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Revision of the conodont zonation of the Wenlock–Ludlow boundary in the Prague Synform

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Abstract. The regional zonation of the Wenlock–Ludlow boundary is established for the Prague Synform using refined data from updated conodont records. The following conodont zones have been recognized in the Prague Synform: the *Ozarkodina sagitta sagitta* Zone, the *Ozarkodina bohemica* Interval Zone, the *Kockelella crassa* Zone, the *Kockelella variabilis variabilis* Interval Zone and the *Ancoradella ploeckensis* Zone. The *Ozarkodina bohemica longa* and *Kockelella ortus absidata* zones are used herein at subzonal level only because the entries of index taxa cannot be precisely detected. The Bohemian conodont zonal scale is correlated with the recently proposed standardized zonation. The established conodont zones are tentatively correlated with global graptolite zonation and matched against generalized eustatic and carbon isotope curves.

Key words: Late Silurian, Wenlock, Ludlow, conodonts, global correlation, stratigraphy.

INTRODUCTION

The definitions of the series and stages of the Silurian System and their correlation are traditionally based on relatively well developed graptolite zonation. The Silurian conodont zonation is rather a complementary correlation tool that is, in general, more complicated because of facies constraints and a high degree of provincialism at some stratigraphic levels caused by diverse palaeo-environmental settings. It is, however, essential for correlation of carbonate-dominated successions. The Wenlock–Ludlow boundary is correlated globally with the first appearance of the graptolite *Neodiversograptus nilssoni* and the graptolite zonation (especially for the Homerian Stage) can be directly applied almost universally. The basis of the conodont zonation of the Wenlock and Ludlow series has been established by Walliser (1964). The regional conodont zonations of parts of this time-span have later been provided, e.g., by Corradini & Serpagli (1999), Viira (1999), Jeppsson et al. (2006), Corriga et al. (2009) and Slavík & Carls (2012). Recently, an updated Silurian correlation chart was published by Melchin et al. (2012). It combines graptolite and conodont zonations plotted against geochemical and sea-level trends. The primary conodont zonation established by Walliser (1964), which includes the *Ozarkodina sagitta sagitta* Zone (Z.) for the Homerian and the *Kockelella crassa* and *Ancoradella ploeckensis* zones for the Gorstian, has been used for decades with only slight refinements and modifications: Aldridge & Schönlaub (1989) included the *Ozarkodina bohemica* Z. into the Homerian. Later, a more complete zonation of the Wenlock–Ludlow boundary interval was established in Sardinia (Corradini & Serpagli 1999; Corriga et al. 2009) (see Fig. 1). It comprises conodont zones based on the most relevant taxa described by Walliser: the *Oz. s. sagitta* and *Oz. bohemica* zones (in the Homerian) and the *K. crassa* Z., *Kockelella variabilis* Interval Zone (I. Z.), *Wurmiella hamata* Z. and *A. ploeckensis* Z. (in the Gorstian). The most detailed refinement of conodont zonation was made by Jeppsson (1997). Later it was finally modified by Jeppsson et al. (2006) who included a number of new conodont zones based on fauna from Gotland. With the exception of the East Baltic (e.g. Märss & Männik 2013), the conodont zonation of the Homerian Stage based on Gotland has not yet been tested in other regions. Two zones, *Ozarkodina bohemica longa* and *Kockelella ortus absidata*, were, however, incorporated to the generalized global conodont zonal scale by Cramer et al. (2011). Their zonation for the Homerian and Gorstian was consequently adopted by Melchin et al. (2012) into the recent Silurian Time Scale. Presently, this zonal scale seems to be of general use. The proposed Homerian zones bear, however, apparent limitations. It is due to the conodont Mulde Event (Jeppsson & Calner 2003), which is related to perturbations in the global carbon cycle (cf. Cramer et al. 2012) and negatively influenced the evolution in

conodont lineages already in the early Homerian. The scarcity of the globally distinguishable taxa with the potential to define short time intervals is then a direct consequence of the event that is accompanied by depositional bias of the carbonate and siliciclastic sedimentation systems on Gotland (cf. Calner & Jeppsson 2003). The occurrences of conodont taxa are largely controlled by local facies changes which are not synchronous in different areas. Accordingly, synchroneity of conodont indexes involved is also often uncertain.

As mentioned above, some of the zones introduced on Gotland have not yet been extended to or even tested in other regions. The problematic biozonal correlation may also be caused by sampling bias (i.e. insufficient size of samples taken in comparison with Gotland) or by the absence of corresponding intervals in the studied sections. This is, for example, also the case of the classic Silurian Cellon section where the newly suggested Homerian zones (*Oz. b. longa* and *K. o. absidata*) are missing because of a gap and/or large condensation (see Corradini et al. 2014). On that account, before worldwide acceptance, there is an urgent need to verify the application of the Baltic conodont zonation in other areas outside northeastern Europe.

The purpose of this paper is the biostratigraphic revision of conodont faunas from the Wenlock–Ludlow boundary in the Prague Synform and their correlation with the recently proposed standardized conodont zonation. The revision is based both on previous and newly obtained conodont data.

BIOSTRATIGRAPHIC OVERVIEW OF THE WENLOCK–LUDLOW BOUNDARY IN THE PRAGUE SYNFORM

In the Prague Synform the late Wenlock and Gorstian are developed as a volcanosedimentary complex that is replaced by largely carbonate sedimentation from the Ludfordian. The facies development of the Wenlock–Ludlow boundary in that region changes in different parts of the former basin (Kříž 1991) and is greatly influenced by volcanic activity. It reflects a regressive–transgressive eustatic regime combined with tectonically unstable basin settings.

According to Kříž et al. (1993), the boundary interval is characterized by three main facies: (1) volcanoclastics and basaltic rocks with subordinate shallow-water limestones, (2) shales and cephalopod limestones and (3) mostly shale facies with tuffite layers without carbonates.

The pioneer biostratigraphic studies of the boundary interval were based on graptolites and date back to the end of the 19th century. For a summary see Kříž et al. (1993), who carried out the major reinvestigation of the boundary interval. The graptolites have been restudied by H. Jaeger and J. Kříž, conodonts by H. P. Schönlaub, chitinozoans and sporomorphs by P. Dufka. The local graptolite zonation can be directly plotted to the present global standard. The conodont studies by Schönlaub provided a database of stratigraphically important taxa with defined local ranges that were directly or tentatively

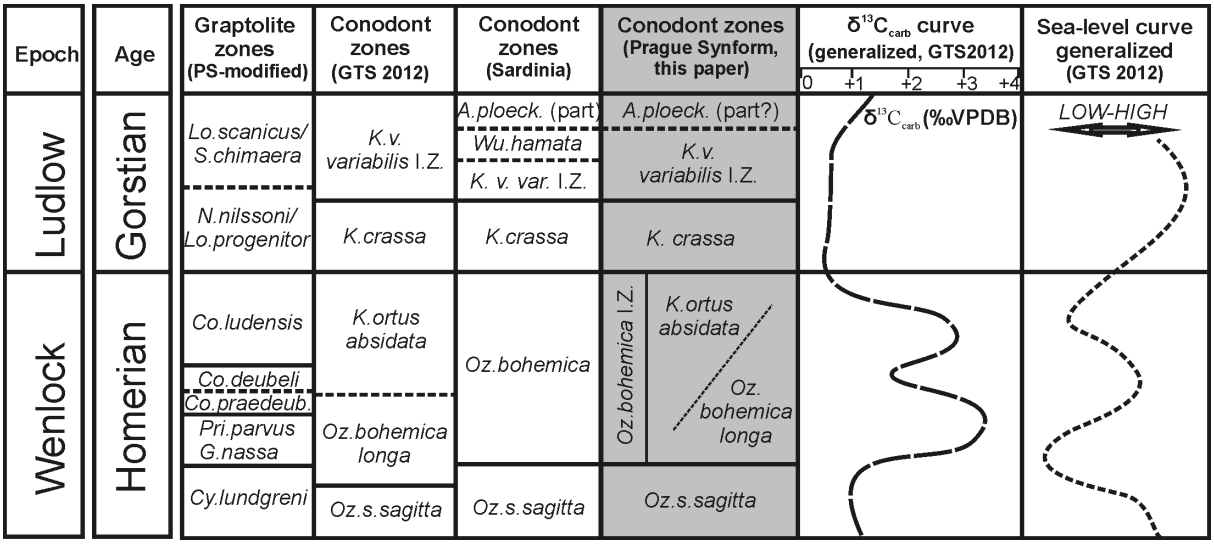


Fig. 1. A correlation chart for the Homerian–Gorstian interval. Graptolite zonation for the Prague Synform is modified according to Štorch et al. (2014) and juxtaposed with conodont zonal scales: (1) standardized – Geological Time Scale, The Silurian Period (Melchin et al. 2012) ('GTS 2012'); (2) Sardinian zonation (Corradini & Serpagli 1999); (3) zonation for the Prague Synform (this paper). The zonations are matched against the generalized carbon isotope and eustatic curves – Geological Time Scale, The Silurian Period (Melchin et al. 2012) ('GTS 2012').

correlated with graptolite zones. In the Homerian Schönlaub (in Kříž et al. 1993) recognized the following index taxa: *Oz. s. sagitta*, *Ozarkodina sagitta rhenana* and *Oz. bohemica*; in the early Gorstian: *K. variabilis*, *K. crassa* and *Ozarkodina inflata*. The taxa *Ozarkodina excavata* (= *Wurmiella excavata s.l.*) and *K. absidata* were reported to cross the Wenlock–Ludlow boundary. These data enable recognition of the *Oz. s. sagitta* and *Oz. bohemica* zones for the Homerian and the *K. crassa* Z. for the Gorstian in the Prague Synform. Recently, Frýda & Frýdová (2014) detected a characteristic Homerian double-peaked positive carbon isotope excursion in the Prague Synform that is partly correlated with the Mulde Event. The stratigraphic position of the excursion is still tentative due to insufficient biostratigraphic data and unknown range of the late Homerian conodont indexes. The presence of *Oz. bohemica* near the rising First Homerian carbon isotope excursion may, however, serve as approximation of the event.

The new study was focussed on localities with conodont-bearing strata that have been described in detail by Kříž et al. (1993). In this paper the original numbering of the sections/localities by these authors is followed: Butovice Section – Na břekvici (No. 584), Arethusina Gorge (No. 687), Lištice Pipeline Section (No. 579), Vysoký Újezd Section (No. 567) and Nad Hostímí Section (unpublished section studied by J. Kříž). The samples were also taken from the Všeradice Section (desribed in Manda et al. 2012 and Štorch et al. 2014). The samples were treated with standard methods and the residues were separated using heavy liquids. In total, 26 samples from the Homerian and Gorstian yielded more than 400, mostly fragmented conodont elements. Only few samples were barren. The most representative specimens are figured (Fig. 2). The material obtained is deposited in the collection of Ladislav Slavík at the Institute of Geology AS CR, v.v.i. under catalogue numbers WELU001–WELU423.

CONODONT ZONES AND THEIR CORRELATION WITH THE STANDARDIZED SCALE

The comparison of previous and newly obtained data enabled recognition of the following conodont zones (see Fig. 1).

Ozarkodina sagitta sagitta Zone

The zone was introduced by Walliser (1964) in the Cellon section (Carnic Alps). In Europe it has also been reported from Sardinia (Serpagli 1971), Gotland (Jeppsson 1997) and the Prague Synform (this paper). Outside Europe it has been recorded in North America (e.g. Barrick & Klapper 1976; Cramer et al. 2006; Barrick et al. 2009). In the Prague Synform it has been recognized in the Arethusina Gorge and Lištice sections in strata corresponding to the *Testograptus testis* Subzone of the *Cyrtograptus lundgreni* graptolite Z. *Ozarkodina s. sagitta* has also been newly recorded in the Nad Hostímí Section. Associated conodonts are *W. excavata s.l.*, *K. o. absidata*, *Delotaxis* ex gr. *silurica*, *Dapsilodus obliquicostatus* and transitional forms between *Oz. s. sagitta* and *Oz. bohemica*. Denticles in these transitional specimens are not fused but the basal cavity is broader than in *Oz. s. sagitta*.

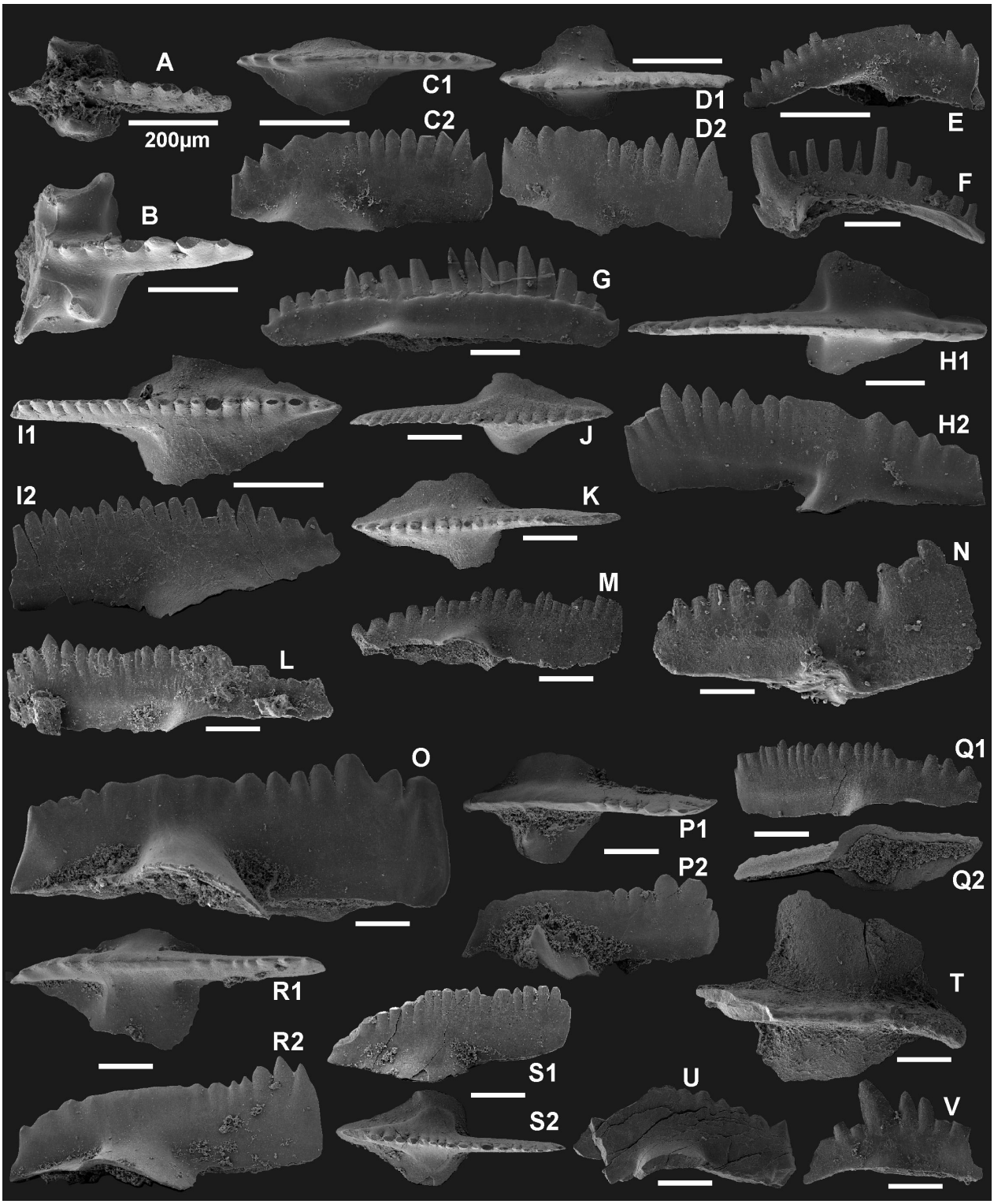
Ozarkodina bohemica Interval Zone

The long-ranging *Oz. bohemica* Z. had characterized the middle and upper Homerian before the zonal refinement of the interval by Calner & Jeppsson (2003). The name-bearer of the zone, *Oz. bohemica s.l.*, comprises a group of forms with unknown ranges described partly as morphotypes or subspecies. Actually, the '*bohemica* interval' is characterized as an acme zone with numerous variable forms, which is delimited by the last occurrences of *Oz. sagitta* and the entry of *K. crassa*. The *Oz. bohemica* Z. has been reported from many regions in Europe, North America and China (for summary see Corradini & Serpagli 1999). The relatively long range of *Oz. bohemica s.l.* roughly corresponds to mid-late Homerian graptolite zones. The index taxon is relatively common in the Prague Synform and can be recognized in several sections: Braník (No. 764), Butovice – Na břekvici, Lištice Pipeline, Vysoký Újezd and U Drdů (No. 760). As in Sardinia, *Oz. bohemica* crosses the boundary into the *K. crassa* Z. The material shows a great variability (cf. Fig. 2). Schönlaub in Kříž et al. (1993) recognized three morphotypes of *Oz. bohemica* (morphs 1, 2 and 3). Viira & Aldridge (1998), however, used a different notation of their material from Estonia. Herein the original morphotype concept by Schönlaub is followed, because the newly obtained material confirms the easy attribution of Pa elements to all three morphotypes that seem to appear in succession. Apart from the morphotypes of *Oz. b. bohemica*, the following associated conodonts were identified: *W. excavata s.l.*, *Ozarkodina typica s.l.*, *Oz. b. longa*, *K. o. absidata*, *K. absidata* ssp., *Panderodus unicostatus*, *Del.* ex gr. *silurica* and *Da. obliquicostatus*.

Ozarkodina bohemica longa Subzone

Calner & Jeppsson (2003) also noticed the high variability of *Oz. bohemica s.l.* in collections from Gotland and introduced a new subspecies, *Oz. bohemica longa* that represents an index for the early-mid Homerian zone. The new zone comprises the main part of the Mulde Event

and its basal part is characterized by major extinctions in pelagic faunas. On Gotland, the *Oz. b. longa* Z. is further subdivided into subzones mostly based on the presence of coniform elements. In the Prague Synform, the zonal index can be recognized as well. The new sampling yielded several elements from the late Homerian, but also from the Gorstian. The specimens figured in Kříž et al. (1993, pl. 1, figs 13, 14) from the uppermost Homerian and lowermost Gorstian as '*Oz. bohemica* morphotype 3' can be attributed to



Oz. b. longa. This, however, does not mean that morphotype 3 and *Oz. b. longa* are equal because there are also short specimens with a fused blade which do not correspond to the diagnosis of the latter. Both taxa have been recorded to range from the *Colonograptus ludensis* graptolite Z. into the Gorstian. The precise delimitation of the taxon range is, however, not possible, because the material is scarce and the successions with conodont-bearing strata are thin. Accordingly, *Oz. b. longa* can be prospectively used as a subzone with not yet precisely defined lower and upper limits. *Ozarkodina b. longa* has been documented in the Butovice – Na břekvici, Lištice Pipeline, Vysoký Újezd and Braník sections.

Kockelella ortus absidata Subzone

The zone has been introduced by Calner & Jeppsson (2003) who consider *K. absidata* Barrick & Klapper, 1976 as a subspecies of *K. ortus* (Walliser, 1964). It is reported from Gotland, from a relatively narrow interval that is linked with an increase in carbonate production. The forms named *K. absidata* have been reported from many areas in Europe and North America. The variability of figured specimens from different regions is, however, very high and thus many of '*K. absidata*' specimens cannot be easily attributed to the strictly confined subspecies that is generally characterized by short elements with well-developed basal lobes (cf. Calner & Jeppsson 2003). The conodont material from the Prague Synform includes specimens that are different both from *K. o. ortus* and *K. o. absidata* (cf. Manda et al. 2012, fig. 4b, d). But, on the other hand, several specimens do fit both to diagnosis and figures of the latter subspecies from Gotland. The taxon, however, seems to be long-ranging (Homerian–Gorstian) and its position with respect to the preceding *Oz. b. longa* Subzone cannot be precisely traced in the Prague Synform. The taxa *Oz. b. longa* and *K. o. absidata* seem to largely overlap and their complete ranges remain unknown. Therefore, these units are treated herein tentatively as subzones of the *Oz. bohemica* I. Z. The index taxon has been recognized in the Butovice – Na břekvici, Lištice Pipeline and Nad Hostími sections. Schönlaub (in Kříž et al. 1993) reported *K. absidata* from the *T. testis* graptolite Subzone to the *Neodiversograptus nilssoni* graptolite Z. from the Lištice (No. 759), Lištice Pipeline and Vysoký Újezd sections. With respect to the variability of the material, the range of '*K. absidata*' provided by Schönlaub cannot be automatically considered as the range of the *K. o. absidata* Z. *Ctenognathodus murchisoni*, an index taxon of the uppermost Homerian conodont zone introduced on Gotland, has not yet been found in the Prague Synform; it seems to be restricted to the Baltic area.

Kockelella crassa Zone

Kockelella crassa is known as the only reliable conodont taxon that marks the base of the Gorstian and whose entry corresponds to the base of the *N. nilssoni* graptolite Z. It has been coined by Walliser (1964) based on the Cellon section. Similarly to the *Oz. s. sagitta* Z. it is a total range zone. The name-bearer of the succeeding *K. v. variabilis* I. Z. completely overlaps the range of *K. crassa*. As summarized by Corradini & Serpagli (1999), the zone can be recognized in Europe (Austria, Bohemia, Sardinia and Gotland) and in North America; the Australian occurrences still need confirmation. In the Prague Synform it has been recorded from the Vysoký Újezd and Butovice – Na břekvici sections. Associated conodont taxa are *K. o. absidata*, *K. v. variabilis*, *Oz. b. bohemica* (morphotypes 2 and 3), *Oz. b. longa*, *W. excavata s.l.* and scarce coniform taxa.

Fig. 2. Selected specimens from the Wenlock–Ludlow boundary of the Prague Synform. **A**, **B**, *Kockelella crassa* (Walliser, 1964). Upper views of Pa elements. A, juvenile specimen; B, incomplete specimen, sample Br1, Butovice Section – Na břekvici, basal Gorstian. **C**, **D**, *Ozarkodina bohemica* (Walliser, 1964). Upper and lateral views of Pa elements, sample Br1, Butovice Section – Na břekvici, basal Gorstian. C, morphotype 1; D, morphotype 3. **P**, **R**, *Ozarkodina bohemica* (Walliser, 1964). Upper and lateral views of Pa elements, sample 2Li, Lištice Pipeline Section; P, morphotype 2; R, morphotype 3 (cf. *Oz. b. longa*), late Homerian. **E**, **V**, *Kockelella ortus absidata* Barrick & Klapper, 1976. Lateral views of Pa elements. E, sample Br1, Butovice Section – Na břekvici, basal Gorstian; V, sample HO2, juvenile specimen, Nad Hostími Section, late Homerian? **F**, *Delotaxis* ex gr. *silurica* (Branson & Mehl, 1933). Lateral view of M? element, sample Br1, Butovice Section – Na břekvici, basal Gorstian. **G**, *Wurmiella excavata* (Branson & Mehl, 1933) *s.l.* Lateral view of Pa element, sample Br1, Butovice Section – Na břekvici, basal Gorstian. **H**, **O**, **T**, *Ozarkodina bohemica longa* Calner & Jeppsson, 2003. Upper and lateral views of Pa elements, H, sample Br1, Butovice Section – Na břekvici, basal Gorstian; O, sample 1Li, Lištice Pipeline Section, late Homerian; T, sample VU1, Vysoký Újezd Section, basal Gorstian. **I**, *Ozarkodina s. sagitta–O. bohemica* transitional form. Upper and lateral views of Pa element, sample Ar2, Arethusina Gorge, upper *Cy. lundgreni* Z. **J–M**, **Q**, **S**, *Ozarkodina s. sagitta* (Walliser, 1964). Upper and lateral views of Pa elements, J, K, L, M, Q – sample Ar1, Arethusina Gorge, upper *Cy. lundgreni* Z., S – sample HO1, Nad Hostími Section, basal Homerian. **N**, *Ozarkodina typica* Branson & Mehl, 1933 *s.l.* Lateral view of Pa element, sample HO3, Nad Hostími Section, late Homerian? **U**, *Kockelella absidata* ssp. Lateral view of Pa element, sample VU3, Vysoký Újezd Section, basal Gorstian.

Kockelella variabilis variabilis Interval Zone

The zone is used herein in the sense of Cramer et al. (2011) as an interval zone above the last occurrence of *K. crassa* and below the entry of *Ancoradella ploeckensis*. In the Prague Synform it is represented by a narrow interval only because of small thickness of available carbonate strata. Besides, this zone can only be indirectly documented by the presence of *K. v. variabilis* and absence of the index of the underlying zone. Accordingly, sampling bias cannot be excluded. The interval zone can be recognized only in the topmost carbonate lenses available in the Butovice Section – Na břekvici (bed No. 13) where the sampled bed is above the *N. nilssoni* graptolite Z. (cf. Kříž et al. 1993). *Kockelella v. variabilis* has also been recognized in the Marble Quarry, but there it already co-occurs with *A. ploeckensis* (Kříž et al. 1986) and in the Mušlovka Section (Chlupáč el al. 1980), where it ranges higher – probably into the *A. ploeckensis* Z. The index of the *A. ploeckensis* Z. is, however, missing in the Mušlovka Section. The associated taxa include only fragments of *Oz. bohemica s.l.* (morphotypes indet.), *Del.* ex gr. *silurica* and *W. excavata s.l.*

Ancoradella ploeckensis Zone

The index taxon of Walliser's (1964) zone that crosses the Gorstian–Ludfordian boundary is very rare worldwide. This applies also to the Prague Synform; it has been documented only in the Požáry Section and Marble Quarry (Kříž et al. 1986). The new sampling has not yet confirmed further occurrences but conodont study of the Gorstian–Ludfordian boundary is still in progress. The only known occurrences of *A. ploeckensis* from the Prague Synform are within the *Saetograptus leintwardinensis–S. linearis* graptolite Z., i.e. in the Ludfordian. Therefore, its earlier entry in the Prague Synform is doubted.

DISCUSSION

More than 20 years have elapsed from the first conodont study of the Wenlock–Ludlow boundary in Bohemia and the conodont zonation of the Homerian–Gorstian has been established for the region based on updated data. The conodont correlation includes the widely recognized (global) conodont zones of different categories (*Oz. s. sagitta*, *Oz. bohemica*, *K. crassa*, *K. v. variabilis* and *A. ploeckensis*). The zones established on Gotland (Jeppsson et al. 2006), *K. o. absidata* and *Oz. b. longa*, are used tentatively as subzones within the *Oz. bohemica* I. Z. Their application should be taken with caution because in the Prague Synform not every datum of '*K. absidata*' may be automatically considered as *K. o. absidata* that marks only the latest Wenlock on Gotland. The problems are the high variability in the lineage and not fully corresponding diagnoses of *K. absidata* by Barrick & Klapper (1976) – 'small basal cavity' and of *K. o. absidata* by Calner & Jeppsson (2003) – 'well-developed basal cavity lips'. An alternative subdivision of the mid-late Homerian interval at regional level can be prospectively based on a modified morphotype concept of *Oz. bohemica s.l.* that has been initiated by Schönlaub (in Kříž et al. 1993). Morphotypes 1, 2 and 3 are found in the succession, but the material is still insufficient to establish the complete ranges. Similarly to Gotland, the composition of conodont faunas in the Prague Synform is influenced by shallowing shortly below the Wenlock–Ludlow boundary (cf. Kříž 1992). The sea-level changes drastically affected the carbonate production and the effects of the conodont Mulde Event influenced phylogenies in early Homerian time. These constraints do not permit a substantial refinement of the conodont zonal scale in this part of peri-Gondwana.

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