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The "Lochkovian-Pragian Event" re-assessed: New data from the low latitude shelf of peri-Gondwana

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ABSTRACT

In the late Lochkovian a regression is documented in several areas of the world, followed by a transgression in the early Pragian. Connected with the eustatic variation, a minor extinction event occurred ("Lochkovian-Pragian Event"), affecting several fossil groups, a strong reduction of carbonate production and sedimentary facies changes. The Carnic Alps are a key area for studying this event, because Lower Devonian rocks are widely exposed, representing diverse sedimentary environments from shallow water to relatively deep shelf. Fourteen sections were measured along the Carnic Alps across the Lochkovian-Pragian boundary. In the shallower part of the basin, both the Polinik and the Seekopf formations span the boundary, but evident erosional surfaces are observable in the field at the Lochkovian-Pragian boundary. Above the unconformity, at places the so-called megaclast horizon is present in the Seekopf Formation. In intermediate settings the Rauchkofel Fm. is unconfomably followed by the Kellerwand Fm., and different parts of the upper Lochkovian and lower Pragian are missing in the various sections. In the deeper parts of the basin the transition from the La Valute Fm. to the Findenig Fm. is slightly diachronous from the latest Lochkovian to the earliest Pragian; however, conodonts and tentaculitids are rare in the marly boundary beds, preventing a precise chronostratigraphic calibration of these levels. At places, evidence of subaerial exposure at the formational boundary is documented. In general, the hiatus seems to be larger in the western part of the Carnic Alps, in correspondence with the shallower parts of the succession, suggesting a sea level drop in the late Lochkovian, followed by a transgression in the Pragian. Data from the Carnic Alps are compared with those of other regions of North Gondwana to demonstrate that the sea-level variation at the Lochkovian-Pragian boundary are of global importance

1. Introduction

At the Lochkovian-Pragian boundary a eustatic variation is documented in several areas of the world. A late Lochkovian regression was followed by a transgression in the early Pragian. The sea level variation generated shallowing in marine successions, or even widespread subaerial exposures, in various North-Gondwana regions. It is also documented in North America where it has been called the Wallbridge unconformity and used to divide the Tippecanoe and Kaskaskia megasequences (Sloss, 1963; Ver Straeten, 2007; Brett et al., 2009a). Due to the sedimentary gap it is difficult to date precisely the maximum regression, and some authors place it in the lower Pragian (e.g., Bábek et al., 2018a, 2018b).

Connected with this eustatic fluctuation, a minor extinction event occurred, affecting several fossil groups. Walliser (1996) named this event as "Lochkovian-Pragian Event" (Lochkov-Prag Event), and considered it a biotic event. Later the event was renamed as "Basal Pragian Event by House (2002). According to Chlupáč et al. (1998) the Lochkovian-Pragian boundary in the Czech Republic is recognized by faunal changes of dacryoconarids, conodonts, chitinozoans, trilobites, brachiopods and other groups. In eastern North America, even where the disconformity is minor, it is associated with a a pronounced faunal turnover between the Helderberg and Oriskany faunas (Ecological-Evolutionary subunits D1 and D2; Brett et al., 2009a). In addition to the

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faunal turnover, the event is expressed by a serious drop in carbonate production and significant changes in sedimentary facies. In several European localities an increase in $\delta^{13}C$ is documented from the late Lochkovian to the earliest Pragian (Buggisch and Mann, 2004; Buggisch and Joachimski, 2006). The Lochkovian-Pragian event is documented in several localities around the world. For a summary refer to Suttner and Kido (2016).

As for conodonts, analysing global data Ziegler and Lane (1987) reported a reduction in diversity in the late Lochkovian and a low diversity interval in the lower Pragian. A similar trend was observed by Talent et al. (1993) in Australia and Slavík and Hladil (2020) in Czech Republic.

In this paper, we provide data on the Lochkovian-Pragian boundary in the Carnic Alps, located at the Italian/Austrian border (Fig. 1). The area is of special interest for studying this event, because Lower Devonian rocks are widely exposed, representing diverse sedimentary environments in a ramp-type margin, from lagoonal to carbonate shoreface to inner platform and then to relatively deep shelf. In addition to several new sections, we restudied the localities described by Schönlaub (1980, 1985), Alberti (1985), Suttner and Kido (2016) and Schönlaub et al. (2017a).

2. Biostratigraphy across the Lochkovian/Pragian boundary

The primary marker for the base of the Pragian is the conodont *Eognathodus sulcatus sulcatus* Philip, 1965 and the GSSP is located in the Velká Chuchle section in Czech Republic (Chlupáč and Oliver, 1989). At that time, the criterion for the Pragian boundary was considered to be the appearance of the first representative of genus *Eognathodus* (Weddige, 1989). Subsequent revision of *Eo. sulcatus*, moved the early eognathodids without an evident sulcus in *Eo. irregularis* Druce, 1971, and the species was later moved to genus *Gondwania* (Bardashev et al., 2002). For a review of the evolution of the Eognathodontidae refer to Murphy (2005).

Slavík and Hladil (2004) and Slavík et al. (2007) demonstrated that the early representatives of *Eognathodus/Gondwania* already occur in the latest Lochkovian, below the GSSP, whereas the true *Eo. sulcatus sulcatus* enters higher in the Pragian. Slavík (2004) proposed a new zonation scheme for the Pragian, in which the lower boundary was recognized by the entry of *Icriodus steinachensis* Al-Rawi, 1977. Klapper and Johnson (1980) distinguished two morphotypes of *Icr. steinachensis* on the basis of the shape of the spindle: the conodont taxon which better approximates the base of the Pragian is now *Icr. steinachensis* β-morph (Slavík, 2004; Becker et al., 2020).

Among other fossil groups, the marker most widely used to approximate the base of the Pragian is the First Appearance Datum of the dacryoconarid *Nowakia acuaria acuaria* (Richter, 1854).

In the Carnic Alps the tools more used to discriminate the Lochkovian/Pragian boundary were the entry of *Icr. steinachensis* β-morph (e.g., Suttner, 2007) or the first appearance of *N. a. acuaria* (e.g., Schönlaub, 1985; Alberti, 1985; Schönlaub et al., 2017a, 2017b).

3. Geological settings

Rocks deposited between the Middle Ordovician and the Upper Triassic are exposed in the Carnic Alps, and represent one of the better exposed and most complete Palaeozoic sequence of the world. During the Palaeozoic the Carnic Alps belong to the Galatian terranes (von Raumer and Stampfli, 2008), that group of terranes which detached from the north Gondwana margin during the Ordovician and moved to the north faster than the main continent. The drift from 50°S in the Late Ordovician to 35°S in the Silurian and to the southern tropical belt during the Devonian (Schönlaub, 1992) is reflected by distinct litho-and biofacies patterns. At the Lochkovian-Pragian boundary the Carnic Alps were in a warm, sub-tropical position in the southern hemisphere, approximately around 30°S.

Rocks from the Middle Ordovician to lower Pennsylvanian constitute the Pre-Variscan Sequence. These deposits were heavily affected by both Variscan (late Bashkirian-Moscovian) (Schönlaub, 1980; Venturini, 1990; Schönlaub and Forke, 2007; Pasquaré Mariotto and Venturini, 2019) and Alpine orogenies (Chattian-Burdigallian; Tortonian-Messinian; Pliocene-Pleistocene) (Venturini, 1990; Läufer et al., 2001; Brime et al., 2008) that developed compressional (mainly Variscan and Chattian-Burdigallian Alpine phases) and strike-slip (mainly Tortonian-Messinian and Pliocene-Pleistocene Alpine phases) structural elements. Nevertheless, even if the lateral transitions between the different parts of the basins are often faulted or thrusted, the stratigraphic framework between these faults/thrusts is still recognizable and continuous. The lithostratigraphy of this sequence was recently revised based on a large amount of literature and personal observations (Corradini and Suttner, 2015) and 36 formations were discriminated. For a recent description of the Pre-Variscan Sequence of the Carnic Alps refer to Corradini and

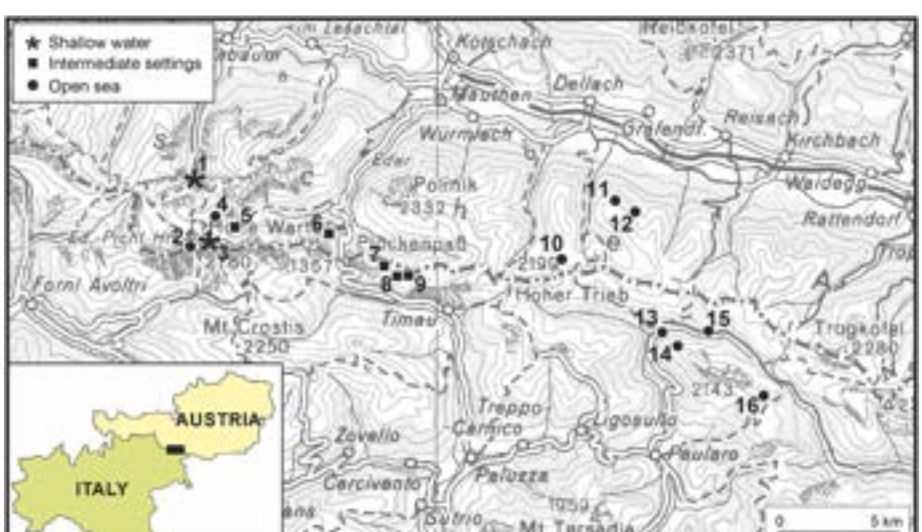

Fig. 1. Geographic map of the Carnic Alps and location of the sections investigated. 1: Hildenfall (HLD); 2: Costone Lambertenghi (CL); 3. Seewarte (SEW); 4: Rauchkofel Boden (RKB); 5: Rauchkofel South (RKS); 6: Steinbergerweg Plöckenpass (SWP); 7: Sopra Casera Pal Piccolo (SPP); 8: Freikofel-B (FRK-B); 9: Freikofel South (FRKS); 10: Lodintörl (LDT); 11:Oberbuchach IV (OB IV); 12: Oberbuchach II (OB II); 13: Stua Ramaz Ponte (SRP); 14: La Valute Cave (LV); 15: Rio Malinfier West (RMW); 16: Cima Pizzul (CP).

Pondrelli (2021).

During the Lochkovian and the Pragian a ramp-type carbonate platform with associated depositional environments occurred. A shallow lagoon was separated from the open sea by a barrier island with shoreface deposits in the inner ramp passing distally to open sea deposits. Six formations were discriminated in this time interval: Polinik Fm., Seekopf Fm., Rauchkofel Fm., Kellerwand Fm., La Valute Fm., and Findenig Fm. (Fig. 2).

In shallow water the inner ramp consists of lagoon and upper shoreface deposits. In the lagoonal environments algal laminites are intercalated with lithoclastic beds. They belong to the Polinik Fm. (Pohler et al., 2015), the age of which is generally referred to Devonian, but a precise dating of the unit, mainly its lower part, is not available. Dolostones and crinoidal limestone are exposed in the lowermost part of the unit, whereas *Amphipora* limestone are abundant in the middle and upper part.

The shoreface deposits are represented by the lithoclastic limestone interbedded with graded calcarenites (Fig. 3C-E) and nodular limestones of the Seekopf Fm. (Suttner et al., 2015). In the upper part crinoidal calcarenites are dominant, intercalated with massive crinoid-rich grainstones and rudstones. The age of the formation spans from the Přídolí to the late Pragian (Pondrelli et al., 2020).

The middle ramp consists of lower shoreface to offshore environments mainly composed of dark grey to black laminated and well-bedded, partly platy limestones intercalated with black shales and marls of various thickness, referred to the Rauchkofel Fm. (Corradini et al., 2015b). Lateral variations are common. The thickness of limestones beds varies from very thin to medium-bedded. Black graptolitic shales are more abundant in the lower part of the unit, where they may constitute levels up to 15 cm thick. In the proximal parts of the basin thick to very thick calcarenitic beds (Fig. 3A) and breccias occur more frequently in the upper part of the unit. The age is limited to the Lochkovian.

These units are unconformably covered by thin to medium-bedded wackestone and packstone, interbedded with lithoclastic beds of packstone and grainstone (Fig. 3B). Pelitic laminae are frequently intercalated, giving an apparent yellowish colour to the unit. These rocks, which span from the Pragian to the Emsian, belong to the Kellerwand Fm. (Pondrelli et al., 2015a).

The outer ramp consists of open sea environments where nodular mudstone to wackestone was deposited (Fig. 3F-J). Rocks are greyish/ochraceous in the lower part, and pinkish/reddish in the upper part, and belong to the La Valute (Corradini et al., 2015a) and the Findenig (Spalletta et al., 2015) formations respectively. Bedding of La Valute Fm. is in general 10–15 cm thick, even if thinner or thicker beds may occur at places. In the uppermost part of the unit, close to the transition to the Findenig Fm., beds become very thin to thin with silty and marly intercalations. The latter unit consists of centimetric thick beds with interlayered millimetric to centimetric red marls, and, at places, some centimetric to decimetric calcarenitic (grainstone) intervals (allodapic layers). The age of the La Valute Fm. spans from the latest lower Lochkovian to the earliest Pragian (Corradini et al., 2019), whereas the Findenig Fm. spans from the uppermost Lochkovian to the Eifelian (Spalletta et al., 2015).

4. Material and methods

Classical collections from some of the sections studied in this paper are stored in various institutions: the Austrian Geological Survey in Vienna houses collections from Oberbuchach II, Oberbuchach IV, Rauchkofel Boden, Rauchkofel South and Seewarte sections; conodonts from Rio Malinfier West section are housed in the Friulian Museum of Natural History in Udine, and material from La Valute Cave is stored in the Palaeontological Museum "D. Lovisato" of Cagliari University; thin sections of the Seewarte section are housed in the Institute of Palaeontology of the University of Vienna. These collections were studied, and implemented by new sampling. Apart from these classical sections, several new sections presented here were sampled during field research

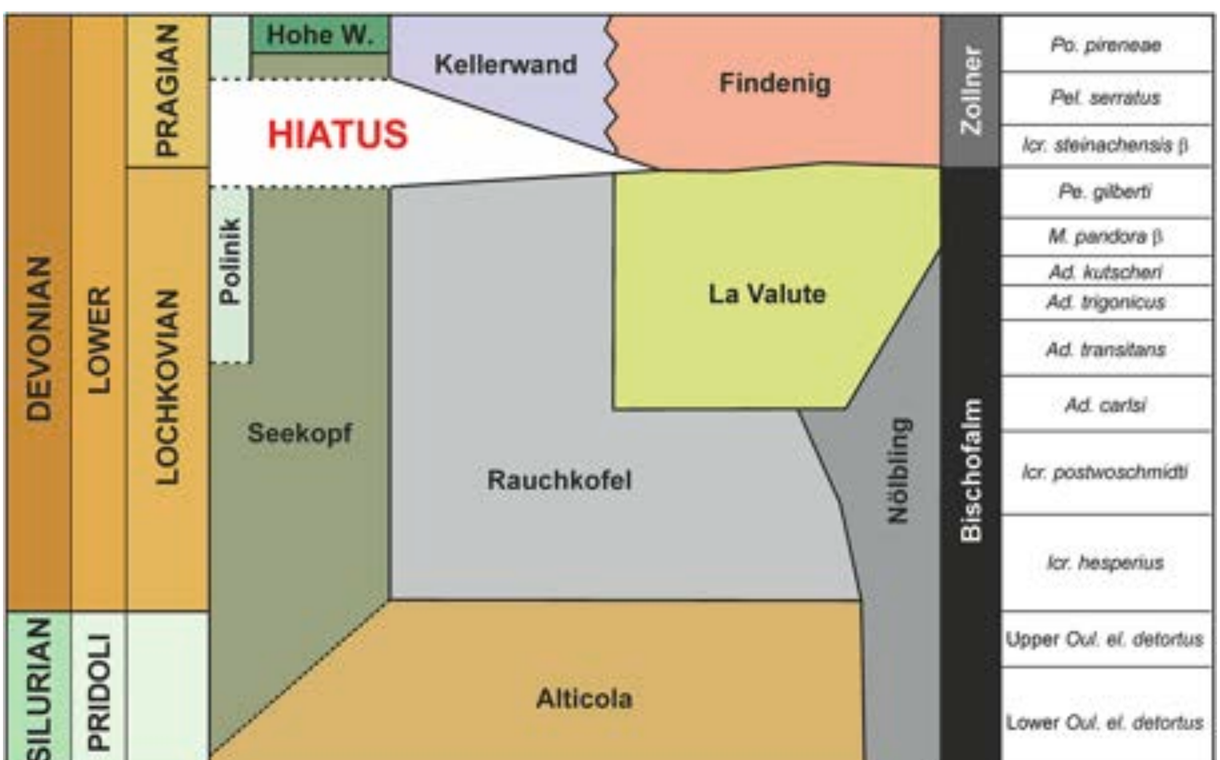

Fig. 2. The stratigraphic scheme of the Carnic Alps from the Přídolí to the Pragian modified after (Corradini et al., 2015c), updated according to the data from Pondrelli et al. (2020) and this paper. From left to right: chronostratigraphy (System, Series, Stage), lithostratigraphy (formations), conodont biostratigraphy.

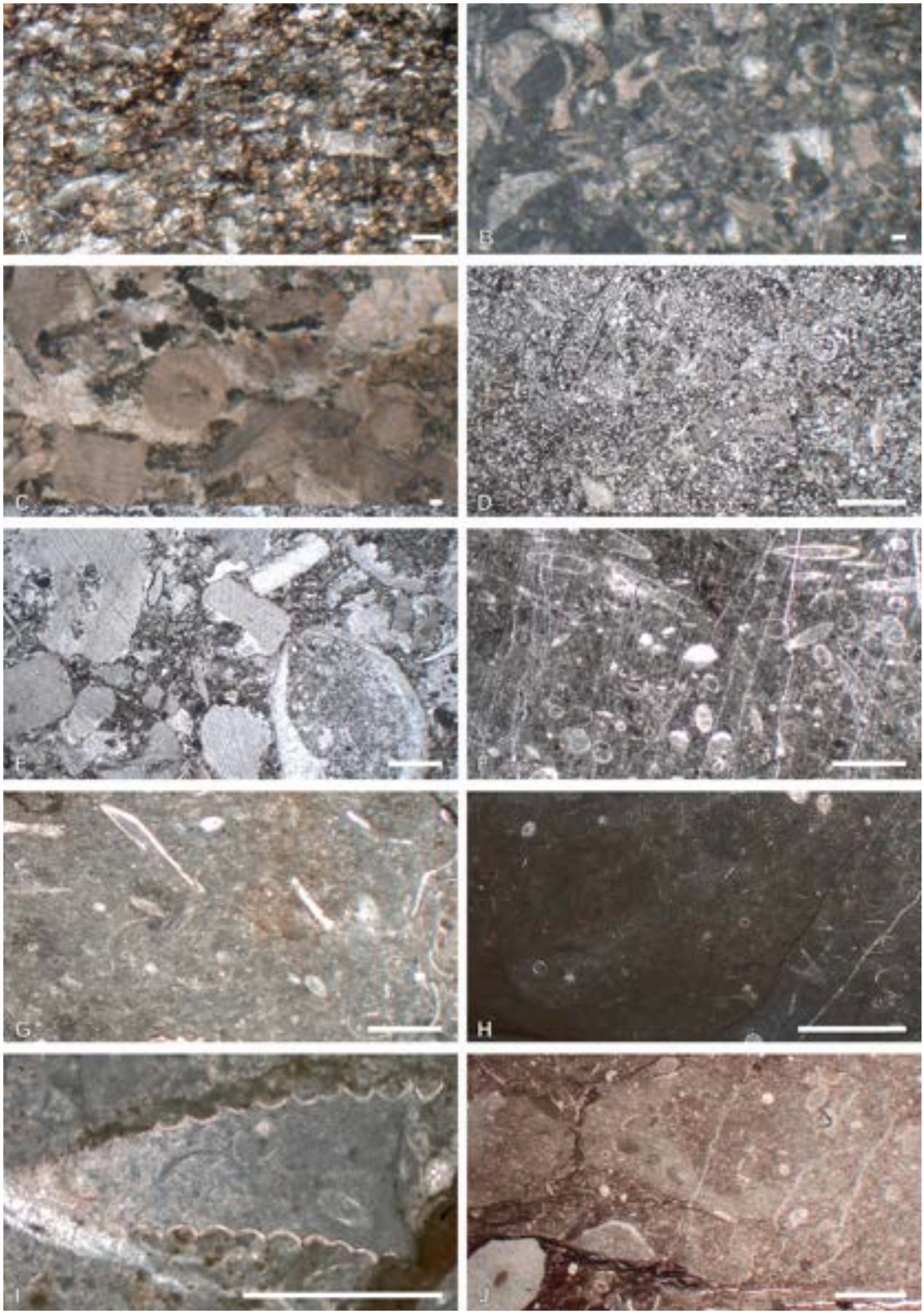

Fig. 3. Selected microfacies for the upper Lochkovian and lower Pragian in the Carnic Alps. Scale bar = 1 mm.
A) dark gray limestone with micritic matrix and small bioclastic fragments, pyrite and concentrations of dolomitic grains along stylolites; Seekopf Formation, Seewarte section, sample Se/02/10. B) rudstone, breccia of reefal debris including micritized crinoid ossicles; Seekopf Formation, Seewarte section, sample Se/02/17. C) bioclastic pack−/grainstone dominated by crionid ossicles with subordinate peloids, matrix partially dolomitized; Seekopf Formation, Seewarte section, sample Se/02/19. D) rudstone with crinoid ossicles. Rauchkofel Formation, Steinbergerweg section, sample Top-Rauch. E) bioclastic grainstone with tentaculites and crinoid ossicles. Kellerwand Formation, Steinbergerweg section, sample SWP-2. F) packstone rich in tentaculites; La Valute Formation, Rio Malinfier West section, sample RMW 15B. G) wacke-packstone with bioclastic debree; La Valute Formation, Costone Lambertenghi section, sample CL 9. H) mud−/wakestone with rare tentaculites; Findenig Formation, Cima Pizzul section, sample CP 7. I) *Nowakia acuaria* (Richter, 1854); Findenig Formation, Cima Pizzul section, sample CP 7. J) packstone with tentaculites, crinoids and abundant bioclastic debree; Findenig Formation, Cima Pizzul section, sample CP 8.

carried on in recent years in the Carnic Alps.

Conodont samples were decalcified using the conventional formic and/or acetic acid techniques; residues were sieved with a 100 μm sieve and picked under a binocular stereomicroscope. These new collections are housed in the palaeontological collections of the Department of Mathematics, Informatics and Geosciences of the University of Trieste (Italy).

One sample (FRK-B A1) was collected and analysed for palynological study. Organic matter was concentrated following the standard procedures at the Organic Matter Laboratory of the University of Perugia (Italy). About 30 g of the sample rock were processed by standard palynological methods (e.g. Aria-Nasab et al., 2016; Galasso et al., 2019; Riding, 2021) consisting of acid digestion by hydrochloric acid (HCl, 37 %) and hydrofluoric acid (HF, 50 %) to remove carbonate and silicate minerals, respectively. The organic residue was then sieved with a 10 μm filter. The very dark brown to black sporomorphs were lightened with bleach, using the method proposed by Buratti and Cirilli (2011) and/or Schultz solution. Transmitted light microscope observations were performed on palynological slides using a Leica DM1000 (Wetzlar, Germany) microscope with camera. Sample, organic residue and slides are stored at the Sedimentary Organic Matter Laboratory of the Department of Physics and Geology of University of Perugia (Italy).

For biostratigraphic assessment, the conodont zonations proposed by Corradini and Corriga (2012) and Valenzuela-Ríos et al. (2015) are followed for the Lochkovian; the scheme proposed by Slavík (2004) is adopted for the lower and middle Pragian: in the upper Pragian we reintroduced the *Po. pireneae* Zone, already used in various schemes (e.g.: Lane and Ormiston, 1979; Becker et al., 2012) to discriminate the younger Pragian Zone. It should be remarked that our concept of the *Po. pireneae* Zone is different than its original chronostratigraphic position by Lane and Ormiston (1979), who considered the species as index in the "upper Pragian". After the redefinition of the Pragian-Emsian boundary by the First appearance Datum of *Polygnathus kitabicus* Yolkin et al., 1994 (Yolkin et al., 1997) and the revision of the type section (Slavík et al., 2017), the boundary was sensibly lowered, and the traditional upper Pragian became the lower Emsian. However, the validity of the *Po. pireneae* Zone in that time interval was already challenged by Valenzuela-Ríos and Murphy (1997), who documented the taxon in the former lower Pragian in Spain, and Slavík (2004), in a similar position in the Czech Republic. Becker et al. (2012) considered the *Po. pireneae* Zone as the last Zone of the newly defined Pragian, and the same was confirmed in the zonation proposed by Corradini et al. (2024). Our data confirm this position, as the taxon entries above the first occurrence of *Pelekysgnathus serratus* Jentzsch, 1962, and below that of *Polygnathus kitabicus*. A new conodont zonation for the Pragian should be provided when the current revision of the Lochkovian/Pragian boundary with the goal to restore its original chronostratigraphic placement will be concluded.

5. Studied sections

In the Carnic Alps several sections expose rocks of late Lochkovian and early Pragian age. They were measured encompassing all the different depositional settings from shallow water to relatively deep open sea. Two sections were measured corresponding to the inner ramp zone (Polinik and Seekopf formations); five were sampled in the medium ramp zone (Rauchkofel and Kellerwand formations); seven were sampled in the outer ramp zone (La Valute and Findenig formations). All the sections are presented in the following chapters from west to east, subdivided according to their depositional settings. Key fossils are illustrated in Figs. 3I, 4, and 5.

5.1. Shallow water settings

The shallow water rocks of the Pre-Variscan sequence of Carnic Alps are represented by the Polinik and the Seekopf formations. Both these units span the Lochkovian-Pragian boundary.

5.1.1. Hildenfall (HLD)

The Hildenfall section (HLD) is located along the abandoned stretch of dirt road between St. Hubertus Chappel and Lake Wolayer, at coordinates 46°37′32.9“ N, 12°51′01.7” E and altitude 1420 m. The section exposes about 25 m of the back-reef/lagoonal limestones of the Polinik Fm., and starts with a 3 m thick bank of massive limestones, followed by about 6 m of well bedded yellowish limestones and a thick sequence of algal laminites. An evident erosional surface is present in the upper part of the section, about 14.5 m above the base of the laminites. Above, the sequence continues with several metres of dark algal laminites with abundant stromatolites. Pelitic interbeds are present irregularly along the section.

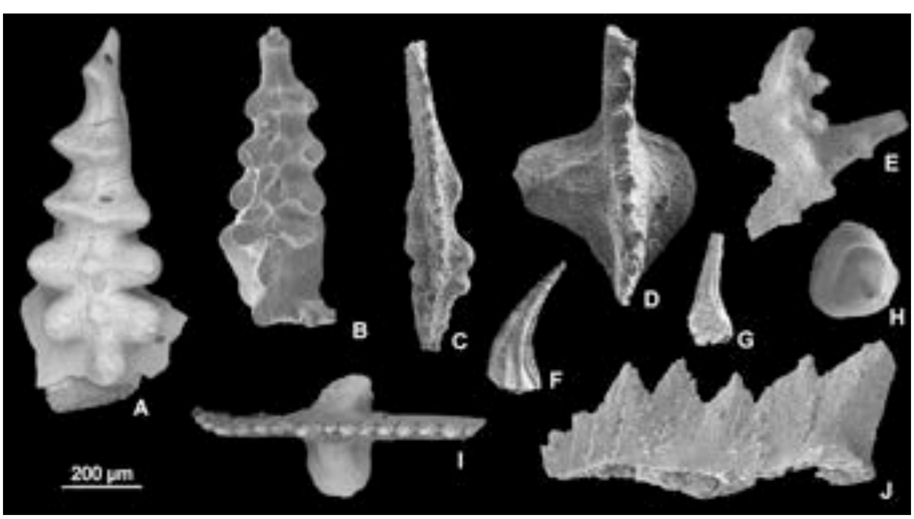

Fig. 4. Selected conodonts from the late Lochkovian and Pragian of the Carnic Alps. A) *Icriodus steinachensis* Al-Rawi, 1977 β-morph. Freikofel-B section, sample FRKB 1 A. B) *Icriodus steinachensis* Al-Rawi, 1977 β-morph. Freikofel South section, sample FRKS 4. C) *Polygnathus pireneae* Boersma, 1973; Seinbergerweg section, sample KELL-TS1. D) *Masaraella pandora* (Murphy et al., 1981) α-morph; Oberbuchach II section, sample 80. E) *Pedavis gilberti* Valenzuela- Ríos, 1984; Rauchkofel Boden section, sample 224d. F) *Decoriconus fragilis* (Branson and Mehl, 1933); Seewarte section, sample Se/02/13. G) *Pedavis* sp.; Seewarte section, sample Se/02/10. H) *Pseudooneotodus beckmanni* (Bischoff and Sannemann, 1958); Cima Pizzul section, sample CP 6. I) *Criteriognathus miae* (Bultynck, 1971); Seinbergerweg section, sample KELL-TS1. J) *Pelekysgnathus serratus* Jentzsch, 1962; Rauchkofel Boden section, sample 237.

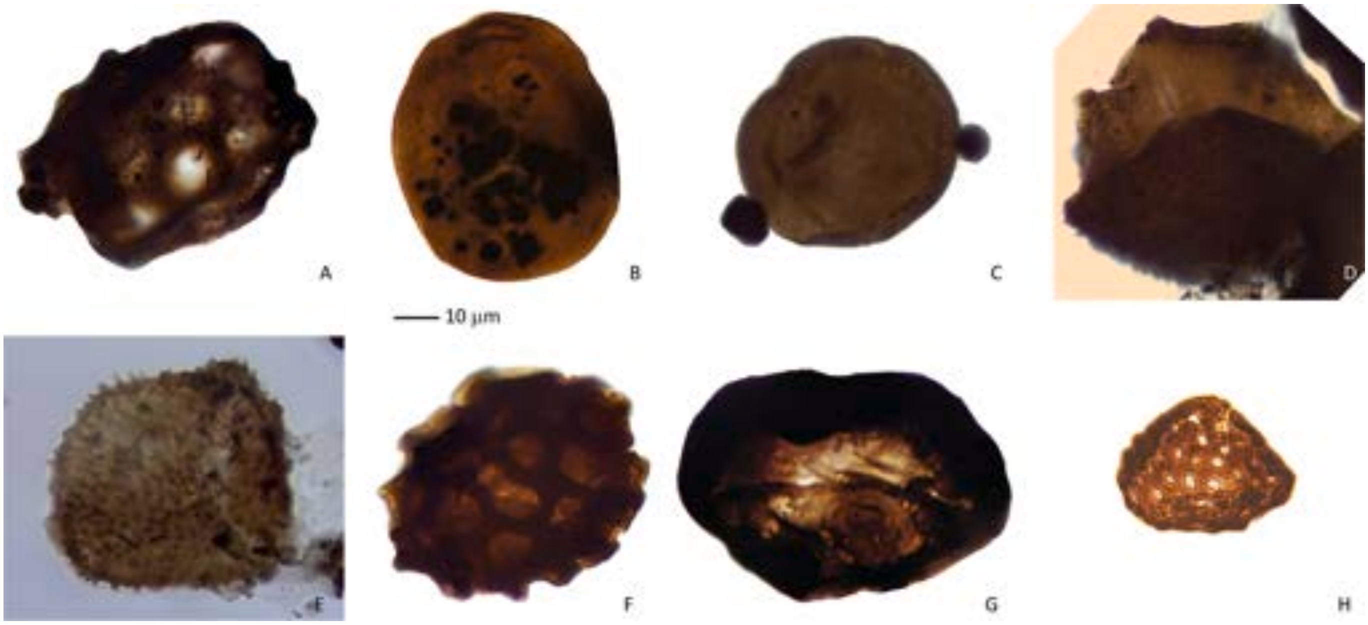

Fig. 5. Selected miospores from sample FRK-B A1 (Freikofel-B section). A, F) *Brochotriletes foveolatus* Naumova, 1953. B) *Archaeozonotriletes chulus* (Cramer) Richardson and Lister, 1969. C) *Gneudnaspora divellomedia* (Tchibrikova) Balme, 1988. D) *Apiculiretusispora plicata* (Allen) Streel, 1967. E) *Dibolisporites bullatus* (Allen) Riegel, 1973. G) *Latosporites ovalis* Breuer et al., 2007. H) *Brochotriletes robustus* (Scott & Rouse) McGregor, 1973.

The only biostratigraphic datum obtained came from the upper part of the yellowish limestones, from where was collected a poorly preserved conodont association with *Lanea* cf. *telleri* (Schulze, 1968) and *Zieglerodina* sp., indicating a middle Lochkovian age. Unfortunately, it is not possible to date the erosional surface.

5.1.2. Seewarte (SEW)

The Seewarte section (SEW) is located along the northwestern and western base of Mt. Seewarte, starting from the southwestern end of the Wolayer Valley, and continuing south across the Italy-Austria border, at coordinates 46°36′44.5“ N, 12°52’21.4” E (base of the section) and altitude 1980 m. 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 restudied for conodont biostratigraphy and microfacies by Suttner (2007). The interval across the Lochkovian/Pragian boundary, about 65 m above the base of the section in the Seekopf Fm., was studied in detail by Suttner and Kido (2016) and is here revised and integrated by further sampling.

The Lochkovian/Pragian boundary is marked in the field by the “megaclast-horizon” (Schönlaub et al., 2004; Suttner, 2007), represented by large irregular blocks up to 10 m large irregularly resedimented within the sequence in a yellowish/orange matrix. The overall texture is matrix-supported. At the base of this level an evident erosional surface is present. At the top, the upper part of the larger blocks extends over the matrix creating another irregular surface draped by thin beds up to 10 cm thick. Above, the sequence continues with 220 cm of irregular thin (2–6 cm) dark beds of mudstone to wackestone, and by thick coarse beds of gray pack-grainstone. Suttner (2007) and Suttner and Kido (2016) collected several samples in this interval: sample 02/14 was collected from below the erosional surface, sample 02/18 was picked at the base of the layers that drape the blocks; other samples were collected from the megaclast-horizon, both in the blocks (02/16, 02/17) and in the matrix (02/15 and 02/15a, b, c) (Fig. 6). Conodonts are quite poorly preserved in this interval, but genus *Pedavis* occurs only below the erosional surface and in one of redeposited mega-clasts (02/17), whereas both *Icr. steinachensis* β and η morphs occur in the megaclast-horizon matrix, indicating a Pragian age for this level.

5.2. Transitional settings

In the intermediate settings the Lochkovian Rauchkofel Fm. and the Pragian-Emsian Kellerwand Fm. deposited. The contact between these units is sharp and is marked by an unconformity, which, in places, is slightly angular.

5.2.1. Rauchkofel South (RKS)

The Rauchkofel South (RKS) section crops out in the northern side of the Valentin valley at coordinates N 46°36′58.5“ N, 12°53’23.0” E and altitude of about 1990 m. The section was studied by Schönlaub (1970), and was chosen as the type section of the Rauchkofel Fm. (Corradini et al., 2015b). Rocks from the Upper Ordovician to the Lower Devonian are exposed, belonging to the following seven formations: Valbertad Fm., Uqua Fm., Plöcken Fm., Kok Fm., Alticola Fm., Rauchkofel Fm. and Kellerwand Fm.

Compared to the other sections described above, the Rauchkofel Fm., that is here about 120 m thick is mainly represented by thin bedded dark limestone, with only a few calcarenitic banks that rarely reach a few metres of thickness. The boundary between the Rauchkofel and the Kellerwand formation is marked by unconformity and likely it is equivalent to the Lochkovian-Pragian boundary. Conodonts are very rare and poorly preserved in the upper part of the Rauchkofel Fm. The younger solid datum is the association collected 20 m below the top of the unit that indicates the middle Lochkovian *Ad. transitans* Zone. Alberti (1985) reported the occurrence of the dacryoconarids *Paranowakia geinitziana* (Richter, 1854) and *Nowakia sororcula* in the upper part of the Rauchkofel Fm. and referred these levels to the Lower *P. geinitziana* Zone of latest Lochkovian age. However, it is difficult to locate precisely these findings. Conodont samples collected at the base of the Kellerwand Fm. yielded only very rare fragments of Ozarkodinids.

5.2.2. Steinbergerweg Plöckenpass (SWP)

The Steinbergerweg Plöckenpass (SWP) section is a long section measured in the eastern slope of Mt. Cellon/Creta di Collinetta along

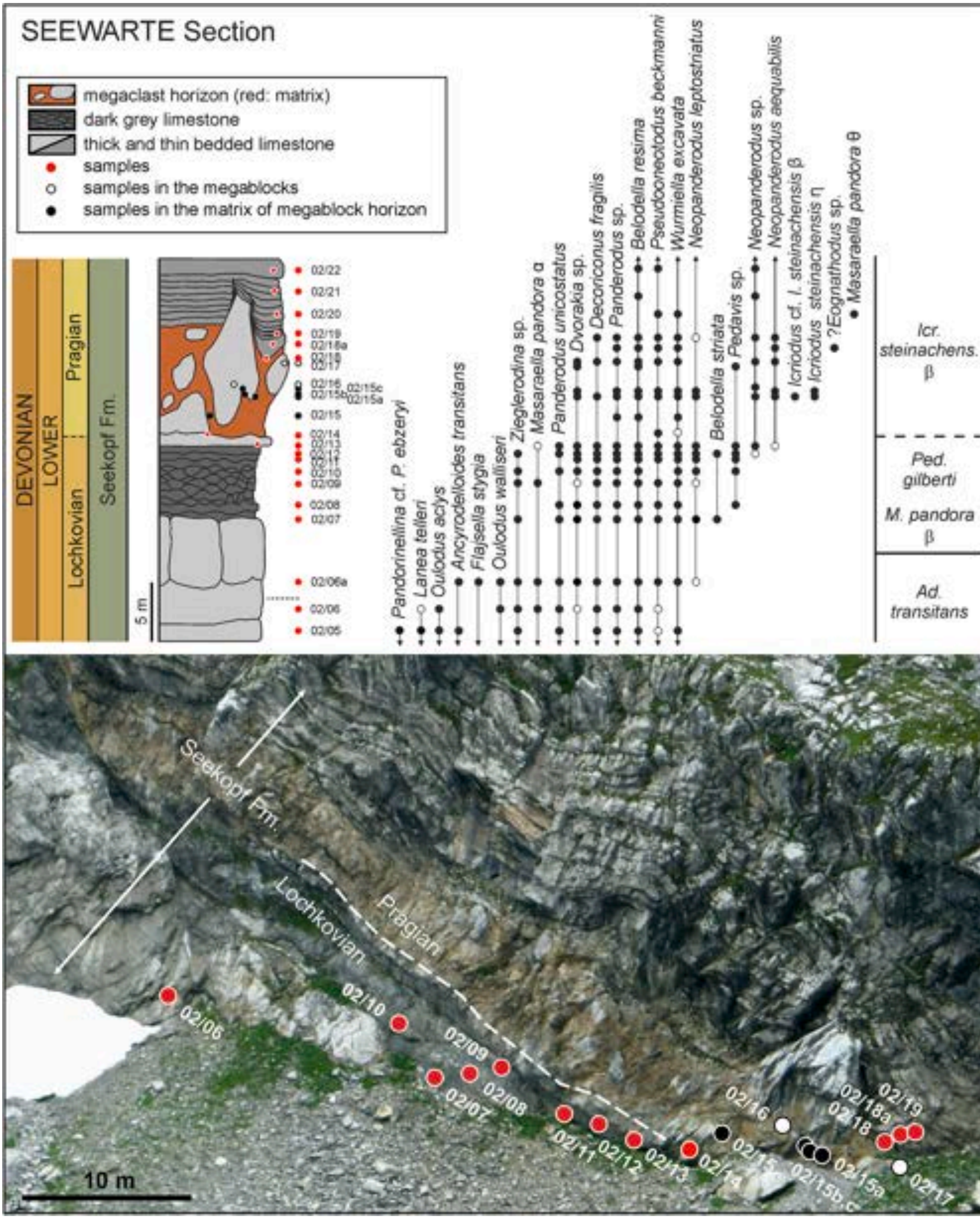

Fig. 6. The Lochkovian/Pragian boundary interval in the Seewarte section. From left to right: Period, Series, Stage, Formation, lithological log (modified after Suttner, 2007), occurrence of conodonts (white dots indicate problematic identification), conodont zones. Arrows at the end of distribution lines indicate that the taxon occur also below or above the illustrated interval. The photo is a view of this part of the section with indication of the position of samples.

path 427–3, at coordinates 46°36′33.09"N, 12°56′23.79″E and altitude 1615 m (base of the section). It is more than 250 m thick and is a classical exposure of the transitional units of the Carnic Alps, ranging from the Lower Lochkovian to the Givetian. The Rauchkofel, Kellerwand, Vinz and Cellon formations are exposed. The section was described by Pondrelli et al. (2020) and is the type section of the Kellerwand and Vinz formations (Pondrelli et al., 2015a, 2015b).

A covered interval occurs between the uppermost breccia bank of the Rauchkofel Fm. and the base of the Kellerwand Fm. Poorly preserved conodonts collected in the uppermost part of the Rauchkofel Fm. suggest a ?late Lochkovian age, and the presence of *Polygnathus pireneae* Boersma, 1973, *Criteriognathus miae* (Bultynck, 1971) and *Gondwania* sp.

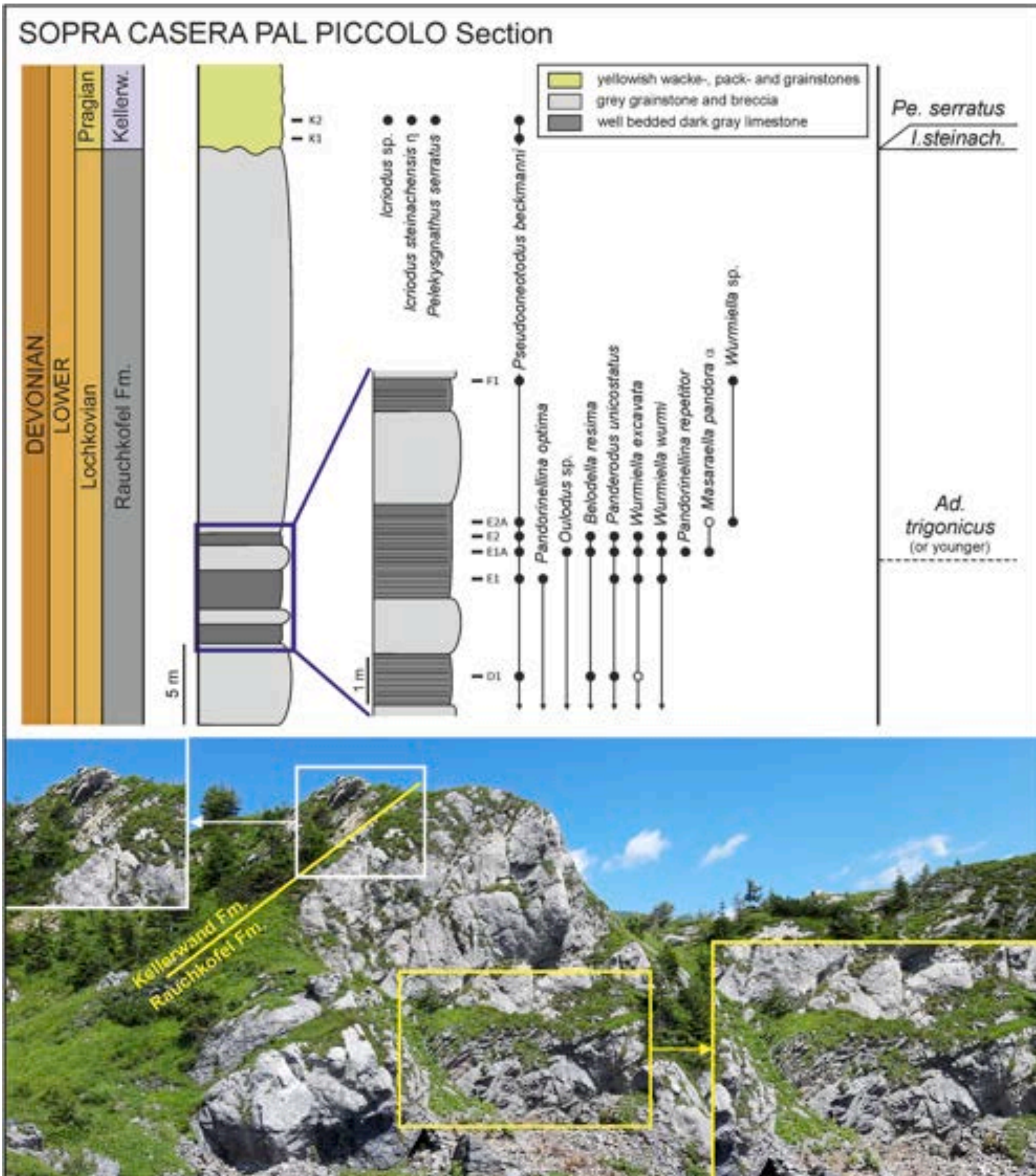

Fig. 7. The Lochkovian/Pragian boundary interval in the Sopra Casera Pal Piccolo section. From left to right: Period, Series, Stage, Formation, lithological log, occurrence of conodonts (white dots indicate problematic identification), conodont zones. Arrows at the end of distribution lines indicate that the taxon occur also below the illustrated interval. The photo is a panoramic view of the upper part of the section with indication of the position of samples. Abbreviations: Kellerw. = Kellerwand Fm.; *steinach.* = *steinachensis* β.

at the base of the Kellerwand Fm. indicate the upper Pragian. However, since the covered interval likely corresponds to the lowermost part of the Kellerwand Fm., the base of the unit can be slightly older.

5.2.3. Sopra Casera Pal Piccolo (SPP)

The Sopra Casera Pal Piccolo (SPP) section is located along a shortcut connecting path n. 401a and 401 north of Casera Pal Piccolo, at coordinates 46°36′02.6" N, 12°58′21.0″ E, and altitude 1620 (base of the section). The section was roughly presented by Corradini and Pondrelli (2021).

The section is a spectacular exposition of the middle and upper part of the Rauchkofel Formation, that is more than 190 m thick and is here represented by an alternation of well bedded limestone and thick calcarenitic and breccia banks, coarser and thicker in the upper part of the section. The upper part of the section is represented by about 25 m of breccia with an erosional surface at the top, capped by a few metres of wackestone to grainstones belonging to the Kellerwand Fm. A low angle angular unconformity is present between these two units (Fig. 7).

Conodonts collected in the limestone beds just below the upper breccia bed indicate a Lochkovian age and can be referred to the *Ad. trigonicus* Zone or to a slightly younger age. The association at the base of the Kellerwand Fm. contains the zonal index *Pelekysgnathus s. serratus* of middle Pragian age.

5.2.4. Freikofel B (FRK B)

The Freikofel (FRK B) section is exposed along path n. 401 a few tens of metres west of the FRKS section at coordinates 46°35′55.5" N, 12°58'44.2" E and altitude 1525 m. The section was preliminary described by Corradini and Pondrelli (2021).

The uppermost part of the Rauchkofel Fm. and the lower part of the Kellerwand Fm. are exposed. The top of the Rauchkofel Fm. consists of a several metres thick coarse breccia bank with an undulated upper surface. The Kellerwand Fm. consists of thin to medium-bedded wackestone and packstones interbedded with lithoclastic beds of packstones and grainstones generally showing normal grading and sometimes a faint lamination. The boundary between the two units is sharp, and emphasized by a dark brown siliciclastic irregular level (Fig. 8), suggesting an unconformity between the two formations. Conodonts from the upper part of the Rauchkofel Fm. do not allow any precise age attribution, whereas the lower beds of the Kellerwand Fm. yielded a Pragian fauna dominated by shallow water Icriodids. *Icriodus steinachensis* β and η morphs enters at the base of the unit, *Icr. castillanus* Carls, 1969 and *Icr.* cf. *simulator* Carls, 1969 occur 2 m above, indicating the *Pel. serratus* Zone, and an association with *Criteriognathus miae* and *Icr. angustoides angustoides* Carls and Gandl, 1969 occur 2.5 m higher, suggesting an upper Pragian age.

This age seems to be confirmed by a preliminary study on microflora from the siliciclastic level sampled between the Rauchkofel and the Kellerwand formations (Fig. 5). Miospores mainly consist of permanent dyad cryptospores such as *Dydospora murusattenuata* (Strother & Traverse) Burgess and Richardson, 1991 and *D. murusdensa* (Strother & Traverse) Burgess and Richardson, 1991, and monad as *Gneudnaspora divellomedia* (Tchibrikova) Balme, 1988. Smooth and ornamented trilete spores were also recorded as *Ambitisporites avitus* Hoffmeister, 1959 and *Archaeozonotriletes chulus* (Cramer) Richardson and Lister, 1969 with *Apiculiretusispora plicata* (Allen) Streel, 1967, *Brochotriletes foveolatus*

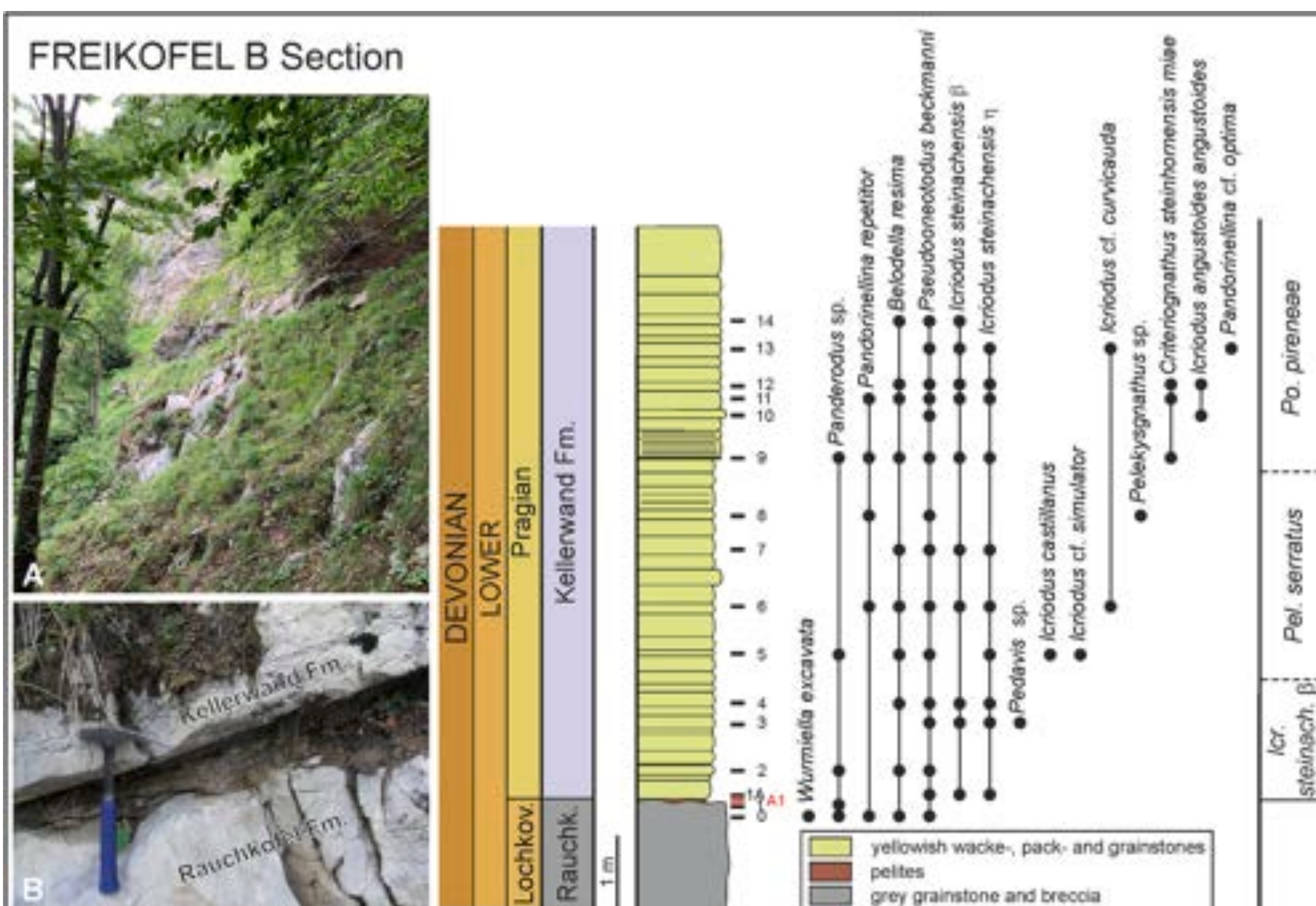

Fig. 8. Panoramic view (a) of the Freikofel-B section and detail across the Lochkovian/Pragian boundary interval (b). From left to right: Period, Series, Stage, Formation, lithological log, samples (red = samples for spores) occurrence of conodonts, conodont zones. Abbreviation: Lochkov. = Lochkovian; Rauchk. = Rauchkofel Fm.; *steinach.* = *steinachensis*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Naumova, 1953, *B. robustus* (Scott & Rouse) McGregor, 1973, *Dibolisporites bullatus* (Allen) Riegel, 1973, and *Latosporites ovalis* Breuer et al., 2007. Based on correlation with palynological assemblages characterized by similar morphological composition and documented from both Laurussia and Gondwana domains (see Breuer and Steemans, 2013 for a review; Marshall, 2016; Riboulleau et al., 2018; Spina et al., 2018; Wellman, 2018), microflora from FRK A1 sample can be tentatively attributed to the Pragian.

5.2.5. Freikofel South (FRKS)

The Freikofel South (FRKS) section is exposed along path n. 401 at coordinates 46°35′55.7“ N 12°58’46.7” E and altitude 1525 m. It was briefly described by Corradini et al. (2015a), and chosen as a reference section for the base of the Kellerwand Fm. (Pondrelli et al., 2015a).

It is a short section exposing the boundary between the Rauchkofel and Kellerwand formation. Conodonts are very scarce, but the occurrence of one element of *Icr. steinachensis* β-morph at the base of the Kellerwand Fm. allow to attribute this level to the Pragian.

5.3. Open Sea environment

In open sea settings the La Valute and the Findenig formations are mostly superposed in continuity. The transition is generally gradual and is exposed in several localities along the Carnic Alps. Aside of the sections presented below, transition beds occur in other areas as, for example, Mt. Cocco in the eastern part of the Carnic Alps. In general, across the formational boundary the lithology is more marly than in other parts of the two units.

5.3.1. Costone Lambertenghi/Seekopf Sockel (CL)

The Costone Lambertenghi/Seekopf sockel section is located along the Italy-Austria border west of the Wolayer Pass, at coordinates 46°36′33.6”N, 12°51′58.5″ E (base), 46°36′32.0“ N 12°51’52.6” E (top) and altitude between 2000 and 2150 m. Strata of Ordovician to Carboniferous ages are here exposed which are tectonically superimposed. The lower and the upper parts belong to different sedimentary sequences, separated by a major thrust. The lower part of the section has been studied in much more detail than the upper part, being more accessible and better exposed. The section was described, among others, by Vai (1967), Schönlaub (1970, 1980) and Brett et al. (2009b). Corriga et al. (2021) demonstrated that in the Costone Lambertenghi section the well-known hiatus between the Ordovician and Silurian is larger than in any other section of the Carnic Alps spanning from the Katian to the lower Ludfordian. Schönlaub (1980) published detailed data on conodont occurrences in the lower part of the section, up to the Middle Devonian: this collection is here revised and implemented with new sampling in key intervals. Alberti (1985) reported on the occurrence of dacryoconarids across the Lochkovian/Pragian Boundary.

The upper Lochkovian and the Pragian are represented by the La Valute and Findenig formations. Conodonts are scarce in this interval, but *Masaraella pandora* β (Murphy et al., 1981), which distribution is limited to the upper Lochkovian, occurs in the upper part of La Valute Fm., and *I. steinachensis* β and *Pandorinellina postoptima* Farrell, 2003 at the base of the Findenig Fm., indicating a lower Pragian age. From the same level Alberti (1985) reported *Nowakia* cf. *sororcula* Lukes, 1982, whereas *N.* aff. *acuaria* enters slightly above. The Lochkovian/Pragian boundary can be traced at the formational boundary (Fig. 9).

5.3.2. Rauchkofel Boden (RKB)

The Rauchkofel Boden section 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 one of the best known and most fossiliferous sections of the whole Carnic Alps. The section is easily accessible along the trail running from the Lake Wolayer to the top of Mount Rauchkofel and is along the geotrail Wolayersee prepared by the Geopark of the 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 litho-, chrono- and conodont bio-stratigraphy of the section, refer to Schönlaub et al. (2017b). More recently the Silurian/Devonian boundary sector was restudied by Corradini et al. (2020).

In the Rauchkofel Boden Section conodonts are very scarce in the upper part of the La Valute and in the Findenig formations, and the base of the Pragian is approximately traced around the formational boundary (Fig. 10) thanks to the occurrence of the dacryoconarid *Nowakia acuaria* at the base of the Findenig Fm. (Schönlaub, 1980; Alberti, 1985; Schönlaub et al., 2017b).

5.3.3. Lodintörl (LDT)

The Lodintörl section is located near Lodintörl, along path n. 448 at

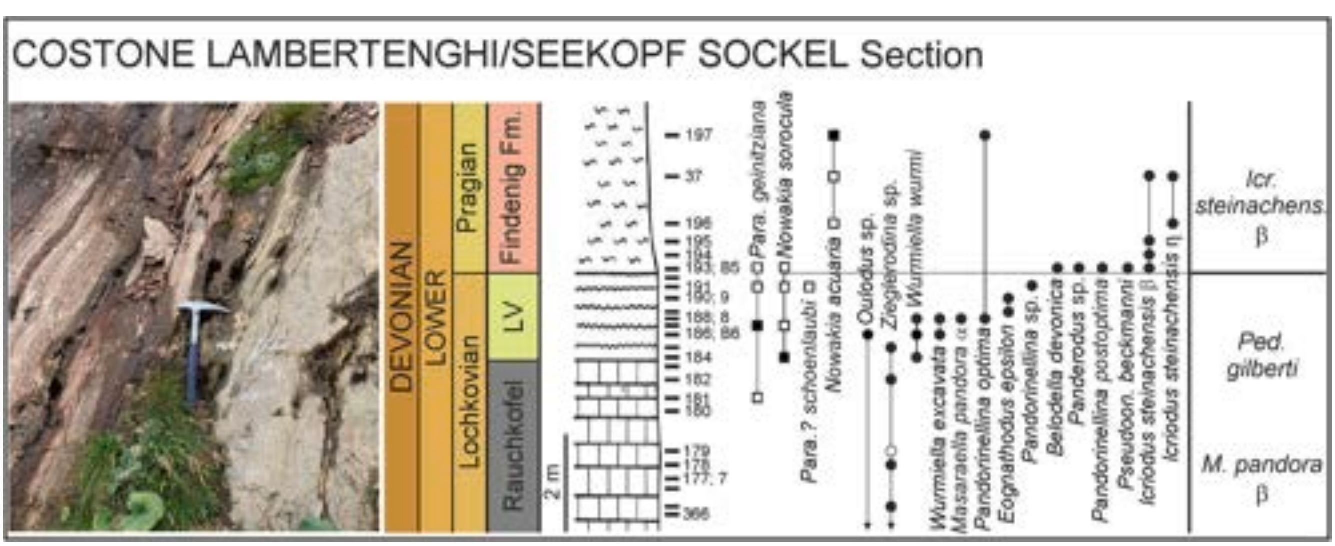

Fig. 9. The Lochkovian/Pragian boundary interval in the Costone Lambertenghi/Seekopf Sockel section. From left to right: Period, Series, Stage, Formation, lithological log (modified after Schönlaub, 1980), occurrence of dacryonarids (squares) and conodonts (circles), conodont zones. White dots indicate problematic identification. Arrows at the end of distribution lines indicate that the taxon occur also below the illustrated interval. The photo is a detail of the Lochkovian/Pragian transition. Abbreviations: LV = La Valute Fm.; *Para.* = *Paranowakia*; *Pseudoon.* = *Pseudooneotodus*; *steinachens.* = *steinachensis.*

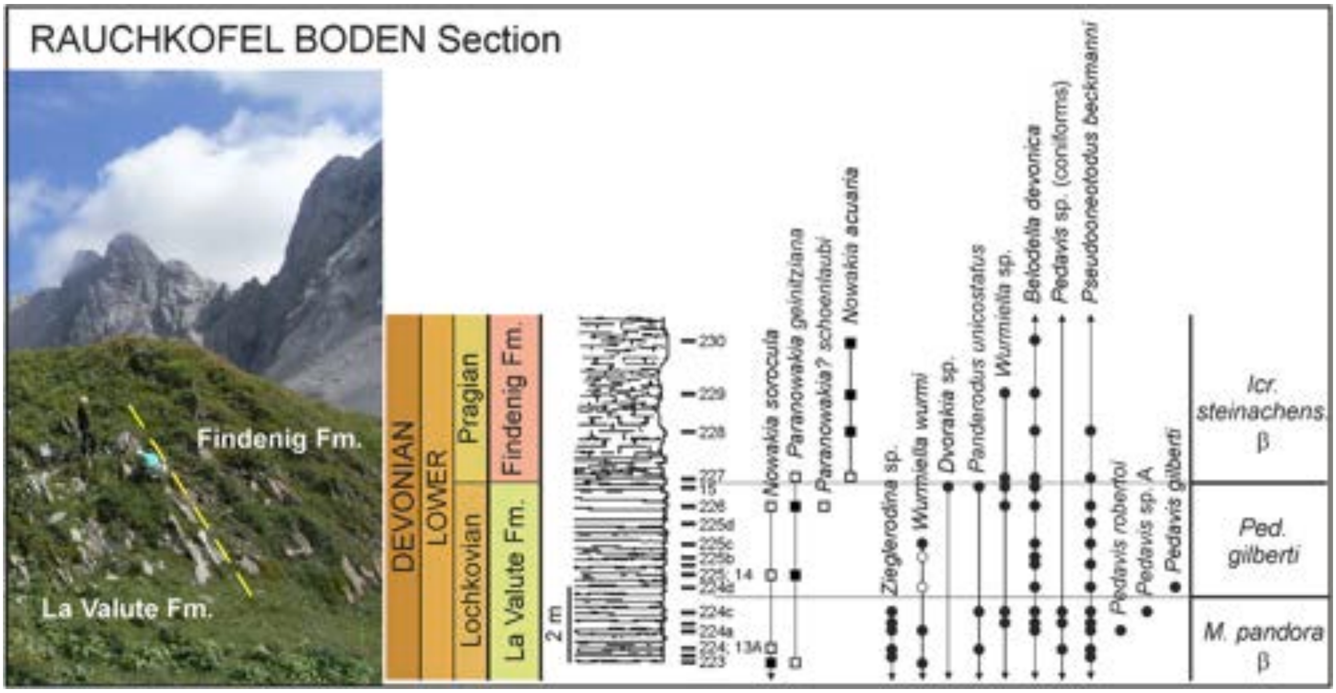

Fig. 10. The Lochkovian/Pragian boundary interval in the Rauchkofel Boden section. From left to right: Period, Series, Stage, Formation, lithological log (modified after Schönlaub et al., 2017b), occurrence of dacryonarids (squares) and conodonts (circles), conodont zones. White dots indicate problematic identification. Arrows at the end of distribution lines indicate that the taxon occur also below or above the illustrated interval. The photo shows Lochkovian/Pragian boundary interval. Abbreviations: *steinachens.* = *steinachensis*.

coordinates 46°35′46″N, 13°06′32″E and altitude of 1855 m. It is a short section exposing the upper part of the La Valute Fm and the lower part of the Findenig Fm. In the uppermost 20 cm of La Valute Fm. there are two levels with evident mud-cracks, suggesting a subaerial exposition at the top of this unit. This is also evidenced by the sharp formational boundary, differently than the other sections investigated, where it is always gradual.

Unfortunately, the conodont samples picked close to the formational boundary were barren, whereas in the lower part of the section only one P1 element of *Lanea omoalpha* (Murphy and Valenzuela-Ríos, 1999) was found in sample LDT 1, and a fragment of *Pseudooneotodus beckmanni* (Bischoff and Sannemann, 1958) in sample LDT 2.

5.3.4. Oberbuchach IV (OB IV)

The Oberbuchach IV section is located along an unpaved side road off the road running from the Gail Valley near Gundersheim to Gundersheim Alm at coordinates 46°37′54.6″N, 13°05′37.3″E and altitude of 1330 m.

The section starts with about 10 m of tectonized beds of the Alticola Fm. followed by 2 m of dark cephalopod limestone and interbedded pelites of the Rauchkofel Fm.; the contact with the overlying La Valute Fm. is sharp and probably faulted. The la Valute Fm. is here 16.5 m thick and grades in the overlying reddish nodular limestone of the Findenig Fm., almost 60 m thick. A few faults affect the upper part of the Findenig Fm. and the upper part of the Emsian is missing.

The Lochkovian-Pragian boundary is tentatively placed at the La Valute-Findenig transition on the basis of a scarce and poorly preserved conodont fauna. However, no conodonts diagnostic for a Lochkovian age occur in uppermost 2 m of the La Valute Fm., and only long-ranging taxa are present in the lower part of the Findenig Fm.

5.3.5. Oberbuchach II (OB II)

The Oberbuchach II section is located along the road running from the Gail Valley near Gundersheim to Gundersheim Alm at coordinates 46°37′37″N, 13°06′15″E and altitude of 1280 m. The section, more than 120 m thick, is a classical exposure of pelagic Devonian deposits of the Carnic Alps, documenting a 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 tentaculitids data, respectively. The conodont collection was recently revised by Schönlaub et al. (2017a), and the Silurian/Devonian boundary sector was restudied by Corradini et al. (2020).

The section starts with a few meters of light grey well bedded cephalopod limestones of the Alticola Fm., grading abruptly into dark platy limestones with interbedded black shales and marls of the Rauchkofel Fm. This unit is about 11 m thick and is overlain by about 15 m of light gray to pale brown limestones belonging to the La Valute Fm. The latter unit becomes more nodular and marly in the upper part before the gradual boundary with the Findenig Fm., represented by more than 40 m of poorly fossiliferous pink and grey flaser and nodular limestones.

The Lochkovian-Pragian boundary is traced in the uppermost part of La Valute Fm., in connection with the entry of the dacyoconarid *Nowakia a. acuaria* (Fig. 11). The scarce conodont associations in the upper part of the La Valute and Findenig formations prevents to define a precise zonation of the upper Lochkovian and Pragian interval, and *I. steinachensis* β-morph occurs a few meters higher than the entry of *N. acuaria*.

5.3.6. Stua Ramaz Ponte (SRP)

The Stua Ramaz Ponte (SRP) section is located along a forest road just south of the bridge on Rio di Lanza creek at Stua Ramaz, at coordinates 46°34′38.6“ N, 13°06’51.4” E, and altitude 975 m. The section was studied by Corradini et al. (2016, 2023).

About 15 m of limestones, strongly affected by ductile folding and slip, with interbedded shales in the upper part of the outcrop are exposed, belonging to the La Valute, Findenig and Hoher Trieb formations. A fault separates the La Valute Fm. from the Findenig Fm. and the Lochkovian/Pragian boundary beds are not exposed.

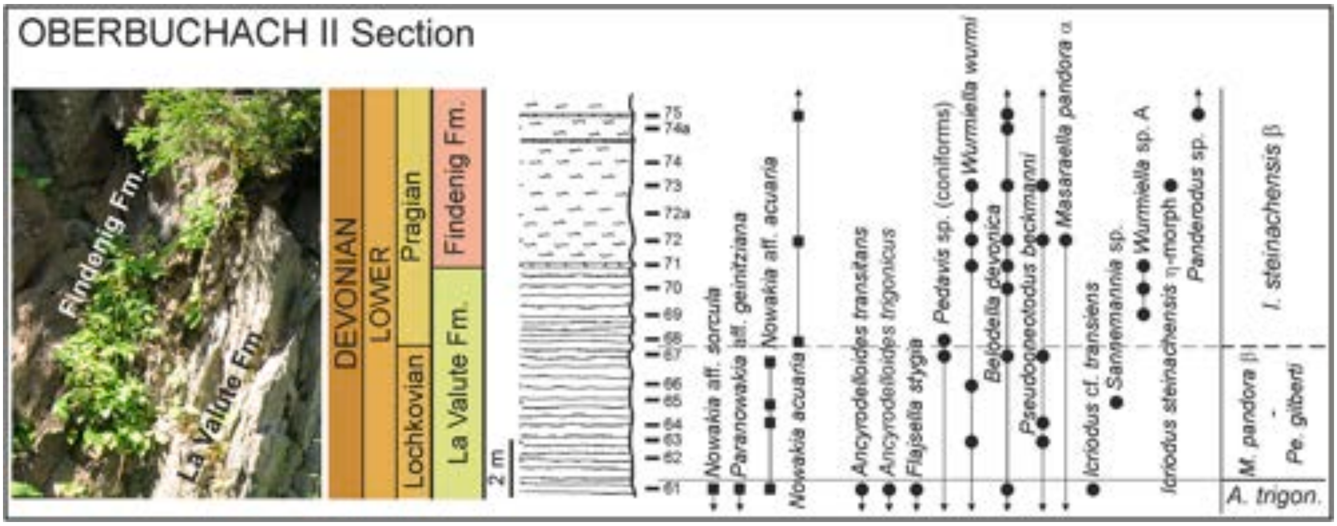

Fig. 11. The Lochkovian/Pragian boundary interval in the Oberbuchach II section. From left to right: Period, Series, Stage, Formation, lithological log (modified after Schönlaub (1985), occurrence of dacryonarids (squares) and conodonts (circles), conodont zones. White dots indicate problematic identification. Arrows at the end of distribution lines indicate that the taxon occur also below or above the illustrated interval. The photo is a detail of the Lochkovian/Pragian boundary interval. Abbreviations: *trigon.* = *trigonicus*.

5.3.7. La Valute Cave (LV)

The La Valute Cave (LV) section is located a few hundred meters NNW of Casera La Valute, just north of the top of La Valute, at coordinates 46°34′16.4“ N, 13°07'19.1” E and altitude 1475 m. It was measured inside and outside a First World War cave and consists of 8 m of nodular limestone exposing the gradual transition between the La Valute and the Findenig formations. The section was studied by Corriga (2011) and Corriga et al. (2011), and the conodont fauna was updated by Corradini et al. (2016, 2023). The LV section is indicated as reference section for the upper boundary of the La Valute Fm. (Corradini et al., 2015a).

A poorly preserved and relatively scarce conodont fauna allowed to date the section to the middle and upper Lochkovian (*Ad. trigonicus* and *M. pandora* β zones). The *M. pandora* β Zone is discriminated by the occurrence of elements of genus *Pesavis*, the first appearance of which approximates the base of the Zone (Valenzuela-Ríos and Murphy, 1997). The transition between the La Valute and the Findenig formations occur about 1 m above the base of the *M. pandora* β Zone; however, since no diagnostic conodonts are documented in the Findenig Fm., a younger age cannot be excluded for the upper part of the section.

5.3.8. Rio Malinfier West (RMW)

The Rio Malinfier West section 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) and altitude 1160 m. 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. The section was preliminary described by Corriga (2011), Corradini et al. (2012) and Corriga et al. (2017), who provided a detailed conodont biostratigraphy. Later it was studied in detail by Corradini et al. (2019), and, limited to part across the the Silurian/Devonian boundary, by Corradini et al. (2020). The data were summarized by Corradini and Pondrelli (2021).

The gradual transition between the La Valute and the Findenig formations is exposed in the uppermost part of the section. However, the very poor and fragmentary conodont fauna does not allow a precise location of the Lochkovian/Pragian boundary.

5.3.9. Cima Pizzul (CP)

The Cima Pizzul section is located at the summit of Mt. Pizzul, at coordinates 46°33′18.6“ N, 13°10'13.9” E and altitude 1975 m. The section was mentioned by Pondrelli et al. (2015c). It is a tectonized section exposing rocks of the Alticola, La Valute and Findenig formations. The boundary between the Alticola and La Valute formations is faulted, and the latter unit is here only 3 m thick indicating that most of the unit is missing. The gradual transition to the Findenig Fm. is exposed: a sample in the uppermost La Valute Fm. yielded an incomplete element of *Masaraella pandora* β, suggesting the eponymous upper Lochkovian Zone. At the base of the Findenig Fm. the dacrioconarid *N. acuaria* is present (Fig. 3I), indicating a Pragian age.

6. Evolution of the Carnic basin across the Lochkovian-Pragian Event

A summary of the stratigraphic data from the investigated sections is provided in Fig. 12 and selected views of the Lochovian-Pragian boundary beds are shown in Fig. 13. The basin evolution around the Lochkovian-Pragian boundary is characterized by a ramp-type depositional profile responding to sea-level fluctuations (Fig. 14) connected with the Lochkovian-Pragian Event. During the uppermost Lochkovian the basin consisted of (shallower to deeper) lagoonal (HLD section) deposits protected by a barrier island system with patch reefs alongside upper shoreface deposits (SEW section - Inner Ramp) passing to lower shoreface and offshore transition (RKS, SWP, SPP, FRK B, FRK S sections - Medium Ramp) and then to offshore deposits where carbonate mud was deposited below fairweather wave base (CL, RKB, LDT, OB IV, OB II, SRP, LV, RMW, CP sections - -Outer Ramp) (Fig. 13A). The thickening and shallowing upward trend documented in the inner to medium ramp settings (Fig. 13B) suggests a progradational stacking pattern following relative sea-level rise (Fig. 13A). Under these conditions, the carbonate factory progressively increased its production, leading to the first carbonate buildups of the Devonian of the Carnic Alps, observed directly in the inner ramp through the presence of reef builders such as corals and stromatoporoids (Hubmann and Suttner, 2007) and reflected in the presence of the same fauna as debris materials in medium ramp settings (Fig. 14A).

At the Lochkovian-Pragian boundary, a forced regression related to sea level drop exposes the previous inner and medium ramp and some limited part of the outer ramp. The upper part of the inner and medium ramp settings, including lagoonal (Fig. 13A), patch reefs, upper shoreface (Fig. 13C), lower shoreface (Fig. 13B) is marked by an extensive

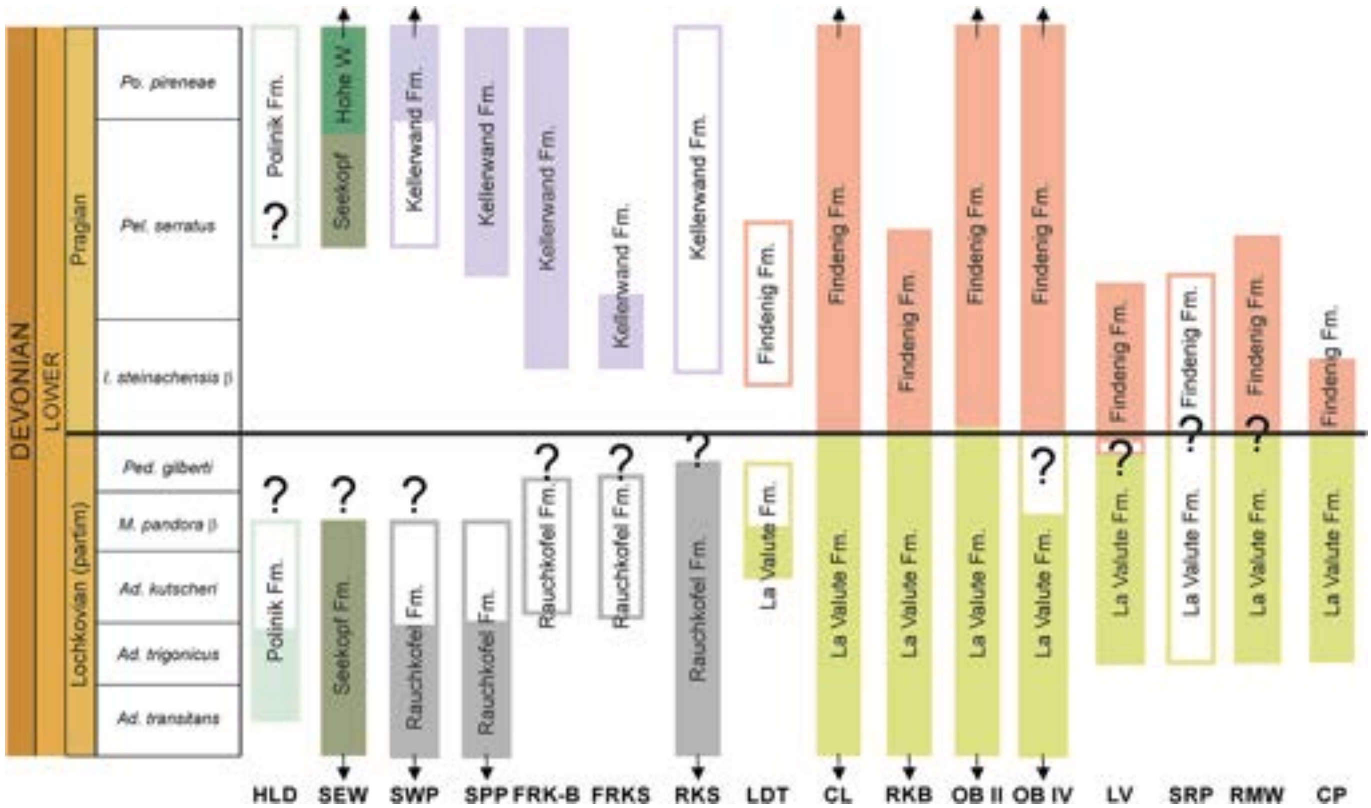

Fig. 12. Stratigraphic range of the sections presented in this paper, to show the hiatus across the Lochkovian/Pragian boundary in shallow water and intermediate settings.
Abbreviations of the sections: CL = Costone Lambertenghi; CP = Cima Pizzul; FRK-B = Freikofel-B; FRKS = Freikofel South; HLD = Hildenfall; LDT = Lodintörl; LV = La Valute Cave; OB II = Oberbuchach II; OB IV = Oberbuchach IV; RKB = Rauchkofel Boden; RKS = Rauchkofel South; RMW = Rio Malinfier West; SEW = Seewarte; SPP = Sopra Casera Pal Piccolo; SRP = Stua Ramaz Ponte; SWP = Steinbergerweg Plöckenpass.

exposure surface (Fig. 14B). This exposure reaches down to part of the outer ramp settings (LDT section; Fig. 13D), while in most of this distal part of the basin the deposition is continuous (Fig. 13E).

The geometry of this surface appears irregular but always roughly parallel to the layering (Fig. 13A, B, C). Significative cuts in the underlying stratigraphic succession to model the paleotopography can be excluded because the unconformity is exposed along the Valentin valley continuously for more than three kilometres. This unconformity is an erosional truncation, characterized by non-deposition and erosion and can be classified more precisely as a disconformity. Instead in the outer ramp, the unconformity is more subtle, marked only locally and only by desiccation cracks that might suggest exposure. The geometry of the surface is regular and lacks morphological evidence of extensive erosion, so that the contact can be defined as a paraconformity, with lack of deposition and possibly subtle erosion (Fig. 13D). The possible hiatus cannot be confirmed so far by other evidence (e.g., conodont data) and the interpretation of the cracks as desiccation cracks instead of synaeresis cracks cannot be unambiguous (Pratt, 1998). Still, the consistent polygonal shape and the V shape lateral geometry are suggestive of an exposure-related sedimentary strucure. In most of the outer ramp, the deposition appears continuous, but marked by a change in lithology, that can be at places gradual and at places sharper, from thin-bedded brownish-gray mudstone-wackestone to very thin-bedded pinkish red marly mudstone-wackestone (Fig. 13E). This continuous boundary represents the lateral continuity (i.e., correlative conformity) to the unconformable boundary within the more proximal units. Where the transition is continuous and gradual, condensed beds starts to develop before the Lochkovian-Pragian boundary and become even more condensed immediately after. Where the transition is continuous and sharp, condensed beds starts to develop after the Lochkovian-Pragian boundary.

The deposition in the shallower part of the basin resumed in the middle Pragian. The hiatus cannot be always quantified because conodont fauna is very scarce in these facies, even if the available data suggest an onlap of the oldest Pragian units (Fig. 12). At places in the upper shoreface settings the disconformity is covered by the "megaclast-horizon" (SEW section; Suttner, 2007; Suttner and Kido, 2016 - Fig. 13C).

The source area of the megaclasts is consistent with a distal to proximal transport at the beginning of the Pragian transgression (Suttner and Kido, 2016). In fact, there is no evidence of the presence of an exposed continental area high and steep enough to generate gravitative-driven processes, which would have been necessary to allow transport from the exposed continent, since the unconformable boundary is always parallel to bedding (Fig. 13B). Moreover, the megaclasts show a pinkish outer surface and are partly dolomitized which suggest that they underwent two diagenetic phases (possibly related to 1. uppermost Lochkovian deposition, and 2. lower Pragian reworking and redeposition), while the matrix undergone only one diagenetic phase (Pragian deposition). In addition, while samples from the matrix contain already a Pragian conodont fauna, conodont samples from the megaclasts show the same assemblage of the Lochkovian samples, although faunal distribution spans the Lochkovian-Pragian boundary (Fig. 6). The weathering which affected these deposits during their subaerial exposure most probably favoured their erosion and reworking toward the shore during the Pragian transgression by storm or tsunami processes (Suttner and Kido, 2016 - Fig. 12C). Above the Lochkovian-Pragian boundary, upper shoreface deposits are found in the inner ramp, while lower shoreface deposits in the medium ramp and marly limestone in the outer ramp. In this latter, distal part of the basin, the succession is

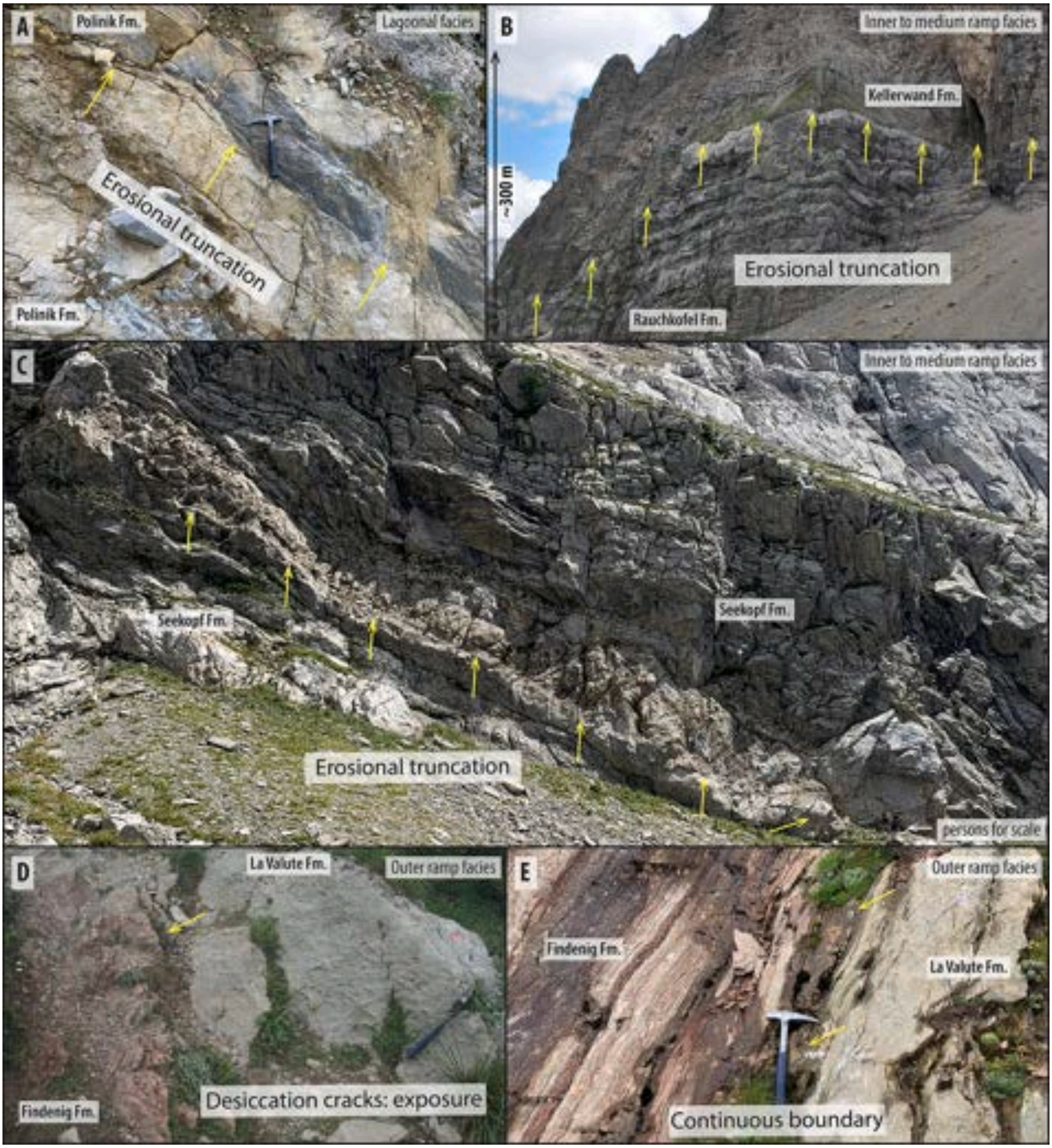

Fig. 13. Images of the Sequence Boundary at the Lochkovian-Pragian transition in the different parts of the basin. A) Disconformity within the lagoonal facies in the inner ramp; Hildenfall section. B) Disconformity in the upper to lower shoreface deposits in the inner to medium ramp exposed in the northern slope of Mt. Creta di Collina. C) Disconformity within the upper shoreface deposits in the inner ramp; Seewarte section. D) Paraconformity between basin deposits in the outer ramp; Lodintörl section. E) Correlative conformity in the basin deposits in the outer ramp; Costone Lambertenghi/Seekopf Sockel section.

condensed and marly.

We interpret this overall evolution as a change from High Stand System Tract (HST: Fig. 14A) to Falling Stage System Tract (FSST: Fig. 14B) and then to Low Stand System Tract (LST: Fig. 14C). The transition between HST and FSST is marked by the sequence boundary (unconformity and correlative conformity). The sea level drop results in turn in a drop in the efficiency of the carbonate factory following at the Lochkovian-Pragian boundary (and most probably also in the last phases of the HST). This low productivity continued during the whole FSST and at least in the first part of the LST.

7. The Lochkovian-Pragian boundary in other peri-Gondwana areas

7.1. Barrandian

The Prague Synform, located in the Czech Republic, represents a classical area of Devonian studies. The historical subdivision of the Lower Devonian in the Lochkovian, Pragian, Zlichovian and Dalejan was based on the lithostratigraphy of the area, where the Lochkov, Praha, Zlíchov and Daleje formations were discriminated (Chlupáč et al., 1985;

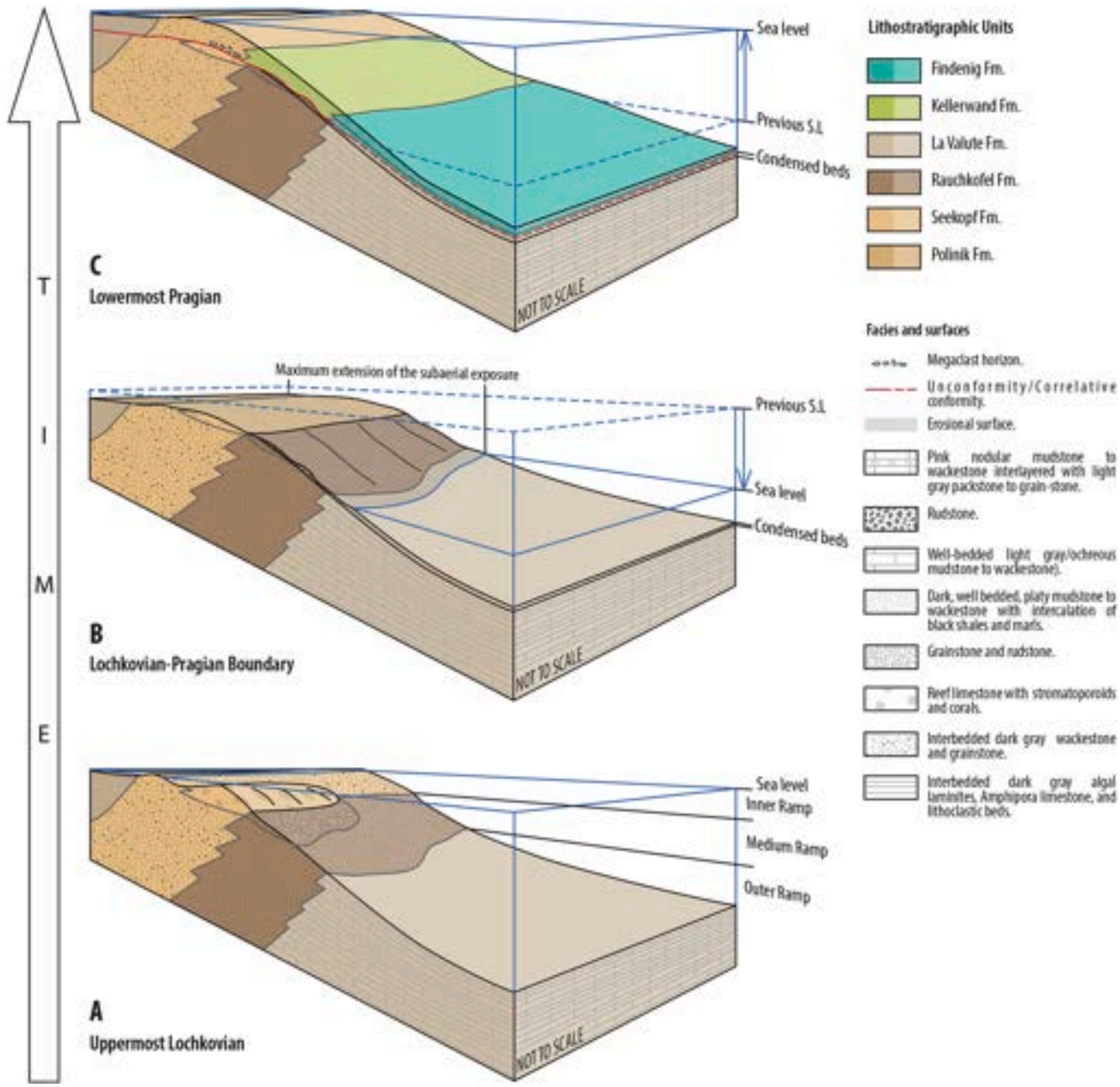

Fig. 14. Conceptual model of the evolution of the Carnic Alps between the uppermost Lochkovian (bottom) and the Lowermost Pragian (top). A) Block diagram representing the spatial distribution of the depositional environments in the uppermost Lochkovian. A progradational stacking pattern is recorded in correspondence of sea level rise (HST). Patch reefs develop in the inner ramp alongside shoreface deposits. Detrital material from the reef is deposited in the medium ramp together with distal shoreface to offshore materials. In the outer ramp carbonate mud is deposited below fair-weather wave base. B) Block diagram representing the spatial distribution of the depositional environments at the Lochkovian-Pragian boundary. Sea level drop exposes the previous inner and medium and some limited part of the outer ramp. Condensed marly beds form in the basin (FSST). C) Block diagram representing the spatial distribution of the depositional environments in the lowermost Pragian. Sea level rises and re-occupy the previously exposed surfaces. Upper shoreface deposits are found in the inner ramp, while lower shoreface deposits in the medium ramp and marly limestone in the outer ramp (LST).

Bábek et al., 2018a, 2018b). The GSSPs of the Lochkovian Stage (=Lower Devonian Series, = Devonian System; Martinsson, 1977and of the Pragian Stage (Chlupáč and Oliver, 1989) are located in this area. A precise biostratigraphy of the area was provided by a huge number of papers on conodonts, dacryoconarids, graptolites, goniatites and other fossil groups, and several sections were studied with various stratigraphic methods. For a recent summary see Slavík and Hladil (2020) and Weinerová et al. (2020).

The Lochkov Formation (lower Lochkovian to lowermost Pragian) is mainly composed of thin bedded and/or nodular limestones; locally chert nodules, marl laminae and thick-bedded, coarse grained crinoidal calcarenites and calcirudites are documented (Chlupáč et al., 1998; Carls et al., 2007; Slavík et al., 2007, 2012). The Praha Formation (lower Pragian to lower Emsian) rests conformably upon the Lochkov Formation. It is subdivided into five members (Chlupáč et al., 1998), constituted by nodular fine-grained calcisiltites and calcilutites, massive and thick-bedded crinoidal calcarenites and calcirudites and thin-bedded calcilutites, calcisiltites and marls. These differences at short distance are interpreted as a result of a highly variable sea bottom topography (Bábek et al., 2018a, 2018b).

Two distinct facies successions are recognized, one in the eastern part Praha-Beroun area, and the other to the south-west in the Koněprusy area, being a shallower sequence exposed in the latter. In most of the Prague Basin the sedimentation was continuous across the Lochkovian/Pragian boundary, but the upper parts of the Lochkov Formation are missing in the Koněprusy area (Slavík, 1998; Bábek et al., 2018a, 2018b; Slavík and Hladil, 2020 and references therein). The upper part of the Lochkov Formation and lower part of the Praha Formation coincide with a regressive-to-transgressive facies succession (Bábek et al., 2018a, 2018b; Hladil et al., 2010; Koptíková et al., 2010a, 2010b; Vacek, 2011). An evident rapid sea-level drop is documented in all the Barrandian, that reach its maximum just before the Lochkovian/Pragian boundary, with widespread subaerial exposures in the Koněprusy area.

In the Prague Synform the Lochkovian/Pragian Event coincides with the boundary between the Lochkovian and Pragian depositional sequences and a distinctive demonstration of relative sea-level changes within the Devonian. Gaps across the boundary are locally present, and a general condensation that started in the late Lochkovian is documented (Slavík and Hladil, 2020). Also, a strong decrease of conodont abundance in the upper Lochkovian and in the Pragian is observed ("Pragian conodont crisis"; Slavík and Hladil, 2020).

7.2. Sardinia

The Sardinian basement is part of the south-European Variscan chain (Carmignani and Pertusati, 1979) and exposes rocks from Cambrian to lower Carboniferous. The Variscan orogeny affected the whole basement producing various degrees of deformation and metamorphism from the NE to the SW of the island, the latter representing the foreland of the chain (Funedda and Oggiano, 2009 and references therein). The better-preserved mid-Palaeozoic sequences are exposed in the southern part of the island, but the features of the SE and the SW are different (Corradini et al., 1998a, 2009; Ferretti et al., 1998; Corradini and Ferretti, 2009). In rough approximation, rocks of SE Sardinia deposited in a relatively deeper environment than those exposed in the southwestern part of the island (Ferretti et al., 2009).

In Southeast Sardinia, Lower Devonian rocks are exposed in the Gerrei tectonic unit. No continuous Lower Devonian sections are documented up to now and the stratigraphy is built combining data from several localities. The Devonian sequence starts with a pelitic unit ("Upper graptolitic shales"), dated to the Lower-Middle Lochkovian by means of the rich graptolitic fauna (Barca and Jaeger, 1990; Piras and Paschina, 2009). This unit is better exposed in the eastern part of the Gerrei sub-region, whereas more to the west, some middle-upper Lochkovian (*Ad. trigonicus* and *M. pandora* β zones) strongly tectonized argillaceous limestones occur (Corradini et al., 2001). Above the sequence continues with an alternation of pelites and marly limestone tentatively dated to the upper Lochkovian-Pragian thanks to the rare occurrence of dacryoconarids (Gessa, 1993). From the Emsian the limestone content started to increase again (Bagnoli, 1979).

In Southwestern Sardinia the oldest Devonian rocks belong to the Genna Muxerru and to the Fluminimaggiore formations (Corriga et al., 2022). These units are mainly represented by black graptolitic shales and dark orthoceratid limestones, respectively. The overlying Mason Porcus Fm. (Gnoli et al., 1990) began to be deposited within the *Icr. postwoshmidti* Zone: it consists mainly of nodular and massive limestones alternating with compact dark siltstones and shales (Gnoli et al., 1990). The stratigraphy of the Lochkovian and Pragian part of the unit is based on relatively rich conodont fauna (e.g., Serpagli et al., 1978; Serpagli and Mastandrea, 1980; Mastandrea, 1985a, 1985b; Gnoli et al., 1988; Olivieri and Serpagli, 1990; Gnoli et al., 1988; Corradini et al., 1998b; Corriga, 2011; Corriga et al., 2022). These studies document the *Ad. transitans*, *Ad. trigonicus*, *Ad. kutscheri* and *M. pandora* β zones in the Lochkovian and the *Pe. serratus* and *Po. pireneae* zones in the Pragian. Due to the strong tectonics who affected the area, only two sections expose rocks of both Lochkovian and Pragian age: the Mason Porcus section (Gnoli et al., 1988; Olivieri and Serpagli, 1990; Corriga, 2011) and the Corti Baccas III section (Mastandrea, 1985b). At Mason Porcus a badly exposed, strongly tectonized interval (Gnoli et al., 1988), separates the *M. pandora* β to the *Po. pireneae* zones. At Corti Baccas III the middle Lochkovian is directly followed through a paraconformity by the *Pe. serratus* Zone. The Lochkovian/Pragian boundary beds are missing in SW Sardinia, and more that 2 Ma are not documented, suggesting the occurence of a sedimentary gap, likely connected with the Lochkovian-Pragian eustatic fluctuation.

7.3. Spain

Spain is a complex agglomeration of terranes, all exposing Proterozoic to Mesozoic rocks (Gibbons and Moreno, 2002). Reconstructions of middle Palaeozoic palaeogeography locates them in various perigondwana positions, according to the authors (e.g., Torsvik and Cocks, 2017; Franke et al., 2017; Golonka, 2020). Lower Devonian rocks are widely exposed in Spain (García-López and Sanz-López, 2002a, 2002b), and data across the Lochkovian-Pragian boundary are available from several regions, mainly in the northern and central part of the country.

In the northern part of the Cantabrian Zone (NW Spain) the upper Lochkovian and the lower Pragian beds belong to the Nieva Formation: a thick sequence of bioclastic and argillaceous limestone and calcareous shales, with abundant benthic fossils, mainly brachiopods (García-López and Sanz-López, 2002a). According to Vera de la Puente (1989) the unit correspond to a shallowing upward sequence with high energy storm generated events, grading into the lower Pragian tidal flat sediments of the Nieva Formation.

In the southern part of the Cantabrian Zone the same time interval is represented by the Felmín Formation, composed by calcareous sandstones, dolostones, siltstones and shales (García-López and Sanz-López, 2002b). Some skeletal grainstones have been related to storm deposits, and microbial mats, stromatolites and mud-cracks are present. The unit deposited in a littoral to lagoonal environment in transition to tidal flats.

Slightly to the south-east, in the Palentine Domain the upper Lochkovian and the lower Pragian are exposed in the Lebanza Formation (García-López et al., 2002). It is composed of bioclastic grainstones and packstones, shales and sandy limestones, where hummocky and tempestite structures are observable. Based on conodont fauna, the Lochkovian/Pragian boundary probably lies in a thick crinoidal limestone bed. The lower Pragian is represented by bioclastic grainstones with coral remains, succeeded by black shales and bioclastic limestones.

In the Spanish Pyrenees several tectonic units were discriminated (Casas Álvaro et al., 2019). Good biostratigraphical data, that allows a precise placing of the Lochkovian/Pragian boundary, are available from the axial zone. In the "el-Compte sedimentary domain" the Rueda Fm. spans the Lochkovian/Pragian boundary. The unit is mainly composed by limestone interbedded with marly shales. Across the boundary it consists of thick bedded to massive nodular, light coloured limestone with marly shales that increase in thickness upwards. A detailed study of Lochkovian conodonts was carried on several sections: for a summary and references refer to Valenzuela-Ríos and Liao (2024). Continuous sections across the Lochkovian/Pragian boundary are rare: according to Valenzuela-Ríos and Liao (2012) the boundary cannot be recognized in many sections due to tectonics, and only in the Compte-I section (Valenzuela-Ríos et al., 2015) the Pragian beds are in continuity above the Lochkovian. Slavík et al. (2016) suggested for the central Pyrenees an uppermost Lochkovian shallowing-upward succession capped by erosion surfaces and overlain by lower Pragian deepening-upward strata.

In the Iberian Chain the Lochkovian/Pragian boundary is exposed in the Nogueras Fm., composed by shally limestones, marls, siltstones and occasionally sand lenses (palaeochannels) or more continuous thin beds, which mostly correspond to lag deposits, interbedded between shales (Carls and Valenzuela-Ríos, 2002; Valenzuela-Ríos et al., 2019). The upper Lochkovian consists of shales with sandy palaeochannels, coquina limestone, iron oolites and some phosphatic pebbles. The boundary bed is represented by a thick sandy-mudstone dark-brown bed, which contains the local Pragian index brachiopod *Vandercammenina sollei* Carls, 1986. In the lowermost Pragian a few thin limestone beds are intercalated with dominant shales and sandstones (Valenzuela-Ríos et al., 2019).

8. Discussion and conclusions

The Lochkovian-Pragian deposits of the Carnic Alps were emplaced in a carbonate ramp. During the uppermost Lochkovian, the inner ramp consisted of a barrier island system with lagoonal deposits separated from the open sea by upper shoreface deposits where the first carbonate buildups of the Carnic Alps started to develop. In the medium ramp, lower shoreface to offshore transitions deposits developed, while in the outer ramp offshore environments are documented. These environments evolved toward the top of the Lochkovian with progradational stacking pattern observable in the inner and medium ramp parts of the basin. In the inner and medium ramp, and only locally in the outer ramp, these deposits are truncated by an erosional surface. The erosional surface develops through the basin as an irregular, undulated surface, that can be followed from the lagoonal to the carbonate buildups, shoreface, offshore transitions and very locally also n the basin materials. In most of the basin, though, the deposition is continuous.

Above the erosional truncation, the deposition resumes in the lowermost Pragian, with the depositions in the inner ramp of a prominent megaclast horizon, on top of which upper shoreface deposits develops passing distally to lower shoreface deposits in the medium ramp and marly limestone in the outer ramp where the succession is condensed.

The evolution of this basin testifies a sea level rise in the uppermost Lochkovian, followed by a sea-level drop and a following transgression in the Pragian. This evolution is associated with geometries and stacking patterns that allow to frame it within a sequence stratigraphic context. The uppermost Lochkovian developed in the last part of an HighStand System Tract; the sequence boundary is coincident with the chronostratigraphic boundary and marks the beginning of the Falling Stage System Tract, while the LowStand System Tract is marked by the onlap on the exposure surface that in the inner ramp lasted until the middle Pragian.

The sea level drop is associated with a widespread subaerial exposure that involved the whole inner and middle and a limited part of the outer ramp. The exposure lasted differently in the various parts of the Carnic basin, according to the physiography of the basin, and can be estimated lasting up to two million-years in the most proximal parts of the basin. This process is associated to the sudden disappearance of the first Devonian carbonate buildups, that cannot adjust to the new physiographic and/or climatic conditions. In turn, this caused a crisis of the carbonate factory, probably because before the sea-level drop, most of the carbonate productivity was located within the inner ramp.

This evolution is similar to the one of the other peri-Gondwana regions, such as Czech Republic, Sardinia, and Spain, and can be correlated to the similar gap in North America (Sloss, 1963; Ver Straeten, 2007; Brett et al., 2009a). This evolution mimic the sea level drop represented by the global Devonian geochemical and sea-level trends (e.g., Becker et al., 2020). These evidences show that the eustatic event across the Lochkovian-Pragian boundary is of global importance and affected the environmental conditions related to a general cooling of about 6 °C from late Lochkovian to the top of the Pragian (Joachimski et al., 2009) and, as a consequence, the life on the Earth. As example, the environmental changes related to the event generated a strong reduction in diversity and abundance of the conodont fauna.

CRediT authorship contribution statement

Carlo Corradini: Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Maria G. Corriga:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Monica Pondrelli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amalia Spina:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Thomas J. Suttner:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data are included in the paper and/or in the figures

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