). However, from today's perspective (Aretz *et al.*, 2021; Hartenfels et al, 2022), the profile at La Serre É would hardly be an option for a suitable GSSP.

Based on taxonomic studies during the last decades, 1. uncertainties of the early siphonodellids (*Siphonodella praesulcata*, *Siphonodella sulcata*) resulted in morphotype groups established by Kaiser and Corradini (2011) and are used worldwide (see Kaiser *et al.*, 2020; Hartenfels *et al.*, 2022), 2. the Morphotyp 5 of *Siphonodella sulcata* is used as index fossil for the current DCB (*e.g.*, Kaiser, 2009; Kaiser *et al.*, 2020; Becker *et al.*, 2021; Hartenfels *et al.*, 2022), 3. the `siphonodelloids´ were discriminated from the early siphonodellids (Becker *et al.*, 2013), and 4. it is recently discussed to what extent *Protognathodus kockeli*, which was proposed as a supplementary index fossil for the DCB, would be applicable (Becker *et al.*, 2016a; Corradini *et al.*, 2011, 2016; Kaiser *et al.*, 2020; Aretz *et al.*, 2021; Hartenfels *et al.*, 2022).

In this review article we provide a brief overview of the stratigraphic architecture of the Graz Paleozoic Rannach Nappe and present the faunistic, geochemical and sedimentologically important markers at the DCB in the western Graz Paleozoic. We also highlight the potential for correlation with regions outside the study area. We discuss criteria currently proposed – 1. the extended *kockeli* Zone suggested by Spalletta *et al.* (2017), and 2. the FAD of *Protognathodus kockeli* suggested by Hartenfels *et al.* (2022) - for a revised DCB position and their application to the Graz Paleozoic as well as to other European, North African, and Asian areas. This discussion requires an evaluation of the applicability of the *kockeli* and the *sulcata/kuehni* Zones (= current DCB level). To this end, we provide a discussion of aspects of conodont biostratigraphy, biofacies, and taxonomy; stable isotope geochemistry ($\delta^{13}C_{carb}$) and litho- and microfacies aspects are also included, as are earlier and more recent biozonation concepts (see Figure 12).

Abbreviations: DCB = Devonian-Carboniferous boundary, GSSP = Global Stratotype Section and Point, HBS = Hangenberg Black Shale, HBSE = Hangenberg Black Shale Event, FAD = first appearance datum, FO = first occurrence, *ck*I = *costatus-kockeli* Interregnum, HSS = Hangenberg Sandstone, HSSE = Hangenberg Sandstone Event.

2. Overview of geology and facies development in the Graz Paleozoic

2.1. OVERVIEW OF GEOLOGY

Within Austria, weakly metamorphosed Paleozoic units are irregularly distributed throughout the Alpine orogen (Figure 1). Their original, pre-Alpine geographical location is uncertain, but it is generally accepted that the units were part of the northern Gondwana margin (*e.g.*, Neubauer *et al.*, 2022). According to tectonic concepts of the Eastern Alps (*e.g.*, Schmid *et al.*, 2004) – except for the Paleozoic remnants south of the Periadriatic fault – they are part of the uppermost tectonic nappes of the Eastern Alps, the Upper Austroalpine Nappe System. The Upper Austroalpine Nappe System consists of highly varied crystalline units with a dominant pre-Alpine metamorphic overprint, and is tectonically overlain by the Greywacke Zone, which itself is largely unconformably overlain by thick Mesozoic sediments of the Calcareous Alps. The Graz Paleozoic and some isolated outcrops in southern Burgenland which both lack Permo-Mesozoic cover sequences, as well as the Gurktal nappe, are part of the Drauzug-Gurktal Nappe System, which is itself part of the Upper Austrian Basement Nappes.

The structure of the Upper Austroalpine Nappe System was triggered by the closure of the

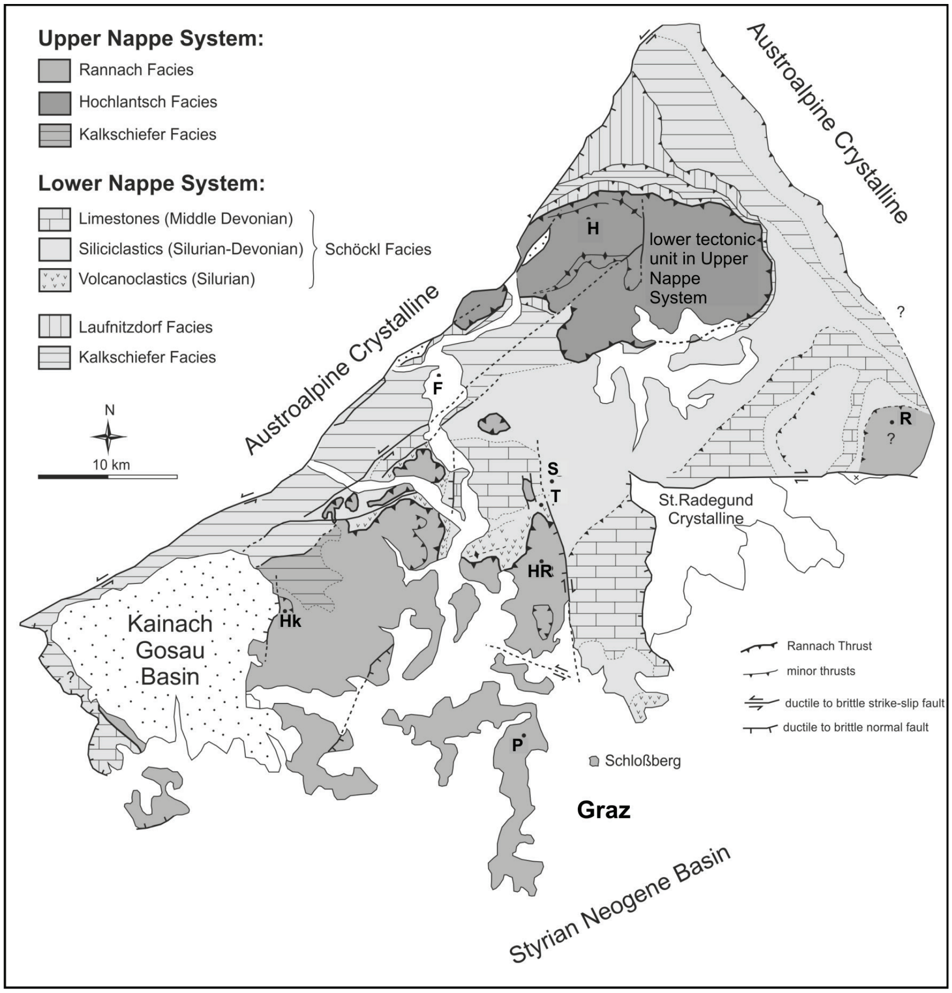

Figure 2 The Graz Paleozoic and its organisation in nappe groups (modified from Gasser *et al.*, 2010). H = Hochlantsch, Hk = Höllererkogel, HR = Hohe Rannach, P = Plabutsch, R = Raasberg, S = Semriach, T = Taschen.

Meliata Ocean (a marginal basin of the Tethys) during the Early Cretaceous. Therefore, the Upper Austroalpine Nappe System is sealed by Upper Cretaceous to Eocene sediments. Later, the Upper Austroalpine Nappe System was dismembered by lateral extrusion, *i.e.*, eastward displacement of the eastern parts of the Eastern Alps (Ratschbacher *et al.*, 1991; Neubauer *et al.*, 2000) and thus brought into its current position.

The internal architecture of the Graz Paleozoic (Silurian to Carboniferous) is composed of a high-grade metamorphosed lower nappe system and a low-grade metamorphosed upper nappe system (Gasser *et al.*, 2010; Figure 2). Each of them is differentiated into individual nappes. In short, the volcanosedimentary sequence contains basal pre-Devonian volcaniclastics, and a pronounced platform- to basinal-facies development during the Devonian. In the structurally higher units, especially in the Rannach Nappe, the depositional environment deepens steadily from the Upper Devonian to the Mississippian, and in the Pennsylvanian the depositional environment becomes abruptly shallow marine (Figure 3).

Resting on metamorphic basement, the nappes of the Graz Paleozoic are unconformably overlain by an Upper Cretaceous sequence, the “Kainach Gosau” (Ebner and Rantitsch, 2000) in the west and by Neogene sedimentary rocks of the Styrian Molasse Basin in the south (Gross *et al.*, 2007).

In contrast to the Lower Nappe System which experienced stronger deformation as well as higher metamorphosis – up to lower amphibolite facies – sequences of the upper nappe system, among them the sequence of the Rannach Nappe, are quite fossiliferous.

2.2. RANNACH NAPPE OF THE GRAZ PALEOZOIC

The sequence of the Rannach Nappe (Figures 3-5) starts with predominantly alkaline metavolcanites (tuffs, lavas) which pass into slightly calcareous sediments and contain fossils from the late Silurian to early Devonian (Ludfordian - Lochkovian). This is followed by various Lower Devonian (Lochkovian) to Upper Devonian (Frasnian) shallow-water platform carbonates. Formations of this depositional episode are comprised to the Rannach Group (Flügel, 2000). Approximately during the Frasnian to Famennian transition, the depositional environment changed to an open, pelagic marine area. This persisted until the late Mississippian (Serpukhovian). The formations of the pelagic facies are combined into the Forstkogel Group (Flügel, 2000). The end of the Rannach Nappe stratigraphic series is formed by lower Pennsylvanian (Bashkirian) shallow-marine birdseye limestones and phytoclast-rich shales of the Dult Group (Flügel, 2000). Detailed descriptions of formations of the Rannach, Forstkogel and Dult Groups, their lithologies, stratigraphic extents and the extensive literature can be found in the explanations for the “Austrian Stratigraphic Chart 2004” (Hubmann *et al.*, 2013).

The pelagic facies of the Forstkogel Group, which consists of micritic deep-marine cephalopod limestones of the Steinberg and Sanzenkogel Formations (Figures 4 and 5), reaches a maximum thickness of 100 m. In the Rannach Nappe east of the Mur (= Eastern Graz Paleozoic) it reduces down to about 30 m. The reasons for the reduced thickness are intraformational stratigraphic gaps in the area of the DCB, which were created by karstification (Ebner, 1978, 1980a, 1980b).

Elementary geochemistry used for interpretations of bathymetry shows clear geographical differences: While in the Graz Paleozoic west of the Mur (= western Graz Paleozoic) the depositional depth in the Mississippian period was around 200 m, in the eastern Graz Paleozoic the water depth was less than 50 m (Nössing, 1974b; Ebner and Prochaska, 1989; Buchroithner *et al.*, 1979). Continuous sequences covering the DCB interval only occur in the western Graz Paleozoic. In the eastern Graz Paleozoic, however, erosion gaps occur in this time interval, with stratigraphic gaps increasing in temporal extent towards the east (Figure 3).

3. The Devonian-Carboniferous boundary (DCB) in the western Graz Paleozoic

The Forstkogel Group is, according to conodonts, divided into the Upper Devonian Steinberg Formation and the Lower Carboniferous (Mississippian) Sanzenkogel Fm. (Figure 4). The strongly condensed and only 220 cm thick Lower Sanzenkogel Fm., comprising the Early Tournaisian *Siphonodella sulcata* Zone to the Late Tournaisian *Scaliognathus anchoralis* Zone, occurs only in the western Graz Paleozoic. Marker beds within the Upper Sanzenkogel Fm. are the Trolp Phosphorite Bed (shale and lydite layer with phosphorite nodules) in the western parts of the Rannach Facies (Ebner, 1978; Bosic, 1998, 1999; Flügel, 2000).

Numerous conodont studies from the Graz Paleozoic have been published since the 1950s because the pelagic limestones of the Forstkogel Group/Rannach Facies yielded rich conodont faunas, which enable a fine-stratigraphic subdivision of the Paleozoic succession. Comprehensive and detailed conodont studies were conducted by Fritz Ebner (*e.g.*, Ebner, 1976a, 1977a, 1977b, 1978, 1980a, 1980b) in the western and eastern Graz Paleozoic. Also, conodont studies from the western Graz Paleozoic were published, for example, by Flügel and Ziegler (1957); Kodsi (1967); Khosrovi-Said (1962); Flajs (1966); Nössing *et al.* (1977); Surenian (1978), Buchroithner *et al.* (1979); Buchroithner and Ebner (1981), and succeeding conodont biostratigraphic and geochemical, high-resolution studies at the DCB at Trolp provide important comprehensive data towards a better understanding of the Hangenberg Crisis at the DCB (Kaiser, 2005; Kaiser *et al.*, 2008, 2009, 2020; Bojar *et al.*, 2013).

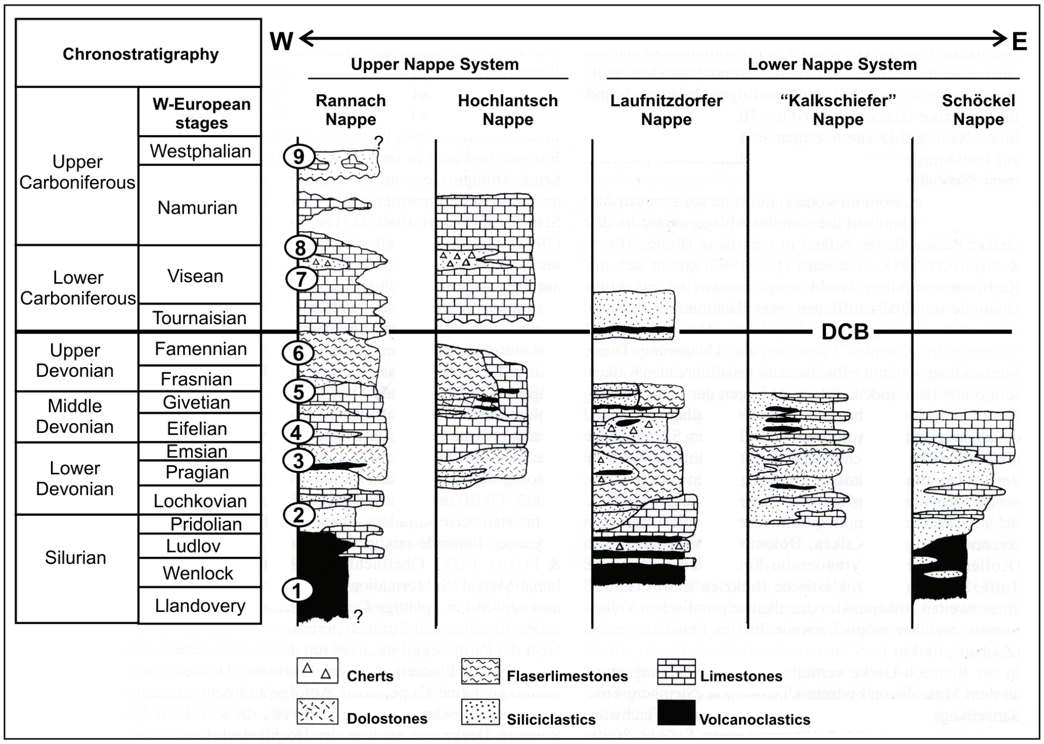

Figure 3 Stratigraphic overview of nappes of the Graz Paleozoic, modified from Ebner *et al.* (2000), Hubmann and Hasenhüttel (1995), Kreutzer *et al.* (1997) and Ebner and Hubmann (2012). Lithostratigraphic column with main lithologies of the Rannach Nappe (Rannach Facies) in the western Graz Paleozoic near Graz: Reinerspitz Group: 1. Kehr Fm., Kötschberg Fm., Rannach Group: 2. Parmasegg Fm., 3. Flösserkogel Fm., Bameder Fm; 4. Plabutsch Fm., 5. Kollerkogel Fm., Forstkogel Group: 6. Steinberg Fm., 7. Sanzenkogel Fm., Dult Group: 8. Höchkogel Fm., 9. Hahngraben Fm.

An overview of localities with DCB successions in the western Graz Paleozoic (Section 3.1), where successions of the Famennian Steinberg Fm. and Tournaisian Sanzenkogel Fm. crop out, is followed by a detailed description of the currently easily accessible Trolp Quarry (Section 3.2).

3.1. OVERVIEW OF LOCALITIES

Faunal and lithologic markers from different lithologic successions from the Graz Paleozoic, such as phosphorite nodules, lydites, fissure fillings, conodont index fossils and mixed conodont faunas, can be easily correlated (Figure 4) and resulted in the reconstruction of the depositional environments (see Section 2.2). The stratigraphic gap between the Steinberg Fm. and the Lower Sanzenkogel Fm. increases from west to east (Figure 3), and complete Famennian and Tournaisian sediments, including the DCB, are recorded at Forstkogel in the Steinberg area (Surenian, 1977, 1978; Nössing, 1974b, Buchroithner *et al.*, 1979; Ebner, 1980a), and at Eichkogel in the Rein area (Figures 4 and 5; Nössing, 1974a; Nössing *et al.*, 1977). Successions at Eichkogel are situated in a forest area and currently covered by forest soil. At Forstkogel, Buchroithner *et al.* (1979) described several quarries where DCB successions crop out, among them the famous Trolp quarry (Figure 6).

Complete successions of the Steinberg Fm. in the western Graz Paleozoic, reaching a thickness of 70 m, are reported at Forstkogel, Eichkogel and Weihermühle in the Gratberg-Au area (Figures 4 and 5; Ebner, 1980a, 1980b). Complete successions of the Sanzenkogel Fm., reaching a thickness of up to 35 m from the *Siphonodella sulcata* to the *Gnathodus bilineatus bollandensis* conodont Zones, are reported at Forstkogel, while a hiatus is already reported from Weihermühle from the lower Tournaisian (Figure 4). The Tournaisian successions at Forstkogel were selected as type locality for the Lower Sanzenkogel Fm., established by Nössing (1974b, 1975). Sedimentologic investigations of the Lower Carboniferous (Mississippian) at Forstkogel were summarized by Ebner and Prochaska (1989).

In the western Graz Paleozoic, DCB successions at Trolp (see Section 3.2) and at Kanzelkogel (north of Graz, Kodsi, 1967) consist characteristically of condensed thin-bedded micritic limestones. At Kanzelkogel, the Upper Devonian and Lower Carboniferous (Mississippian) are separated by a several-decimetre-thick sequence of thin-bedded limestones with mixed Devonian and Carboniferous conodont faunas (Kodsi, 1967, Figure 12). However, the *Protognathodus* or *Siphonodella* index conodont faunas were not recorded at Kanzelkogel probably due to a stratigraphic gap, or condensation and an incomplete sampling. Unfortunately, these successions do no longer exist due to mining activity.

3.2. TROLP SECTION (FORSTKOGEL, STEINBERG AREA)

The Trolp section is an abandoned quarry (ÖK Sheet 163 Voitsberg) located at Forstkogel about 8 km from the city Graz, beside the street from Steinberg to Rohrbach (Figures 5 and 6). Trolp is the type locality of the Late Devonian conodont *Polygnathus styriacus* first described by Ziegler (1957). The Famennian-Tournaisian pelagic cephalopod limestones at Trolp have been intensively investigated due to rich conodont faunas, and sampling by Sandberg and Ebner in 1980 was followed by conodont studies of, for example, Ebner (1980a), Nössing (1975), Kaiser 2005, Kaiser *et al.* (2008, 2020). It was formally proposed as a candidate for the GSSP at the DCB, but the scarcity of macrofossils did not fulfill the criteria required (Ebner, 1980a; Ziegler and Sandberg, 1984a; Ji *et al.*, 1989).

The tectonically inverted (upside-down) successions at Trolp are dated as Late Famennian *expansa-praesulcata* Zone to Late Tournaisian *Gnathodus* typicus Zone (Ebner, 1980a; Kaiser, 2005). A detailed, bed-by-bed or cm-by-cm sampling of DCB beds is required at Trolp due to the condensation of successions (Figures 7 and 8) which may produce a bias of the conodont record; re-numbering of DCB beds was necessary due to weathering and missing old numbers, as well as due to the high-resolution sampling of the successions. As shown in Figure 9, sample and bed numbers of Kaiser (2005) are correlated with bed numbers established by C. Sandberg and F. Ebner in 1980, and Ebner (1980a). The *praesulcata* and *kockeli* Zones, and the *sulcata/kuehni* Zone (DCB level) are readily recognized by their zonal index fossils (Ebner, 1980a, Kaiser, 2005; Kaiser *et al.*, 2009, 2020; Figures 9 and 10a). The Middle *praesulcata* Zone of the standard conodont zonation (Ziegler and Sandberg, 1984b), recognized at Trolp by Sandberg and Ebner in 1980, Ebner (1980a), Bojar *et al.* (2013), Kaiser (2005), and by Kaiser *et al.* (2008) was not considered recently due to the asynchronous last occurrence of *Palmatolepis gracilis gonioclymeniae* defining the base of the Middle *praesulcata* Zone (see discussions in Kaiser, 2005; Kaiser *et al.*, 2009; Corradini *et al.*, 2016; Spalletta *et al.*, 2017). The asynchronous last occurrence of this taxon resulted in different levels of the base of the Middle *praesulcata* Zone as previously recorded at Trolp by the above mentioned authors.

The eastern part of the quarry which is well accessible consists of well-exposed Lower Carboniferous beds, representing the lower member of the pelagic Sanzenkogel Formation ("Untere Sanzenkogel-Schichten"), and of bedded to massive upper Famennian beds, representing the Steinberg Formation. The succession consists of light-grey to brownish pelagic nodular cephalopod limestones and micritic Flaser-limestones of the Famennian Steinberg Fm. and Tournaisian Sanzenkogel Fm.; continuous limestone successions (Figures 7-10a and 10b) deposited during the Hangenberg Crisis interval are recorded at Trolp, which is globally characterized by black shales, sandstones or hiatuses. The stratigraphically lower part of the section consists of bedded to massive limestones of the *praesulcata* Zone, and a lithologic change is marked by a thin, ~1 cm thick shaly layer (basal Bed 10) at the base of thin-bedded limestones that disappears laterally (N 47º04'08", E 15º19'09"). Bojar *et al.* (2013, Figure 3d) recorded a continuous limestone succession lacking this layer in a lateral, different position next to previous mentioned sampling points (N 47º04'29", E 15º19'15"). This shaly or marly level was regarded by Flügel and Ziegler (1957) as a tectonic disturbance, which locally separated the Devonian and Carboniferous at Steinberg. Due to its stratigraphic position, Kaiser (2005) suggested an equivalent level of the Hangenberg Black Shale (HBS) since the lithologic change is accompanied by the major conodont biofacies change (Figure 11) indicating the main extinction phase of the Hangenberg Crisis at the *costatus-kockeli* Interregnum (*ck*I, after Kaiser *et al.*, 2009 = mass extinction-based level within the Middle *praesulcata* Zone, correlative with the HBSE and HSSE). This interpretation is supported by the onset of conodont radiations and the entry of *Protognathodus meischneri*, *Protognathodus collinsoni*, *Protognathodus semikockeli* and *Protognathodus kockeli* immediately above in thin-bedded limestone successions conformably overlying the shaly layer (Kaiser *et al.*, 2020; Figures 9 and 10a). The occurrence of stratigraphically leaked younger Carboniferous faunas - mainly siphonodellids and *Gnathodus* - in Devonian samples were recognized about at the level of this shaly layer, or in younger levels, respectively.

The base of the Carboniferous has been fixed at Trolp in Bed 16 by the first occurrence of index conodonts at the same stratigraphic levels (Figures 8, 9 and 12): *Polygnathus purus subplanus*, an index conodont for the base of the Tournaisian (*e.g.*, Kaiser *et al.*, 2009; Spalletta *et al.*, 2017), as well as *Siphonodella sulcata* (M5) and *Protognathodus kuehni*, which were used to define the joint *sulcata/kuehni* Zone and the DCB (Kaiser *et al.*, 2020; Becker *et al.*, 2021). Conodont index fossils previously recorded by Ebner (1980a) and Nössing (1975) at Trolp, and their correlation with index fossils recorded by Kaiser (2005) and Kaiser *et al.* (2020) are shown in Figure 9; the biostratigraphic correlation of the Hangenberg Event and the DCB from the Carnic Alps and Rhenish Massif is shown in Figure 8. At stratigraphically younger levels, *Siphonodella bransoni* (*Siphonodella duplicata* M1), as well as *Pseudopolygnathus multistriatus* were recorded (Ebner

1980a). The condensed Tournaisian sequence is intercalated by the 20 cm thick Trolp Phosphorite Bed (Figures 4 and 14), marking the beginning of the Upper Sanzenkogel Fm. (base of the upper Tournaisian) after Nössing (1975), or the base of the middle Tournaisian as suggested by Kaiser (2005), respectively. It is correlative with the end of the erosional gap within parts of the Rannach Nappe, and interpreted as deepening and upwelling at the shelf margin at the base of the *Scaliognathus anchoralis* Zone (base of upper Tournaisian; Ebner, 1998; Ebner *et al.*, 2000).

Conodont biofacies at Trolp (Figure 11) indicates a dominance of *Bispathodus*, *Branmehla* and *Palmatolepis* in pre-Hangenberg Crisis (pre-extinction) levels in the *praesulcata* Zone (Kaiser 2005). The conodont mass extinction in the *ck*I at Trolp (base of Bed 10), and major biofacies change to an impoverished *Polygnathus*-*Protognathodus* biofacies with stunted faunas, is connected to the extinction of Famennian taxa which predominated in the Famennian, such as *Branmehla suprema*, *Bispathodus costatus*, *Palmatolepis gracilis expansa*, and *Pseudopolygnathus marburgensis trigonicus*. The beginning of radiations in the basal *kockeli* Zone, recorded in the basal part of the thin-bedded limestones (Bed 10/11), is succeeded by faunal recovery and the 2nd radiation phase (Figure 10a) in the

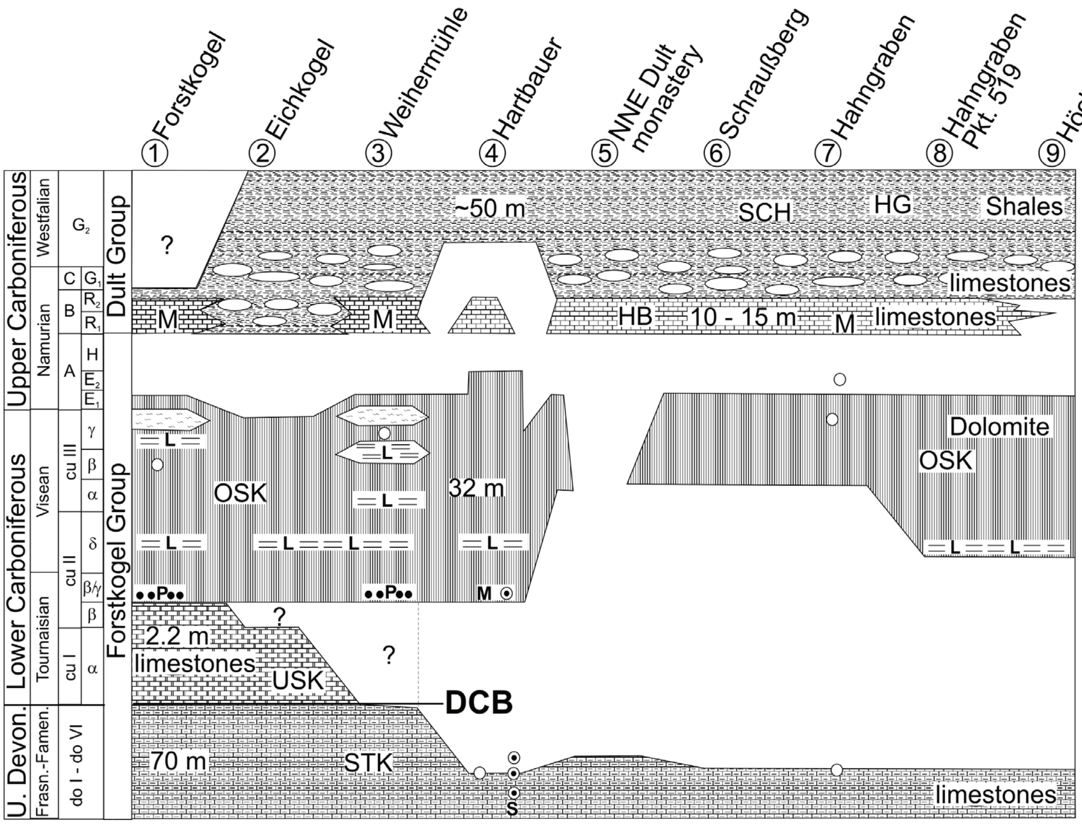

Figure 4 Outcrop areas (1 – 9, from west to east) within the Upper Devonian and Carboniferous of the Rannach Nappe (Rannach Facies) in the Graz Paleozoic (modified from Ebner, 1978, 1980b; Ebner *et al.*, 2000). 1. Forstkogel, Steinberg area (Trolp Quarry, locations 3, 4 in Figure 5), 2. Eichkogel, Rein area (for location see Figure 5), 3. Weihermühle, Gratwein/Au area (location 1 in Figure 5), 4. Hartbauer/Kanzelkogel (location 2 in Figure 5), 5. NNE Dult monastery (location 6 in Figure 5), 6. Schraußberg, 7. Hahngraben (location 5 in Figure 5), 8. Hahngraben Pkt. 519, 9. Höchkogel. Forstkogel Group: STK: Steinberg Formation, USK: Lower Sanzenkogel Fm., OSK: Upper Sanzenkogel Fm., P = phosphorites of Trolp Bed, L = lydites, the lowermost = Hart Bed. Dult Group: Höchkogel Fm.: HB Hartbauer Member, SCH Schrausbauer Mb., HG Hahngraben Fm., M = conodont mixed faunas (time of origin), S = fissure filling, black circle = components of fissure filling, white circle = mixed faunas (components).

basal Lower Carboniferous *sulcata/kuehni* Zone. It is connected to the return of normal-sized conodont faunas, and an increasing abundance of pseudopolygnathids and siphonodellids, but the *Polygnathus*-*Protognathodus* biofacies remains in the Lower Carboniferous.

Faunal evolution during the Hangenberg Crisis is precisely documented at Trolp (Kaiser *et al.*, 2020). A faunal assemblage of the Lower *Protognathodus* fauna, with *Protognathodus meischneri* and *Protognathodus collinsoni*, enters at a level with the initial litho- and biofacies change (Bed 10, Figures 9, 10a and 11), and the absence of *Bispathodus costatus* and *Protognathodus kockeli* at the same level in Bed 10 is interpreted as the event-based *ck*I. The succeeding entry of *Protognathodus semikockeli* recently established by Hartenfels *et al.* (2022) occurs immediately above, and the entry of *Protognathodus kockeli* s.str. slightly above marks the start of the *kockeli* Zone (Figures 9 and 10a). The *Protognathodus* fauna at the DCB at Trolp even occurs in association with *Siphonodella praesulcata* and *Siphonodella sulcata* which was also recorded by Sandberg *et al.* (1983).

At Trolp, a phyletic lineage of the early protognathodids (*Protognathodus meischneri*, *Protognathodus collinsoni*, *Protognathodus semikockeli*, *Protognathodus kockeli* s.str., advanced *Protognathodus kockeli*, *Protognathodus kuehni* (see figure 6 in Kaiser *et al.* 2020) as proposed by Ziegler (1973), Ziegler and Leuteritz (1970) and Hartenfels *et al.* (2022) is recognized on the basis of the shape and the ornamentation of the cup of typical morphotypes (Figures 12 and 13). Many specimens, however, can be designated as atypical morphotypes (Figure 13; see Kaiser *et al.*, 2019 *unpublished*) recorded by Nössing (1975), Ebner (1980a) and Kaiser *et al.* (2020).

Stable isotopes ($\delta^{13}C$) at Trolp (Kaiser *et al.* 2008; Figure 10b), used for the reconstruction of

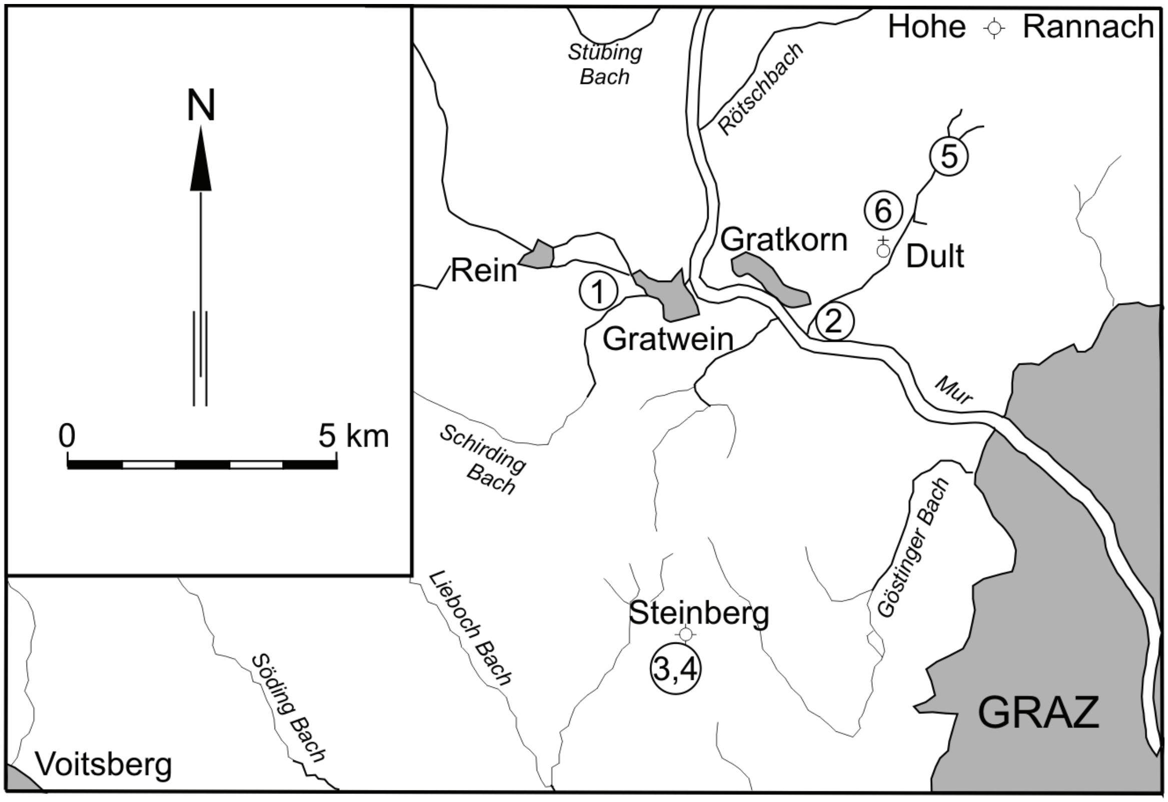

Figure 5 Geographic map and locations of outcrop areas near Graz in the western Graz Paleozoic, modified from Ebner (1980a). 1: Section Weihermühle, 2: Section Hartbauer, 3, 4: Steinberg area, 5: Section Hahngraben, 6: Section NNE Dult Monastery.

changes in the marine dissolved inorganic carbon reservoir, revealed a positive excursion in $\delta^{13}C_{carb}$ in the *ck*I and *kockeli* Zone to values of up to 3‰ (V-PDB). Two minor positive $\delta^{13}C_{carb}$ peaks were recorded in the *praesulcata* Zone, with values reaching 2.5‰ and 2.7‰, and one positive peak was measured in the Upper *expansa* Zone (*Bispathodus ultimus* Zone after Becker *et al.*, 2021). The onset of continuously decreasing carbon isotope values is at the base of the *sulcata/kuehni* Zone (DCB). A $\delta^{13}C_{org}$ excursion was measured from the sedimentary organic matter at Trolp, and oxygen isotope values of conodont apatite at Trolp are remarkable high indicating low seawater temperatures (*unpublished data*). Element geochemistry conducted by Bojar *et al.* (2013) at Trolp indicates a decrease of detrital influence in the lower Tournaisian and was interpreted as transgression.

4. Discussion

4.1. LITHO,- BIO, -AND CHEMOSTRATIGRAPHY AT TROLP AND CORRELATIONS OUTSIDE THE REGION

Characteristic markers and abundant conodonts at Trolp allow a high time-resolution study of major environmental changes around the DCB. These can be well correlated with coeval markers from continuous limestone successions as well as siliciclastic-dominated successions in North-America, Asia, Europe, North-Africa from pelagic, hemipelagic and neritic realms as discussed as follows, indicating environmental changes on a global scale.

4.1.1. LITHOSTRATIGRAPHY AND LITHOFACIES

At Trolp, a characteristic lithofacies change (Figure 7), from bedded or massive limestones to thin-bedded limestones (mud- to wackestones, Kaiser 2005), is correlative with the global change to siliciclastics (HBS, HSS) and the anoxic episode of the Hangenberg Crisis in the extinction-based *ck*I and *kockeli* Zone (Figure 8-10). In continuous, pelagic limestone successions in the Carnic Alps (Grüne Schneid, Figure 8), and in hemipelagic to pelagic, more proximal successions in the Montagne Noire (La Serre É, *e.g.*, Flajs and Feist, 1988; Feist *et al.*, 2021) and in the Moravian Karst (Kumpan *et al.*, 2021), a lithofacies change from bedded to thin-bedded, condensed limestones can be correlated with equivalent changes at Trolp. This lithofacies change is globally recorded, and correlative for example with black shales and/or sandstones in pelagic but more deeper settings in the Carnic Alps (Kronhofgraben), Pyrenees (Milles), as well as in hemipelagic settings in the Rhenish Massif (Figure 8), for example at Drewer, or in neritic successions in the Meseta and Anti-Atlas, Morocco (Ain Jemaa, El Atrous, M´Karig, Lambidia), and in the Alborz Mts., Iran (Mighan, Chelcheli), as reported by several authors (*e.g.*, Cygan and Perret, 2002; Kaiser, 2005; Kaiser *et al.*, 2006, 2007, 2011, 2013, 2018; Becker *et al.*, 2016b; Bahrami *et al.*, 2021; Parvizi *et al.*, 2021; Königshof *et al.*, 2021).

The lithofacies change was caused by a global carbonate crisis at the end of the Devonian (Li *et al.*, 2022) due to ceased carbonate sedimentation, enhanced C_{org} burial and marine anoxia during the Hangenberg Black Shale Event (HBSE), and the succeeding “Hangenberg glaciation” during the Hangenberg Sandstone Event (HSSE; *e.g.*, Isaacson *et al.*, 2008; Kaiser *et al.*, 2006; Lakin *et al.*, 2016). The main regressive phase which led to the global deposition of Hangenberg Sandstone equivalents cannot be recognized by a clear sedimentological marker at Trolp, while the onset of the anoxic episode may be represented by the thin shaly layer (base of Bed 10), which is, however, only locally developed.

Tournaisian cherty sediments at Trolp (Trolp Phosphorite Bed, Figures 4 and 14), can be correlated with the basal middle Tournaisian as suggested by Kaiser (2005), and with the faunal turnover during the Lower Alum Shale Event which is globally characterized by a lithologic change from limestones to cherty rocks, the equivalents of the Rhenish Lower Alum Shale of the Middle *crenulata* Zone (Becker, 1993a, 1993b; Kaiser *et al.*, 2018). It is coeval with transgressive shales, partly associated with phosphorite nodules, for example at Kronhofgraben, Carnic Alps (Schönlaub, 1969; Kaiser, 2005), Puech de la Suque and La Serre É, Montagne Noire (Lethiers and Feist, 1990; Kaiser, 2005; Feist *et al.*, 2021), and at El Atrous, Jebel Ouaoufilal, M´Fis, M´Karig, Anti-Atlas, Morocco (Kaiser *et al.*, 2011, 2013, 2018). The base of the upper Tournaisian anchoralis Zone is globally characterized by an end of an erosional gap, deepening and upwelling. It is correlative with cherty sediments all over the Graz Paleozoic and with the end of an erosional gap within the Rannach Nappe, interpreted as deepening and upwelling event by Ebner (1998) and Ebner *et al.* (2000).

4.1.2. BIOSTRATIGRAPHY AND CONODONT BIOFACIES

A continuous record of biofacies change at the DCB can be well recognized at Trolp, as well as in continuous limestones in the Carnic Alps, Grüne Schneid (Figure 11), and there is no hiatus in each phases of the Hangenberg Crisis. The dominance of the *Protognathus* fauna and the *Polygnathus purus* group in the *kockeli* and *sulcata/kuehni* Zones at Trolp, Grüne Schneid and elsewhere characterizes the 1st (FO of *Protognathodus kockeli*, = base of *kockeli* Zone) and 2nd (FO of *Protognathodus kuehni*, FO of *Siphonodella sulcata* M5, = basal Tournaisian transgression) faunal recovery phases after the Hangenberg extinction (Figure 14). The 3rd radiation phase is in the middle *sulcata/kuehni* Zone (FO of *Siphonodella sulcata* M4, *Gattendorfia* level = Tournaisian transgression).

At Trolp, the Hangenberg extinction-based *ck*I is recognized by the absence of *Bispathodus costatus* and *Protognathodus kockeli* at same level, and the extinction of almost all upper Famennian conodont taxa among the pseudopolygnathids, polygnathids, bispathodids, branmehlids and palmatolepids (see Kaiser *et al.*, 2009, 2020). It is recognized by a major biofacies change from a Famennian *Bispathodus-Branmehla-Palmatolepis* biofacies to a characteristic, impoverished latest Famennian and earliest Tournaisian *Polygnathus-Protognathodus* biofacies. The *ck*I and the major conodont biofacies change are recorded at the base of the thin-bedded limestones at Trolp, as well as in continuous pelagic and hemipelagic limestone successions at the base of thin-bedded limestones in the Carnic Alps at Grüne Schneid (Kaiser, 2007; Figure 11), in the Moravian Karst at Krtny (Kumpan *et al.*, 2021), and in the Montagne Noire at La Serre É (Flajs and Feist, 1988; Feist *et al.*, 2021, Kaiser unpublished data) at correlative levels, and is caused by major environmental changes during the HBSE and HSSE.

Conodont faunal distributions and lithofacies at Trolp display distal, pelagic depositional environments, with sediment deposition in ca. 200 m water depth (*e.g.*, Nössing, 1975). For comparison, litho- and biofacies, and the depositional environments in the Carnic Alps at Grüne Schneid (Schönlaub *et al.*, 1988, 1991) are similar to that of Trolp, and a rich *Protognathodus* fauna occurs in both regions (Kaiser *et al.*, 2020). Differences only related to single occurrences of *Protognathodus* specimens in pre-Hangenberg extinction levels (*praesulcata* Zone) at Grüne Schneid, with minor differences in biofacies, only. Accordingly, a slightly higher abundance of *Bispathodus* than of *Palmatolepis* occurs in the Famennian in pre-crisis levels at Trolp (Figure 11) which is an indicator for more shallow depositional environments according to previous biofacies models (see Kaiser *et al.* 2017). For example, *Bispathodus* abundantly occurs in neritic settings in Iran (Alborz Mts., *e.g.*, Mighan, Chelcheli), Morocco (Tafilalt, *e.g.*, El Atrous), and in hemipelagic settings in the Rhenish Massif (*e.g.*, Hasselbachtal), Montagne Noire (*e.g.*, La Serre, Puech de la Suque), Moravian Karst (*e.g.*, Lesni Lom), as reported by several authors (*e.g.*, Kaiser, 2005; Hartenfels and Becker, 2016; Feist *et al.*, 2021; Kaiser *et al.*, 2011, 2018; Bahrami *et al.*, 2011, 2021; Königshof *et al.*, 2021; Kumpan *et al.*, 2021; Parvizi *et al.*, 2021).

In contrast, siphonodellids, as indicator for more deeper environments (see Kaiser *et al.*, 2017) are slightly more abundant at Trolp in pre-event levels when compared to Grüne Schneid, and *Sipho-*

http://dx.doi.org/10.18268/BSGM2024v76n3a210524

nodella is not recorded in the *ck*I and *kockeli* Zone at Grüne Schneid and elsewhere in the Carnic Alps. Protognathodids, previously suggested as an indicator for more shallow environments, occur at Grüne Schneid in pre-event levels, while this faunal group is not recorded in pre-event levels at Trolp and elsewhere in the Graz Paleozoic. In summary, faunal distribution of *Protognathodus* and *Siphonodella* indicates more shallow depositional environments at Grüne Schneid than at Trolp in pre-event levels, which is, however, not in accordance with the *Bispathodus* biofacies at Trolp as mentioned above.

In this respect, previous biofacies concepts for example of Sandberg and Ziegler (1979), Dreesen *et al.* (1986) and Ziegler and Weddige (1999), have to be re-considered (see Kaiser *et al.*, 2017, 2020). Paleogeographic provincialism and migration pattern, competition and feeding (Mossoni *et al.*, 2015), but also decreasing ecological niches around the DCB due to global shelf anoxia (Algeo *et al.*, 1995; Li *et al.*, 2022) and major eustatic sea-level fall with longterm and short-termed regressions (*e.g.*, Johnson *et al.*, 1985; Kaiser *et al.*, 2011; Babek *et al.*, 2016), as well as climate cooling (Issacson *et al.*, 2008; Brezinski *et al.*, 2009; Lakin *et al.*, 2016), caused more likely characteristic faunal assemblages and biofacies changes. The occurrence of either *Protognathodus* or *Siphonodella* around the DCB is thus more likely related to major environ-

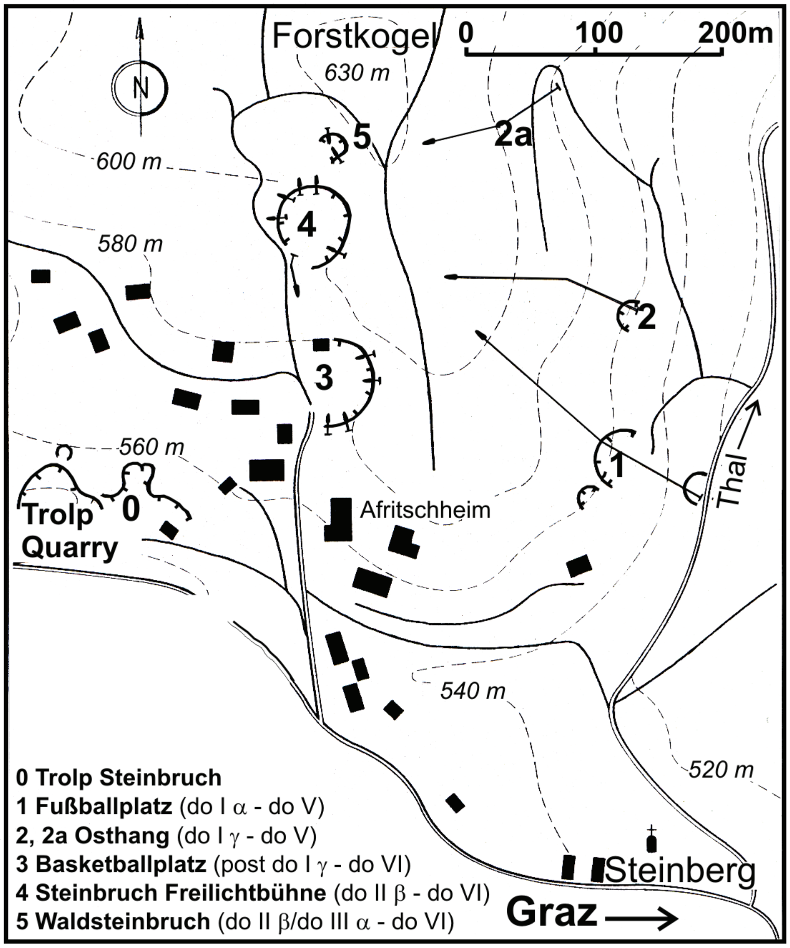

Figure 6 Locations of the Trolp Quarry (0) and other Upper Devonian outcrops (1-5) at Forstkogel in the Steinberg area, modified from Buchroithner *et al.* (1979).

mental changes during anoxic, transgressive and and regressive phases of the Hangenberg Event, and is regarded as biotic opportunism by several authors (*e.g.*, Kaiser, 2005, Kaiser *et al.*, 2008, 2009; Corradini *et al.*, 2011; Spalletta *et al.*, 2017). Thus, disregarding taxonomic uncertainties as discussed below, the occurrence of *Protognathodus* in pre-Hangenberg Event levels in the Carnic Alps and other regions in Europe, Asia and North-Africa could thus be linked with an opportunistic lifestyle during environmental changes probably related to the Drewer Event (early Hangenberg phase) in the *praesulcata* Zone (see Section 4.1.3).

4.1.3. STABLE ISOTOPES AND CHEMOSTRATIGRAPHY

Chemostratigraphy as a formal stratigraphic method is a useful tool for global correlations of chronological boundaries (see Sial *et al.*, 2019), correlations of event-related successions (*e.g.*,

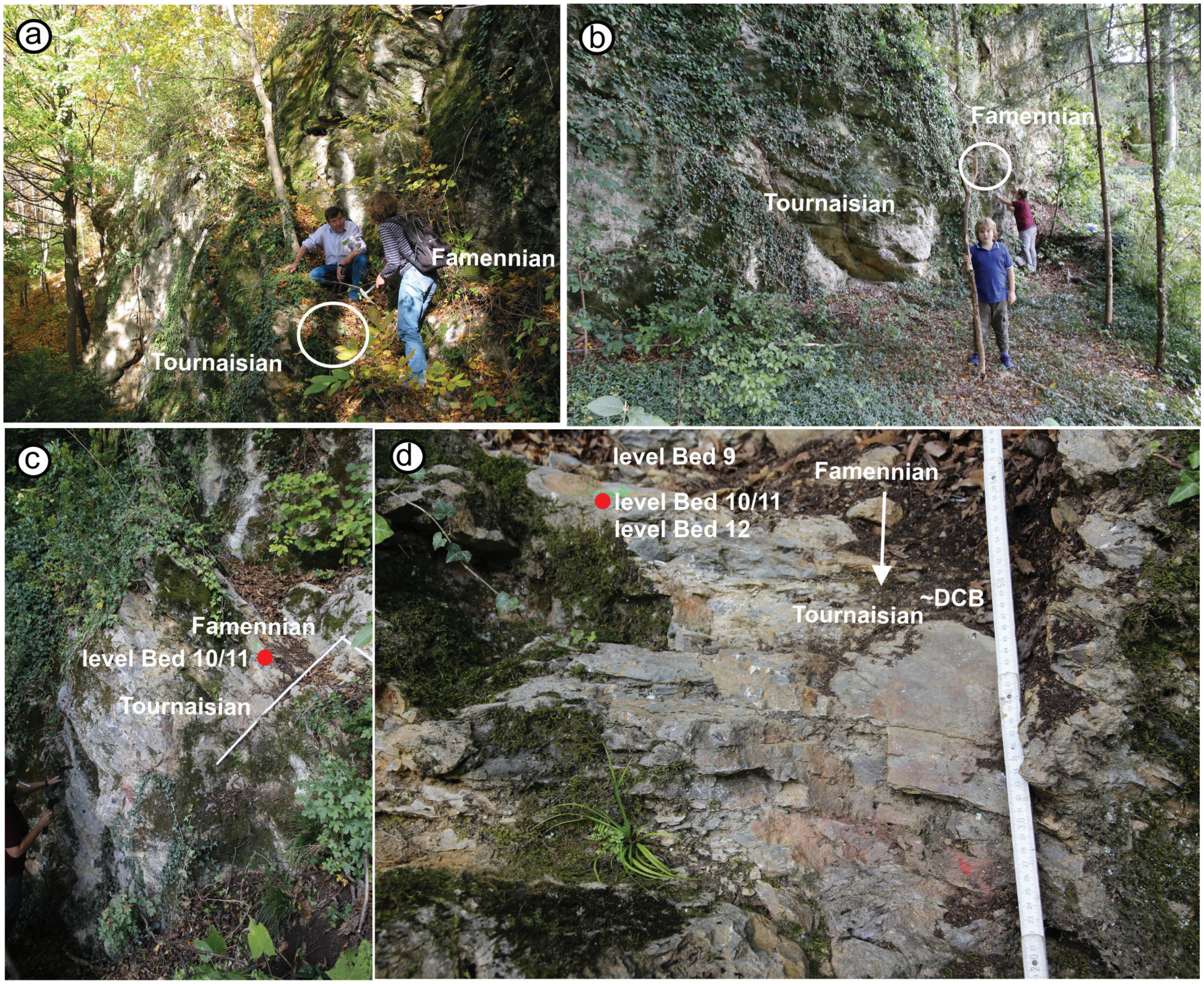

Figure 7 Outcrop overview and field studies at the abandoned, tectonically disturbed Trolp Quarry, a) sampling in 2002, with Prof. Fritz Ebner (Leoben), b-d) new sampling in 2019, a-b) circles = thin-bedded limestones shown in c-d, and sampling locations. c-d) thin-bedded, continuous limestone successions at the DCB.

Algeo and Shen, 2024), and Hangenberg event-related successions at the DCB (Kaiser *et al.*, 2016). In this respect, positive carbon isotope excursions recorded at Trolp from different levels in the Upper *expansa* (*ultimus* Zone) and *praesulcata* Zones, as well as in the *ck*I and *kockeli* Zone (Figure 10b) can be well correlated outside the region (Figure 10c), and thus indicate enhanced marine C_{org} burial and global perturbations of the cabon cycle. Accordingly, a minor positive peak in $\delta^{13}C_{carb}$ in the Upper *expansa* Zone at Trolp, with increasing values of more than 2‰, is widely known from the Middle (*costatus* Zone) and Upper *expansa* Zone as distinctive positive carbon isotope excursions of up to 3‰ in the Carnic Alps (Kaiser *et al.*, 2008), Franconia, southern Germany (*unpublished data*, Kaiser *et al.*, 2022), and the Moravian Karst (*unpublished data*, Kumpan *et al.*, 2018), and were correlated previously with the small-scaled "Epinette" (Middle *expansa*) and "Etreoungt" (Upper *expansa*) bioevents (Kaiser *et al.*, 2008). Increasing $\delta^{13}C_{carb}$ values and positive carbon isotope excursions in shallow-water successions were also recorded from the Middle and Upper *expansa* Zone in South China (*costatus* and *ultimus* Zone, Zhang *et al.*, 2019), in northern Iran (Parvizi *et al.*, 2021), and in Belgium (Kumpan *et al.*, 2014b). In deeper pelagic settings (Kronhofgraben, Carnic Alps), a positive $\delta^{13}C_{org}$ spike of 2‰ is recorded as well in the middle part of the Middle *expansa* Zone (Kaiser *et al.*, 2008). Worldwide, transgressive shale and black shale deposits (Algeo *et al.*, 1995; Li *et al.*, 2022; Sahoo *et al.*, 2023), and enhanced C_{org} burial episodes, as also indicated by an increasing $\delta^{13}C_{carb}$ baseline on a global scale (Zhang *et al.*, 2019), are recorded in the *expansa* Zone probably connected with the Dasberg Crisis in the Lower and basal Middle *expansa* Zones (see Hartenfels, 2011), and with the Epinette and Etreoungt Events in the middle Middle and Upper *expansa* Zone (*e.g.*, Kaiser *et al.*, 2008; see also Di Pasquo *et al.*, 2019).

Two minor positive $\delta^{13}C_{carb}$ peaks in the *praesulcata* Zone at Trolp, reaching values of more than 2.5‰, can be correlated with coeval positive peaks and/or increasing carbon isotope values of up to 3‰ recorded from the Carnic Alps at Grüne Schneid, Rio Boreado, Casera Malpasso, Großer Pal (Figure 10cA; Kaiser *et al.*, 2006, 2008), and in Franconia (Kaiser *et al.*, 2022, *unpublished data*), as well as by positive C_{org} peaks in the Rhenish Massif (Figure 10c B; Kaiser *et al.* 2006). These geochemical anomalies were interpreted as anoxic phases of the Drewer Event during the early phase of the Hangenberg Crisis in the *praesulcata* Zone (Kaiser *et al.*, 2020). The Drewer Event was previously correlated with the regressive Drewer Sandstone and equivalents elsewhere (Streel, 1999; see also Kaiser *et al.*, 2011, 2016), and was previously regarded as a short-term glaciation episode during a humid event at the LL-LE miospore transition (*e.g.*, Streel *et al.*, 2000). The Drewer level in the Rhenish Massif is characterized by at least two distinctive shale horizons (Becker *et al.*, 2021). Wet climate and enhanced detritus influx (= regressive Drewer Sandstone Event) probably caused enhanced marine bioproductivity and suceeding global shelf anoxia already in the *praesulcata* Zone, well before the HBSE, and may expressed by enhanced carbon burial as indicated by the positive $\delta^{13}C_{carb}$ peaks.

A significant increase of $\delta^{13}C_{carb}$ values by almost 2‰ at Trolp is at the base of the thin-bedded limestones associated with the conodont mass extinctions and the major conodont biofacies change in Bed 10 as discussed in Section 4.1.2. The positive $\delta^{13}C$ Hangenberg-excursion in the *ck*I and *kockeli* Zone of values up to 3‰ was globally recorded (Figure 10c, *e.g.*, Kaiser *et al.*, 2006, 2016; Cramer *et al.*, 2008; Kumpan *et al.*, 2014a; Matyja *et al.*, 2021; Qie *et al.*, 2021; Becker *et al.*, 2021). The onset of the positive excursion indicates global changes of the carbon cycle during the Hangenberg Crisis which was caused by enhanced C_{org} burial during the deposition of the HBS and equivalents (*e.g.*, Kaiser *et al.*, 2006). Enhanced bioproductivity, high rates of continental weathering and terrestrial nutrient influx due to erosion of organic matter during an upper Famennian sea-level lowstand (Babek *et al.*, 2016) contributed to enhanced organic carbon burial. This finally resulted in a succeeding major, glacio-eustatic sea-level fall during wet and cold climate, time-equivalent to the deposition of the regressive Hangenberg Sandstone and global equivalents, and a glaciation pulse (Hangenberg glaciation) at the end of the Famennian (*e.g.*, Kaiser *et al.*, 2006; Isaacson *et al.*, 2008; Brezinski *et al.*, 2009; Lakin *et al.*, 2016).

A distinctive decrease of $\delta^{13}C_{carb}$ values, starting in the lower Tournaisian *sulcata/kuehni* Zone at Trolp, reflects an overall long-term trend in the lower Tournaisian at same levels in numerous settings in European, Asian and North-American regions (Figure 10c, Kaiser *et al.*, 2016, and references therein). This trend may be explained by a reduced sedimentation rate of marine organic matter, or by an enhanced delivery of light carbon into the oceans from continental weathering of organic-rich sediments during a short-term warming episode in the basal Tournaisian (Kaiser *et al.*, 2006; Marshall *et al.*, 2020). Decreasing carbon isotope values at Trolp were reported as well by Bojar *et al.* (2013). However, their data and interpretations are related to uncorrect positions of the *kockeli* Zone (= Upper *praesulcata* Zone) and the DCB (see Bojar *et al.* 2013, Figure 3a). The DCB is fixed by the authors by the late FO of *Siphonodella sulcata* previously recorded by Ebner (1980a) from his Bed 8 (see Figure 9). The authors ignore that the DCB was correctly fixed by Ebner (1980a) in his Bed 4 with the FO of *Polygnathus purus subplanus* as an index fossil for the DCB (Kaiser *et al.*, 2009; Spalletta *et al.*, 2017). Bed 4 of Ebner is correlative with Bed 16 of Kaisers studies, according to thickness of the limestones and the FO´s of *Polygnathus purus subplanus*, *Protognathodus kuehni* and *Siphonodella sulcata* (M5) in Bed 16. Thus, main parts of the *kockeli* Zone and the DCB of Bojar *et al.* (2013) can be regarded as younger, Tournaisian successions, and these biostratigraphic misinterpretations resulted in misinterpretations of geochemical proxies at Trolp (see Zhang *et al.*, 2019, Figure 3). Further, the transgressive episode as interpreted from element geochemistry, and regarded as DCB-level by Bojar *et al.* (2013), is more likely the expression of the lower Tournaisian transgression (*Gattendorfia* level) in the middle *sulcata/kuehni* Zone (*sulcata* Event after Kalvoda and Kukal, 1987).

4.2. SCENARIOS FOR A POTENTIAL GSSP POSITION AT THE DCB

4.2.1. AN EVENT-BASED SCENARIO

The event-based, early phase of the Hangenberg Crisis, recognized at Trolp by bio,- litho- and chemostratigraphy (Section 4.1), is the initial main Hangenberg mass extinction Event among many marine organisms (*e.g.*, Kaiser *et al.*, 2016, Figure 3). It is correlative with the global deposition of the transgressive Rhenish HBS (= HBSE) and its equivalents elsewhere, and the main anoxic phase of the Hangenberg Crisis, indicated by the first significant positive peak in $\delta^{13}C_{carb}$, $\delta^{13}C_{org}$ (*e.g.*, Kaiser *et al.*, 2006). The global change from cephalopod limestones to black shales, or to high-condensed, thin-bedded limestones, has a worldwide correlation to numerous pelagic, hemipelagic and neritic settings in Asia, America and Europe (*e.g.*, Kaiser *et al.*, 2016; Becker *et al.*, 2016a, 2021; Aretz *et al.*, 2021, Kumpan *et al.*, 2021; Matyja *et al.*, 2021, Königshof *et al.*, 2021; Komatsu *et al.*, 2014; Qie *et al.*, 2021).

The HBSE (former middle part of the Middle *praesulcata* Zone) can be recognized biostratigraphically for example by miospores, and is dated as the LN miospore Zone (Sandberg *et al.*, 1972; Streel, 2009). The base of the LN miospore Zone provides correlation into the terrestrial realm and into macrofossil-free high-latitude settings. Furthermore, this level can be recognized by sequence stratigraphy and the drowning unconformity at the base of a maximum flooding interval (*e.g.*, Van Steenwinkel, 1993a, 1993b; Kaiser *et al.*, 2011). After summaries in Becker *et al.* (2016a), this episode of worldwide marine anoxia can be geochemically determined in various regions by organic geochemistry, inorganic carbon isotopes, magnetosusceptibility, element geochemistry, and by gamma ray spectroscopy (*e.g.*, Marynowski and Filipiak, 2007; Kaiser *et al.*, 2006; Cramer *et al.*, 2008; Kumpan *et al.*, 2014a, 2014b, 2015).

In siliciclastic-dominated successions, it is unclear which taxa range through the anoxic and regressive phase (HBSE, HSSE) due to fossil poor sediments, while in continuous pelagic limestone successions at Trolp and Grüne Schneid, the *ck*I (HBSE, HSSE) marks an important level. This level is characterized by main conodont extinctions, decreasing number of faunas, poor and stunted faunas, and major biofacies change. Alternative zonation concepts (Figure 12) do not consider the main Hangenberg extinction level instead, the level of the *ck* is the top part of the *ultimus* Zone (Spalletta *et al.*, 2021), or the base of the extended *kockeli* Zone (Corradini *et al.*, 2017).

The HBSE was previously proposed as a natural DCB (Walliser, 1984). However, an event-based scenario is difficult to establish because 1. event-related successions are often accompanied by leakage, reworking, and impoverished faunas, and 2. hiatuses and C_{org} burial phases well before the HBSE, connected with the Dasberg, Etreoungt and Drewer Events as discussed in Section 4.1.3, resulted in the asynchronous onset of global black shale depositions and stratigraphic gaps (see figure 2a in Bojar *et al.*, 2013).

4.2.2 THE BASE OF THE KOCKELI ZONE

The base of the *kockeli* Zone (= Upper *praesulcata* Zone), as well as the extended *kockeli* Zone (= *ck*I/ *kockeli* Zone to base of the *bransoni* Zone, see Figure

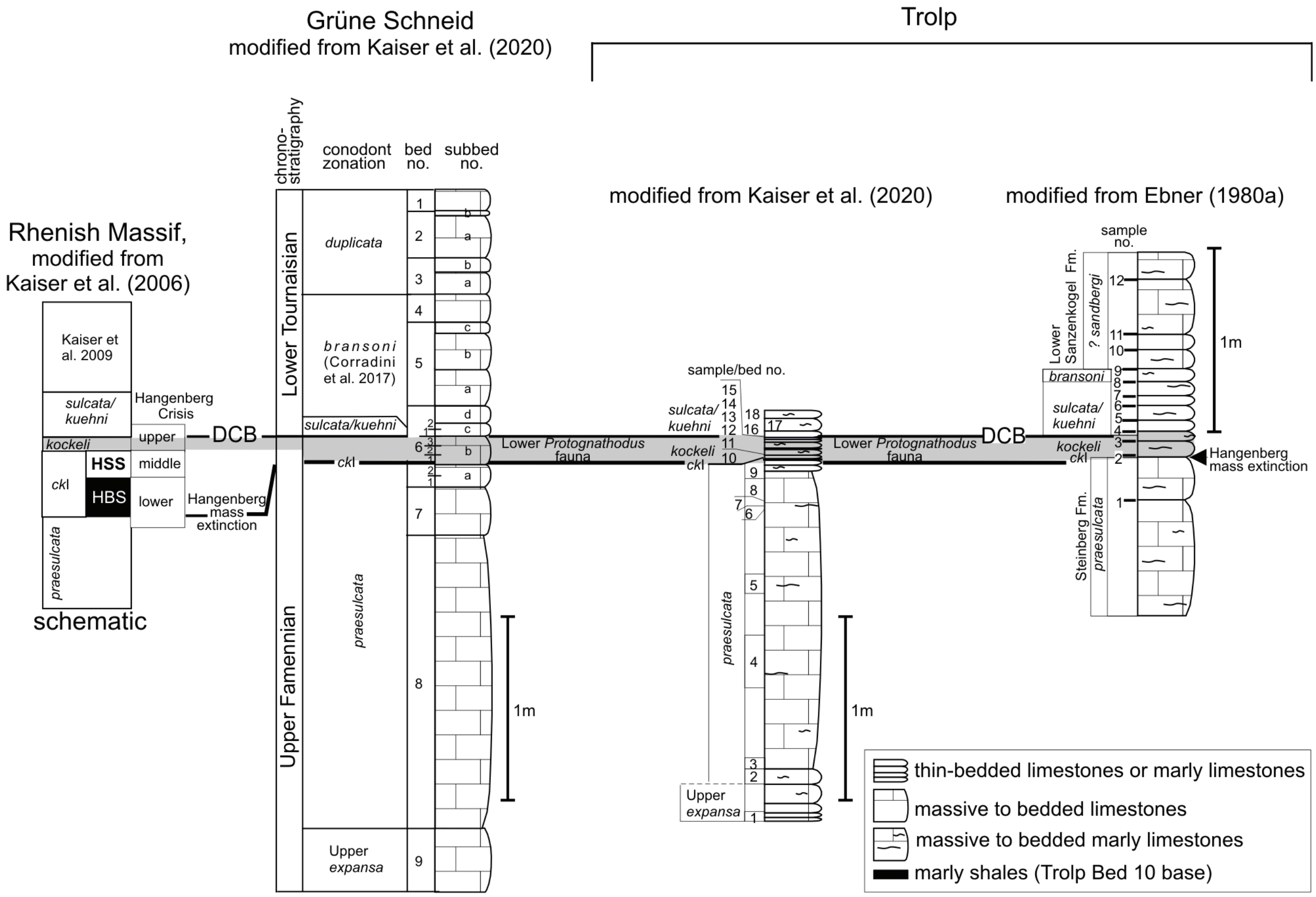

Figure 8 Stratigraphic correlation of Hangenberg Event successions at the DCB from Trolp (Graz Paleozoic), Grüne Schneid (Carnic Alps), and Rhenish Massif.

http://dx.doi.org/10.18268/BSGM2024v76n3a210524

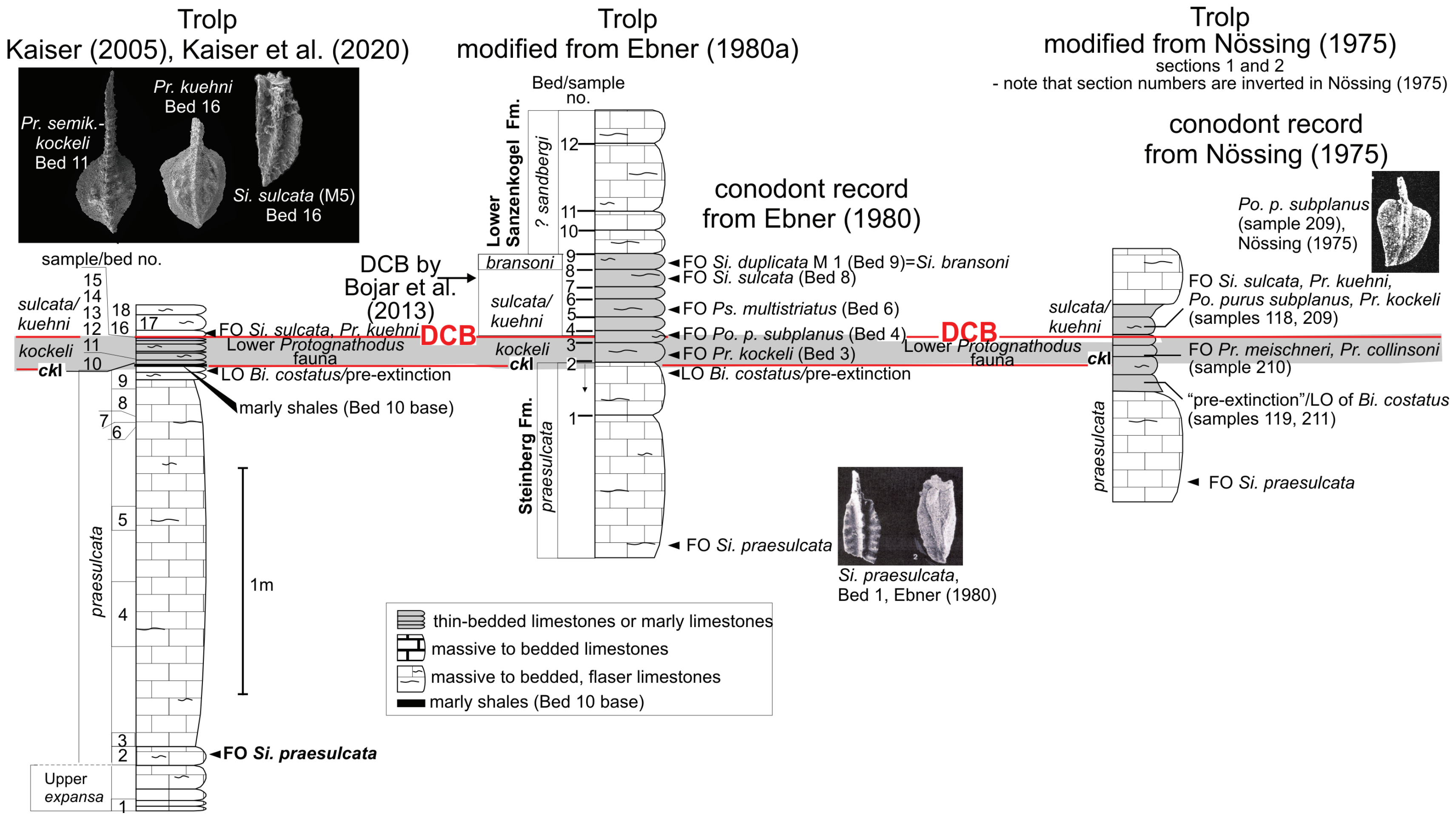

Figure 9 Conodont faunal correlation, and correlation of different but equivalent sample and bed numbers at Trolp, after Nössing (1975), Ebner (1980), Kaiser (2005), Bojar *et al.* (2013) and Kaiser *et al.* (2020), and selected zonally diagnostic conodonts from Trolp, *ck*l = *costatus-kockeli* Interregnum.

12) are not applicable as a potential DCB position as discussed as follows. The start of the *kockeli* Zone is probably within the upper LN miospore Zone, but the correlation into the terrestrial realm is difficult (*e.g.*, Becker *et al.*, 2016a). The entry of *Protognathodus kockeli* in its former definition of Bischoff (1957) - related to diagnostic features as curvature (bending) and shape of the cup as well as platform ornamentation - is affected by the restricted distribution of *Protognathodus kockeli* in many regions and widespread facies-controlled, discontinuous conodont sampling across the base of the *kockeli* Zone due to carbonate-poor deposits and late entry of the index fossil with the first carbonates (see Kaiser *et al.*, 2020). The *kockeli* Zone is commonly not preserved due to the absence of *Protognathodus kockeli* at this level, as previously reported and additionally discovered recently in the Alborz Mts., Iran (*e.g.*, Mighan, Chelcheli; Bahrami *et al.*, 2021; Königshof *et al.*, 2021; Parvizi *et al.*, 2021), Carnic Alps (*e.g.*, Kronhofgraben, Plan di Zermula; Kaiser *et al.* 2009; Spalletta *et al.* 2021), Anti-Atlas (*e.g.*, M´Karig, El Atrous; Kaiser *et al.*, 2011), Moravian Karst (Krtny; Kumpan *et al.*, 2021), or due to an impoverished *Polygnathus*-*Protognathodus* biofacies at the end of the Famennian (partly without *Protognathodus kockeli*), respectively, for example in the Rhenish Massif (*e.g.*, Oese, Oberrödinghausen; Kaiser *et al.*, 2017; see Becker *et al.*, 2021), Holy Cross Mountains (Kowala; Matyja *et al.*, 2021), Illinois Basin, Indiana, USA (Over, 2021). Stratigraphic gaps are caused by the reduced formation of carbonates due to a global carbonate crisis during this time span, resulting from continuing Famennian sea-level fall (Babek *et al.*, 2016) as the longterm regression continued until the Carboniferous, and from continuing major global cooling (*e.g.*, Isaacson *et al.*, 2008; Brezinski *et al.*, 2009; Kaiser *et al.*, 2022, *unpublished data*). The absence of the lower *Protognathodus* conodont assemblages (*Protognathodus meischneri*, *Protognathodus collinsoni*, *Protognathodus kockeli*) does not necessarily suggest stratigraphical gaps because erosional surfaces are missing (*e.g.*, Rhenish Massif, Iran and elsewhere, see Becker *et al.*, 2021; Königshof *et al.*, 2021) but is caused by biofacies changes and the deteriorating environment after the early and middle Hangenberg phase.

The entry of *Protognathodus kockeli* could be affected by local fossil reworking or leakage, for example in the Carnic Alps (Corradini *et al.*, 2017; see discussions in Kaiser *et al.*, 2020). Reworking and mixing of conodonts at this level is the result of the major eustatic fall associated with the HSSE and the Hangenberg glaciation in the middle Hangenberg phase, while leakage is the result of paleokarstic phenomena in the Graz Paleozoic and Carnic Alps (*e.g.*, Ebner, 1980b; Schönlaub *et al.*, 1991).

Also, the uncertainties of the FAD of the "one-row" (*Protognathodus semikockeli* after Hartenfels *et al.*, 2022) and the "two-rows" morphotype of *Protognathodus kockeli* (*Protognathodus kockeli* s.str. after Hartenfels *et al.*, 2022), and the start of the *kockeli* Zone either during the middle (regressive episode of the HSSE, based on stable isotopes and the FO of *Protognathodus semikockeli* and *Protognathodus kockeli* at Trolp and Grüne Schneid, Kaiser *et al.*, 2022 unpublished data), or late phase of the Hangenberg Crisis (after the facies break related to the HSSE (Hartenfels *et al.*, 2022) have to be considered. The base of the *kockeli* Zone (former Upper *praesulcata* Zone) was previously established by the "two-rows" *Protognathodus kockeli* (Bischoff, 1957), while it was established by the "one-row" *Protognathodus kockeli* by Corradini *et al.* (2011). Based on conodont studies at Borkewehr (Rhenish Massif; Hartenfels *et al.*, 2022) from limestone successions overlying the regressive Hangenberg sandstone equivalent, the FO of *Protognathodus kockeli* s.str. (two-rows) within the evolutionary lineage of *Protognathodus semikockeli* (one-row) and *Protognathodus kockeli* s.str. in the post-regressive Hangenberg phase is proposed as future GSSP for the DCB.

4.2.2.1. CONSIDERATIONS OF PROTOGNATHODUS

Taxonomic and biostratigraphic uncertainties within typical morphotypes of the early *Protognathodus* faunas are known for many years and were re-mentioned in Corradini *et al.* (2011), Kaiser *et* *al.* (2019 unpublished, 2020) and Hartenfels *et al.* (2022). Originally, Bischoff (1957), Ziegler and Leuteritz (1970), and Ziegler (1969) only considered randomly the high spectrum of *Protognathodus* morphotypes. Generally, the high spectrum of intermediate morphotypes of *Protognathodus* species attests to the completeness of the stratigraphic record, as at Trolp, Grüne Schneid (Kaiser *et al.*, 2020), Puech de la Suque (France) and Borkewehr (Hartenfels *et al.*, 2022). However, taxonomic uncertainties are related to intraspecific variability concerning juvenile-adult and early-advanced forms, as well as intermediates between all species of the early *Protognathodus* fauna (Kaiser *et al.*, 2019, 2020; Hartenfels *et al.*, 2022). This was previously recognized in the early siphonodellids, too; the high spectrum of intermediate morphotypes of *Siphonodella praesulcata* and *Siphonodella sulcata* at La Serre É and elsewhere have been taxonomically re-evaluated (Kaiser and Corradini, 2011), and morphotype groups of both *Siphonodella praesulcata* and *Siphonodella sulcata* were established and widely used (Figure 12, see Section 4.2.3.1).

Diagnostic features of the *Protognathodus* fauna are related to the cup morphology (curvature and shape of the cup) and platform ornamentation (Bischoff, 1957; Ziegler and Leuteritz, 1970), and a phyletic lineage of the early protognathodids (Ziegler, 1973), based on the typical morphotypes and their transitional forms (intermediates), was suggested at Trolp and Grüne Schneid (Kaiser *et al.*, 2020), comparable to Puech de la Suque from Bed 10 overlying the HBS (Hartenfels *et al.*, 2022). Accordingly, a well-exposed succession of *Protognathodus meischneri*, *Protognathodus collinsoni*, *Protognathodus semikockeli*, *Protognathodus kockeli* and *Protognathodus kuehni* could be recorded in these two regions. After Kaiser *et al.* (2020), the typical morphotype of *Protognathodus kuehni* at Trolp has at least on one side of the cup distinctive transverse ridges running radial from the platform edge to the carina, and the shape of the cup is wide and slightly asymmetric according to the original diagnosis of Ziegler and Leuteritz (1970).

Three new *Protognathodus* species are defined based on the arrangement of the cup ornamentation which focused on the developing of row of nodes (Hartenfels *et al.*, 2022), without considering the shape and curvature of the cup, and the platform ornamentation `scattered nodes´ which are discussed by the authors, only (see also Corradini *et al.*, 2011, and Kaiser *et al.*, 2020). Transitional forms, transitional forms between *Protognathodus kockeli* and *Protognathodus kuehni*, but also morphotypes previously determined as *Protognathodus kuehni* are included in *Protognathodus kockeli* s.str. (Hartenfels *et al.*, 2022), and thus enlarged the spectrum of morphotypes to be determined as *Protognathodus kockeli*.

Atypical morphotypes of `*Protognathodus*´ species with a high morphological variability, related to the shape of cup and the ornamentation of the platform, are recorded in the Graz Paleozoic (Figure 13), Carnic Alps, and other regions (see Kaiser *et al.*, 2020; Corradini *et al.*, 2011, Hartenfels *et al.*, 2022), and as stated in Hartenfels *et al.* (2022), "... atypical characteristics [within the genus *Protognathodus*],...result in a significant morphological complexity". At Trolp, within all species of *Protognathodus*, typical and also atypical morphotypes at Trolp are observed at the same stratigraphic levels in the uppermost Famennian and lower Tournaisian (Nössing, 1975; Kaiser *et al.*, 2020) which were partly included in the three new *Protognathodus* species (*Protognathodus semikockeli, Protognathodus kockeli s.str., Protognathodus kockeli*) recently established (Hartenfels *et al.*, 2022). For example, data at Trolp (Figure 13) indicate that beside specimens with a *Protognathodus*-like shape of cup, instead extremely narrow, atypical (instead of wide in comparison to holotypes) outlines of the shape of the cup in all species of the protognathodids are recorded from the *kockeli* to *bransoni* Zones (Kaiser *et al.*, 2020). Other morphologic characteristics are an extended posterior tip, a strong asymmetry due to an extended outer side of the cup, an enlarged outer margin which is commonly broken, or a strongly bent carina, in contrast to specimens with a straight carina.

Similar to the group of `siphonodelloids´,

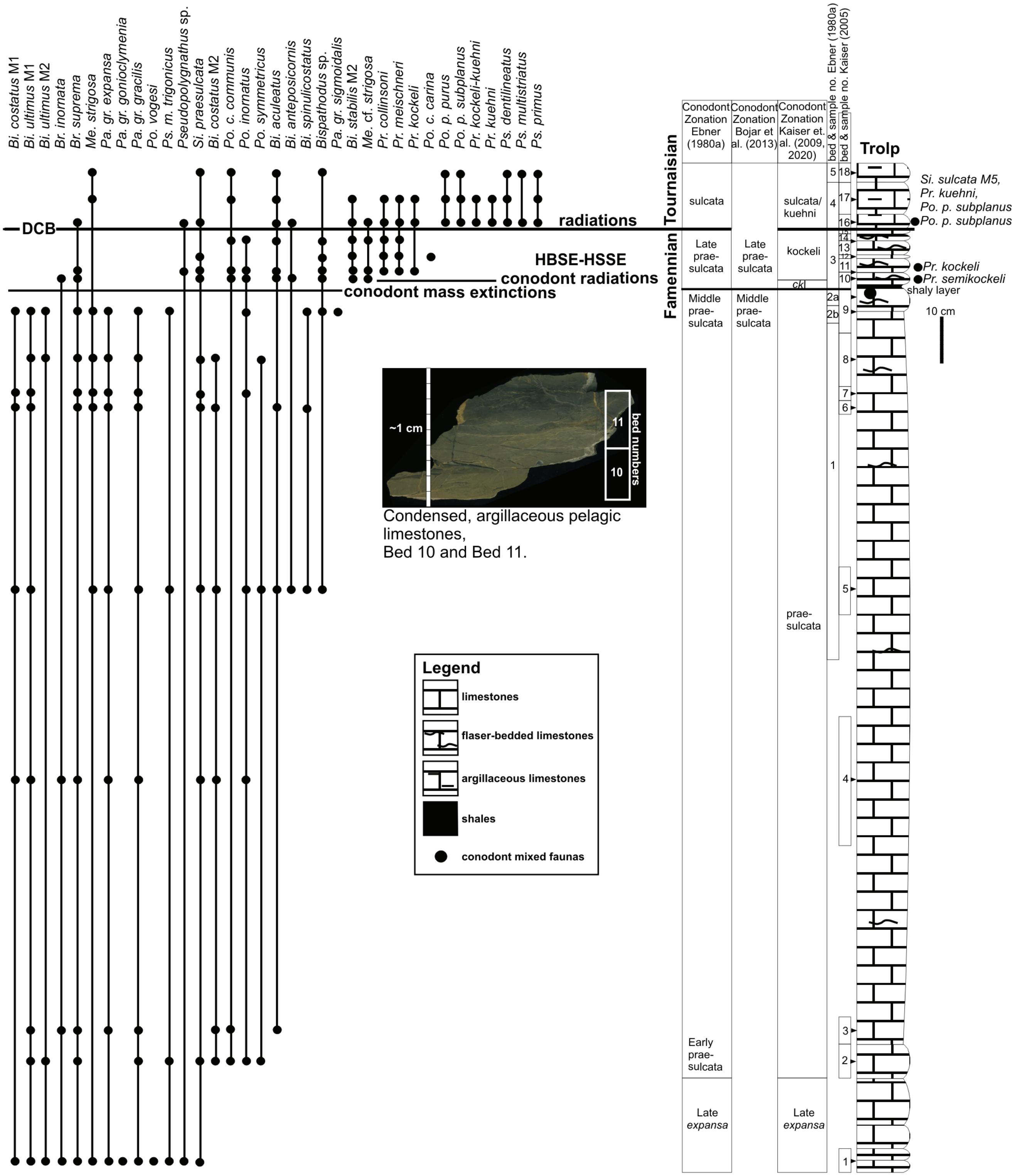

Figure 10a Lithology and conodont biostratigraphy at Trolp, data from Kaiser (2005) and Kaiser *et al.* (2008, 2009). Updated detail records of *Protognathodus* at the DCB in Kaiser *et al.* (2020). *Si.* = *Siphonodella*, *Po.* = *Polygnathus*, *Ps.* = *Pseudopolygnathus*, *Bi.* = *Bispathodus*, *Br.* = *Branmehla*, *Pa.* = *Palmatolepis*, *Me* = *Mehlina*, M = morphotype, *ckl* = *costatus-kockeli* Interregnum. Black circle = mixed conodont faunas. According to the recent taxonomic re-evaluation by Hartenfels *et al.* (2022), *Protognathodus semikockeli* and *Protognathodus kockeli* s.str. occurs at Trolp in the thin-bedded limetones.

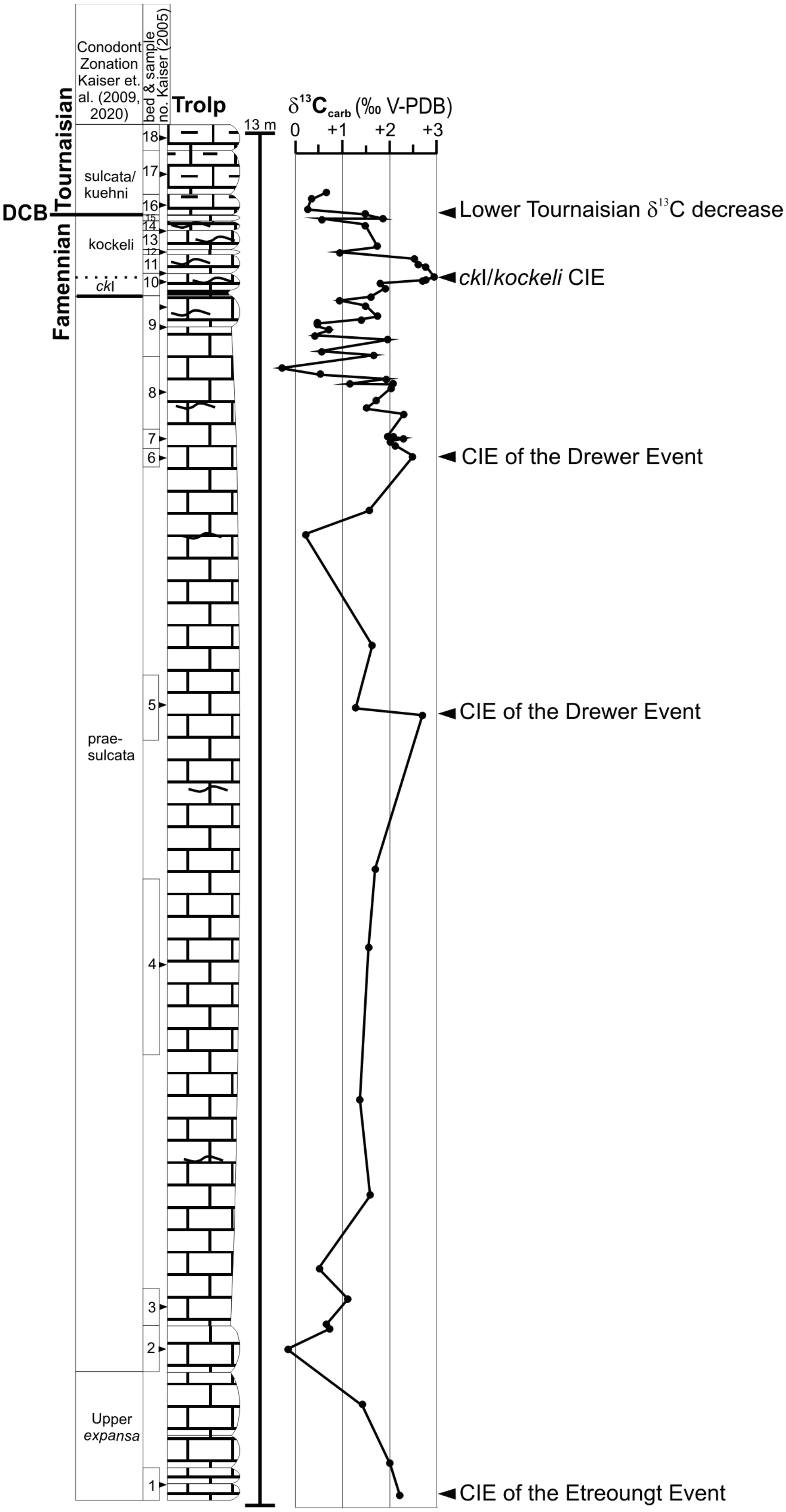

Figure 10b Geochemistry of carbon isotopes at Trolp, data from Kaiser (2005) and Kaiser *et al.* (2008), *ck*I = *costatus-kockeli* Interregnum, CIE=carbon isotope excursion.

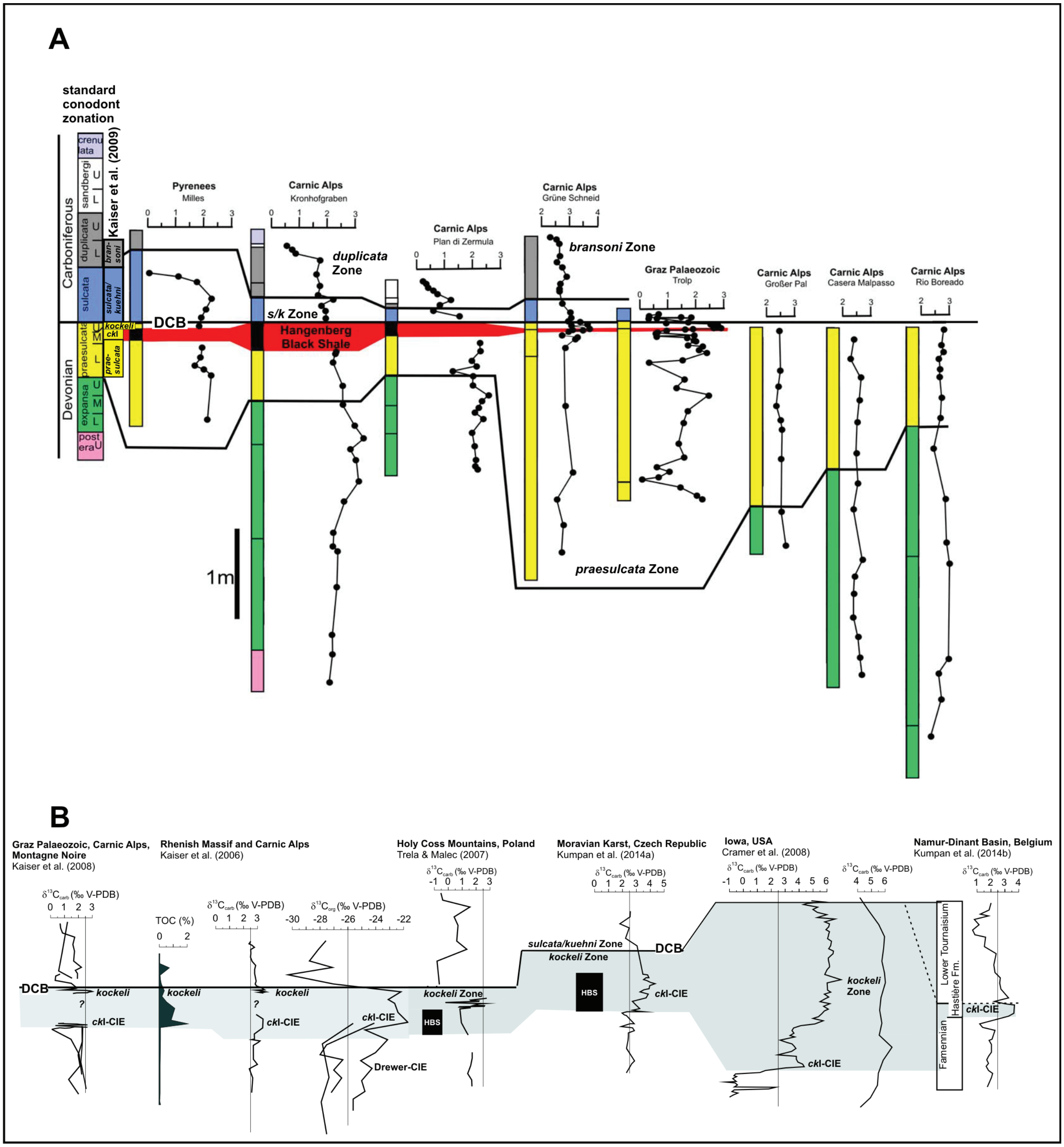

Figure 10c Geochemical ($\delta^{13}C_{carb}$) and biostratigraphic correlation of different DCB successions from southern and middle Europe and North America with the western Graz Paleozoic (Trolp), indicating same trends from the Famennian to Tournaisian in carbon isotopes. A. modified from Kaiser (2005), B. modified from Kaiser *et al.* (2016).

which has morphological features of *Siphonodella*, *Polygnathus* and *Pseudopolygnathus*, and were established previously (Becker *et al.*, 2013), the morphological complex group of *Protognathodus* faunas with atypical diagnostic features could be regarded as *Protognathodus*–like `protognathoids´, and can have morphological features of the late *Protognathodus*, of *Bispathodus* and of *Gnathodus* regarding platform ornamentation and shape of the cup as discussed below. Also, homeomorphic morphological features could be problematic because the early protognathodids can have overlapping ranges with the late *Protognathodus* (*e.g.*, *Protognathodus* praedelicatus, see Habibi *et al.*, 2008; see discussion in Hartenfels *et al.*, 2022), with *Bispathodus* (*e.g.*, *Bispathodus stabilis*, Ziegler 1973, 1974) and with *Gnathodus* (see below). These atypical faunas (`protognathoids´) probably originated during the early phase of the Hangenberg Crisis (Drewer Event) in the *praesulcata* Zone, with ?*Protognathodus meischneri* and ?*Protognathodus collinsoni*, and evolved probably during the anoxic (HBSE) or the regressive phase (HSSE) of the Hangenberg Event, with ?*Protognathodus semikockeli* and ?*Protognathodus kockeli* (see Figure 13), and spreaded around the DCB and in the lower Tournaisian. Their occurrence could be related to an opportunistic lifestyle during major environmental changes related to the Hangenberg Event, which can be regarded as "bottleneck" for the evolution of the Idiognathodontidae to which *Protognathodus* belong. Because protognathoids spread in the *kockeli* Zone, but mainly in the *sulcata/kuehni* Zone, or probably even later (Figure 14; see Corradini *et al.*, 2011; Kaiser *et al.*, 2020), the extended *kockeli* Zone (base of the former *kockeli* Zone to the base of the *bransoni* Zone) is not applicable due to the spread of these still unknown faunas regarding their stratigraphic and distributional pattern, and also due to their unknown ancestor and descendent relationship.

At Trolp, a stratigraphically leaked younger fauna is recorded by single specimens of *Gnathodus* at the same stratigraphic level as the early *Protognathodus* fauna, and leaked *Gnathodus* were found in the *sulcata/kuehni* Zone, or in older (*praesulcata* Zone) levels. Mixed faunas and homeomorphy (see below) within the Idiognathodontidae family (*Gnathodus* and *Protognathodus*) could produce a bias of the faunal record in the lower Tournaisian, especially in 1) condensed successions, 2) in stunted or juvenile-dominated assemblages, 3) in Lower Carboniferous, siliciclastic-dominated successions with fossil-poor limestones and scarce conodont faunas, without associated other diagnostic faunas and/or co-occurrence with `homeomorphic´faunas (*e.g.*, Kaiser *et al.*, 2020; see Königshof *et al.*, 2021 and Parvizi *et al.*, 2021). At Shahmirzad, (Alborz Mts., northern Iran), *Protognathodus kockeli* even occurs at same level as *Gnathodus cuneiformis* and *Protognathodus praedelicatus* in the upper Tournaisian Lower *typicus* Zone to *anchoralis-latus* Zone (Habibi *et al.*, 2008, see discussion in Hartenfels *et al.*, 2022). In contrast, leaked faunas among the late (*Siphonodella bransoni*, *Siphonodella duplicata*, *Siphonodella quadruplicata*) siphonodellids are generally easy to distinguish from the early (*Siphonodella praesulcata*, *Siphonodella sulcata*) siphonodellids, as at Trolp in mixed faunal assemblages around the thin-bedded limestone successions (Figure 10a).

Lane *et al.* (1980) provided an extended discussion of the differences between *Gnathodus* and *Protognathodus* and the differences in cup shape and cup terminations between early and late *Protognathodus*, with diagnoses of both genera. However similar diagnostic features between the early *Protognathodus* fauna, the late *Protognathodus* fauna ([*Protognathodus cordiformis*], *Protognathodus praedelicatus*, see also discussion in Hartenfels *et al.*, 2022), and *Gnathodus* (Ziegler, 1973; Lane *et al.*, 1980; Dzik, 1997, 2006), and their overlapping ranges in the lower, middle or upper Tournaisian must be considered.

Examples of atypical morphotypes or homeomorphy as discussed as follows are partly described in synonymies for *Protognathodus kockeli* (Hartenfels *et al.*, 2022). Atypical `*Protognathodus*´ specimens can have a cup-morphology, which is similar to the late protognathodids regarding the termination of the margin and the wideness of the cup, and also confusion with *Gnathodus* may be related to the platform ornamentation of *Protognathodus kockeli*,

http://dx.doi.org/10.18268/BSGM2024v76n3a210524

where, for example, nodes as ridge-forming row of "denticles", partly with an adcarinal through, are developed (*e.g.*, Corradini *et al.*, 2011, plate 1, figure 18; Kaiser *et al.*, 2020, plate 2, figure 1), or incipient parapet-like morphologies on one side of the platform and a strong asymmetry, *e.g.*, in Sardinia, Corradini *et al.* (2011, pl. 1, Figure 15), at Trolp, Kaiser *et al.* (2020; plate 3, figure 19, 22), in Morocco, Lalla Mimouna, Becker *et al.* (2013, plate 3, figure 9, with an unusual wide posterior carina, similar to specimen from Oklahoma figured by Over, 1992, see below), or in China, Wang and Yin (1988,; Figure 15).

Protognathodus specimens from the DCB transition were previously determined as *Gnathodus* in the Rhenish Massif (*e.g.*, Luppold *et al.*, 1984, pl. 6, Figure 2) or as *Protognathodus praedelicatus* in the Carnic Alps or Montagne Noire (Flajs and Feist, 1988; Schönlaub *et al.*, 1988). Subjective determinations of *Protognathodus* species from North Africa (Korn *et al.*, 2004), and from China, are evident (Wang and Yin, 1988: pl. 22, Figure 1-19; and compare synonymy list in Corradini *et al.*, 2011, and discussions therein, p. 25). Over (1992) described *Protognathodus* n. sp. from the *kockeli* Zone (= Upper *praesulcata* Zone) from North-America, which can be distinguished after the author from *Gnathodus* by its relatively symmetrical platform and lack of the offset of the outer and inner anterior platform margins. Specimens of *Protognathodus kockeli* from this region (Oklahoma, Woodford Shale) have a wide posterior carina, similar to that figured specimen from Morocco (see above, Becker *et al.*, 2013). This species is regarded by Over (1992) as an intermediate between *Protognathodus kockeli* and *Protognathodus* sp. B. Over (1992) suggested that *Protognathodus* sp. B may represent the ancestor of *Gnathodus punctatus* (with FAD in the late Kinder-

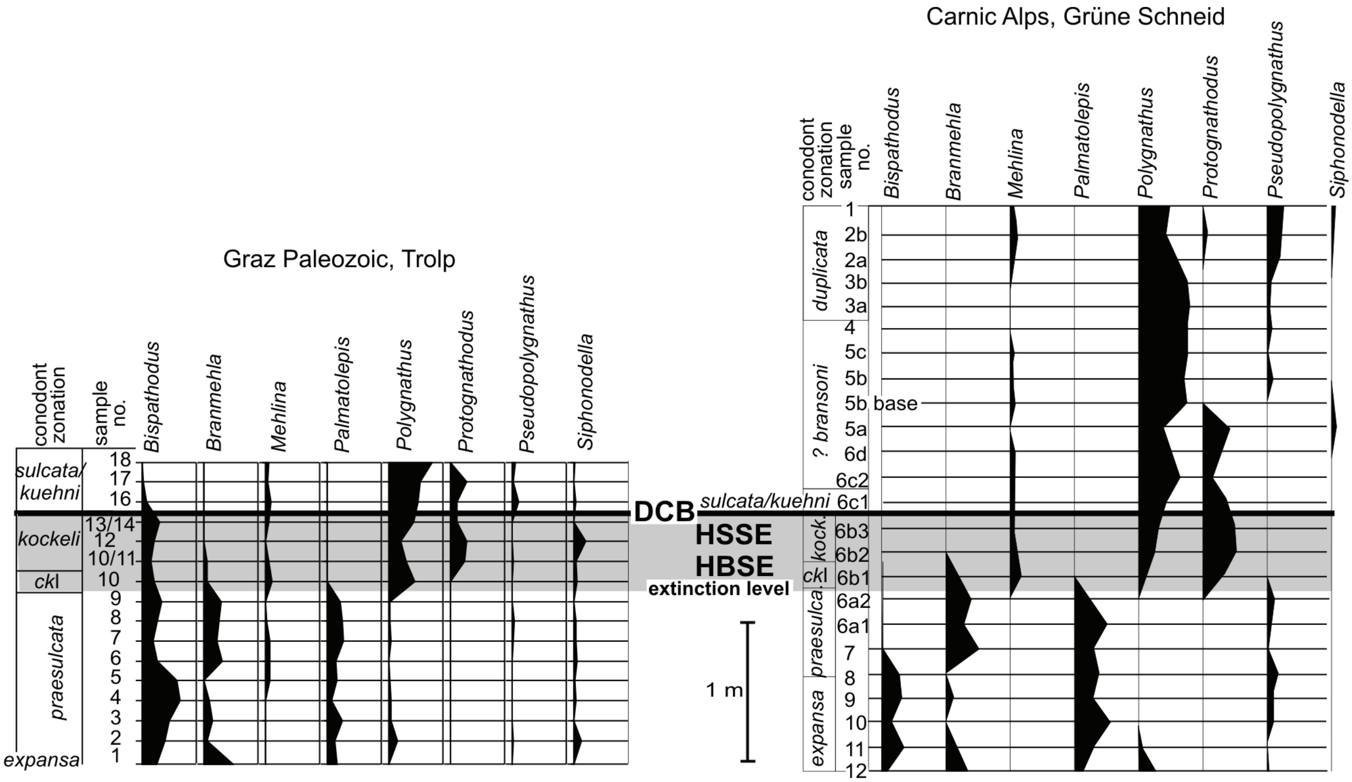

Figure 11 Conodont biofacies change and mass extinctions at the DCB from the Graz Paleozoic (Trolp) and Carnic Alps (Grüne Schneid), data from Kaiser (2005, 2007), *ckl* = *costatus-kockeli* Interregnum.

hookian) which has a broadly expanded posterior carina. Similar specimens have been illustrated from La Serre, Montagne Noire (Flajs and Feist, 1988, pl. 9, Figure 9, 10), and fused nodes on the platform (plate 9, figure 10) could be transitional to *Protognathodus praedelicatus* but was determined as *Protognathodus kockeli* after Corradini *et al.* (2011).

Furthermore, juvenile specimens of *Protognathodus meischneri* and *Bispathodus stabilis* are difficult to distinguish (Ziegler, 1973). Both have overlapping ranges in the ?upper/uppermost Famennian and lower Tournaisian, and confusions with stunted or juvenile ?*Protognathodus meischneri* and *Bispathodus stabilis* occur at Trolp and elsewhere (Kaiser *et al.*, 2020; see also Corradini *et al.*, 2016). Ziegler *et al.* (1974) have demonstrated the ancestry of *Protognathodus*; *Bispathodus stabilis* Morphotype 2, which has an expanded basal cavity extending to the posterior tip of the blade (end of the platform), was shown to be the ancestor of the *Protognathodus* lineage by the authors, illustrated on plate 3, Figure 2. *Bispathodus stabilis* Morphotype 2 lacks only the wider expansion of the cup to distinguish it from *Protognathodus meischneri*, and *Protognathodus meischneri* has a distinctly flat basal cavity.

However, as stated in Kaiser *et al.*, (2020), the shape of the cup of adult specimens of ?*Protognathodus meischneri* at Trolp (Figure 13, narrow shape of cup) can be similar to adult specimens of *Bispathodus stabilis stabilis* (see Hartenfels, 2011), and thus confusions in the determinations of both species exist, also in regard to the ornamentation of the platform which can be similar between *Protognathodus collinsoni* and *Bispathodus stabilis bituberculatus* and *Bispathodus aculeatus*, or between *Bispathodus stabilis stabilis* and *Protognathodus meischneri* (Hartenfels, 2011; Hartenfels and Becker, 2016; see Hartenfels, 2011, plate 31), *e.g.*, Matyja *et al.*, (2021, Figure 5A.d: aff. *Protognathodus meischneri*); Königshof *et al.*, (2021); Becker *et al.*, (2013, plate 3, Figure 5: *Protognathodus meischneri* [?with initial nodes on the platform]); Matyja *et al.*, (2021, with a doubtful *Protognathodus*, Figure 7a-c [similar to her *Bispathodus aculeatus*]); Kumpan *et al.*, (2021, *Protognathodus* cf. *meischneri*, Figure 5.7 [with an initial node on the platform]). The doubtful specimens of *Protognathodus meischneri* or *Protognathodus collinsoni*, partly discussed in Hartenfels *et al.*, (2022), occur in pre-extinction levels (*praesulcata* Zone) or in the Hangenberg Crisis level as single specimens in hemipelagic or neritic settings at La Serre É, Montagne Noire (Flajs and Feist, 1988; Kaiser, 2005, 2009; Feist *et al.*, 2021), Lesní Lom, Moravian Karst (Kumpan *et al.*, 2021), Mighan and Chelcheli, Alborz Mts., Iran (Parvizi *et al.*, 2021; Bahrami *et al.*, 2021; Königshof *et al.*, 2021), Lalla Mimouna, Anti-Atlas, Morocco (Becker *et al.*, 2013), Kowala, Holy Cross Mountains, Poland (Matyja *et al.*2021), Grüne Schneid, Carnic Alps (Corradini *et al.*, 2017; Kaiser *et al.*, 2020). Also, the occurrence of questionable *Protognathodus meischneri* and *Protognathodus collinsoni* in pre-Hangenberg Event levels from different regions (*e.g.* at La Serre E) must be considered in respect to their FAD and ancestor relationship to the new species *Protognathodus semikockeli* recently established (see also discussion in Hartenfels *et al.*, 2022).

In summary, beside the diagnostic features of the shape and curvature of the cup of the *Protognathodus* fauna see Figure 13), morphological complexity of the ornamentation of the platform may resulted in subjective determinations. Therefore, these morphological complexities in shape of the cup and ornamentation of the platform (`protognathoids´) should be focused on in future studies, comparable to the `siphonodelloids´ which are discriminated from the homeomorphic siphonodellids.

4.2.3 THE DEVONIAN-CARBONIFEROUS BOUNDARY AND CURRENT INDICATORS IN THE SULCATA/KUEHNI ZONE

At the base of the *sulcata/kuehni* Zone, the 2nd faunal recovery among conodonts (Figure 14) is connected with an increasing abundance of pseudopolygnathids and siphonodellids (*e.g.*, Kaiser, 2005; Kaiser *et al.*, 2017), and with a change from poor, rare and stunted conodont faunas in the *ck*I/*kockeli* Zone (1st radiation phase) to more abundant and normal-size faunas indicating the post-extinction/

http://dx.doi.org/10.18268/BSGM2024v76n3a210524

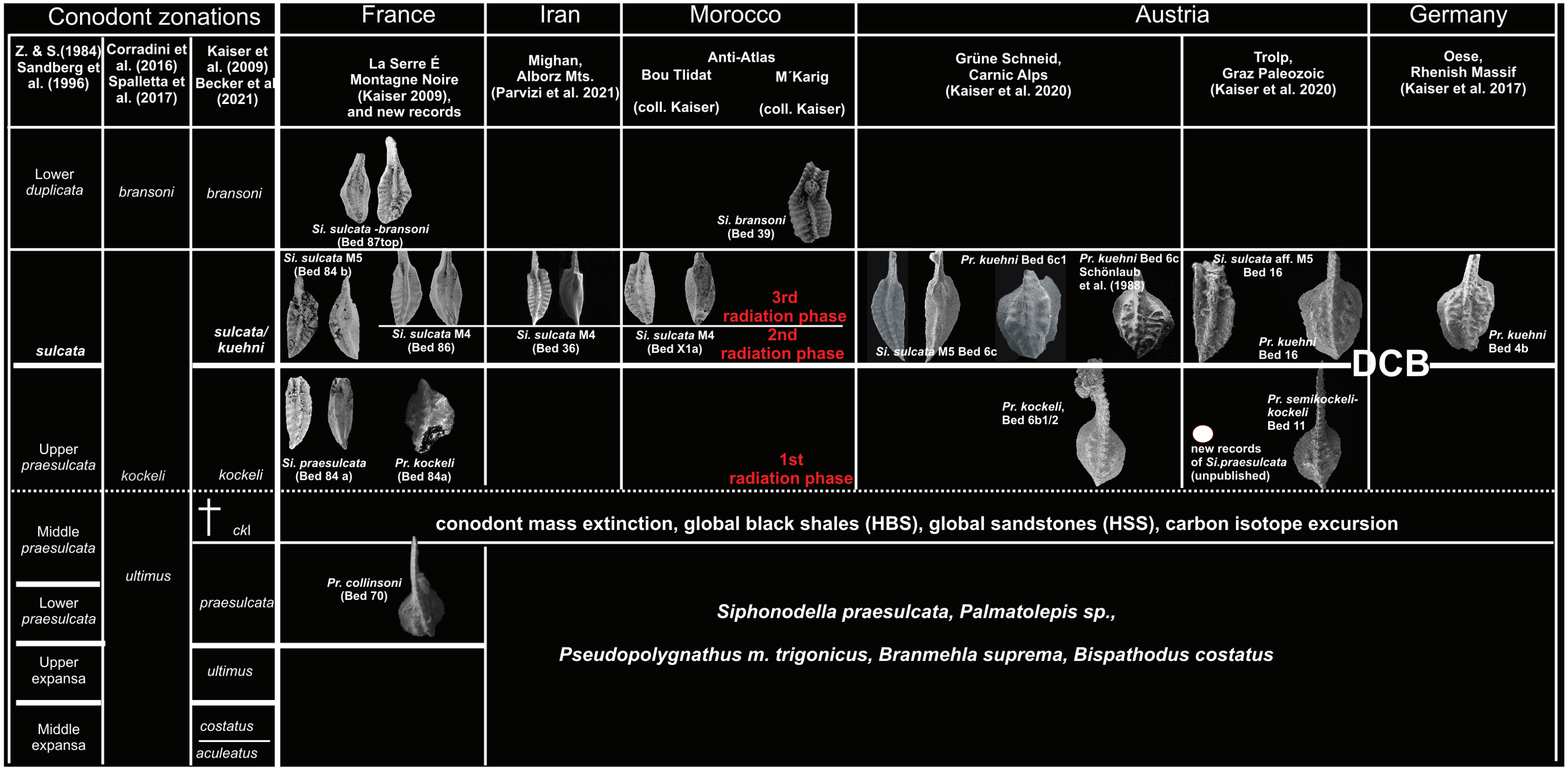

Figure 12 Correlation of significant DCB index conodonts – *Siphonodella sulcata* Morphotype 5 and *Siphonodella sulcata* Morphotype 4, *Protognathodus kuehni* - recently discovered from different paleogeographical regions. s/k Zone = *sulcata/kuehni* Zone, *ckl* = *costatus-kockeli* Interregnum. The FAD of *Siphonodella sulcata* M5 is congruent to that of *Protognathodus kuehni*. Note that specimens from La Serre É shown are the earliest *Siphonodella sulcata*-morphotypes to occur at the base of the Tournaisian in Bed 84, while specimens shown on Figure 1 in Aretz and Corradini (2021), are recorded by Kaiser (2009) from younger stratigraphic levels at La Serre É from Bed 86 (left specimen, advanced *Siphonodella sulcata*) and from Bed 85 (advanced *Siphonodella praesulcata*).

post-crisis level. The 1st and 2nd recovery phases (see Figure 12) each coincide with global post-extinction sea-level rises and deepening episodes, as interpreted, for example, by microfacies at Trolp (Kaiser, 2005) and Grüne Schneid (Kaiser, 2007). At Trolp and Grüne Schneid, it is characterized by more fine-grained micritic limestones – mud- and wackestones - when compared to under- and overlying beds which are pack- and floatstones. The 2nd faunal recovery phase are about time-equivalent to the return to full carbonate depositional conditions and continuing in the lower Tournaisian (middle *sulcata/kuehni* Zone, *Gattendorfia* level, 3rd faunal recovery phase). The onset of a distinctive decrease of $\delta^{13}C_{carb}$ values started in the *sulcata/kuehni* Zone at Trolp with the onset of the 2nd radiation phase, and can be correlated to numerous other settings in European, Asian and

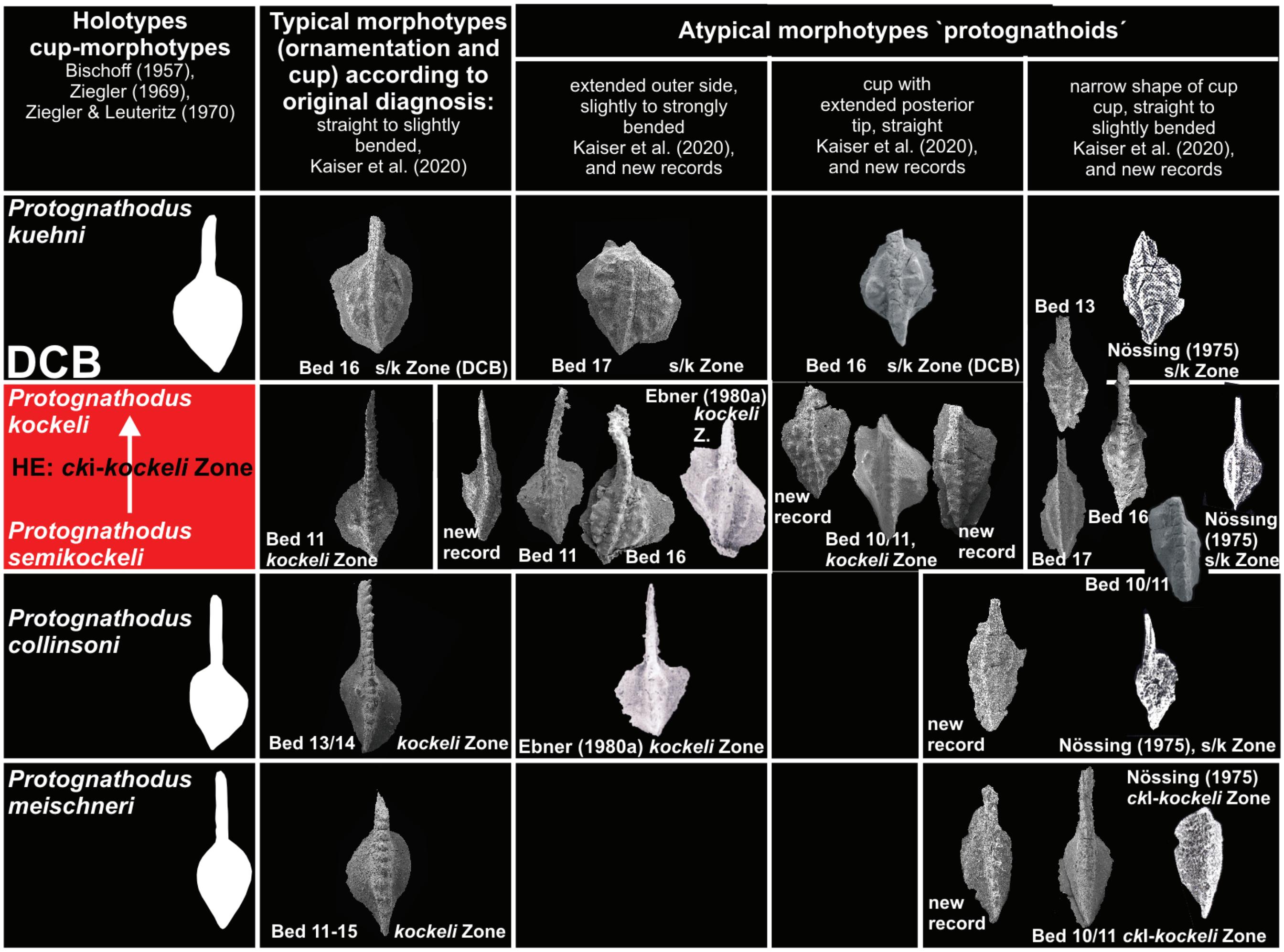

Figure 13 Conodont faunas from the DCB at Trolp. Typical and atypical (`protognathoids´) morphotypes of *Protognathodus* related to the shape of the cup and platform ornamentation. A high morphological complexity within *Protognathodus semikockeli* and *Protognathodus kockeli* (for diagnosis see Hartenfels et al. 2022) is evident from the Hangenberg Event (ckl-kockeli Zone). The `three-rows´ and `four-rows´ specimen related to the platform ornamentation are determined as *Protognathodus kockeli* (Hartenfels et al. 2022; Corradini et al. 2024), comparable to the record herein from Bed 16. Specimens from Beds 10, 11 (*ck*l, base of *kockeli* Zone) belong to *Protognathodus semikockeli* (`one-row´) or *Protognathodus kockeli* s.str. (`two-rows´) after Hartenfels et al. (2022). The advanced *Protognathodus kockeli* (4-rows-specimen from Puech de la Suque, Bed 16, collection S.Kaiser) figured in Corradini et al. (2024) originated from the *bransoni* or even *duplicata* Zone (compare Corradini *et al.* 2024, p. 24, 25).

North-American regions (see Section 4.1.3).

Between the 1st (base of *kockeli* Zone) and 2nd recovery phases, a short regressive episode (DCB regression) corresponds to significant survivor extinctions in ammonoids, brachiopods, trilobites and foraminifers at the end of the *kockeli* Zone to a roughly contemporaneous terrestrial extinction, and to abruptly decreasing carbon isotope values globally recorded (Figure 14; *e.g.*, Kaiser *et al.*, 2006, 2016). The level of the DCB regression enables a correlation of pelagic (conodonts, ammonoids) with shallow-water environments (brachiopods, corals, see review in Kaiser *et al.*, 2016), and can also be correlated into the terrestrial realm by the LN/VI miospore Zone boundary (*e.g.*, Clausen *et al.*, 1994). The DCB regression is indicated at Trolp by microfacies change from micritic limestones to bioclastic pack- to floatstones reported by Kaiser (2005) and Bojar *et al.* (2013, Figure 3c) although the latter authors assigned this level to the Upper *praesulcata* Zone based on the uncomplete conodont record as mentioned in Section 4.1.3.

The different morphotypes of *Siphonodella sulcata*, especially morphotypes 4 and 5, are globally widespread (see Section 4.2.3.1), and *Protognathodus kuehni* has a widespread geographic distribution which is reported in numerous studies from the *sulcata/kuehni* Zone (Corradini *et al.*, 2011; Kaiset *et al.*, 2020; see discussion in Hartenfels 2022). However, this taxon can have, as well as *Protognathodus kockeli*, a late entry, for example at the GSSP at La Serre É (*e.g.*, Flajs and Feist, 1988; Feist *et al.*, 2021). Therefore, the *sulcata/kuehni* Zone has a high global correlation potential and the FO´s of *Siphonodella sulcata* and *Protognathodus kuehni* can be correlated to many other regions globally (see Kaiser and Corradini, 2011; Corradini *et al.*, 2011; and extended references in Kaiser *et al.*, 2020; Königshof *et al.*, 2021; Qie *et al.*, 2021; Corradini *et al.*, 2021; Spalletta *et al.*, 2021; Kumpan *et al.*, 2021; Matyja *et al.*, 2021; Becker *et al.*, 2021; Feist *et al.*, 2021; Komatsu *et al.*, 2014). While the extended *kockeli* Zone leaves the event-related successions and the DCB undivided, as recently used for example at Grüne Schneid, La Serre E, and Milles (Feist *et al.*, 2021, Spalletta *et al.*, 2021; Aretz *et al.*, 2021; Figure 12), a precise conodont biozonation at the DCB can be applied by the use of *Siphonodella sulcata* M5 and *Protognathodus kuehni*.

At Trolp, the typical morphotype of *Protognathodus kuehni* and *Siphonodella sulcata* M5 first occur at same stratigraphic levels (Figure 10a, 12). Also, *Siphonodella sulcata* ?M4 was figured in Nössing (1975) in the basal *sulcata/kuehni* Zone. The *sulcata/kuehni* Zone can thus be established in the Graz Paleozoic, and at correlative levels in the Carnic Alps and Moravian Karst, based on the co-occurrence of both *Siphonodella sulcata* M5 and *Protognathodus kuehni* (Figure 12; Kalvoda *et al.*, 2015; Kaiser *et al.*, 2020; Kumpan *et al.*, 2021). Sampling of continuous limestone successions there supports the coeval FAD of both taxa at the base of the Tournaisian. After Kaiser *et al.* (2020), this supports the use of a joint biozone in event-related successions, because their co-occurrences are evidenced from these three different regions; the utility of a joint biozone enhances the possibility of using either the biostratigraphic index *Siphonodella sulcata* or *Protognathodus kuehni*, if one or the other has a late entry or is as yet unrecorded in a region due to facies-controlled rare or diachronous occurrences (*e.g.*, Kaiser *et al.*, 2009; Corradini *et al.*, 2011; Spalletta *et al.*, 2017).

4.2.3.1. CONSIDERATIONS OF SIPHONODELLA

Within siphonodellids, the abundance of intermediate forms attests to the completeness of the stratigraphic record as at La Serre É (Figure 12; between *Siphonodella praesulcata*, *Siphonodella sulcata* M4 and M5, and advanced siphonodellids); the differences between *Siphonodella praesulcata* and *Siphonodella sulcata* are stated in Sandberg *et al.* (1972). However, the occurrence of intermediate forms may have resulted in subjective determination of the first occurrence of *Siphonodella sulcata* (*e.g.*, Ziegler and Sandberg, 1996; Kaiser, 2009; Becker *et al.*, 2016a), but *Siphonodella*-morphotype groups can be clearly distinguished and recorded the spectrum of morphotypes and intermediates, which spread in the lower Tournaisian (Kaiser and Corradini, 2011). These groups are used to distinguish between *Siphonodella praesulcata* (M2, M3) and *Siphonodella sulcata* (M1, M4-M7), and also between early (M4, M5) and advanced forms (M1, M6, M7) of *Siphonodella sulcata*, the latter are recorded especially in younger Tournaisian successions at La Serre É (Kaiser and Corradini, 2011). The morphotype groups are based mainly on the curvature of the carina, a feature which had been used for the current GSSP level at La Serre É (Flajs and Feist, 1988, see also Sandberg *et al.*, 1972), as well as shape of the platform, a pseudokeel which contains a pit (basal cavity), and the ornamentation. *Siphonodella sulcata* Morphotype 4 already has slight constrictions anteriorly but is otherwise similar to *Siphonodella sulcata* M5. The *Siphonodella sulcata* M1, M6 and M7 are representatives of advanced forms, and are intermediates between *Siphonodella sulcata* and *Siphonodella bransoni* (former *Siphonodella duplicata* M1) because they are strongly bended and have constrictions anteriorly.

Siphonodella sulcata M4 and M5 are easy to recognize, most widespread, and common in North America, Asia, and Europe (Figure 12, Kaiser and Corradini, 2011, figure 7; see Kaiser *et al.* 2020). The globally most widespread *Siphonodella sulcata* M5 is the earliest morphotype which occur at the base of the Tournaisian, for example at Trolp, Grüne Schneid (Kaiser *et al.*, 2020), La Serre É (Kaiser, 2009; Kaiser and Corradini, 2011; Feist *et al.*, 2021), Lalla Mimouna (Anti-Atlas, Morocco, Becker *et al.*, 2013), Lesni Lom (Moravian Karst, Czech Republic; Kalvoda *et al.*, 2015), Kowala (together with *Protognathodus kuehni* and *Polygnathus purus subplanus*, Holy Cross Mountains, Poland; Malec, 2014; Matyja *et al.*, 2021), Borkewehr (Rhenish Massif, Hartenfels *et al.*, 2022). *Siphonodella sulcata* M4 was found in lower Tournaisian successions, for example at Bou Tlidat (Maider, Anti-Atlas, Morocco; collection S.I. Kaiser; see Kaiser *et al.*, 2011; Becker and Kaiser, 2023), Mighan (Alborz Mts. northern Iran, Parvizi *et al.*, 2021) and at Shahmirzad (Alborz Mts.; Habibi *et al.*, 2008). *Siphonodella sulcata* M4 evolved from *Siphonodella sulcata* M5 based on the record at La Serre É, and represents most probably the marker for the 3rd radiation phase in the *sulcata/kuehni* Zone at the *Gattendorfia* level (*sulcata* Event). *Siphonodella bransoni* is also recorded from successions at M´Karig, Tafilalt, Anti-Atlas (collection S.I. Kaiser; see Kaiser *et al.*, 2011; Becker and Kaiser, 2023). For the occurrence of *Siphonodella praesulcata* in neritic settings in Morocco, Iran, China, Vietnam, see Kaiser (2005), Kaiser *et al.* (2011), Becker *et al.* (2013), Komatsu *et al.* (2014), Parvizi *et al.* (2021), Bahrami *et al.* (2021), Qie *et al.* (2021). In shallow-water settings at Gedongguan, Muhua, Nanbiancun and Dapoushang (South China), *Siphonodella sulcata* occurs, also in association with *Protognathodus kuehni*, at the base of the Tournaisian (Qie *et al.*, 2021), and *Siphonodella sulcata* is also reported from shallow-water settings for example from northeastern Vietnam (Komatsu *et al.*, 2014). In summary, siphonodellids also occur in neritic successions, and the *sulcata/kuehni* Zone can be established in pelagic, hemipelagic and neritic settings based on *Siphonodella sulcata* and/or *Protognathodus kuehni*. However, an evaluation of various records from different paleogeographical settings of the earliest Morphotype 5 and Morphotype 4 of *Siphonodella sulcata* at the base of the Tournaisian is needed (*e.g.*, Becker *et al.*, 1984; Qie *et al.*, 2021; Komatsu *et al.*, 2014; Matyja *et al.*, 2021, Hartenfels *et al.*, 2022; see also Aretz *et al.*, 2021, and references therein).

Siphonodella sulcata M4 and M5 can be clearly distinguished from *Siphonodella praesulcata*, from the late siphonodellids (see Section 4.2.2.1), and from *Siphonodella*-like `siphonodelloids´; the latter have overlapping ranges with *Siphonodella praesulcata* mainly in the *praesulcata* Zone, as documented *e.g.*, in Becker *et al.* (2013). The `siphonodelloids´ originated and evolved in pre-Hangenberg event levels in the *expansa* Zone probably connected with enhanced C_{org} burial phases and/or shallowing phases during the Epinette and Etreoungt Events (for environmental changes during the events see Kaiser *et al.*, 2008), and spread in the *praesulcata*

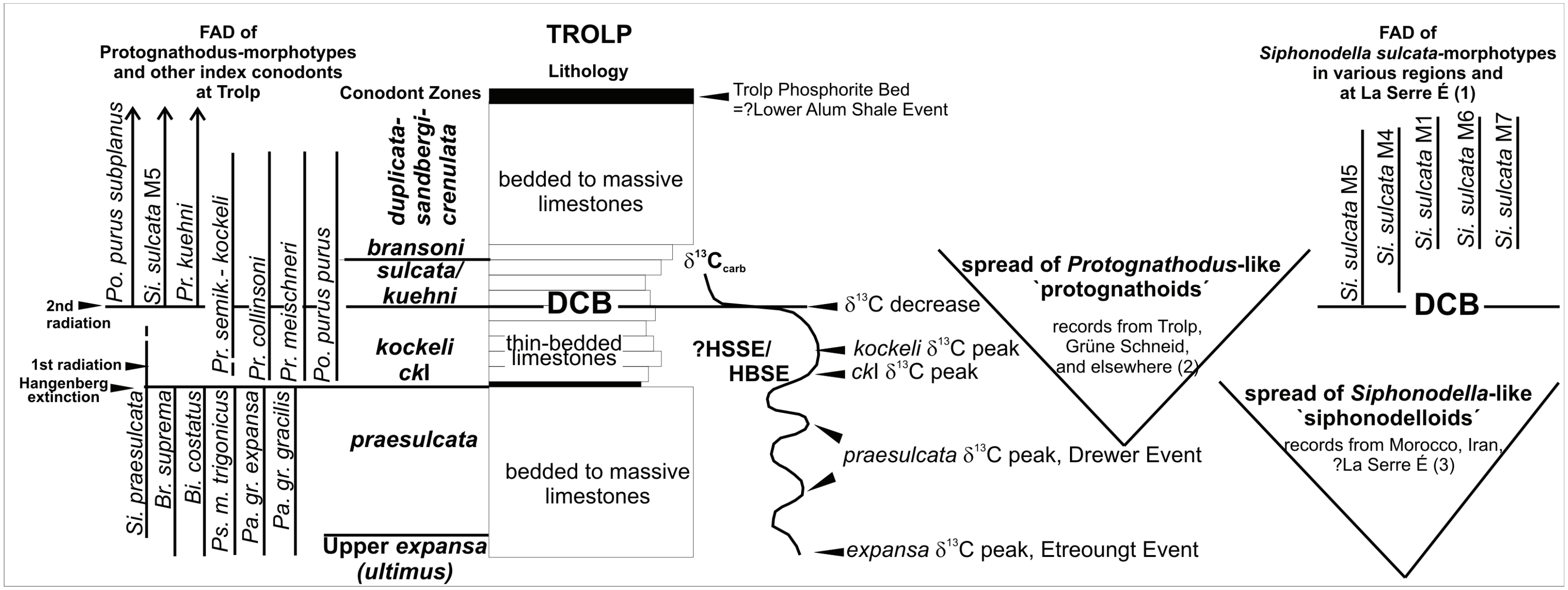

Figure 14 Schematic overview of bio- litho- and chemostratigraphic markers at Trolp in the western Graz Paleozoic. (1) Kaiser and Corradini (2011, and references), (2) Kaiser *et al.* (2020, and references), (3) Becker *et al.* (2013), Parvizi *et al.* (2021), S.I. Kaiser (2019, ***unpublished data***). ***Si.* = *Siphonodella*, *Po.* = *Polygnathus*, *Ps.* = *Pseudopolygnathus*, *Bi.* = *Bispathodus*, *Br.* = *Branmehla*, *Pa.* = *Palmatolepis*, *Me* = *Mehlina*, *M* = *morphotype*, *ckl* = *costatus-kockeli*** Interregnum.

Zone; its occurrence is related to biotic opportunism comparable with the spread of `protognathoids´ during the Hangenberg Event (Figure 14). `Siphonodelloids´ are most widespread in hemipelagic or shallow-water settings, for example in Morocco (*e.g.*, Becker *et al.*, 2013), Iran (*e.g.*, Parvizi *et al.*, 2021), and probably at La Serre É (Figure 14).

5. Summary

Characteristic lithologic, chemo- and biostratigraphic markers at the DCB in the western Graz Paleozoic are well displayed at the famous Trolp section in the Steinberg area. Geochemical and lithologic characteristics, conodont extinctions, the end of mass extinctions and radiations, and the coeval FO of index conodonts are recognized at Trolp. These characteristic markers can be easily correlated globally, and afford the possibility for correlations into the pelagic, hemipelagic and neritic realms.

A hiatus is unlikely at Trolp. This is supported by the complete record of conodont zones during the Hangenberg Crisis, the abundance of intermediate forms which attests to the completeness of the conodont stratigraphic record, and by the absence of an erosional (sedimentary) gap. Conodonts are abundant and enable a high-resolution conodont stratigraphy, and radiation and extinction events are well recorded. The main Hangenberg extinction level in the former Middle *praesulcata* Zone (*costatus-kockeli* Interregnum = *ck*I) is easily recognized at the base of thin-bedded limestones, and is accompanied by a succeeding major conodont biofacies change and an impoverished and stunted *Polygnathus*-*Protognathodus* fauna. The index conodonts *Siphonodella praesulcata* and *Siphonodella sulcata* occur in the DCB beds at Trolp together with the early *Protognathodus* fauna (*Protognathodus meischneri*, *Protognathodus collinsoni*, *Protognathodus* semi*kockeli*, *Protognathodus kockeli*, *Protognathodus kuehni*) in the continuous, thinly bedded limestone succession.

The DCB at Trolp is recognized by the first occurrence of both *Protognathodus kuehni* and *Siphonodella sulcata* M5 at same stratigraphic level and document the start of the *sulcata/kuehni* Zone. The supplementary diagnostic conodont fauna for the Lower Carboniferous, *Polygnathus purus subplanus* first appears at this level, too. *Siphonodella sulcata* Morphotype 5 and *Protognathodus kuehni* have a high correlation potential and a congruent FAD which can be used for defining the start of the joint *sulcata/kuehni* Zone; their phyletic lineages can be reconstructed in several regions. Thus, the use of the earliest morphotypes of *Siphonodella sulcata* M5 - and probably of *Siphonodella sulcata* M4 - and of *Protognathodus kuehni*, contribute to global correlations and biozonations. Morphotype 5 and Morphotype 4 are the earliest *Siphonodella sulcata*-morphotype to occur widely in Europe, North-Africa, Asia and North America at the base of the Tournaisian, without noteworthy overlapping ranges with `siphonodelloids´ (Figure 14).

A well-exposed succession of the early *Protognathodus* fauna, and the earliest morphotypes of *Protognathodus meischneri*, *Protognathodus collinsoni*, *Protognathodus semikockeli*, *Protognathodus kockeli*, and *Protognathodus kuehni* are recorded at Trolp. However, atypical `*Protognathodus*´ morphotypes – proposed herein as *Protognathodus*-like `protognathoids´ - regarding diagnostic features of the cup and ornamentation of the platform (Figure 13) and partly evaluated by Hartenfels *et al.* (2022) - occur at Trolp and elsewhere around the DCB. Comparable with the *Siphonodella*-like `siphonodelloids´ which evolve and spread during late Famennian environmental changes in the *expansa* and *praesulcata* Zones connecting with the Epinette/Etreoungt and Drewer Events, the atypical morphotypes evolved and spread somewhat later, during late/latest Famennian and earliest Tournaisian environmental changes connecting with the Drewer Event in the *praesulcata* Zone (early phase of the Hangenberg Event) and in the *ck*I and *kockeli* Zone connecting with the middle and late phase of the Hangenberg Event (Figure 14). The record of their precise stratigraphic and distributional pattern is important for future evaluation of phylogenetics because ancestor and descendent relationships of this faunal group are still unclear. Also, homeomorphy between the early and late protognathodids, gnathodids, and bispathodids, and a high morphological spectrum within the genera, could produce a bias of the conodont record in event-related successions. This is especially important due to overlapping ranges between these faunal groups at the DCB as well as in the Tournaisian. Thus, the extended *kockeli* Zone and the use of *Protognathodus kockeli* proposed recently as index fossil for the DCB, raises more questions than answers. The extinction-based *ck*I (HBSE), and the base of the former *kockeli* Zone (= Upper *praesulcata* Zone) are, however, needed for a precise biozonation scheme.

Carbon isotopes ($\delta^{13}C_{carb}$) at Trolp show characteristic positive excursions and trends in the early, middle and late phases of the Hangenberg Crisis that can be readily correlated to many other regions worldwide. Accordingly, two positive $\delta^{13}C_{carb}$ peaks in the *praesulcata* Zone represents C_{org} burial episodes of the early Hangenberg phase (Drewer Event). The onset of a distinctive positive carbon isotope excursion in the early/middle Hangenberg phase correlates with the initial conodont mass extinction episode (*ck*I) of the Hangenberg Crisis during globally widespread deposition of black shales (HBS), which precedes the main regressive episode during globally widespread deposition of regressive sandstones (HSS). This main anoxic episode of the Hangenberg Crisis (HBSE) is recorded in the thinly bedded limestone succession, and its onset may recorded in a locally developed thin shaly layer at the base of this succession. Because the pelagic fossil record of the regressive phase (HSSE) is generally unknown due to globally widespread, conodont-poor siliciclastics, stratigraphic gaps, it is recently unclear whether the main regressive phase of the Hangenberg Crisis is recorded in the thinly bedded limestone succession and needs further studies. The positive carbon isotope excursion in the late Hangenberg phase (*kockeli* Zone) at Trolp is time-equivalent to the first post-extinction recovery phase; the onset of a distinctive decrease of carbon isotope values in the *sulcata/kuehni* Zone is coeval with the second conodont radiation phase; it can be correlated with same trends in many other successions worldwide.

5. Conclusions

The western Graz Paleozoic is of global significance because the phases of the Hangenberg Crisis at the DCB can be well reconstructed in continuous limestone successions at Trolp, and significant markers in bio,- litho- and chemostratigraphy can be well correlated outside the region. Conodont extinctions (*costatus-kockeli* Interregnum), conodont radiations and end of mass extinctions can be recognized at Trolp. The earliest morphotypes of *Siphonodella sulcata* M5, as well as of *Protognathodus meischneri*, *Protognathodus collinsoni*, *Protognathodus* semi*kockeli*, *Protognathodus kockeli* and *Protognathodus kuehni* are recorded at Trolp. The globally common *Siphonodella sulcata* Morphotype 5 and Morphotype 4, as well as *Protognathodus kuehni*, have a high correlation potential worldwide and can be used for the joint *sulcata/kuehni* Zone; their phyletic lineages can be reconstructed from many regions.

Due to the spread of atypical morphotypes of *Protognathodus* (´protognathoids´) at the DCB and in the Tournaisian related to the Hangenberg Event can be regarded as `bottleneck´ for the evolution of this faunal group. The previously suggested extended *kockeli* Zone and the recently proposed use of *Protognathodus kockeli* as index fossil for the DCB are not applicable due to the spread of these still unknown atypical morphotypes, and due to their unknown stratigraphic and distributional pattern and overlapping ranges with other homeomorphic groups. Also, the use of the extended *kockeli* Zone and the exceptional increasing amounts of morphological complex faunas especially among *Protognathodus kockeli* biased the conodont record and leaves the DCB and the Hangenberg event-related successions undivided. A conodont biozonation scheme with a fine-stratigraphic subdivision, however, is needed for multidisciplinary, high-resolution studies at the DCB. A strict biozonation and taxonomic concept enables further insights into the first-order Hangenberg mass extinction, also in respect to the age of the enigmatic end-Devonian glaciation. The loss of biozones in Hangenberg Event-related successions would present a potential loss of information and would throwback the scientific affords and progresses for several decades back.

Contributions of authors

(1) Conceptualization: SIK; (2) Analysis or data acquisition: SIK, BH; (3) Methodologic/technical development: SIK; (4) Writing of the original manuscript: SIK, BH; (5) Writing of the corrected and edited manuscript: SIK, BH; (6) Graphic design: SIK, BH; (7) Fieldwork: SIK, BH; (8) Interpretation: SIK, BH; (9) Financing: BH.

Financing

This research did not receive any specific grant from funding agencies in the public, commercial, or non-profit sectors.

Acknowledgements

Thanks go to G.W. Rasser and F. Ebner for their support in field work at Trolp, to C. Gasco (SMNS) for SEM records, and to A. Bahrami and P. Isaacson for their helpful comments and suggestions for the manuscript, and to the late C. Sandberg, W. Qie and M. Aretz for the review of the former version of the manuscript.

Conflict of interest

There is no conflict of interest

Handling editor

Ali Bahrami.

References

Algeo, T.J., Berner, R.A., Maynard, J.B., Scheckler, S.E., 1995, Late Devonian Anoxic Events and Biotic Crises: “Rooted“ in the Evolution of Vascular Land Plants: GSA Today, 5(3), 45, 62-66.

Algeo, T.J., Shen, J., 2024, Theory and classification of mass extinction causation: National Science Review, 11(1), 1-21. http://doi.org/10.1093/nsr/nwad237

Aretz, M., Corradini, C., 2021, Global review of the Devonian-Carboniferous Boundary: an introduction: Palaeobiodiversity and Palaeoenvironments, 101, 285-293. https://doi.org/10.1007/s12549-021-00499-8

Aretz, M., Corradini, C., Denayer, J., 2021. The Devonian-Carboniferous Boundary around the globe: a complement. Palaeobiodiversity and Palaeoenvironments, 101(2), 633-662. https://doi.org/10.1007/s12549-021-00495-y

Bábek, O., Kumpan, T., Kalvoda, J., Gryga, T.M., 2016, Devonian/Carboniferous boundary glacioeustatic fluctuations in a platform-to-basin direction: A geochemical approach of sequence stratigraphy in pelagic settings: Sedimentary Geology, 337, 81-99. https://doi.org/10.1016/j.sedgeo.2016.03.009

Bahrami, A., Corradini, C., Over, D. J., Yazdi, M., 2011, Upper Devonian-Lower Carboniferous conodont biostratigraphy in the Shotori Range, Tabas area, Central-East Iran microplate: Bollettino della Società Paleontologica Italiana, 50(1), 35–53.

Bahrami, A., Königshof, P., Hartkopf-Fröder, C., Kaiser, S.I., 2021, Late Devonian–Mississippian conodont biostratigraphy of the Chelcheli section, NE Shahrud (Eastern Alborz, North Iran): PalZ, Paläontologische Zeitschrift, 96, 449-469. https://doi.org.10.1007/s12542-021-00575-6

Becker, R.T., 1993a, Anoxia, eustatic changes, and Upper Devonian to Lowermost Carboniferous global ammonoid diversity, in House, M.R. (ed.), The Ammonoidea: Environment, ecology, and evolutionary change. The Systematics Association Special Volume, 47: Oxford, Clarendon Press, 105-164

Becker, R.T., 1993b, Analysis of ammonoid palaeobiogeography in relation to the global Hangenberg (terminal Devonian) and Lower Alum Shale (Middle Tournaisian) events: Annales de la Société Géologique de Belgique, 115(2), 459-473.

Becker, R.T., Kaiser, S.I., 2023, The Devonian-Carboniferous Boundary in Morocco: Review and test of the "Devonian-Carboniferous Boundary calendar" of the International DCB Task Group: International Union of Geological Sciences Commission on Stratigraphy, Subcommission on Devonian Stratigraphy Newsletter, 38, 47-66.

Becker, R.T., Bless, M.J.M., Brauckmann, C., Friman, L., Higgs, K., Keupp, H., Korn, D., Langer, W., Paproth, E., Racheboeuf, P., Stoppel, D., Streel, M., Zakowa, H., 1984, Hasselbachtal, the section best displaying the Devonian-Carboniferous boundary beds in the Rhenish Massif (Rheinisches Schiefergebirge): Courier Forschungs-Institut Senckenberg, 67, 181-191.

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 Becker, R.T., El Hassani, A., Tahiri, A. (eds.), Field Guidebook, International Field Symposium "The Devonian and Carboniferous of Northern Gondwana" Document de l'Institut Scientifique Rabat, 27, 109-120.

Becker, R.T., Kaiser, S.I., Aretz, M., 2016a, Review of chrono-, litho- and biostratigraphy across the global Hangenberg Crisis and Devonian–Carboniferous Boundary, in: Becker, R.T., Königshof, R., Brett, C.E. (eds.), Devonian Climate, Sea Level and Evolutionary Events: Geological Society, London, Special Publications, 423, 355-386.

Becker, R.T., Hartenfels, S., Weyer, D., Kumpan, T., 2016b, The Famennian to Lower Viséan at Drewer (northern Rhenish Massif): Münstersche Forschungen zur Geologie und Paläontologie, 108, 158-178.

Becker, R.T., Hartenfels, S., Kaiser, S.I., 2021, Review of Devonian-Carboniferous Boundary sections in the Rhenish Slate Maontains (Germany): Palaeobiodiversity and Palaeoenvironments 101(2), 357-420. https://doi.org/10.1007/s12549-020-00469-6

Bischoff, G., 1957, Die Conodonten-Stratigraphie des rheno-herzynischen Unterkarbons mit Berücksichtigung der Wocklumeria-Stufe und der Devon/Karbon-Grenze: Abhandlungen des Hessischen Landesamtes für Bodenforschung, 19, 64 p.

Bojar, A.V., Neubauer, F., Koeberl, Ch., 2013, Geochemical record of Late Devonian to Early Carboniferous events, Palaeozoic of Graz, Eastern Alps, Austria, in: Gasiewicz, A., Slowakiewicz, M. (eds.), Palaeozoic Climate Cycles: Their Evolutionary and Sedimentological Impact: Geological Society London, Special Publication 376, 87–108. https://doi-org.pbidi.unam.mx:2443/10.1144/SP376.15

Bosic, R., 1998, *Gnathodus* praebilineatus aus dem Lydithorizont der Oberen Sanzenkogel Formation (Karbon, Grazer Paläozoikum): Mitteilungen der Abteilung für Geologie und Paläontologie, Landesmuseum Joanneum 56, 351-365.

Bosic, R., 1999. Zur Conodonten-Stratigraphie der Oberen Sanzenkogel Formation (Karbon, Grazer Paläozoikum): Geologica et Palaeontologica 33, 167-189.

Brezinski, D.K., Cecil, C.B., Skema, V.W., Kertis, C.A., 2009, Evidence for long-term climate change in Upper Devonian strata of the central Appalachians: Palaeogeography, Palaeoclimatology, Palaeoecology 284(3-4), 315–325. https://doi.org/10.1016/j.

palaeo.2009.10.010

Buchroithner, M.F., Ebner, F., 1981, Conodont Zonation and Biofacies within the European Part of the Alpine Mediterranean Mountain Belts: IGCP Project No. 5 Newsletter, 3, 35-37.

Buchroithner, M.F, Ebner, F., Surenian, R., 1979, Die Entwicklung der Steinbergkalke (Oberdevon, Grazer Paläozoikum) an ihrer Typuslokalität: Mitteilungen des naturwissenschaftlichen Vereines für Steiermark 109, 71-84.

Clausen, C.-D., Korn, D., Feist, R., Leuschner, K., Groos-Uffenorde, H., Luppold, F.W., Stoppel, D., Higgs, K., Streel, M., 1994. Die Devon/Karbon-Grenze bei Stockum (Rheinisches Schiefergebirge). Geologie und Paläontologie von Westfalen 29, 71-95.

Corradini, C., Kaiser, S.I., Perri, M.C., Spalletta, C., 2011, Conodont genus *Protognathodus* and its potential as a tool for defining the Devonian/Carboniferous boundary: Rivista Italiana di Paleontologia e Stratigrafia, 117(1), 15-28. https://doi.org/10.13130/2039-4942/5960

Corradini, C., Schönlaub, H.P., Kaiser, S.I., 2017a, The Devoninain/Carboniferous boundary in the Grüne Schneid Section: Berliner Institut für Erdwissenschaften, Karl-Franzens-Universität Graz, 23, 271-275.

Corradini, C., Spalletta, C., Mossoni, A., Matyja, H., Over, D.J., 2017b, Conodonts across the Devonian/Carboniferous boundary: a review and implication for the redefinition of the boundary and a proposal for an updated conodont zonation: Geological Magazine,154(4), 888-982. https://doi.org/10.1017/s001675681600039x

Corradini, C., Mossoni, A., Corriga, M.G., Spalletta, C., 2021, The Devonian/Carboniferous boundary in Sardinia (Italy): Palaeobiodiversity and Palaeoenvironments, 101(2), 507-514. https://doi.org/10.1007/s12549-019-00411-5

Corradini, C., Henderson, C., Barrick, J.E., Ferretti, A., 2024, Conodonts in Biostratigraphy. A 300-million-years long journey through geologic time: Newsletters on Stratigraphy. https://doi.org/10.1127/nos/2024/0822

Cramer, B.D., Saltzman, M.R., Day, J.E., Witzke, B.J., 2008. Record of the Late Devonian Hangenberg global positive carbon-isotope excursion in an epeiric sea setting: carbonate production, organic-carbon burial and paleoceanography during the Late Famennian: Special paper. Geological Association of Canada, 48, 103–118.

Cygan, C., Perret, M.F., 2002, Conodonts from the Upper Devonian-Lower Carboniferous succession of Milles (Arize Massif), in Pyrenees FieldTrip, Guidebook, ECOS VIII, France-Spain.

Di Pasquo, M., Grader, G.W., Kondas, M., Doughty, P.T., Filipiak, P., Rice, B.J., Isaacson, P.E., 2019, Lower Sappington Formation palynofacies in Montana confirm Upper Famennian black shale paleoenvironments and sequences across western North America: Palaeogeography, Palaeoclimatology, Palaeoecology, 536, 109370, 1-19. https://doi.org/10.1016/j.palaeo.2019.109370

Dreesen, R., Sandberg, C.A., Ziegler, W., 1986. Review of Late Devonian and early Carboniferous conodont biostratigraphy and biofacies models as applied to the Ardenne shelf (Belgique): Annales de la Société géologique de Belgique, 109(1), 27-42.

Dzik, J., 1997, Emergence and succession of Carboniferous conodont and ammonoid communities in the Polish part of the Variscan sea: Acta Palaeontologica Polonica, 42(1), 57-170.

Dzik J., 2006, The Famennian "Golden Age" of conodonts and ammonoids in the Polish part of the Variscan Sea: Palaeontologia Polonica, 63, 1–359.

Ebner, F., 1976a, Das Silur/Devon-Vorkommen von Eggenfeld - ein Beitrag zur Biostratigraphie des Grazer Paläozoikums: Mitteilungen der Abteilung für Geologie, Paläontologie und

Bergbau am Landesmuseum, 37, 3-33.

Ebner, F., 1976b. Die Schichtfolge an der Wende Unterkarbon/Oberkarbon in der Rannach-Fazies des Grazer Paläozoikums. Verhandlungen der Geologischen Bundesanstalt A, 2, 65-93.

Ebner, F., 1977a. Die Gliederung des Karbons von Graz mit Conodonten. Jahrbuch der Geologischen Bundesanstalt A., 120(2), 449-493.

Ebner, F., 1977b. Die Transgression der Folge der Dult (Oberkarbon, Paläozoikum von Graz). Mitteilungen des naturwissenschaftlichen Vereines für Steiermark 107, 35-53.

Ebner, F., 1978. Stratigraphie des Karbon der Rannachfazies im Paläozoikum von Graz, Osterreich: Mitteilungen der Österreichischen Geologischen Gesellschaft, 69, 163-196.

Ebner, F., 1980a, Conodont localities in the surroundings of Graz/Styria: Abhandlungen der Geologischen Bundesanstalt, 35, 101-127.

Ebner, F., 1980b, Steinbergkalke und Sanzenkogel-Schichten im Kalvarienbergzug W von Gratwein: Mitteilungen des naturwissenschaftlichen Vereines für Steiermark, 110, 47–53.

Ebner, F., 1998, Das Paläozoikum auf ÖK-Blatt 163 Voitsberg: Mitteilungen des Referates für Geologie und Paläontologie am Landesmuseum Joanneum, 2, 111-136.

Ebner, F., Prochaska, W., 1989, Geochemical characterization of Carboniferous sedimentary rocks within the Rannach-Group of the Paleozoic of Graz (Eastern Alps, Austria): Geological Society of Greece, Special Publications, 1, 23-33.

Ebner, F., Rantitsch, G., 2000, Das Gosaubecken von Kainach – ein Überblick: The late crecaceous Kainach Gosau Basin, an overview: Mitteilungen der Gesellschaft für Geologie- und Bergbaustudenten Österreichs, 44, 157-172.

Ebner, F., Hubmann, B., 2012, The Rannach Facies of the Graz Palaeozoic (Eastern Alps, Austria): Field Trip Guide, 29th IAS Meeting of Sedimentology, Schladming: Journal of Alpine Geology, 54, 145-187.

Ebner, F., Hubmann, B., Weber, L., 2000, Die Rannach- und Schöckel-Decke des Grazer Paläozoikums: Mitteilungen der Gesellschaft der Geologie und Bergbaustudenten Österreichs, 44, 1-44.

Feist, R., Cornée, J.-J., Corradini, C., Hartenfels, S., Aretz, M., Girard, C., 2021, The Devonian-Carboniferous boundary in the stratotype area (SE Montagne Noire, France): Palaeobiodiversity and Palaeoenvironments, 101(2), 295-311. https://doi.org/10.1007/s12549-019-00402-6

Flajs, G., 1966, Conodonten stratigraphische Untersuchungen im Raum von Eisenerz., Nördliche Grauwackenzone: Mitteilungen der Geologische Gesellschaft in Wien 59(2), 157-212.

Flajs, G., Feist, R., 1988, Index conodonts, trilobites and environment of the Devonian-Carboniferous boundary beds at La Serre (Montagne Noire, France): Courier Forschungsinstitut Senckenberg, 100, 53-107.

Flügel, H.W., 2000, Die lithostratigraphische Gliederung des Paläozoikums von Graz (Österreich), in Flügel, H.W. and Hubmann, B., Das Paläozoikum von Graz: Stratigraphie und Bibliographie, band 13: Wien, Verlag derÖsterreichischen Akademie der Wissenschaften, 7-59.

Flügel, H., Ziegler, W., 1957, Die Gliederung des Oberdevons und Unterkarbons am Steinberg westlich von Graz mit Conodonten. Mitteilungen des naturwissenschaftlichen Vereines für Steiermark 87, 25-60.

Gasser, D., Stüwe, K., Fritz, H., 2010, Internal structural geometry of the Paleozoic of Graz. International Journal of Earth Sciences 99, 1067-1081. https://doi.org/10.1007/s00531-009-0446-0

Gross, M., Fritz, I., Piller, W.E., Soliman, A., Harzhauser, M., Hubmann, B., Moser, B., Scholger, R., Suttner, T.J., Bojar, H.P., 2007, The Neogene of the Styrian Basin - Guide to Excursions: Joannea - Geologie und Paläontologie, 9, 117-193.

Habibi, T., Corradini, C., Yazdi, M., 2008, Famennian-Tournaisian conodont biostratigraphy of the Shahmirzad section, central Alborz, Iran: Geobios, 41, 763–777.

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: Munster, Verlaghaus Monsenstein und Vannerdat, Münstersche Forschungen zur Geologie und Paläontologie 105, 17–527.

Hartenfels, S., Becker, R.T., 2016, Age and correlation of the transgressive Gonioclymenia Limestone (Famennian, Tafilalt, eastern Anti-Atlas, Morocco): Geological Magazine, 155(3), 586-629. https://doi.org/10.1017/S0016756816000893

Hartenfels, S., Becker, R.T., Herbig, H.-G., Qie, W., Kumpan, T., De Vleeschouwer, D., Weyer, D., Kalvoda, J., 2022, The Devonian-Carboniferous transition at Borkewehr near Wocklum (northern Rhenish Massif, Germany) – a potential GSSP section: Palaeobiodiversity and Palaeoenvironments, 102, 763-829. http://doi.org/10.1007/s12549-022-00531-5

Histon, K., Hubmann, B., Messner, F., 2010, A preliminary study of the upper Silurian nautiloid cephalopods from the Eggenfeld section (Graz Paleozoic, Austria): Bollettino della Società Paleontologica Italiana, 49(1), 65-74.

Hubmann, B., Hasenhüttl, C., 1995, Zur Entwicklung der hohen Deckengruppe des Grazer Paläozoikums. Exkursionspunkte zu ausgewählten Profilen: Exkursionsführer zur 2. Tagung Österreichischen Paläontologischen Gesellschaft, 1-43, Graz.

Hubmann, B., Pohler, S., Schönlaub, H.-P., Messner, F., 2003, Paleozoic coral-sponge bearing successions in Austria: Berichte der Geologischen Bundesanstalt, 61, 1-92.

Hubmann, B., Ebner, F., Ferretti, A., Histon, K., Kido, E., Krainer, Neubauer, F.; Schönlaub, H. P., Suttner, T. J., 2013, The Paleozoic Era(them): Abhandlungen der Geologischen Bundesanstalt, 66(9), 9-133.

Isaacson, P.E., Díaz-Martínez, E., Grader, G.W., Kalvoda, J., Babek, O., Devuyst, F.X., 2008, Late Devonian–earliest Mississippian glaciation in Gondwanaland and its biogeographic consequences: Palaeogeography, Palaeoclimatology, Palaeoecology, 268(3-4), 126-142. https://doi.org/10.1016/j.palaeo.2008.03.047

Ji, Q., Wang, Z., Sheng, H., Hou, J., Feng, R., Wei, J., Wang, S., Wang, H., Xiang, L., Fu, G., 1989, The Dapoushang Section. An Excellent Section for the Devonian-Carboniferous Boundary Stratotype in China: Beijing, China, Science Press, 165 pp.

Johnson, J.G., Klapper, G., Sandberg, C.A., 1985, Devonian eustatic fluctuations in Euramerica. Geological Society of America Bulletin, 96(5), 567-587. https://doi.org/10.1130/0016-7606(1985)96<567:DEFIE>2.0.CO;2

Kaiser, S.I., 2005, Mass extinctions, climatic and oceanographic changes at the Devonian-Carboniferous boundary: Germany, Ruhr-Universität Bochum, Fakultät für Geowissenschaften, doctoral thesis, 156 p.

Kaiser, S.I., 2007, Conodontenstratigraphie und Geochemie (δ13Ccarb, δ13Corg, δ18Ophosph) aus dem Devon-Karbon Grenzbereich der Karnischen Alpen: Jahrbuch der Geologischen Bundesanstalt, 146, 301-314.

Kaiser, S.I., 2009, The Devonian/Carboniferous stratotype section La Serre (Montagne Noire) revisited: Newsletters on Stratigraphy, 43(2), 195-205. https://doi.org/10.1127/0078-0421/2009/0043-0195

Kaiser, S.I., Corradini, C., 2011, The

early siphonodellids (Conodonta, Late Devonian-Early Carboniferous): overview and taxonomic state: Neues Jahrbuch für Geologie und Paläontologie. Abhandlungen, 261(1), 19-35. https://doi.org/10.1127/0077-7749/2011/0144

Kaiser, S.I., Steuber, T., Becker, R.T., Joachimski, M.M., 2006, Geochemical evidence for major environmental change at the Devonian–Carboniferous boundary in the Carnic Alps and the Rhenish Massif: Palaeogeography, Palaeoclimatology, Palaeoecology, 240(1-2), 146–160. https://doi.org/10.1016/j.palaeo.2006.03.048

Kaiser, S.I., Becker , R.T., El Hassani, A., 2007, Middle to Late Famennian successions at Ain Jemaa (Moroccan Meseta) – implications for regional correlation, event stratigraphy and synsedimentary tectonics of NW Gondwana: Geological Society of London, Special Publications, 278(1), 237-260. https://doi.org/10.1144/sp278.11

Kaiser, S.I., Steuber, T., Becker, R.T., 2008, Environmental change during the Late Famennian and Early Tournaisian (Late Devonian – Early Carboniferous) – implications from stable isotopes and conodont biofacies in southern Europe: Geological Journal, 43(2-3), 241–260. https://doi.org/10.1002/gj.1111

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, in Palaeontographica Americana. Studies in Devonian Stratigraphy: Proceedings of the 2007 International Meeting of the Subcommission on Devonian Stratigraphy and IGCP 499: Lawrence, Kansas, Allen Press, 99-143.

Kaiser, S.I., Becker, R.T., Steuber, T., Aboussalam, Z.S., 2011, Climate-controlled mass extinctions, facies, and sea-level changes around the Devonian-Carboniferous boundary in the eastern Anti-Atlas (SE Morocco): Palaeogeography, Palaeoclimatology, Palaeoecology, 310(3-4), 340-364. https://doi.org/10.1016/j.palaeo.2011.07.026

Kaiser, S.I., Becker, R.T., Hartenfels, S., Aboussalam, Z.S., 2013. The Middle Fammennian/Middle Tournaisian at El Atrous, Morocco. Document de L'Institut Scientifique, Rabat, 27, 77-86.

Kaiser, S.I., Aretz, M., Becker, R.T., 2016, The global Hangenberg Crisis (Devonian-Carboniferous transition) – review of a first order mass extinction, in Becker, R.T., Königshof, R., Brett, C.E. (eds.), Devonian Climate, Sea Level and Evolutionary Events, Geological Society, London, Special Publications, 423, 1-51. https://doi.org/10.1144/sp423.9

Kaiser, S.I., Kumpan, T., Cígler, V., 2017, New unornamented siphonodellids (Conodonta) of the lower Tournaisian from the Rhenish Massif and Moravian Karst (Germany and Czech Republic): Neues Jahrbuch für Geologie und Paläontologie, 286(1), 1–33. https://doi.org/10.1127/njgpa/2017/0684

Kaiser, S.I., Becker, R.T., Hartenfels, S., Aboussalam, Z.S., 2018, The global Hangenberg Crisis and Lower Alum Shale Event at El Atrous (southern Tafilalt Platform): Münstersche Forschungen zur Geologie und Paläontologie, 110, 327-338.

Kaiser, S.I., Rasser, M.W., Schönlaub, H.P., Hubmann, B., Sandberg, C.A., Streel, M., Bahrami, A., Yazdi, M., Paproth, E., Kumpan, T., 2019, The Hangenberg Crisis at the Devonian-Carboniferous boundary (DCB) – a "bottleneck" for conodonts: Kölner Forum Geologie und Paläontologie, 23, 1-345.

Kaiser, S.I., Kumpan, T., Rasser, M.W., 2020, High-resolution conodont biostratigraphy in two key sections from the Carnic Alps (Grüne Schneid) and Graz Paleozoic (Trolp) - implications for the biozonation concept at the Devonian-Carboniferous boundary: Newsletters on Stratigraphy, 53(3), 249-274. https://doi.org/10.1127/nos/2019/0520

Kaiser, S.I., Joachimski,, M.M., Kumpan,, T., Hartenfels, S., Girard, C., Rasser,, M.W., 2022. Late Devonian Ice Age: trigger for the 1st order Hangenberg mass extinction at the Devonian-Carboniferous boundary, in 93rd Annual Meeting of Paläontologische Gesellschaft, September 19th to 23rd 2022: Stuttgart, Günter Schweigert, Abstract Volume, p. 31.

Kalvoda, J., Kukal, Z., 1987, Devonian-Carboniferous boundary in the Moravian Karst at Lesní Lom Quarry, Brno-L'sen, Czechoslovakia: CFS Courier ForschungsInstitut Senckenberg 98, 95-117.

Kalvoda, J., Kumpan, T., Bábek, O., 2015, Upper Famennian and Lower Tournaisian sections of the Moravian Karst (Moravio-Silesian Zone, Czech Republic): a proposed key area for correlation of the conodont and foraminiferal zonations: Geological Journal, 50(1), 17-38. https://doi.org/10.1002/gj.2523

Khosrovi-Said, A., 1962, Stratigraphische Ergebnisse im Paläozoikum beiderseits des Pailgrabens (Graz N.) mit Hilfe von Conodonten: Anzeiger der Österreichischen Akademie der Wissenschaften, Mathematisch-Naturwissenschatliche Klasse, 99: 89-90.

Königshof, P., Bahrami, A., Kaiser, S.I., 2021, Devonian-Carboniferous boundary sections in Iran: Palaeobiodiversity and Palaeoenvironments, 101(2), 613-632. https://doi.org/10.1007/s12549-020-00438-z

Kodsi, M.G., 1967, Zur Kenntnis der Devon/Karbon-Grenze im Paläozoikum von Graz: Neues Jahrbuch für Geologie und Paläontologie Mitteilungen, 7, 415-427.

Komatsu, T., Kato, S., Hirata, K., Reishi, 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. https://doi.org/10.1016/j.palaeo.2014.03.021

Korn, D., Belka, Z., Fröhlich, S., Rücklin, M., Wendt, J., 2004, The youngest African clymeniids (Ammonoidea, Late Devonian) – failed survivors of the Hangenberg Event: Lethaia, 37(3), 307-315. https://doi.org/10.1080/00241160410002054

Kreutzer, L.H., Schönlaub, H.P., Hubmann, B., 1997, The Devonian of Austria, in Schonlaub, H.P. (ed.), . IGCP Project 421, North Gondwanan Mid-Paleozoic Biodynamics, Inaugural Meeting Vienna, sept. 17-21, 1997 Guidebook, Berichte der Geologischen Bundesanstalt, 40, 42-59.

Kumpan, T., Bábek, O., Kalvoda, J., Frýda, 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(2), 201–215. https://doi.org/10.1017/S0016756812001057

Kumpan, T., Bábek, O., Kalvoda, J., Matys Grygar, T., Frýda, J., 2014b, Sea-level and environmental changes around the Devonian–Carboniferous boundary in the Namur–Dinant Basin (S Belgium, NE France): a multi-proxy stratigraphic analysis of carbonate ramp archives and its use in regional and interregional correlations. Sedimentary Geology 311, 43–59. https://doi.org/10.1016/j.sedgeo.2014.06.007

Kumpan T., Bábek, O., Kalvoda, J., Matys Grygar, T., Frýda, J., Becker R.T., Hartenfels, S., 2015. Petrophysical and geochemical signature of the Hangenberg Events: an integrated stratigraphy of the Devonian-Carboniferous boundary interval in the Northern Rhenish Massif (Avalonia, Germany): Bulletin of Geosciences, 90(3), 667-694. http://dx.doi.org/10.3140/bull.geosci.1547

Kumpan, T., Kaiser, S.I., Joachimski, M.M., Rasser, M.W., 2018, Conodont biostratigraphy and geochemistry of pelagic Devonian-Carboniferous boundary successions at Trolp (Graz Paleozoic) and Grüne Schneid (Carnic Alps), in The fossil week, abstract book, 5th International Palaeontological Congress from July 9th to 13th, 2018 (France) 828.

Kumpan, T., Kalvoda, J., Babek, O., Matys Grygar, T., Fryda, J., 2021, The Devonian-Carboniferous boundary in the Moravian Karst (Czech Republic): Palaeobiodiversity and Palaeoenvironments, 101 (2), 473-486. https://doi.org/10.1007/s12549-019-00409-z

Lakin, J.A., Marshall, J.E.A., Troth, I., Harding, I.C., 2016, Greenhouse to icehouse: a biostratigraphic review of latest Devonian–Mississippian glaciations and their global effects, In Becker, R.T., Königshof, P., Brett, C. E. (eds), Devonian Climate, Sea Level and Evolutionary Events: Geological Society, London, Special Publications 423. 439-464. http://doi.org/10.1144/SP423.12

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, 117-168.

Lethiers, F., Feist, R., 1990, Ostracodes, stratigraphie et bathymétrie du passage Dévonien- Carbonifère au Vise´en inférieur en Montagne Noire (France): Geobios, 24(1), 71–104. https://doi.org/10.1016/0016-6995(91)80038

Li, S., Wignall, P.B., Poulton, S.W., Hedhli, M., Grasby, S.E., 2022, Carbonate shutdown, phosphogenesis and the variable style of marine anoxia in the late Famennian (Late Devonian) in western Laurentia: Palaeogeography, Palaeoclimatology, Palaeoecology, 589, http://doi.org/10.1016/j.palaeo.2022.110835

Luppold, F.W, Hahn, G., Korn, D., 1984, Trilobiten-, Ammonoideen- und Conodonten-Stratigraphie des Devon/ Karbon-Grenzprofiles auf dem Müssenberg (Rheinisches Schiefergebirge): CFS Courier Forschungs institut Senckenberg, 67, 91-121.

Malec, J., 2014, The Devonian/Carboniferous boundary in the Holy Cross Mountains (Poland): Geological Quaterly, 58(2), 217-234. https://doi.org/10.7306/gq.1142

Marshall, J.E.A., Lakin, J., Troth, I., Wallace-Johnson, S.M., 2020, UV-B radiation was the Devonian-Carboniferous boundary terrestrial extinction kill mechanism: Science Advances, 6(22), 1-8. https://doi.org/10.1126/sciadv.aba0768

Marynowski, L., Filipiak, P., 2007, Water column euxinia and wildfire evidence during deposition of the Upper Famennian Hangenberg event horizon from the Holy Cross Mountains (central Poland): Geological Magazine, 144(3), 569–595. https://doi.org/10.1017/s0016756807003317

Matyja, H., Woroncova-Marcinowska, T., Filipiak, P., Branski, P., Sobien, K., 2021, The Devonian/Carboniferous boundary interval in Poland: multidisciplinary studies in pelagic (Holy Cross Mountains and Sudetes) and ramp (Western Pomerania) successions: Palaeobiodiversity and Palaeoenvironments, 101(2), 421-472. https://doi.org/10.1007/s12549-020-00442-3

Mossoni, A., Carta, N., Corradini, C., Spalletta, C., 2015, Conodonts across the Devonian/Carboniferous boundary in SE Sardinia (Italy): Bulletin of Geosciences, 90(2), 371-388. https://doi.org/10.3140/bull.geosci.1524

Neubauer, F., Genser, J., Handler, R., 2000, The Eastern Alps: Result of a two-stage collision process: Austrian Journal of Earth Sciences, 92, 117-134.

Neubauer, F., Liu, Y., Dong, Y., Chang, R., Genser, J., Yuan, S., 2022, Pre-Alpine tectonic evolution of the Eastern Alps: from prototethys to paleotethys: Earth Science Reviews, 226, 103923. https://doi.org/10.1016/j.earscirev.2022.103923

Nössing, L., 1974a, Nachweis des tieferen Unterkarbons im Paläozoikum von Graz: Anzeiger der Österreichischen Akademie der Wissenschaften Wien, Mathematisch-naturwissenschaftliche Klasse, 111, 39-41.

Nössing, L., 1974b, Beitrag zur Kenntnis des Oberdevons und Unterkarbons des Grazer Paläozoikums: Graz, Fakultät an der Karl-Franzens, Universität in Graz, Inaugural Dissertation zur Erlangung des Doktoratgrades der philosophischen.

Nössing, L., 1975, Die Sanzenkogelschichten (Unterkarbon), eine biostratigraphische Einheit des Grazer Paläozoikums: Mitteilungen des naturwissenschaftlichen vereines für Steiermark, 105, 79-92.

Nössing, L., Ebner, F., Flügel, H.W., 1977, Zur Geologie des Eidikogels bei Rein nordwestlich von Graz: Mitteilungen des naturwissenschaftlichen Vereins für Steiermark 107, 81-88.

Over, D.J., 1992, Conodonts and the Devonian–Carboniferous boundary in the upper Woodford Shale, Arbuckle Mountains, south-central Oklahoma: Journal of Paleaontology 66(2), 293-311. https://doi.org/10.1017/S0022336000033801

Over, D.J., 2021. The Devonian-Carboniferous boundary in the United States. Palaeobiodiversity and Palaeoenvironments 101(2), 529-540. https://doi.org/10.1007/s12549-020-00428-1

Parvizi, T., Bahrami, A., Königshof, P., Kaiser, S.I., 2021, Conodont biostratigraphy of Upper Devonian–Lower Carboniferous deposits in eastern Alborz (Mighan section), North Iran: Palaeoworld 31(1), 69-85. https://doi.org/10.1016/j.palwor.2021.01.008

Qie, W., Sun, Y., Guo, W., Nie, T., Chen, B., Song, J., Liang, K., Yin, B., Han, S., Chang, J., Wang, X., 2021, Devonian-Carboniferous boundary in China: Palaeobiodiversity and Palaeoenvironments, 101(2), 589-612. https://doi.org/10.1007/s12549-021-00494-z

Ratschbacher, L., Frisch, W., Linzer, H.-G., Merle, O., 1991, Lateral extrusion in the Eastern Alps, 2. Structural analysis: Tectonics 10(2), 257-271. https://doi.org/10.1029/90tc02623

Sahoo, S.K., Gilleaudeau, G.J., Wilson, K. & Hart, B., Barnes, B.D. Faison, T., Bowman, A.R., Larsen, T.E., Kaufman, A.J., 2023, Basin-scale reconstruction of euxinia and Late Devonian mass extinctions: Nature, 615, 640-645. https://doi.org/10.1038/s41586-023-05716-2

Sandberg, C.A., Ziegler, W., 1979, Taxonomy and biofacies of important conodonts of Late Devonian styriacus-Zone, United States and Germany: Geologica et Palaeontologica 13, 173-212.

Sandberg, C.A., Streel, M., Scott, R.A., 1972, Comparison between conodont zonation and spore assemblages at the Devonian-Carboniferous boundary in the western and central United States and in Europe, in Abstracts Congress of Stratigraphy and Geology of the Carboniferous: Krefeld, Germany, 179-203.

Sandberg, C. A., Ziegler, W., Ebner, F., 1983, Possible Devonian-Carboniferous Boundary stratotypes in central U.S.A., West Germany and Austria, in Congreso Internacional de Estratigrafía y Geología del Carbonífero: Madrid, Spain, 315 p.

Schmid, S.M., Fügenschuh, B., Kissling, E., Schuster, R., 2004, Tectonic map and overall architecture of the Alpine orogen: Eclogae geologicae Helvetiae, 97, 93-117. https://doi.org/10.1007/s00015-004-1113-x

Schönlaub, H.P., 1969, Conodonten aus dem Oberdevon und Unterkarbon des Kronhofgrabens (Karnische Alpen, Österreich): Jahrbuch der Geologischen

Bundesanstalt A, 112(2), 321-354.

Schönlaub, H.P., 2018, Review of the Devonian/Carboniferous boundary in the Carnic Alps: Jahrbuch der Geologischen Bundesanstalt A, 158(1-4), 29-47.

Schönlaub, H.P., Feist, R., Korn, D., 1988, The Devonian-Carboniferous boundary at the section „Grüne Schneid" (Carnic Alps, Austria): A preliminary report: CFS Courier Forschungs-Institut Senckenberg 100, 149-167.

Schönlaub, H.P., Klein, P., Magaritz, M., Rantitsch, G., Scharbert, S., 1991, Lower Carboniferous paleokarst in the Carnic Alps (Austria, Italy): Facies 25, 91-118. https://doi.org/10.1007/bf02536756

Sial, A.B., Gaucher, C., Ramkumar, M., Ferreira, V.P., 2019, Chemostratigraphy as a Formal Stratigraphic Method, in Sial, A.B., Gaucher, C., Ramkumar, M., Ferreira, V.P. (eds.), Chemostratigraphy Across Major Chronological Boundaries: USA: American Geophysical Union, Geophysical Monograph series 240, 1-25. https://doi.org/10.1002/9781119382508.ch1

Spalletta, C., Perri, M.C., Over, J., Corradini, C., 2017, Famennian (Upper Devonian) conodont zonation: revised global standard: Bulletin of Geosciences 92(1), 31-57. https://doi.org/10.3140/bull.geosci.1623

Spalletta, C., Corradini, C., Feist, R., Korn, D., Kumpan, T., Perri, M.C., Pondrelli, M., Venturini, C., 2021, The Devonian-Carboniferous boundary in the Carnic Alps (Austria and Italy). Palaeobiodiversity and Palaeoenvironments 101(2), 487-505. https://doi.org/10.1007/s12549-019-00413-3

Surenian, R., 1977, Biostratigraphie und Sedimentologie der Steinbergkalke (Oberdevon) des Steinberg westlich von Graz: Austria, Universität Graz, Unveröffentlichte Dissertation, 1-137.

Surenian, R. von, 1978, Die Conodontenfauna des Steinbergkalkes (Oberdevon, Paläozoikum von Graz): Mitteilungen des naturwissenschaftlichen Vereins für Steiermark, 108, 121-135.

Streel, M., 1999, Quantitative palynology of Famennian events in the Ardenne–Rhine regions: Abhandlungen der Geologischen Bundesanstalt 54, 201–212.

Streel, M., 2000, Global Famennian climates based on palynomorph quantitative analysis, in Rodrigues, M.A.C., Pereira, E., Ordovician-Devonian Palynostratigraphy in Western Gondwana:Update, Problems and Perspectives: Brasil, UERJ/Faculdade de Geologia, 77-103.

Streel, M., 2009. Upper Devonian miospore and conodont zone correlation in Western Europe. Geological Society, Special Publications 314, 163–176.

Streel, M., Caputo, M.V., Loboziak, S., Melo, J.H.G., 2000, Late Frasnian-Famennian climates based on palynomorph analyses and the question of the Late Devonian glaciations: Earth Science Reviews, 52(1-3), 121-173. https://doi.org/10.1016/S0012-8252(00)00026-X

Van Steenwinkel, M., 1992, . The Devonian–Carboniferous boundary: comparison between the Dinant synclinorium and the northern border of the Rhenish Slate Mountains, a sequence-stratigraphic view: Annales de la Société Géologique de Belgique, 115(2), 665-681.

Van Steenwinkel, M., 1993, The Devonian–Carboniferous boundary in southern Belgium: biostratigraphic identification criteria of sequence boundaries: Special Publications of International Association of Sedimentologists, 18, 236–246. https://doi.org/10.1002/9781444304015.ch13

Wang, C.Y., Yin, B.A., 1988, Conodonts, in: Yu, C.M. (ed.), Devonian-Carboniferous boundary in Nanbiancun, Guilin, China. Aspects and records: Beijing, Science Press. 165-195.

Walliser, O.H., 1984, Pleading for a natural D/C boundary: CFS Courier Forschungs-Institut

Senckenberg 67, 241-246.

Zhang, X., Joachimski, M.M., Over, J., Ma, K., Huang, C., Gong, Y., 2019, Late Devonian carbon isotope chemostratigraphy: A new record from the offshore facies of South China: Global and Planetary Change, 182, 103024. https://doi.org/10.1016/j.gloplacha.2019.103024

Ziegler, W., 1957, Paläontologischer Teil, in Flügel, H., Ziegler, W. (eds.), Die Gliederung des Oberdevons und Unterkarbons am Steinberg westlich von Graz mit Conodonten, Mitteilungen des naturwissenschaftlichen Vereins für Steiermark, 87, 25-60.

Ziegler, W., 1969, Eine neue Conodontenfauna aus dem höchsten Oberdevon: Fortschritte in der Geologie vom Rheinland und Westfalen 17, 343-360.

Ziegler and Leuteritz, 1970, in Koch, M., Leuteritz, K., Ziegler, W., 1970, Alter, Fazies und Paläogeographie der Oberdevon/Unterkarbon-Schichtenfolge an der Seiler bei Iserlohn: Fortschritte in der Geologie vom Rheinland und Westfalen, 17, 679-732.

Ziegler. W., 1973, Catalogue of Conodonts Volume I: Stuttgart, Schweizerbart, 504 p.

Ziegler, W., Sandberg, C.A., 1984a, Important candidate sections for a stratotype of conodont based Devonian-Carboniferous boundary: CFS Courier Forschungs-Institut Senckenberg 67, 231-239.

Ziegler, W., Sandberg, C.A., 1984b, Palmatolepis-based revision of upper part of standard Late Devonian conodont zonation: Geological Society of America, Special Papers, 196, 179-194. https://doi.org/10.1130/SPE196-p179

Ziegler, W., Sandberg, C.A., 1996, Reflexions on Frasnian and Famennian stage boundary decisions as a guide to future deliberations: Newsletters on Stratigraphy, 33(3), 157-180.

Ziegler, W., Weddige, K., 1999, Zur Biologie, Taxonomie und Chronologie der Conodonten: Paläontologische Zeitschrift 73(1/2), 1-38. https://doi.org/10.1007/BF02987980

Ziegler, W., Sandberg, C.A., Austin, R., 1974, Revision of Bispathodus group (Conodonta) in the Upper Devonian and Lower Carboniferous: Geologie und Paläontologie, 8, 97-112.