First evidence for the Homerian (late Wenlock, Silurian) positive carbon isotope excursion from peri-Gondwana: new data from the Barrandian (Perunica)

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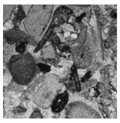

The Homerian (late Wenlock, Silurian) carbon isotope excursion is documented for the first time from peri-Gondwana based on new data from the Barrandian (Perunica). It is also the first time that this excursion has been found outside of the palaeoplates that subsequently formed the supercontinent Laurussia (*i.e.*, Laurentia, Baltica and Avalonia). The typical two-peaked Homerian $\delta^{13}C$ excursion is documented from a highly fossiliferous shallow-water limestone succession formally established here as the Kozel Limestone Member of the Motol Formation. Application of $\delta^{13}C$ chemostratigraphy considerably improves the stratigraphic resolution within the Kozel Limestone Member and enables more precise dating of its very diverse fauna. The present data reveal recovery of benthic communities after a series of mid-Homerian extinction events (*i.e.*, the Mulde conodont and the end *lundgreni* graptolite bioevents) started much earlier than has been hitherto described from other world occurrences. • Key words: Silurian, Homerian carbon isotope excursion, Peri-Gondwana, Perunica, Barrandian area, Kozel Limestone Member.

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The Silurian Period is the time interval with probably the highest stratigraphic resolution of all of the Palaeozoic periods. The rather cosmopolitan nature of Silurian marine faunas makes possible application of a global chronostratigraphy. The current Silurian timescale assumes a correlation between stage boundaries and graptolite zones (*e.g.*, Loydell 2012) and as a result graptolite-bearing successions can be correlated directly to the global chronostratigraphic zonation (see discussion in Cramer *et al.* 2010, 2011). However, usage of the global chronostratigraphic zonation in non-graptolitic Silurian successions is more difficult. Silurian conodont as well as organic microfossil biozonations are still generally less precise than graptolite biozonations (*e.g.*, Cramer *et al.* 2011). For this reason intensive studies of the applicability of different sedimentological, geophysical and geochemical methods for improving the stratigraphic resolution of non-graptolitic Silurian successions were started about 25 years ago. The latter studies have suggested that carbon isotope chemostratigraphy is one of the most promising methods.

The Silurian Period was a time of several distinct and rapid changes in the global carbon cycle. These geochemical events were closely linked to major crises in the marine ecosystem as well as to palaeoclimatic changes (see Jeppsson 1998; Munnecke *et al.* 2003; Noble *et al.* 2005, 2012; Loydell 2007; and Calner 2008 for reviews). Some of those perturbations in the carbon cycle have been documented globally (see Calner 2008 for review) and as such they have become important stratigraphic tools for global correlation of Silurian successions. Integration of graptolite, organic microfossil and conodont biostratigraphy with carbon isotope chemostratigraphy seems to be the most promising tools for improvement of Silurian stratigraphic correlation (*e.g.* Loydell *et al.* 1998, 2003; Kaljo *et al.* 2003, 2007; Munnecke *et al.* 2003; Cramer *et al.* 2006, 2010, 2011, 2012; Kaljo & Martma 2006; Jeppsson *et al.* 2007; Lenz *et al.* 2006; Loydell & Frýda 2007, 2011; Calner *et al.* 2012).

Distinct positive $\delta^{13}C$ excursions appear to occur throughout the Silurian (see summary and references in Cramer *et al.* 2011). Only three of these $\delta^{13}C$ excursions have hitherto been recorded from the Barrandian (Perunica): a) that associated with the late Aeronian graptolite *sedgwickii* Event (Štorch &

Frýda 2009, 2012), b) the mid-Ludfordian excursion associated with the conodont Lau and graptolite *kozlowskii* events (Lehnert *et al.* 2003, 2007; Manda *et al.* 2012; Gocke *et al.* 2013; Frýda & Manda 2013), and c) the Silurian–Devonian boundary (Klonk) excursion which is associated with several bioevents (Hladíková *et al.* 1997, Buggisch & Mann 2004, Manda & Frýda 2010).

In this short paper we report for the first time a new Silurian $\delta^{13}C$ excursion from the Barrandian area – the Homerian (late Wenlock, Silurian) carbon isotope excursion – which represents its first recognition in peri-Gondwana (Fig. 1), in contrast to the series of mid-Homerian extinction events (*i.e*, the Mulde conodont and the end *lundgreni* graptolite bioevents) which were already reported from the latter area (Štorch 1995, Gutiérrez-Marco *et al.* 1996, Pittau *et al.* 2006). Special attention is also paid to an improvement of the internal stratigraphy of the Homerian Kozel Limestone Member (new member) and dating of its very diverse fauna in respect to the mid-Homerian extinction events.

Homerian of the Barrandian

The Homerian (late Wenlock) strata of the Barrandian form upper part of the Motol Formation. The definition and stratigraphic range of the Motol Formation, named originally as "motolské vrstvy" by Perner & Kodym (1919), has been changed several times (*e.g.*, Bouček 1934, 1953). According to the present definition by Kříž (1975), the Motol Formation comprises the uppermost Telychian (Llandovery) and the entirety of the Wenlock. The lower part of the Motol Formation is sedimentologically more uniform than its upper part. The formation is represented mostly by calcareous clayey shales. In its middle and upper parts volcanic rocks and limestones are significant. Facies distribution was strongly influenced by synsedimentary tectonic movements and volcanic activity in the upper part of the Motol Formation (Bouček 1934, 1953; Horný 1955a–c, 1960; Kříž 1991). The thickness of the Motol Formation varies from 80 m to 300 m (Kříž 1998).

The Homerian was the period of greatest facies differentiation within the Motol Formation. High activity within several volcanic centres (*i.e.*, Svatý Jan Volcanic Centre, Řeporyje Volcanic Centre and Nová Ves Volcanic Centre) gave origin to shallow areas generating a complex facies pattern from very shallow intertidal limestones to deeper water shales deposited in an anoxic environment (see for details Bouček 1953; Horný 1955a–c, 1960, 1962; Fiala 1970; Kříž 1991, 1992, 1998; Štorch 1998). The central area of the Svatý Jan Volcanic Centre was emergent during the latest Wenlock and Ludlow forming a volcanic island. During the latest Wenlock, shallow water environments surrounding the island gave origin to the mostly crinoidal limestones. The latter shallow water limestones are named and formally established here as the Kozel Limestone Member (new member). Complete definition of this new lithostratigraphic unit of the Motol Formation is given in appendix.

Studied sections

The sections described in the present paper (49°57′ 22.082″ N, 14°5′ 50.293″ E, sections No. 759 and 760 of Kříž *et al.* 1993; for precise geographic positions of the both sections see Kříž 1991, fig. 48) are located in the Central Segment of the Prague Basin. The sections are situated on the left (north) bank of the Berounka River, south of the village of Lištice near Beroun. Hejna (2012) reported a comment made by Josef Antonín Každý (1723–1798) in his chronicle testifying that this area was quarried for limestone already in the eighteenth century. Both sections have been intensively studied since the first half of the nineteenth century. Barrande used the name "*Rochers de Kozel*" or "*Kozel*" for this area (Kříž 2013, pers. comm.). The stratigraphic position of both sections was analyzed during the last century (*e.g.*, Kodym *et al.* 1931; Havlíček *et al.* 1958; Horný 1955a–c, 1962, 1965, 1971; Kříž 1991, 1992, 1998; Kříž *et al.* 1993; Dufka 1995; and Manda 1996). The most detailed description of the two sections was given by Kříž (1992) and Kříž *et al.* (1993), who discussed their lithologies, faunal communities and biostratigraphy.

Section No. 759 starts with a lens of grey micritic limestone bearing crinoid detritus and weathered volcanic glass, which was deposited on a thick unit of volcanic rocks. Kříž (1992) noted an occurrence of the *Buceqia obolina* brachiopod Community from basal layers of the section. In addition to the nominate brachiopod *Buceqia obolina* (Barr.), he mentioned the presence of five other brachiopods [*Cryptatrypa philomella* (Barr.), *Bleshidium papalas* Havl., *Aratoechia minerva* (Barr.), *Hircinisca* cf. *rhynchonelliformis* Havlíček & Plodowski, *Striispirifer aurelius* Havl.], four trilobites [*Cheirurus obtusatus* Hawle & Corda, *Kosovopeltis inopinata* Šnajdr, *Odontopleura prevosti prevosti* (Barr.), *Aulacopleura konincki* (Barr.)], and five bivalves ["*Nucula*" *simplicitor* Barr., *Butovicella migrans* (Barr.), *Isiola lyra* Kříž, *Slava* cf. *pelerina* Kříž, and *Cardiola* aff. *agna* Kříž]. Kříž (1992) also noted the occurrence of diverse acritarchs and rare spores found by Pavel Dufka. Only two long-ranging chitinozoan species, *Ancyrochitina ancyrea* (Eisenack) and *Conochitina tuba* (Eisenack), were found in section No. 759. About 1 m above the base of the section (bed No. 6 of Kříž 1992) a thick bed of greenish-grey tuffitic shales occurs which contains graptolites *Pristiograptus dubius* (Suess) *s.l.*, and *Monograptus flemingii* (Salter), the brachiopod *Buceqia obolina*, the trilobite *Cheirurus obtusatus*, and the plant *Prototaxites* sp. Kříž (1992) noted the occurrence of the graptolite *Monograptus flemingii* also in upper part of

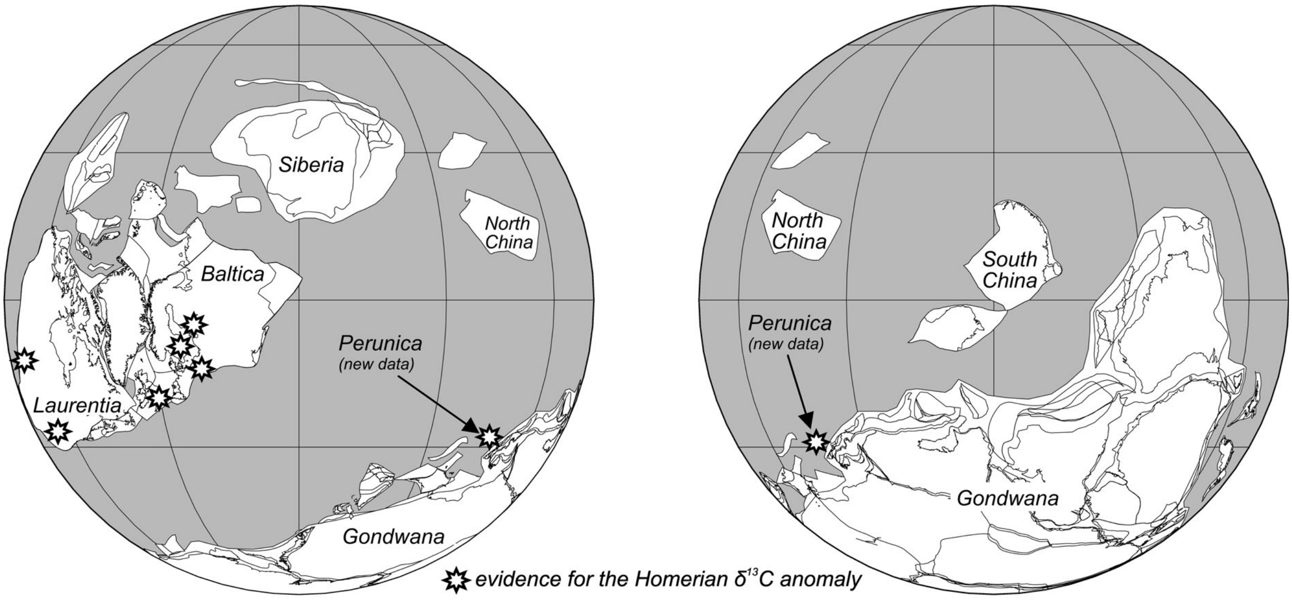


Figure 1. Palaeogeographical distribution of published records of the late Wenlock Homerian δ^{13}C excursion based on the review by Calner (2008); palaeogeographical reconstruction modified after Torsvik (2009).

section No. 759, about 7 m above the base of the limestone sequences. From the same level he also mentioned the occurrence of the conodont species *Ozarkodina excavata excavata* (Branson & Mehl) and *Kockelella absidata* (Barrick & Klapper). Later Kříž *et al.* (1993) mentioned the occurrence of *Ozarkodina sagitta sagitta* (Walliser) from the basal part of section No. 759 (bed No. 3).

Manda (1996) produced a detailed analysis of the fossil community from the lower part of section No. 759 and reported additional species: seven trilobites [*Cyphoproetus putzkeri putzkeri* Šnajdr, *Sphaeroxochus mirus* Beyrich, *Trochurus speciosus* Beyrich, *Aulacopleura nitida* (Barr.), *Leonaspis* sp., *Harpes crassifrons* (Barr.), *Bumastus bouchardi* (Barr.)], sixteen brachiopods (see below), twenty cephalopods [*Parakionoceras mimus* (Barr.), *Kionoceras bacchus* Barr., "*Orthoceras*" *sylphideum* Barr., "*Orthoceras*" *littorale* Barr., "*Orthoceras*" *valens* Barr., *Michelinoceras*? *semilaeve* (Barr.), *Michelinoceras*? *cavum* (Barr.), *Orthocycloceras*? *pedum* (Barr.), *Rizosceras* cf. *latens* (Barr.), *Rizosceras ignotum* (Barr.), *Phragmoceras* n. sp. *aff. gradatum* (= *Phragmoceras* cf. *ventricosum* Sowerby, see Manda 2007), *Plagiostomoceras endymion* (Barr.), *Plagiostomoceras xanthus* (Barr.), *Murchisoniceras* sp., *Pseudocycloceras* aff. *venustulum* Barr., "*Orthoceras*" aff. *memor* Barr., *Sphooceras truncatum* (Barr.), *Sphooceras disjunctum* (Barr.), *Protobactrites styloideum* (Barr.), *Metarizoceras* sp. n.], five bivalves [*Nutricula gravida* Kříž, *Patrocardia alifera* (Barr.), *Spanila* (= *Kenzieana*) *cardiopsis* (Barr.), *Slava fibrosa* (Sow.), *Maminka comata* Barr.], one rostroconch (*Conocardium* sp.), three hyolithids [*Hyolithus bicostatus* Novák, *Hyolithus cultellus* Novák, *Ceratotheca unguiformis* Novák], two graptolites [*Cyrtograptus lundgreni* Tullberg, *Cyrtograptus* cf. *perneri* Bouček], machaeridian *Plumulites minimus* Barr., and rugose coral *Syringaxon* sp.

Manda (1996) established a new *Eoplectodonta sowerbyana–Atrypa* Community which is, according to him, "known from the southern part of level 3 at locality No. 759 only". The latter community contains two dominant brachiopods, *Eoplectodonta sowerbyana* (Barr.) (25%) and *Atrypa* cf. *margarita* (Barr.) (10%), and eighteen less frequent brachiopods [*Quasistrophonella haueri* (Barr.), *Aratoechia minerva*, *Placocliftonia colibri* (Barr.), *Oglupes scarabeus* Havl., *Cyphomena joachimiata* Havl., *Hircinisca praehircina* Havl., *Eospirifer praesecans* Havl., *Striispirifer aurelius*, *Kozlenia kozlensis* Havl., *Septatrypa zelia* (Barr.), *Ptychopleurella* sp. n., *Leptaena* sp., *Strophoprion* sp., *Myriospirifer* sp., *Isorthis* sp., *Bleshidium* sp., *Meristina* sp., and *Buceqia obolita*]. The *Eoplectodonta sowerbyana–Atrypa* Community contains also five trilobites [*Staurocephalus murchisoni* (Barr.), *Phacopidella glockeri* (Barr.), *Sphaeroxochus mirus*, *Kosovopeltis inopinata*, and *Cheirurus obtusatus*], three cephalopods [*Protobactrites styloideum*, *Oonoceras* sp., *Orthocycloceras pedum*], two bivalves [*Cardiola agna agna*, *Butovicella migrans*], and one crinoid [*Syndetocrinus dartae* Kirk].

The second studied section [*i.e.*, section No. 760 of Kříž (1992) also called "U Drdů" after the family name of the farm owners who lived SE of the section] starts approximately 25 m stratigraphically above top of the section No. 759. The lower about 20 m of the section is formed by pyroclastics and granulates, with greenish tuffites containing lapilli and fragments of lava in its upper part. The main part of section No. 760, about 63 m thick, consists of limestone beds belonging to the Kozel Limestone Member and representing its stratotype. The section is formed mainly by massive lenticular grey tuffitic bioclastic crinoidal limestone with levels of brown tuffites with small lenses of grey bioclastic crinoidal tuffitic limestones (Figs 2, 3). In the middle part of the section massive limestones occur showing at some levels cross-bedding (*e.g.*, Fig. 4D). Tuffitic layers are almost absent in the uppermost 11 m of the section. The Kozel Limestone Member of the section No. 760 is overlain by a thick unit of volcanic rocks.

The fauna of the Kozel Limestone Member found at its stratotype section consists mostly of crinoids, corals, bryozoans, stromatoporoids, brachiopods, gastropods and trilobites. The limestone sequence in section No. 760 starts with a sequence of crinoidal limestones interbedded with thin tuffite levels (Figs 3, 4). The basal beds of the crinoidal limestones often contain small fragments of tuffites (Fig. 2A) covered by a limonitic layer and they bear a high diversity fauna. Kříž (1992) found a rich brachiopod, trilobite, and coral fauna from his beds No. 24 and 25, which contains nineteen brachiopods [*Mendacella venustula* (Barr.), *Resserella canalis* (Sow.), *Isorthis* (*A.*) *cliens* Havl., *Rhynchotreta cunicula* Havl., *Anastrophia deflexa* (Sow.), *Cyrtia spiriferoides* Bouček, *Rufispirifer nucula* (Barr.), *Protomegastrophia miranda* (Barr.), *Striispirifer aurelius*, *Atrypa margarita*, *Nucleospira lentilca* Havl., *Whitfieldella ypsilon* (Barr.), *Kozlenia kozlensis*, *Atrypina paulula* Havl., *Eospirifer praesecans*, *Amphistrophia harperi* Havl., *Dicoelosia* sp., *Strophochonetes gluma* (Barr.), *Skenidioides* sp.], rostroconch *Conocardium* sp., trilobite *Harpidella hama* (Šnajdr), and fourteen corals [*Heliolites decipiens* (McCoy), *H. irregularis* Wentzel, *H. bohemicus* Wentzel, *H. spongodes* Lindström, *Helioplasmolites wentzeli* Galle, *Stelliporella lamellata* Wentzel, *Propora poctai* Galle, *Favosites fidelis* Barr., *F. gotlandicus* Lamarck, *F. forbesi* Milne-Edwards & Haime, *Halysites catenularia* (Linn.), "*Barrandeolites*" *bowerbanki* (Milne-Edwards & Haime), *Entelophyllum confusum* (Počta), and *E. prosperum* (Barr.)]. In addition to those species Kříž (1992) noted also the occurrence of stromatoporoids and bryozoans.

Kříž (1992) found another rich fauna in the middle part of section No. 760 (top of bed No. 60) which includes nine brachiopods [*Meristina mora* Michalík, *Resserella canalis*, *Atrypa margarita*, *Strophoprion euglypha* (Dalman), *Leptostraphiella nebulosa* (Barr.), *Shagamella margarita* (Barr.), *Cyrtia spiriferoides*, *Isortis (Arcuala) cliens*, and *Protomegastrophia miranda*], six trilobites [*Proetus kopaninensis* Šnajdr, *Tropidocoryphe*? *praecurrens* Šnajdr, *Interproetus* sp., *Eophacops trapeziceps* Barr., *Richterarges* sp. n. aff. *ambiguus* (Barr.), and *Cheirurus obtusatus*], and stromatoporoids. Kříž (1992) reported also nine conodont samples (from beds No. 24, 28, 30, 40 top, 70 bottom, 73 bottom, 82 top, 86 centre and 86 top) from the section No. 760 which gave a uniform fauna characterized only by *Ozarkodina bohemica* (Walliser).

Havlíček (1995) revised the stratigraphic distribution of brachiopod communities from the Motol and Kopanina formations which was partly based on new material collected by Kříž during his study of Wenlock/Ludlow boundary in the Prague Basin (Kříž *et al.* 1993). Havlíček modified his previous definition of the *Hircinisca–Ancillotoechia* brachiopod Community (see Havlíček & Štorch 1990, 1999) which included about 50 brachiopod species. He noted 23 brachiopod species of the *Hircinisca–Ancillotoechia* brachiopod Community in the basal part (beds No. 24 and 25) of section No. 760, with twelve common species [*Mendacella venustula*, *Resserella canalis*, *Isorthis* (*A.*) *cliens*, *Linoporella punctata* (Vern.), *Leptaena* sp., *Rhynchotreta cunicula*, *Ancillotoechia ancillans* (Barr.), *Atrypina paulula*, *Kozlenia kozlensis*, *Nucleospira lentilca*, *Cyrtia spiriferoides* and *Rufispirifer nucula*], eight rare species [*Craniops* (*Paracraniops*?) sp., *Protomegastrophia miranda*, *Orhoria amelia* Havl., *Amphistrophiella* cf. *funiculata* (McCoy), *Coolinia pecten* (Lin.), *Terazkia expandens* (Barr.), *Krizistrophia miniconcha* Havl., and *Pliocyrtia sambuca* Havl.] and three very rare species [*Hostimex hostimensis* Havl., *Atrypa margarita*, and *Eospirifer praesecans*].

Dufka (1995) published results of his analysis of organic microfossils from both sections (No. 759 and 760). He reported high diversity assemblages of dispersed trilete miospores and cryptospores belonging to the *Artemopyra brevicosta–Hispanaediscus verrucatus* Assemblage Zone. According to Dufka (1995) the occurrences of numerous sporomorphs only in the Svatý Jan Volcanic Centre supports previous sedimentological evidence that this volcanic elevation was emergent during the latest Wenlock. He noted that the ratio of sporomorph and acritarch abundances is very low in samples from section No. 759, but very high for samples from section No. 760, which fits with previous sedimentological interpretation of the Kozel Limestone Member as having been deposited in a very shallow environment (Horný 1955a–c, 1959; Kříž 1992; Kříž *et al.* 1993).

Sampling and methods

Carbonates from both sections (*i.e.*, No. 759 and 760 of Kříž 1992) of the Wenlock Motol Formation were sampled in order to investigate the complete carbon isotope record across the Kozel Limestone Member. This new sampling campaign included 39 carbonate samples for carbon isotope study and covered a stratigraphic interval through the whole thickness of the Kozel Limestone Member in its stratotype (Figs 3, 4, and appendix).

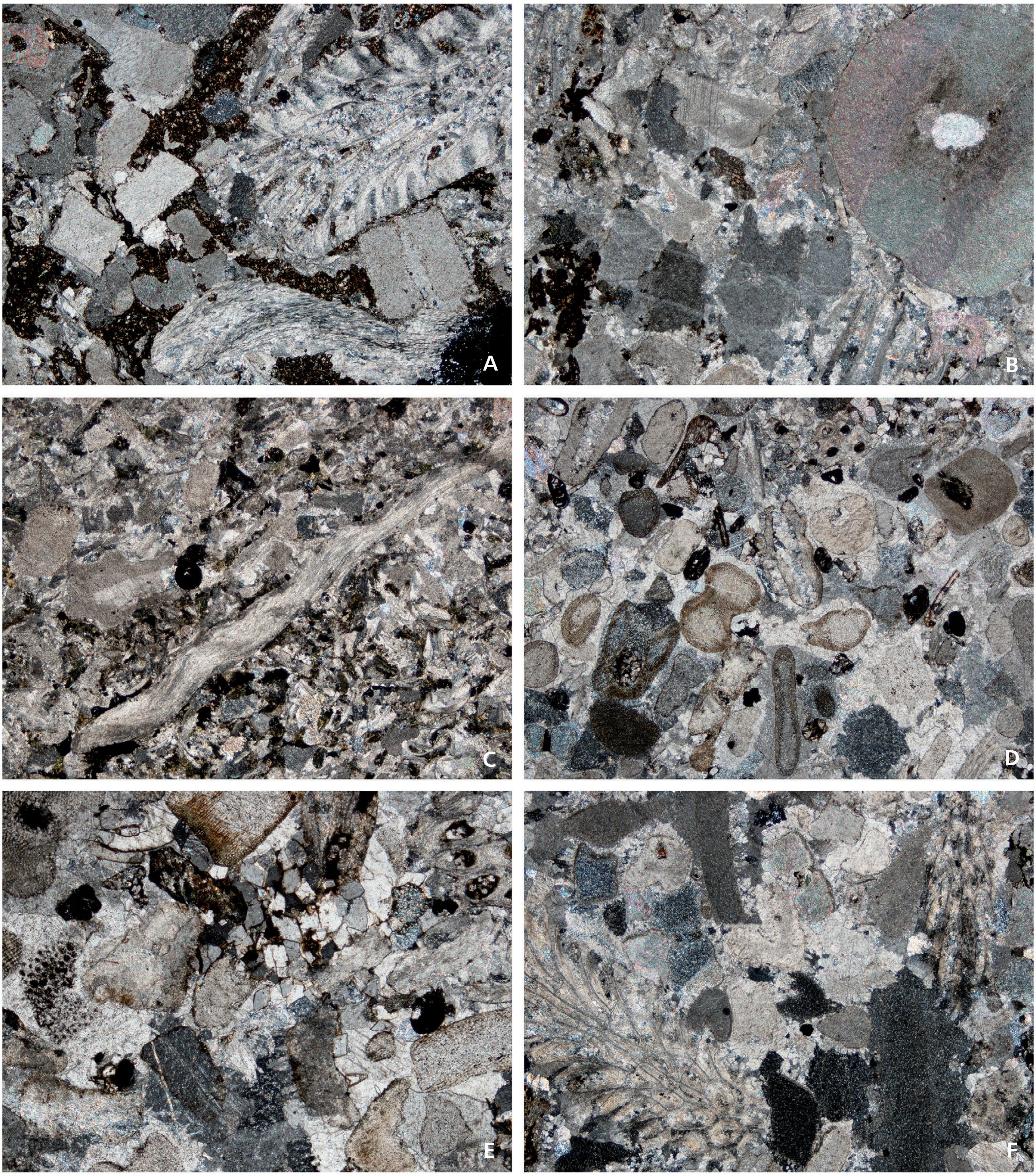


Figure 2. Lithologies of selected levels at the stratotype of the Kozel Limestone Member (section No. 760; bed numbers after Kříž *et al.* 1993) – thin sections. • A – crinoid-coral-brachiopod-bryozoan grainstone/rudstone containing small amount of volcanic products; bed No. 24; boundary of R1- and F1-δ^{13}C chemostratigraphic zones. • B – mostly crinoid grainstone; bed No. 30b; lower part of the F1-Zone of the δ^{13}C chemostratigraphic zonation. • C – crinoid-brachiopod grainstone; bed No. 37; the F1-Zone of the δ^{13}C chemostratigraphic zonation. • D – crinoid-bryozoan grainstone showing intensively micritized crinoid columnals rounded by transportation; bed No. 51; upper part of the F1-Zone of the δ^{13}C chemostratigraphic zonation. • E – dolomite crystals in sample about 35 cm above base of bed No. 51. • F – crinoid-coral-bryozoan grainstone/rudstone; middle part of bed No. 63; boundary of R2- and F2-δ^{13}C chemostratigraphic zones.

A few milligrams of rock powder were recovered with a dental drill from cut and polished slabs. Grainstones, rudstones, and packstones represent the dominant limestone lithology of the Kozel Limestone Member (Fig. 2; see the appendix). Where possible, wackestones were sampled, but most analyses were carried out on grainstones. Based on previous study of thin sections, the samples with an occurrence of dolomite were rejected from carbon isotope study (Fig. 2E). The carbonate powder was reacted with 100% phosphoric acid at 70 °C using a Gasbench II connected to a Thermo Delta 5 mass spectrometer. All values are reported in ‰ relative to V-PDB by assigning a δ^{13}C value of +1.95‰ and a δ^{18}O value of 2.20‰ to NSB 19. Accuracy and precision were controlled by replicate measurements of laboratory standards and were better than ±0.1‰ for both carbon and oxygen isotopes. The nonparametric Mann-Kendall test was used for testing the presence of the monotonic increasing or decreasing trend of δ^{13}C values.

Results

δ^{13}C record

The carbon isotope data are summarized in Figure 3. The carbon isotope composition of carbonates from the two sections is different. The δ^{13}C values of the five samples from section No. 759 range from –1.67‰ to –0.46‰, however the δ^{13}C values of 34 samples from the section No. 760 range from +0.87‰ to +3.23‰. A distinct positive two-peaked δ^{13}C excursion was found in the δ^{13}C record from section No. 760 (Fig. 3). The δ^{13}C values rise rapidly from +1.54‰ (bed No. 20) to +3.23‰ (bed No. 24) at the base of section No. 760. It is noteworthy that the δ^{13}C values reached such high values over an interval having a thickness of about 1.65 m (Fig. 2). Four samples from about a 2 m thick interval (beds No. 28 to No. 30) just above the highest δ^{13}C value of the section No. 760 have similar δ^{13}C values ranging from +2.43‰ to +2.62‰. The δ^{13}C values in the following interval, approximately 20 m thick (interval from bed No. 31 to bed No. 54), slowly decline to a value of +0.94‰. In the subsequent interval, about 24 m thick, the δ^{13}C values steadily increase to value of +2.62‰ (bed No. 63), and again fall to a value of +0.87‰ (bed No. 75), forming a distinct second peak of the positive carbon isotope excursion (Fig. 3). The δ^{13}C values of samples from the top part of section No. 760, from bed No. 75 to bed No. 86, are rather constant varying around +1.0‰.

Interpretation and discussion

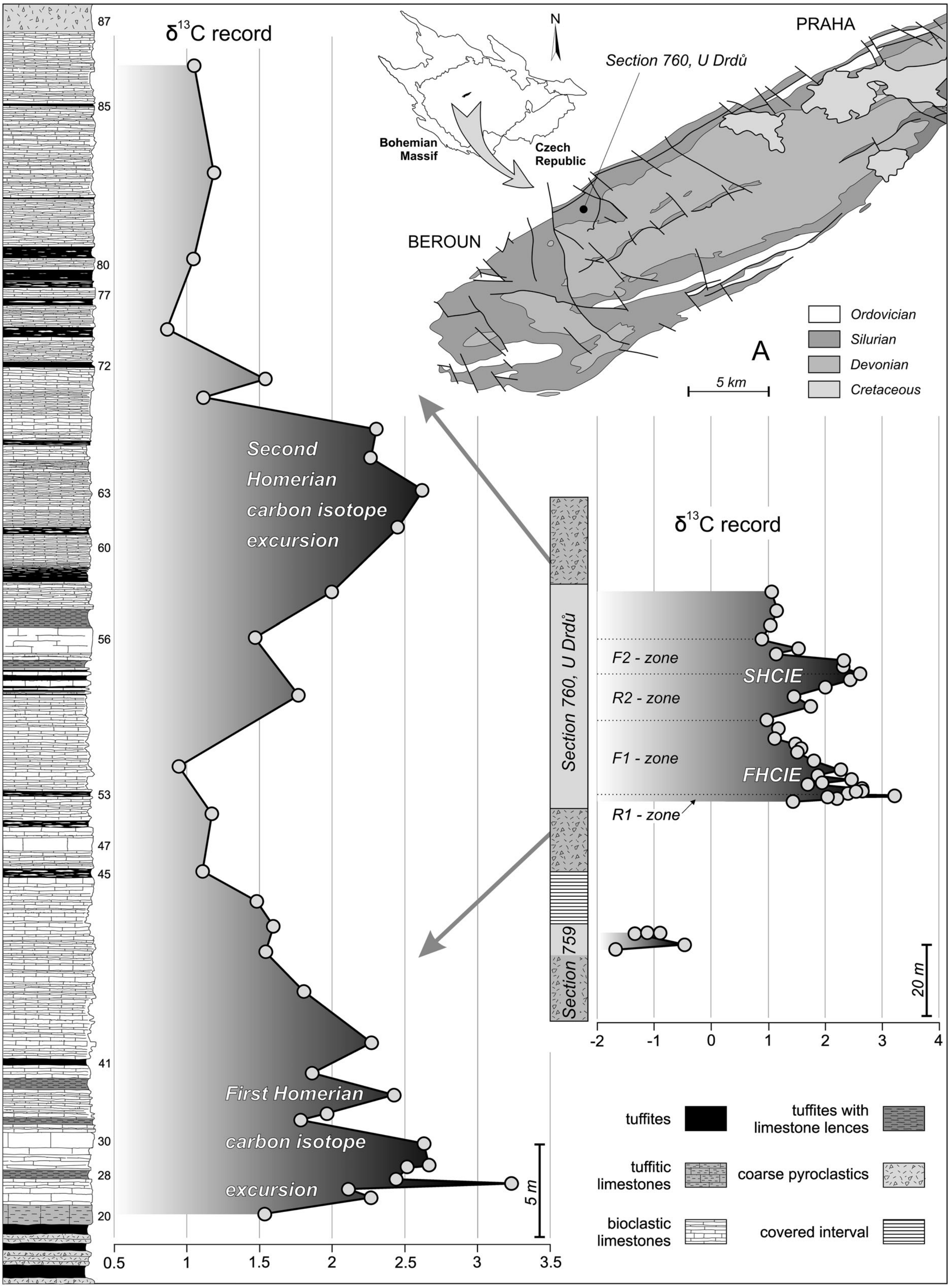
δ^{13}C record

The newly gathered data from stratotype section of the Kozel Limestone Member (*i.e.*, section No. 760) have revealed a distinct two-peaked positive δ^{13}C excursion (see Fig. 3), which occurs within the stratigraphic interval known by the presence of the Homerian carbon isotope excursion. Because of its typical shape (double-peak) as well as its supposed stratigraphic position (*i.e.*, Homerian) we interpret the δ^{13}C excursion as the Homerian δ^{13}C excursion. The latter isotopic excursion has been hitherto documented from several sections on Baltica (*e.g.*, Wenzel & Joachimski 1996; Samtleben *et al*. 1996; Kaljo *et al.* 1997, 2003, 2007; Kaljo & Martma 2006; Calner *et al.* 2006, 2012; Calner 2008), Laurentia (*e.g.*, Lenz 1993; Saltzman 2001; Noble *et al.* 2005, 2012; Lenz *et al.* 2006; Cramer *et al.* 2006, 2010) and Avalonia (*e.g.*, Corfield *et al.* 1992; Loydell 2007; Ray *et al.* 2011a, b; Marshall *et al.* 2012). It is noteworthy that all hitherto recorded occurrences of the Homerian carbon isotope excursion have been described from palaeoplates that subsequently formed the supercontinent Laurussia (*i.e.*, from Laurentia, Baltica and Avalonia). Discovery of the Homerian carbon isotope excursion in peri-Gondwana (Perunica) is thus new evidence for its more widespread and potentially global occurrence.

The carbon isotope excursion can be divided into several distinct geochemical phases that show differing dynamics. This can be used for a definition of chemostratigraphic zones similar to those suggested for the younger mid-Ludfordian carbon isotope excursion (Frýda & Manda 2013). In contrast to the latter carbon isotope excursion, no long-lasting steady period of high δ^{13}C values was observed in the Homerian carbon isotope excursion in either the Barrandian area (Fig. 3) or in other parts of the world.

The course of the Homerian carbon isotope excursion can be divided into two periods of rapid increase in δ^{13}C values which are equivalent to the rising limbs of the older (*i.e.* R1-Zone) and younger (*i.e.* R2-Zone) peaks and two periods of rapid decrease of δ^{13}C values which are equivalent to the falling limbs of the older (*i.e.* F1-Zone) and younger (*i.e.* F2-Zone) peaks. As suggested by Frýda & Manda (2013) the lower and upper boundaries of these chemostratigraphic zones should be defined on the basis of a statistically significant change in the evolution of the δ^{13}C record. In case of section No. 760 there is a problem

Figure 3. The δ^{13}C record across the two sections (No. 759 and 760 of Kříž 1992) of the Motol Formation showing the late Wenlock Homerian δ^{13}C excursion. Distribution of Silurian rocks in the Barrandian area (Perunica), including the position of the studied sections as well as the δ^{13}C chemostratigraphic zonation of section No. 760, are shown (right). Section modified after Kříž *et al*. (1993).


δ13C record
Second Homerian carbon isotope excursion
First Homerian carbon isotope excursion
5 m
0.5
1
1.5
2
2.5
3
3.5
87
85
80
77
72
63
60
56
53
47
45
41
30
28
20
PRAHA
N
Section 760, U Drdů
Bohemian Massif
Czech Republic
BEROUN
Ordovician
Silurian
Devonian
Cretaceous
A
5 km
δ13C record
Section 760, U Drdů
Section 759
F2 - zone
SHCIE
R2 - zone
F1 - zone
FHCIE
R1 - zone
20 m
-2
-1
0
1
2
3
4
tuffites
tuffites with limestone lences
tuffitic limestones
coarse pyroclastics
bioclastic limestones
covered interval

with using this definition for the R1-zone because of the low number of measured $\delta^{13}C$ values (see Fig. 3) and thus only the boundary between the R1- and F1-zones is defined. The nonparametric Mann-Kendall test reveals statistically significant decreasing trends of $\delta^{13}C$ values for the F1- and F2- zones and statistically significant increasing trends of $\delta^{13}C$ values for the R2-Zone ($p < 0.05$ in all cases).

At the present state of knowledge all carbonate beds of section No. 760 up to bed No. 25 (of Kříž *et al.* 1993) belong to the $\delta^{13}C$ chemostratigraphic R1-Zone of the Homerian carbon isotope excursion. The mostly carbonate sequence between bed No. 25 and the lower part of bed No. 54 belongs to the $\delta^{13}C$ chemostratigraphic F1-Zone and that between beds No. 54 and No. 63 to the R2-Zone. The chemostratigraphic F2-Zone starts within bed No. 63 and ends roughly at bed No. 75 (Figs 3, 4).

It is noteworthy that the precise position of the chemostratigraphic boundaries, as with biostratigraphic boundaries, depends on sampling density. The present $\delta^{13}C$ chemostratigraphy of section No. 760 is based on only 34 measurements and it is thus evident that the chemostratigraphic resolution of this section may be improved in future by additional sampling.

Kozel Limestone Member

The Kozel Limestone Member (see appendix for its definition and a list of its older informal names) is restricted to the Central Segment of the Prague Basin (Kříž 1992). Its stratotype as well as parastratotype sections represent the most important late Wenlock fossil localities of the Barrandian having been known since the first half of the nineteenth century. During the last 200 years this limestone succession has yielded many tens of fossil species including mainly brachiopods, corals, trilobites, gastropods, cephalopods, and bivalves. Many of those species are known only from this limestone unit or have it as its type locality. In addition, some fossil groups (*e.g.*, stromatoporoids) have never been studied and others have not been revised during the last 100 years (*e.g.*, gastropods). Because of its very rich fossil record, establishing the age of the Kozel Limestone Member has been the subject of many studies during the last century (*e.g.*, Kodym *et al.* 1931; Bouček 1934; Havlíček *et al.* 1958; Horný 1955a–c, 1962, 1965, 1971; Havlíček & Štorch 1990, 1999; Kříž 1991, 1992, 1998; Kříž *et al.* 1993; Havlíček 1995; Dufka 1995; and Manda 1996). In the following paragraphs the stratigraphic significance of all hitherto available biostratigraphic data from sections No. 759 and 760 is briefly discussed and a new, more detailed zonation of the Kozel Limestone Member based on $\delta^{13}C$ chemostratigraphy is proposed.

Graptolites

Kříž (1992) and Kříž *et al.* (1993) analysed the available biostratigraphic data useful for dating of the Kozel Limestone Member. They mentioned that the graptolite *M. flemingii* is the last graptolite found below its base at the top of section No. 759. The youngest occurrence of this graptolite is recorded in the *C. lundgreni* Biozone (Štorch 1994). Because of this biostratigraphic datum Kříž (1992) concluded that the age of the Kozel Limestone Member could correspond to the period between the *P. dubius parvus* Biozone and the *M. vulgaris* Biozone (= *M. ludensis* Biozone). Manda (1996) mentioned the occurrence of *Cyrtograptus lundgreni* and *Cyrtograptus* cf. *perneri* Bouček, 1933 (det. P. Štorch) in the lower part of section No. 759 and concluded that "if the species is really *Cyrtograptus perneri*, it would indicate the time inverval between the last occurrence of the species *Cyrtograptus radians* and the first occurrences of *Testograptus testis* (assemblage zone *Cyrtograptus lundgreni* – Štorch 1994)". The latter conclusion is, however, somewhat inaccurate because the co-occurrence of *Cyrtograptus lundgreni*, *Cyrtograptus perneri* and *Monograptus flemingii* is well known from the base of the *Cyrtograptus lundgreni* Biozone onwards (*e.g.*, Lenz & Melchin 1989, Štorch 1994, Williams & Zalasiewicz 2004). Nevertheless the finding of *Cyrtograptus* cf. *perneri* may suggest a narrower stratigraphic interval for the beds in the lower part of section No. 759 than the previously reported occurrence of *M. flemingii.* The latter species is known to disapear at the end of *Cyrtograptus lundgreni* Biozone, thus later than *Cyrtograptus perneri* (*e.g.*, Štorch 1994). Taken together, the present limited graptolite data from section No. 759 provide evidence for its placement within the *Cyrtograptus lundgreni* Biozone, as already noted by Kříž (1992).

Conodonts

Kříž (1992) and Kříž *et al.* (1993) noted the occurrence of three conodont species from section No. 759. *Ozarkodina s. sagitta* was found in its lower part and *Ozarkodina ex. excavata* and *Kockelella absidata* in the upper part. One conodont species, *Ozarkodina bohemica*, was reported from nine conodont samples (beds No. 24, 28, 30, 40 top, 70 bottom, 73 bottom, 82 top, 86 centre and 86 top) from section No. 760 (Kříž 1992). Murphy *et al.* (2004) recently transferred *Ozarkodina excavata* to a new conodont genus *Wurmiella*, but this taxonomical placement was later rejected by Suttner (2007). The stratigraphic range of the *Wurmiella* (= *Ozarkodina*) *excavata* is rather long, from the Wenlock to the Lochkovian (*e.g.*, Corradini & Corriga 2012) and so its occurrence in section No. 759 is of low biostratigraphic significance. On the other hand, the other conodont species, *Ozarkodina s. sagitta* and *Kockelella*

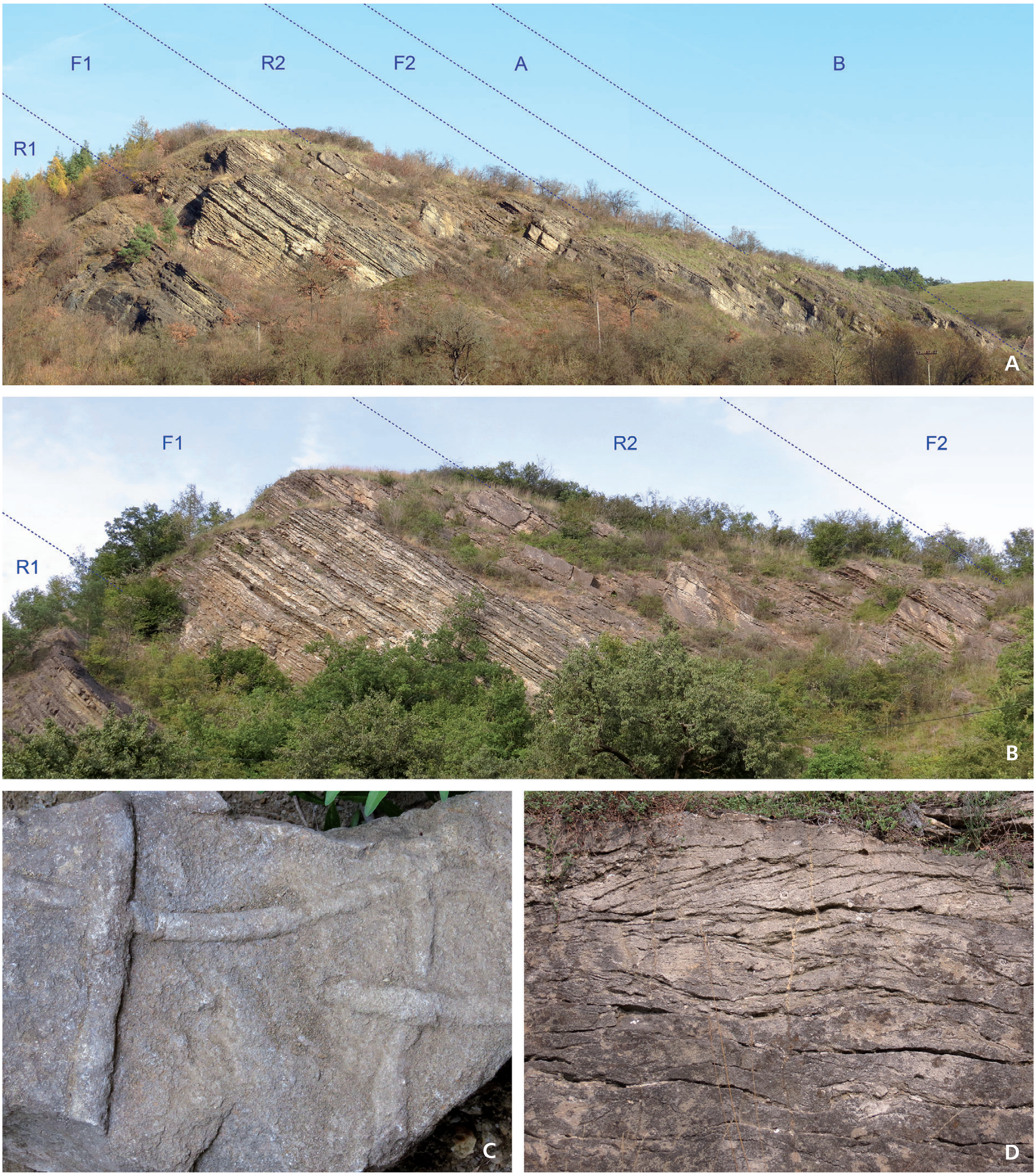


Figure 4. Stratotype of the Kozel Limestone Member (section No. 760). • A – complete view showing its $\delta^{13}C$ chemostratigraphic zonation (R1-, F1-, R2-, and F2-zones). Interval marked as A represents upper part (about 15 m) of the limestone succession of the Kozel Limestone Member above the Homerian $\delta^{13}C$ excursion. Interval marked as B corresponds to the volcanic unit overlying the Kozel Limestone Member. • B – detailed view of the lower part of section No. 760. • C – sample from the middle part of the F1-Zone with traces of the ichnogenus *Palaeophycus* (det. R. Mikuláš, Prague) which occurs mostly in the shallow water *Cruziana* ichnofacies. • D – view of bed No. 63 showing cross-bedding in the shallow water limestones.

absidata, reported from section No. 759 are biostratigraphically more significant. The FAD of *Ozarkodina s. sagitta* corresponds roughly to the base of the *C. lundgreni* Biozone and the latter conodont species became extinct before the end of the *C. lundgreni* Biozone (Jeppsson & Calner 2003, Loydell *et al.* 2010, Cramer *et al.* 2011). On the other hand, the conodont *Kockelella absidata* suggests a much younger age. Jeppsson *in* Calner & Jeppsson (2003) placed *Kockelella absidata* into the species *K. ortus* (Walliser) as its subspecies *Kockelella ortus absidata*. The FAD of *K. ortus absidata* occurs at the base (Calner & Jeppsson 2003) or within (Cramer *et al.* 2011) the *Colonograptus deubeli–Colonograptus praedeubeli* graptolite Biozone. Thus the occurrence of *Ozarkodina s. sagitta* in the basal part of section No. 759 suggests an age corresponding to the *C. lundgreni* Biozone. However, *K. ortus absidata* from the upper part of section No. 759 (Kříž 1992) suggests an age corresponding to the *K. ortus absidata* conodont Biozone or to the *Colonograptus deubeli–C. praedeubeli* or younger graptolite biozones (see Cramer *et al.* 2011).

Ozarkodina bohemica, the only conodont species found in section No. 760, is a long-ranging taxon known from the lower Wenlock to lower Ludlow (Calner & Jeppsson 2003, Jeppsson *et al.* 2006). Jeppsson *in* Calner & Jeppsson (2003) established a new subspecies, *Ozarkodina bohemica longa*, within the morphological range of *Ozarkodina bohemica.* However, there are no published data as to which subspecies the specimens from section No. 760 belong. Thus the occurrence of *Ozarkodina bohemica* in beds No. 24 to 86 of section No. 760 is suggesting only that age of the latter beds is somewhere between early Wenlock and early Gorstian. But, if the determination of *Kockelella absidata* (= *K. ortus absidata*) from the underlying section (No. 759) is correct, than a "conodont age" for section No. 760 should correspond to the interval from the *Colonograptus deubeli–C. praedeubeli* Biozone to the early Gorstian.

Organic microfossils

Dufka (1995), based on his analysis of organic microfossils, concluded that the age of the limestone succession of section No. 760 is latest Wenlock. He noted also that *Synorisporites*? *libycus*, which he found in 13 samples from section No. 760 (from bed No. 31 to 86), has been recorded only from the younger *Synorisporites libycus–Lophozonotriletes poecilomorphus* Biozone of Ludlow age. Dufka (1995) interpreted the occurrence of this taxon as evidence for its early origin in the *Artemopyra brevicosta–Hispanaediscus verrucatus* Assemblage Zone. In his figure 2 Dufka (1995) suggested a possible zonation of sections No. 759 and 760. According to him, all beds in section No. 759 and the basal tufitic part of section No. 760 are equivalent to the *Cyrtograptus lundgreni* Biozone. The first limestone beds of stratotype section (No. 760), up to the level around bed No. 35 could belong to *P. dubius parvus* Biozone. An interval above bed No. 35 is suggested to be equivalent to "levels with *G. nassa*". The top of section No. 760 he placed in the *M. vulgaris* (= *ludensis*) Biozone. However, it is noteworthy that the internal division of section No. 760 suggested by Dufka (1995, fig. 2) is not supported by any biostratigraphic data. It is noteworthy that the organic microfossils do not exclude even an early Gorstian (Ludlow) age for the upper part of section No. 760 (see Burgess & Richardson 1991, 1995; Beck & Strother 2001, 2008; Steemans *et al.* 2012).

Age of the Kozel Limestone Member inferred from biostratigraphy

Precise biostratigraphic dating of the Kozel Limestone Member is difficult because of a lack of biostratigraphically significant fossils. Also, interpretation of the biostratigraphic data from the underlying sequence forming section No. 759 is not easy. As shown above, the graptolite data (*i.e.*, *P. dubius s.l.*, *M. flemingii*, *C. lundgreni* and *C.* cf. *perneri*) indicates the *Cyrtograptus lundgreni* Biozone (Turek 1990, Štorch 1994, Manda 1996); however, the conodont data suggest a much younger age (*K. ortus absidata* conodont Biozone) being equivalent to the *Colonograptus praedeubeli–Colonograptus deubeli* Biozone or younger graptolite biozones. Thus conodont and graptolite data from section No. 759 seem to be in conflict, but we hope that on-going conodont and organic microfossil sampling will solve this problem in near future.

Age of the Kozel Limestone Member inferred from lithostratigraphy

The approximately 60 m thick limestone sequence of section No. 760 was deposited during a period of low volcanic activity within the Svatý Jan volcanic centre. The latter limestone sequence is underlain and overlain by thick units of volcanic rocks which were formed during main activity of the Svatý Jan Volcano (see details and references in Kříž 1992 and Kříž *et al.* 1993). According to Kříž (1998, p. 90), "Evidence for the age of the main activities of the Svatý Jan Volcano can be interpreted from two levels of tuffites (redeposited tuffs) more than 1 m thick that occur in the sequence of shale in the Všeradice Section (the Southern Segment) just below the base of the *M. dubius parvus* Biozone and at the base of the *C. colonus* Biozone. The shales between these two levels at Všeradice most probably represent an equivalent of the quiet phase of the Svatý Jan Volcano when the Kozel Limestone Complex (= Kozel Limestone Member) was deposited in the Svatý Jan Volcanic Centre area."

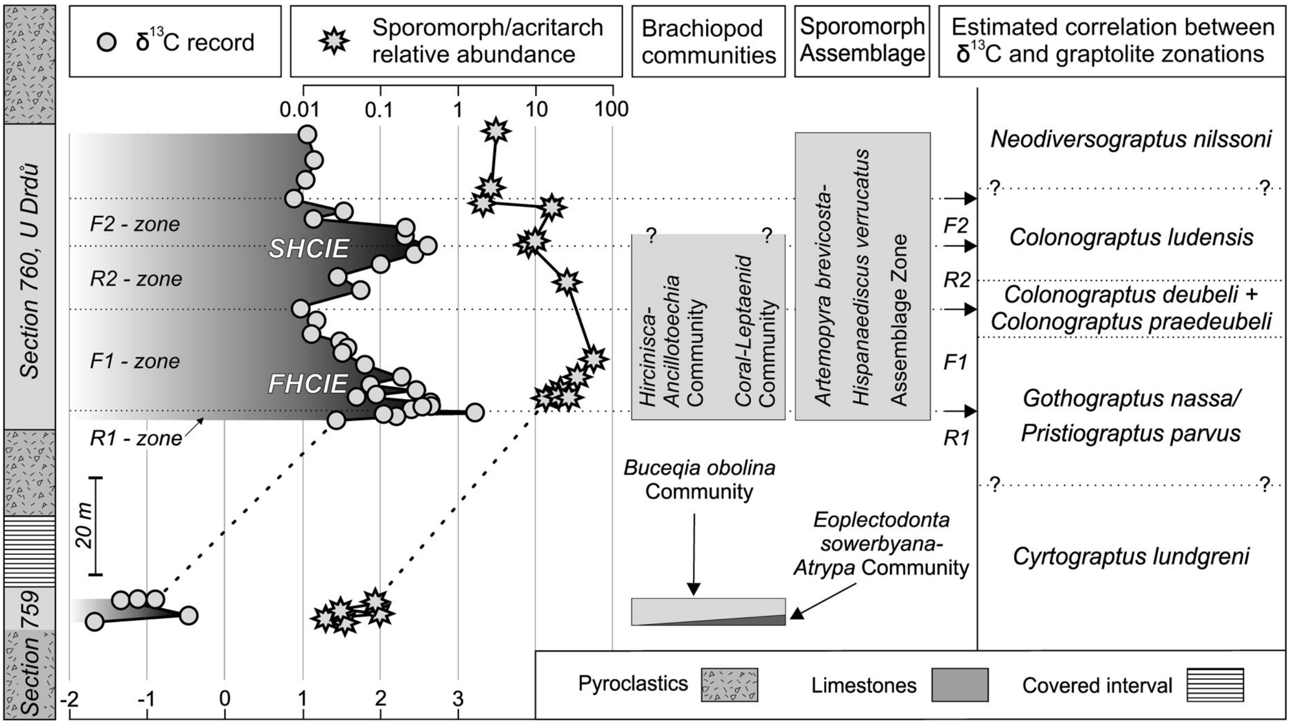


Figure 5. Diagram showing the δ^{13}C chemostratigraphic zonation, sporomorph/acritarch relative abundance (based on data from Dufka 1995), stratigraphic distribution of brachiopod communities, and estimated correlation between the δ^{13}C chemostratigraphic and graptolite zonations.

New research by Kozłowska-Dawidziuk *et al.* (2001) at the Všeradice section, however, revealed more complex relationships. The stratigraphic position of the first tuffitic bed (*i.e.*, just below the base of the *Pristiograptus parvus–Gothograptus nassa* Biozone) was confirmed. Kozłowska-Dawidziuk *et al.* (2001) reported the occurrence of an additional thin tuffitic bed (about 25 cm thick) within the upper third of the *Colonograptus deubeli–C. praedeubeli* Biozone. A third tuffitic bed (about 1.2 m thick) lies within the lower Ludlow *Neodiversograptus nilssoni* Biozone (about 1 m above its base; see fig. 2 in Kozłowska-Dawidziuk *et al.* 2001). Based on this new data, if we accept the stratigraphic correlation suggested by Kříž (1998), this suggests that the youngest part of the Kozel Limestone Member may be of the earliest Gorstian age (Ludlow).

Age of the Kozel Limestone Member inferred from δ^{13}C chemostratigraphy

Even though the Homerian δ^{13}C excursion was firstly described more that 20 years ago (Corfield *et al.* 1992), its correlation with the global Silurian chronozones is still not completely established. The main reason for this situation is the fact that the majority of records of the Homerian δ^{13}C excursion have been described from limestone successions, which generally lack graptolites. The current Silurian timescale assumes a correlation between stage boundaries and graptolite zones and because of that a correlation of graptolite-lacking successions to the global Silurian chronostratigraphic zonation is often difficult (Cramer *et al.* 2006; Loydell 1998, 2007, 2012; Loydell *et al.* 2010). Cramer *et al.* (2011, 2012) summarized recent knowledge on correlation of the Homerian δ^{13}C excursion with the graptolite and conodont zonations. They showed that the first peak of the two-peaked Homerian δ^{13}C excursion occurs within the *Ozarkodina bohemica longa* Biozone and the second peak in the *Kockelella ortus absidata* Biozone. These conodont biozones have, however, rather long stratigraphic ranges, the first approximately from upper part of *Cyrtograptus lundgreni* graptolite Biozone to about base of *Colonograptus deubeli–C. praedeubeli* graptolite Biozone. The following younger *Kockelella ortus absidata* conodont Biozone ends close to the base of Ludlow Series (Cramer *et al.* 2011). Correlation of the Homerian δ^{13}C excursion with the more precise graptolite zonations is not without problems (compare data from Kaljo *et al.* 2007; Cramer *et al.* 2006, 2011; Noble *et al.* 2012). Some uncertainties are probably influenced by a low density of chemostratigraphic and/or biostratigraphic samples, by different local graptolite zonations (Kaljo & Martma 2006; Lenz *et al.* 2006; Loydell 2007, 2012; Noble *et al.* 2005) and maybe also by not exactly synchronous appearances of zonal graptolite taxa in different areas of Laurentia, Avalonia and Baltica (*e.g.*, Loydell 1998, 2007; Cramer *et al.* 2006, 2011; Noble *et al.* 2005, 2012; Marshall *et al.* 2012).

Present summaries of the stratigraphic position of the Homerian $\delta^{13}C$ excursion (Cramer *et al.* 2011) suggest that the excursion started in the uppermost part of the *Cyrtograptus lundgreni* Biozone, reaches its maximum within the *Pristiograptus parvus–Gothograptus nassa* Biozone and ends within the *Colonograptus deubeli–C. praedeubeli* Biozone. In the upper part of the latter graptolite biozone the $\delta^{13}C$ values start to rise to their second peak, which is reached within the *Colonograptus ludensis* graptolite Biozone. The excursion ends before the end of the latter biozone (but see also Marshall *et al.* 2012).

Published data suggest the following correlation of the graptolite zonation with the $\delta^{13}C$ chemostratigraphic zonation of the Homerian $\delta^{13}C$ excursion (Fig. 5). The chemostratigraphic R1-Zone ranges from the uppermost part of the *Cyrtograptus lundgreni* Biozone to about the middle of the *P. parvus–G. nassa* Biozone and the following F1-Zone ends within the *C. deubeli–C. praedeubeli* Biozone. The chemostratigraphic R2-Zone ranges from the *C. deubeli–C. praedeubeli* Biozone to about the middle of the *C. ludensis* Biozone and the following F2-Zone ends before the base of the Ludlow Series. Nevertheless it is noteworthy that precise correlation of the graptolite and $\delta^{13}C$ chemostratigraphic zonation still needs more densely spaced sampling from different sections globally. At present, the local records of Silurian carbon isotope excursions may appear vary as a result of such factors as sample spacing, stratigraphic completeness, and sediment accumulation rate (*e.g.*, Sadler 2012).

If the above-mentioned correlation is used as a preliminary estimation, the following internal stratigraphic zonation of the studied sections may be proposed. The low $\delta^{13}C$ values from limestone beds of section No. 759 suggest that their age is older than the uppermost part of the *Cyrtograptus lundgreni* Biozone, what is in a good agreement with published graptolite data (Kříž 1992, Kříž *et al.* 1993, Manda 1996), but partly in conflict with conodont data (see above).

The new chemostratigraphic data enable also more precise stratigraphic correlation within the stratotype section of the Kozel Limestone Member (section No. 760) than that based on available biostratigraphic data (see discussion above). The basal part of section No. 760 up to bed No. 25 (of Kříž *et al.* 1993) belongs to the top of the $\delta^{13}C$ chemostratigraphic R1-Zone and its most probable age corresponds to the *P. parvus–G. nassa* Biozone (Figs 3, 4, and 5). The succeeding, mostly carbonate sequence between bed No. 25 and bed No. 54 belongs to the $\delta^{13}C$ chemostratigraphic F1-Zone and thus it should correspond to interval from the upper part of the *P. parvus–G. nassa* Biozone and lower part of the *C. deubeli–C. praedeubeli* Biozone. The beds from No. 54 to No. 63 (*i.e.*, the R2-Zone of the Homerian carbon isotope excursion) correspond to the upper part of *C. deubeli–C. praedeubeli* Biozone and lower part of the *Cyrtograptus ludensis* Biozone. The bed from No. 63 to roughly bed No. 75 (the chemostratigraphic F2-Zone) corresponds to the same graptolite biozone (*i.e.*, to the *Cyrtograptus ludensis* Biozone).

The age of the upper approximately 15 m of section No. 760 is not certain. The second peak of the Homerian $\delta^{13}C$ excursion ends in the majority of published $\delta^{13}C$ records just below the base of the Ludlow Series or even above its base (see discussion in Marshall *et al.* 2012). The $\delta^{13}C$ values of limestones from the upper approximately 15 m of section No. 760 (Fig. 3) vary by about +1‰ and seem to belong to typical post-peak values. If so then the age of the uppermost part of section No. 760 may correspond to the lowermost Gorstian. On the other hand, the uppermost part of the section No. 760 has been interpreted as belonging to top of the Homerian by all previous researchers. However, at present there is no biostratigraphic evidence from this part of the section, which demonstrates its Homerian age and rejects the Gorstian age. Nevertheless the question of the age of the upper part of section No. 760 is not yet solved and needs in the future more detailed study.

Homerian bioevents and the *Hircinisca–Ancillotoechia* brachiopod Community

The graptolite extinction event within the Homerian was one of the first recognized Silurian bioevents (Jaeger 1959, 1991). During this bioevent, known as "Große Krise" or *lundgreni* Bioevent, up to 95% of all graptolite species became extinct in some regions and the crisis involved also other planktonic groups such as acritarchs, prasinophytes and radiolarians (*e.g.*, Koren' 1991; Štorch 1995; Kaljo *et al.* 1996; Lenz & Kozłowska-Dawidziuk, 2001, 2002; Porębska *et al.* 2004; Lenz *et al.* 2006; Noble *et al.* 2005, 2012). Study of conodont faunas revealed distinct crises known as the Mulde bioevent (Jeppsson *et al.* 1995, Calner & Jeppsson 2003, Jeppsson & Calner 2003, Calner *et al.* 2006). Loydell (2007) showed that the Mulde Event conodont extinctions precede the dramatic graptolite extinction (*i.e.*, the "Große Krise" or *lundgreni* Bioevent), sea-level fall and positive $\delta^{13}C$ Homerian excursion. Published data suggest that two regressive episodes during the mid to late Homerian were recorded in many areas. The onset of the first regression occurred late in the *Cyrtograptus lundgreni* Biozone with the lowest sea-level in the early part of the *Gothograptus nassa* Biozone and the second regression occurred just before or within the *Colonograptus ludensis* Biozone (*e.g.*, Loydell 1998, 2007; Calner & Jeppsson 2003; Johnson 2006; Noble *et al.* 2012). Organic microfossil data from sections No. 759 and 760 suggests a similar pattern (Fig. 5). Relative sporomorph/acritarch abundance plotted on a logarithmic scale suggests its great variability. The highest terrestrial input inferred from the highest values of relative sporomorph/acritarch abundance occurred in the $\delta^{13}C$ chemostratigraphic F1-Zone which corresponds to the upper part of the *P. parvus–G. nassa* or lower part of *C. deubeli–C. praedeubeli* graptolite biozones. During the F1-Zone the relative abundance of sporomorphs is about 1000 times higher than during deposition of the underlying section, No. 759 (Fig. 5). Stricanne *et al.* (2006), who analysed palynological signals across the mid-Ludfordian carbon isotope excursion (Ludlow, Silurian) on Gotland reported similar pattern.

The Homerian conodont extinction interval occurs within the upper part of the *Cyrtograptus lundgreni* Biozone before the sea-level fall at which time the main graptolite extinction occurred. According to Cramer *et al.* (2012), the overlying *Gothograptus nassa* Biozone represents an interval with the surviving fauna, and the younger biozones (*i.e.*, *C. deubeli–C. praedeubeli* and *C. ludensis*) represent the eventual recovery and re-radiation following the biotic event. Cramer *et al.* (2012, fig. 9) suggested that the *C. deubeli–C. praedeubeli* Biozone corresponds to an interval when new species originated from surviving lineages, and during the younger *C. ludensis* Biozone a major radiation of new lineages occurred.

In this context, the age of the very diverse *Hirciniska–Ancillotoechia* brachiopod Community known from the Kozel Limestone Member is somewhat surprising. This brachiopod community includes about 50 brachiopod species and even more species of other benthic groups (Barrande's locality Kozel). Only about 10% of the 50 brachiopod species belong to surviving species known from older units (see Havlíček & Štorch 1990, 1999; Havlíček 1995). These facts suggest that the *Hirciniska–Ancillotoechia* brachiopod Community does not represent a surviving fauna, but a new brachiopod fauna. The $\delta^{13}C$ chemostratigraphy has revealed that the appearance of the high diversity *Hirciniska–Ancillotoechia* Community was in the uppermost part of the R1-Zone, that corresponds to the lower part of the *P. parvus–G. nassa* Biozone. Thus the origin of a new high diversity fauna in the Barrandian area fits with a post-crisis period during low sea-level, but occurs long before the presumed recovery during the *C. ludensis* Biozone (see Cramer *et al.* 2012; see here Fig. 5). Faunal elements of the *Hirciniska–Ancillotoechia* Community have been documented also in younger strata of section No. 760 up to bed No. 60 (Kříž 1992, Kříž *et al.* 1993, Havlíček 1995). Bed No. 60 corresponds to the highest value of the second peak of the Homerian $\delta^{13}C$ excursion and so to the *C. ludensis* Biozone (Figs 3, 4). The stratigraphic range of the *Hirciniska–Ancillotoechia* Community is thus rather long (from the *P. parvus–G. nassa* Biozone to the *C. ludensis* Biozone) including the survival and recovery intervals of Cramer *et al.* (2012). The present data from the Barrandian thus suggest that recovery of benthic faunas after the series of mid-Homerian extinction events (*i.e.*, the Mulde conodont and the *lundgreni* graptolite bioevents) started much earlier than has hitherto been described from other world areas.

Conclusions

New $\delta^{13}C$ data across the Kozel Limestone Member have highlighted several new aspects that are of importance for both regional and global stratigraphic correlations as well as for increased understanding of the late Wenlock Homerian carbon isotope excursion. The main conclusions are summarized below:

1. The newly collected $\delta^{13}C$ data provide for the first time evidence for the Homerian (late Wenlock) positive carbon isotope excursion in peri-Gondwana. In addition, our data present the first evidence for this isotope excursion outside of palaeocontinents that later formed the supercontinent Laurussia (Fig. 1).
2. The $\delta^{13}C$ excursion may be divided into four distinct geochemical phases having different $\delta^{13}C$ dynamics. The Homerian positive carbon isotope excursion has a characteristic double-peak (Fig. 3), which consists of two periods when $\delta^{13}C$ values increased significantly as well as two periods when these values declined significantly. These time periods are used herein to define a new $\delta^{13}C$ chemostratigraphic zonation (R1-, F1-, R2-, and F2-zones) of the Homerian positive carbon isotope excursion. The newly established $\delta^{13}C$ chemostratigraphic zonation may be used for future improvement of intercontinental correlations and for integration of the graptolite and conodont biostratigraphic zonations with the $\delta^{13}C$ chemostratigraphy.
3. Application of $\delta^{13}C$ chemostratigraphy considerably improves the stratigraphic resolution within the Kozel Limestone Member and enables more precise dating of its highly diverse fauna. The present data reveal that the recovery of benthic communities after the series of mid-Homerian extinction events (*i.e.*, the Mulde conodont and the *lundgreni* graptolite bioevents) started much earlier than has been hitherto described from other world occurrences.

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Appendix

On-going systematic study of Homerian (late Wenlock) carbonate sequences in the Central Segment of the Prague Basin (*sensu* Kříž 1992) reveals a chaos in usage of their informal lithostratigraphic names. To prevent future misunderstandings we establish here a new formal lithostratigraphic name (Kozel Limestone Member) for the limestone sequence studied in present paper.

Kozel Limestone Member (new member)

(*vápence Kozla* in Czech lithostratigraphic nomenclature)

Etymology. – According to geographic name "*Kozel*" or "*V Kozle*", which has been used for natural rock outcrops formed by newly established stratigraphic unit at its type area.

Previous informal names. – Limestone unit involved here into a new lithostratigraphic unit (Kozel Limestone Member) has been intensively studied by geologists and paleontologists since the first half of the nineteenth century, but no formal lithostratigraphic name was hitherto established for it. However several informal names were used for it during last two centuries: "*Rochers de Kozel*" or "*Kozel*" (Barrande 1852–1881, Perner 1903–1911), "V Kozle" (Želízko 1904), "*útesová facie*" (Perner & Kodym 1919), "*korálové vápence*" (Kodym *et al.* 1931), "*kalkige Fazies*" (Bouček 1934), "*kopaninské vápence*" (Svoboda & Prantl 1953), "*lištické facie*" (Horný 1954), "*lištické vápence*" (Horný 1954, but not Horný 1955, and Kříž 1987), "*organodetritické dolomitické vápence komplexu 'Kozla'*" (Horný 1955a), "*organodetritické tufitické dolomitické vápence, facie 'Kozla'*" (Horný 1965), "*vápence facie 'Kozla'*"(Horný 1965, Štorch 1987), "*karbonátový komplex 'Kozla'*" (Horný 1971), "*'Kozel' Limestone Complex*" (Kříž *et al*. 1993, Kříž 1998).

Definition. – Mostly crinoidal, and locally tuffaceous and dolomitic limestone unit occurring in the Central Segment of the Prague Basin and forming the upper part of the Motol Formation above the *C. lundgreni* graptolite Biozone. Newly established Kozel Limestone Member belongs to the Motol Formation *sensu* Kříž (1975).

Stratotype and parastratotype. – Section No. 760 described in detail by Kříž *et al*. (1993) on the left (north) bank of the Berounka River, about 1 km south of the village of Lištice near Beroun is selected here as stratotype of the Kozel Limestone Member. The latter section is one of two complete and uncovered sections (*i.e.*, section No. 760 and "Kozel Syncline" section situated about 1.5 km E of section No. 760, and 600 m W of estuary of the Kačák brook) across whole thickness of the Kozel Limestone Member. Lithology of some levels of "Kozel Syncline" section differs from the stratotype section (see below) and for this reason the "Kozel Syncline" section is established here as a parastratotype of the Kozel Limestone Member. The both sections (stratotype and parastratotype) are situated on the left (north) bank of the Berounka River and this area is the type area for the Kozel Limestone Member.

Lithology. – Lithologic properties of the Kozel Limestone Member were strongly influenced by its shallow water origin as well as volcanic activity of neighbouring Svatý Jan Volcano. Crinoidal-coral-brachiopod-bryozoan grainstones, rudstones and packstones containing variable amount of tuffitic and/or dolomitic component represent the most frequent lithotypes of the Kozel Limestone Member. Alternation of these lithotypes latterally as well as vertically is rather quick, often at distances of few meters. The Kozel Limestone Member involves locally also several tuffitic and dolomitic layers which are developed laterally for several hundreds meters, but not across the whole geographic distribution of the Kozel Limestone Member. There is a distinct increasing trend in amount of tuffitic material occuring in limestone sequence from southeast (parastratotype) to northwest (stratotype) but opposite trend in occurrence of dolomite as was already noted by Horný (1955c).

Geographic distribution. – The Kozel Limestone Member is restricted to the Central Segment of the Prague Basin and reaches maximal thickness about 60 m at its south limit close to the Tobolka Fault (Horný 1965, Kříž 1992). Northwards its thickness decreases and its occurrences could be traced for several kilometers along the Tachlovice Fault up to the village of Vysoký Újezd (about 5 km SW of Prague). Total tickness of the Kozel Limestone Member about 3 km N of its type area (sections at village of Svatý Jan pod Skalou) reached several tens meters (Štorch 1987 and 2014 pers. comm.). Details on individual occurrences of the Kozel Limestone Member (but under different informal names mentioned above) could be found in Svoboda & Prantl (1953), Horný (1954, 1955a–c, 1960, 1965, 1971), Kříž (1984, 1998), Kříž *et al*. (1993), and Štorch (1987).

Fauna. – The high diverse fauna of the Kozel Limestone Member consists mostly of crinoids, corals, stromatoporoids, brachiopods, bryozoans, gastropods and trilobites (for details see Barrande 1852–1881; Želízko 1904; Perner 1903–1911; Kodym *et al.* 1931; Bouček 1934; Havlíček *et al.* 1958; Horný 1955a–c, 1962, 1965, 1971; Havlíček & Štorch 1990, 1999; Kříž 1991, 1992, 1998; Kříž *et al.* 1993; Havlíček 1995, and references herein).

Age. – Middle and upper part of the Homerian and probably the lowermost Gorstian (see discussion above).

Relation to lithostratigraphic units. – The Kozel Limestone Member could be easily distinguished from adjacent rocks of the Motol Formation. In its type area the Kozel Limestone Member is underlain by an interval, more than 20 m thick, formed by volcaniclastic rocks. The youngest strata of the Kozel Limestone Member are overlain by volcaniclastic and volcanic rocks having a total thickness of several hundreds meters. Laterally the Kozel Limestone Member is passing into calcareous and tuffitic shales (see detailed discussion in Svoboda & Prantl 1953; Horný 1955a–c, 1965, 1971; Kříž 1984, 1992, 1998; Kříž *et al.* 1993; Štorch 1987).

Relation to biostratigraphic units. – As mentioned above precise biostratigraphic dating of the Kozel Limestone Member is difficult because of a lack of biostratigraphically significant fossils (see above). Available data suggests that its age is younger than the *C. lundgreni* graptolite Biozone. Upper limit of the Kozel Limestone Member is difficult to infer from biostratigraphic data, again because of a lack of stratigraphically significant fossil. However its age inferred from chemostratigraphic data suggests that the Kozel Limestone Member corresponds to an interval from the *P. parvus–G. nassa* Biozone to the lowermost Gorstian (see discusion above).

Relation to chemostratigraphic units. – The Kozel Limestone Member corresponds roughly to the two-peaked Homerian $\delta^{13}C$ excursion and involves all four chemostratigraphic zones of the Homerian carbon isotope excursion (*i.e.*, R1-, F1-, R2- and F2-zones established above) and a short interval above the F2-Zone (see discussion in present paper).