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Review of the Devonian/Carboniferous boundary in the Carnic Alps

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Devonian
Carboniferous
Conodonts
Hangenberg Crisis

Contents

Abstract

In this report, the present knowledge about the Devonian/Carboniferous boundary is reviewed. We start with the Ordovician age, because in our view the foregoing time is essential for understanding the geodynamic evolution of this time interval. For the Ordovician to the Devonian Periods an increasing degree of sea-floor mobility can be inferred resulting in more or less distinct regressive and transgressive cycles caused by different endogenic and exogenic factors. The culmination of these perturbations occurred during the second half of the Devonian and the beginning of the Carboniferous Period when the Carnic Alps were affected by strong extensional geotectonics creating a distinct horst-and-graben-like morphology of the seafloor.

Representative sections for the D/C boundary including biostratigraphic marker groups are described in more detail for the Grüne Schneid, Kronhofgraben, Cima di Plotta und Pal Grande sections. The first seems to be a candidate for the type section although the index fossil for the definition of the base of the Carboniferous needs further discussion by a specific Working Group. From the viewpoint of the Carnic Alps at present neither *Protognathodus kockeli* nor *Pr. kuehni* are good choices. As an alternative the former index species for the base of the Carboniferous, *Siphonodella sulcata,* entering in bed no. 6c (personal comment by Sandra Kaiser, Stuttgart State Museum of Natural History), i.e. one subbed below the projected older boundary by Schönlaub et al. (1992) should be reconsidered as a candidate for the definition of the D/C boundary. The latter is affected by a sequence of events known as Hangenberg Crisis.

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Eine Übersicht über die Devon/Karbon-Grenze in den Karnischen Alpen (Österreich/Italien)

Zusammenfassung

In diesem Report wird der gegenwärtige Kenntnisstand über die Devon/Karbon-Grenze in den Karnischen Alpen zusammengefasst. Die Arbeit beschäftigt sich auch mit der Vorläuferzeit vom Ordovizium bis in das Oberdevon, da schon während dieser langen Zeit mehr oder weniger deutliche trans- und regressive Phasen die geodynamische Entwicklungsgeschichte geprägt haben. Sie sind Ausdruck eines mobilen Krustengeschehens, dessen Höhepunkt im Oberdevon und Unterkarbon im Zuge verstärkter extensionaler Tektonik zum Ausdruck kam. Dabei bildete sich das Sedimentationsbecken in eine deutliche Horst- und Graben-Struktur um.

Als Kandidaten für die Devon/Karbon-Grenze werden die Profile Grüne Schneid, Kronhofgraben, Cima di Plotta und Großer Pal hinsichtlich ihrer biostratigrafischen Besonderheiten ausführlicher behandelt. Insbesondere das Profil an der Grünen Schneid scheint ein guter Kandidat für das Typusprofil dieser Grenze zu sein, auch wenn eine internationale Einigung über eine Conodonten-Leitart für den Beginn des Karbons noch aussteht und es weiterer Diskussionen durch eine Arbeitsgruppe bedarf. Nach dem hier skizzierten Kenntnisstand in den Karnischen Alpen scheinen weder *Protognathodus kockeli* noch *Pr. kuehni* geeignete Kandidaten zu sein. Die lange Zeit als Leitform für den Beginn des Karbons gehandelte Art *Siphonodella sulcata*, die nach einer persönlichen Mitteilung von Sandra Kaiser (Staatliches Museum für Naturkunde Stuttgart) im Profil Grüne Schneid ihr Erstauftreten in der Subbank 6c etwas höher als *Protognathodus kockeli* oder *Pr. kuehni* hat, sollte hingegen erneut als Kandidat diskutiert werden. Dieses Vorkommen liegt nur eine Subbank unter der ursprünglich von SCHÖNLAUB et al. (1992) vorgeschlagenen D/C-Grenze. Letztere wird durch signifikante Veränderungen der Umwelt beeinflusst, die als Hangenberg-Krise weltweit bekannt ist.

Current knowledge

The time interval between the Devonian and Carboniferous Periods is crucial for the geological history of the Carnic Alps in both Austria and Italy. Since the Middle Ordovician, i.e. almost 470 million years ago, in this region a huge pile of varying sediments accumulated on the sea floor without major breaks (Text-Fig. 1). They reflect different climatic settings from high-latitude cold-water to mid-latitude warm-water realms. During this long time, rich faunas and floras flourished in the sea culminating in highly diverse Devonian reefs followed by moderately deep-water cephalopod limestones across the D/C boundary. Then, rather suddenly, the depositional regime changed to flysch-type siliciclastic sediments named the Hochwipfel Formation. The Devonian/Carboniferous boundary is well defined by index fossils of conodonts, goniatites and trilobites; its exact position, however, has still been a matter of discussion.

The Carnic Alps have been a cradle of geology for almost two centuries. Since the second half of the 19th century, the carbonate and siliciclastic successions have been a playground for generations of earth scientists, in particular for palaeontologists, stratigraphers, sedimentologists, and structural geologists from all over the world. Scientific research of this rich heritage is still going on. Meanwhile several hundred papers dealt with almost all fossil groups ranging from eye-catching macroscopic creatures to micro- and nannofossils.

In the Lower Palaeozoic, the record of life comprises different marine environments ranging from shallow water lagoonal deposits to coral-stromatoporoid buildups, forereef and slope to offshore pelagic settings. The faunal and floral groups comprise rich occurrences of highly diverse rugose and tabulate corals, stromatoporoids, trilobites, cephalopods, gastropods, bivalves, brachiopods, echinoderms, graptolites, bryozoans, ostracods, radiolarians, algae and a high variety of microfossil groups.

The rich paleontological heritage of both faunas and floras of the Paleozoic strata of the Carnic Alps is documented in several hundred scientific publications.

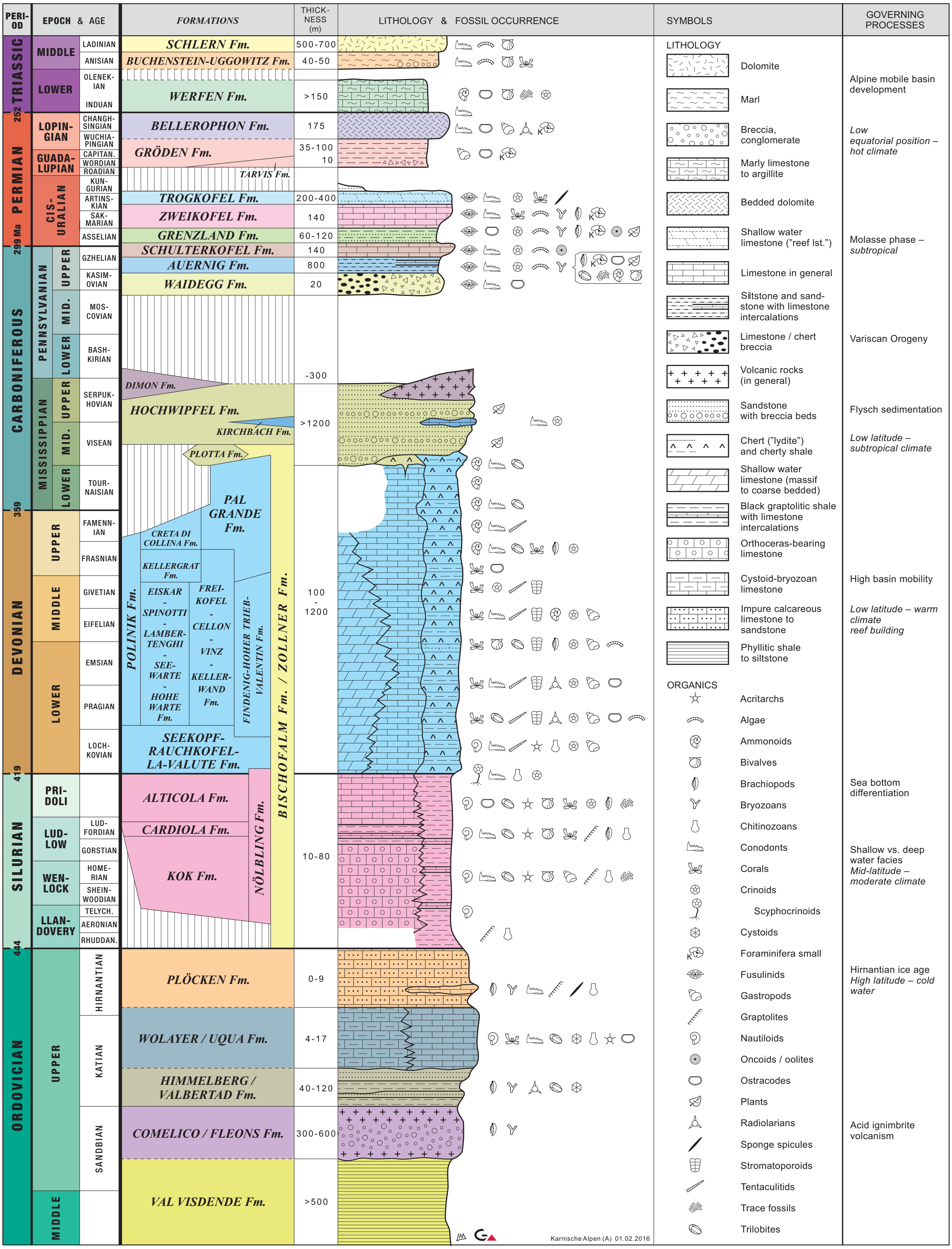
In comparison with older strata, Middle and Upper Devonian faunas are characterized by a decline of endemism and provincialism and the appearance of cosmopolites. In particular, the Upper Devonian and Lower Carboniferous fossil remains (goniatites, trilobites, conodonts) comprise cosmopolites with little biogeographic significance although similarities with coeval occurrences in northern and western Europe are obvious. This is also true for the fossil assemblages from the post-Variscan cover sequence with its typical “Palaeotethyan character” reaching as far as South China and Texas.

During the Variscan Orogeny in the Carboniferous Period some 320 million years ago, the lower Paleozoic rock sequence was compressed, folded and more or less strongly tectonized. These orogenic processes were followed by a short event of crustal uplifting and subsequent subsidence resulting in renewed marine ingressions in the late Carboniferous. At the end of the Paleozoic Era, i.e., between 299 and 251 million years ago in the Permian Period, this area was characterized by a warm and temporarily even arid climate in an equatorial position. While to the north of the Gail River the sedimentary rocks of this age are dominated by red colors reflecting continental deposits, the southern part represented a shallow sea rich in all kinds of marine life. The several hundred meters thick limestone successions of mountains Trogkofel and the Reppwand cliff were formed during this time.

The Variscan Orogeny of the Gailtal Alps (to the north of the Gailtal Fault) was more intensive than that of the Carnic Alps, because of high-grade metamorphism resulting in granitic rocks, micaschists, gneisses, amphibolites and marbles. These basement rocks are unconformably covered by continental deposits of Permian age followed by carbonate rocks of Triassic and Jurassic age.

Between the Triassic Period, i.e., between 251 and 229 million years, the continental plates crossed the equator and continued to drift in northern direction during the Mesozoic and Cenozoic Eras. The limestone and dolomite massifs of the Gailtal Alps represent rocks of this age. Between 30 and 20 million years ago, the Alps slowly started to rise to become the present mountain chain.

During the Pleistocene Epoch, which started some 2.6 million years ago, the glaciers formed the Alpine landscape. After its climax in the last Ice Age between 22,000 and 18,000 years ago, the more than 1,000 m thick ice streams started to melt quite rapidly. The meager rocky landscape was settled by pioneering plants, which were succeeded by forests between 14,000 and 13,000 years and finally by men.



Text-Fig. 1.
Rock succession of the Carnic Alps with stratigraphic subdivision (left), names of formations, thickness, main lithology, occurrences of fossils and governing processes including palaeogeographic settings and indication of climate (italics). © Monika Brüggemann-Ledolter (Geological Survey of Austria) after Hans P. Schönlaub.

Review of sedimentary and tectonic history

The time interval from the Middle Ordovician to the end of the Permian has not only resulted in a thick pile of sedimentary rocks and fossils, but also reflects the climatic impact and the crustal responses on the sedimentary rock sequence. In fact, sediments deposited in a cool climate varied significantly from those in mid or low latitudes; opening and closing of oceans through plate movements including subduction processes and volcanism were responsible for thinning or thickening of the underlying continental (or oceanic) crust as were collisional processes on active or passive plate margins. All these processes affected the sedimentary regime and left its traces in the sedimentary record. In addition, the biogeographical distribution of fossils and paleomagnetic reconstructions roughly constrains the position of plates. We briefly discuss this record in the following chapter followed by the focus on the D/C boundary event.

Important stratigraphic markers

Middle and Upper Ordovician

In the Middle and Upper Ordovician, a cold-water influence has been well known in the Carnic Alps for many years (SCHÖNLAUB, 1992, 1993; HAVLÍČEK et al., 1987) although most brachiopods, cystoids, ostracods and conodonts are more closely related to coeval warm water faunas of northern Europe. In particular, the contrasting lithologies of the shallow water Wolayer Formation and the more open-marine Uggwa Formation suggest different settings, which obviously is confirmed by the preceding key elements of the deep-water *Foliomena* fauna of Katian age (HARPER et al., 2009). The latter has strong relationships to Sardinia, Portugal, China and other far-eastern occurrences.

In conclusion, during the Ordovician the sedimentary basin of the Carnic Alps seems to be split into two different realms.

Silurian

The subdivision into distinct lithofacies is even enlarged during the following Silurian Period (SCHÖNLAUB, 1979). In fact, three types of lithofacies, each with distinct faunal assemblages, can be recognized:

1. The dominating lithologies are limestones and dolomites of some 60 m thickness. They are divided into the shallow Wolayer facies and the more open marine Plöcken facies. Both are very fossiliferous consisting of abundant nautiloids, trilobites, bivalves, brachiopods and graptolites as well as many microfossils including conodonts and a diverse assemblage of nannofossils (acritarchs, chitinozoans).
2. The graptolitic facies named Bischofalm facies is represented by black siliceous shales, cherts (lydites), alum shales and greenish mudstones. Since the pioneering studies of JAEGER (1975), JAEGER & SCHÖNLAUB (1980) and JAEGER et al. (1975), a continuous record from the base of the Silurian to the Silurian/Devonian boundary and the end of the Lochkovian Stage has been established.
3. The third facies representing an intermediate lithology is named Nölbling facies. It is characterized by a mixture of the above-mentioned two main lithologies, i.e. black shales and marls as well as black and grey limestone intercalations. The fossil content is rather poor and consists of graptolites, few nautiloids and conodonts.

It is worth mentioning that only few sections exhibit a continuous sedimentary rock sequence across the Ordovician/Silurian boundary. In the limestone-dominated facies, a discontinuity is well expressed with several conodont zones missing at the base of the Silurian. Whether or not these sedimentary gaps were caused by local uplifting or by non-deposition in a marine environment is still a matter of discussion.

During the Ludlowian and Pridolian Series, a more or less uniform graptolite fauna developed in Europe exhibiting only minor local modifications. According to JAEGER (1976) and BARCA & JAEGER (1990), strikingly similar and closely contemporaneous shifting of lithofacies occurred between northern Africa and Baltica. This change in facies was controlled by simultaneous sea-level rise and fall, which affected a hypothesized single continental plate along its passive margins.

In conclusion, during the Silurian Period the occurrences of sedimentary basins continued to shift into lower latitudes of approximately 30–35° south. In addition, crustal subsidence increased resulting in different lithofacies. For details of the sequence stratigraphy, the reader is referred to BRETT et al. (2009).

Devonian

In the Carnic Alps the Devonian Period is characterized by variably thick limestone sequences, reef development and interfingering facies ranging from lagoonal sediments, carbonate buildups, slope deposits, condensed pelagic cephalopod limestones to deep-water offshore-condensed pelagic mudstones. The ratio of thickness between shallow water limestones and contemporary cephalopod limestones is in the order of 1,200–1,300 m : 100 m and thus indicates differentially subsiding mobile basins affected by extensional tectonics (VAI, 1980; KREUTZER, 1990, 1992a, b; VAI & SPALLETTA, 1982; SPALLETTA et al., 1980; SPALLETTA & VENTURINI, 1988, 1990; SCHÖNLAUB, 1992; VENTURINI, 2006). According to the model presented by VAI & SPALLETTA (1982) in the Upper Devonian the ramp connecting the reef complex with the basin changed to a steep fault-controlled slope followed by the formation of fault scarps with slope breccias, olistostromes, density flows and turbidites.

In conclusion, the Devonian calcareous sediments were deposited in the tropical belt of some 30° south or less. The thick carbonate buildups and associated limestones are composed of typical fabrics and components and all kinds of fossils, e.g. rugose and tabulate corals, stromatoporoids, crinoids, brachiopods, trilobites, algae and stromatolites indicating a warm agitated sea for most of the Devonian ending at the Frasnian/Famennian boundary.

In short, the Southern Alps represented a highly mobile subsiding basin affected by tensional tectonics throughout the Devonian. The temporary southward drifting of the African Plate relative to the South Pole may have caused thinning of the crust.

Faunal evidences and characteristics of D/C boundary beds

At the end of the Devonian Period, the sedimentary regime changed significantly: After the demise of reefs and its main "guilds", an overall uniform lime and marly lime deposition occurred which were recently named the Pal Grande Formation (SPALLETTA et al., 2015). It mainly consists of grayish and reddish mudstones and wackestones rich in fossils such as goniatites, clymeniids, brachiopods, trilobites and conodonts (PERRI & SPALLETTA, 1998a, b; PERRI & SPALLETTA, 2001).

According to SCHÖNLAUB et al. (1991), uninterrupted sedimentation across the D/C boundary only occurred at few places. The majority of 47 sections investigated during this study stopped during the Famennian Stage; some 20, however, crossed the D/C boundary or lasted until the very end of the Devonian.

For concluding remarks, this more general succession of events can further be strengthened by faunistic and isotopic data.

Representative sections for the D/C boundary

In the Carnic Alps there are at least three general types of DCB sections, i.e.,

(i) continuous carbonate deep-water sections without any obvious stratigraphic gaps,

(ii) deep-water sections, where the carbonate sedimentation is discontinuous, with argillaceous intercalations around the D/C boundary suggesting the equivalence of the Hangenberg Black Shale in Germany,

(iii) sections with a hiatus at the DCB due to tectonic activity in the early Carboniferous (?) causing uplift of the basin and a distinct karst formation, and

(iv) in some other settings the carbonate succession ends in the late Famennian Stage. For more details, we refer to SCHÖNLAUB et al. (1991).

In the following chapter, these four main types occurring at the DCB are described in more detail (Text-Fig. 2). It should be noted, however, that there are more sections available in Austria and Italy in which the limestone succession extends close to the end of the Famennian or the DCB is exposed (e.g., EBNER, 1973a, b; GEDIK, 1974; SPALLETTA et al., 1998, 2017; PERRI & SPALLETTA, 2001; KAISER, 2005; KAISER et al., 2009).

Grüne Schneid Section

Coordinates: UTM 33, 341110 E, 5163820 N (Text-Fig. 2)

In the Carnic Alps, the best-studied section across the D/C boundary is exposed west of the summit of Cellon mountain at an altitude of 2,142 m on the Austrian, i.e. northern side of the crest forming the Austrian/Italian border some 25 m west of the marker point n-129. It is accessible after some two hours along the trails nos. 146 and 147 running from Plöckenpass (Passo Monte Croce Carnico) on the Italian side of the mountain chain to the crest west of the summit of Cellon mountain (Text-Figs. 3, 4).

Text-Fig. 3.
Willi Ziegler in the early 1990s visiting the Grüne Schneid Section. Photo: Hans P. Schönlaub.

During the past decades at Grüne Schneid Section, several studies have been performed rendering this succession to one of the most important in the world (VON GAERTNER, 1931; SCHÖNLAUB et al., 1988, 1992; SCHÖNLAUB, 1993; KORN, 1992; FEIST, 1992; KAISER, 2005, 2007; KAISER et al., 2006; CORRADINI et al., 2017).

Text-Fig. 2.
Topographic map showing the four representative sites for the DCB in the Carnic Alps. 1: Kronhofgraben Section, 2: Großer Pal Section, 3: Grüne Schneid Section, 4: Cima di Plotta Section.

Text-Fig. 4.
Close-up of the middle portion of the Grüne Schneid Section. Dotted line indicates D/C boundary according to Schönlaub et al. (1992).

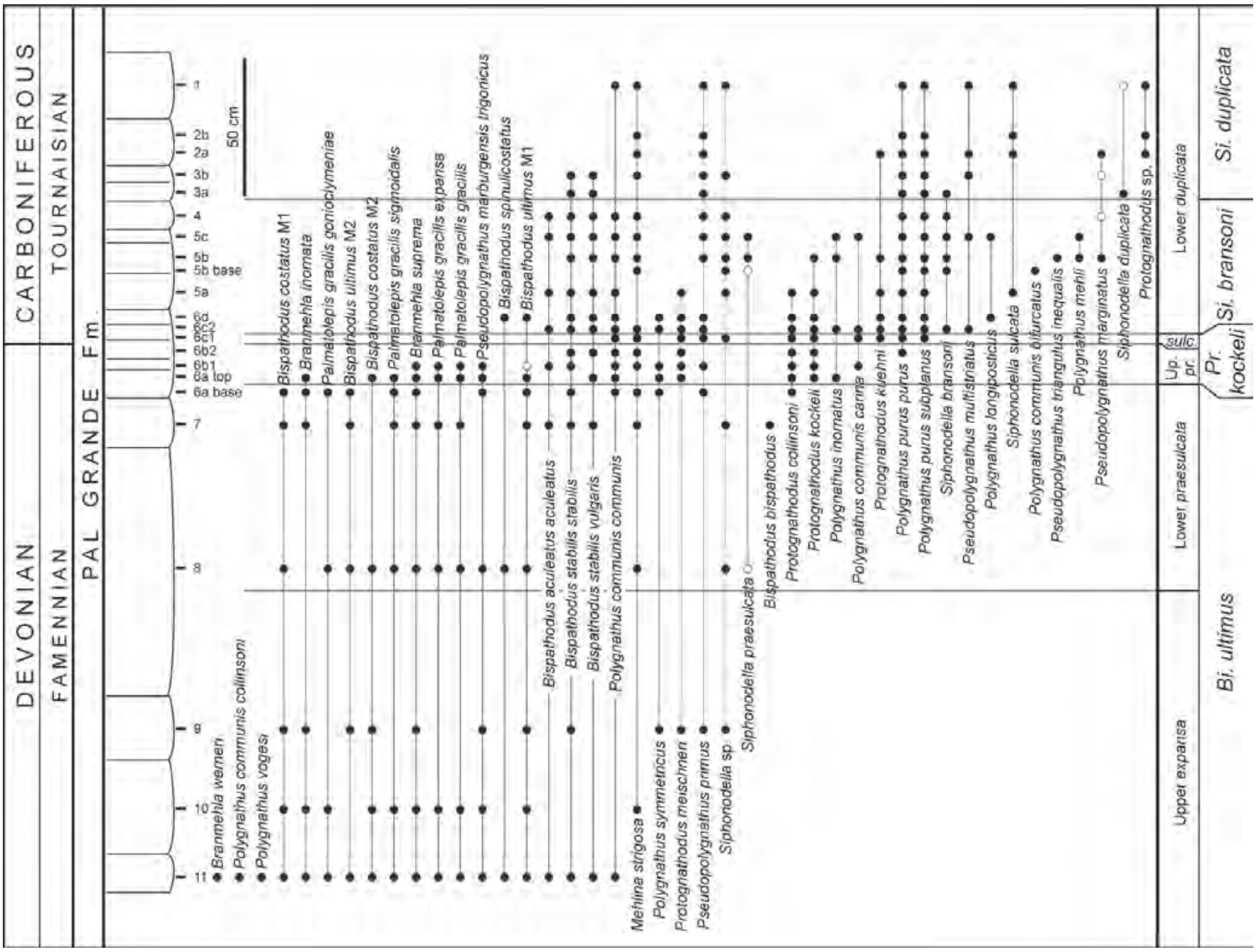
The section comprises light grey limestones of the Pal Grande Formation. Depending on the international agreement about the position of the D/C boundary the studied Famennian part has a thickness of 4.95 m, the basal Carboniferous is 0.965 m thick (Schönlaub et al., 1988, 1992).

Based on conodonts, ammonoids and trilobites there is no gap in sedimentation across the boundary (Text-Fig. 5, 6).

The new conodont biozonation shown in Text-Figure 5 is the use of a conodont biozonation concept proposed recently by Spalletta et al. (2017). Its use at Grüne Schneid was highly and controversially debated, because it assumed that the Hangenberg Event is related to subbed no. 6a due to the occurrence of *Protognathodus kockeli* (collection S.I. Kaiser, SMN Stuttgart) in top of subbed 6a.

It should be noted here that Kaiser (2005, 2007) proposed to place the D/C boundary at the base of subbed no. 6c1 with the entry of *Protognathodus kuehni*. This level is one subbed lower than the position preferred by Schönlaub et al. (1992), i.e. the base of subbed no. 6d with the entry of *Siphonodella sulcata*. Very recently, a well-preserved representative of this species was also found in subbed no. 6c (Sandra I. Kaiser, pers. com., work in progress).

Pr. kockeli first appears in bed 6a (Sandra I. Kaiser, work in progress). Up to now three elements of this index species were found among several hundreds of conodonts. Seemingly, there is no indication of reworking or neptunian-dikes present in this part of the section (see also Schönlaub et al., 1988: Pl. 1, Fig. 2). However, the section is condensed and bed 6 is a single thick bed, subdivided in four sub-beds for stratigraphical purposes (6a–d).



Text-Fig. 5.
Conodont distribution at Grüne Schneid Section after Corradini et al. (2017). Note that the index conodont for the base of the Carboniferous, *Siphonodella sulcata*, already occurs in subbed no. 6c (collection S.I. Kaiser, SMN Stuttgart).

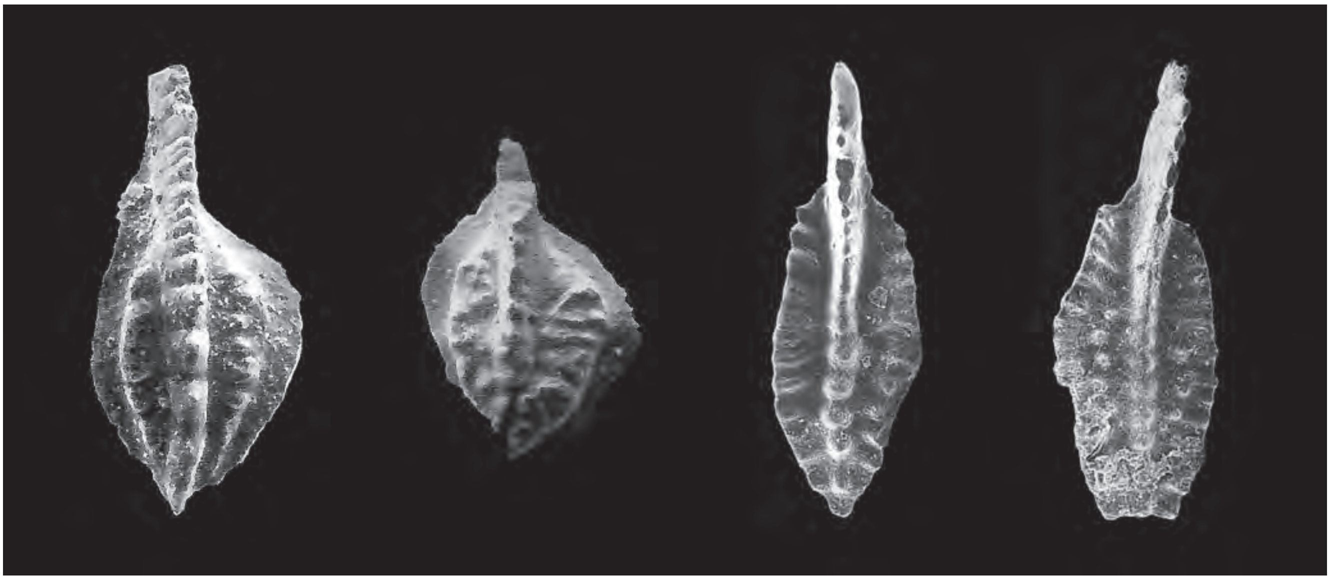
In our opinion, this early occurrence of *Pr. kockeli* excludes this taxon as candidate for the base of the Tournaisian Stage as it co-occurs at Grüne Schneid with several typical late Famennian conodonts (CORRADINI et al., 2017). It is hence recommended to either resample this interval or to choose another conodont species to define the D/C boundary.

According to D. KORN, the 11 cm thick subbed no. 6b can be subdivided into a lower 4 cm thick more argillaceous ammonoid-free horizon (6b1) which presumably corresponds to the Hangenberg Black Shale of the Kronhofgraben Section further to the east. The following uppermost beds of the Devonian immediately below the proposed boundary (bed nos. 6b2 and 6c) are characterized by small goniatites. Goniatites from the succeeding beds and subbeds indicate the base of the Gattendorfia Stage of the Lower Carboniferous, i.e. the base of the Mississippian. Based on the ammonoid fauna the Lower Carboniferous portion of the Grüne Schneid Section can easily be correlated with other D/C boundary sections from the northern margin of the Rhenish Massif.

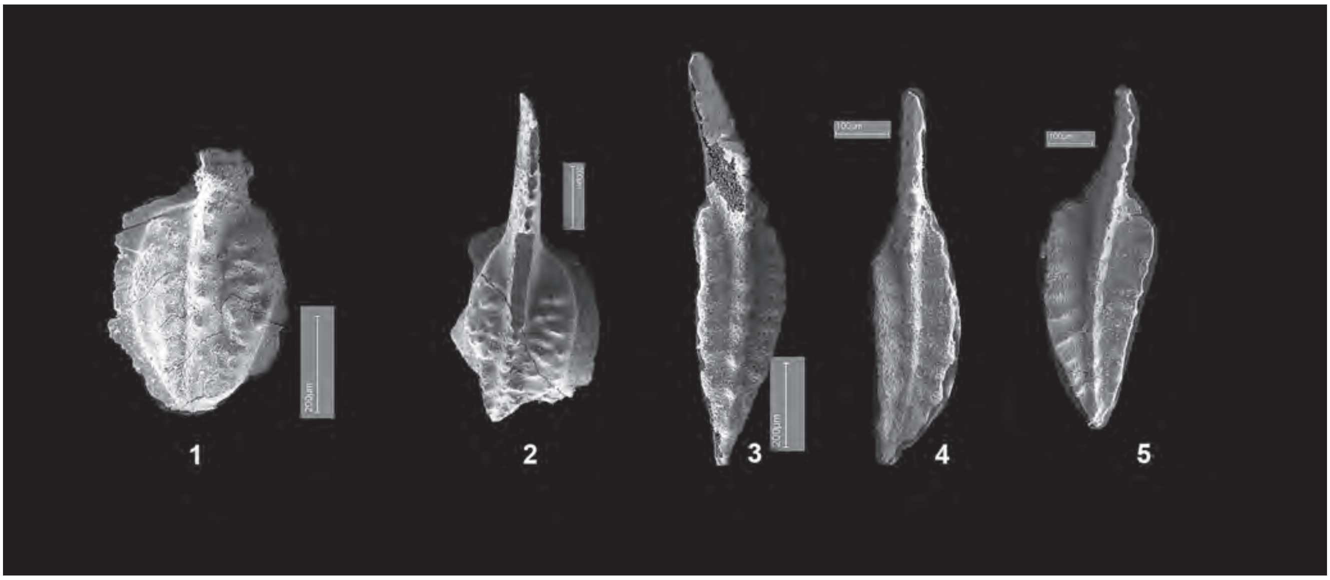
According to R. FEIST (in SCHÖNLAUB et al., 1992; FEIST, 1992) each limestone bed yielded trilobites, which belong to three successive associations:

1. In the late Upper Devonian both blind forms and those with reduced eyes are occurring,
2. followed by those with normally occulated trilobites in a short interval immediately below the D/C boundary (subbeds nos. 6b2 and 6c) and
3. a lowermost Carboniferous association with only occulated forms although the size of the eyes is small.

Raimund Feist pointed out that the reduction of eyes presumably reflects an adaptation to a deeper environment below the photic zone. In addition, these and other characters suggest an endobenthic mode of life. However, this



Text-Fig. 6.
Index conodonts of Grüne Schneid Section. From left to right *Protognathodus kockeli* (subbed 6c), *Protognathodus kuehni* (subbed 6c), *Siphonodella praesulcata* (subbed 5c), *Siphonodella sulcata* (subbed 5b). From SCHÖNLAUB et al. (1988, 1992).



Index conodonts from Grüne Schneid Section (from KAISER, 2005, 2007). Figures 1, 2 *Protognathodus kuehni* (subbed 1, 5a), Figures 3, 4, 5 *Siphonodella praesulcata* (subbed 5a, 3b, 1).

habit changed towards exclusively good developed eyes in subbed nos. 6b and 6c suggesting a slightly shallower environment. In general, this bathymetric change reflects the final stage of the end-Devonian regression. Following this shallowing at the beginning of the duplicata conodont zone (subbeds nos. 5c, 4, 3, 2, 1) a slight deepening occurred with the appearance of trilobites with reduced eyes together with forms with normal eyes.

At Grüne Schneid the conodont biofacies also changed between the subbeds nos. 6a and 6b: At this horizon a sudden decrease of representatives of *Palmatolepis, Pseudopolygnathus* and *Branmehla* contrasted with a striking increase of species of *Polygnathus* and *Protognathodus*. According to DREESEN (in SCHÖNLAUB et al., 1992) this change suggests a sudden lowering of sea-level just before the D/C boundary and coincides with the above-mentioned change of trilobites with blind or reduced eyes to those with normal eyes.

Based on the comprehensive study of KAISER (2005) and KAISER et al. (2008) changes of conodont biofacies are well recognizable in the succession from the Lower *expansa* Zone to the *quadruplicata* Zone. In the *expansa* Zone, a palmatolepid-polygnathid biofacies dominates indicating a shallowing environment. In the Upper *expansa* Zone, a palmatolepid-bispathodus biofacies can be recognized which characterizes a deeper setting, which also prevails during the following palmatolepid-bispathodid-branmehlid biofacies reflecting a transgressive trend. In accordance with previous studies by SCHÖNLAUB et al. (1992), the authors also noted that the topmost beds of the Devonian are characterized by a major faunal change and the onset of a protognathid-polygnathid biofacies in the *kockeli* Zone, which *"reflect a complex pattern of oceanographic and climate change in the Upper Famennian-Lower Tournaisian"* (KAISER et al., 2008: 256).

Kronhofgraben Section

Coordinates: UTM 33, 349799 E, 5163211 N (Text-Fig. 2)

This succession east of Plöckenpass is a representative for deeper-water sections, where the carbonate sedimentation is discontinuous, with a 30 cm thick argillaceous intercalation suggesting the equivalence of the Hangenberg Black Shale at or around the presumed D/C boundary (Text-Fig. 7). This section is characterized by a deep-water assemblage of trilobites occurring in black limestone lenses intercalated in cherts of lowermost Viséan age. According to HAHN & KRATZ (1992), all taxa are blind and apparently small. Hence, this fauna represents a trilobite community of the deep and completely dark bathyal part of the water column unknown from the Culm basin of Germany where a low level of light still existed at the sea-bottom.

At this site according to HAHN & KRATZ (1992) the following small and blind trilobite taxa were recovered:

Diacoryphe RICHTER & RICHTER 1951

Liobolina RICHTER & RICHTER 1951

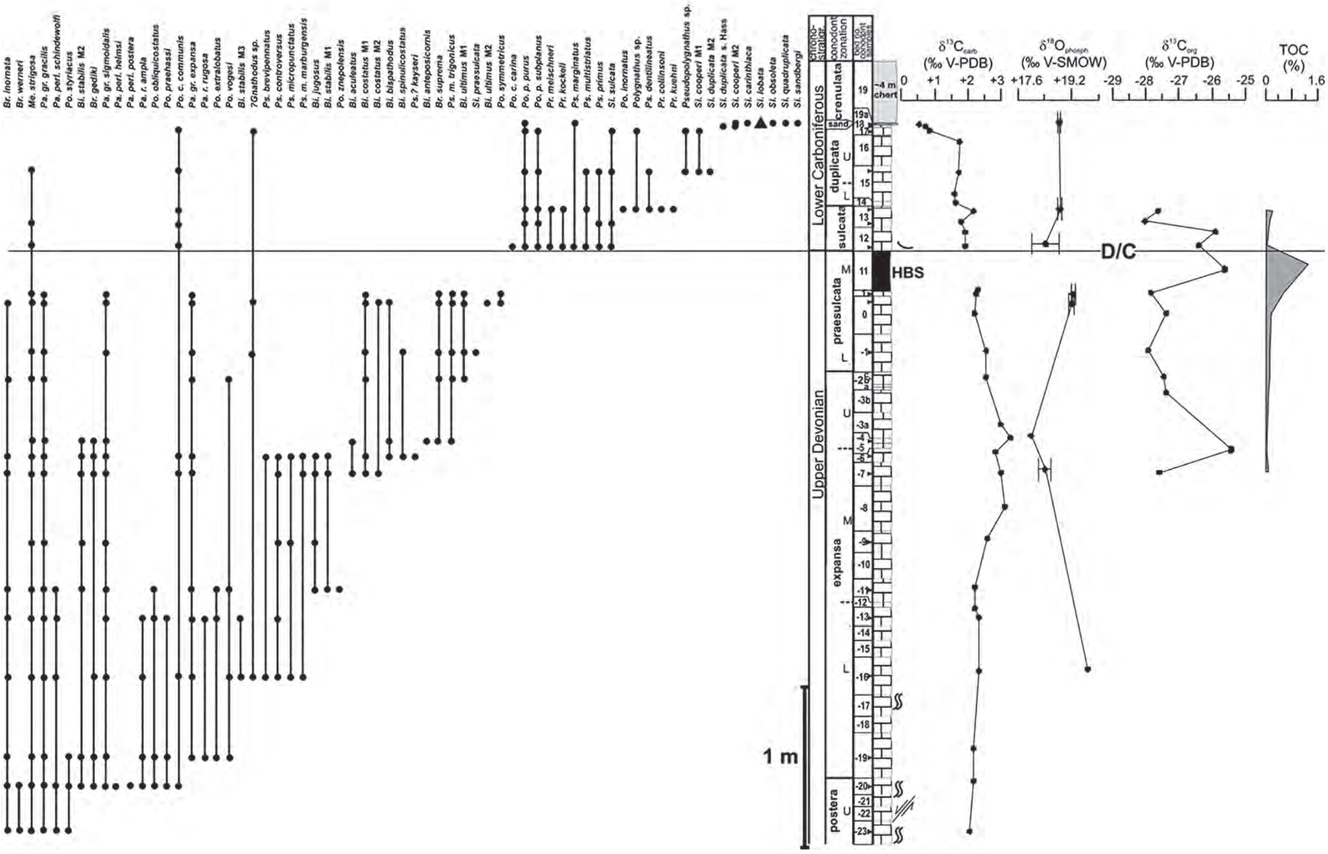
Silesiops (*Chlupacula*) HAHN & WUNN-PETRY 1983

?*Silesiops* CHLUPÁĈ 1966

?*Archegonus (Phillipole)* RICHTER & RICHTER 1937

The accompanying conodont fauna mainly comprises representatives of the genus *Siphonodella* indicating a siphonodellid biofacies in ostracod-rich non-bioturbated mudstone lenses (Text-Fig. 8). This setting also characterizes a deep-water environment and thus contrasts to the foregoing *Protognathodus-Polygnathus* fauna, which dominates the limestone beds overlying the equivalents of the Hangenberg Black Shale.

Text-Fig. 7.
The Kronhofgraben Section. Note the black shale at the right side of the hammer. On the left margin of the photo the black cherts overly the limestone sequence of the Pal Grande Formation. Photo: Hans P. Schönlaub.



Text-Fig. 8.
Conodont zonation, $\delta^{13}C_{carb}$, $\delta^{13}C_{org}$, and δ^{18} O_{phosph} values at Kronhofgraben. HBS: Hangenberg Black Shale equivalent (after KAISER, 2005).

Cima di Plotta Section

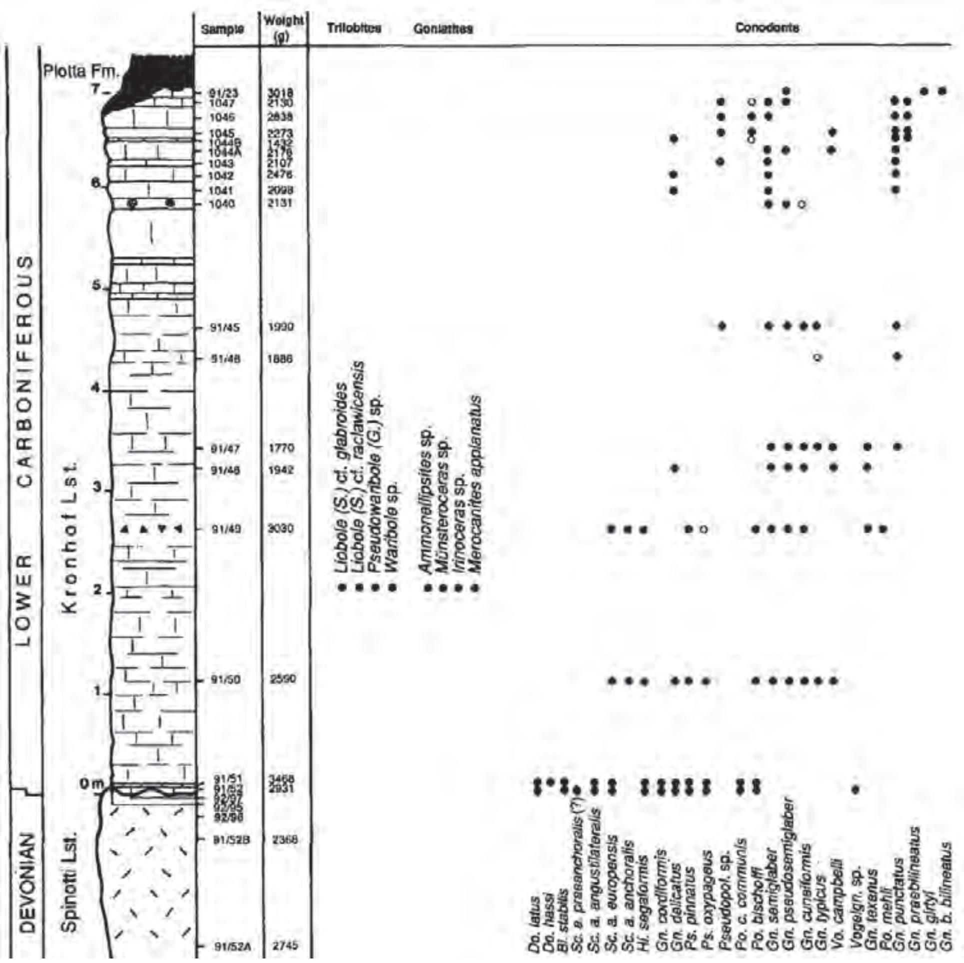
Coordinates: UTM 33, 339706 E, 5162243 N (Text-Fig. 2)

With the exception of the Kirchbach Formation, the youngest pre-Variscan limestones of the Carnic Alps occur at section Cima di Plotta east of Marinelli Hut (SCHÖNLAUB & KREUTZER, 1993). At this locality, shallow water limestones of presumably Middle Devonian age are disconformably overlain by some seven meters of cephalopod limestones of the Pal Grande Formation (Text-Figs. 9, 10). According to SCHÖNLAUB & KREUTZER (1993), they represent the youngest limestones prior to the onset of the flysch-type sedimentation of the Hochwipfel Formation at the end of the pre-Variscan sedimentary cycle.

Text-Fig. 9.
Cima di Plotta Section in the foreground. The unconformity between the Middle Devonian massive limestones in the foreground and the coarsely bedded Pal Grande Formation is exposed in the upper part of the limestone cliff (see white line). The contact between the Mississippian limestones (Pal Grande Formation) and the overlying Serpukhovian Plotta Formation is exposed near the surface of the grass-grown hill (Text-Fig. 10). Photo: Hans P. Schönlaub.

Text-Fig. 10.
Detail of Cima di Plotta Section showing disconformity between greyish Mississippian limestones (Pal Grande Formation) and unconformably overlying blackish Serpukhovian Plotta Formation. Note the distinct relief between both formations. Photo: Hans P. Schönlaub.

Overlying this limestone sequence of presumably lowermost Viséan age (Mississippian) a broad spectrum of distinct paleokarst features has been recognized including an extensive paleorelief, collapse breccias, silcrete horizons, fissures and small strata-bound ore deposits. In the subsurface even caves with cave sediments and paleokarst-related cements occur. According to Schönlaub et al. (1991), a drop in sea level (or alternatively uplift) during the late Tournaisian or early Viséan Stage resulted in extensive limestone dissolution and karstification at the surface and the subsurface including the formation of fissures, caves and breccias. At the same time, a high-porosity silcrete regolith developed at the surface exhibiting microporous and alveolar textures and void fillings of quartz, chalced-



Text-Fig. 11.
Distribution of trilobites, goniatites and conodonts from the Pal Grande Formation (formerly named "Kronhof Limestone") of Cima di Plotta Section (after Schönlaub & Kreutzer, 1993).

ony and mosaic quartz. Spar calcite coating of the caves may represent original speleothems, which predate densely laminated fine-grained internal cave sediments. Supposedly, radial fibrous calcite in the fissures was formed in a phreatic environment. Finely, during the transgression of the Hochwipfel Formation a slow rise in sea level promoted the formation of crystal silt and clastic internal sediment in fissures and the formation of breccias. At the end, a strong subsidence resulted in the formation of the flysch trough, which was filled by more than 1,000 m of siliciclastic rocks.

At Cima di Plotta Section the Mississippian part of the section comprise mainly wackestones and less abundantly mudstones and bioclastic packstones. The fauna consists of conodonts, trilobites and some goniatites (Schönlaub & Kreutzer, 1993). The trilobite assemblage is characterized by mixed blind and those with big or very big eyes; the only provisionally studied goniatites suggest an equivalent of the Erdbach Limestone of Sauerland in Germany and, consequently, belong into the lower part of the Viséan Stage of the type area in Belgium (Molinacean Substage, Poty et al., 2014). Following Kerp et al. (2006), they correspond to the Goniatite Stage of *Pericyclus* cuIIγ. The occurrences of conodonts such as *Gnathodus homopunctatus* and early representatives of *Gnathodus bilineatus bilineatus* and *Gn. praebilineatus,* respectively, are the main arguments for this age assignment (Text-Fig. 11).

Großer Pal (Pal Grande) Section

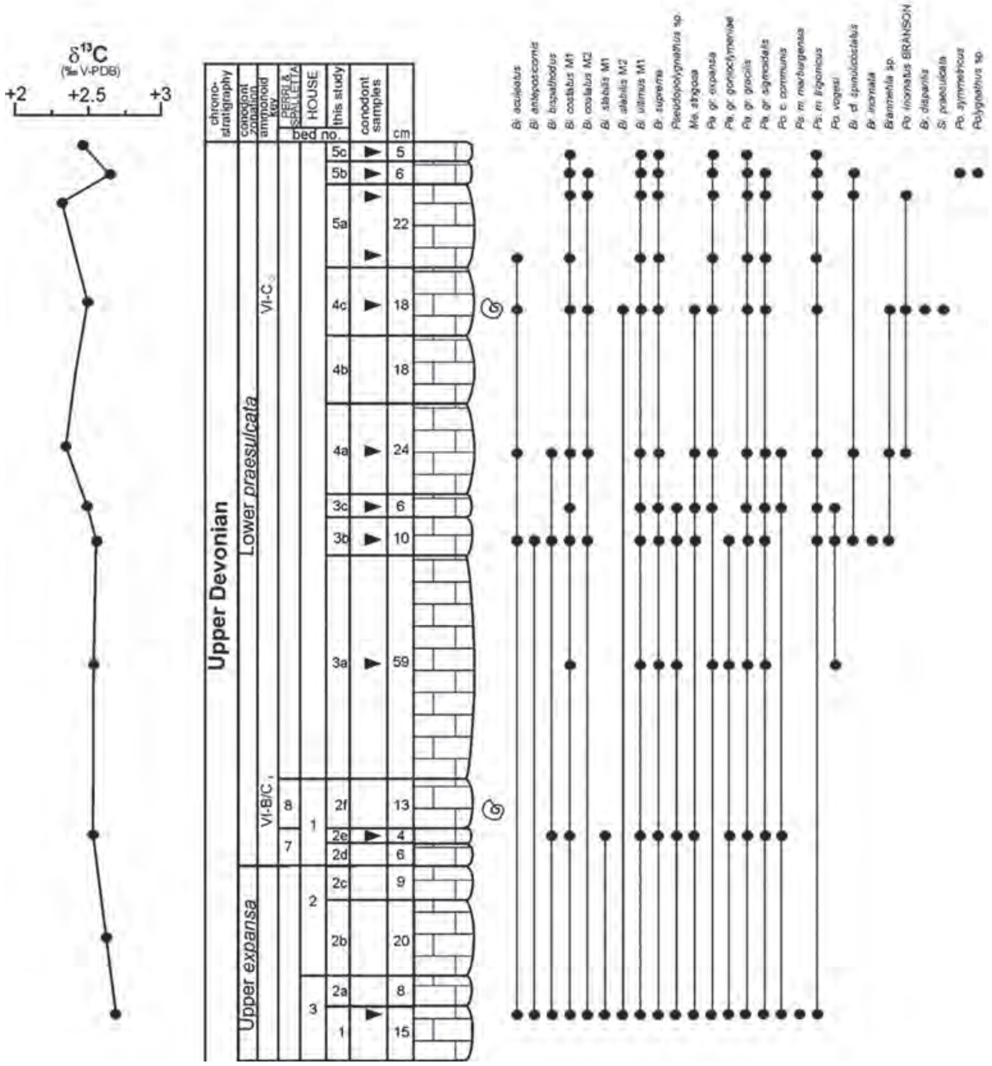
Coordinates: UTM 33, 346068 E, 5162664 N near boundary stone n-155a (Text-Fig. 2)

At the famous Großer Pal Section, some 6 km east of Plöckenhaus, the Famennian limestone succession has provided a rich conodont, ammonoid and trilobite assemblage ranging up to the Wocklumeria Stage. The uppermost limestone beds are overlain by the siliciclastic Hochwipfel Formation and thus, the equivalents of the Hangenberg Shale are not exposed (Text-Fig. 12). In the past four sections were studied for conodonts between the boundary stones n-155a and n-156.

Since the beginning of the 20th century the ammonoid and trilobite fauna was repeatedly studied by Schindewolf (1921), Richter (1913), Richter & Richter (1926) and von Gaertner (1931) following earlier studies of Frech (1887, 1894, 1902). For details, the reader is referred to the review of Schönlaub (1980) and Kaiser et al. (2009). In the 1960s, H. Alberti restudied the trilobites but this study was never completed. As far as trilobites are concerned, Richter (1913), Richter & Richter (1926) identified the following taxa: *Skemmatoceras elegans* Münster, *Phacops wocklumeriae* Richter, *Phacops anophtalmus* Frech, *Typhloproetus carinthiacus* Drevermann, *Typhloproetus gortanii* Richter, *Drevermannia carnica* Richter, *Caunoproetus palensis* Richter.

Without new systematic collecting, House & Price (1980) reviewed the Devonian ammonoid faunas of the Carnic Alps and in particular those from Großer Pal. In an up-to-date terminology the old collections of ammonoids from the Clymenia and Wocklumeria Stages comprise the following taxa: *Clymenia laevigata* (Münster), *Cl. singulata* Gümbel, *Cl. spiratissima* (Schindewolf), *Cymaclymenia striata* (Münster), *Kosmoclymenia subundulata* (Wedekind), *Discoclymenia cucullata* (von Buch), *Pr. sulcatum* (Münster), *Cyrtoclymenia lata* (Münster), *Progonioclymenia acuticosta* (Münster), *Kosmoclymenia undulata* (Münster), *Lobotornoceras escoti* (Frech), *Imitoceras lineare* (Münster), *Alpinites kayseri* (Schindewolf), *Cycloclymenia planorbiformis* (Münster), *Protoxyclymenia dunkeri* Münster), *Kosmoclymenia bisulcata* (Münster), *Costaclymenia binodosa* (Münster) and *Gonioclymenia speciosa* (Münster). The uppermost beds yielded *Kalloclymenia subarmata* (Münster), *Parawocklumeria distorta*, *Glatziella* sp. and *Cyrtoclymenia angustiseptata* (Münster). Additional ammonoid faunas are mentioned by Kaiser et al. (2009).

Text-Fig. 12.
The uppermost portion of Pal Grande Section II east of border stone n-155e. Photo: Hans P. Schönlaub.



Text-Fig. 13.
Conodont stratigraphy and $\delta^{13}C_{carb}$ values of Großer Pal Section II (KAISER, 2005).

Although this fauna has never been described in detail, it became obvious that with few exceptions the whole assemblage consists of dwarf-like small specimens indicating a fairly deep environment for the cephalopod limestones of the Pal Grande Formation. The conodonts were recently reviewed in SCHÖNLAUB (1980) based on unpublished data by Herbert Auferbauer. KAISER et al. (2009) recorded more than a dozen additional taxa from Section II (Text-Fig. 13).

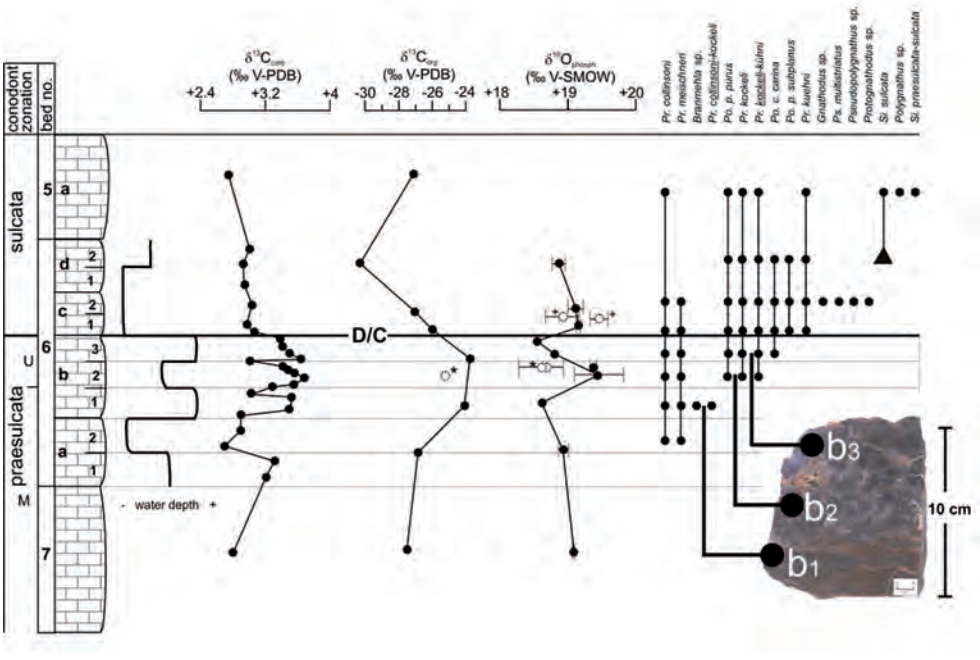
Mineralogy, geochemistry, stable isotopes and sea-level fluctuations

The studied and approximately 6 m thick Grüne Schneid Section comprises bioturbated wackestones with ostracodes, echinoderms, trilobites, ammonoids, brachiopods, radiolarians and bivalves. There is neither a break in sedimentation nor of any major change of the palaeoenvironment. Moreover, a significant biotic crisis cannot be recognized at the boundary level. Obviously, the successive changes of the faunas available at this section were related to subtle changes of sea level.

The available geochemical data on common and trace elements and on stable isotopes of carbon and oxygen at Grüne Schneid and Kronhofgraben sections display a similar pattern and confirm the conclusions drawn above. There is neither a distinct change of isotopes across the D/C boundary indicating major cessation of primary production in the sea or significant temperature changes nor is there any significant change of element distribution at either side of the boundary except for the barium and manganese contents (Text-Figs. 8, 14).

According to KAISER et al. (2008), a weak but significant positive carbon isotope signal in micrites and in the sedimentary organic matter occurs at Malpasso, Rio Boreado and Kronhofgraben sections from the Middle to the Upper *expansa* Zones, as could also be confirmed by new data from Franconia (KAISER et al., 2017). The positive excursions in the Carnic Alps coincide with a decrease in the oxygen isotope values of conodont apatite.

This signal indicates changes in the global carbon cycle during an episode of high seawater temperatures. Oxygen isotope data of conodont phosphate reflect sea-surface temperatures straddling between 25 and 29° C. However, according to KAISER (2005) and KAISER et al. (2006) at Grüne Schneid Section in the equivalent strata of the Hangenberg Event and the Hangenberg Black Shale, i.e. subbed 6b1 a positive isotope excursion of $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ was shown including increasing temperatures from the base



Text-Fig. 14.
Conodont zonation, $\delta^{13}C_{carb}$, $\delta^{13}C_{org}$, and $\delta^{18}O_{phosph}$ values at Grüne Schneid Section (KAISER, 2007). Water depth inferred from microfacies and occurrences of trilobites. Triangle = conodont record from SCHÖNLAUB et al. (1992). * values measured from Bed 6b (b1–b3), + values measured from Bed 6c (6c1–c2). After KAISER et al. (2006).

of the *S. praesulcata* Zone to the Hangenberg Black Shale horizon (subbed 6b1). The high seawater temperatures in the Lower Tournaisian are in accordance with a postulated warm climate during this time (KAISER, 2005: 90).

According to KAISER et al. (2006), this $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ isotope excursion at Grüne Schneid in 6b1 apparently correlates with coeval sections in the Rhenish Massif in which prior to the main regressional phase an increase in the deposition of organic matter is indicated. It was explained by redrawn of CO_2 from the atmosphere and increased formation of black shales (HBS) followed by a global regression of glacio-eustatic origin (KAISER et al., 2015). However, this apparently global event has not been demonstrated for the Grüne Schneid Section although a minor peak of some 4° C occurs (see also recent geochemical data from Grüne Schneid by KUMPAN et al., 2014 and BABEK et al., 2016).

As pointed out by SCHÖNLAUB et al. (1992) the Grüne Schneid Section suggests an overall stable and moderately deep marine environment at the passage from the Devonian to the Carboniferous. However, depth related changes of trilobites and conodonts can be recognized at the base of subbed no. 6b1. At this level water depth increased until the base of subbed 6c with minor fluctuations. At this horizon coinciding with the appearance of *Siphonodella sulcata* a slight lowering of sea-level occurred which lasted through the basal part of the Lower Carboniferous until the onset of the duplicata conodont zone when a moderately deeper environment was established (Text-Fig. 14).

In comparison with the Kronhofgraben section, the latter represents a deep-water offshore limestone section with the intercalation of the 30 cm thick black Hangenberg Shale at the D/C boundary. At Kronhofgraben data on the lithofacies, conodont biofacies and composition of the macrofauna indicate a deeper environment than at Grüne Schneid.

The 30 cm thick pyritiferous Hangenberg Black Shale at Kronhofgraben intercalated in the Pal Grande Formation corresponds to subbed no. 6b1 at Grüne Schneid, which also displays increased clay content. State-of-the-art geochemical analysis across this shale horizon indicate that it is moderately to strongly enriched in heavy metals and in particular high contents of cobalt, chromium, copper, nickel and lead. In addition, high contents of organic carbon, sulfur, arsenic, antimony, uranium and lanthanum and selected Rare Earth elements such as Lanthan, Dysprosium and Ytterbium were recorded. Locally, the FeS_2 content increases to more than 11 %.

In our opinion, this shale intercalation indicates a starvation event that affected the ocean at the end of the Devonian. Apparently, this event – although weaker expressed – can be seen at Grüne Schneid Section. We consider this shale event as a submerged deep-water anoxic deposit formed in an aphotic stagnant basin under reducing conditions. In our concluding remarks the strong subsidence was caused by extensional rifting prior to the Variscan orogenetic climax (Text-Fig. 14).

Conclusions

Based on an international agreement and ratification by the International Commission on Stratigraphy (ICS) the Devonian/Carboniferous boundary was drawn at the La Serre Section E' in the Montagne Noire of Southern France by the first appearance of the index conodont *Siphonodella sulcata* (PAPROTH 1991). However, it was soon realized by experts (e.g., ZIEGLER & SANDBERG, 1996) that this section is not an ideal one since the boundary interval is represented by an oolitic facies, lacks ammonoids and other biostratigraphically important fossil groups (see comprehensive summaries in KAISER et al., 2015 and BECKER et al., 2016). Moreover, an evolutionary lineage from *Siphonodella praesulcata* to *S. sulcata* is not well established (KAISER, 2009), which finally gave rise to a new Working Group on the DCB. Hence, besides the designation of auxiliary stratotypes in China and Germany and the proposal for an event-based boundary characterized by the occurrence of the Hangenberg Black Shale (WALLISER, 1984, 1996) different opinions about the choice and designation of the La Serre Section as type section for the DCB persisted until present times.

Since the establishment of an ICS Working Group to redefine the Devonian/Carboniferous boundary (Montpellier, September 2016), the DCB has been under revision and new criteria for definition are being discussed, e.g., base of *Protognathodus kockeli* Zone, beginning of radiation, top of major regression and end of mass extinction. If these criteria are generally applied and finally ratified most of the worldwide known sections would face a lower position of the DCB than at present state.

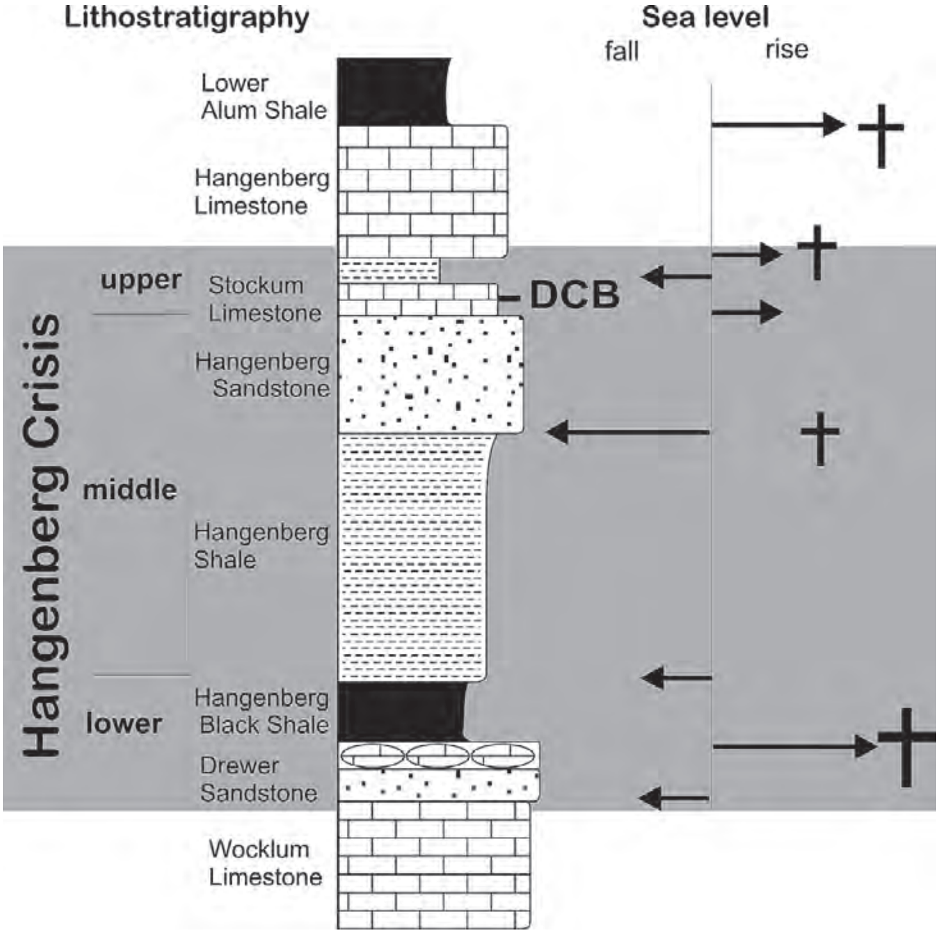
According to Kaiser et al. (2015), the global Hangenberg Crisis near the Devonian/Carboniferous boundary (DCB) represents a mass extinction comparable to the 'Big Five' first-order Phanerozoic events (Text-Fig. 15). It affected the marine and terrestrial environments within a geologically short time span of approximately 100–300 kyr. The sequence of events started (1) with a minor eustatic sea-level fall in the uppermost Famennian and was followed by widespread deposition of black shales (Hangenberg Black Shale). This event is hold responsible for the extinction of ammonoids, trilobites, conodonts, stromatoporoids, corals, deep-water ostracodes and probably also for placoderms, chitinozoans and early tetrapods. Apparently, brachiopods, neritic ostracodes, bryozoans and echinoderms were less severely affected. This phase coincided with a global carbonate crisis and a distinctive positive carbon isotope excursion as a consequence of climate-salinity-driven oceanic overturns and widespread off-shore marine eutrophication.

The middle crisis (2) is characterized by a gradual eustatic sea-level fall that caused the progradation of the siliciclastic shallow-water Hangenberg Sandstone, which does not occur in the Carnic Alps. However, it produced widespread unconformities, reworking and hiatuses known also in the Carnic Alps (e.g. sections Cima di Plotta, Pal Grande and many others). According to Kaiser et al. (2015) this regression coincided with a regional if not global glaciation and deposition of diamictites in South America and different parts of Africa as well as tropical mountain glaciers in eastern North America. It may have followed the drawdown of atmospheric CO_2 levels due to the massive burial of organic carbon, which are represented as black shale deposits.

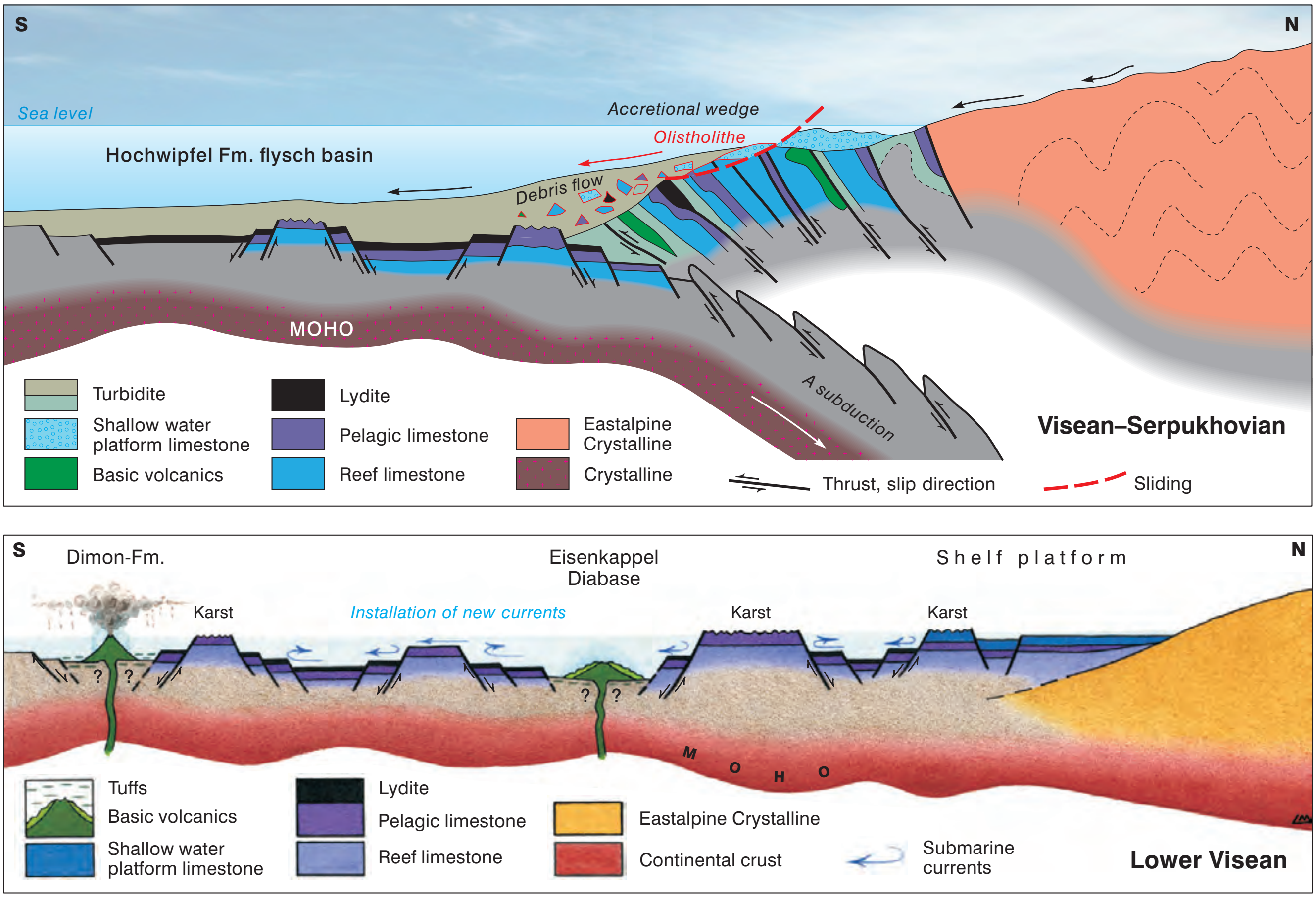
The upper Hangenberg Crisis (3) in the latest Famennian is characterized by a post-glacial transgression and expressed as a second carbon isotope spike and the early radiation of several fossil groups. During this interval, smaller-scale sea-level oscillations and climatic fluctuations are still occurring as well as minor reworking events and unconformities. Still poorly understood are the extinctions of the last clymeniid ammonoids, phacopid trilobites, placoderms and some brachiopod and foraminifera groups.

The post-crisis interval during the Lower Tournaisian is characterized by continuing sea-level rise and significant radiations under greenhouse conditions.

At Grüne Schneid Section, Kaiser (2005, 2007) proposed to place the position of the DCB at the base of subbed 6c1 with the entry of *Protognathodus kuehni*. This horizon is one subbed below the original boundary drawn by Schönlaub et al. (1992) at subbed 6d when *Siphonodella sulcata* was first recognized.



Text-Fig. 15.
The Hangenberg Crisis. Extinction episodes, sedimentology and sea-level changes at the Devonian/Carboniferous boundary. Crosses denote extinction episodes (after Kaiser et al., 2015: Fig. 2).



Text-Fig. 16.
Tectonic transformation from horst-and-graben-style tectonics during the Devonian to the Lower Carboniferous Viséan Stage of the Carnic Alps (below) to the formation of an accretionary wedge in the Viséan to Serpukhovian Stages of the Carboniferous resulting in mass movements (olistostromes and olistoliths) of shallow water platform sediments into the flysch basin. Graphic strongly modified by M. Brüggemann-Ledolter from Läufer et al. (1993, 2001).

From the data described in the introductory chapters for the Ordovician to the Devonian Periods, an increasing degree of sea-floor mobility can be inferred resulting in more or less distinct regressive and transgressive cycles. Whether or not these pulses were solely caused by drifting plates within the Rheic Ocean, subduction processes at active plate margins or enhanced spreading activities cannot be answered from our local perspective. Without doubt, the culmination of these geodynamic perturbations occurred during the second half of the Devonian and the beginning of the Carboniferous Period when the Carnic Alps were affected by strong extensional tectonics creating a distinct horst-and-graben-like morphology of the seafloor. At the beginning of the Variscan Orogeny during the “Middle” Carboniferous, this tectonic turnover increased and changed to an accretionary wedge (Text-Fig. 16).

The Upper Devonian (Famennian) to Lower Carboniferous sediments reflect an off-shore pelagic environment inhabited by pelagic organisms such as cephalopods, trilobites, bivalves, conodonts, radiolarians, foraminifera and some echinoderms.

The results from 47 sections covering the eastern and central Carnic Alps indicate that the limestone sedimentation lasted without major breaks from the Late Devonian to the base of the Viséan Stage. However, this huge pile of calcareous sediments was affected by distinct subsurface and surface karst features, which are related to the unconformity that separates the Late Devonian–Lower Carboniferous limestone sequences from the overlying siliciclastic flysch deposits of the Hochwipfel Formation. At the Cima di Plotta Section east of Marinelli Hut and west of Plöckenpass (Passo Monte Croce Carnico) the unconformity between the limestone succession and the overlying flysch deposits is best displayed (Text-Figs. 8–10). The silcrete horizon atop the limestone sequence apparently reflects a regolith or fossil soil horizon suggesting the development of karst during an emersion associated with this unconformity.

According to Kaiser et al. (2008, 2009) the general faunal changes in the Upper Devonian might have been influenced by local tectonics, i.e., short-term repeated regressive-transgressive pulses influencing the environment.

New data on stable isotope data from southern Europe including the Carnic Alps reflect a complex pattern of oceanographic and climatic change in the Upper Famennian–Lower Tournaisian interval. For these changes repeated enhanced C_{org} burial and fluctuating seawater temperatures are hold responsible reflected by positive carbon isotope excursions in micrites (Kaiser et al., 2008).

The causal factors for these global changes are explained by a combination of several factors including high marine productivity leading to elevated rates of organic matter burial, increasing seawater temperatures during the Middle to Upper *expansa* Zones, stepwise transgressions, global spread of swamp vegetation indicating a humid climate and Eo-Variscan tectonic movements resulting in uplift, erosion and re-sedimentation. It should be noted, however, that with the exception of the Hangenberg Black Shale widespread black shale deposition are missing in the Middle *expansa* Zone interval of the Carnic Alps and hence do not apply to this region or support this "black shale idea" from a local perspective.

However, according to Sandra I. Kaiser (pers. comm.) one explanation is coming from the Carnic Alps, which supports the model of enhanced C_{org} burial probably on a global scale: Although in the Carnic Alps shales of the *expansa* Zone do not occur, enhanced C_{org} burial resulted in positive carbon isotope excursion during this time. Such an excursion helps to identify events (in this case a globally enhanced C_{org} burial) even when they are not lithologically expressed (as in the Carnic Alps). Consequently, the Carnic Alps apparently play a key role in recognizing environmental changes in the *expansa* Zone of the Famennian.

Recently, the Frasnian-Famennian (F-F) biotic crises has been linked to climatic perturbations triggered by volcanic cataclysm, which is documented by mercury anomalies as the diagnostic proxy (Racki et al., 2018). Based on such anomalies at other major extinction events of the Phanerozoic (e.g. LOME, in the Late Ordovician, Permian-Triassic and the Cretaceous-Paleogene boundaries), the general implication was drawn that paroxysmal volcanic activity promoted global warming, marine anoxia and rising sea level as the prime driver of lethal global extinctions (Jones et al., 2017; Lécuyer, 2018; Bjerrum, 2018; Zou et al., 2018). At present, the climatic perturbations at the DCB of the Carnic Alps are not well understood as they can either be attributed to a rise in sea-water temperature and a short-termed transgressive phase and warm temperatures during the Hangenberg Black Shale deposition (Kaiser et al., 2006) or driven by an opposing short-lived glacio-eustatic sea-level fall.

In the Carnic Alps biofacies changes are reflected in the distribution of ammonoids, trilobites and conodonts. They are well recognizable and can be correlated with environmental changes. With regard to trilobites, the reduction of eyes in the late Upper Devonian presumably reflects an adaptation to a deeper environment below the photic zone. However, this habit changed towards exclusively good developed eyes in subbed nos. 6b2 and 6c at Grüne Schneid Section immediately below the D/C boundary suggesting a slightly shallower environment. In general, this bathymetric change reflects the final stage of the end-Devonian regression. Following this shallowing at the beginning of the *duplicata* conodont Zone (subbeds nos. 5c, 4, 3, 2, 1) a slight deepening occurred with the appearance of trilobites with reduced eyes together with forms with normal eyes.

The change from a palmatolepid-polygnathid to a palmatolepid-bispatodid-branmehlid conodont biofacies might also be influenced by anoxic conditions and repeated transgressive phases causing changing sedimentary pattern. According to Kaiser et al. (2008), enhanced burial of organic matter in the Upper *praesulcata* Zone can be referred to high rates of continental weathering and a glacioeustatic sea-level rise. The protognathids and some polygnathids start to radiate in the Upper *praesulcata* Zone following the main extinction of the Hangenberg Event at horizon 6b1. In the Austrian part of the Carnic Alps, the latter is only locally developed at Kronhofgraben Section; in Italy it has been recognized at Plan di Zermula Section A on the north-western edge of Monte Zermula.

To conclude, in our opinion the first appearance of *Protognathodus kockeli* does not seem to be a good candidate for the base of the Tournaisian Stage as it co-occurs at Grüne Schneid with several typical late Famennian conodonts, goniatites and ammonoids. Based on new data kindly provided by Sandra Kaiser (preliminary results published in Kumpan et al., 2018) we rather are in favour of the index conodonts *Siphonodella sulcata* and/or *Protognathodus kuehni* to define the base of the Carboniferous to be placed at Grüne Schneid Section at the base of subbed 6c. It thus confirms the position of the DCB originally suggested by Kaiser (2005).

Acknowledgements

This review on the D/C boundary in the Carnic Alps benefitted very much from various authors and previous studies. Most of these are cited in the text but special thanks go to Sandra I. Kaiser (Stuttgart) and Carlo Corradini (Cagliari) who kindly provided special information and advice on ranges and revisions on older conodont collections stored at local institutions. In addition, the author is much indebted to Monika Brüggemann-Ledolter from the Geological Survey of Austria for the graphics used in this report. We feel this is no final end of the story covering the D/C boundary. However, from the viewpoint of the Carnic Alps a major step has been reached which may serve as solid scientific base for further studies on this subject.

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