



## Article

# Running across the Silurian/Devonian Boundary along Northern Gondwana: A Conodont Perspective

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**Abstract:** The Global Stratotype Section and Point (GSSP) of the Silurian/Devonian boundary, Lower Devonian Series and Lochkovian Stage was formally placed in 1977 at Klonk, in the Czech Republic, at the first appearance of the graptolite *Uncinatograptus uniformis uniformis* (Příbyl). However, since then, correlation of this limit has been often hampered in carbonate facies where graptolites are uncommon or totally absent. A large calcareous deposition occurred at the Silurian/Devonian boundary along the northern and peri-Gondwana margin, thus representing an ideal location to select and test a possible additional biostratigraphic marker of the limit among conodonts. The first appearance of *Caudicriodus hesperius* almost simultaneously at the base of the Devonian in Bohemia, the Carnic Alps, Sardinia, Morocco and elsewhere indicates that this taxon is the conodont that best approximates the beginning of the Period. The first or last appearance of other species (e.g., *Ozarkodina confluens*, *Zieglerodina klonkensis*, *Z. remscheidensis* and *Caudicriodus woschmidtii*) may help to recognise the boundary as well.

**Keywords:** chronostratigraphy; biostratigraphy; correlation; Palaeozoic; Silurian/Devonian GSSP



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## 1. Introduction

Graptolites and conodonts represent the best biostratigraphical tools for the Silurian and the Devonian, and most of the Stage limits of both Periods have been traditionally placed referring just to those fossil groups. However, graptolites mainly characterise organic-rich pelitic facies (*sensu* [1]) where, unluckily, conodonts are generally absent, whereas conodonts dominate in calcareous settings where graptolites are commonly lacking. This makes a precise tuning between conodont and graptolite biozonation schemes difficult, unless mixed lithologies, i.e., intercalations of black shales within limestones and *viceversa*, are present in the investigated succession. Some of the graptolite/conodont biostratigraphical zonation schemes already proposed (e.g., [2–14]) have also tried to establish a comparison with other fossil groups (e.g., chitinozoans, dacroconarids, trilobites, crinoids, spores, armoured fishes, acanthodians, macroplants, ammonoids, ostracodes, sharks, etc.) in an attempt to provide a connecting “bridge” between conodont and graptolite data (Figure 1) [7,15].

The first appearance datum of the graptolite *Uncinatograptus uniformis uniformis* (Příbyl) has been chosen to define the Silurian/Devonian boundary, and its Global Boundary Stratotype Section and Point (GSSP) has been formally located in the Klonk section, Czech Republic [16], palaeogeographically placed at that time along northern Gondwana. However, for the reasons discussed above, the Silurian/Devonian limit can be easily followed by the marker graptolite taxon in siliciclastic facies, but it becomes hardly applicable in calcareous dominated settings.

| Age (Ma) | PERIOD   | EPOCH/AGE |            | GRAPTOLITE ZONATION                              | CONODONT ZONATION                             | CHITINOZOAN ZONATION          | SPORE ZONATION   | ARMORED FISH ZONATION | ACANTHODIAN ZONATION           | MACRO-PLANTS          |
|----------|----------|-----------|------------|--|---|-------------------------------|--|-----------------------|--------------------------------|-----------------------|
| 417      | DEVONIAN | EARLY     | Lochkovian | <i>Uncinagraptus uniformis</i>                   | <i>Caudicriodus postwoschmidti</i>            | <i>Fungochitina lata</i>      | <i>Emphanisporites micromatus - Streelisporea newportensis</i> | <i>Rhinopteraspis</i> | <i>Nostolepis minima</i>       | <i>Zosterophyllum</i> |
| 418      |          |           |            |  | <i>Caudicriodus hesperius</i>                 | <i>Eisenachitina bohemica</i> | <i>Phialaspis, Protopteraspis, Pteraspis rostrata</i>          |                       |                                |                       |
| 419      | SILURIAN | PŘÍDOLÍ   |            | <i>Istrograptus transgrediens / "M". perneri</i> | Upper <i>Oul. el. detortus/ Z. klonkensis</i> | <i>Angochitina superba</i>    | NOT ZONED  |                       | <i>Trimerolepis timanica</i>   |                       |
| 420      |          |           |            |  |   |                               |  |                       | <i>Poracanthodes punctatus</i> |                       |

Figure 1. Main biostratigraphical markers across the Silurian/Devonian boundary. Modified after Becker et al. (2020) [15] and Melchin et al. (2020) [7].

Several additional sections, located in the same geographical region of the GSSP, expose calcareous sediments across the Silurian/Devonian boundary, documenting a variety of depositional settings, from very shallow water to moderately deep or deep-shelf environments [17]. The literature from some of these areas report fossil names, the validity and age-ranges, which are in strong need of a deep taxonomic revision. For some other sites, including the type area (i.e., Bohemia, Carnic Alps, Sardinia and Morocco) [11,17–21], recent conodont studies, integrating new sampling with historical collections, have been run in the attempt to provide a precise updating both of the biostratigraphy and the taxonomy of the rich conodont associations there reported.

The aim of this contribution is to integrate and correlate these new conodont data with the old literature inside and outside the northern Gondwana region (Figure 2) in an attempt to provide a global synthesis on the conodont occurrences along northern Gondwana at the Silurian/Devonian boundary and offer an efficient tool for locating the boundary level in carbonate facies.

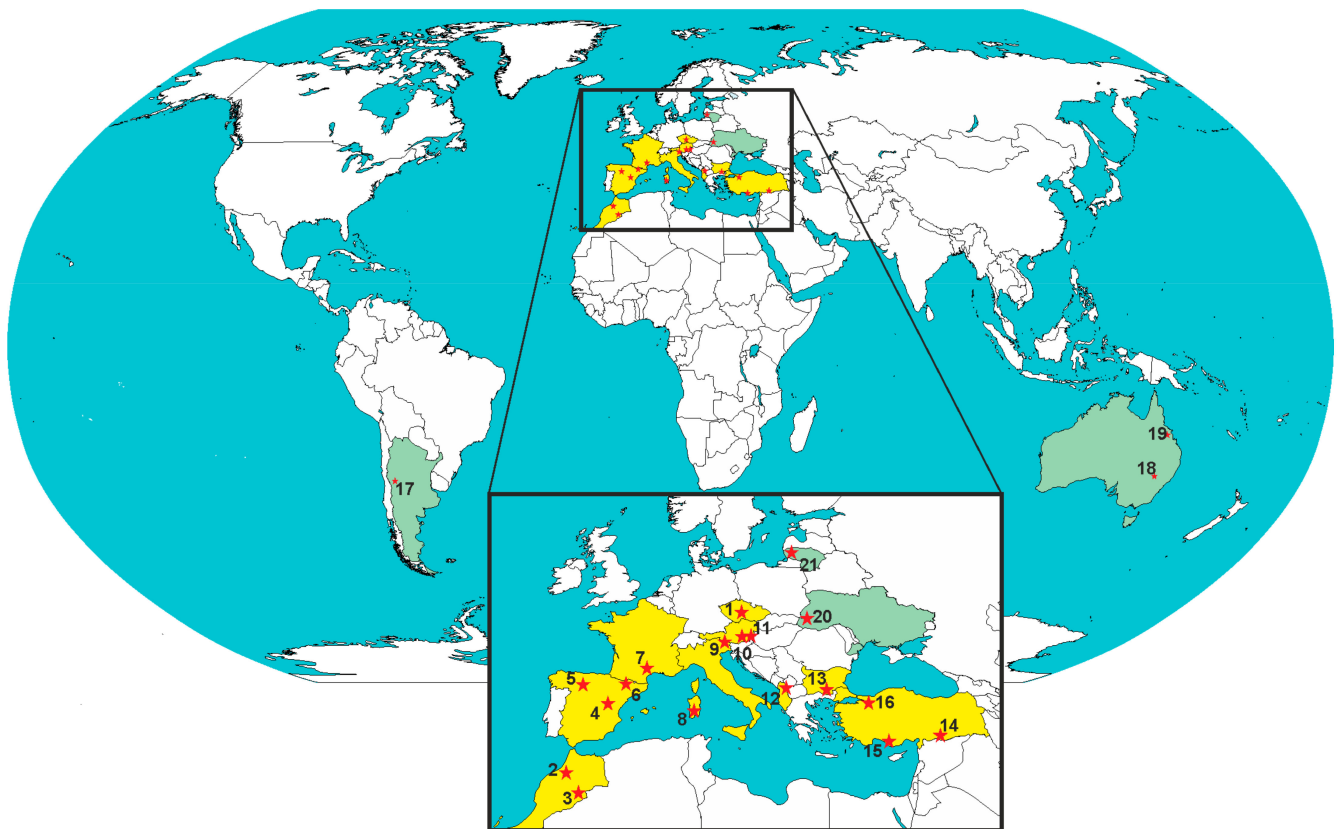


Figure 2. Main areas investigated in this paper. Yellow: northern Gondwana regions; green: other

studied areas. Red stars refer to conodont localities analysed in this study, labeled according to the order in which they are discussed in the text. 1. Barrandian (Czech Republic); 2. Western Meseta (Morocco); 3. Tafilalt (Morocco); 4. Iberian Chain (Spain); 5. Palentine Domain (Spain); 6. Pyrenees (Spain); 7. Montagne Noire (France); 8. Sardinia (Italy); 9. Carnic Alps (Italy and Austria); 10. Graz Paleozoic (Austria); 11. Burgenland (Austria); 12. Albania; 13. Bulgaria; 14. Arabian Plate (Turkey); 15. Taurides (Turkey); 16. Pontides (Turkey); 17. Precordillera (Argentina); 18. New South Wales (Australia); 19. Broken River (Australia); 20. Podolia (Ukraine); 21. Lithuania.

## 2. Palaeogeography across the Silurian/Devonian Boundary

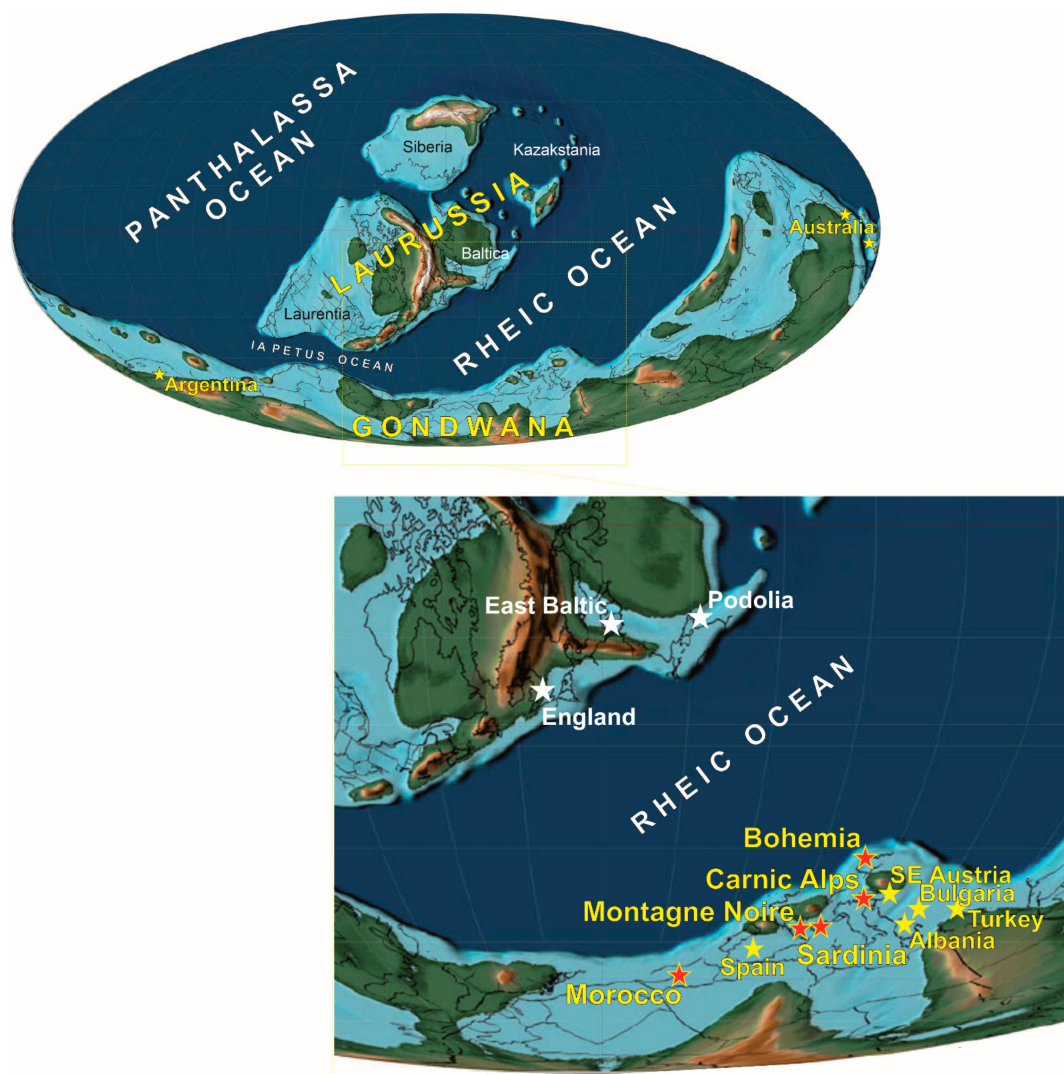
The present-day distribution of Silurian/Devonian basin fragments in modern geographical configurations is the end result of intensive orogenic and drifting/rifting episodes. Through a combination of studies on fauna and flora distribution (e.g., [22–30]), the application of sedimentological criteria combined with palaeoclimatological approaches and the measurement of palaeomagnetic signals (see, among others, [31–42]), and by the analysis of structural/geodynamical patterns and sea-level fluctuations (e.g., [43–46]), diverse past palaeogeographical configurations have been proposed (e.g., [47,48]).

Most of the sectors comprising peri-Gondwana and northern Gondwana are now included in South-Central Europe (Czech Republic, South Germany, Spain, Portugal, France, Austria, Italy and probably Romania), North Africa (Morocco, Algeria, Tunisia, Libya, Niger and Egypt), the Middle East (Turkey, Syria, Jordan, Iraq and Saudi Arabia), Florida and parts of southeastern USA [27]. Sequences of different thicknesses were deposited, whose difference in relative completeness are due to either non-deposition or to erosion. Marked variations in the dominant lithofacies are attributed to the various palaeogeographical positions of the basin fragments during the Silurian–Devonian interval.

The transition to the Devonian, 419 Ma ago, led to completion the general process of continental plate convergence that had characterised the Silurian Period [7]. Most continental areas occupied one hemisphere, whereas the other was mainly represented by water (“Proto-Pacific” or Panthalassa Ocean) [15]. Laurussia had in fact originated from the merging of Laurentia and Baltica. Siberia and Kazakstania were located at nearby settings (Figure 3). This large continental block was bordered in the southern part by remnants of two oceans, which were going soon to be closed: the Iapetus Ocean to the West and the Rheic Ocean to the East, leaving the place to the Proto-Tethys.

Palaeogeographical maps commonly depict a continuous continental ribbon at highest southern latitudes, having present-day geographical areas of South-Central Europe and North Africa at the meridional flank of the Rheic Ocean. However, their relative positioning has been subject to several shifts and re-assemblages, moving from a general amalgamation (see a summary in [49–51]) to a “palaeogeographical splitting” in a series of microterranes (e.g., [52,53]). Whatever was the precise location of these sectors at that time, it is unanimously accepted that a strong connection was active between all areas belonging to, or close to, the northern Gondwana margin during Silurian and Devonian times.

The palaeogeographical configuration adopted in this study (Figure 3) follows Scotese (2014) [54] in placing all areas of northern Gondwana along a continuous margin at high latitudes, with the Prague Synform (Barrandian area, Czech Republic), where the GSSP for the Silurian/Devonian boundary has been selected [16], at lowermost latitudes and in a promontory position.



**Figure 3.** Palaeogeographical distribution of published conodont records across the Silurian/Devonian boundary along northern Gondwana. Stars indicate data analysed in the present paper, with red stars pointing to collections studied directly by the Authors. Palaeogeographical reconstruction after Scotese (2014) [54].

### 3. The Silurian/Devonian Boundary

Sedgwick and Murchison formally introduced the Devonian System in 1839 in south-western England, following suggestions provided by Lonsdale, who had first proposed the name Devonian [55]. Regarding System boundaries, an exhaustive history on the Silurian/Devonian limit was recently summarised by Becker et al. (2020) [15], who remarked how, following the British graptolite school and the occurrences there in the Ludlow Bone Bed, the extinction of graptolites was initially regarded to be the marker for locating the start of the Devonian. It was then realised that graptolites were not extinct, and after a detailed and time-consuming search for the best marker(s) of the Silurian/Devonian boundary [16], it was decided to define the base of the Devonian on the first appearance of the graptolite *Uncinagraptus uniformis uniformis* and of the trilobites of the *Warburgella rugulosa* group. The GSSP for the Silurian/Devonian boundary, Lower Devonian Series and Lochkovian Stage was finally located 35 km southwest of Prague in the southwestern part of the Barrandian region (see below), specifically within Bed 20 in the Klonk section [16]. In the upper part of that bed, immediately above the limit, the occurrences of *U. uniformis uniformis* and *U. uniformis angustidens* (Příbyl) were recorded [56].



Conodonts are present as well in the Klonek section. However, in recent years some late Silurian–Early Devonian marker genera were subject to a taxonomic revision, as they were revealed to be a “waste-basket” of different lineages. As a consequence, a global reorganisation of the conodont biozonation schemes of the Silurian and the Devonian occurred (see a detailed discussion in [21]).

The appearance of the conodont genus *Icriodus* has been considered for a long time as equivalent to the start of the Devonian. In particular, the *Caudicriodus woschmidti* Zone was believed to represent the basal Devonian conodont zone. It should be noted, however, that some Authors, but not all, include the early representatives of the genus (“*Icr.*” *woschmidti* Ziegler and “*Icr.*” *hesperius* Klapper and Murphy) within the genus *Caudicriodus* Bullynck. Jeppsson (1988) [57] remarked that the occurrence of *Caud. woschmidti* slightly anticipates that of *U. u. uniformis* in many sections, but Corradini and Corrigan (2012) [11] explained this apparent discrepancy as simply due to a facies control. Carls et al. (2007) [58] recognised in *Caudicriodus hesperius* the main species previously included within the early Lochkovian *Caud. woschmidti*, occurring together with other undetermined species of the same genus. Even if *Caudicriodus hesperius* enters slightly higher in the lower Lochkovian from the type locality, Carls et al. (2007) [58] elected this taxon as the conodont species closest to the Lower Devonian boundary. This opinion is mostly accepted among conodont workers, and the *Caudicriodus hesperius* Zone appears as the first conodont zone of the Devonian System in most conodont biozonation schemes.

#### 4. Silurian/Devonian Boundary Event, Carbon Isotope Excursion and Conodont Diversity

The most important and worldwide event that marks the Silurian/Devonian boundary is based just on the first occurrence of the index graptolite *Uncinagraptus u. uniformis*. It was defined by Walliser (1985) [59] as the Silurian/Devonian Boundary Event. Later, this event was characterised as a marked environmental change [60] and some Authors considered this event as a pronounced extinction event (e.g., [61,62]). The Carbon Isotope Excursion (CIE) at the Silurian/Devonian boundary was described by Hladíková et al. (1997) [63] based both on the Silurian/Devonian GSSP at Klonek and its auxiliary stratotype at the Budňany rock section near Karlštejn in the Prague Synform. The excursion was later confirmed from many other sections around the stratotype area (e.g., [62,64]). Buggish and Mann (2004) [64] proposed worldwide carbon isotope stratigraphic trends across the Silurian/Devonian transition. Similar trends had already been documented in other periods and correlated world-wide (e.g., [65,66]). The onset of the CIE in the latest Přídolí, with the peak of the excursion at the boundary or in the earliest Lochkovian, was confirmed in many other areas of the world, e.g., [67–70] (Laurentia), [71–75] (East Baltica-Podolia and Lithuania), [76,77] (Carnic Alps). A possible driver can be considered the enhanced organic carbon burial of rapidly evolving terrestrial biota [71]. However, irrespective of various interpretations of likely triggers of the Silurian/Devonian boundary CIE, its correlation potential is large and can be roughly linked with the origin of the genus *Icriodus* that represents one of the most important events among Devonian conodont faunas—i.e., the *Icriodus* Event [78]. The oldest icriodid is found in the same bed with the FAD of *U. u. uniformis*, that is immediately followed by *C. hesperius* in the Prague Synform [21]—the conodont marker of the base of the Devonian. The Event well represents conodont response to the environmental change at the systemic boundary. With respect to conodonts, it is not an extinction event because the base of Lochkovian is characterised by a radiation in conodont taxa (mostly icriodids and ozarkodinids of genus *Zieglerodina*) that is reflected in both increased diversity and overall abundance of conodont faunas (cf. [78]).

The Silurian/Devonian CIE has, however, a misleading terminology. The excursion is often referred to in literature as the “Klonek Event”. This name has its origin in the “Klonek Secundo-Unnamed Event”—a conodont event by Jeppsson (1998) [57] that corresponds to the origin of *Oul. el. detortus* in the *Oul. el. elegans*—*Oul. e. detorta* lineage. However, the taxon enters close to middle of the Přídolí, being ca 2 m.y. older than the Silurian/Devonian

boundary. Therefore, the name of the original Silurian/Devonian Boundary Event by Walliser in relation to the CIE is preferred and recommended in this paper.

### 5. Taxonomic Note

The taxonomy of late Silurian and Early Devonian conodonts has been widely revised in the last twenty years, and several genera were proposed to discriminate part of the forms previously included in a “basket” genus or even in a single species. As example, form elements previously attributed to *Spathognathodus steinhornensis remscheidensis* Ziegler were later renamed *Ozarkodina remscheidensis* (Ziegler) in terms of natural species (multielement apparatus), which is now included in several species of the genus *Zieglerodina* (e.g., *Z. remscheidensis*, *Z. planilingua* (Murphy and Valenzuela-Ríos), *Z. zellmeri* Carls et al., *Z. klunkensis* Carls et al., *Z. ivochlupaci* Carls et al., *Z. mashkova* (Drygant), *Z. formosa* (Drygant), *Z. eladioi* (Valenzuela-Ríos), *Z. schoenlaubi* Corradini et al., *Z. petrea* Hušková and Slavík, *Z. camelfordensis* (Farrell), *Z. prosoplatys* (Mawson et al.), etc.). This makes referring to fauna documented in old papers difficult, because we cannot convert the name *Oz. remscheidensis* to the present species concept, unless for figured specimens that always represent a very minor part of the association. This is why in the various chapters of this paper we cannot sometimes provide further details, and we report the occurrence of “various species of *Zieglerodina*” or to *Zieglerodina* sp.

Other cases are easier to interpret, as there is a general agreement at specific level, but the same species is attributed by Authors to diverse genera, since some of the genera created are not accepted by some, or even the majority, of Authors. As an example, the former *Icriodus woschmidti* is named in different papers as *Icriodus woschmidti*, *Caudicriodus woschmidti* or *Cypricriodus woschmidti*. The same occurs for *Oulodus elegans detortus* (Walliser), also sometimes indicated as *Delotaxis elegans detorta* or even *Oulodus detortus* or *Delotaxis detorta*, with only limited taxonomical justification.

Additionally, the former multielement genus *Ozarkodina* is now subdivided into various genera and the genus name *Ozarkodina* is limited to a few species with a well-defined shape of the elements of the apparatus. Other species are now moved to various genera (*Wurmiella*, *Zieglerodina*, *Walliserognathus*, *Ancyrodelloides*, *Lanea*, *Flajsella*, etc.), and those that are not hosted in these new genera are generically attributed to “*Ozarkodina*”.

### 6. The Silurian/Devonian Boundary along the Northern Gondwana Margin

The conodont distribution across the Silurian/Devonian boundary is dealt with in the following chapters, starting from the type of area. Then, the northern Gondwana sectors are discussed from West to East.

#### 6.1. Bohemia (Czech Republic)

Unmetamorphosed Lower Palaeozoic rocks are part of the Teplá-Barrandian Unit (TBU), which is located in the central part of the Bohemian Massif [79]. This unit includes Neoproterozoic to Middle Devonian volcano-sedimentary rocks of the Prague Synform, which were subject to the Cadomian and Variscan orogenies [80]. The central part of the Prague Synform (also termed the Prague Basin) is an asymmetrical elliptical structural depression, which represents an erosional relic of Lower Palaeozoic volcanosedimentary successions [81,82].

The uppermost Silurian (Požáry Fm.) and the Silurian/Devonian boundary are characterised by lower subtidal to upper slope deposits and slope-to-basin-floor distal calciturbidites [83,84]. Volcanic activity gave rise to submarine elevations and triggered intense carbonate sedimentation around them during the late Silurian [85]. The almost continuous Silurian/Devonian sedimentation is testified by the onset of Lochkovian carbonate deposition, which represents the upper slope to toe-of-slope facies ranging from coarse crinoidal massive limestones to black-grey rhythmities with cherts from the Lochkov Formation.

The Silurian/Devonian boundary is predominantly developed in sedimentary strata of diverse slope topography. In historically the first GSSP erected globally (the Klunk section)

the base of the Devonian is defined by the index graptolite *U. uniformis uniformis* (Figure 4). Traditionally, the most useful markers for the recognition of the Silurian/Devonian boundary are, besides graptolites, also conodonts, chitinozoans, trilobites or crinoids of the genus *Scyphocrinites* Zenker. The trilobites *Tetinia minuta* (Příbyl and Vaněk), and *Warburgella rugulosa* (Alth) were formerly used as additional markers to approximate the position of the Silurian/Devonian boundary in several sections around the Prague Synform [86]. Later, Carls et al. (2007) [58] identified the boundary more precisely based on the occurrence of *Caudicriodus hesperius* at the base of Bed 159 in the Požáry section.

Due to the fact that conodonts are abundant in carbonate successions of many different facies, they are, in some cases, the only faunal group that permits relatively precise recognition of the Silurian/Devonian boundary. Due to convenient facies development (limestones alternating with siltstones), the GSSP of the Silurian/Devonian boundary of the Prague Synform contains both the critical graptolites but also conodonts [57,87,88]. The late Silurian–Early Devonian conodont fauna is dominated by numerous genera primarily belonging to Spathognathodontidae and Icriodontidae, apart from a few representatives of Prioniodontidae. The conodonts of the boundary interval have been extensively studied [2,13,21,57,58,78,87,89,90]. Regional conodont zonation of the Lochkovian of the Prague Synform was developed by Slavík (2011) [91] and Slavík et al. (2012) [92]. The zonation for the latest Přídolí is more complicated, because Jeppsson (1988) [57] modified the first zonal concept of Walliser (1964) [2] and introduced a new zonation for the latest Přídolí based on conodonts from the GSSP section at Klonk. He refined the “single zonal scale” (i.e., the *eosteinhornensis* Zone) for the Přídolí Series and introduced the *Ligonodina e. detorta* Biozone (= *Oulodus el. detortus*). The application of the *detortus* Biozone was then used almost globally for the identification of the latest Přídolí (e.g., [10]), but it was problematic, as was revealed by Gouwy and Corradini (2006) [93], and then largely discussed by Carls et al. (2007) [58]. The first occurrence of the nominal taxon, *Oul. el. detortus*, occurs below the taxon *osteinhornensis* s.s., i.e., much deeper down in the Přídolí. Among the most important markers of the late Silurian in the Prague Synform are: *Zieglerodina zellmeri* and “*Ozarkodina*” *eosteinhornensis* s.l. (Walliser). The Devonian base is characterised by the first appearance of the earliest icriodontids—*Caud. hesperius* and *Caud. woschmidti*. Among spathognathodontids the most significant taxa are *Z. petrea*, *Z. remscheidensis* and “*Oz.*” *optima* (Moskalenko) (see the summary in [21,94]). *Zieglerodina petrea* has a conspicuous gap in denticulation in P1 element near the cusp, similarly as taxa belonging to genus *Cuspigrandiosa* Murphy and *Z. paucidentata* (Murphy and Matti) (see discussion in [95]) and represents a promising “paucidentate” marker for the recognition of the Devonian base using the spathognathodontid clade [21]).

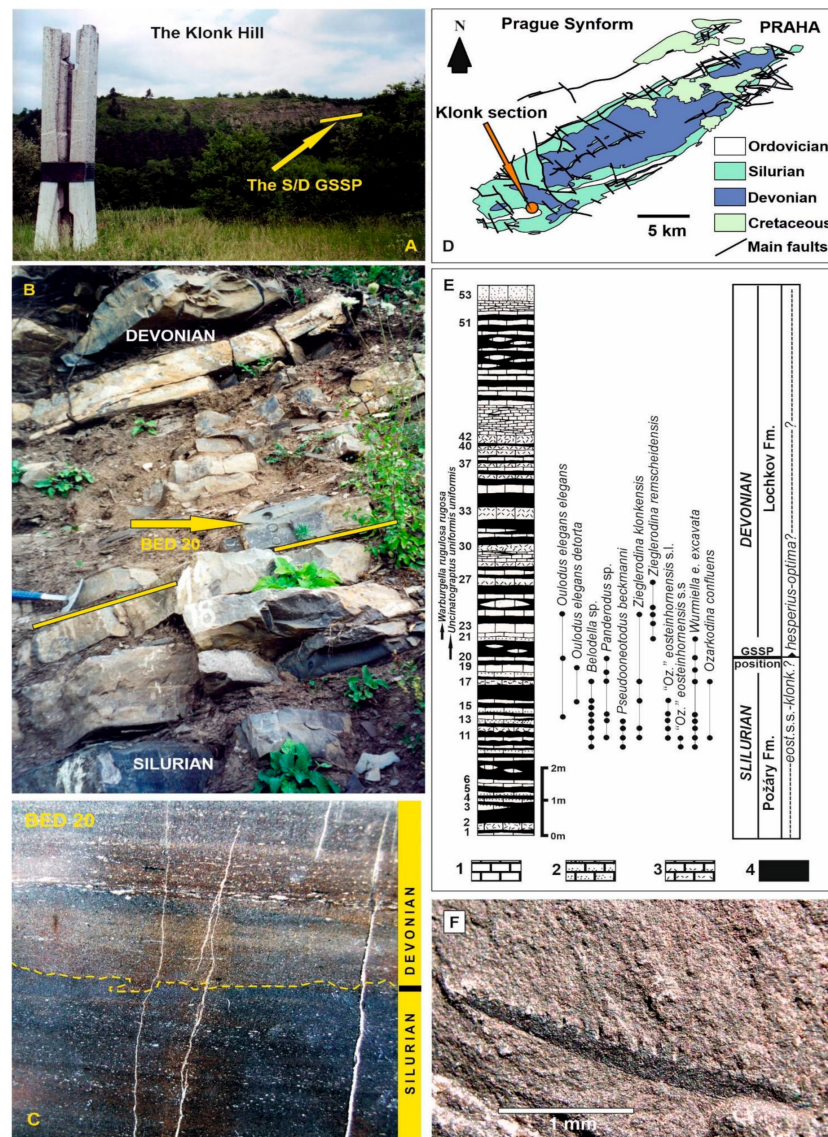
## 6.2. Morocco

Rocks across the Silurian/Devonian boundary were studied in two regions of Morocco: the Western Meseta and the Tafilalt.

In the Western Meseta, approximately located between the cities of Rabat, Marrakesh, Essauira and Taza, a sequence belonging to the southern Variscids is exposed, including rocks from the upper Silurian to the Carboniferous. For a summary of the geology of the area we refer to Becker and El Hassani (2020) [96]. In most of the region, the Přídolí is represented by graptolitic shales from where Charrière and Regnault (1989) [97] recorded *U. u. uniformis*, the basal Devonian index species, near the Douar Rouda village. Unfortunately, no conodonts were collected from the nodular limestones just above the graptolitic shales. More to the North-West, Benfrika et al. (2007) [98] studied a few sections of Přídolí to Middle Devonian age between Rabat and Tiflet, two of those spanning the Silurian/Devonian boundary. Silurian and Lochkovian are represented by thick sequences of black shales with intercalations of dark limestones. The boundary is placed with the graptolite index (e.g., [99]). Conodonts are very rare, and only two elements of *Caud. woschmidti* were documented above the first appearance of *U. u. uniformis*. Below the boundary, only a few elements of “*Oz.*” *eosteinhornensis* s.l. are present, whereas the scarce



association from the lowermost Lochkovian includes *Zieglerodina remscheidensis*, *Belodella devonica* (Stauffer) and *Decoriconus fragilis* (Branson and Mehl). Benfrika et al. (2007) [98] observed that *B. devonica* first occurs in levels with *U. u. uniformis* and suggested that it can be used as a regional index for the base of the Devonian.



**Figure 4.** The Global Stratotype Section and Point (GSSP) for the base of the Devonian at Klonek Hill near Suchomasty. (A)—A view of the Klonek hill near Suchomasty. The yellow line marks the Silurian/Devonian boundary. (B)—A close-up view of the Silurian/Devonian boundary interval, the base of the Devonian begins in the upper part of Bed 20, as indicated by the yellow arrow. (C)—Bed 20, a polished section with marking of the boundary (yellow dotted line). (D)—A location of the GSSP of the Silurian/Devonian boundary at Klonek in simplified geological map of the central part of the Prague Synform. (E)—Conodont data from the Silurian–Devonian interval showing the position of the first occurrences of stratigraphically relevant taxa in relation to the GSSP. Data from [57,87,88]. Lithology: 1. Micritic and very fine-grained bioclastic limestones. 2. Medium-grained bioclastic limestones. 3. Coarse-grained, mostly crinoidal bioclastic limestones. 4. Calcareous mudstones up to shaly micrites. Abbreviations in biozonation: *eost. s.s.* = *eosteinhornensis* s.s., *klonk.* = *klonkensis*. (F)—The index graptolite, *Uncinatograptus uniformis uniformis*, the GSSP-defining taxon, from Bed 20, Klonek section.



### 6.3. Morocco

Rocks across the Silurian/Devonian boundary were studied in two regions of Morocco: the Western Meseta and the Tafilalt.

In the Western Meseta, approximately located between the cities of Rabat, Marrakesh, Essauira and Taza, a sequence belonging to the southern Variscids is exposed, including rocks from the upper Silurian to the Carboniferous. For a summary of the geology of the area we refer to Becker and El Hassani (2020) [96]. In most of the region, the Přídolí is represented by graptolitic shales from where Charrière and Regnault (1989) [97] recorded *U. u. uniformis*, the basal Devonian index species, near the Douar Rouda village. Unfortunately, no conodonts were collected from the nodular limestones just above the graptolitic shales. More to the North-West, Benfrika et al. (2007) [98] studied a few sections of Přídolí to Middle Devonian age between Rabat and Tiflet, two of those spanning the Silurian/Devonian boundary. Silurian and Lochkovian are represented by thick sequences of black shales with intercalations of dark limestones. The boundary is placed with the graptolite index (e.g., [99]). Conodonts are very rare, and only two elements of *Caud. woschmidti* were documented above the first appearance of *U. u. uniformis*. Below the boundary, only a few elements of "*Oz.*" *eosteinhornensis* s.l. are present, whereas the scarce association from the lowermost Lochkovian includes *Zieglerodina remscheidensis*, *Belodella devonica* (Stauffer) and *Decoriconus fragilis* (Branson and Mehl). Benfrika et al. (2007) [98] observed that *B. devonica* first occurs in levels with *U. u. uniformis* and suggested that it can be used as a regional index for the base of the Devonian.

In the Tafilalt region, located in southeastern Morocco, rocks from Ordovician to Carboniferous age are widely exposed. The Silurian and lowermost Devonian interval is represented by pelitic and marly sediments with interbedded limestone beds and lenses [100,101]. In the first approximation, they are represented by orthoceratid-rich limestones ("*Orthoceras* limestones") and by crinoidal limestones ("*Scyphocrinites* limestones"). The "*Orthoceras* limestones" occur from the Ludlow to the Lochkovian, whereas the "*Scyphocrinites* limestones" are documented across the Silurian/Devonian boundary, but their precise age has been disputed for a long time (e.g., [100–102]), until Corrigan et al. (2014a, 2014b) [18,19] precisely defined the stratigraphical range of the two types of lobolithes and associated crinoidal crowns on the basis of a rich conodont fauna recovered from three sections South of Erfoud. The Authors demonstrated that the "*Scyphocrinites* limestones" occur across the Silurian/Devonian boundary and that the more primitive cirrus lobolithes and genera *Scyphocrinites* and *Carolicrinus* are documented in the whole Přídolí, whereas the advanced plate lobolithes and genera *Camarocrinus* and *Marhoumacrinus* are present in the topmost Přídolí beds and in the basal Lochkovian [19]. The conodont association across the boundary is rich and diversified [18] and enables the development of a precise biostratigraphical framework. The base of the Devonian is identified in all the three sections by the joint first occurrence of *Caud. hesperius* and *Caud. woschmidti*. *Ozarkodina confluens* (Branson and Mehl) is present up to the upper Přídolí, and *Z. remscheidensis* has its first occurrence between the LO of *Oz. confluens* and the FO of icriodids. *Oulodus el. detortus* is limited to the Přídolí, whereas *Oul. el. elegans* enters in the Lochkovian. The genus *Belodella*, abundant in the Meseta, is not present.

### 6.4. Spain

The Silurian/Devonian boundary in Spain is present in several geological areas, i.e., the Eastern Iberian Chains (Cadenas Ibéricas Orientales), the Guadarrama spur of the Iberian Meseta, the Palentine Domain (Cantabrian Zone, NW Spain) and in the Spanish Central Pyrenees.

In the Eastern Iberian Chains, the boundary interval is represented by the Luesma Formation that comprises the uppermost Ludlow, Přídolí and part of the Gedinnian (=Lochkovian). The formation is 225 m thick and mostly consists of quartzites, shales and conglomerates. According to Carls (1977) [103] and Carls and Valenzuela-Ríos (2002) [104], the lowermost Gedinnian fauna *d1bβ2* contains the earliest Devonian conodonts. In the

Guadarrama area, the Silurian/Devonian boundary is developed in siliciclastic strata of the almost 900 m thick Alcolea Formation, where the boundary interval is formed by quartzites and sandstones. There, Fauna IV and Fauna V consist mostly of homalonotid trilobites and rhynchonellid and spiriferid brachiopods with correlation value, but no conodonts are reported [103]. In the Palentine Domain (NW Spain, Cantabrian Zone), the equivalent of the Luesma Fm. is the Carazo Formation, an up to 380 m-thick sequence of sandstones, siltstones and shales. The upper member of the Carazo Fm. [105] contains silty and bioclastic limestones. These produced Silurian and Devonian conodonts in the Arauz section [106]. Predominantly carbonate successions prevail in several sections in the Spanish Central Pyrenees but only two sections provided conodonts: the Caballé 1 section with dark orthoceratid limestones [107,108] and the Llesui section with dark-grey nodular limestones [109,110].

Among the most important additional markers for the Silurian/Devonian boundary interval in siliciclastic successions are the trilobite *Acastella heberti* (Gosselet) and the brachiopods *Platyorthis* ex gr. *monnieri* (Rouault) and *Howeella mercurii* (Gosselet) that co-occur together with *Zieglerodina remscheidensis* and *Caud. woschmidti* in the Eastern Iberian Chains. In the Palentine Domain, the Lower Devonian markers are the chitinozoans *Urnochitina urna* (Eisenack) and *Eisenackitina bohémica* (Eisenack), the trilobite *Acastella* cf. *heberti*, and the acanthodians *Nostolepis striata* Pander and *N. costata* Goujet. These taxa occur above the Silurian/Devonian boundary (see [106]).

The conodont record from the Silurian/Devonian boundary is restricted to several sections in three geological areas. In the Eastern Iberian Chains, the section Cabezo del Pino contains the earliest Devonian taxon *Caudicriodus woschmidti* and *Zieglerodina r. remscheidensis*. In the Palentine Domain, the section Arauz provided the upper Silurian conodont fauna followed by typical earliest Devonian conodont markers: the oldest icriodontids—*Caud. woschmidti*, “*Icr.*” *angustoides* ssp. and transitional forms *Caud. woschmidti*—“*Icr.*” *transiens*. These are accompanied by spathognathodontids—*Z. r. repetitor*, *Z. remscheidensis* ssp. *Z.* The section comprises a complete succession from the uppermost Silurian to the lower Pragian with many described conodont, brachiopod, chitinozoan and vertebrate markers. The Pirenean Caballé 1 section provided *Zieglerodina?* cf. 40 (aff. *remscheidensis*) and *Z. eladioi* [107] that can be assigned either to the uppermost Přídolí or to the basal Lochkovian, and the Devonian marker *Caud. woschmidti* [108]. In the Llesui section, only late Silurian conodont taxa—*Ozarkodina confluens*, *Oulodus e. elegans*, *O. cf. siluricus* and *O. e. detortus* have been recorded [109,110] and thus the Silurian/Devonian boundary cannot be precisely delimited. Another instructive Esera 3 section provided only non-conodont markers for the Silurian/Devonian boundary [111].

#### 6.5. Montagne Noire (South France)

Although a precise location of the Montagne Noire in the Late Devonian is still debated, its position during the Early Palaeozoic along the northernmost margin of Gondwana or in the peri-Gondwana sector, somewhere between Laurussia and Gondwana, is generally agreed. Situated today at the southern margin of the French Central Massif, the Montagne Noire belongs to the external tectonic zone of the Variscan belt ([112] and references therein). A South-facing pile of low-grade to non-metamorphic rocks is there exposed, spanning the Precambrian to the early Carboniferous, and unconformably covered to the S and SE by post-Variscan Carboniferous, Permian and Triassic rocks overlain in turn by Cenozoic deposits [113]. The Palaeozoic succession was affected by poliphased Hercynian deformation and syntectonic metamorphism; in contrast, the Alpine deformation was practically absent, resulting in good preservation of fossils and sedimentary fabrics.

Biostratigraphical studies on the Devonian and lower Carboniferous based on rich conodont associations have led to the definition of three boundary stratotypes: Givetian/Frasnian, Frasnian/Famennian and Devonian/Carboniferous. In contrast, conodont associations from Silurian and Lower Devonian carbonates are scarce and in strong need of a comprehensive taxonomic revision based on recent conodont biostratigraphy [113].

Two main stratigraphical situations may be recognised in the Montagne Noire: a nappe domain, best represented by the Pic-de-Bissous and Mont Peyroux areas, and the “*écailles de Cabrières*”. The former documents the Devonian resting unconformably on the Lower Ordovician, whereas only in the latter a composite section has recorded in continuity an Upper Ordovician to Devonian sequence, including the recognition of the Silurian/Devonian boundary in marine Bohemian facies within a sandy limestone series yielding conodonts and chitinozoans [113–116].

In the Cabrières area, the composite sequence of the “Plateau de Falgairas” derives from the integration of four complementary subprofiles (La Rouquette, La Chataignère, Col de l’Orte and Tiberet), each correlated with bio- and lithostratigraphical criteria [115]. The sequence starts with black pyritic mudstones, with intercalation of black shales, thin levels of grey limestone and black fossiliferous calcareous nodules, and continues with black shales with calcareous nodules, then thin, cephalopod-rich beds passing to brown silts and finally banded limestones with thin beds containing crinoid ossicles. Above, about 35 m of platy limestones with fossiliferous levels are exposed, followed by a few metres of quartzitic and dolomitic sandstones with iron oxide and cross-beddings [113]. Biostratigraphical data were provided on the basis of conodonts [115] and chitinozoans [117].

The upper part of the platy limestone yields orthocone nautiloids [118], brachiopods, trilobites, ostracods, bivalves and crinoids. Conodonts from this interval document the *Oz. crispa* and “*Oz.*” *eosteinhornensis* s.l. zones [115]. Additionally, cephalopod-rich beds studied by Serventi and Feist (2009) [118] provided elements of *Oul. el. detortus*, thus documenting the upper Přídolí eponymous zone. A bivalve association from the same beds confirms that age (Kříž, pers. com.).

The quartzitic and dolomitic sandstones representing the upper part of the sequence are barren of conodonts. Poorly preserved casts of echinoderms and brachiopods are documented on bedding planes. According to brachiopods, the age is basal Devonian (“Gedinnian”) [94]. Based on a personal communication by Havlíček in Feist (1985) [116], the brachiopod assemblage contains *Glossinotoechia*, *Sicorhynchia*, *Iridistrophia*, *Strophonella*, *Cyrtina*, *Atrypa*, *Isorthis*, *Resserella*, *Parmothina* and closely matches the characteristic fauna of the Bohemian Lochkovian.

Chitinozoans from the “plateau de Falgairas” were studied by De Boch (1982) [117], who documented 20 chitinozoan species belonging to eight genera, assigned to four assemblages documenting the upper Ludlow, Přídolí and Lochkov. The assemblages IIIa and IIIb (*Eisenackitina bohemica*, *Ancyrochitina* cf. *fragilis* Eisenack, *Ancyrochitina* sp. and *Ancyrochitina* ex gr. “*ancyrea*”) and IV (*Angochitina devonica* Eisenack, *Angochitina* sp., *Ancyrochitina* sp., *Ancyrochitina* ex gr. “*ancyrea*”, *Cingulochitina* sp., *Sphaerochitina* sp. and *Margachitina caternaria* Obut) are attributed to the Lochkovian, with the assemblage IIIa possibly representing a transition zone between the Silurian and the Devonian [117].

In the Pic de Bissous area, a lowermost Devonian fauna attributed to “*Spathognathodus steinhornensis remscheidensis*” by Feist and Schönlaub (1974) [115], and likely representing various species of *Zieglerodina*, beside *Z. remscheidensis*, was documented. However, the basal Devonian index taxa *Caud. woschmidtii* and *Caud. hesperius* are missing.

#### 6.6. Sardinia (Italy)

The Sardinian basement is part of the South European Variscan chain [119] and exposes metamorphic rocks of Cambrian to early Carboniferous age. Different sequences are exposed in the southeastern and southwestern parts of the island: the Silurian and Lower Devonian parts recall the coeval sequences of Thuringia and Bohemia, respectively [120–124].

In SE Sardinia upper Silurian rocks are represented by a sequence of nodular limestone of Ludfordian to Přídolí age, informally named “Ockerkalk”. A precise conodont stratigraphy of the unit was provided [124–130]. Above the “Ockerkalk”, a pelitic unit named “Upper Graptolitic Shales” crops out. Graptolites are the only fossils abundant in the unit, and document three graptolite zones of the Lochkovian. No section exposes the Silurian/Devonian boundary, which likely lies at the formation transition.

Silurian and lowermost Devonian rocks of SW Sardinia are among the most studied sediments of the whole Palaeozoic sequence of the island, due to the rich fossiliferous content. However, despite the richness and the good preservation of the fossil remains, outcrops are, in general, strongly tectonised and often constituted by a group of scattered blocks exposed here and there, without any undisturbed sections [123,131–134]. The latest Silurian and/or earliest Devonian conodonts are documented from various localities (e.g., [135,136]), but the boundary is exposed only in the Mason Porcus section [130,137,138].

A conodont zonal scheme for the Silurian was prepared by Corradini and Serpagli (1998, 1999) [5,139]; the upper part of it was later updated by Corradini and Corriga (2012) [11] in their Přídolí-Lochkovian zonation. Additionally, Corriga et al. (2009) [140] provided a summary of Silurian conodont occurrences in the Silurian of Sardinia.

Due to the scarcity of sections exposing the Silurian/Devonian limit it is difficult to provide a detailed series of events along the boundary beds. Combining data from the Mason Porcus section [130] and various other outcrops, it is possible to state that *Ozarkodina confluens* has its last occurrence in the latest Silurian beds, just below the first appearance of *Zieglerodina remscheidensis*. The FO of *Caud. hesperius* marks the base of the Devonian, whereas *Caud. woschmidti* enters just above.

#### 6.7. Carnic Alps (Austria and Italy)

In the Carnic Alps, located across the Italian–Austrian border, one of the best exposed and complete Palaeozoic successions in the world, ranging from the Middle Ordovician to the late Permian, is exposed. Rocks from the Middle Ordovician to the earliest Pennsylvanian age belong to the pre-Variscan sequence and represent one of the better preserved and most studied sequences for this interval. For a recent overview of the pre-Variscan sequence, refer to [20,141,142].

In the Carnic Alps, sediments across the Silurian/Devonian boundary are exposed in various depositional settings from very shallow water to basin [17]. Four main lithofacies, representing different depths of deposition and hydrodynamic conditions, have been described [143–145]. The Wolayer-facies is characterised by proximal sediments and the Bischofalm-facies by deep water euxinic deposits; 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, whereas in the western sector the sequence recalls an intermediate feature between the Wolayer and the Plöcken facies [146,147].

The lithostratigraphy of the pre-Variscan sequence has been recently formalised [148] 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. The Alticola Fm. [149] consists of a well bedded cephalopod 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. [150] consists of a grayish very shallow water lithoclastic limestone with abundant fossil debris of Přídolí-early Pragian age. The Nölbling Fm. [151] is made of black graptolitic shales with interbedded layers and nodules of a dark cephalopod wackestone to mudstone; its age spans the early Silurian through the end of the Lochkovian. The Bischofalm Fm. [152] consists of black pelites and alum shales of Llandovery to Lochkovian age. The lower part of the Rauchkofel Fm. [153] is represented by a mainly laminated dark grey well-bedded platy mudstone to wackestone with intercalations of black shales and marls, and locally calcarenites.

The conodont stratigraphy of several sections exposing rocks across the Silurian/Devonian boundary was studied in great detail in, from East to West, Rifugio Lambertenghi Fontana III [77], Seewarte [17,154], Rauchkofel Boden [20,144], Valentintörl [95], Cellon [2,12,155], Freikofel South II [17], Oberbuchach II [156,157], Oberbuchach Ib [158,159], Rio Malinfier West [160] and Monte Cocco II [161]. Based on conodont faunas from most



of these sections and other scattered data, Corradini and Corrigan (2012) [11] proposed a conodont zonation scheme for the Přídolí and the Lochkovian.

Corradini et al. (2020) [17] studied in detail the conodont distribution across the Silurian/Devonian boundary in the Carnic Alps, and recognised a calendar of events (First Occurrences and Last Occurrences) just below or above the boundary. In the latest Silurian the last occurrence of *Ozarkodina confluens* is registered, just followed by the LO of *Wurmiella alternata* Corradini and Corrigan, and by first occurrences of *Zieglerodina remscheidensis* and *Z. eladioi*. The latest Silurian events are the LO of *Zieglerodina zellmeri* and *Zieglerodina klonkensis*, just below the FO of *Caud. hesperius*; that is, the conodont index taxon for approximating the base of the Devonian. *Caudicriodus woschmidti* enters at the same level, whereas *Zieglerodina schoenlaubi* just above. Various species of *Zieglerodina* (*Z. formosa*, *Z. mashkovae* and *Z. petrea*) and a species of *Cuspigrandiosa* (*Cuspigrandiosa* sp. K Corrigan et al.) have their First Occurrence within the lowermost Lochkovian *Caud. hesperius* Zone. Recent unpublished data from newly studied sections confirm this list of events.

#### 6.8. Graz Palaeozoic and Burgenland (South-East Austria)

Beside the Carnic Alps, latest Silurian and basal Devonian conodonts were documented in a few other localities in southeastern Austria; more precisely, South of Graz and in the South Burgenland.

The Graz Palaeozoic exposes rocks from Silurian to Carboniferous age. For a summary of the stratigraphy refer to Hubmann and Gross (2015) [162]. The Silurian part of the sequence is dominated by alkaline mafic lavas and pyroclastics, succeeded by progressive carbonate production during the late Silurian and Devonian [163]. Conodonts across the Silurian/Devonian boundary were documented by Ebner (1976, 1994) [164,165] from the Eggenfeld section: data are very scarce, but the occurrence of “*Oz.*” *eosteinhornensis* s.l. indicates a Přídolí age for a 2.40 m-thick interval of dark bedded dolostones. Above, after about 1 m of tuffitic shales, a few elements of *Caud. hesperius* were documented from a 20 cm dolomitic level.

In the Burgenland, poorly preserved conodonts were documented from the “Baron von Kottwitz” quarry, near the Austrian-Hungarian boundary. Suttner and Lukeneder (2004) [166] collected two P1 elements of *Oz. confluens* from a two-meter-thick interval with beds consisting almost exclusively by serpulid tubes. Above, the sequence continues with a tectonically stressed unit of dolomites, shale and siltstone a few metres thick. From the lower part of that Suttner (2009) [167] collected a basal Lochkovian fauna, with *Caud. woschmidti*, “*Oz.*” *eosteinhornensis* s.l., *Zieglerodina remscheidensis* and possibly other species of *Zieglerodina*, and rare conodont elements.

#### 6.9. Balkans

In the Balcan region, conodonts around the Silurian/Devonian boundary are well documented only in Albania and Bulgaria.

Information on the Silurian/Devonian boundary in Albania is scarce and limited to a few outcrops in the “Korabi Zone”, in the northeastern part of the country, where the rock sequence is strongly faulted and metamorphosed and consists of various clastic and carbonate rock with intercalations of mostly acid volcanics [168]. Silurian rocks are mainly represented by graptolitic shales, whereas limestones are dominant in the Devonian. However, fossils are extremely rare except graptolites of Silurian age and rare dacryoconarids in the Devonian. A few poorly preserved conodonts were documented by Schönlaub and Meco (1986) [168] and Meco (2010) [169]. *Ozarkodina confluens* and “*Oz.*” *eosteinhornensis* s.l. were collected from the upper Přídolí, whereas *Caud. woschmidti* and *Z. cf. remscheidensis* were recovered from the lower Lochkovian.

In Bulgaria, the sedimentary strata of the boundary interval occur in the western part of the country in three Alpine tectonic structural units: the West Balkan Unit, the Lyubash Monocline and the Morava Unit. Stratigraphically, the most important is the Gorna Vrabcha 2 section in the Morava Unit because of the presence of carbonates. The upper Silurian

and Lower Devonian carbonate-siliciclastic rocks are preserved as isolated and tectonically disturbed outcrops with shale-limestone alternation and nodular limestones in the Přídolí and Lochkovian. These rocks belong to the 185 m-thick Vrabcha Formation of Spassov (1973) [170]. The Silurian/Devonian boundary in the Gorna Vrabcha 2 section was studied for conodonts [170–174] and for graptolites [175].

In general, the most important additional markers of the boundary in West Bulgaria are graptolites. These are present mostly in the siliciclastic strata of the Balkan and Lyubash Unit and belong to the Přídolí *ultimus-parultimus* and *branickensis-lochkovens* zones, and Lochkovian *uniformis* and *hercynicus* (see [174]). The index graptolite *U. u. uniformis* is, however, missing in the Morava Unit, where the best markers for the base of the Devonian are conodonts. Additionally, the lower Lochkovian in the Balkan Unit can be approximated by the dacryoconarid tentaculite *Homoctenowakia bohemica* (Bouček) [176].

The stratigraphy of the siliciclastic-carbonate member (the Morava Unit) is based on conodont data. The Ludfordian to Lochkovian interval in the Gorna Vrabcha Section 2 indicates the *siluricus*, *eosteinhornensis* and *woschmidti* zones [175]. The uppermost Silurian is characterised by *Wurmiella excavata* (Branson and Mehl) and “*Ozarkodina*” *eosteinhornensis* s.l. The first occurrence of *Caud. woschmidti* (Ziegler) defines approximately the base of the Devonian. According to Boncheva et al. (2007) [174], the lower Lochkovian taxa include also *Zieglerodina remscheidensis*, “*Icr.*” *postwoschmidti* Mashkova, “*Icr.*” *rectangularis* Carls and Gandl and some coniform taxa (*Belodella*, *Panderodus*, *Pseudooneotodus*).

#### 6.10. Turkey

The complicated stratigraphy and tectonics of Turkey make any attempt to generalise a global description of the region difficult. The actual configuration of Turkey results from the amalgamation of numerous and separate terranes. The Devonian is there mainly documented in the Pontides, Taurides and Arabian Plate, with the former having an Avalonian affinity and the latter two a clear Gondwana one [177]. Some of these areas expose successions documenting the Silurian/Devonian limit; some others reveal strong unconformities at the period boundary. However, even in continuous sections, the Silurian/Devonian boundary is only tentatively assigned within a large stratigraphic interval.

The Arabian Plate exposes a sequence in southeastern Anatolia where the Silurian/Devonian boundary is provisionally located in the uppermost part of the Dadaş Formation, a restricted inner-shelf unit evolving to a tidal flat in the upper part [178]. The Dadaş Formation unconformably covers the Middle-Upper Ordovician and is represented by basal dark organic-rich shales with interbedded limestones and sandstones, passing to summital sandstones, marls and calcareous siltstones. The faunal association has documented palynomorphs, brachiopods, bryozoans, graptolites, conodonts, crinoids, corals and ostracods assigned to the late Silurian-Early Devonian. Unluckily, the conodont marker for the boundary *Caud. woschmidti* is not present [179], and precise data on the occurrence of other taxa that may help to place the boundary are not available.

The Devonian exposed in the Taurides appears mostly in continuity with the Silurian and a complete Devonian sequence documents a transition between an inter- to supratidal shallow facies to a deep shelf at the end of the period [177,180]. However, the boundary is not precisely placed. The Taurides derive from the assemblage of numerous tectono-stratigraphic units, among which the autochthonous Geyikdağı Unit documents a rich Palaeozoic sequence of carbonate and siliciclastic sediments of terrestrial to deep water environment [181]. The Silurian/Devonian in the Saimbeyli-Tufanbeyli area (Eastern Taurides) is recorded at the passage between the upper part of the Yukari Yayla Formation, represented by shales, sandstones, siltstones and limestone with *Orthoceras* and the Ayı Tepesi Formation, constituted by shales, sandstones, micritic limestones and sandstones ([181]). The Yukari Yayla Formation had been attributed to the latest Landoverly to earliest Wenlock and post-middle Ludlow by Göncüoğlu et al. (2004) [182], who regarded the Lower Devonian deposited over an unconformity. However, in sample CON-11, collected in the uppermost part of the “*Orthoceras* limestone” interval, the Authors collected *Zieglerodina*

*dina eladioi* (Valenzuela Rios): the species is documented from the latest Přídolí to the middle Lochkovian [183]; therefore, the Silurian/Devonian boundary should occur in the uppermost part of the “*Orthoceras* limestone” unit or in the lowermost part of the overlying dark siltstones and shales. Unfortunately, no other biostratigraphical data are available.

In the central Taurides, Göncüoğlu and Kozur (2000) [184] studied four conodont samples in the upper part of the Ovacik section, where some metres of limestone are exposed. The lower sample, collected at the base of the limestones just above a transition from siltstones, yielded *Caud. woschmidti*, *Z. remscheidensis*, *Zieglerodina* sp., *Pseudooneotodus beckmanni* (Bischoff and Sannemann) and *Panderodus unicostatus* (Branson and Mehl), indicating a lowermost Lochkovian age. No data are available from older strata, and slightly above, a middle Lochkovian fauna is reported.

Several microterranes are included in the Pontides. The Ordovician-Lower Devonian exposed in the Çamdağ area (Zonguldak Terrane) documents the most complete successions and includes the Silurian-Lower Devonian Findıklı Formation [185]. The lower part of the Findıklı Formation is represented by a siliciclastic unit with intercalated graptolitic black shales referred to the Silurian by acritarchs and graptolites [186], followed by “*Orthoceras*” limestones with fragmentary conodonts possibly of late Silurian (Přídolí) age [187]. Boncheva et al. (2009) [188] collected a poorly preserved Silurian and Lower Devonian fauna from the Kalabak Dere section. The authors tentatively located the Silurian/Devonian boundary in a 25 m interval between samples 130-B and 130-C. They reported “*Oz.*” *eosteinhornensis*, and *Oul. el. detortus* from samples 130-B, and fragments of *Caud. woschmidti* from sample 130-C. However, the state of preservation of figured elements makes precise taxonomic determinations very difficult.

## 7. The Silurian/Devonian Boundary in More Distant Areas of Gondwana

Beside the North Gondwana terranes that faced the Rheic ocean, in the other areas of North Gondwana detailed data on conodonts across the Silurian/Devonian boundary are documented only from Argentina and Australia.

### 7.1. Argentina

Argentina was part of southwest Gondwana, and at the Silurian/Devonian boundary was located at high southern latitudes. Upper Silurian and lowermost Devonian conodonts were documented [189–191] from the Los Espejos Formation of the San Juan Precordillera. The unit is represented by marine siliciclastic rocks, mainly shale, sandstone and siltstone [192,193], and is interpreted as deposited on storm-dominated clastic shelf from offshore to shoreface settings [194,195]. The lower part of the Los Espejos Formation is predominantly composed of reddish and greenish phosphate-rich bioturbated mudstone and shale. In the middle part, the shaly succession includes thin sandstone beds bearing a shelly fauna and abundant trace fossils of the *Cruziana* Ichnofacies [196]. This shelly fauna is composed of abundant brachiopods belonging to the genera *Harringtonina*, *Clarkeia*, and *Australina*, among others, associated with trilobites, nautiloids, ostracods and crinoids. The upper part of the formation is characterised by a fossiliferous burrowed mudstone interbedded with a coquinoid sandstone. Latest Silurian and basal Devonian conodonts were reported from coquinoid beds and lenses in the Ancha creek and Poblete sections. A precise biostratigraphical assignment is difficult due to the abundance of reworked material. The late Přídolí fauna is dominated by the endemic species *Ozarkodina huenickeni* Gómez et al. and includes “*Oz.*” *eosteinhornensis* s.l., “*Oz.*” *eosteinhornensis* s.s., *Oulodus el. elegans*, *Wurmiella excavata* and some coniform species (*Dapsilodus obliquicostatus* (Branson and Mehl), *Panderodus unicostatus*, *Pseudooneotodus beckmanni*, *Ps. bicornis bicornis* Drygant, *Ps. bic. contiguus* Corradini). The Lochkovian is discriminated in the upper part of the Poblete section thanks to the presence of *Caud. cf. hesperius*. The association includes *Oz. huenickeni*, *W. excavata*, *Ps. beckmanni*, *Pand. unicostatus* and *Zieglerodina* sp.

## 7.2. Australia

In the latest Silurian and Early Devonian, Australia was located in eastern Gondwana at tropical latitudes. Silurian and Devonian conodonts were documented in several papers dealing with different areas (for a summary see Simpson, 1995 [197]). The basal Devonian index *Caud. woschmidti* is widely documented, but a sequence across the Silurian/Devonian boundary is exposed only in a few localities (e.g., [198,199]). Farrell (2003, 2004) [199,200] studied the sequence in central western New South Wales, and detected the Silurian/Devonian boundary within the Camelford limestone, a massive limestone almost 400 m thick with intercalation of argillaceous and conglomeratic intervals. The conodont fauna is dominated by coniforms (mainly *Panderodus* and *Belodella*), whereas ozarkodinids (*Zieglerodina* sp., *W. excavata* and *Ozarkodina* sp.) and *Oul. el. detortus* are rare and show irregular occurrences. The base of the Devonian is indicated by the first occurrence of *Caud. hesperius*.

At Broken River Crossing, in Northeast Queensland, Simpson (2000) [198] described three sections from the upper member of the Jack Limestone, a thickly bedded and massive limestone with crinoid stems, bryozoans, brachiopods and stromatoporoids. In the uppermost part of the unit the Author collected icriodids that he attributed to *Caud. hesperius*, together with ozarkodinids referable to *Zieglerodina* sp. However, Barrick et al. (2021) [201] moved the icriodids figured by Simpson to a new species of the genus *Praeicriodus*, specifically *Pr. simpsoni* Barrick et al., and claimed a latest Silurian age for these levels.

## 8. The Silurian/Devonian Boundary on the Northern Side of the Rheic Ocean

North of the Rheic suture upper Silurian and lowermost Devonian rocks are mainly represented by siliciclastics, shallow-marine and/or continental deposits (e.g., [202,203]), indicating depositional environments not suitable for the presence of conodonts. When data on conodonts are missing, the stratigraphy is mainly based on chitinozoans for shallow marine rocks. In Great Britain the Silurian/Devonian boundary is represented by non-marine rocks and any consideration on the boundary is a speculation [204]. In other areas, a hiatus is present across the Silurian/Devonian boundary.

A few conodont data are available only from Podolia and Baltica.

### 8.1. Podolia

Podolia is an historical region now mainly located in western Ukraine. Uppermost Silurian and Lower Devonian conodonts have been widely investigated for many years (e.g., [205–210]). Drygant and Szaniawski (2012) [211] studied in detail several sections of the Dniester River basin and compared new data with old collections, resulting in a regional zonation for the latest Přídolí to the early Pragian time frame. In the Silurian the Authors discriminated the “Oz.” *eosteinhornensis* s.l. Zone, whereas the *Caud. hesperius* Zone included all the lower Lochkovian. The first occurrence of *Caud. hesperius* was used to identify the Silurian/Devonian boundary, whereas *Caud. woschmidti* enters slightly higher. A few taxa have their first or last occurrence approximately at the boundary level: *Ozarkodina confluens*, “Oz.” *eosteinhornensis* s.l. and *Oul. el. detortus* are limited to the Přídolí, whereas *Zieglerodina remscheidensis*, *Z. formosa* and *Decoriconus fragilis* enters at the very base of the Lochkovian. Additionally, *Zieglerodina klonkensis* is reported only from the uppermost Silurian beds.

### 8.2. Baltic Area

In the Baltic area (Gotland, Estonia, Lithuania) a hiatus is present between the Silurian and the Lower Devonian (e.g., [212–214]) and up to the complete Přídolí is often missing. Therefore, the Silurian/Devonian boundary is not documented. Late Přídolí conodonts are documented only from a few localities, as the Milaiciai 103 borehole from where Spiridonov et al. (2020) [75] discriminated a *Z. remscheidensis* Zone in the upper part of the *Oul. el. detortus* Zone. *Ozarkodina confluens* shortly occurs with *Z. remscheidensis*, whereas

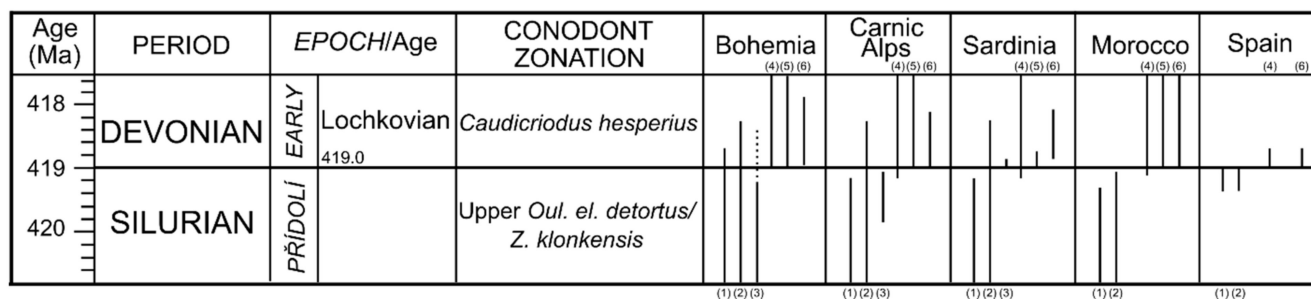


*Oul. el. detortus* and “*Oz.*” *eosteinhornensis* s.l. disappear in the upper part of the zone. A few species are still present in the uppermost limestone sample (*Oz. ambigua* Viira, *Oul. el. elegans* and *Z. remscheidensis*), where *Zieglerodina inordinata* (Viira) has its only occurrence. Above, a sharp transition to siliciclastics prevents any younger conodont datum.

## 9. Discussion and Conclusions

Conodont whose first appearance datum (FAD) best approximates the base of the Devonian System is *Caudicriodus hesperius*. Other taxa have their first or last appearances close to the first appearance of *Caud. hesperius*, and can be useful to reach a relatively precise allocation of the Silurian/Devonian boundary (Figure 5):

- *Ozarkodina confluens* is in general limited to the Silurian, and has its last occurrence in the uppermost Přídolí strata, but in Bohemia it occurs also just above the boundary.
- *Zieglerodina remscheidensis* enters in the latest Silurian beds, just above the LO of *Oz. confluens*, in the Carnic Alps, Sardinia and Morocco, whereas elsewhere is documented close to the base of the Devonian, together with *Caud. hesperius*.
- *Zieglerodina klonkensis* is the marker of the last Silurian zone in the regional zonation for Bohemia, where its range ends just slightly above the boundary. The species rarely occurs in the latest Silurian of the Carnic Alps and Podolia, and a single specimen is documented from the lowermost Lochkovian of Sardinia.
- *Caudicriodus woschmidti* is a Devonian species. Its first occurrence is often accompanied by the FO of *Caud. hesperius*, whereas at place (i.e., Bohemia) *C. woschmidti* occurs in a slightly younger bed.
- *Oulodus elegans detortus* has been considered a good marker for the upper Přídolí for a long time. However, it ranges in most of the Přídolí and in the lowermost Lochkovian; therefore, its utility for recognising the position of the boundary is limited.



**Figure 5.** Correlation between conodont markers across the Silurian/Devonian boundary in the investigated areas. 1: *Ozarkodina confluens*; 2: *Oulodus elegans detortus*; 3: *Zieglerodina klonkensis*; 4: *Zieglerodina remscheidensis*; 5: *Caudicriodus hesperius*; 6: *Caudicriodus woschmidti*.

Aside from these species that widely occur in peri-Gondwana terranes and elsewhere, a few others show good potential for correlation of the uppermost Silurian and lowermost Devonian beds, but up to now are documented only locally or in a few areas, or are very rare. Among these, *Z. eladioi*, *Z. petrae* and *Z. schoenlaubi* should be mentioned.

It is noteworthy to mention that the earliest icriodontids which represent the most reliable markers for the Silurian/Devonian boundary recognition are facies-limited and thus not represented or rare in most pelagic environments. According to our analyses, ozarkodinids are less sensitive to water depth; thus, they may have a more universal dispersal in oceanic waters. Therefore, an agreement on such a universal boundary marker of the spathognathodontid clade could be the future direction of our research.

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