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CONODONT BIOSTRATIGRAPHY AND LITHOSTRATIGRAPHY ACROSS THE PERMIAN-TRIASSIC BOUNDARY AT THE LUKAČ SECTION IN WESTERN SLOVENIA

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Abstract. Detailed conodont biostratigraphy and lithostratigraphy of the Late Permian and Early Triassic beds were studied at the Lukač section in western Slovenia. The analyzed section is composed of the Bellerophon Formation ("bellerophon limestone member" and "evaporite-dolomite member") and the newly introduced Lukač Formation ("transitional beds", "streaky limestone member" and "carbonate-clastic beds member"). The Permian-Triassic boundary interval is represented by "transitional beds" of carbonate facies deposited in shallow restricted marine conditions. The presence of *Hindeodus parvus* in sample L1 in the "transitional beds" marks the systemic boundary between Permian and Triassic. The studied interval is characterized by a diverse microfauna that contains conodonts, foraminifers, ostracods and gastropods. Six conodont zones have been recognized, in ascending order, the latest Changhsingian (uppermost Permian) *praeparvus* Zone, and the Griesbachian (lowermost Triassic) *parvus, lobata, staeschei-isarcica, postparvus* and *anceps* zones. This faunal succession represents the first known and the most complete conodont biozonation across the Permian-Triassic interval from the entire Dinaric region. The recognized conodont biozones can be correlated with the biozonation of the Southern Alps and of the GSSP Meishan D section.

Riassunto. La sezione di Lukač in Slovenia occidentale è stata studiata in dettaglio nella parte del Permiano terminale e del Triassico basale, sia dal punto di vista litostratigrafico che dal quello biostratigrafico a conodonti. La successione analizzata comprende la Formazione a Bellerophon, con I membri dei "bellerophon limestone" ed "evaporite-dolomite" e la Formazione Lukač di nuova introduzione (che comprende i membri "transitional beds", "streaky limestone" e "carbonate-clastic beds"). L'intervallo in corrispondenza del limite Permiano-Triassico è rappresentato dai "transitional beds" presenti con una facies carbonatica deposta in ambienti di acque basse confinate. La presenza di *Hindeodus parvus* nel campione L1 entro i "transitional beds" indica il limite tra i sistemi Permiano e Triassico. L'intervallo studiato è caratterizzato da una microfauna diversificata che comprende conodonti, foraminiferi, ostracodi e gasteropodi. Vengono riconosciute sei zone a conodonti. In ordine ascendente esse sono la Zona a *praeparvus* del Changhsingiano superiore (Permiano sommitale), e le zone del Griesbachiano (Triassico basale) *parvus, lobata, staeschei-isarcica, postparvus* e *anceps.* Questa successione faunistica rappresenta la zonazione a conodonti più completa attraverso l'intervallo del limite Permiano-Triassico per l' intera regione Dinarica. Le biozone a conodonti riconosciute possono essere correlate con le biozonazioni definite nelle Alpi Meridionali e nella sezione di Meishan D, GSSP della base del Triassico.

Introduction

The stratigraphy of Permian-Triassic Boundary beds has been intensively studied in many parts of the world for many years after the establishment of the Permian-Triassic Working Group (PTWG) in 1981. Stratigraphically, the most important conodont species across the PTB belong to the genera *Hindeodus* and *Isarcicella*. The Global Stratotype Section and Point (GSSP) of the PTB were ratified by IUGS in 2001 (Yin et al. 2001). The first appearance datum (FAD) of the species *Hindeodus parvus* (Kozur & Pjatakova) in bed 27c of the Meishan D section in South China marks the base of the Triassic System. The approved proposal clearly separates the event stratigraphic and biostratigraphic boundaries and is of key importance, not only for defining the GSSP of the basal Triassic boundary, but also to study the P/T mass extinction and recovery (Wang 1999). *Hindeodus parvus* is an easily recognizable species with wide geographic distribution and it is

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the first globally distributed species that appears just above the minimum faunal diversity indicated by a minimum in $\delta^{13}C$ and has no facies restriction (Kozur 1996; Kozur et al. 1996).

During the last few decades, conodont study of the P-T interval has been intensified in the Dinarides. Early Triassic (Olenekian) conodont faunas have been identified in many sections (Serbia: Pantić 1971; Budurov & Pantić 1973, 1974; Urošević & Sudar 1980; Sudar 1986; Bosnia: Aljinović et al. 2006a, Aljinović et al. 2011; Hrvatović et al. 2006; Croatia: Herak et al. 1983; Jelaska et al. 2003; Slovenia: Kolar-Jurkovšek 1990; Kolar-Jurkovšek & Jurkovšek 1995, 1996, 2001).

The presence of hindeodids and isarcicellids in the Dinarides was documented just recently. In the Outer Dinarides of Croatia, *H. parvus* was reported from the Školski Brijeg section of the Gorski Kotar region (Aljinović et al. 2006b). Additional data are based on the recovery of *Isarcicella* in the Plavno section of the Knin area (Aljinović et al. 2011). The two faunas are assigned to the Griesbachian *parvus-isarcicella* and *isarcica* zones.

Elements of *Hindeodus typicalis* belonging to the Lower *praeparvus* Zone (Changhsingian) were collected in the Komirić section in the Jadar Block of Vardar Zone in NW Serbia (Sudar et al. 2007).

Conodonts from the Permian-Triassic interval of Slovenia were first reported by Kolar-Jurkovšek & Jurkovšek (2007) who documented rich *Hindeodus-Isarcicella* associations. Based on the identified taxa *H. parvus, H. typicalis, Hindeodus* sp.*, I. turgida, I. lobata, I. staeschei, I. isarcica, Isarcicella* sp. A at least three Lower Triassic faunas can be recognized.

Biostratigraphic studies across the Permian-Triassic Boundary (PTB) of the Lukač section (46° 03′ 46″N, 14° 03′ 52″ E) in the Žiri area continued in the period 2008-2010. The section is located in the north-western part of the External Dinarides (Fig. 1). In a paleogeographic sense, Upper Paleozoic and Lower Triassic beds of this region were formed on an extensive Slovenian Carbonate Platform that became established during the Late Permian, and remained stable until late Anisian time (Buser et al. 2007, 2008). The Bellerophon Formation is an Upper Permian carbonate, known also as the "Žažar Formation" in Slovenia, here composed of the "bellerophon limestone member" and "evaporite-dolomite member". The Lower Triassic Lukač Formation, equivalent to the Werfen Formation of the Southern Alps, follows and consists of the "transitional beds" including the P/T boundary, the "streaky limestone member" and the "carbonate-clastic beds member".

Because of its conodont content recently reported by Kolar-Jurkovšek & Jurkovšek (2007), the Lukač section is an important section for the Permian-Triassic Boundary in Slovenia. Traditionally, the PTB in the Žiri area was defined lithologicaly within the dolostone resting above the limestone of the Bellerophon Formation (Grad & Ogorelec 1980; Mlakar & Placer 2000). The occurrence of *Hindeodus parvus* allows the identification of the Triassic base (Yin 1993, 1996; Paull & Paull 1994; Henderson & Baud 1996; Yin et al. 2001, 2005). In the Masore section west from Žiri, Buser (1986) assigned a lowermost Triassic age to the laminated limestone based on the foraminifers *Earlandia tintinniformis* and the annelid *Spirorbis phlyctaena.*

A study of foraminifer faunas from the Lukač section was therefore also undertaken and four new species have been introduced: *Multidiscus zhiriensis*, *M. compressiusculus* and *Globivalvulina lukachiensis* from the Upper Permian, and *Lingulonodosaria slovenica* from the lowermost Triassic (Nestell et al. in press). The species "*Cyclogyra*" *mahajeri*, "*Earlandia*" *gracilis*, and "*E.*" *tintinniformis*, were found in the "transitional beds" below the first occurrence of the conodont species *Hindeodus parvus*. Thus, these foraminifer taxa appear to be ecological species and their appearance coincides with a stressful shallow water environment. There is an interval devoid of foraminifers above the systemic boundary. The first nodosariid foraminifers appear in two intervals, approximately 2 m and 5 m above the boundary. Both intervals with nodosariids are confined to the last occurrences of *Hindeodus parvus* within the *Isarcicella staeschei-isarcica* conodont Zone (Nestell et al. in press).

This paper presents the results of a micropaleontological study focused on conodonts. Plates 1-7 document the conodont faunas of the Lukač section including some elements in open nomenclature. The recovery of rich and diversified *Hindeodus-Isarcicella* faunas in the Lukač section of western Slovenia enables resolution of a very fine biostratigraphy of the P-T interval beds. The herein defined conodont zones represent the first conodont biozonation of the Permian-Triassic interval in the entire Dinaric region. The recognized conodont faunas of the studied section in Slovenia are important also for high resolution correlation with equivalent age strata in other areas.

Materials and methods

The present study is based on conodont collections from the Lukač section. The first sampling in 2006 focused on the PTB interval only (Kolar-Jurkovšek & Jurkovšek 2007). In the next two years additional collecting of the Permian-Triassic interval was carried out. Later, samples were also taken of interesting carbonate sequences of the higher levels of the Lukač Formation, as well as the Bellerophon Formation.

Altogether 124 carbonate samples were collected from the Bellerophon and Lukač Formations and 53 of them produced conodonts. The carbonate samples were collected with a minimum weight of 2.5 kg, except those from the "transitional beds" that averaged between 4 to 5 kg. A standard technique to recover conodonts was applied with

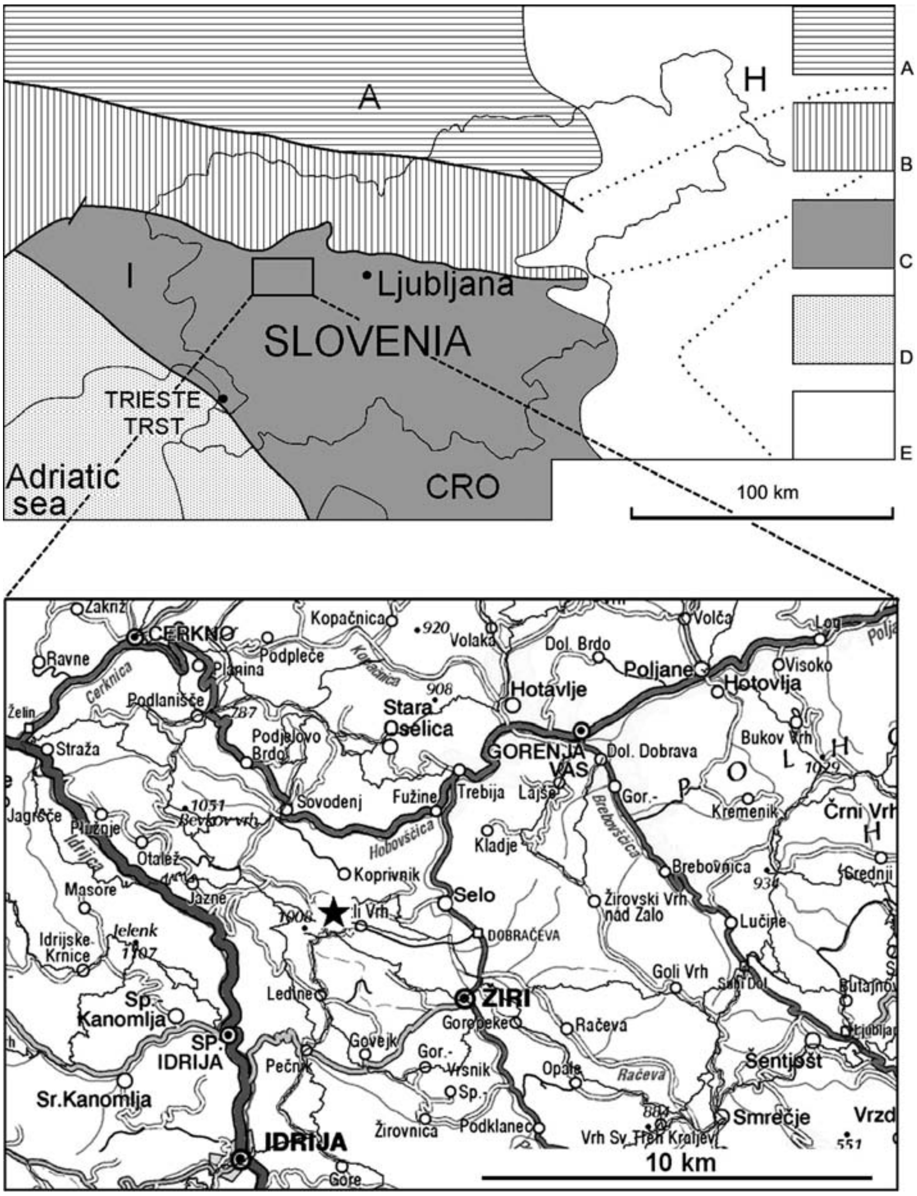

Fig. 1 - Geographic position of the Lukač section (star) and the map of geotectonic units in Slovenia: A- Eastern Alps, B - Southern Alps, C - External Dinarides, D - Adriatic-Apulia foreland, E - Pannonian basin (modified after Placer 1999).

use of acetic acid followed by heavy liquid separation. The sampled horizons are shown in Figs. 2, 3. The productive samples with conodont distribution and abundance are shown in Fig. 4. Indentified conodont elements are assigned to 15 species of 3 genera.

The illustrated conodont elements presented herein were photographed at the JEOL JSM 6490LV Scanning Electron Microscope at the Geological Survey of Slovenia. All recovered material described herein is housed at the Geological Survey of Slovenia / Geološki zavod Slovenije with repository numbers 3791-3808, 3822-3837, 3840-3852, 3862-3870, 3945-4027, 4106-4116, 4119-4126, 4133, 4136-4148, 4713-47615 and abbreviated GeoZS.

Lithology

The Permian part of the section consists of the **"bellerophon limestone member"** at the base of the section overlain by the **"evaporite-dolomite member"** (Upper Permian). Evaporites transitionally change to 3.3 m thick sequence of **"transitional beds"** that are concordantly overlain by a ca 30 m thick alternation of dark grey and light grey thin-bedded rocks named the **"streaky limestone"** sensu Mlakar (2002). The "streaky limestone member" gradually passes upward to the medium or thick-bedded red **"carbonate-clastic member"**. The latter two members belong to the herein introduced Lukač Formation (Fig. 2).

The **"bellerophon limestone member"** is represented by black nodular or faintly bedded limestone that predominantly consists of arenite- or rudite size fossil detritus and a micritic matrix. The fossil association found in the "bellerophon limestone member" suggests reefal origin of the detritus. The predominantly micritic microfacies implies deposition under low energy conditions (backreef-lagoonal).

Well bedded, intensively recrystallized biomicrite occurs at the top of the "bellerophon limestone member". These strata pass continuously to the ca 30 m thick **"evaporite-dolomite member"** and are represented by planar, 0.5-3 m thick dolomite beds with dissolved cm-sized molds of primary evaporitic minerals typical of

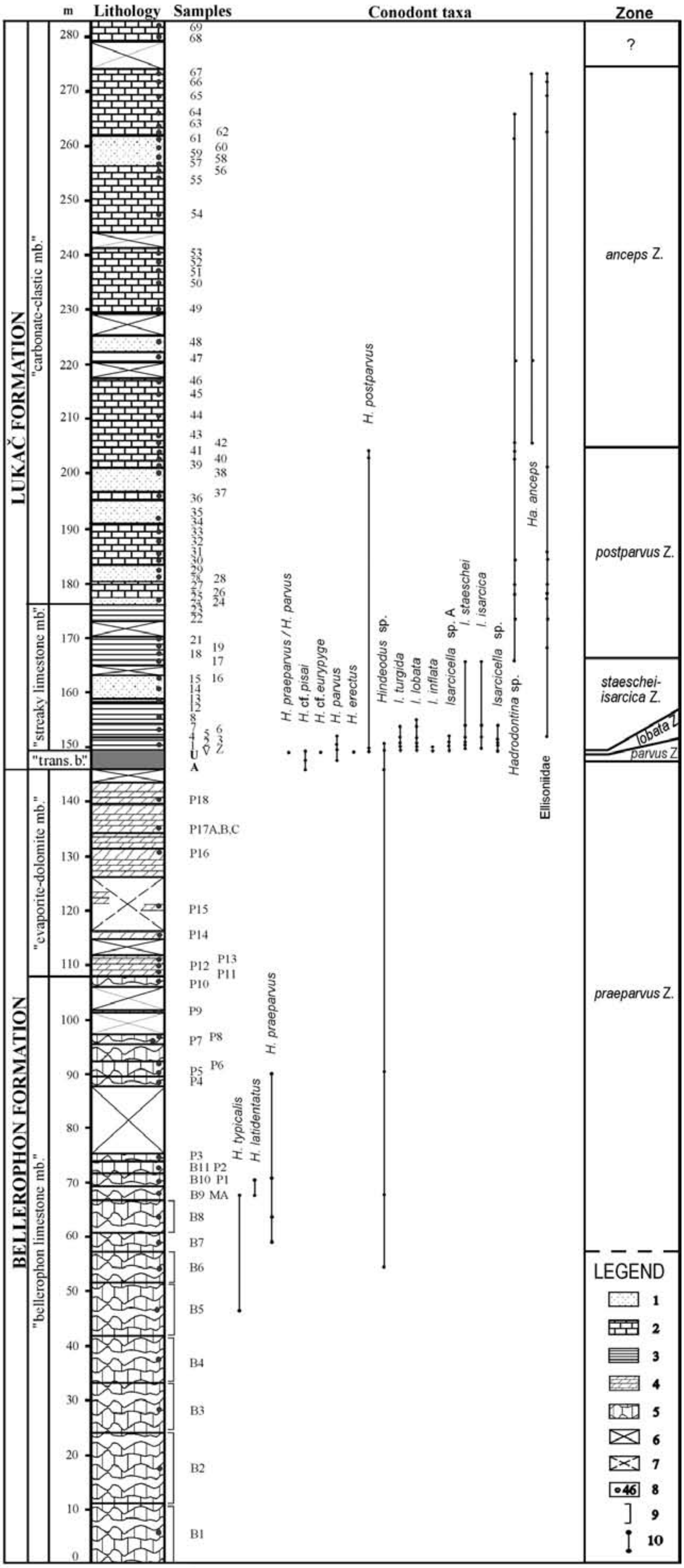

Fig. 2 - Geological column of the Upper Permian and Lower Triassic sediments of the Lukač section in western Slovenia. 1- calcareous siltstone, 2- limestone (oolitic grainstone and laminated silty micrite/biomicrite), 3- thin-bedded streaky limestone, 4- evaporitic dolomite (partly rauchwacke type deposits), 5- black nodular Bellerophnon limestone, 6- covered interval, 7- partly covered interval, 8- position of sample, 9- composite sample for conodont analysis, 9- range of conodont taxa.

rauchwacke-type deposits. The characteristics of the "evaporite-dolomite member" deposits suggest deposition under hypersaline conditions. Evaporite minerals have been removed by dissolution, possibly under supratidal conditions.

Evaporite-type dolomite concordantly passes to the **"transitional beds"** which consist of light yellow to red coloured carbonate beds that vary in thickness from 0.03 to 0.62 m. The 3.3 m thick transitional interval (Fig. 3) consists of *laminated mudstone, laminated micritic/biomicritic limestone* and plane parallel or trough ripple cross-laminated *grainstone*. The *laminated mudstone* consists dominantly of lime micritic laminae that alternate with laminae composed of mixed lime mud, and clay with a 5-7% siliciclastic coarse-silt component. The *laminated micritic/biomicritic limestone* consists of micritic laminae that alternate with bioclastic laminae (very often containing ostracods). Some lamina contains a rather high amount of siliciclastic detritus. The *grainstone* consists of ooid and bioclastic (ostracod) detritus and sparry calcitic cement.

Grey or pail-red *dolomite* and less *dedolomite* occurs also in the "transitional beds" with homogenous micro- to macrocrystalline structure and occasionally preserved ooid ghosts.

The "transitional beds" were deposited in shallow marine conditions. The presence of micrite rich microfacies types imply more restricted conditions with the predominance of suspending settling of fines. Trough and ripple cross-lamination found in the grainstone imply migration of ooid detritus due to oscillatory and/or tidal currents.

The "transitional beds" are conformably overlain by the approximately 30 m thick **"streaky limestone member"** of the Lukač Formation (samples from V through 25). This unit consists of very thin bedded light and dark grey bed couplets. The beds are irregular planar, hummocky and wavy shaped. Dark coloured interbeds consist of calcareous bioclastic material with minor siliciclastic component. Bioclastic detritus consists of silicified ostracods and rarely recrystallized ooids. Dark coloured interbeds consist predominantly of siliciclastic-clayey material reworked by organisms. Within the thin-bedded streaky alternation some 0.3 m thick recrystallized ooid rich deposits occasionally occur. A wavy and hummocky structure observed in the streaky limestone suggests deposition in a shallow subtidal environment and deposition by oscillatory and/or storm currents. Irregularly shaped beds were formed due to intensive bioturbation.

In the upper part of the section to its very end there is the approximately 80 m thick **"carbonate-clastic member"** of the Lukač Formation that consists of: a) *ooid-grainstone*, b) *laminated silty micrite/biomicrite* and of c) *calcareous siltstone* (Fig. 2). Rarely ooid rich *biocalcarenite* occurs. In the uppermost 30 m of the succession the ooid grainstone beds decrease and lime mudstone occurs more often. The lime mudstone has a nodular appearance.

Wave ripple cross-lamination was found in the ooid grainstone as well as in the calcareous siltstone. Plane parallel lamination can be seen only in the calcareous siltstone. Reworking by organisms is often present and can be seen as mottling of the siliciclastic and carbonate material.

Deposition of the calcareous siltstone implies intensive terrigenous input in a very shallow depositional environment. The ripple cross-lamination found in the ooid grainstone as well as in the laminated siltstone exhibits characteristics of oscillatory currents related to waves. Plane parallel lamination can be seen only in the calcareous siltstone and is probably due to suspension settling.

Conodont biostratigraphy and correlation

Conodont biozonation

The collected conodont material from the Lukač section is marked by the prevailing elements of the genera *Hindeodus* and *Isarcicella* that are present in the higher part of the section accompanied by representatives of the genus *Hadrodontina.* The absence of gondolellids is evident. The conodont stratigraphy of the Lukač section is based on *Hindeodus-Isarcicella* population, except in the youngest recognized zone. The conodont faunas were recovered from both formations developed in the section, the Bellerophon and the Lukač Formations.

Remarks on identified conodont elements. There are different opinions about the taxonomy of the *Hindeodus-Isarcicella* stock. In the preparation of this work we took into consideration results from the Dolomites in Italy published by Perri & Farabegoli (2003) and they seem to be most relevant to our study. The continuous sections of the P-T interval in the Dolomites produced prolific conodont faunas that enabled the establishment of a fine conodont biozonation. It should be mentioned here that our study area and the Italian sections in the Dolomites are actually geographically close. The obtained faunas thus shared the same or similar environmental conditions as documented readily by the striking absence of pelagic elements such as gondolellids. In contrast, the well known faunas from Oman, Iran, Himalayas and China are characterized by co-occurrence of shallow-water elements and pelagic forms (Kozur 1996; Wang 1999; Orchard & Krystyn 1998; Yin et al. 2001; Krystyn et al. 2003; Korte et al. 2004; Jiang et al. 2007).

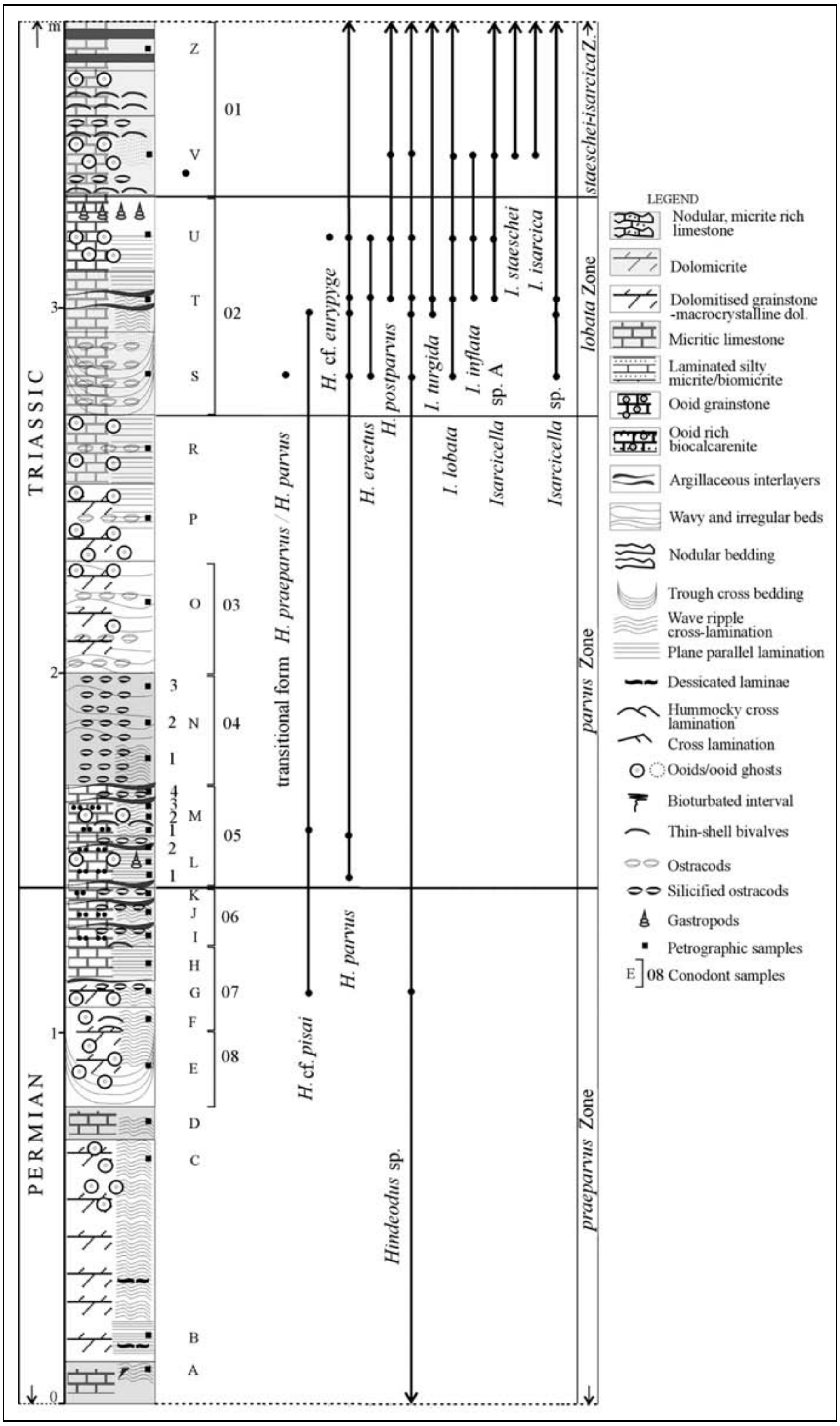

Fig. 3 - Geological column of the Permian-Triassic interval beds in the Lukač section.

In discriminating the elements of the *Hindeodus-Isarcicella* stock, the concept of Perri & Farabegoli (2003) was applied, who defined the genus *Isarcicella* for Pa elements as having a wide and inflated cup bearing lateral ornamentation (nodes, denticles) and extending this interpretation also for elements with an asymmetrical and swollen cup, but with a smooth surface. In contrast, Nicoll and co-workers (2002) assigned inflated elements without lateral denticles on the cup to *Hindeodus.* These forms indeed are perfectly transitional between *Hindeodus* and *Isarcicella*. Therefore, the generic affiliation of some species such as *turgida*, *lobata and inflata* is retained and they are assigned to *Isarcicella* in this paper.

There are slight differences in distinguishing forms with an inflated cup and smooth surface, such as in *I. lobata* and *I. inflata.* The two species mainly differ in the degree of the expanded cup and they can be differentiated based on a different length/width ratio. *I. inflata* is characterized by an extremely swollen asymmetrical cup, whose both sides are very much expanded. *I. lobata* is distinguished for a less swollen cup presenting a bulge forming a lobe in the more expanded side. The other side of the cup is reduced. *I. lobata* and *I. inflata* have nearly the same range, but are not synchronous in their first appearance datum (FAD). The morphological similarity between *Hindeodus inflatus* and *Isarcicella inflata* was pointed out by Chen and co-workers (2009).

Six conodont zones have been recognized throughout the entire section, in ascending order, the latest Changhsingian (latest Permian) *praeparvus* Zone, and the Griesbachian (earliest Triassic) *parvus, lobata, staeschei-isarcica, postparvus* and *anceps* zones.

The conodont fauna collected in the lowermost part of the section (samples from B1 through B6) is very poor. Only two samples produced very small faunule consisting of *Hindeodus typicalis* (sample B5), and *Hindeodus* sp. accompanied with a few ramiform elements (sample B6). This part of the section belongs to an unnamed conodont zone.

Hindeodus praeparvus Zone

Lower limit: first appearance datum of *Hindeodus praeparvus* Kozur, 1996.

Upper limit: first appearance datum of *Hindeodus parvus* (Kozur & Pjatakova, 1976).

Associated taxa: *Hindeodus typicalis, H. latidentatus, Hindeodus* sp., and *H.* cf. *pisai* in the uppermost part.

In the studied section the name-bearing taxon first appears in sample B7 and is present through sample P5 in the "bellerophon limestone member" of the Bellerophon Formation. Due to unfavorable lithology the uppermost portion of Permian strata ("evaporite-dolomite member") was sampled only in a 3 m interval above sample P17 (P17A,B,C) that was barren of any microfauna. According to comparable data from the Southern Alps, *H. praeparvus* ranges into the following conodont zone, the *H. parvus* Zone.

Range: from samples B7 ("bellerophon limestone member" of the Bellerophon Formation) through L (05) ("transitional beds" of the Lukač Formation).

Hindeodus parvus Zone

Lower limit: first appearance datum of *Hindeodus parvus* (Kozur & Pjatakova, 1976).

Upper limit: first appearance datum of *Isarcicella lobata* Perri & Farabegoli, 2003.

	B5	B6	B7	B8	B10	MA	P5	07	05	L1	M1	02-01	02	S	T	U	V	1A	1B	2	3	4	7
Hindeodus typicalis	1					1																	
Hindeodus latidentatus					1	1																	
Hindeodus praeparvus			1	3	2		6																
Hindeodus praeparvus/H. parvus														1									
Hindeodus cf. *pisai*								1			2		1										
Hindeodus cf. *eurypyge*																1							
Hindeodus parvus									1	1			1	6	2	6		1				1	
Hindeodus erectus														1	4	13							
Hindeodus postparvus															12	26	3						
Hindeodus sp.		1				3	2	1					2	3	9	31	3	2					
Isarcicella turgida															3			2		2		2	1
Isarcicella lobata														2	5	10	3			1	1		2
Isarcicella inflata															1	4	4						
Isarcicella sp. A															1	3	2			1		2	
Isarcicella staeschei																	6	4		4		6	8
Isarcicella isarcica																	4					2	4
Isarcicella sp.												1		1	3			4		1		2	4
Hadrodontina anceps																							
Hadrodontina sp.																							
Ellisoniidae																						12	
Ramiform elements		1	2				2					3	2	3	10	18		1	1			10	5

	8	13	17	18	19	22	25	26	27	30	31	32	33	39	40	41	42	43	44	47	50	52	60	61	62	63	64	65	66	67
Hindeodus typicalis																														
Hindeodus latidentatus																														
Hindeodus praeparvus																														
Hindeodus praeparvus/H. parvus																														
Hindeodus cf. *pisai*																														
Hindeodus cf. *eurypyge*																														
Hindeodus parvus																														
Hindeodus erectus																														
Hindeodus postparvus															1	1														
Hindeodus sp.																														
Isarcicella turgida																														
Isarcicella lobata	1																													
Isarcicella inflata																														
Isarcicella sp. A																														
Isarcicella staeschei			1																											
Isarcicella isarcica			4																											
Isarcicella sp.																														
Hadrodontina anceps																	4			2										3
Hadrodontina sp.			7			2		2	2	5					3	1	4			1				3			2			
Ellisoniidae					2	4	1	5	3	7	5			2											5			1	3	3
Ramiform elements	2	1	6	2		1		2	1			1	1		1			4	8	5	7	6	5	9		2	5		10	8

Fig. 4 - Conodont distribution in samples from the studied Lukač section, Slovenia.

Associated taxa: *Hindeodus* cf. *pisai, Hindeodus* sp.

H. parvus first occurs in sample L1 ("transitional beds" of the Lukač Formation), and it is present throughout the following conodont zone, *Isarcicella lobata* Zone and its last occurrence is recorded in the *Isarcicella staeschei-isarcica* Zone (sample 4 – "streaky limestone member" of the Lukač Formation). This conodont zone is characterized by poverty of the fauna and is marked by the presence of rare specimens here assigned to *H.* cf. *pisai*.

Range: from samples L1 through R in the "transitional beds" of the Lukač Formation.

Isarcicella lobata Zone

Lower limit: first appearance datum of *Isarcicella lobata* Perri & Farabegoli, 2003.

Upper limit: first appearance datum of *Isarcicella staeschei* Dai & Zhang, 1989 and *I. isarcica* (Huckriede, 1958).

Associated taxa: transitional form *H. praeparvus/H. parvus*, *H.* cf. *pisai, H.* cf. *eurypyge, H. parvus, H. erectus, H. postparvus, Hindeodus* sp., *I. turgida, I. lobata, I. inflata, Isarcicella* sp. A, and *Isarcicella* sp.

I. lobata first occurs in sample S ("transitional beds" of the Lukač Formation). This zone is marked by the entry of several new taxa and it represents a recovery event. One taxon, *H. erectus* has its range (FOD and LOD) within this zone (from samples S through U), whereas four other taxa have their entry, being in this zone: the FOD of *H. postparvus, I. turgida, I. inflata* and *Isarcicella* sp. A (sample T). *Hindeodus* cf. *eurypyge* appears only in this zone (sample U).

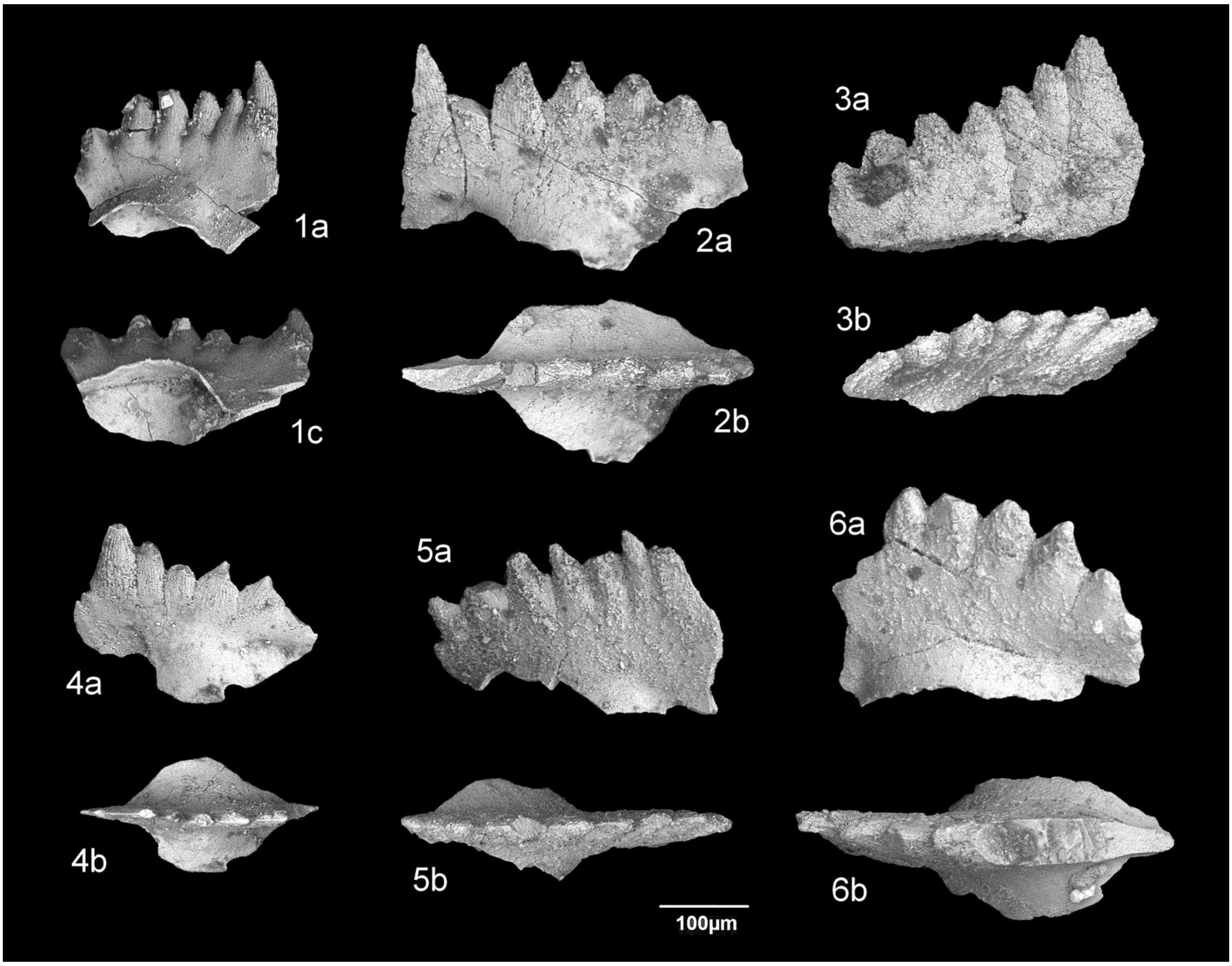

PLATE 1

All specimens are from the Lukač section, Bellerophon Formation, "bellerophon limestone member", uppermost Permian, *praeparvus* Zone. a – lateral view, b – upper view, c – oblique lower view.

Fig. 1 - *Hindeodus latidentatus* (Kozur, Mostler & Rahimi-Yazd), sample MA (GeoZS 3945);
Fig. 2 - *Hindeodus* sp., sample MA (GeoZS 3945);
Figs 3-6 - *Hindeodus praeparvus* Kozur; 3, 5, 6 - sample P5 (GeoZS 4019); 4 - sample B8 (GeoZS 4113).

Range: samples S, T, U in the "transitional beds" of the Lukač Formation.

Isarcicella staeschei-isarcica Zone

Lower limit: first occurrence datum of *Isarcicella staeschei* Dai & Zhang, 1989 and *I. isarcica* (Huckriede, 1958).

Upper limit: last occurrence datum of *Isarcicella staeschei* Dai & Zhang, 1989 and *I. isarcica* (Huckriede, 1958) and the first appearance of *Hadrodontina* sp. *(H.* ex gr. *aequabilis).*

Associated taxa: *H. parvus, H. postparvus, Hindeodus* sp., *I. turgida, I. lobata, I. inflata, Isarcicella* sp. A, and *Isarcicella* sp.

This zone is marked by the co-occurrence of *I. staeschei* and *I. isarcica*. Six taxa that appeared in the previous zone continue with their range into this zone. They are *H. postparvus, I. turgida, I. lobata, I. inflata, Isarcicella* sp. A and *Isarcicella* sp. All associated taxa have the LOD within this zone, except *H. postparvus*. Thus, the fauna of this zone is still part of the recovery event. Robust *Hadrodontina* elements are fragmented and some of them can be identified only as *Hadrodontina* ex gr. *aequabilis* due to their preservation. They first entry at the zone top (sample 17) where both *I. staeschei* and *I. isarcica* last occur.

Range: from samples V through 17 in the "streaky limestone member" of the Lukač section.

Hindeodus postparvus Zone

Lower limit: first occurrence datum of *Hindeodus postparvus* Kozur, 1989 without the presence of *I. isarcica* (Huckriede, 1958) and *I. staeschei* Dai & Zhang, 1989.

Upper limit: last occurrence datum of *Hindeodus postparvus* Kozur, 1989.

Associated taxa: *Hadrodontina* sp., Ellisoniidae.

This conodont zone is marked by the last stratigraphic range of *H. postparvus* (without the presence of *I. isarcica* and *I. staeschei)* with the association of ellisoniids.

Range: from samples 18 ("streaky limestone member") through 41 ("carbonate-clastic member") of the Lukač section.

Hadrodontina anceps Zone

Lower limit: last occurrence datum of *Hindeodus postparvus* Kozur, 1989.

Upper limit: first occurrence datum of *Hadrodontina anceps* Huckriede, 1958.

Associated taxa: *Hadrodontina* sp., Ellisoniidae.

Range: from samples 42 through 67 of the "carbonate-clastic member" of the Lukač Formation.

The samples of the uppermost part of the Lukač section in the "carbonate-clastic member" (samples 68-70) were devoid of conodonts.

Comparison of conodont faunas

A comparison of Late Permian-Early Triassic conodont faunas with most important sections in the adjacent areas including Croatia, Serbia, Italy, Austria, Hungary, as well as the Meishan section in South China, is presented and illustrated in Fig. 5.

Croatia

Very rare specimens of the *Hindeodus-Isarcicella* stock have been collected in the lowermost Triassic of Croatia. The genus *Hindeodus (H. parvus, Hindeodus* sp.) was reported from the lower part of the basal, dolomitized, oolitic bar facies F-1 in the Školski Brijeg section of the Gorski Kotar region (Aljinović et al. 2006b). The genus *Isarcicella (I. staeschei, I. isarcica)* was documented in dolomite at the base of the Plavno section in the Knin area (Aljinović et al. 2011). The two Griesbachian faunas were attributed to the *parvus-isarcicella* and *Isarcicella isarcica* zones. Sedimentary facies of the Gorski Kotar region show characteristics of a shallow marine, storm influenced shelf (Aljinović et al. 2006b).

Serbia

The Komirić section in the Jadar Block (Vardar Zone, External Dinarides) is characterized by the wide distribution of Permian and Triassic deposits that have been intensively studied micropaleontologically and sedimentologically (Sudar et al. 2007; Nestell et al. 2009; Crasquin et al. 2010). The shallow water marine carbonates are composed of the Upper Permian "Bituminous Limestone" and of the Lower Triassic Svileuva Formation. A diversified microfauna composed of conodonts, ostracods and foraminifers was collected from the "Bituminous Limestone". The recovered conodont fauna is represented by: *Ellisonia* sp., *H. praeparvus*, *H. typicalis*, *H.* cf. *H. latidentatus*, *Hindeodus* sp., and it is attributed to the Lower *praeparvus* Zone (Changhsingian, latest Permian). A correlation of upper Permian levels of the Komirić and Meishan D section can be done based on the FAD of *H. praeparvus* in the Komirić section, because the first appearance of *H. praeparvus* is recorded in sample MS 1203/2, and in bed 24c in the Meishan section, respectively (Yin et al. 2001).

Italy

The Tesero and Bulla sections (Dolomites, Italy) are important for definition of the Permian-Triassic boundary in the western Tethys due to finding of conodonts and a high precision biostratigraphy that allowed the P-T boundary location within the lowermost Werfen Formation (Farabegoli & Perri 1998; Nicora et al. 1999; Perri & Farabegoli 2003; Farabegoli et al. 2007). The sections are characterized by a medium to high rate of shallow marine sedimentation 5-10 cm ky^{-1} that enabled the study of morphological trends among

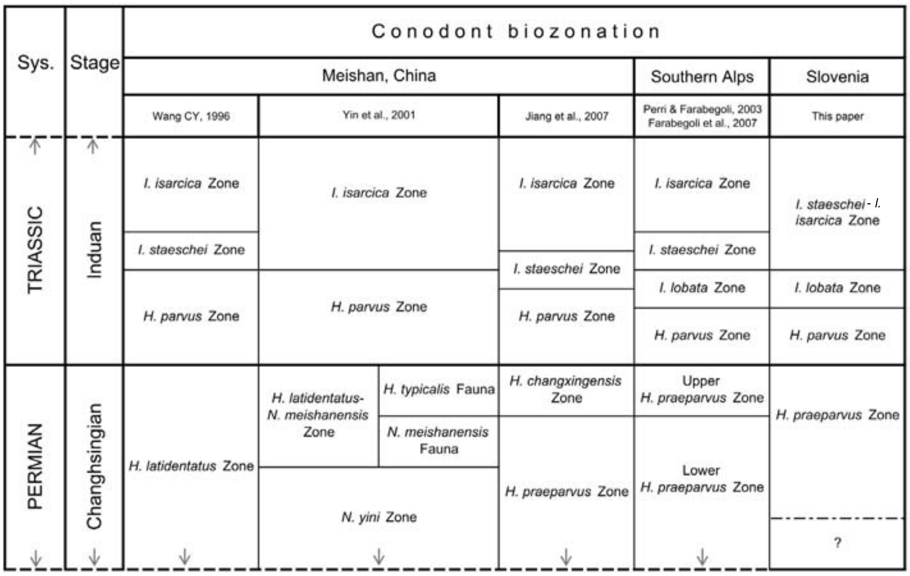

Fig. 5 - Correlation scheme of shallow water conodont biozones across the Permian-Triassic boundary interval of the studied Slovenian section with some selected areas.

the *Hindeodus-Isarcicella* genera (Perri & Farabegoli 2003). Altogether 12 taxa were determined: four species of *Hindeodus (H. parvus, H. pisai, H. praeparvus, H. typicalis)* and eight species of *Isarcicella (I. changxingensis, I. inflata, I. isarcica, I. lobata, I. peculiaris, I. prisca, I. staeschei, I. turgida*) and the absence of gondolellids was evidenced. Based on biostratigraphical data, a precise subdivision of the interval from the uppermost Permian (top of the Bellerophon Formation) to the lowermost Triassic (Mazzin Member of the Werfen Formation) into seven conodont biozones, Lower and Upper *praeparvus, parvus, lobata, staeschei, isarcica, aequabilis*, was proposed.

The Dienerian and Smithian local conodont zonation for the Dolomites was introduced by Perri (1991). Based on vertical distribution of the euryhaline genera, three biozones *Hadrodontina aequabilis, Hadrodontina anceps* and *Pachycladina obliqua*, have been differentiated. The zones are marked by the successive occurrence of the marker taxa and zone limits are characterized by the synchronous entry and disappearance of the index taxon, except for *Hadrodontina anceps* occurring just below the disappearance of the previous species, *Hadrodontina aequabilis* (Perri 1991, text-fig. 3). It is important to note that the FOD of *H. aequabilis* and the LOD of *Isarcicella isarcica* are synchronous in bed 27 of the Bulla section that is at 46 m above the lithostratigraphic boundary (Perri 1991).

According to the opinion of Perri (1991), the *H. aequabilis, H. anceps* and *P. obliqua* may have local value in a subdivision.

Austria

In the Gartnerkofel-1 core of the Carnic Alps, a multidisciplinary study was carried out on the Upper Permian Bellerophon Formation and the Lower Triassic Werfen Formation (Holser & Schönlaub 1991). No diagnostic conodonts were recovered from the topmost Bellerophon Formation but only a few ramiform fragments. The conodont examination of the Werfen Formation provided quite rich conodont faunas that enabled the recognition of the Assemblages A–E, the first four based on the *Hindeodus-Isarcicella* associations (Schönlaub 1991). Assemblage A was obtained from the lowermost Tesero Horizon. It is characterized by *Hindeodus* cf. *H. latidentatus, H. minutus* and the first occurrence of *H. parvus* was correlated to the *Otoceras woodwardi* Zone. Assemblage B represents the acme zone of *Hindeodus parvus.* In Assemblage C, *Hindeodus parvus* is still present and is characterized by a single occurrence of *Isarcicella turgida.* Assemblage D is marked by a rich occurrence of *Isarcicella isarcica* that ranges from 32.2 to 42.4 m above the formation boundary. The youngest recovered Assemblage E is represented by an apparatus described as *Ellisonia aequabilis* (Staesche).

The recovered conodonts from the boundary beds have a weak thermal overprint with a CAI (Colour Alteration Index) of 3 suggesting a temperature range between 110 to 200^{0}C (Epstein et al. 1977).

Hungary

The boundary interval was studied in the Bükk Mountains (NE Hungary in the three sequences: Bálvany-North, Bálvany-East, Gerenvár) (Sudar et al. 2008). The conodont faunas were obtained from thin, 2 m thick intervals (samples N1, N2, N8.1; Ge 136, Ge 133, Ge 132.1) and from a single bed (E4.3) in the Bálvany-East section. The samples yielded a *Hindeodus-Isarcicella* association, except that a single gondolellid fragment was recovered 6 m above the base of the Gerenvár Limestone in the Bálvany-East section.

Based on the obtained conodont associations, two conodont zones can be recognized, the Late Permian

(Changhsingian) *praeparvus* Zone and the Early Triassic (Induan) *parvus* Zone. The first zone is marked by *Hindeodus praeparvus, Hindeodus* sp., *Hindeodus /Isarcicella* sp., *Isarcicella* cf. *I. prisca*, whereas the latter zone by *Hindeodus praeparvus, H. parvus,* and *Hindeodus* sp. A striking dominance of hindeodids over isarcicellids (including the transitional form *Hindeodus/Isarcicella*) is documented (Sudar et al. 2008). The CAI (Conodont Alteration Index) of 3-5 indicates a diagenetic zone.

South China – Meishan Section D

The GSSP Meishan section is characterized by the presence of gondolellids and hindeodids. Gondolellids clearly dominate throughout the Changxing Limestone, but within the "transitional beds" the gondolellid dominanace changes into a hindeodid dominance (Jiang et al. 2007). The change from warm water gondolellid to hindeodid biofacies was possibly caused by ecologic stress (Kozur 1994) that also caused the disappearance of most Permian taxa, but favoured ecologically tolerant hindeodids.

The co-occurrence of gondolellids and hindeodids enabled the recognition of two biozonations based on pelagic and shallow water elements and their alignement. Six shallow water conodont zones can be differentiated in the PTB interval: the Changhsingian *latidentatus, praeparvus, changxingensis* zones, and the Induan *parvus, staeschei* and i*sarcica* Zones (Jiang et al. 2007, fig. 3).

A correlation scheme of shallow water conodont biozones across the PTB interval for the selected areas is presented in the Fig. 5.

Conclusions

The Permian-Triassic interval of the Lukač section in western Slovenia was studied sedimentologically and micropaleontologically by using conodonts. The analyzed section is composed of the Bellerophon Formation ("bellerophon limestone member" and "evaporite-dolomite member") and the Lukač Formation ("transitional beds", "streaky limestone member" and "carbonate-clastic member"). The Lukač Formation is here introduced for the first time.

The predominantly micritic microfacies of the Permian Bellerophon Member suggests deposition in backreef or lagoonal conditions changing upward to deposition of "evaporite-dolomite member" in a hypersaline very shallow or, possibly supratidal conditions. The "transitional beds", where the P-T boundary has been located, have also been deposited in shallow restricted marine conditions. Occasional presence of grainstone implies the migration of detritus due to oscillatory and/or tidal currents.

Wavy and hummocky structure observed in the overlain "streaky limestone member" that follows the boundary interval suggest deposition in a shallow subtidal environment by oscillatory and/or storm currents, whereas mottling structures point to an intensive activity of organisms.

Sedimentary rocks in the "carbonate-clastic member" show characteristics of shallow marine deposition of ooid or bioclastic detritus by oscillatory currents. A prevailing deposition of carbonate was periodically punctuated by terrigenous input of silty siliciclastic material. The deposition was strongly influenced by oscillatory wave or storm currents

The predominantly subtidal deposition in the Lukač Formation implies general deepening of the environment associated with increased terrigenous influx during the Early Triassic time.

The studied P-T interval beds are characterized by a diverse microfauna. The entire section is characterized by a *Hindeodus-Isarcicella* association and only the highest part of the section is marked by the presence of ellisoniids, predominantly *Hadrodontina.* The absence of gondolellids is noteworthy. Six conodont zones have been recognized and these are in ascending order, the latest Changhsingian (uppermost Permian) *praeparvus* Zone, and the Griesbachian (lowermost Triassic) *parvus, lobata, staeschei-isarcica, postparvus* and *anceps* zones.

The first occurrence of *H. parvus* in sample L1 in the "transitional beds" marks the systemic boundary between the Permian and Triassic. A rapid entry of several conodont taxa is observed in the highest level of the "transitional beds", in the *lobata* Zone and in the succeeding *staeschei-isarcica* Zone in the lowermost part of the "streaky limestone member", both represent a recovery event.

The introduced conodont biozonation for the Lukač section is the first proposed for the P-T interval in Slovenia as well as in the entire Dinaric region. The recognized conodont fauna of the Lukač section enables correlation with the sequences in the Southern Alps in Italy, Austria, Hungary and with the GSSP Meishan D section in South China.

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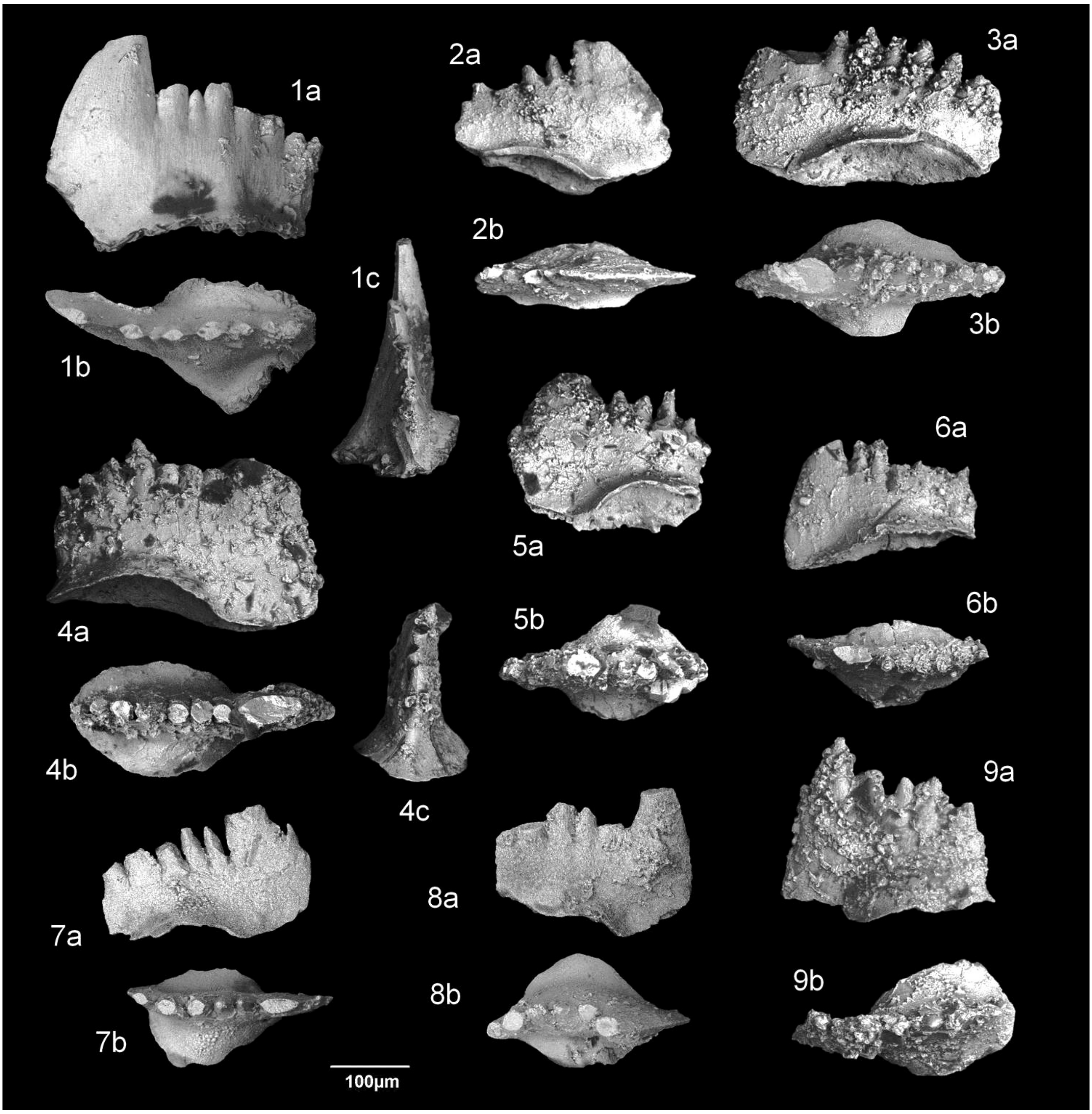

PLATE 2

All specimens are from the Lukač section, Lukač Formation, lowermost Triassic: specimen on fig. 1 - sample L1 (GeoZS 4133), "transitional beds", *parvus* Zone; all other specimens from the "streaky limestone member", *lobata* Zone: sample S (GeoZS 3866); except figs. 8, 9 - sample T (GeoZS 3867). a - lateral view, b - upper view, c - posterior view.

Figs 1, 3, 5, 6 - *Hindeodus parvus* (Kozur & Pjatakova);
Fig. 2 - *Hindeodus praeparvus / H. parvus* – transitional form;
Figs 4, 9 - *Hindeodus* sp.;
Figs 7, 8 - *Isarcicella* sp.

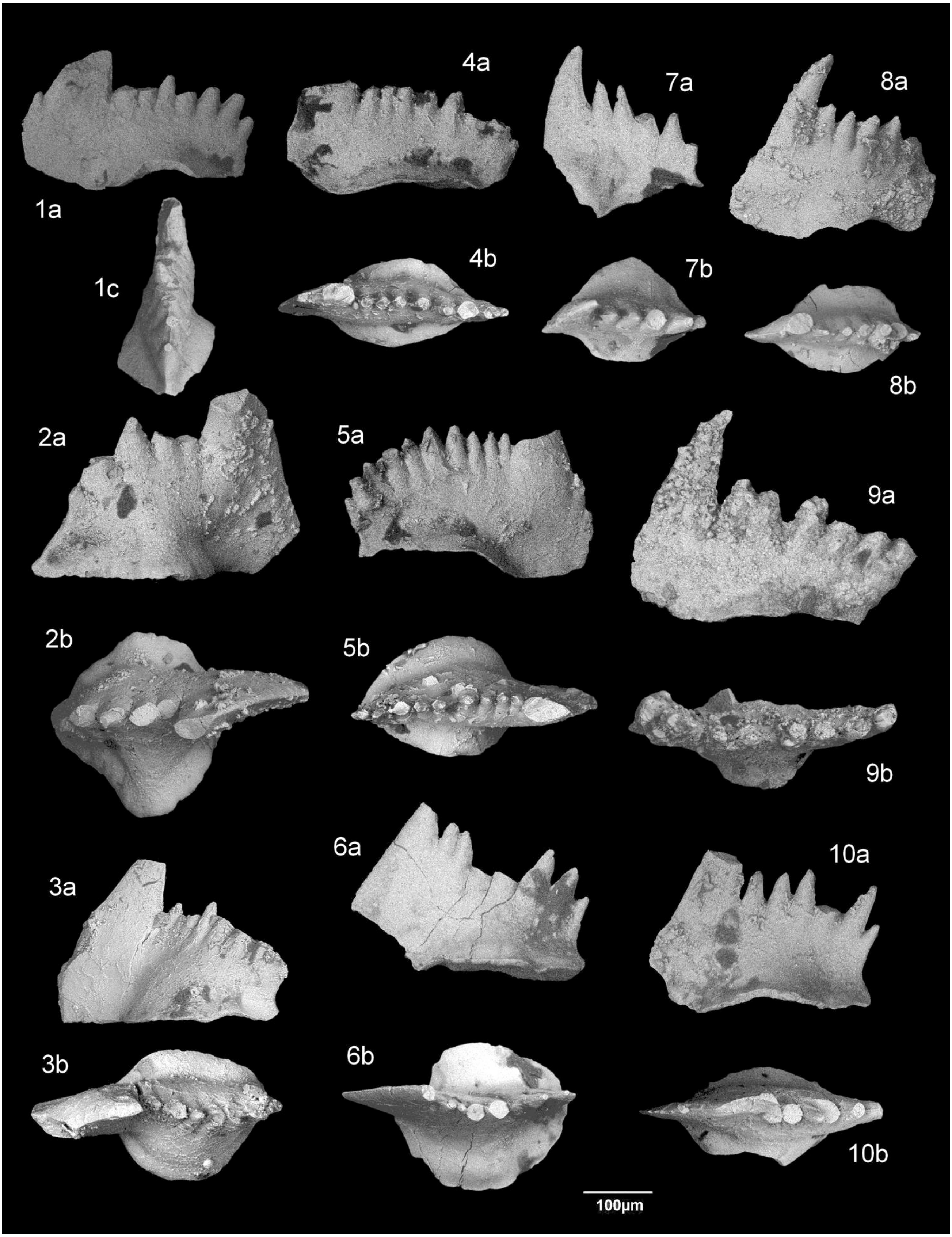

PLATE 3

All samples are from the Lukač section, Lukač Formation, "streaky limestone member", lowermost Triassic, *lobata* Zone: sample T (GeoZS 3867); except fig. 3 - sample S (GeoZS 3866); and fig. 8 - sample U (GeoZS 3868). a - lateral view, b - upper view, c - posterior view.

Figs 1, 5 - *Hindeodus parvus* (Kozur & Pjatakova);
Fig. 2 - *Isarcicella lobata* Perri & Farabegoli;
Fig. 3 - *Isarcicella* sp.;
Fig. 4 - *Isarcicella turgida* (Kozur, Mostler & Rahimi-Yazd);
Fig. 6 - *Hindeodus* sp.;
Figs 7-10 - *Hindeodus erectus* Kozur.

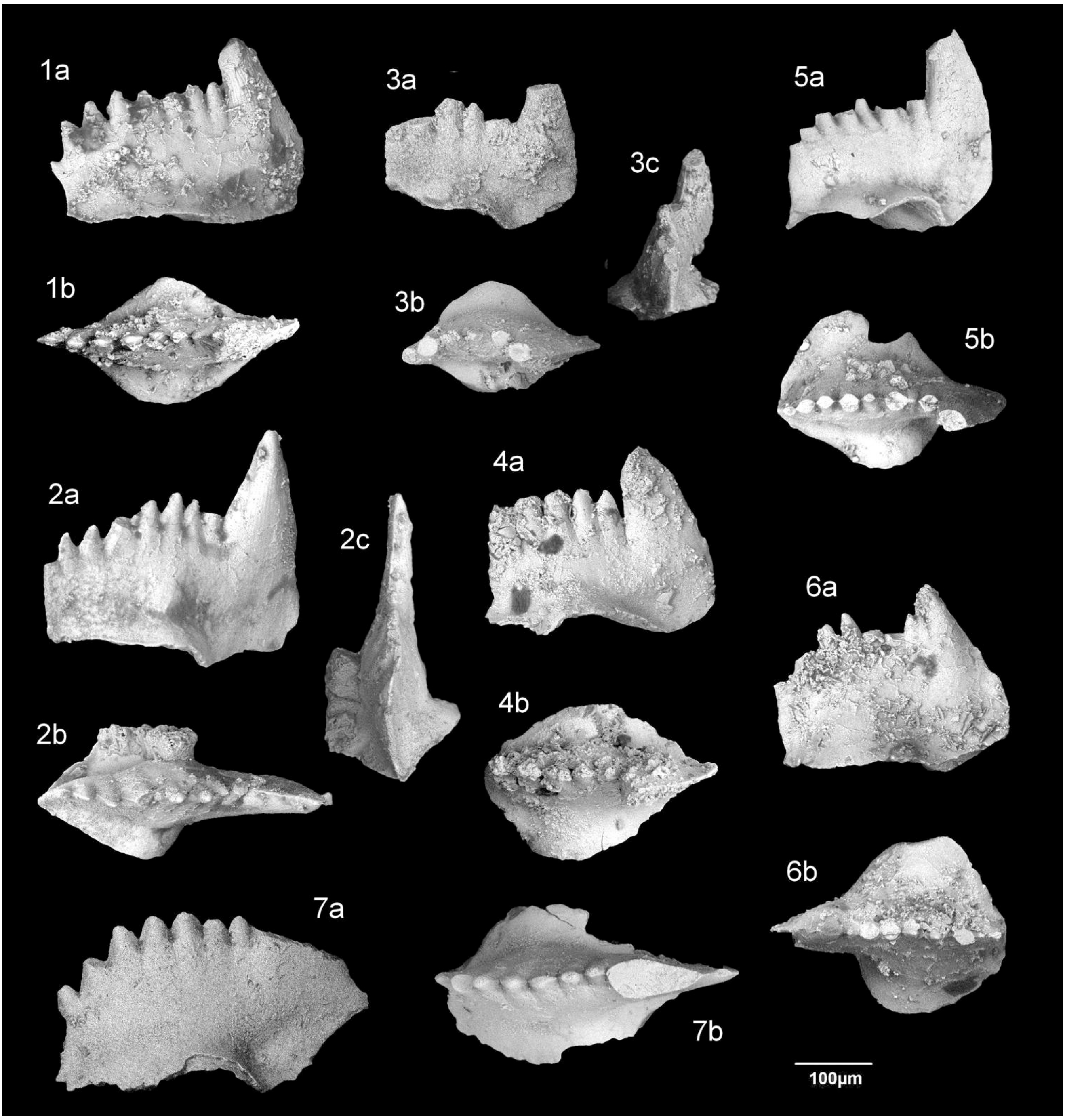

PLATE 4

All samples are from the Lukač section, Lukač Formation, "streaky limestone member", lowermost Triassic, *lobata* Zone: sample U (GeoZS 3868); except figs. 3, 7 - sample T (GeoZS 3867). a - lateral view, b - upper view, c - posterior view.

Figs 1-3, 7 - *Hindeodus parvus* (Kozur & Pjatakova);
Figs 4-6 - *Hindeodus* sp.

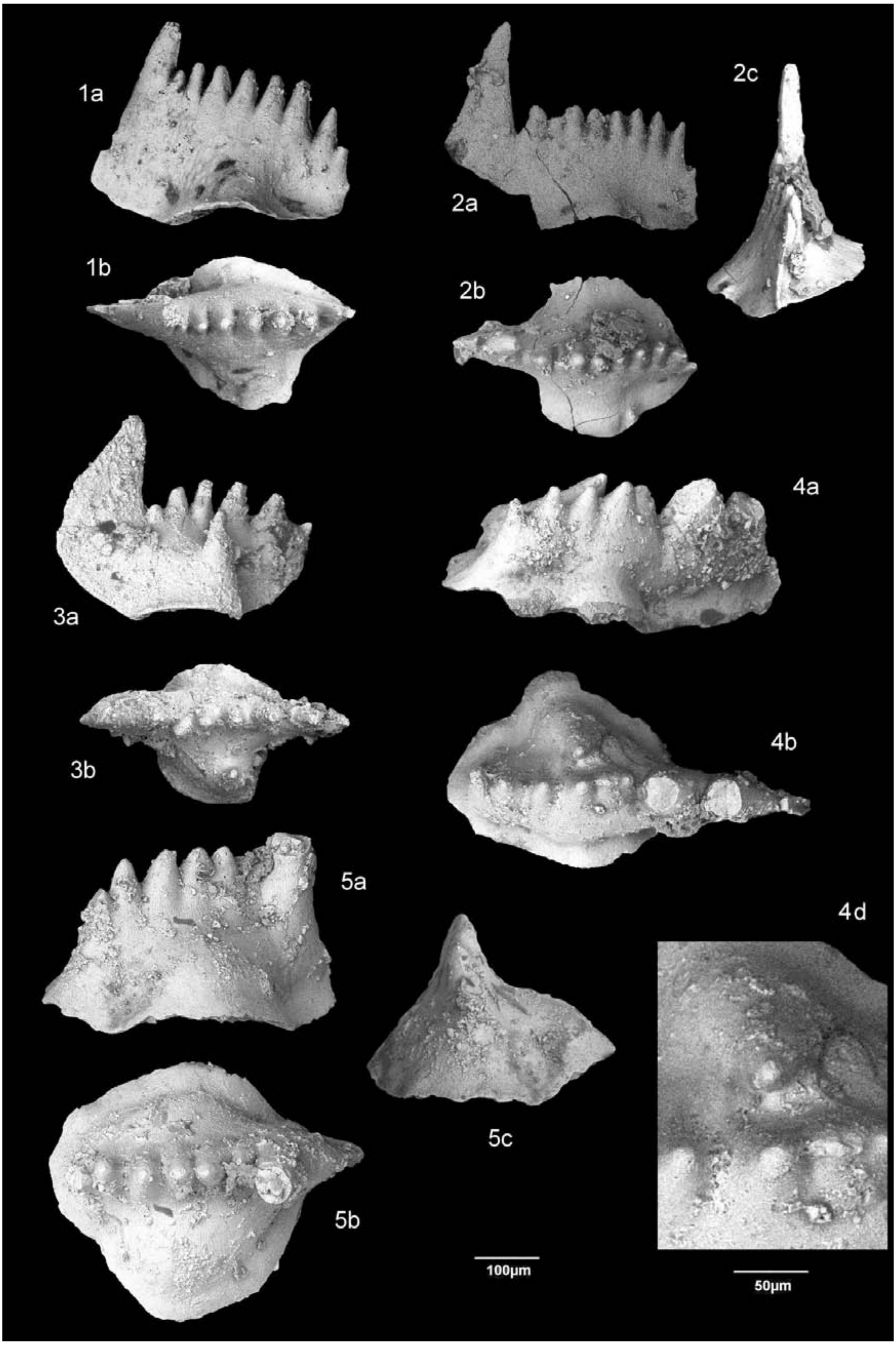

PLATE 5

All samples are from the Lukač section, Lukač Formation, "streaky limestone member", lowermost Triassic: sample V (GeoZS 3869), *staeschei-isarcica* Zone; except fig. 2 - sample U (GeoZS 3868), *lobata* Zone. a - lateral view, b - upper view, c - posterior view, d - microstructure of upper surface.

Fig. 1 - *Isarcicella lobata* Perri & Farabegoli;
Fig. 2 - *Hindeodus* sp.;
Figs 3, 4 - *Isarcicella staeschei* Dai & Zhang;
Fig. 5 - *Isarcicella inflata* Perri & Farabegoli

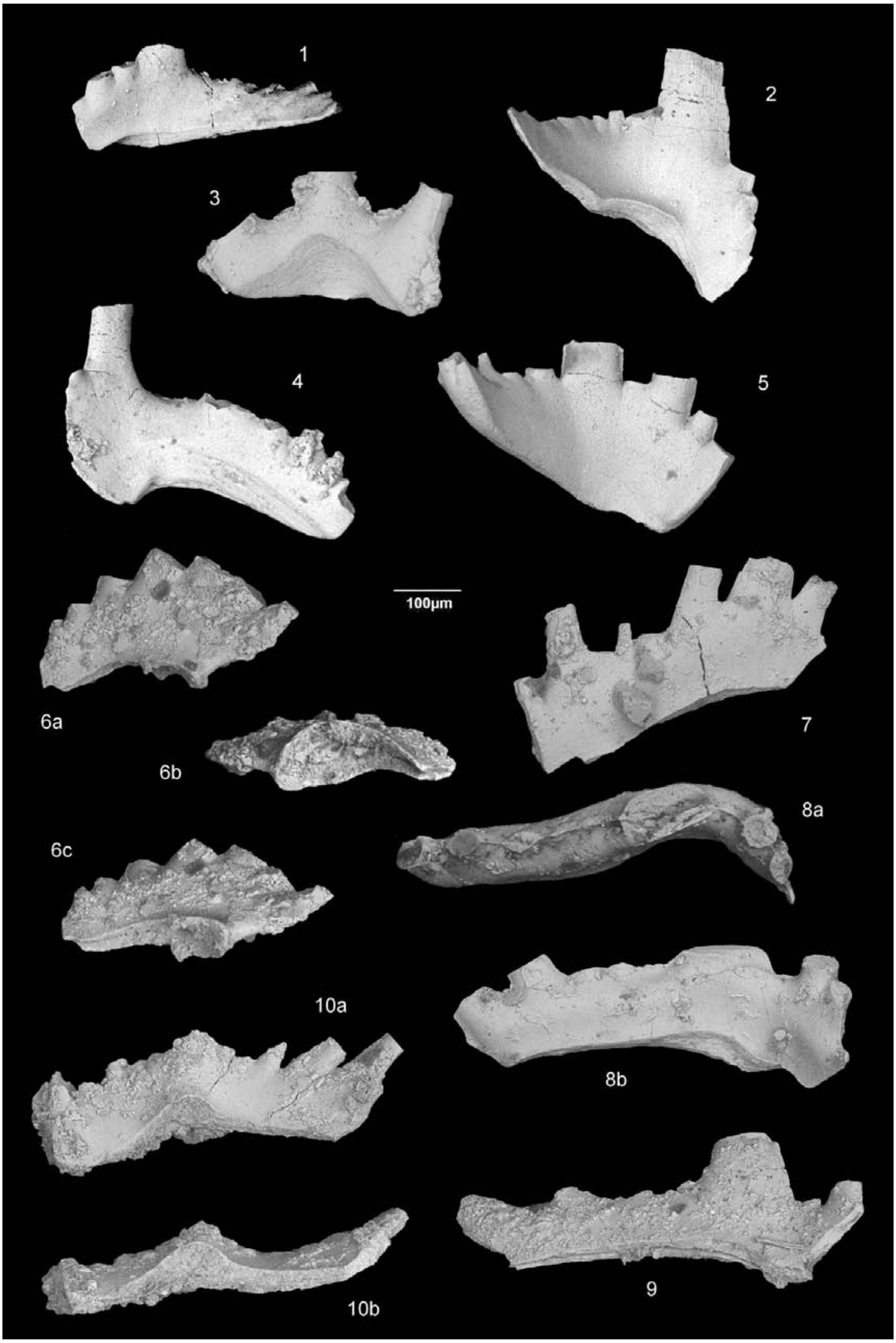

PLATE 6

All specimens are from the Lukač section Lukač Formation, lowermost Triassic: fig. 1-5 – "streaky limestone member", *staeschei-isarcica* Zone: sample 4 (GeoZS 3797); fig. 6-9 – "streaky limestone member", *postparvus* Zone: sample 22 (GeoZS 3836); fig. 7, 8, 10: "carbonate-clastic member", *postparvus* Zone: fig. 7, 8 – sample 26 (GeoZS 3948), fig. 10 - sample 27 (GeoZS 3949).

Figs 1-5 - Ellisoniidae *(Ellisonia* or *Hadrodontina)*: 1 – Pb, 2, 5 - Sb, 3 - M, 4 - Sa elements.
Figs 6-10 - *Hadrodontina* sp.: 6 - Pa, 7 -?Sc, 8, 9 - Sc, 10 - Sb elements.

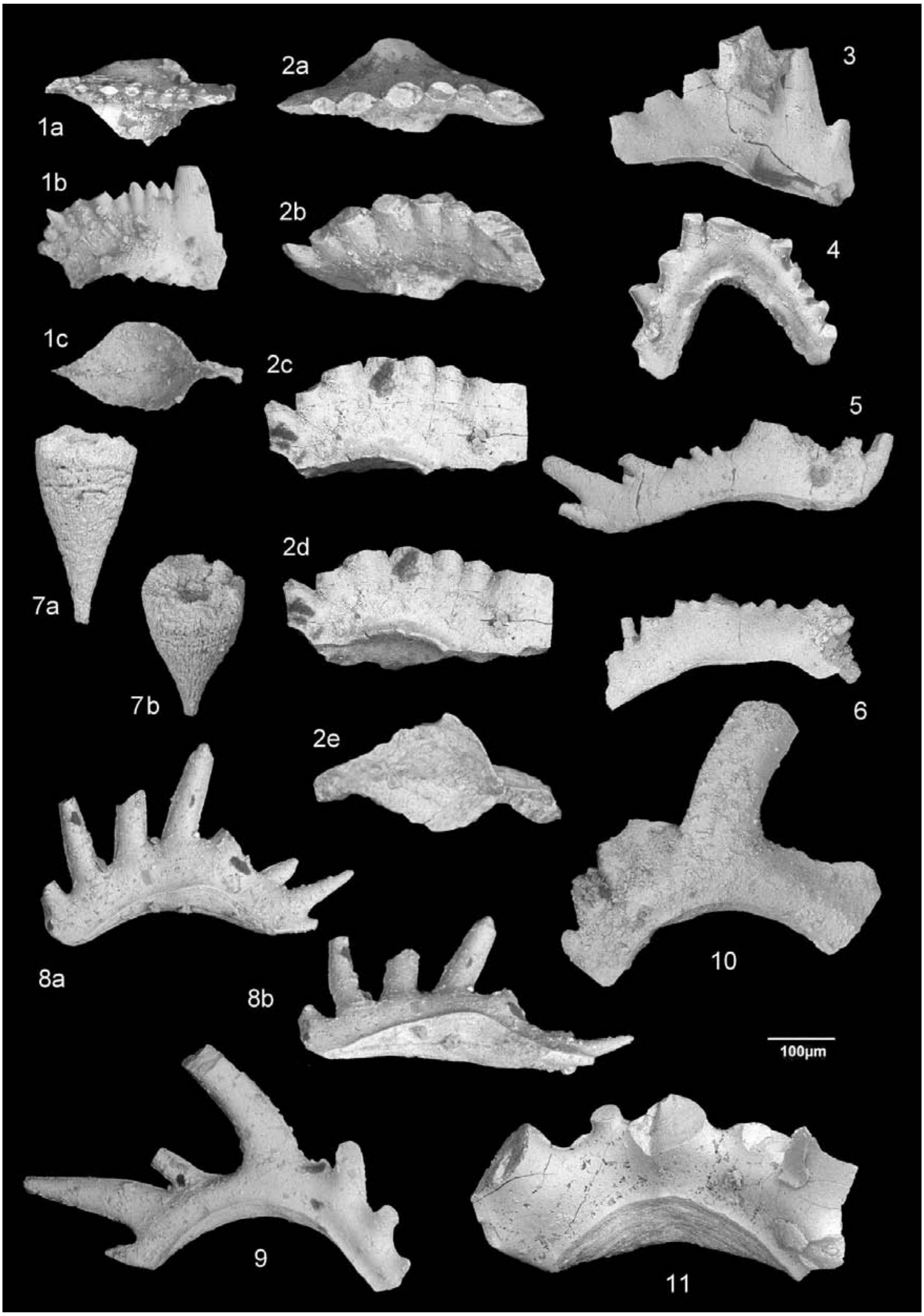

PLATE 7

All specimens are from the Lukač section, Lukač Formation, "carbonate-clastic member", lowermost Triassic: fig. 1-7 *postparvus* Zone, fig. 1 - sample 41 (GeoZS 3974), fig. 2 - sample 40 (GeoZS 3973), fig. 3-6 - sample 30 (GeoZS 3952), fig. 7 - sample 32 (GeoZS 3960); fig. 8 - 11 *anceps* Zone: fig. 8, 9 - sample 61 (GeoZS 4137), fig. 10 - sample 64 (GeoZS 4140), fig. 11 - sample 67 (GeoZS 4143).

Figs 1 - *Hindeodus postparvus* Kozur;
Fig. 2 - *Hindeodus* ex gr. *postparvus* Kozur;
Figs 3-6, 8-10- *Hadrodontina* sp.: 3, 8 - Pb, 4 - M, 5, 10 - Sc, 6 -?Sb, 9 -?Sc elements;
Fig. 7 - Articulata (Roveacrinidae): dorsal spine of theca;
Fig. 11 - *Hadrodontina anceps* Staesche, Sb element.

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