Conodonts across the Silurian/Devonian boundary in the Carnic Alps (Austria and Italy)

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ABSTRACT

In the Carnic Alps, located across the border between Italy and Austria, several sections span the Silurian/Devonian boundary in different sedimentary settings, from very shallow water to moderately deep shelf. All studied sections yielded conodonts and based on the first and last occurrences of the conodont taxa in the upper part of the Upper *Oul. el. detortus* Zone and in the lower part of the *I. hesperius* Zone a detailed conodont biostratigraphic framework was able to be constructed for this interval. Comparison of data from different depositional settings demonstrates that, although the majority of species are documented everywhere in the Carnic basin, a few taxa, mainly represented by coniforms, are limited to shallow water, whereas others, mainly ozarkodinids, occur only in open sea deposits.

1. Introduction

The Silurian/Devonian boundary is defined by the first appearance datum of the graptolite species *Monograptus uniformis* Pribyl in the Klonk section, Czech Republic. Graptolites are abundant and easy to study in pelitic facies represented by black shales, but are rare (and often absent) in calcareous facies. On the other hand, conodonts are abundant in limestones, and are very rare in the shales. Thus, different biostratigraphic schemes have been developed for the two facies, utilizing graptolites for the shales (e.g., Koren et al., 1996; Melchin et al., 2004; Sadler et al., 2009; Cramer et al., 2011) and conodonts for the limestones (e.g., Aldridge and Schönlaub, 1989; Corradini and Serpagli, 1999; Jeppsson et al., 2006; Cramer et al., 2011; Corradini and Corriga, 2012; Corradini et al., 2015a). A comparison of the schemes based on graptolites and conodonts is difficult due to the limited co-occurrence of those fossils in the same rocks, even though several attempts have been made (e.g., Cramer et al., 2011; Melchin et al., 2012). However, the precise time equivalence of zonal bases of the two schemes is often approximated.

Because the base of the Devonian is defined by the FAD of a graptolite, the precise placement of the S/D boundary in many calcareous sections is difficult. In general, the entry of representatives of the genus *Icriodus* are considered as evidence of Devonian age. For a long time the *I. woschmidti* Zone was considered to be the basal Devonian conodont zone of the Devonian (Walliser, 1964; Aldridge and Schönlaub, 1989; Corradini and Serpagli, 1999; Corriga and Corradini, 2009; Corriga et al., 2009a). According to Jeppsson (1988), *I. woschmidti* Ziegler occurs slightly before *M. uniformis* in many sections, but that fact could be due to facies control (Corradini and Corriga, 2012). Carls et al. (2007) noted that most of the early Lochkovian *Icriodus* attributed to *I. woschmidti*, actually belong to *I. hesperius* Klapper and Murphy or to other undescribed species of *Icriodus*, and stated that *I. woschmidti* enters slightly higher in the lower Lochkovian, based on data from the type locality only. Therefore, these authors suggested that the conodont taxon "with wide distribution that appears closest to the Lower Devonian boundary" is *I. hesperius* (Carls et al., 2007, p. 157–158). This opinion is accepted by several authors (e.g., Corriga, 2011; Corradini and Corriga, 2010, 2012; Slavík et al., 2012; Mavrinskaya and Slavik, 2013; Corradini et al., 2015a; Schönlaub et al., 2017b) and the basal Devonian conodont zone has been redefined accordingly, as the *I. hesperius* Zone, in all the more recent biozonation schemes (Corradini and Corriga, 2012; Corradini et al., 2015a). Also, it should be noted that *I. woschmidti* is documented at the Silurian/Devonian boundary or in the lowermost Devonian in several localities around the world (see Suttner et al., 2018 and references therein). However, typically icriodontids are found in shallow water deposits (Bultynck, 2003), but may be rare in other marine environments.

In the Carnic Alps several sections expose sediments across the

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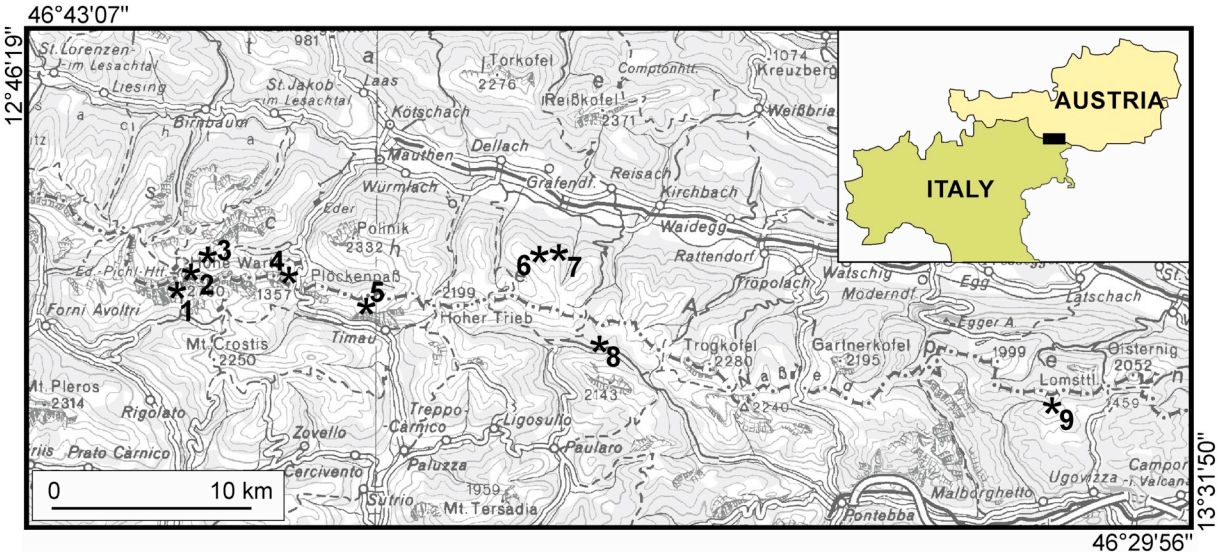

Fig. 1. Map of the Carnic Alps with locations of the studied sections: 1) Rifugio Lambertenghi Fontana III; 2) Seewarte; 3) Rauchkofel Boden; 4. Cellon; 5) Freikofel South II; 6) Oberbuchach II; 7) Oberbuchach Ib; 8) Rio Malinfier West; 9) Monte Cocco II.

Silurian/Devonian boundary (Fig. 1) in various depositional settings, from very shallow water to moderately deep, to deep shelf environments. Herein we present conodont data from nine mainly calcareous sections in order to define a series of first or last occurrences of conodont taxa in the uppermost Silurian and lowermost Devonian beds, that can be used to approximate the Silurian/Devonian boundary, beside the first occurrence of *Icriodus*. Furthermore, the comparison of the conodont associations from the different sections provides evidence for a possible palaeoecological control on the distribution of taxa in shallow and deeper depositional settings.

2. Geological setting

The Carnic Alps are located on either side of the Italian-Austrian border. Here, one of the best exposed and complete Palaeozoic successions in the world, ranging from the Middle Ordovician to the late Permian, is exposed. During the early Palaeozoic the Carnic Alps belonged to the group of terranes (Galatian terranes; von Raumer and Stampfli, 2008) that detached from the northern Gondwana margin during the Early Ordovician and moved northward faster than the main supercontinent. The drift, from about 50°S in the Late Ordovician, to 35°S in the Silurian and to the tropical belt in the Devonian (Schönlaub, 1992) is reflected by distinct litho- and biofacies patterns.

Three sedimentary sequences are distinguished in the Carnic Alps: the Pre-Variscan, the Permo-Carboniferous and the Alpine. The Pre-Variscan sequence includes rocks of Middle Ordovician to lowermost Pennsylvanian age and represent one of the better preserved and continuous succession for this interval in the world. This sequence was affected by the Variscan Orogeny during the late Bashkirian and early Moscovian (Schönlaub, 1980; Venturini, 1990; Schönlaub and Forke, 2007) and by extensional as well as compressional and transpressional Alpine phases (Venturini, 1990; Läufer, 1996), which formed a fold and thrust belt. Despite the severe deformation, the succession is mostly non-metamorphic (Brime et al., 2008).

Four main lithofacies, representing different depths of deposition and hydrodynamic conditions, have been described in the Silurian and lowermost Devonian of the Carnic Alps (Schönlaub, 1979, 1980; Wenzel, 1997). The Wolayer-facies is characterized by proximal sediments and the Bischofalm-facies by deep water euxinic deposits, whereas the Plöcken-facies and the Findenig-facies are intermediate between the former. In rough approximation, the four facies seem to replace each other from north-west to south-east in the western and central sectors of the Carnic Alps. The depositional features suggest an overall transgressional regime from the Llandovery through Ludlow. A general sea-level curve for the Silurian of the Carnic Alps was presented by Brett et al. (2009).

The lithostratigraphy of the Pre-Variscan sequence was recently formalized (Corradini and Suttner, 2015) and thirty-six formations were discriminated. Four units span the Silurian/Devonian boundary (Alticola Fm., Seekopf Fm., Nölbling Fm. and Bischofalm Fm.), whereas the Rauchkofel Fm. starts at the very base of the Lochkovian (Fig. 2). These units are briefly introduced below, and for a detailed description

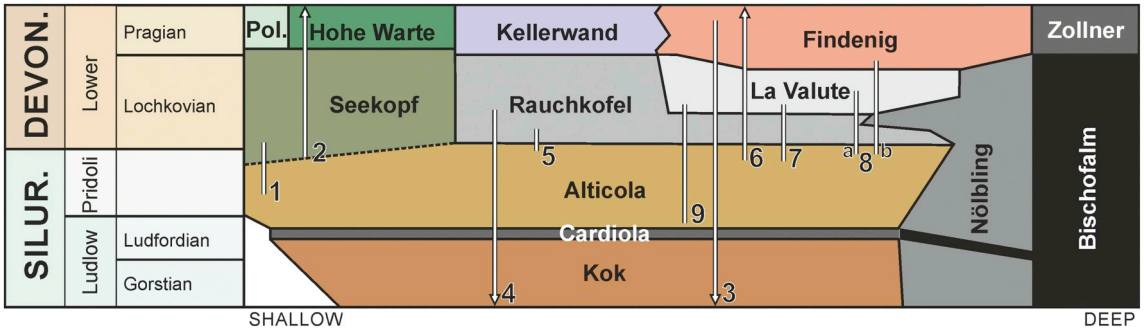

Fig. 2. Lithostratigraphic scheme of the uppermost Silurian and lowermost Devonian of the Carnic Alps (after Corradini et al., 2015c, modified). Vertical bars indicate the stratigraphic range of the studied sections: 1) Rifugio Lambertenghi Fontana III; 2) Seewarte; 3) Rauchkofel Boden; 4. Cellon; 5) Freikofel South II; 6) Oberbuchach II; 7) Oberbuchach Ib; 8) Rio Malinfier West (a: lower part; b: upper part); 9) Monte Cocco II. Abbreviation: Pol. = Polinik Fm.

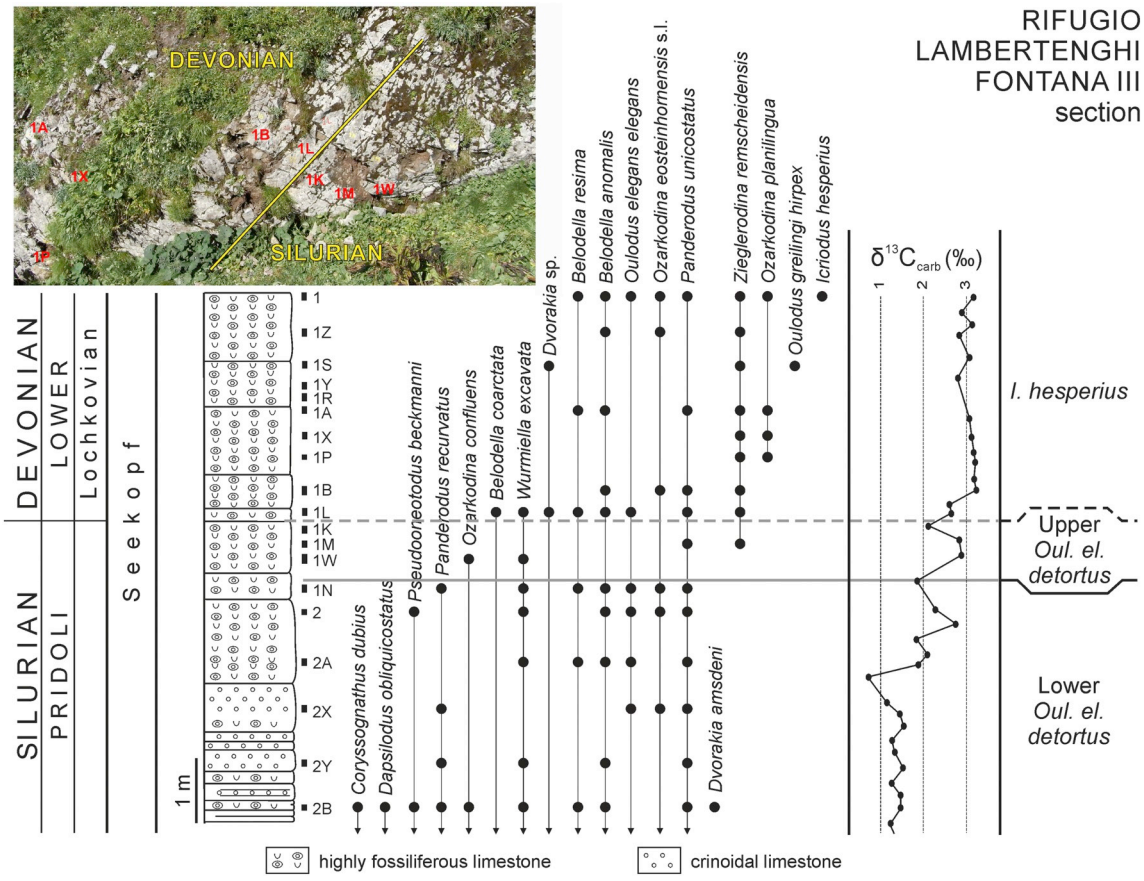

Fig. 3. Distribution of conodonts across the Silurian/Devonian boundary in the Rifugio Lambertenghi Fontana III (RLF III) section. From left to right: series, stage, formation, lithological log (after Corradini and Corriga, 2010, modified), samples, distribution of taxa, $\delta^{13}C_{carb}$ data (after Corriga et al., 2009b), conodont zones. Arrows at the end of distribution lines indicate that the taxon also occurs below the illustrated interval. The photo shows the detail of the section across the S/D boundary, with indication of the samples.

see Corradini and Suttner (2015). The Alticola Fm. (Ferretti et al., 2015) consists of well bedded cephalopod bearing wackestone to packstone of Ludlow-earliest Lochkovian age; the Silurian/Devonian boundary lies in the uppermost part of the unit, very close to its top. The Seekopf Fm. (Suttner et al., 2015) consists of a mostly grayish very shallow water lithoclastic limestone with abundant fossil debris, of Přídolí-early Pragian age. The Nölbling Fm. (Schönlaub et al., 2015a) consists mainly of black shales with nodules and layers of dark cephalopod wackestone to mudstone. Its age spans the early Silurian through the end of Lochkovian. The Bischofalm Fm. (Schönlaub et al., 2015b) consists of black siliceous and alum shale of Llandovery to Lochkovian age. The Rauchkofel Fm. (Corradini et al., 2015b) consists of mainly laminated dark grey well bedded platy mudstone to wackestone with intercalation of black shales and marls, and locally conglomerates, of Lochkovian age.

3. Biostratigraphy

The biostratigraphic scheme used in this paper was established by Corradini and Corriga (2012) for the Přídolí and Lochkovian of the Carnic Alps. In the latest Přídolí the Upper *Oul. el. detortus* Zone is discriminated as the interval above the last occurrence of either *Dapsilodus obliquicostatus* (Branson and Mehl) or *Panderodus recurvatus* (Branson and Mehl) or *Coryssognathus dubius* (Rhodes). The base of the Devonian is discriminated by the FAD of *I. hesperius*, marker of the eponymous zone. In the upper part of the lower Lochkovian the *I. postwoschmidti* Zone is distinguished. However, because the marker is very rare, the base of the zone can be tentatively recognized by the first occurrence of *Pandorinellina optima* (Moskalenko), or *Lanea omoalpha* Murphy and Valenzuela-Rios, or *Wurmiella wurmi* (Bischoff and Sannemann), as already done by Corriga et al. (2016) and Schönlaub et al. (2017b).

4. Material and methods

Studied material belongs to previous collections stored in various institutions and also includes new material. The Geoscience Centre of the Georg-August University of Göttingen (Germany) hosts the original collection from the Cellon section by Walliser; the Austrian Geological Survey in Vienna, Austria (GBA), houses the collections from Rauchkofel Boden, Seewarte, Oberbuchach Ib and Oberbuchach II; the collection from Monte Cocco II is stored at the Palaeontological Museum of Modena and Reggio Emilia University, Italy (IPUM); conodonts from Rio Malinfier West and Freikofel South II are stored at the Museo Friulano di Storia Naturale in Udine, Italy (MFSNgp); the collection from Rifugio Lambertenghi Fontana III, and recently collected material from Cellon, Rauchkofel Boden and Seewarte are housed at the Palaeontological Museum of Cagliari University, Italy (MDLCA).

New conodont samples were decalcified using the conventional formic acid technique in the laboratories of the Department of Chemical and Geological Sciences of Cagliari University. Residues were sieved with a 100 μm sieve and picked under a binocular stereomicroscope.

5. Study sections

Data from nine sections have been considered in this study of conodont faunas across the Silurian/Devonian boundary in the Carnic Alps. From west to east: Rifugio Lambertenghi Fontana III, Seewarte,

Rauchkofel Boden, Cellon, Freikofel South II, Oberbuchach II, Oberbuchach Ib, Rio Malinfier West and Monte Cocco II (Fig. 1). These sections are distributed along the whole Carnic Alps, covering various geological settings (Fig. 2), from shallow water to moderately deep shelf. Detailed information on the geographic position, the lithostratigraphy and depositional settings of these sections, as well as the discussion on conodonts' ranges across the Silurian/Devonian boundary, is discussed below.

5.1. Rifugio Lambertenghi Fontana III (RLF III)

The Rifugio Lambertenghi Fontana III section (Fig. 3) is located in a World War I trench, immediately west of the path from Rifugio Lambertenghi Romanin to Mt. Capolago, at coordinates 46°26′22.7″ N, 12°52′05.4″ E. The section exposes about 15 m of shallow water very coarse-grained grainstones and packstones of the Seekopf Fm. and was studied by Corradini and Corriga (2010). The section is highly fossiliferous, and the fossil content increases toward the top of the section. However, the state of preservation of the fauna is poor. Crinoids are always abundant and brachiopods often present, in places concentrated in centimeter-thick shelly horizons. The fauna also includes bivalves, nautiloid cephalopods, rare trilobites and solitary corals. Conodont ranges in the upper part of the section are updated below.

Conodonts are rare in the upper part of the section, and some samples were barren. The base of the Upper *Oul. el. detortus* Zone has been placed just above sample RLF III 1N, where *Panderodus recurvatus* has its last occurrence. *Ozarkodina confluens* (Branson and Mehl) has its last occurrence in sample RLF III 1W, and *Zieglerodina remscheidensis* (Ziegler) enters just above (sample RLF III 1M); *Zieglerodina* sp. A Corriga et al., 2016 is present in sample 1S, and *Icriodus hesperius* is reported only from sample RLF III 1 (Fig. 3). The S/D boundary is placed about 3.5 m below the top of the section, at the level of sample RLF III 1L by Corradini and Corriga (2010) combining conodont and $\delta^{13}C_{carb}$ data: in fact, it lies in the upper part of the prominent $\delta^{13}C_{carb}$ shift, and just before the $\delta^{13}C_{carb}$ values reach their maximum. This shift in $\delta^{13}C_{carb}$ began in the latest Přídolí, and the position of the S/D boundary within the ascending limb of this positive excursion (Silurian/Devonian boundary Klonk $\delta^{13}C_{carb}$ Excursion) has been documented from different areas, globally (e.g., Saltzman, 2002; Buggisch and Mann, 2004; Jacobi et al., 2009; Malkowski et al., 2009).

5.2. Seewarte (Sew)

The Seewarte section (Fig. 4) is located along the northwestern and western base of Mt. Seewarte, starting from the western end of the Wolayer Valley, and continuing south across the state border, at coordinates 46°36′44.5″ N, 12°52′21.4″ E (base). It is a long, almost 350 m thick, classical section exposing rocks from the uppermost Silurian to the Emsian, and it is the type section of the four formations of the shallow water sequence exposed (Seekopf Fm., Hohe Warte Fm., Seewarte Fm. and Lambertenghi Fm.). The section was described in detail by Bandel (1969), and the conodont fauna was studied by Suttner (2007). The lowermost part of the section was resampled in detail for this study. The Seewarte Fm. consists of grey wackestone-packstones and interbeds of densely packed bioclastic grainstones.

Conodonts are very abundant in the lower part of the Seewarte section, where the association is dominated by *Wurmiella*, mainly *W. excavata* (Branson and Mehl). The last occurrence of *Ozarkodina confluens* occurs in sample 4 (Fig. 4). *Zieglerodina remscheidensis* (Ziegler) enters in sample 5; from the same level a poorly preserved element, tentatively assigned to *Z.* cf. *eladioi* (Valenzuela-Rios), was recovered. The Silurian/Devonian boundary can be tentatively placed just below sample 01/03, where Suttner (2007) collected an element attributed to the genus *Icriodus*. *Dvorakia* aff. *chattertoni* Klapper and Barrick occurs up to sample 01/04, 50 cm above the boundary.

5.3. Rauchkofel Boden (RKB)

The Rauchkofel Boden section (Fig. 5) is located on the southwestern slope of Mt. Rauchkofel, at coordinates 46°36′54″ N, 12°52′30″ E, and an altitude of 2175 m. It is easily accessible along the trail running from the Lake Wolayer to the top of Mount Rauchkofel and is one of the best known and most fossiliferous sections of the whole Carnic Alps. About 65 m of calcareous rocks spanning the Upper Ordovician to the Lower Devonian are exposed. Several papers deal with various aspects of the geology, stratigraphy and fossil content of the section, since it was described for the first time by Heritsch (1929) and von Gaertner (1931). For a summary of these works and an updated chrono-, litho- and conodont bio-stratigraphy of the section, refer to Schönlaub et al. (2017b). Conodonts were illustrated by Schönlaub (1980), Schönlaub et al. (2017b) and, limited to the Ordovician, by Ferretti and Schönlaub (2001).

In the Rauchkofel Boden section the Přídolí and the lower Lochkovian are represented by the Alticola and the Rauchkofel formations. The Silurian/Devonian boundary is drawn in the uppermost part of the Alticola Fm., about 40 cm below its top, where the basal Devonian conodont *Icriodus woschmidti* was recovered (Fig. 5). The overlying Rauchkofel Fm. (Corradini et al., 2015b) is here extremely condensed and consists of 1.80 m thick thin-bedded limestone beds interbedded with black shales of Lochkovian age.

The Upper *Oul. el. detortus* Zone is identified at the Rauchkofel Boden section in beds of samples 7X-200 (Schönlaub et al., 2017b). Due to the scarcity of conodonts in the middle part of the Alticola Fm. in this section, some taxa that normally already occur in older beds here enter (*Oulodus el. elegans* (Walliser), *Oul. el. detortus* (Walliser) and *Zieglerodina planilingua* (Murphy and Valenzuela-Ríos) or are limited to this zone (*Z. zellmeri* Carls et al.). In the upper part of the Upper *Oul. el. detortus* Zone the last occurrence of *Oz. confluens* is recorded in sample 7Z, just followed by the first occurrences of *Z. remscheidensis* and *Z. eladioi* in sample 199, and by the last occurrence of *Z. zellmeri* in sample 7W.

The *Icr. hesperius* Zone is discriminated in a very short interval, 40 cm thick, across the boundary between the Alticola and the Rauchkofel formations (Fig. 5). The index taxon is not present, and the S/D boundary is recognized by the first occurrence of *I. woschmidti*, which enters at the same level of *I. hesperius* in the Carnic Alps (Corradini and Corriga, 2012). *Zieglerodina* sp. A occurs within the *I. hesperius* Zone (samples 221 and 7A).

5.4. Cellon

The Cellon section (Fig. 6) is located in a narrow avalanche gorge on the eastern flank of Mt. Cellon, at an altitude of about 1500 m, at coordinates 46°36′32″ N, 12°56′31″ E, close to the Austrian/Italian border. It is accessible by a short walk from Plöcken Pass/Passo di Monte Croce Carnico. Rocks from the Upper Ordovician to the Lower Devonian belonging to six lithostratigraphic units (Uqua Fm., Plöcken Fm., Kok Fm., Cardiola Fm., Alticola Fm. and Rauchkofel Fm.) are exposed at this locality.

The Cellon section is likely the most famous Silurian section in the world, and is the reference section for many Ordovician, Silurian and Devonian studies. The conodont fauna was studied and described by Walliser (1957, 1964), whose pioneering work on the section resulter in the first proposed Silurian conodont zonation (Walliser, 1964). Subsequent studies on the Cellon section have documented the composition and distribution of several fossil groups (bivalves, brachiopods, nautiloids, graptolites, foraminifers, ostracods, acritarchs, chitinozoans, trilobites and corals), microfacies, isotope signatures, taphonomic and palaeoenvironmental indicators and eustatic sea-level changes. For a complete review of the previous studies on the Cellon section refer to Corradini et al. (2015a).

Beside Walliser (1957, 1964), a few papers deal with conodonts

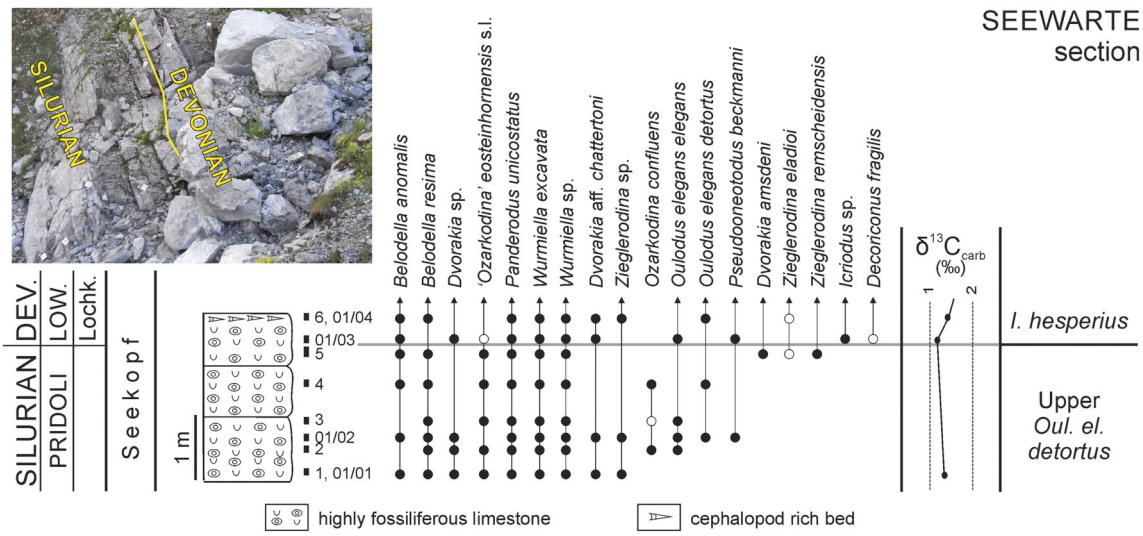

Fig. 4. Distribution of conodonts across the Silurian/Devonian boundary in the Seewarte section. From left to right: series, stage, formation, lithological log, samples, distribution of taxa (white dots indicate problematic identifications), $\delta^{13}C_{carb}$ data (after Suttner, 2007), conodont zones. Arrows at the end of distribution lines indicate that the taxon also occurs above the illustrated interval. The photo is a view of the lower part of section with indication of the S/D boundary. Abbreviations: Dev. = Devonian; Low. = Lower; Lochk. = Lochkovian.

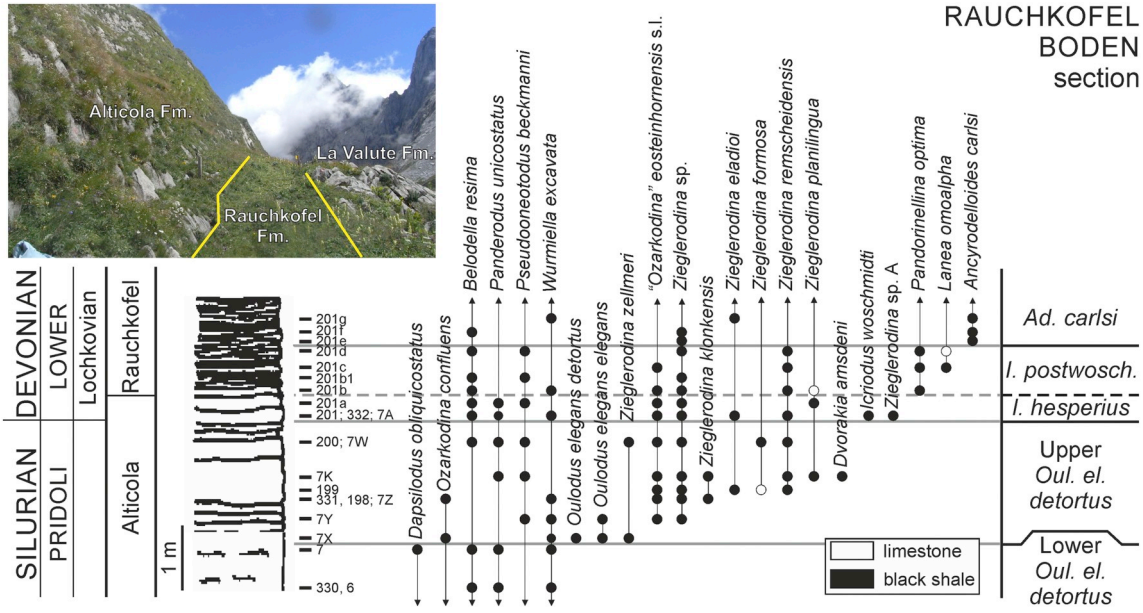

Fig. 5. Distribution of conodonts across the Silurian/Devonian boundary in the Rauchkofel Boden section (RKB) section. From left to right: series, stage, formation, lithological log (after Schönlaub et al., 2017b, modified), samples, distribution of taxa (white dots indicate problematic identifications), conodont zones. Arrows at the end(s) of distribution lines indicate that the taxon also occurs below or above the illustrated interval. The photo is a panoramic view of the part of the section where the S/D boundary is exposed with formational boundaries indicated.

from the Cellon section: Ferretti and Schönlaub (2001) revised the biostratigraphy of the Ordovician part of the section, Corradini et al. (2015a) updated the Silurian conodont biostratigraphy, and Corriga et al. (2016) studied the lower Lochkovian strata. A summary of the conodont stratigraphy of the whole section was presented by Corradini et al. (2017).

The Silurian/Devonian boundary in the Cellon section (Fig. 6) is located in the uppermost part of the Alticola Fm., just below sample 47B (Walliser, 1964; Schönlaub, 1980; Corradini et al., 2015a; Corriga et al., 2016), that yielded the first representatives of *I. hesperius* (Corradini et al., 2015a). The lithostratigraphic boundary between the Alticola and the Rauchkofel formations is located a few centimeters above the conodont-based S/D boundary, between beds 47B and 47C. It should be noted that the first occurrence of diagnostic graptolites of the Lochkovian is recorded about 1.5 m above, where Jaeger (1975) recorded the occurrences of *Monograptus uniformis*, *M.* cf. *microdon* and *Linograptus posthumus* just below sample 50. However, no graptolites have been reported from the lowermost part of the Rauchkofel Fm., so the discrepancy between conodont and graptolite data can be explained by the difficulty of recovering graptolites in the limestones (Corriga et al., 2016).

The Upper *Oul. el. detortus* Zone has been discriminated in beds 43-47A. Rare specimens of *Z. ivochlupachi* Carls et al. occur within the zone. *Wurmiella alternata* Corradini and Corriga disappears within the middle of the zone, whereas *Oz. confluens* in the uppermost part of the Upper *Oul. el. detortus* Zone (sample 46), just below the first occurrence of *Z. remscheidensis* (sample 46A), and the first occurrence of *Zieglerodina zellmeri* (sample 47A). The lowermost Devonian beds are

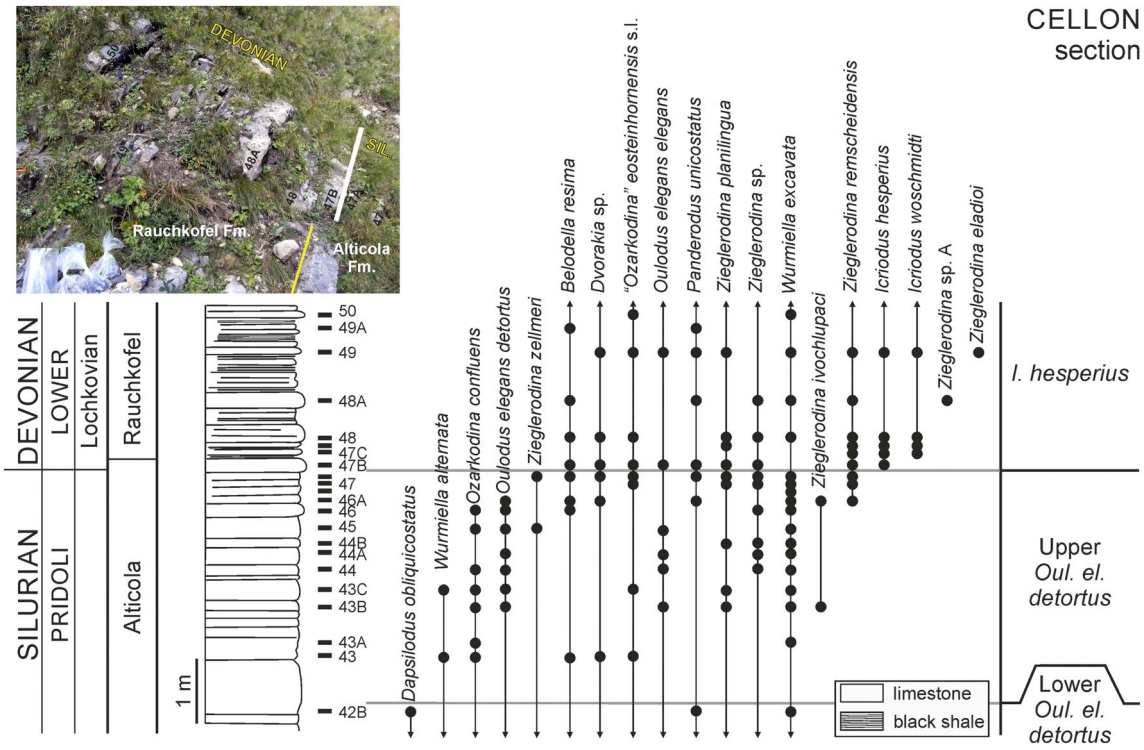

Fig. 6. Distribution of conodonts across the Silurian/Devonian boundary in the Cellon section. From left to right: series, stage, formation, lithological log (after Corriga et al., 2016, modified), samples, distribution of taxa, conodont zones. Arrows at the end(s) of distribution lines indicate that the taxon also occurs below or above the illustrated interval. The photo shows the detail of the section across the S/D boundary, with indication of S/D boundary, formational boundaries, and the samples.

attributed to the *I. hesperius* Zone by the entry of the index taxon in sample 47B. *Icriodus woschmidti* enters just above, in sample 47C. *Zieglerodina* sp. A is documented from sample 48 (Corriga et al., 2016).

5.5. Freikofel South II (FRS)

The Freikofel South II section (Fig. 7) is located on the southern flank of Mt. Freikofel along the path from Casera Pal Grande di Sotto to Casera Pal Piccolo, at coordinates 46°35′54.9″ N, 12°58′32.3″ E, and altitude 1552 m. It is a short section, less than 4 m thick, exposing the uppermost beds of the Alticola Fm. and the basal part of the Rauchkofel Fm. (Fig. 7). The section is presented here for the first time.

At the base, the section begins with about 40 cm of grey, well-bedded "Orthoceratid limestones" belonging to the Alticola Fm., passing into dark grey wackestones to grainstones of the Rauchkofel Fm. At this locality the Rauchkofel Fm. mainly consists of packstones to grainstones showing hummocky-cross stratification sometimes passing to wave ripples and interlayered with shales, which is indicative of deposition within the offshore transition.

Conodonts are in general quite scarce in the FRS section, and the state of preservation is poor, with the exception of sample FRS 0 collected at the base of the section, which yielded a relatively abundant and well-preserved fauna. The whole section can be attributed to the basal Devonian *I. hesperius* Zone by the occurrence of the index taxon in sample FRS 0 (Fig. 7).

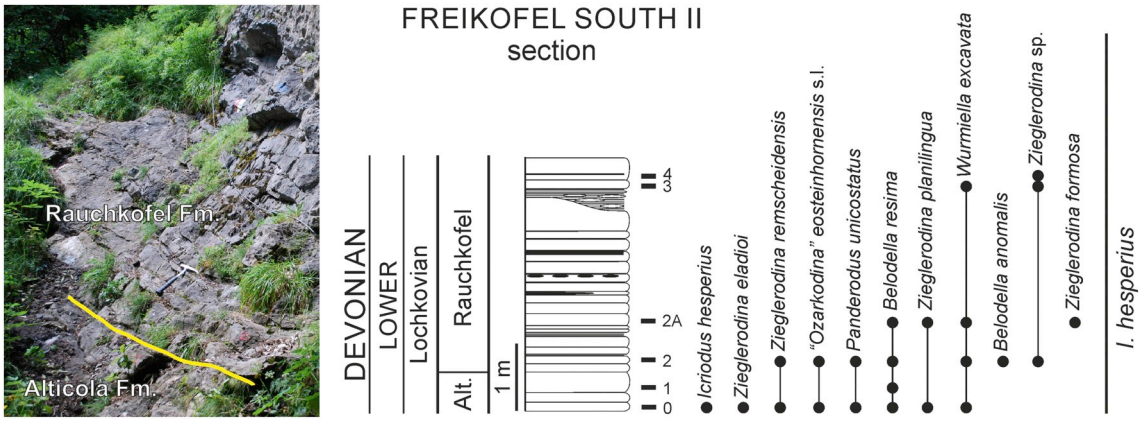

Fig. 7. Distribution of conodonts across the Silurian/Devonian boundary in the Friekofel South II (FRS) section. From left to right: series, stage, formation, lithological log, samples, distribution of taxa, conodont zones. The photo is a panoramic view of the part of the section with indication of the boundary between the Alticola and the Rauchkofel formations. Abbreviation: Alt. = Alticola.

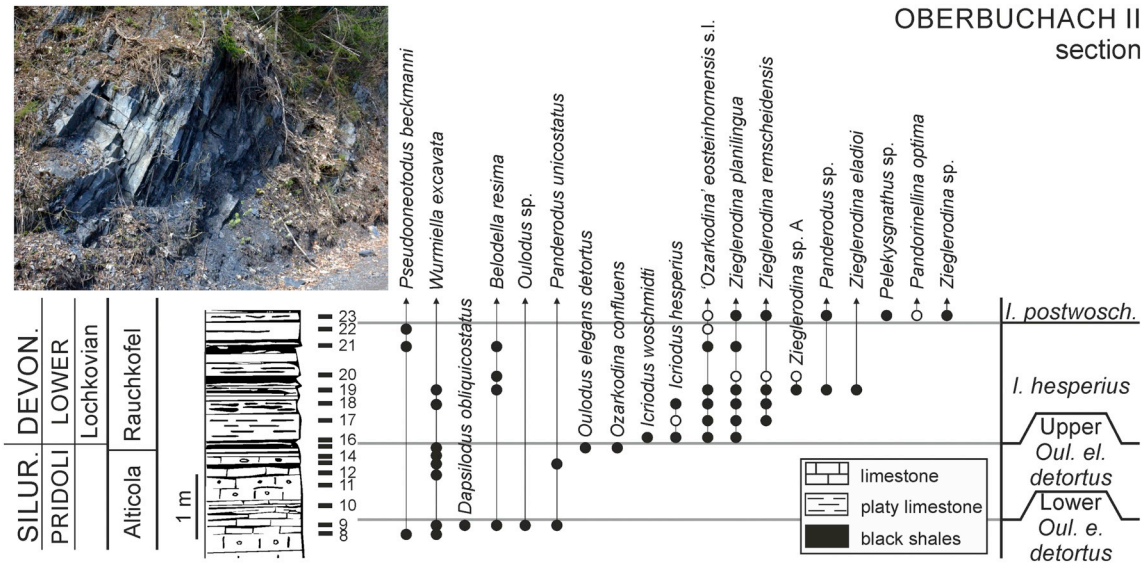

Fig. 8. Distribution of conodonts across the Silurian/Devonian boundary in the Oberbuchach II section. From left to right: series, stage, formation, lithological log (after Schönlaub, 1985, modified), samples, distribution of taxa (white dots indicate problematic identifications), conodont zones. Arrows at the end of distribution lines indicate that the taxon also occurs above the illustrated interval. The photo is a general view of the Rauchkofel Fm. in the section.

5.6. Oberbuchach II (Ob II)

The Oberbuchach II section (Fig. 8) is located along the road running from the Gail Valley near Gundersheim to Gundersheim Alm at the altitude of 1280 m and coordinates 46°37′37″ N, 13°06′15″ E. The section, more than 120 m thick, is a classical exposure of pelagic Devonian deposits of the Carnic Alps, documenting a continuous pelagic sedimentation from the Přídolí to the Middle Devonian (upper Givetian). The section was first studied by Jaeger and Schönlaub (1980), who focused on the Lochkovian part. Research was extended to the upper part of the section in the following years, and Schönlaub (1985) and Alberti (1985) published detailed conodont and tentaculites data, respectively. The conodont data were recently revised by Schönlaub et al. (2017a).

The section starts with a few meters of light grey well bedded limestones of the Alticola Fm., grading abruptly into dark platy limestones with interbedded black shales and marls of the Rauchkofel Fm., which is about 11 m thick at this locality. The formational boundary at Oberbuchach II section is more or less coincident with the Silurian/Devonian boundary.

Conodonts are in general not very abundant in the lower part of the section. This part can be attributed to the Lower *Oul. el. detortus* Zone based on the occurrence of *D. obliquicostatus* in sample 9 (Fig. 8). The upper part of the Alticola Fm. belongs to the Upper *Oul. el. detortus* Zone. *Ozarkodina confluens* was recovered from sample 14, which is the same horizon where *Oul. el. detortus* has its sole occurrence within the section. Both *I. hesperius* and *I. woschmidti* were recovered from sample 16, as such the Silurian/Devonian boundary is placed at this level within the section. Conodonts are more abundant in the lower part of the Rauchkofel Fm., and "*Oz." eosteinhornensis* s.l. (Walliser), *Z. remscheidensis* and *Z. planilingua* are common. Both *Zieglerodina* sp. A and *Z. eladioi* have their first occurrences in sample 18, just above the pelitic level where Jaeger and Schönlaub (1980) recovered the graptolite *Monograptus uniformis*.

5.7. Oberbuchach Ib (Ob Ib)

The Oberbuchach Ib section (Fig. 9) is located along the road running from the Gail Valley near Gundersheim to Gundersheim Alm at an altitude of 1120 m, at coordinates 46°37′38″ N, 13°06′32″ E. At the base of the section a few beds of the Alticola Fm. grade into the Rauchkofel Fm., which is represented by dark Orthoceratid limestone alternating with black graptolitic shales (Fig. 9). The upper part of the section is characterized by light grey limestone, in place nodular, with centimetric marly interbeddings, belonging to the La Valute Fm. Together with the nearby Oberbuchach I section, the Oberbuchach Ib section was studied by Jaeger and Schönlaub (1980), who provided data on Silurian and Lochkovian graptolites and conodonts. The conodont fauna was recently revised by Schönlaub and Corradini (2017).

The conodont fauna is scarce and poorly preserved in the Oberbuchach Ib section and does not allow a precise biostratigraphic placement of the Silurian/Devonian boundary. The lower bed of the section is assigned to the "*Oz. eosteinhornensis* s.s. horizon" (upper part of the Lower *Oul. el. detortus* Zone), whereas conodonts collected from the Rauchkofel Fm. permit the assignment of a generic lower Lochkovian age for this unit (Schönlaub and Corradini, 2017). Poorly preserved graptolites tentatively attributed to *M. praehercynicus*? were reported by Jaeger and Schönlaub (1980) about 50 cm above the base of the Rauchkofel Fm. The upper part of the unit is middle Lochkovian in age based on the occurrence of *Ancyrodelloides carlsi* (Boersma).

5.8. Rio Malinfier West (RMW)

The Rio Malinfier West section (Fig. 10) is exposed along the road from Paularo to Cason di Lanza Pass, in the forest about 100 m west of the Rio Malinfier Creek, at coordinates 46°34′50.8″ N, 13°07′53.7″ E (base) and 46°34′48.8″ N, 13°07′51.9″ E (top). The section is partly overturned, strongly tectonized, and documents about 100 m of limestones and black shales attributed to the Alticola, Rauchkofel, La Valute, Nölbling and Findenig formations. A distinct fault, running at about 40 m above the base, cuts the section into two exposures. Even if the units exposed below and above the fault are mostly the same, the two parts of the section are largely different, suggesting that the fault adjoins two sequences of the same age deposited in slightly different environments (for details see Corradini et al., 2019).

The section was roughly described by Corriga (2011), Corradini et al. (2012) and Corriga et al. (2017), who provided a detailed conodont biostratigraphy of the section. The section is studied in detail by Corradini et al. (2019). The state of preservation of the conodont fauna is quite poor, with many elements broken, and an average abundance of 2.7 conodonts/kg.

Due to the fault within the Rio Malinfier West section, the Silurian/

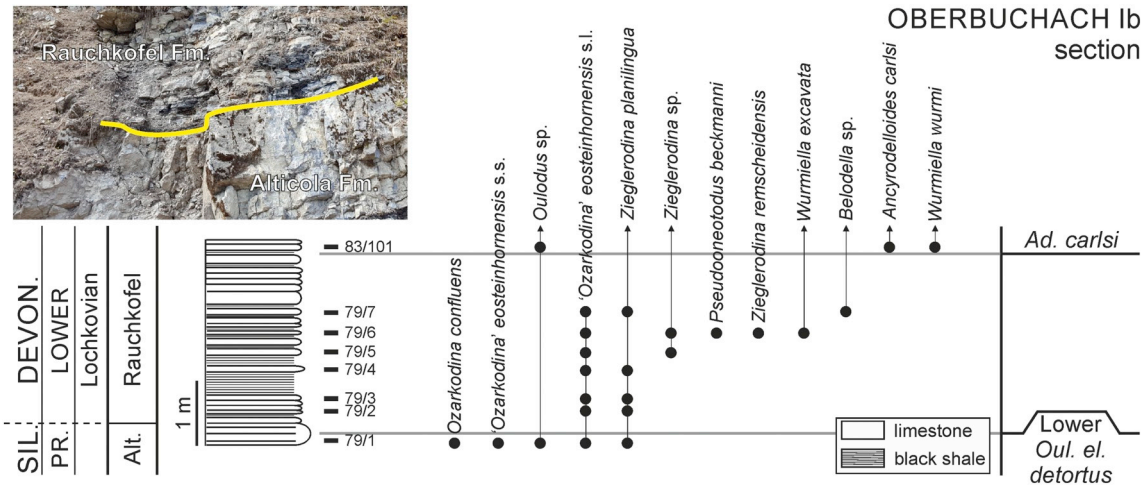

Fig. 9. Distribution of conodonts across the Silurian/Devonian boundary in the Oberbuchach Ib section. From left to right: series, stage, formation, lithological log (after Schönlaub and Corradini, 2017, modified), samples, distribution of taxa, conodont zones. Arrows at the end of distribution lines indicate that the taxon also occurs above the illustrated interval. The photo shows the detail of the section across the S/D boundary, with indication of the formational boundary. Abbreviations: Alt. = Alticola; Pr. = Přídolí; Sil. = Silurian.

Devonian boundary occurs at two different horizons: one close to the base of the section (Fig. 10a), and the other about 45 m above the base of the section (Fig. 10b), about 4 m above the fault that subdivides the section into two parts. The lower part of the section (Fig. 10a), belonging to the Alticola Fm. (samples RMW Y-1A), can be assigned to a general Přídolí age, due to the occurrence of *Wurmiella alternata* in sample RMW X and *Oulodus elegans elegans* in sample RMW 1 (Fig. 10b). Unluckily, the conodont association does not allow a more precise biostratigraphic assignment. Above the covered interval, the lower part of the Rauchkofel Fm. (samples RMW 1B) can be tentatively assigned to the *I. hesperius* Zone, whereas the entry of *Lanea omoalpha* in sample RMW 1X indicates the base of the *I. postwoschmidti* Zone.

Above the fault, the Alticola Fm. can be assigned to the Upper *Oul. el. detortus* Zone based on the occurrence of the marker *Oulodus elegans detortus* and *Wurmiella alternata* in sample RMW 7A (Fig. 10b). The base of the Devonian is recognized by the occurrence of *Icriodus hesperius* in sample RMW 8. As a result, the Silurian/Devonian boundary is coincident with the slightly tectonized lithostratigraphic boundary between the Alticola and Rauchkofel formations. The interval up to sample RMW 9 can be assigned to the *I. hesperius* Zone, likely to the lower part of the zone, because of the presence of *Zieglerodina* sp. A which is documented only from the lower part of the zone.

5.9. Monte Cocco II (MC II)

The Monte Cocco II section (Fig. 11) is located in the northern flank of Monte Cocco at coordinates 46°33′03″ N, 13°26′47″ E. It consists of about 17 m of cephalopod limestone, belonging to three lithostratigraphic units: Alticola Fm., Rauchkofel Fm. and La Valute Fm. The section and the rich conodont fauna were studied by Corriga and Corradini (2009). Conodont data and the biostratigraphy across the Silurian/Devonian boundary are updated in this paper.

The lower part of the section exposes about 14 m of the Alticola Fm.: a grey-pale brownish cephalopod wackestone, which at some levels wheathers to dark red due to the abundance of iron minerals. The upper part of the unit is more grayish in colour and progressively grades to the grey packstone of the overlying Rauchkofel Fm., which is about 1.5 m thick.

The base of the Upper *Oul. el. detortus* Zone is detected just above sample MC II 4A, where *Coryssognathus dubius* and *Belodella anomalis* have their last occurrence (Fig. 11). *Zieglerodina zellmeri* occurs in sample MC II 5, *Oz. confluens* is present up to sample MC II 5D, and *Z. klonkensis* Carls et al. has its last occurrence in sample MC II 5E, which is the same level as the first occurrence of *Z. remscheidensis* and *Z. eladioi*.

The Silurian/Devonian boundary was placed by Corriga and Corradini (2009) just below sample MC II 5F, where *I. hesperius* and *I. woschmidti* co-occur, together with an unusually early occurrence of *Pedavis biexoramus* Murphy and Matti. *Lanea omoalpha* enters slightly above in sample MC II 6, allowing recognition of the base of the *I. postwoschmidti* Zone (Corriga et al., 2016).

6. Discussion

About thirty conodont taxa are documented across the Silurian/Devonian boundary interval in nine sections from the Carnic Alps (Figs. 12, 13). Comparing the data from these sections not only makes it possible to obtain information on their stratigraphical distribution, but also to examine the possibility of palaeoecological control on the deposition and the occurrence of conodont associations.

6.1. Lithostratigraphy and general basin setting

The studied sections demonstrate a clear shallow-to-deeper water depositional profile (Fig. 1). The Rifugio Lambertenghi Fontana III and Seewarte sections consist mostly of poorly to moderately sorted grainstones/packstones belonging to the Seekopf Fm. The Cellon and Freikofel South II sections are both characterized by the transition between the Alticola and Rauchkofel formations that occurs just above the Silurian-Devonian boundary. In these sections the Alticola Fm. consists of wackestones to packstones while the Rauchkofel Fm. is characterized by grainstones/packstones showing hummocky-cross stratification at places passing upward to wave ripples, interlayered with shales. In the Rauchkofel Boden section the Silurian/Devonian boundary lies in the uppermost part of the Alticola Fm., too, but the Rauchkofel Fm. is represented by an alternation of limestone and pelites. In the Monte Cocco II section the wackestone of the Alticola Fm. grades into the packstone of the Rauchkofel Fm. and the Silurian-Devonian boundary is coincident with the formational boundary. The Oberbuchach II, Oberbuchach Ib and Rio Malinfier West a-b sections show the transition between Alticola and Rauchkofel formations as well, but in these sections the units appear finer-grained and centimeter-thick shaly intercalations within the Rauchkofel Fm. are present. Here the Silurian-Devonian boundary could be confidently placed at the Oberbuchach II section, whithin the lowermost part of the Rauchkofel Fm. Accordingly, the lithofacies distribution of these nine sections depicts a ramp-type

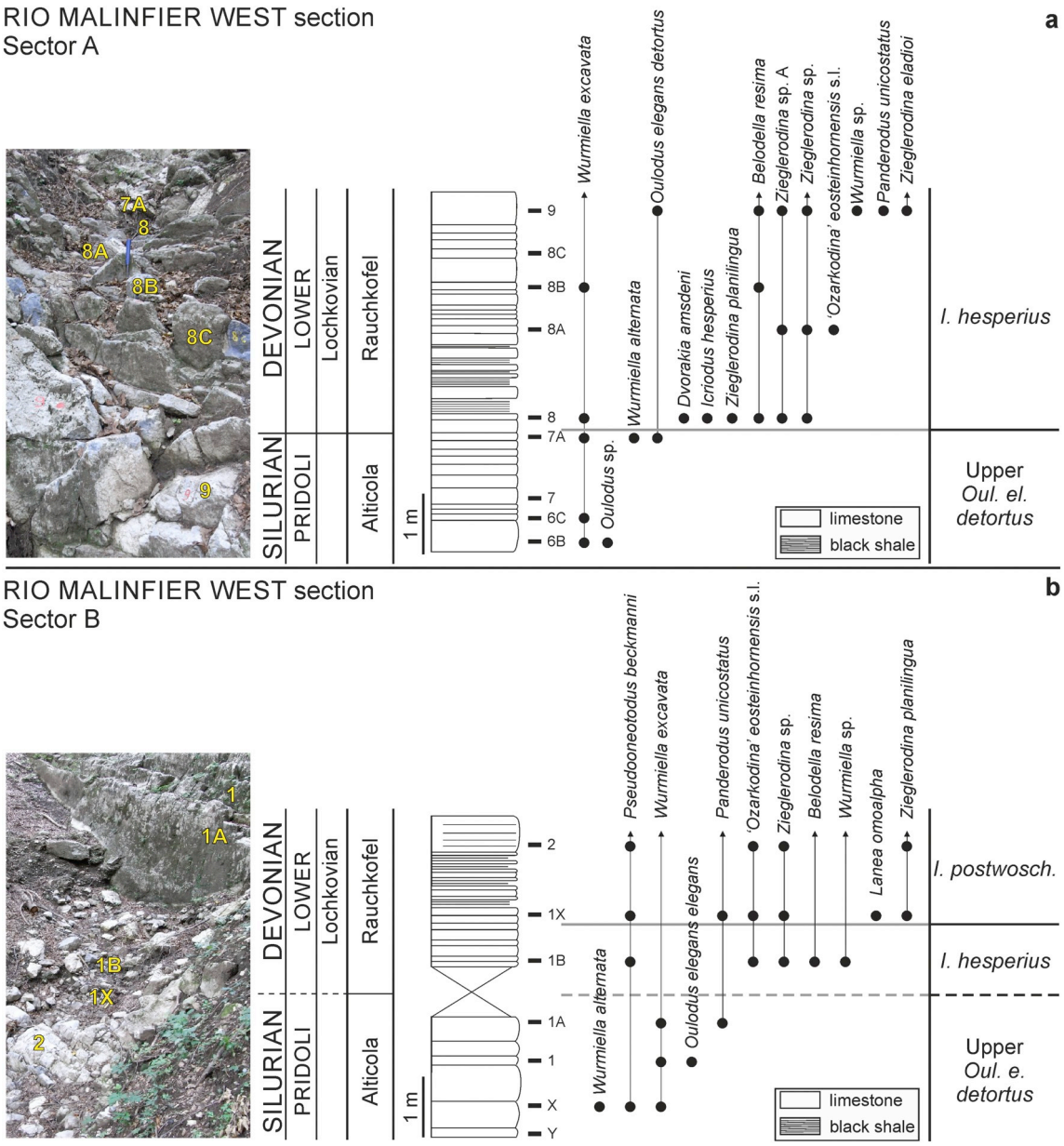

Fig. 10. Distribution of conodonts across the Silurian/Devonian boundary in the Rio Malinfier West section. a: the boundary in the lower part of the section; b: the boundary in the upper part of the section. The photos show the detail of the section across the S/D boundary, with indication of the samples. From left to right: series, stage, formation, lithological log, samples, distribution of taxa, conodont zones. Arrows at the end of distribution lines indicate that the taxon also occurs above the illustrated interval.

physiographic profile with inner shelf (RLFIII-Sew), transitional inner to outer shelf (Cellon-FRS), outer shelf (RKB- MC II) and outer shelf/slope (Ob II-Ob Ib-RMW a,b) deposits in a progradational context.

6.2. Stratigraphy

Most of the documented taxa are relatively long-ranging across the Silurian/Devonian boundary, but a few species have their first or last occurrence datum close to the boundary, and therefore may help to approximate the position of the boundary itself. *Ozarkodina confluens* is a characteristic Silurian species, which in all localities has its last occurrence in the upper part of the Upper *Oul. el. detortus* Zone. *Wurmiella alternata* occurs up to just above the last occurrence of *Oz. confluens*. *Zieglerodina remscheidensis*, once considered to have its FAD in the earliest Devonian (Carls et al., 2007), is often documented in the latest Silurian beds, with its first occurrence just below the first occurrence of *Icriodus hesperius*. *Zieglerodina eladioi* is a small Lochkovian species, but in the Rauchkofel Boden and, possibly, in the Seewarte sections has been recovered in the latest Přídolí, at the same level of the first occurrence on *Z. remscheidensis*. *Zieglerodina klonkensis* is a species typical of the latest Přídolí, but its occurrence is rare in the Carnic Alps and it has only been recovered within the Upper *Oul. el. detortus* Zone, and became extinct just below the S/D boundary. Also, *Zieglerodina zellmeri* that is documented in most of the Přídolí in the Carnic Alps (Corradini and Corriga, 2010, 2012; Corradini et al., 2015a; Corriga et al., 2016) became extinct at the same level, whereas in other regions, such as Bohemia, it occurs only in the lower Přídolí (Carls et al., 2007).

The first occurrence of *Icriodus hesperius* (and the base of the nominative zone) serves as the conodont datum for the base of the Devonian. However, in many sections in the Carnic Alps (e.g., Oberbuchach II, Monte Cocco II) *Icriodus woschmidti* and *I. hesperius* both have their first occurrences in the same horizon, whereas in other

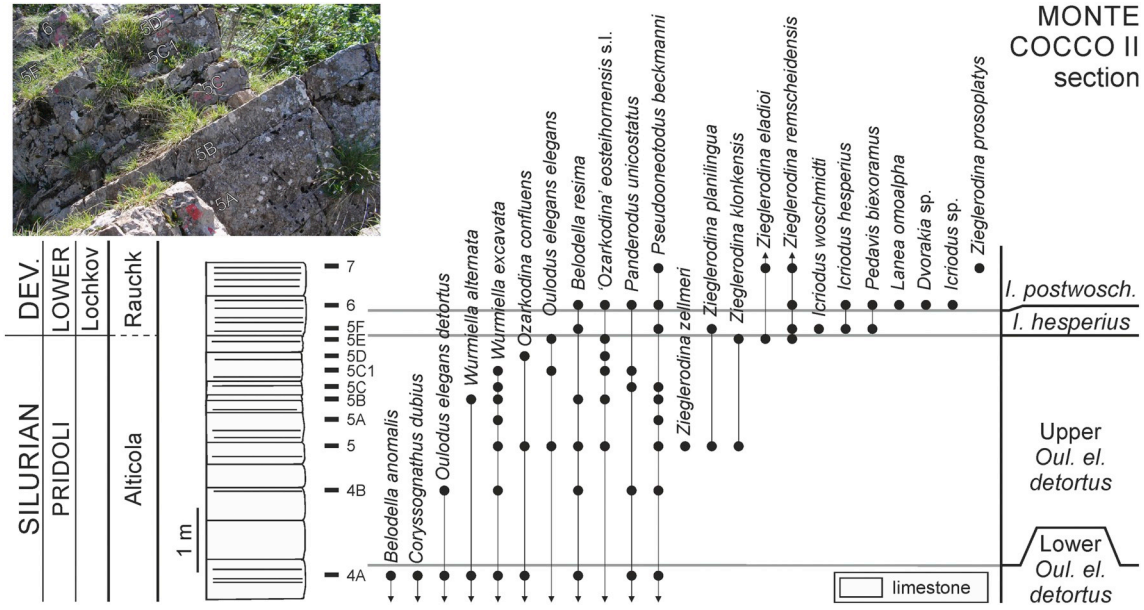

Fig. 11. Distribution of conodonts across the Silurian/Devonian boundary in the Monte Cocco II section. From left to right: series, stage, formation, lithological log (after Corriga and Corradini, 2009, modified), samples, distribution of taxa, conodont zones. Arrows at the end(s) of distribution lines indicate that the taxon also occurs below or above the illustrated interval. The photo shows the detail of the section across the S/D boundary, with position of samples. Abbreviations: Dev. = Devonian; Lochkov. = Lochkovian; Rauchk. = Rauchkofel.

sections (e.g., Cellon) *I. woschmidti* enters slightly above. *Zieglerodina* sp. A occurs in the lowermost Lochkovian. Almost everywhere it has its first occurrence just above the first occurrence of *I. hesperius*. The species has its first occurrence at the base of the Rauchkofel Fm. only in the lower part of the Rio Malinfier West section, together with the first occurrence of *I. hesperius*. However, in that section the boundary between the Alticola and the Rauchkofel Fm is tectonized, and elsewhere *I. hesperius* occurs in the uppermost part of the Alticola Fm.; therefore it may be that the latter species has a slightly later first occurrence in that section.

In terms of carbon isotope stratigraphy, our data from Rifugio Lambertenghi Fontana III and Seewarte sections confirms that the Silurian/Devonian boundary lies in the upper part of the prominent Klonk $\delta^{13}C_{carb}$ Excursion, and just before the $\delta^{13}C_{carb}$ values reach their maximum, as documented in other regions (e.g., Saltzman, 2002; Buggisch and Mann, 2004; Jacobi et al., 2009; Malkowski et al., 2009). Also, data by Buggisch and Mann (2004) from Cellon and Oberbuchach II sections show the same trend, but it is difficult to precisely tie their graphs (Buggisch and Mann, 2004, Fig. 6) with the position of conodont samples.

6.3. Palaeoecology

Two of the studied sections (Rifugio Lambertenghi III and Seewarte) were deposited in a shallow water environment, whereas all the others section are indicative of a moderately deep shelf depositional environment. The great majority of conodont taxa occur in sections representing both depositional environments, whereas only a few are restricted to part of the basin (Fig. 13).

Some species of *Zieglerodina* (*Z. eladioi*, *Z. formosa*, *Z. klonkensis*, *Z. mashkovae* and *Z. zellmeri*) are relatively common in open sea sections, but are not documented in shallow water deposits. *Pedavis biexoramus* is a rare taxon documented only at Monte Cocco II, and, above the interval studied in this paper, at Oberbuchach II (Schönlaub, 1985; Schönlaub et al., 2017a). Taxa occurring only in shallow water facies (Rifugio Lambertenghi III and Seewarte) are *Oulodus greilingi hirpex* Mawson, a few simple cone species and belodellids: *Dvorakia* aff. *chattertoni*, *Decoriconus fragilis* (Branson and Mehl) and *Belodella coarctata*.

The occurrence of *Oul. el. detortus*, an index species from the latest Přídolí that ranges in to the early Lochkovian, deserves special attention. In most of the studied sections this species is limited to the Silurian, or enters in the lowermost Lochkovian, as it does at the Rio Malinfier West section where *Oul. el. detortus* co-occurs together with *Zieglerodina* sp. A. However, in the shallow water Seewarte section it is documented to range up to the base of the *I. postwoschmidti* Zone (Suttner, 2007). If not reworked, *Oul. el. detortus* appears to have a longer range in shallow water environments than in basinal environments.

Wurmiella alternata demonstrates the opposite trend, and has a shorter range in shallow water environments. The species was described from the Lower *Oul. el. detortus* Zone of the Rifugio Lambertenghi Fontana III section (Corradini and Corriga, 2010), but, later, *W. alternata* was documented from the whole Přídolí in deeper sections (e.g., Cellon section, Corradini et al., 2015a).

7. Conclusions

This study is a summary of the conodont distribution and diversity of 32 taxa recovered from nine sections in the Carnic Alps that span shallow to deep marine environments during the Silurian/Devonian boundary interval. First and last occurrence datums (FOD and LOD) of the following nine species documented in latest Silurian and earliest Devonian strata allow a relatively precise allocation of the Silurian/Devonian boundary, at least in the Carnic Alps (from oldest to youngest): (1) LOD of *Ozarkodina confluens*, just followed by (2) LOD of *Wurmiella alternata*, and by (3) FOD of *Zieglerodina remscheidensis* and *Z. eladioi*, and by (4) LOD of *Zieglerodina zellmeri* and *Zieglerodina klonkensis*, and by (5) FOD of *Icriodus hesperius* and *Icriodus woschmidti*, and by (6) FOD of *Zieglerodina* sp. A. The S/D boundary is placed at the level of the FOD of *I. hesperius*.

All of the first and last occurrence datums for these conodont taxa are documented during the ascending limb of the Klonk Excursion in the uppermost Přídolí and across the S/D boundary, just below the peak $\delta^{13}C_{carb}$ values of the excursion in the lowermost Lochkovian. While these are localized datums that have been well-documented within the

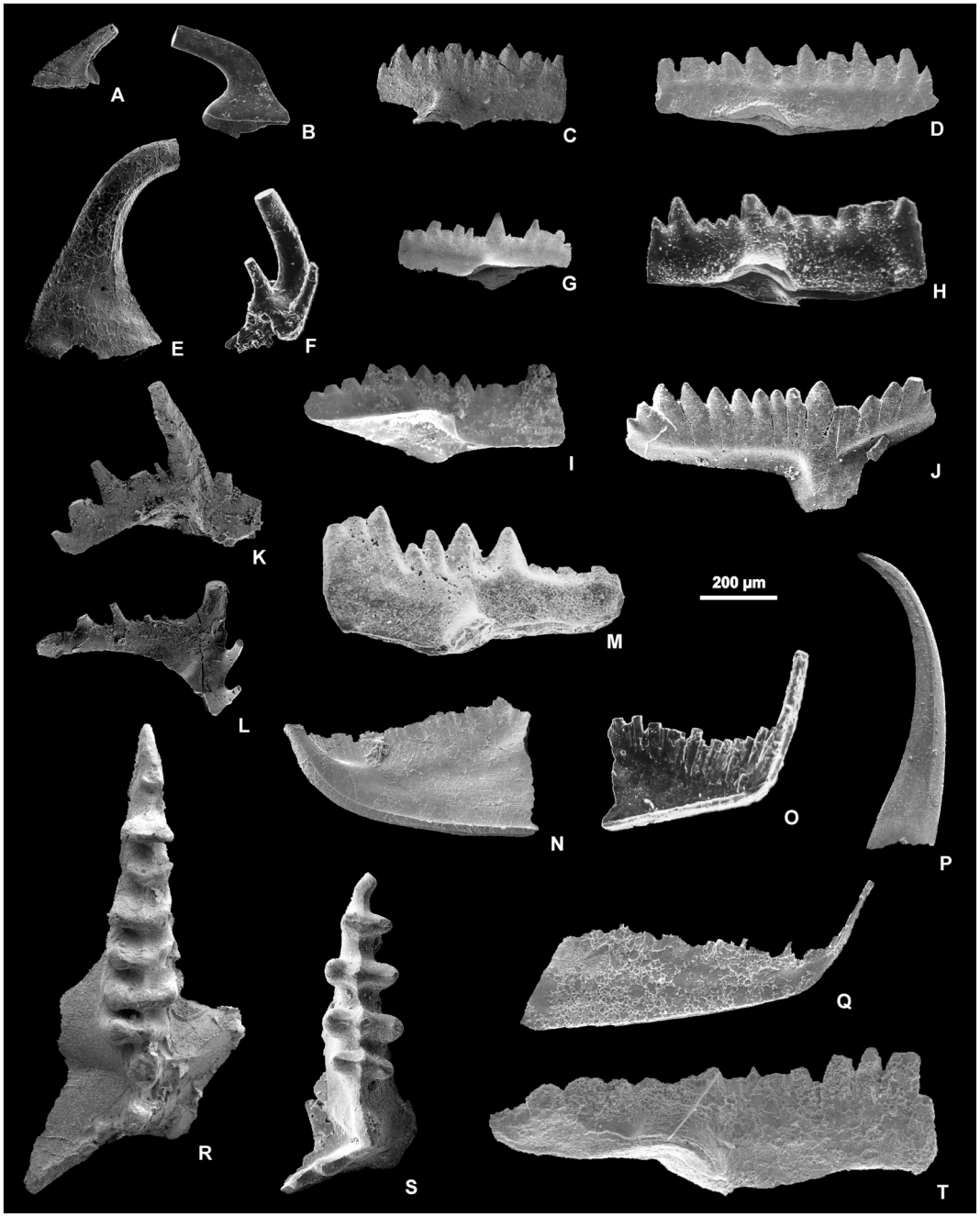

Fig. 12. Selected conodonts from beds around the Silurian/Devonian boundary in the Carnic Alps.
A) *Decoriconus fragilis* (Branson and Mehl, 1933), lateral view of S1 element GBA-2006/1/11-04, Seewarte section, sample Se/01/06a/04. B) *Dvorakia amsdeni* Barrick and Klapper, 1992, lateral view of S1 element MFSNgp 48347, Rio Malinfier West section, sample RMW 8. C) *Zieglerodina eladioi* (Valenzuela-Ríos, 1994), lateral view of P1 element MDLCA 30405, Rauchkofel Boden Section, sample RKB 11. D) *Wurmiella alternata* Corradini and Corriga, 2010, lateral view of P1 element MDLCA 30000/1, Rifugio Lambertenghi Fontana section, sample RLF 9. E) *Dvorakia* aff. *D. chattertoni* Klapper and Barrick, 1983, lateral view of S2 element GBA-2006/1/14-27, Seewarte section, sample Se/01/03/04. F) *Coryssognathus dubius* (Rhodes, 1953), lateral view of S0/S1 element MLDCA 30038, Rifugio Lambertenghi Fontana III section, sample RLF III 2B. G) *Zieglerodina* sp. A Corriga et al., 2016, lateral view of P1 element MDLCA 30338, Cellon section, sample 48A. H) *Zieglerodina remscheidensis* (Ziegler, 1960), lateral view of P1 element MDLCA 30063, Rifugio Lambertenghi Fontana III section, sample RLF III 1×. I) *Pandorinellina optima* (Moskalenko, 1966), lateral view of P1 element GBA-2016/014/0069, Rauchkofel Boden Section, sample 201D. J) *Zieglerodina planilingua* (Murphy and Valenzuela-Rios, 1999), upper-lateral view of P1 element IPUM 28192, Monte Cocco II section, sample MC II 5F. K) *Oulodus greilingi hirpex* Mawson, 1986, lateral view of P1 element GBA-2006/1/11-26, Seewarte section, sample Se/01/06/04. L) *Oulodus elegans detortus* (Walliser, 1964), lateral view of S2 element GBA-2006/1/05-15, Seewarte section, sample Se/01/06a/04. M) *Ozarkodina confluens* (Branson and Mehl, 1933), lateral view of P1 element IPUM 27680, Monte Cocco II section, sample MC II 0. N) *Belodella resima* (Philip, 1965), lateral view of P1 element MDLCA 30352, Cellon section, sample 55. O) *Belodella anomalis* Cooper, 1974, lateral view of S0 element MDLCA 30028, Rifugio Lambertenghi Fontana III section, sample RLF III 2B. P) *Panderodus unicostatus* (Branson and Mehl, 1933), lateral view of element MDLCA 30353, Cellon section, sample 55. Q) *Belodella coarctata* Barrick and Klapper, 1992, lateral view of S0 element MDLCA 30033, Rifugio Lambertenghi Fontana III section, sample RLF III 1L. R) *Icriodus hesperius* Klapper and Murphy, 1975, upper view of P1 element MDLCA 30351, Cellon section, sample 49. S) *Icriodus woschmidti* (Ziegler, 1960), upper view of P1 element IPUM 28196, Monte Cocco II section, sample MC II 5F. T) *Zieglerodina zellmeri* Carls et al., 2007, lateral view of P1 element MDLCA 30069, Rifugio Lambertenghi Fontana section, sample RLF 8.
A, D, E, K and L refigured after Suttner (2007); B refigured after Corriga et al. (2017); C and I refigured after Schönlaub et al. (2017b); D, F, H, O, Q and T refigured after Corradini and Corriga (2010); G, N, P and R refigured after Corriga et al. (2016); J, M and S refigured after Corriga and Corradini (2009).

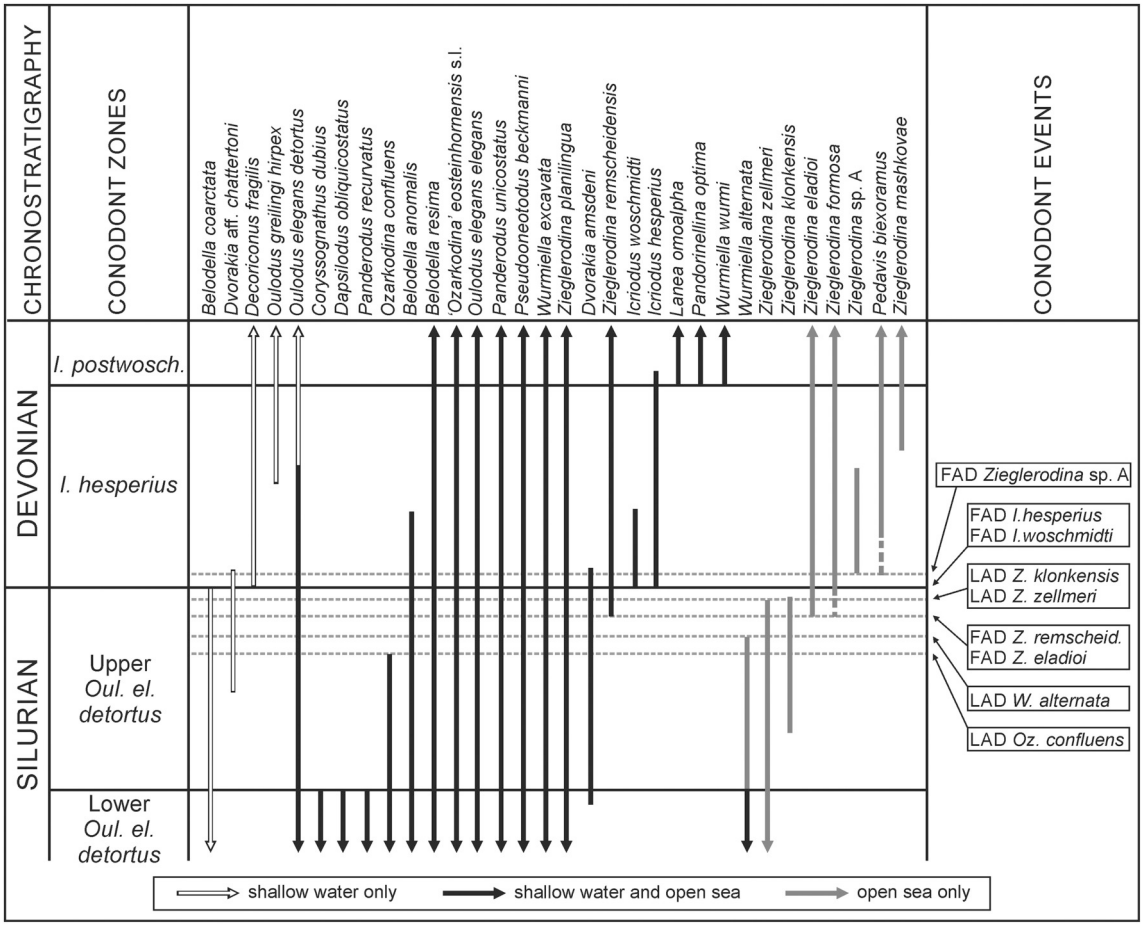

Fig. 13. Distribution of main conodont taxa across the Silurian/Devonian boundary in the Carnic Alps. Arrows at the end(s) of distribution lines indicate that the taxon also occurs below or above the illustrated interval. White lines indicate taxa occurring only in shallow water sections; grey lines indicate taxa occurring only in open sea sections; black lines indicate taxa occurring everywhere. Important first and last occurrences around the Silurian/Devonian boundary are highlighted.

Carnic Alps, it is possible that the first and last occurrences of these species from this region actually correspond to the global first and last appearance datum for these conodont taxa.

Although the majority of the 32 conodont taxa occur in both shallow and relatively deep water settings, several conodonts have distributions which are limited to either the proximal or the distal part of the basin. Four taxa (*Belodella coarctata*, *Dvorakia* aff. *chattertoni*, *Decoriconus fragilis* and *Oulodus greilingi hirpex*), of which three are components of coniform apparatuses, have been found exclusively in shallow water deposits. Six taxa, mainly species of *Zieglerodina*, are documented only from deeper marine deposits. Two taxa which seem to have had a wide palaeoenvironmental distribution for most of their ranges appear to have limited occurrences in shallow water (*Oulodus elegans detortus*) or in open marine environments (*Wurmiella alternata*) in the last part of their distribution.

Another conclusion, specifically important for regional lithostratigraphy of the Carnic Alps is that the Silurian/Devonian boundary is located near the transition between the Alticola and the Rauchkofel formations with some differences depending on the physiographic conditions. In particular, in the outer shelf the S/D boundary lies near the base of the Rauchkofel Fm. or at the formational boundary between the Alticola and the Rauchkofel formations, whereas in more proximal open sea sections it is placed in the uppermost part of the Alticola Fm. In shallow marine settings, the position of the Silurian/Devonian boundary is more complex to trace, because of the transition from deeper (Alticola Formation) to shallow marine conditions (Seekopf Formation) that started during the late Přídolí.

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