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na Moravě a ve Slezsku

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in Moravia and Silesia

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The unconformity between steeply dipping Lower Cretaceous limestones of the Pieniny Unit and the overstepping Eggenburgian sandstones reveals that major tectonic events affected the Pieniny Klippen Belt before the Early Miocene. Abandoned quarry in Podbranč; (Western Slovakia). Photo: D. Plašienka, 2007.

Reconstruction of the Swedish Alum Shales sea floor in the late Middle Furongian. The discarded exuviae of *C.* (*Meoctenopyge*) *tumida* lie on the sea floor in the centre, while nearby the small crustaceans *Rehbachiella* (right) and *Skara* (left) are feeding. A tiny crustacean larva (extreme left, bottom) swims close to the sea floor while two olenid trilobites *Ctenopyge angusta* (left) swim in the water column. Three voraciously predatorial conodont animals swim towards the observer from the top right. Author: E. N. K. Clarkson, 2002.

Cover page: The "Husova kazatelna" (Hus's Pulpit, according to local inhabitants called also "Čertova kazatelna" – Devil's Pulpit), a big boulder of durbachitic melagranite (the Čertovo břemeno "type") of the Central Bohemian Plutonic Complex (13 km N of Milevsko, 11.5 km WNW of Monínec). Photo: F. V. Holub, 2008.

Below: Detail of the fresh durbachitic melagranite with phenocrysts of K-feldspar showing the Carlsbad twining. Quarry Vepice (9 km NW of Milevsko, 15.5 km W of Monínec). Photo: F. V. Holub, 2008.

Durbachitic melagranites together with porphyritic amphibole-biotite melasyenite (durbachite s. s.) are members of the ultrapotassic *durbachite suite* that is typical for the Moldanubian Zone of the Variscan Orogenic Belt. These rocks are also called the "Čertovo břemeno type" after their typical locality – the Čertovo břemeno (Devil's Burden) Hill situated near by Monínec.

GEOLOGICKÉ VÝZKUMY NA MORAVĚ A VE SLEZSKU

Geological research in Moravia and Silesia

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TRILOBITE BIOSTRATIGRAPHY OF THE KRÁLŮV DVŮR FORMATION (UPPER KATIAN, PRAGUE BASIN, CZECH REPUBLIC): GLOBAL FAUNAL CHANGES OR FACIES-RELATED DISTRIBUTION?

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Key words: Teplá-Barrandian Unit, Katian, Prague Basin, trilobite associations

Abstract

*Eight trilobite associations and sub-associations have been distinguished in the late Katian Králův Dvůr Formation. Spatial distribution of these associations reflects lithology but their succession was dictated also by global climatic changes and palaeogeographical positioning. Locally developed "Podolí Ore Horizon" trilobite association contains low-diversity but specific forms showing survivals from the underlying Bohdalec Formation combined with the late Katian taxa (*Chlustinia, Duftonia, Onnia, *etc.). The* Amphitryon – Kloucekia *Association is newly established for the lower two thirds of the formation. It is characterized by abundant benthic scavenger-predators accompanied by filter feeders and common pelagic/nektic predators. Within* Amphitryon –Kloucekia *Association can be distinguished four sub-Association 1) the newly established* Onnia ultima *sub-Association is characterized by a dominance of Onnia and Flexicalymene; it is developed at the lowermost levels of the formation, 2) the deeper-water* Nankinolithus granulatus *sub-Association (originally established as horizon), 3) rather shallow-water, brachiopod-dominated* Dedzetina-*Tretaspis sub-Association with rare trilobites and 4) the trilobite-dominated* Tretaspis anderssonni *sub-Association (originally horizon). Last three sub-associations are considered as rather facies-related, with limited stratigraphical applicability only. Impure bioclastic limestone below top of the formation contains a rich shallow- and temperate-water* Marekolithus kosoviensis *Association, which better corresponds with the original horizon concept. This association is dominated by small benthic scavenger-predator trilobites, which are associated by the filter feeder* Marekolithus. *The* Mucronaspis *Association of medium-sized scavenger-predators is characteristic for the uppermost portion of formation and persisted till the early onset of the glaciation at the base of Hirnantian. Minute detritus feeders are rare but present in all the above-discussed associations excluding the last one.*

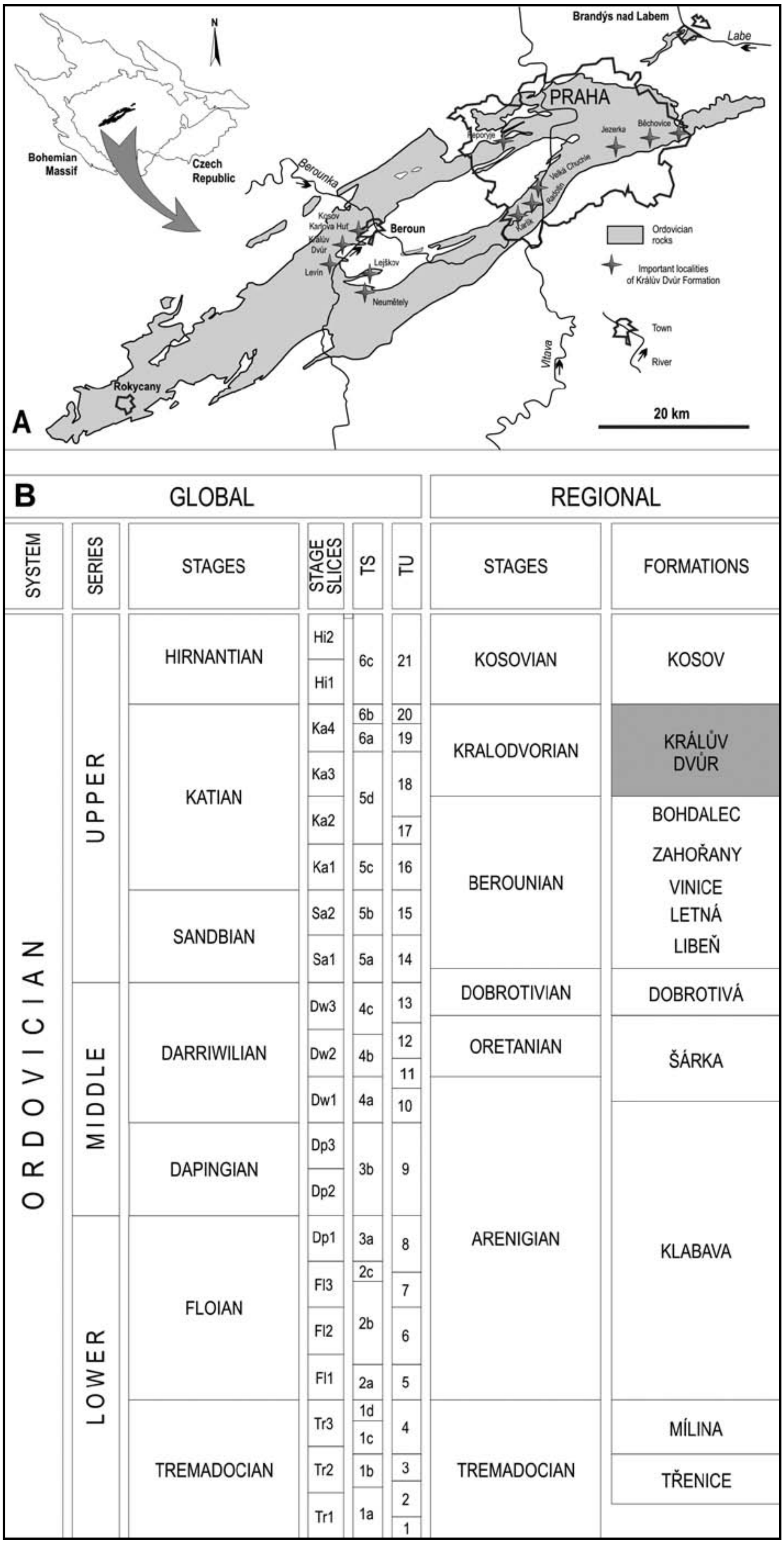
Introduction

Trilobites of the Králův Dvůr Formation (see fig. 1) belong to the most diversified within the Ordovician of the Prague Basin; they have been investigated since first half of the 19th century (see Barrande 1846, 1852, 1872, Hawle – Corda 1847, Novák 1883; for review of the older data see Havlíček – Vaněk 1966, Shaw 2000, Chlupáč 2002). They share many elements with the temperate-water trilobite assemblages of Baltica (see Kielan 1960, Bruton – Owen 1979, Owen 1981), Avalonia (Ingham 1970, Owen – Romano 2010), Kazakhstania (Apollonov 1974) and also with the European peri-Gondwana – nowadays Sardinia and Iberia (e. g. Hammann 1974, Hammann – Leone 1997). The spatial distribution of fauna of the Králův Dvůr Formation was studied by Havlíček – Vaněk (1966), they proposed the first zonation based mostly on trilobites and on brachiopods. This concept has been further developed by Havlíček – Vaněk (1990) and by Havlíček (1998). Shaw (2000) critically discussed their approach but he accepted the horizon concept in general. The upper part of the Králův Dvůr Formation was studied in detail by Štorch – Mergl (1989). The first occurrence of the Hirnantian fauna in the upper part of Králův Dvůr Formation recently discussed Mergl (2011) and the distribution of the agnostid *Arthrorhachis* is analyzed by Budil et al. (in press). Recently, Budil et al. (2009a-c, 2010) provided partially re-defined concept of Havlíček – Vaněk (their communities are considered to represent associations considering them as facies related). However, this revised approach was not properly published.

The association versus assemblage and horizon approach

The concept of trilobite associations of Budil et al. (2007a, b), Mergl et al. (2008) and Fatka – Mergl (2009) is followed here, instead of the traditional horizon and community concept of Havlíček (1998). One of important problems is the autochtonity of fossils. Similarly, the designation "trilobite horizon" as applied in the Králův Dvůr Formation by Havlíček – Vaněk (1966) is considered as inaccurate, especially for lower and middle levels of the unit. The occurrence of key species is rather facies related and/or or locality related (e. g. *Nankinolithus granulatus* occurs only sporadically outside the locality Lejškov). In addition, several tens to hundred meters thick sedimentary successions represent such trilobite horizons. The non-genetic, descriptive designation "Trilobite Association" is appropriate see Turvey – Zhou (2002, 2004).

Study of trilobite associations of the Králův Dvůr Formation is complicated by the absence of thick continuous sections, especially in lower and middle levels of the unit. The situation is comparatively better in upper part of the formation (see Štorch – Mergl 1989). The soft shale and claystones forming major part of the formation are often tectonically affected. This tectonics involves usually



GLOBAL						REGIONAL	
SYSTEM	SERIES	STAGES	STAGE SLICES	TS	TU	STAGES	FORMATIONS
ORDOVICIAN	UPPER	HIRNANTIAN	Hi2 Hi1	6c	21	KOSOVIAN	KOSOV
		KATIAN	Ka4	6b	20	KRALODVORIAN	KRÁLŮV DVŮR
				6a	19		
			Ka3	5d	18		
			Ka2		17	BEROUNIAN	BOHDALEC ZAHOŘANY VINICE LETNÁ LIBEŇ
			Ka1	5c	16		
		SANDBIAN	Sa2	5b	15		
			Sa1	5a	14		
	MIDDLE	DARRIWILIAN	Dw3	4c	13	DOBROTIVIAN	DOBROTIVÁ
			Dw2	4b	12	ORETANIAN	ŠÁRKA
					11		
			Dw1	4a	10	ARENIGIAN	KLABAVA
		DAPINGIAN	Dp3 Dp2	3b	9		
	LOWER	FLOIAN	Dp1	3a	8		
			Fl3	2c 2b	7		
			Fl2		6		
			Fl1	2a	5		
		TREMADOCIAN	Tr3	1d 1c	4	TREMADOCIAN	MÍLINA
			Tr2	1b	3		TŘENICE
			Tr1	1a	2		
					1		

Fig. 1: A – A map of the distribution of the Ordovician rocks in the Barrandian area. The asterisks show the position of the major localities of the Králův Dvůr Formation. Modified after Manda (2008). B – The stratigraphical position of the Králův Dvůr Formation.

intensive folding. In addition, the belts of the Králův Dvůr Formation are commonly represented by tectonically limited blocks. There is also relative lack of exposures because of heavy weathering of the clayey shale (but great help sometimes represent the temporary exposures originated during diverse building activities). These all above-discussed aspects obscure the analysis.

Review of trilobite associations of the Králův Dvůr Formation

More than 60 trilobite species established from the Králův Dvůr Formation are grouped into eight trilobite associations and sub-associations (see tab. 1, fig. 2).

Their spatial distribution reflects rather lithology, especially in lower and middle levels of the formation, while the succession in upper part was directly influenced by the onset of global climatic changes induced by the Boda Event (see Fortey – Cocks 2005), and the subsequent onset of the Hirnantian glaciation in the uppermost portion of the sequence (see also Mergl 2011).

1. The "Podolí Ore Horizon" Trilobite Association (newly defined) locally present at the base of the formation is characterized by very scarce and poorly known trilobite fauna with apparent mixing of species known from the underlying Bohdalec and the Králův Dvůr formations: *Onnia* cf. *ultima*, *Chlustinia mikulasi* (= *keyserlingi fide* Vaněk – Valíček 2001), *Selenopeltis* sp., *Octillaenus*? sp., *Actinopeltis* cf. *gryphus*, *Duftonia juspa konika* (nomen nudum, MS Šnajdr) and *Kloucekia* sp.

2. The *Amphitryon-Kloucekia* Trilobite Associa-

species/(sub)associations	Podoli Ore Horizon	*Onnia ultima*	*Nankinolithus*	*Dedzetina -Tretaspis*	*Tretaspis*	*Marekolithus*	*Mucronaspis*
„Encrinurus“ sp.						R	
Actinopeltis barrandei					R		
Actinopeltis carolialexandri			C		R	R?	
Actinopeltis insocialis						C	
Actinopeltis cf. *gryphus*	R						
Alceste latissima					R	R	
Amphitryon radians		C	C		C		
Areia bohemica			R		R		
Arthrorachis tarda			R	R	R		
Birmanites kielanae			R		R		
Brongniatella platynota			R				
Bumastus sp.						R	
Carmon mutilus			C		R		
Cerampyx gratus			R				
Cyclopyge marginata			R		R		
Decoroproetus solus					R	R	
Degamella gigantea					R	R	
Dindymene fridericiaugusti			R		R	R	
Dionide speciosa			C		C	R	
Dreyfussina ? simaki					R		
Duftonia morrisiana					?	C	?
Duftonia juspa konika (MS)	R						
Dysplanus wahlenbergianus			R		C		
Eoleonaspis cf. *olini (=mirka)*						R	
Eoleonaspis koral					R	R	
Eoleonaspis musca					R		
Eoleonaspis peregrina			R		R	R	
Flexicalymene declinata		C	C		C		
Girvanopyge sp.					R		
Gravicalymene asperula					C	C	
Hadromeros fortis					R		
Harpidella cf. *kielanae*					R		

species/(sub)associations	Podoli Ore Horizon	*Onnia ultima*	*Nankinolithus*	*Dedzetina -Tretaspis*	*Tretaspis*	*Marekolithus*	*Mucronaspis*
Chlustinia keyserlingi	R		R		R		
Illaenus hospes					R		
Kloucekia ruderalis	?	R	C		C	?	
Lonchodomas portlocki			C	R	R		
Marekolithus kosoviensis						C	
Microparia speciosa		C	C		C	C	
Miraspis sp.						R	
Mucronaspis ganabina						C	
Mucronaspis grandis			?		?	C	C
Nankinolithus granulatus			C		?		
Octillaenus hisingeri	?				R	R	
Onnia ultima	?	C	R?		?		
Phillipsinella parabola			R		R	R	
Platylichas milosi					R		
Pseudosphaerexochus pectinifer			R				
Raphiophorus tenellus			C		R	R	
Selenopeltis vultuosa	?		C		R		
Sphaerexochus latens					R		
Staurocephalus cf. *clavifrons*						R	
Stenopareia oblita						C	
Stubblefieldia neglecta					R		
Symphysops armatus			R		?	R	
Telephina fracta			?		R		
Thorslundops? sp.						R	
Tretaspis anderssoni			?	R	C		
Trochurus sp.						R	
Trochurus toernquisti						R	
Xenocybe michle						R	
Zazvorkaspis neutra					R		
Zdicella (=Delgadoa) zeidlerí			C		R		
Zdicella? sola			R			R	

Tab. 1: The occurrence of the trilobites in the Králův Dvůr Formation. Modified after Shaw (2000).

tion (newly defined) is confined to the lower two thirds of the formation (see also fig. 4). It is characterized by the dominance of benthic scavenger-predatory forms associated with filter feeders and common pelagic/nektic predators. The association includes two previously defined trilobite "horizons" (*Tretaspis granulatus* and *Tretaspis seticornis sensu* Havlíček – Vaněk 1966) and one newly defined sub-association.

2.1. The *Onnia ultima* Trilobite sub-Association (newly defined) is known near the base of the formation at the locality Lejškov, Velká Chuchle and several other outcrops. It is poorly diversified, with dominant *Onnia ultima*, *Flexicalymene declinata*, *Amphitryon radians*, *Microparia speciosa* and only rare *Kloucekia ruderalis*.

2.2. The rather deeper-water *Nankinolithus granulatus* Trilobite sub-Association (horizon sensu Havlíček – Vaněk 1966) contains 29 trilobite species ranged to the following genera: *Nankinolithus*, *Onnia*, *Amphitryon*, *Kloucekia*, *Actinopeltis*, *Microparia*, *Flexicalymene*, *Octillaenus*, *Selenopeltis*, *Nobiliasaphus*, *Lonchodomas*, *Phillipsinella* etc. and the agnostoid *Arthrorhachis*.

2.3. Rather shallow-water *Dedzetina-Tretaspis* brachiopod-dominated sub-Association (= compact shales with *Foliomena* and *Dedzetina sensu* Havlíček and Vaněk 1966) locally occurs in middle levels of the formation. Three species of rare, minute trilobites are known from this sub-association: *Lonchodomas portlocki*, *Arthrorhachis tarda*, and *Tretaspis anderssoni*.

2.4. *Tretaspis anderssoni* Trilobite sub-Association (horizon *sensu* Havlíček – Vaněk 1966) is characteristic by highly diversified trilobites (44 species known); it shows proportional presence of the main feeding strategies (see fig. 3). It also shares many species with the older *Nankinolithus granulatus* sub-Association (see tab. 1, fig. 2). However, it is distinguished from the later sub-association by the presence of *Tretaspis anderssoni* as well as by somewhat higher position in the sequence. However, both index species are often mismatched in older collections. Both sub-associations characterized by dominance of benthic scavengers and planktonic or nektonic forms. The typical genera of the *T. anderssoni* sub-association are *Tretaspis*, *Amphitryon*, *Kloucekia*, *Microparia*, *Actionopeltis*, *Flexica-*

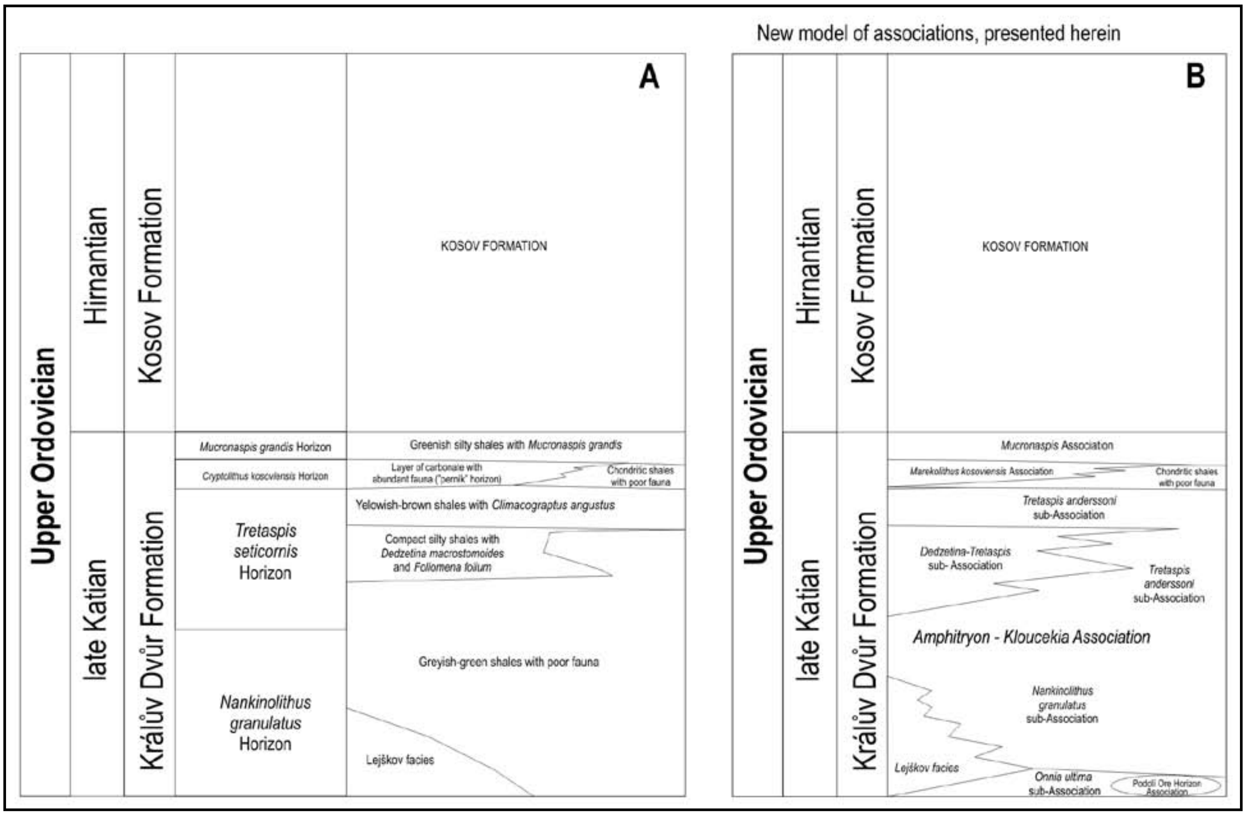


Fig. 2: A – The classical (Havlíček – Vaněk 1966 and Havlíček in Chlupáč et al. 1998) concept of trilobite horizons in the Králův Dvůr Formation. B – A new proposal of trilobite associations (see text).

lymene, *Octillaenus*, *Selenopeltis*, *Nobiliasaphus*, *Lonchodomas*; rare but typical are *Arthrorhachis*, *Phillipsinella* etc.

The richly fossiliferous, dark grey to almost black claystones are traditionally called the "Lejškov facies" of the Králův Dvůr Formation (Havlíček – Vaněk 1966, Havlíček 1998). It was supposed to be restricted to the lower part of the formation. However, the occurrence of index *Nankinolithus granulatus* together with *Normalograptus angustus* and *Dicellograptus* cf. *laticeps* (determination by P. Štorch; see Budil et al. in press) combined with the questionable co-occurrence of *N. granulatus* and *T. anderssonni* (see Vonka – Kolář 2006) approves the comparatively wider stratigraphical range of *N. granulatus*.

3. Diversified fauna of the *Marekolithus kosoviensis* Trilobite Association (horizon *sensu* Havlíček – Vaněk 1966) is confined to calcareous claystone in the uppermost levels of the formation. It contains the index filter feeder *Marekolithus* associated with shallow-water, small benthic scavenger-predators. Thirty trilobite species of the genera *Marekolithus*, *Mucronaspis*, *Duftonia*, *Actinopeltis*, *Stenopareia*, *Flexicalymene*, *Decoroproetus* and *Diacanthaspis* are known. The upper part of these claystone yielded slightly different association with *Staurocephalus* and rare but significant *Eoleonaspis* (= *Bojokoralaspis*). The association is supposed to be allochtonous, representing remains of rather shallow-water origin transported into the deeper part of basin (for different interpretation see Shaw 2000). In our opinion, this interval represents material transported by mudflows produced by the global sea level fall. It could reflect the onset of glaciations. In this association, Mergl (2011) recently described the first elements of the Hirnantian fauna, although this level is traditionally considered as of uppermost Katian in age.

4. The *Mucronaspis* Trilobite Association (horizon *sensu* Havlíček – Vaněk 1966) of medium-sized scavenger-predators is characteristic for the uppermost portion of the formation and persists to the appearance of the first dropstone level at the base of Hirnantian. Only two species of *Mucronaspis* – *M. grandis* and *M. ganabina* occur in the association, and very rare *Duftonia*? sp. The association clearly shows stress conditions and probably reflects a sudden deterioration of environment, when only a few species survived.

Supposed feeding modes of trilobites of the Králův Dvůr Formation

All supposed feeding strategies defined by Fortey – Owens (1999) were recognized within each of the eight trilobite associations and sub-associations (see also Budil et al. 2009 a, c, 2010) in the Králův Dvůr Formation. Their frequencies, however, strongly vary in separate association (see fig. 3). Numerous small benthic scavenger-predatory strategists (acastoids, calymenids, diversified illaenids, cheirurids, rare lichids) accompanied by rare large scavenger/predatory forms (e. g. *Birmanites*), common filter-feeders (*Nankinolithus*, *Cerampyx*, *Lonchodomas*, *Raphiophorus*), minute particle feeders (*Phillipsinella*, very rare *Harpidella*), and common pelagic/nectic? predator-scavengers (*Amphitryon*, cyclopygids, odontopleurids, rare *Telephina*) constitute the deeper-water trilobite-dominated *Nankinolithus granulatus* sub-Association in the gray and green claystones. Minute

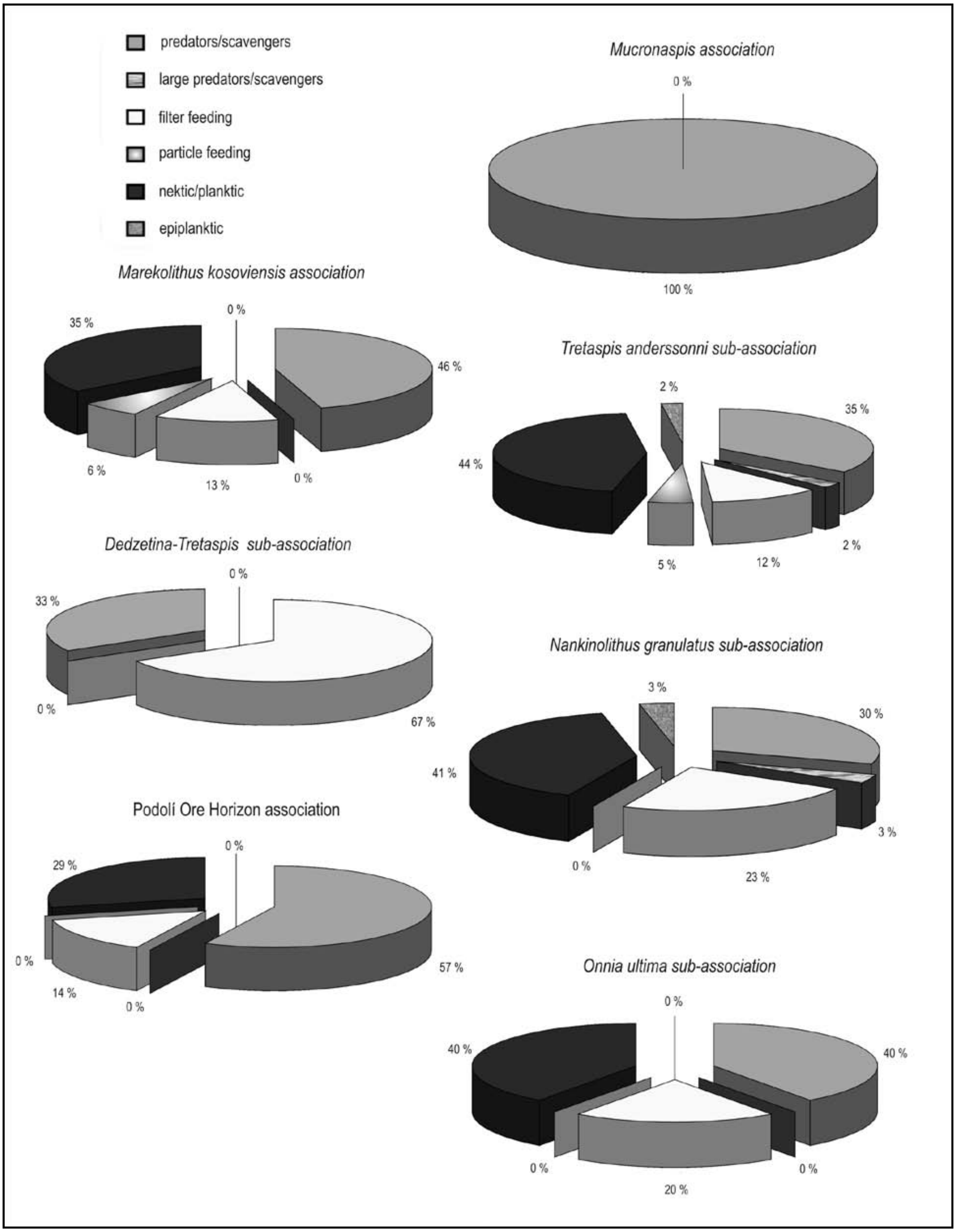


Fig. 3: The comparison of possible feeding modes in different associations of trilobites of the Králův Dvůr Formation.

filter feeders (*Tretaspis*, *Lonchodomas*) and benthic and/or epi-planctic agnostids (*Arthrorhachis*) prevail in the brachiopod-dominated *Dedzetina – Tretaspis* Association. Trilobite-dominated *Tretaspis anderssoni* sub-associations show a comparable composition with the *Nankinolithus granulatus* sub-Association. The *Marekolithus kosoviensis* Association is restricted to the bed of calcareous claystone to impure bioclastic limestones in the upper levels of the formation. Numerous small and medium-sized benthic scavenger-predatory strategists of this association probably used several different life strategies (dalmanitids, acastoids, calymenids, cheirurids, illaenids, very rare lichids and encrinurids). They are accompanied by filter feeders (common *Marekolithus*, very rare *Thorslundops*?)

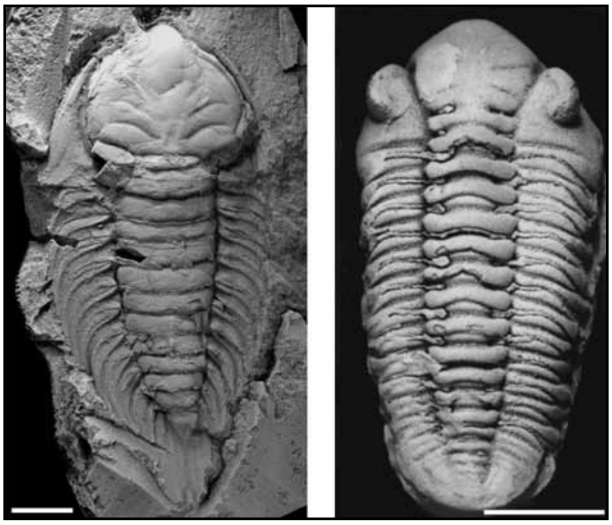


Fig. 4: *Amphitryon radians* (Barrande, 1846) and *Kloucekia* ? *ruderalis* (Hawle and Corda, 1847) (= *K. pachypa* Přibyl and Vaněk, 1980) – two typical elements of the newly defined *Amphitryon-Kloucekia* association confined to the lower and middle parts of the Králův Dvůr Formation. The scale bar represents 5 mm.

and rare, minute particle feeders (*Decoroproetus*). Active nectic/pelagic forms are represented by cyclopygids, rare odontopleurids and possibly also by some cheirurids. Only medium-sized scavenger-predatory strategists survived to the youngest, monotypic *Mucronaspis* Association.

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THE LIFE AND TIMES OF THE OLENID TRILOBITES

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Key words: Olenidae, trilobites, evolution, ontogeny, environment

Abstract
The Middle Cambrian of Bohemia contains a widespread fauna which can be traced from eastern Newfoundland, through central Britain, Scandinavia and the Montagne Noire in France and further east. Whereas the upper Cambrian (Furongian) in Bohemia consists of volcanics and alluvial sediments, in the Scandinavian (Baltica) and Avalonian successions, dysoxic facies prevail, dominated by the olenid trilobites. The Furongian of southern Sweden forms a superb natural laboratory for studying processes and patterns of evolution in the olenids. The rapid turnover of species and superb preservation of the fossils allows evolutionary changes to be assessed stratophenetically, and at the microevolutionary scale. Also, the dynamics of the evolving faunas can be assessed and their relations with environmental fluctuations established by bed-by-bed collecting and analysis. Moreover since all trilobite growth stages often occur along with the adults, it is possible to establish the complete or partial ontogeny of many species, and to explore the relationhips between ontogeny and phylogeny. Information gained from various lines of evidence from the faunas can be used, along with geochemical approaches to build up a coherent picture of an extinct environment and its inhabitants; this paper summarises old and new explorations in this field.

Introduction

The Barrandian syncline is surely one of the world's richest and most famous localities for well-preserved trilobites. Yet in the Cambrian, marine sediments containing them are confined to the Jince Formation of the Middle Cambrian. The Lower Cambrian consists mainly of continental conglomerates, and the later Middle Cambrian and Upper Cambrian are mainly alluvial, the latter deposited in an active and long-continued volcanic setting (Havlíček 1971, Geyer et al. 2008). The characteristic general of the Jince Formation include *Paradoxides*, *Ellipsocephalus*, *Conocoryphe* and others, immortalised in one of Zdeněk Burian's paintings, and these are elements of a very diverse and widespread fauna which can be traced from eastern Newfoundland, through southern France and northern Spain, Wales and central England, and Scandinavia.

The Scandinavian Cambrian successions are likewise rich in trilobites, and it is interesting to compare and contrast these with the Bohemian faunas. The Lower Cambrian in Scandinavia consists mainly of sandstones, with trilobites in shales at a few horizons. Then, with the deposition of the middle to upper Cambrian shale sequence we are in a unique facies known as the Alum Shales. The Middle Cambrian consists mainly of genera such as those of the Jince Formation; it is remarkably rich and diverse. In southern Sweden alone there are two horizons of limestone, in which there are 12 and 15 agnostoid and 7 and 13 polymeroid genera respectively. Above these there is a remarkable transition, testifying to a major environmental perturbation, for the highest horizon of the Middle Cambrian consists almost entirely of the agnostoid trilobite *Agnostus pisiformis* which literally occur in uncountable millions. (Terfelt et al. 2008). The base of the overlying Furongian is defined as the FAD of *Glyptagnostus reticulatus*, following which is a sequence of beds dominated by trilobites of the Family Olenidae, the main subject of this presentation. These do not, of course, occur in Bohemia since the Furongian sediments are continental. Would there have been a similar sequence in the Barrandian if there had been marine sediments? It is tempting to think so. In Newfoundland, and in Wales and England, the Furongian faunas are dominated by olenids, but by contrast, the coeval trilobites in the Montagne Noire in southern France is quite different, with a strongly Chinese aspect (Shergold et al. 2000).

The Alum Shales of Scandinavia

Before going further, we should consider the paleogeography of the time (fig. 1). During the Cambrian, the

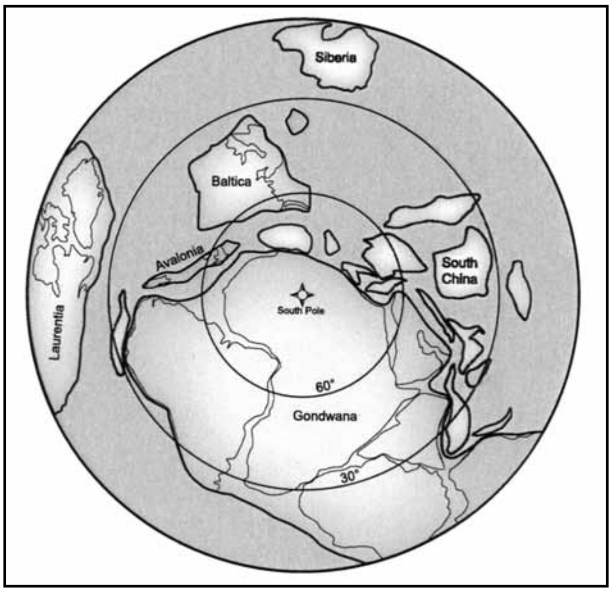

Fig. 1: The Late Cambrian world with the position of Baltica in southern latitudes (from Terfelt).

Laurentian continent sat astride the equator, as it did for the later Palaeozoic. On the other side of the globe lay Gondwana, not yet split into separate landmasses, and in between were the free continents of Kazachstania and Siberia, while in higher southerly latitudes there resided the continent of Baltica, now Scandinavia and Russia west of the Urals. This was the 'heartland' of the olenid trilobites, and it was here, in cool dysoxic waters where they evolved and proliferated, and from where they migrated to other areas. They were able also to colonise the cool deep water surrounding other continents where the temperature was similar to that to which they were accustomed. We shall consider first the Scandinavian olenid faunas of Furongian time, later we shall examine the final stages of their evolution.

We have noted the vast numbers of *Agnostus pisiformis* at the top of the Middle Cambrian. Occasional specimens of the earliest olenid, *Olenus alpha* are found therein. Above this the fauna is dominated by other olenid trilobites, the type genus *Olenus* belonging to the earliest zones of the Furongian where it occurs at certain levels with *Homagnostus obesus*. Interestingly, agnostoids become very rare above this level; there are only a few occurrences, but these are of great value in providing tie points with other continental masses, since the agnostoids have a very wide distribution. Likewise there are rare instances of large polymeroids ("tourists" to use the apt words of Anna Żylińska) from other continental masses which can be used in the same way (Rushton 1967, 1983, Żylińska 2000). The spectacular change from the high-diversity Middle Cambrian trilobite fauna to the low-diversity Furongian fauna is far from well understood at the present time.

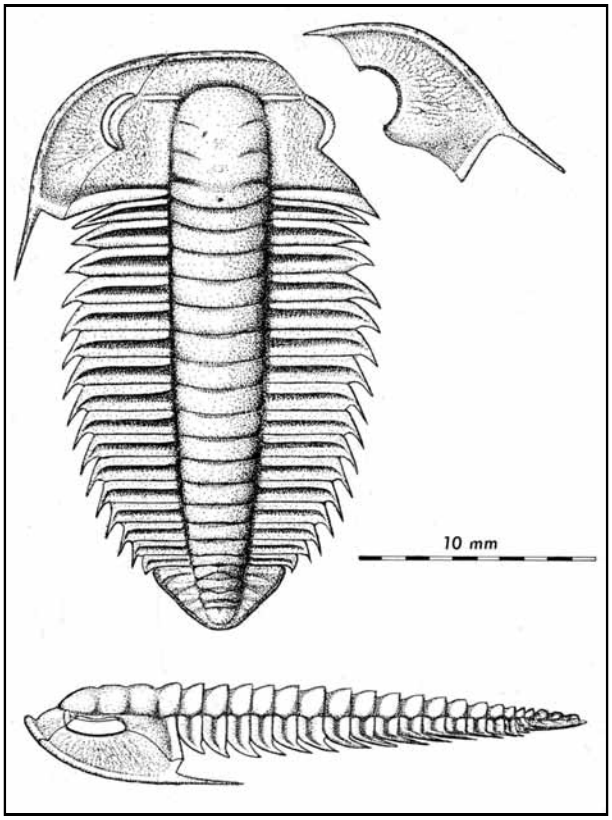

Fig. 2: Reconstruction of *Olenus wahlenbergi* Westergård in dorsal and lateral views. Andrarum, Skåne, Sweden.

Andrarum, Skåne, Sweden

The best place to study the Furongian succession is at the old quarries at Andrarum, in eastern Skåne, the southernmost part of Sweden. Here some 80 metres of Furongian sediment are exposed, overlying 30 metres of Middle Cambrian; they are mainly dark shales with some limestone beds, and very many calcareous concretions. They were exploited for the extraction of alum between 1636 and 1912, and the remains of the old workings are still visible, as well as the red heaps of shale from which the alum has been boiled out. The olenids occur in countless numbers in some parts of the shale sequence, but are almost universal, and often superbly preserved in the concretions.

The Andrarum succession forms a superb natural laboratory for studying very many aspects of trilobite evolution, the relationship of the trilobites to changing environments and the other organisms within it, changing diversity, biotic turnovers, and the overall environment. Our intention over many years of research, and for the foreseeable future, has been to elucidate as much as possible about the Alum Shale environment and its faunas, using as many kinds of diverse evidence as possible, and to try to link them in to a common synthesis.

Biostratigraphy and olenid evolution

Although there are four 'barren intervals' within the Furongian sequence, the succession is otherwise remarkably complete. The rate of faunal turnover is very high, and in consequence the olenid trilobites are of great use in stratigraphy. The overall succession has been known for at least 150 years. A basic scheme of evolutionary relationships was given by Westergård (1922) and elaborated further by Henningsmoen (1957). A recent biostratigraphical revision (Terfelt et al. 2008) links four agnostoid zones with 28 zones based on olenids. In ascending order these are the zones of *Olenus* (6), *Parabolina* (2), *Leptoplastus* (6), *Ctenopyge* (8), *Parabolina lobata* (1). *Peltura* (3) *Westergaardia* (1) and *Acerocare* (1) Since there is only one olenid species in each zone in the lower part of the sequence, evolutio-

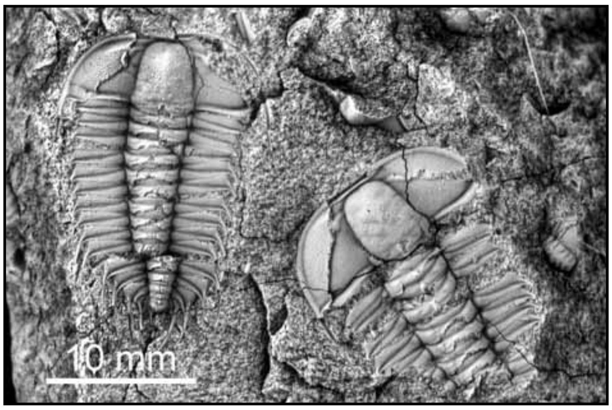

Fig. 3: Type specimens of *Parabolina spinulosa* Wahlenberg. Andrarum, Skåne, Sweden.

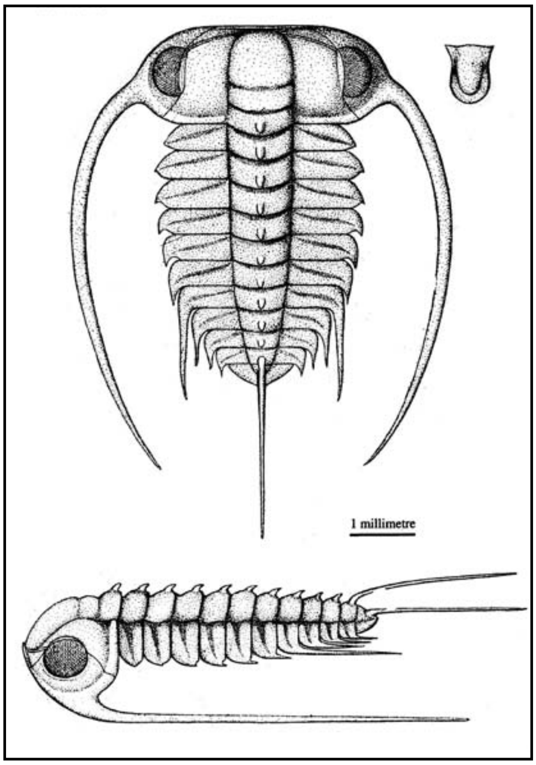

Fig. 4: *Ctenopyge angusta* Westergård. Adult specimen, reconstructed. The long genal spines would support the body above the sea floor, the gills above the dysoxic sea floor. Västergötland, Sweden.

nary relationships at the generic and specific level are easy to determine stratophenetically. The *Olenus* and overlying *Parabolina* zones (fig. 2, 3) have only one species at each level and are dominated by rather 'ordinary-looking' trilobites. Above this, in the *Leptoplastus* zone, some very interesting things begin to happen. (Ahlberg et al. 2006). Firstly the rate of evolutionary change and faunal turnover speeds up dramatically. Secondly, new morphotypes originate, especially forms with very long genal spines. Such morphology provided a springboard for later innovations in the *Ctenopyge* zones (figs 4–6). Thirdly there may be up to four olenid species co-existing. Towards the top of the Furongian, such bizarre forms disappear, and more standard olenid types prevail. Evolutionary convergence is common and some morphotypes are virtually 'repeats' of earlier ones, presumably suggesting similar adaptations.

Microevolution and faunal dynamics

Species-to-species transitions in olenids, and at the same time, faunal dynamics within populations can readily be undertaken by band-by-band collection and counting within a quadrat. The first such analysis was undertaken by Kaufmann (1933) on limestone beds within barren shale intervals in the *Olenus* zones, and indicated four successive trends involving the lengthening and narrowing of the pygidium. Further studies were undertaken in fossiliferous shales of the same age, elsewhere in the quarry (Clarkson et al. 1998), confirming at least one of these microevolutionary trends, and showing that agnostoids and olenids could either occur separately or together. Further studies, with broadly similar conclusions (though more critical of Kaufmann's work), were presented by Lauridsen – Nielsen (2005). Another, very detailed bed-by-bed study, in the *Leptoplastus* zones (Ahlberg et al. 2006) showed that particular faunal associations are often confined to discrete sedimentary packages, or arise after an unfossiliferous interval. Some species may range through several sedimentary changes. Here there are three or even four olenid species at some levels.

Olenid ontogenies

The preservation of many olenids in the concretions is exquisite, and they are often still well-preserved, though flattened, in the shales. Moreover, the juveniles are frequently preserved with the adults which enables detailed studies of ontogeny, i. e. development from early larva to adult, to be undertaken. The use of the scanning electron microscope has greatly facilitated this end. So far, the ontogenies of ten or more olenid species have been worked out and these studies are continuing (figs 4–6) (Clarkson – Taylor 1995a, 1997, Clarkson – Ahlberg 2002, Clarkson et al. 2003, 2004, Tortello – Clarkson 2003, 2008). These studies also shed light on the relationship between ontogeny and phylogeny: *Parabolina*, for example, is a direct descendant of *Olenus*, the

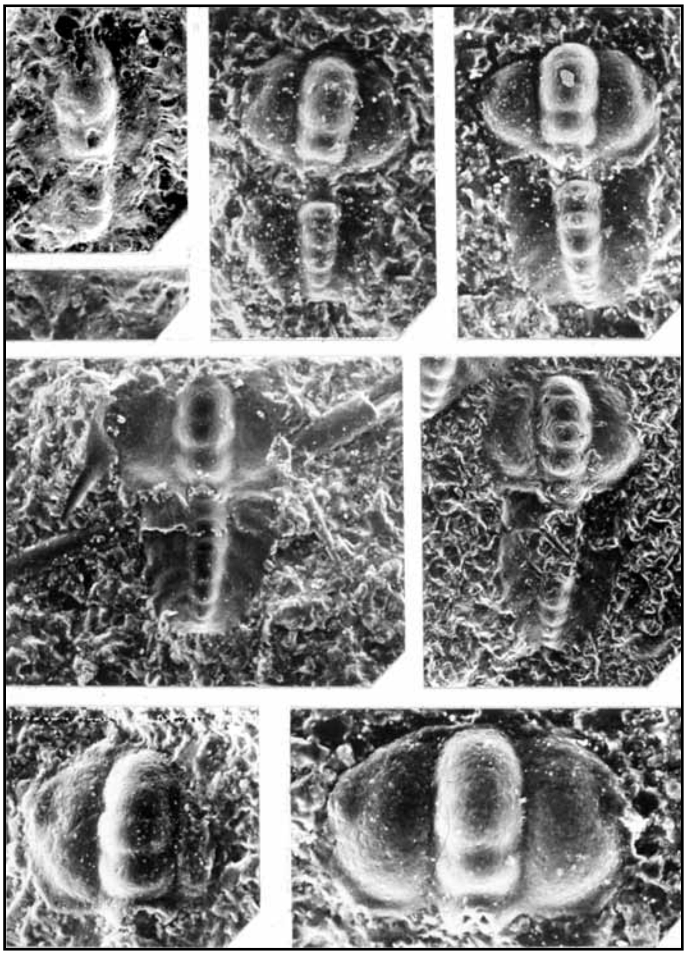

Fig. 5: *Ctenopyge angusta*. Westergård. Juvenile stages of ontogeny (SEM photographs, for size compare the scale bar at the fig. 6) Västergötland, Sweden.

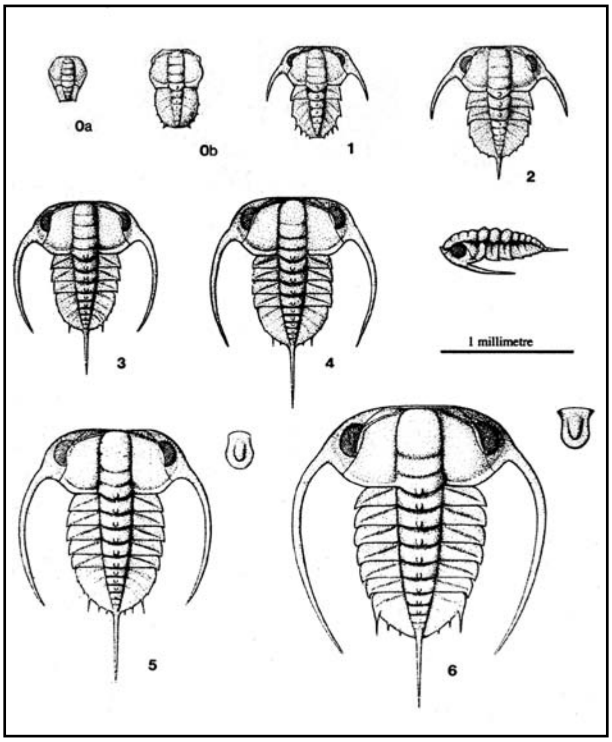

Fig. 6: *Ctenopyge angusta*. Westergård. Juvenile stages, reconstructed. Västergötland, Sweden.

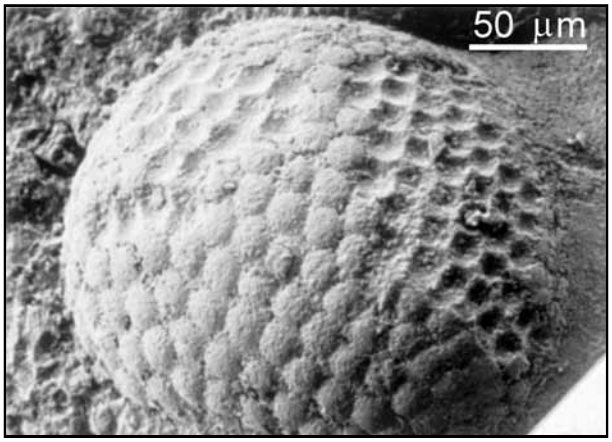

Fig. 7: *Ctenopyge angusta*. Westergård. Holochroal compound eye. SEM photograph.

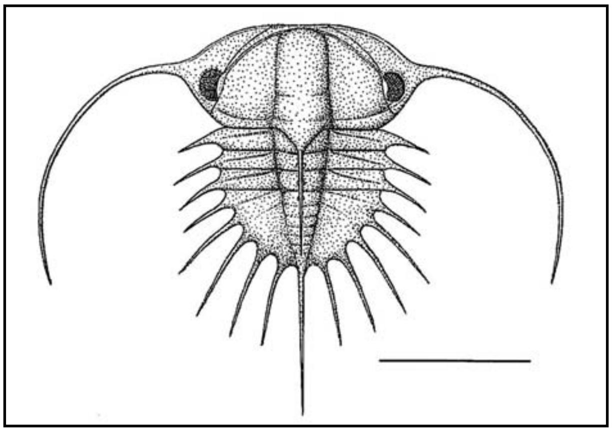

Fig. 8: *Ctenopyge ceciliae* Clarkson & Ahlberg, a planktonic olenid, reconstructed. Scale bar 500 microns. Skåne, Sweden.

'new' characters having arisen by mosaic heterochrony (Clarkson – Taylor 1995a). Moreover, ontogenetic development in some olenids is tightly constrained, with sizes of instars plotting out in discrete groups. In others, however, especially *Parabolina* and *Protopeltura* there seems to be much less restraint on developmental variability, a subject being actively investigated now.

Olenid life habits and functional morphology

The excellent preservation gives plenty of scope for investigations of functional morphology and life habits. Olenids seem to have lived as vagrant benthos, adapted to low oxygen conditions. Some may have fed on the kind of chemosynthetic bacteria typical of such environments (Fortey 2000). The compound holochroal eyes of some olenids (Clarkson 1973) are often well-preserved and offer much scope for detailed optical analysis (fig. 7). One miniaturised and spiny species, *Ctenopyge ceciliae*, (Clarkson – Ahlberg 2002, Schoenemann – Clarkson 2010) (fig. 8) became planktonic, as indicated not only by its tiny size and spinosity, but also from the optics of its eyes, adapted to strong light. The most extreme modification of the basic olenid ground plan began in the *Leptoplatus* zone. In this and the following *Ctenopyge* zones some olenids developed very long genal spines (probably used for resting on the sea floor keeping the gills well above the dysoxic or anoxic sea-floor mud) Clarkson – Taylor 1995b, Clarkson et al. 2003, 2004) (fig. 4). But the body spinosity of these remarkable trilobites, so evident in many olenids at this stratigraphical level, is not fully explained, even though they can be reconstructed from various angles. It is not easy to interpret, for example, the strange morphology of *Ctenopyge ahlbergi* (fig. 9). Many of these species are superficially similar in form to odontopleurids. Interestingly, towards the top of the Furongian, the olenids reverted to much more normal and less bizarre morphology. A specialised fauna of late Cambrian – Tremadocian olenids found in northern Norway (Nikolaisen – Henningsmoen 1985) include forms with unusual morphologies which would well repay studies of their life habits.

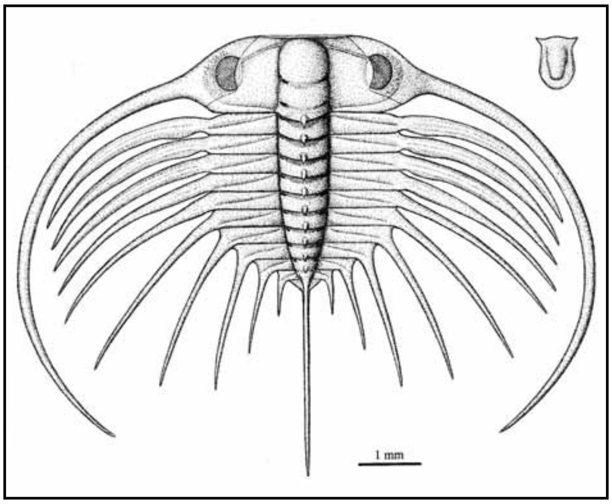

Fig. 9: *Ctenopyge ahlbergi* Clarkson, Ahlgren & Taylor, reconstructed, one of the most highly modified of all olenids. Västergötland, Sweden.

Brachiopods

Brachiopods are uncommon in the Furongian, apart from the articulated benthic finkelbergine *Orusia*. This occurs in great abundance in the *Parabolina* zone, sometimes alone, and forming substantial monospecific assemblages, and sometimes together with *Parabolina*. It is found in Scandinavia, in north Wales, and has recently been discovered in the Montagne Noire, southern France (D. A. T. Harper, pers. comm.). Its presence must represent times when the sea floor was firm and probably more oxygenated than usual, and its geographical and detailed stratigraphical distribution are being investigated at present, as an important component in the overall history of changes in the Alum Shale environment.

Other associated faunas

The associated faunas, which give further insights into the environments of the time are of two main kinds. Firstly there are the astonishingly well-preserved *Agnostus*, stem-group crustaceans, pentastomids etc. described by the active research groups in Bonn and latterly Ulm. (Müller – Walossek 1985 and many subsequent references). The crustaceans and other groups may well have inhabited the flocculent layer on the sea floor, and formed an active part of the benthos. These were first discovered in 1975 when a search was being made for conodonts, the latter subsequently described by Müller – Hinz (1991). They are preserved as a thin bacterial film which spread over the whole surface after the death of the arthropods. Secondly a fauna of phosphatised olenid fragments, beautifully preserved, was found at the top of the *Peltura scarabaeoides* zone (Ahlberg et al. 2005). Amongst the fragmentary olenids, perhaps the best preserved so far known, were chaetognaths and conodonts, pelmatozoa columnals, a possible camaroid, a possible conulariid, and fossils of unknown affinity. These must have lived in dysoxic rather than almost anoxic conditions, and the sea floor must at that time have been firm enough to allow colonisation by sessile organisms.

Geochemistry

The Alum Shales have long been known for their heavy elements, V, Mo, Ni, U etc., Schovsbo (2001, 2003) has documented shoreward enrichment in uranium, and environmental fluctuations within the *Olenus* zone based on geochemistry. Further work in progress at Lund University seeks to provide a carbon isotope curve, calibrated against a high reolution biostratigraphy for the Middle Cambrian though Furongian. So far two major excursions have been recorded, the negative DICE (DrumIan Carbon Isotope excursion) in the *Pt. atavus* zone of the Middle Cambrian, and the SPICE (Steptoean Positive Carbon Isotope Excursion) in the lower Furongian *Olenus* and *Homagnostus* obesus zone (Ahlberg et al. 2009, 2–16). These link with global changes in other continents.

Barren intervals

The lack of fossils in the barren intervals may be the result of a complete lack of oxygen during sedimentation. But there is good geochemical evidence that some, at least, resulted from an excess of oxygen at the time remobilising the unconsolidated mud and dissolving the fossils (Schovsbo 2000, 2002). The barren intervals are not necessarily barren of all fossils, but only of trilobites, brachiopods and other organisms with calcareous shells. They may contain phosphatocopines, which are small bivalved arthropods; one such instance where the phosphatocopines in aggregates; the faeces of some predator, has recently been described from the *Agnostus pisiformis* zone (Eriksson – Terfelt 2010).

Changing sea levels

There is no question that many of the enviroinmental fluctuations within the Furongian are closely linked to changing sea-levels. A major flooding event has been recognised at the base of the Middle Cambrian, likewise several fluctuations within the Furongian. The *Parabolina* zone, for example seems to have been a time of relatively low sea-level. There is much scope for further detailed investigations, linking sea-level fluctuations seen in Scandinavia with global events.

An extinct environment

Not only do living organisms become extinct, but the environments they inhabited may become extinct too. Although there may be some resemblances to sediments on the anoxic or dysoxic shelves of the Atacama and Namibian deserts, the Alum Shales environment is best regarded as both unique and extinct (fig. 10).

The later history of the olenids

Olenid trilobites are well known from Middle Ordovician rocks in Jämtland, Sweden (Månsson 1998), in Argentina (Harrington – Leanza 1957, Balsiero et al. 2010) and North America, where the long-ranging genus *Triarthrus* persists until towards the end of the Ordovician (Ludvigsen – Tuffnell 1995). In most cases, however, the olenids form part of a more diverse and 'normal' fauna

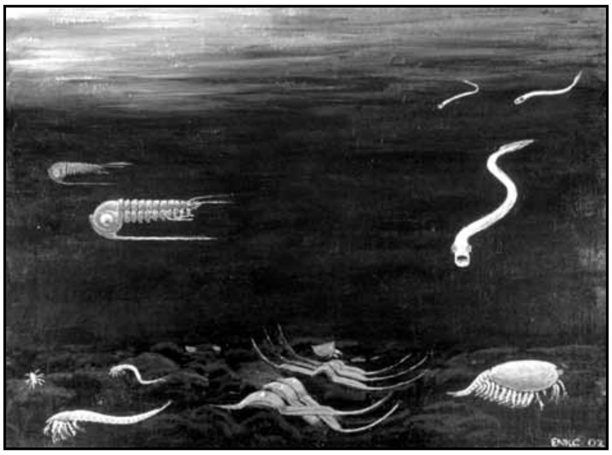

Fig. 10: Reconstruction of the Swedish Alum Shales environment in the late Middle Furongian, with *Ctenopyge angusta* and conodont animals (swimming), moulted C. (*Mesoctenopyge*) fragments, and small crustaceans in the flocculent layer on the sea floor.

during the Ordovician. Though they may form spectacular monospecific assemblages (fig. 11) they appear to have lost their specialised adaptation to dysoxic facies, and during the Ordovician lived in waters of more standard oxygen levels (Balseiro et al. 2010). An interesting case of survival in changing circumstances.

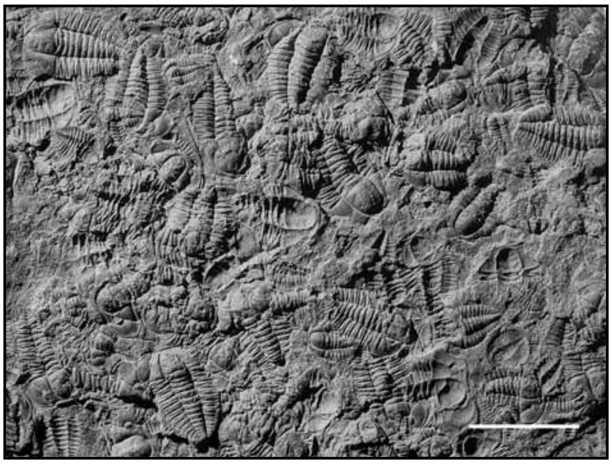

Fig. 11: *Leptoplastides salteri* Raw. A monospecific assemblage of an olenid from the Tremadocian Shineton Shales, Shropshire, England. Scale bar 20 mm.

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PALAEOGEOGRAPHY AND STRATIGRAPHY OF THE BOHEMIAN CRETACEOUS BASIN (CZECH REPUBLIC) – AN OVERVIEW

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Key words: Bohemian Cretaceous Basin, palaeogeography, stratigraphy

Abstract
Palaeogeographically, the area of the present day Bohemian Cretaceous Basin (BCB) formed a narrow Seaway between the North Sea Basin and the Tethys Ocean during the Late Cretaceous. The BCB together with adjacent Brannau-Regensburg Basin (Danubian Cretaceous Group) in Bavaria were a part of the peri-Tethyan shelf zone and contain a record of recurrent warm-temperate faunal assemblages with several incursions of Boreal fauna. The distribution of the coarse siliciclastic sediments demonstrate a significant control of stratigraphic architecture by tectonic activity and spatially variable sediment supply during the lifetime of the Bohemian Cretaceous Basin. Intra-basinal correlations of the BCB are based on application of both, non-biostratigraphic and biostratigraphic or eventostratigraphic methods. Nevertheless, some difficulties still appear with intra- and interbasinal correlation of the BCB (e. g., continental/marine, nearshore-offshore, entry of biomarkers or Boreal/Tethys correlations).

Late Cretaceous palaeogeography and tectonosedimentary history

The Bohemian Cretaceous Basin (BCB), the largest of the intracontinental basins within the Bohemian Massif, extends across Saxony, Bohemia, Moravia and Silesia. During the late Cretaceous the area of present day Bohemian Cretaceou Basin formed a narrow Seaway connecting the North Sea Basin and the Tethys Ocean (fig. 1).

According to general palaeogeographic context, the BCB was surrounded by an archipelago of emerged paleo-highs (Central European Island, West and East Sudetic Islands) (fig. 1) from which the nearshore siliciclastic sediments were derived. The quartzose to subarcosic sandstone (Quadersansteine) lithofacies is unique and most dominant for BCB in contrast with chalk facies developed in the most part of the North Sea Basin in the Central and Western Europe. A diverse recurrent assemblages of warm-water fauna (e. g. rudists, colonial hexacorals, nerineid and actaeonellid gastropods, thick-shelled bivalves, rock-boring and cemented bivalves) were associated with paleo-highs while temperate benthic fauna inhabited their shoreface and offshore zones (Kollmann et al. 1998, Žítt – Nekvasilová 1996). Palaeobotanical data (Knobloch 1991) reveal a subtropical/tropical climate conditions which prevailed over long periods of the whole lifetime of the BCB. Thus the Bohemian Cretaceous Basin and the adjacent Brannau-Regensburg Basin (Danubian Cretaceous Group) in Bavaria formed a peri-Tethyan shelf zone during the Late Cretaceous.

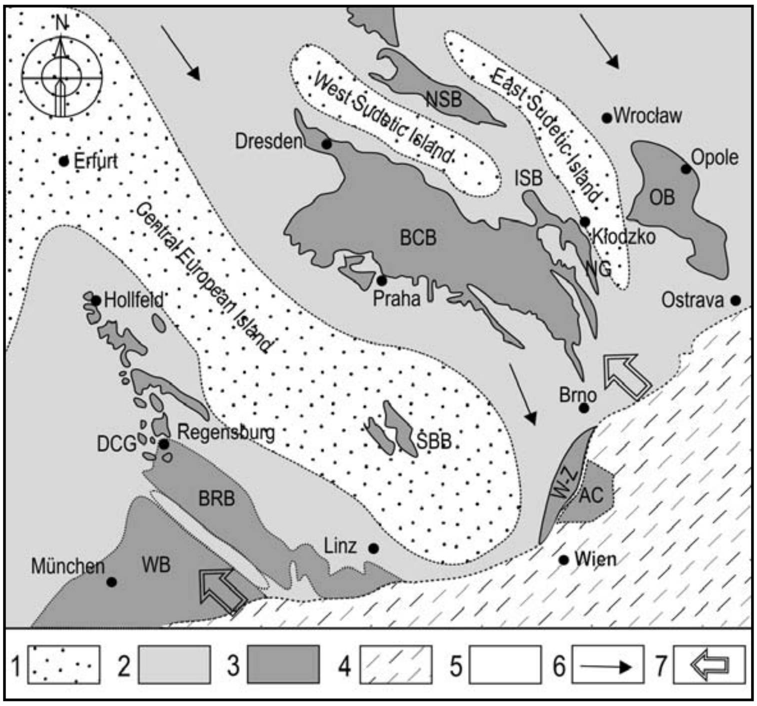

Fig. 1: Simplified paleogeographic situation of the Bohemian Massif and adjacent areas during the Cretaceous. Explanation: 1 – emerged paleo-highs; 2 – epicontinental seas; 3 – preseved Cretaceous basins: BCB, Bohemian Cretaceous Basin; NSB, North Sudetic Basin; ISB, Intrasudetic Basin; NG, Nysa Graben; OB, Opole Basin; SBB, South Bohemian Basins; DCG, Danubian Cretaceous; BRB, Brannau-Regensburg Basin; WB, Wasserburg Basin; W–Z, Waschberg–Ždánice Zone; AC, Autochtonous Cretaceous recognized in the deep cores beneath the foreland basin deposits and Flysch Belt of the West Carpathians; 4 – deep marine basins; 5 – outer margin of Alpine and Carpathian nappes; 6 – cool bottom currents; 7 – warm surface currents (adapted from Valečka – Skoček 1991).

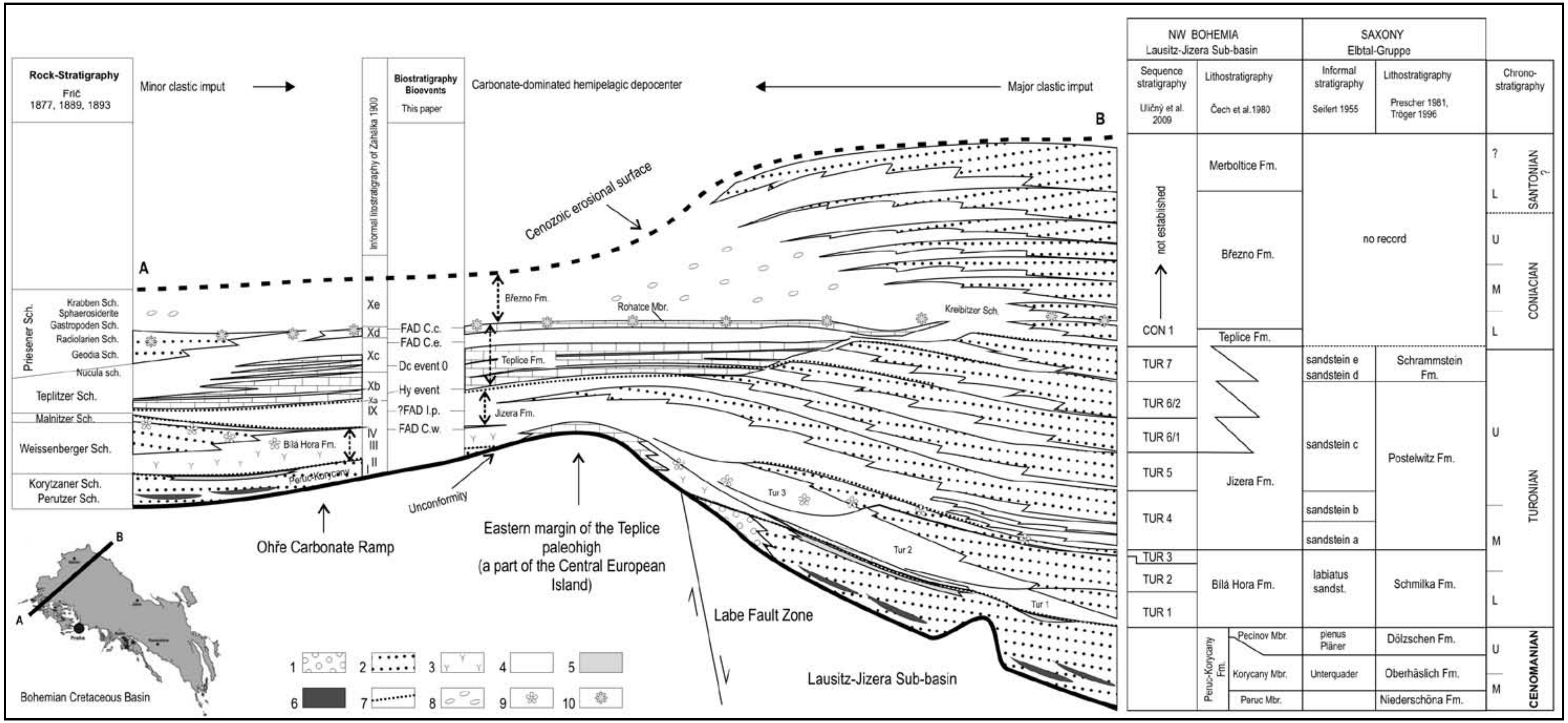

Fig. 2: Idealised regional cross-section of the NW part of the BCB showing principal lithofacies, regional stratigraphic units of the Late Cretaceous sediments in NW Bohemia and in Saxony, genetic stratigraphic units, informal lithostratigraphic units, biostratigraphic markers and some bioevents. Explanation: 1 – conglomerates; 2 – sandstones (Quadersandsteine); 3 – spiculitic sandstones to siltsones; 4 – marlstones to calcareous claystones; 5 – plenus Bed; 6 – coal; 7 – glauconitic beds; 8 – clay ironstone nodules; 9 – LAD *Mytiloides hercynicus*; 10 – *Cremnoceramus deformis crassus* Event.

However, several incursions of typical Boreal fauna are evidenced by the occurrences of belemnites in the BCB (Košťák et al. 2004).

The BCB was formed probably during the mid-Cretaceous reactivation of the main fault zones of the Variscan basement of the Bohemian Massif in combination with features of the global transgression (Cenomanian transgression). The Elbe Fault Zone and conjugate, NNE trending, Jizera System faults played a significant role in the tectono-sedimentary evolution of the BCB. The tectonosedimentary evolution of the BCB can be subdivided into three periods or phases (Uličný et al. 2009).

In the Cenomanian, the fluvial, estuarine and shallow shoreface facies association reflects a long-term sea-level rise (Phase I). During the late Cenomanian and the Turonian, coarse clastic sediments filled two main depocenters within the BCB (Phase II): the Lausitz-Jizera in the NW and the Orlice-Žďár in the SE. Significant changes in basin geometry, deposition of thick clastic wedges with extensive basinal muds and long-term sea-level fall took place in the Coniacian and the Santonian (Phase III). Maximum preserved thickness of Cenomanian to Santonian deposits is ca. 1 000 m in the Lausitz-Jizera sub-basin (fig. 2). The data on organic maturity analyses of the sediments of the BCB indicate that the deposition in the basin probably continued beyond the Santonian. However, these sediments have been eroded during the Cenozoic inversion and erosion (Uličný – Franců 1996).

Lithostratigraphy, genetic stratigraphy and chemostratigraphy

Stratigraphic subdivision of the BCB is based on the regional lithostratigraphic concept (Čech et al. 1980) (fig. 2) which follows the formerly established rock-stratigraphic concept of Frič. But some lithostratigraphic units are defined in terms of cyclostratigraphy (Bílá Hora Fm., Jizera Fm.) or allostratigraphy (bases of the Bílá Hora and Teplice Formations). More recently, sequence/or genetic stratigraphic concept was used by Uličný et al. (2009) (fig. 2) to correlate marginal marine and basinal Turonian sequences in NW Bohemia (fig. 1). Cyclostratigraphic and chemostratigraphic analyses are also used for the Cenomanian (Uličný et al. 1997) and Turonian (Štaffen 1999, Wiese et al. 2004) intra- and inter-basinal correlations as well as litho-events (Valečka – Skoček 1991).

Biostratigraphy and palaeontology

Macrofossils (inoceramids, ammonites, belemnites, echinoderms, sponges, brachiopods, vertebrates) and micro-or nannofossils (foraminifers, calcareous nanoplankton, palynomorphs) have been studied for biostratigraphic correlation.

CENOMANIAN

According to palynomorph analyses (Svobodová 1999), fluvial deposits of the Peruc Member in the lowermost segment of the fill of the SE part of the BCB are of Early Cenomanian age. Rare occurrences of *Mytiloides atlanticus* in the Korycany sandstone indicate a Middle Cenomanian age. Ammonites of *Calycoceras guerangeri* and *Metoicoceras geslinianum* zones of the Upper Cenomanian are known from the Korycany and Pecínov members of the Peruc-Korycany Formation. Among inoceramids, *Inoceramus pictus* and its subspecies have been found in these zones. A prominent *plenus* Event is developed both in rocky-shore and basinal facies in the BCB within the *M. geslinianum* zone (Košťák et al. 2004, Svoboda 2006). *Mytiloides hattini* is also associated with this zone. Nevertheless, ammonites and inoceramids are usually missing at the Cenomanian/Turonian boundary. Only calcareous nannoplankton could identify a regional stratigraphic gap (including *N. juddi* and a part of *W. devonense* zones) at the Cenomanian/Turonian boundary in the boreholes in the south central part of the BCB (Švábenická in Čech et al. 2005).

TURONIAN

Near the base of the Bílá Hora Formation, Lower Turonian inoceramids of *Mytilodes kossmati* and *M. mytiloides* and ammonites of *Mammites nodosoides* are frequent. The last appearance datum (LAD) of *M. hercynicus* and *M. subhercynicus* is more prominent than their entry in the Bílá Hora Formation (fig. 2). In the basinal facies, the first appearance datum (FAD) of *Collignoniceras woolgari* is well recognized at the Lower/Middle Turonian boundary. The base of the Upper Turonian, usually defined as FAD of the inoceramid *I. perplexus*, has not been precisely established in the BCB yet. In the Úpohlavy Quarry, a significant *Hyphantoceras reussianum* Event (fig. 2) and a short-term incursion of *Preactinocamax bohemicus* in the Late Turonian was reported by Wiese et al. 2004 and by Košťák et al. (2004). A stratigraphic gap was recorded within the *H. reussianum* Event and discussed by (Čech 1989, Wiese et al. 2004, Vodrážka et al. 2009). The position of the Turonian/Coniacian stage boundary was studied (inoceramids, calcareous nannoplankton) at the type locality of the Březno Formation in the SW part of the BCB (Čech – Švábenická 1992). *Didymotis* events at this stage boundary (fig. 2) and the entry of calcareous nannoplankton species *Marthasterites furcatus* were discussed by Čech (1989, 2009) and by Švábenická (2010).

CONIACIAN

For Lower Coniacian, inoceramid *Cremnoceramus deformis crassus* is the most conspicuous in all facies in the BCB, while *C. erectus*, a biomarker for the base of the Coniacian, is scarce. The Lower/Middle Coniacian boundary is well marked in the BCB by the FADs of inoceramids *Volviceramus koeneni* and *Platyceramus mantelli* rather than by ammonites. The Upper Coniacian is characterized by the occurrence of inoceramid *Magadiceramus subquadratus* in the boreholes in NW Bohemia (Macák – Müller 1963). The Coniacian strata of the Březno Formation can be also well subdivided on the basis of benthic foraminifers (Hercogová 1974).

SANTONIAN

According to foraminifers and ostracods, Santonian species (*Gyroidinoides globosa*, *Gavelinella pertusa* and *Colcocythere costanodulosa*) appear within the Coniacian *M. subquadratus* Zone (for discussion see Čech et al. 1987). The uppermost fill of the BCB (Merboltice Formation) contains only long-range agglutinated foraminifers.

There are still several difficulties with stratigraphic subdivision and correlation of the Cretaceous deposits of the BCB. 1) determination of the age of the fluvial sediments and the correlation of non-marine and marine strata, 2) correlation of the different but coeval facies (rocky shore sediments – basinal muds – progradational clastic wedges, 3) time transgressive character of some lithological units in view of biostratigraphy and genetic stratigraphy, 4) the absence or scarce occurrence of some marker fossils (ammonites), 5) changes in the stratigraphic value of some taxa (e. g. *M. furcatus*), 6) different concepts of the stage/substage boundaries in several groups of fauna and flora, 7) correlation with adjacent intracontinental basins around the Bohemian Massif, 8) Boreal/Tethys correlation.

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CAMBRIAN AND ORDOVICIAN FOSSIL-LAGERSTÄTTEN IN THE BARRANDIAN AREA

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Key words: Cambrian, Ordovician, Fossil-Lagerstätten

Abstract

Exceptionally preserved fossils showing typical characters of the so called Konservat-Lagerstätten are shortly mentioned from Cambrian and Ordovician sediments of the Barrandian area. Fossils with well preserved soft parts were ascertained in several different levels of two Cambrian units of the Příbram-Jince Basin as well as in diverse levels of the Skryje-Týřovice Basin. Other exceptionally preserved fossils are shortly discussed from numerous Lower to Upper Ordovician levels of the Prague Basin.

Introduction

The existing evidence of exceptional preservation of fossils in the so called Fossil-Lagerstätten (see Seilacher 1970, Seilacher et al. 1985, Allison, 1988), provide a unique window in fossil communities, including Cambrian and Ordovician. However, lagerstätte are generally rare. Despite their rarity, they play a fundamental role in understanding evolution of the life, but also in reconstructing of trophic web in the past (e. g. Butterfield 2002, Briggs – Crowther 2007).

Cambrian and Ordovician successions of the Barrandian area are well known by skeletal fauna studied for more than 150 years. Despite such a long tradition of palaeontological research and the high level of recent knowledge, soft-bodied remains preserved in Lagerstätten are obviously underestimated. During the two recent projects (GAČR 205/06/0395 "Palaeoecology and trophic structure of selected Cambrian and Ordovician fossil assemblages in the Barrandian area" and GAČR 205/09/1521 – "Palaeoecological interactions in Cambrian and Ordovician communities in the Barrandian area") diverse exceptionally preserved soft-bodied fossils (= Konservat-Lagerstätten) were discovered in numerous levels in the Barrandian area. Four selected levels with exceptionally preserved fossils are shortly discussed here (fig. 1).

1. Paseky Shale Member (early Cambrian),
2. Buchava and Jince formations (middle Cambrian),
3. Klabava and Šárka formations (Lower-Middle Ordovician),
4. Letná Formation (Upper Ordovician).

Material and methods

In this chapter, the papers summarizing palaeontological and stratigraphical data are refered and the most recent discoveries of exceptionally preserved fossils are shortly discussed.

1. *Paseky Shale Member (early Cambrian)*

Preservation of legs and some other soft-parts was established in two quite spectacular arthropods, *Kodymirus* and *Vladicaris* (see Chlupáč 1996 and also Mikuláš 1996). Earlier data on stratigraphic distribution of other taxa described from the Paseky Member were recently compiled by Fatka et al. (2004).

Recent discoveries:

- so called elephant skin surfaces were established at several levels of the Paseky Shale Member,
- the enigmatic genus *Eldonia* was found at the Kočka locality,
- earlier not established fossil groups were ascertained (e. g. hyolithids).

2. *Jince and Buchava formations (middle Cambrian)*

Published data on all fossil taxa, including their stratigraphic and geographic distribution within the Buchava and Jince formations were compiled (Fatka 1990, Fatka et al. 2004, Geyer et al. 2008).

Recent discoveries:

Soft parts and other kinds of exceptionally preserved fossils were established in numerous samples. Some of these discoveries were studied in detail; several papers describing these finds were submitted during GAČR 205/09/1521:

- one of the oldest graptoloids was described by Maletz et al. (2005),
- the first occurrence of the enigmatic genus *Wiwaxia* was published (Fatka et al. 2011a),

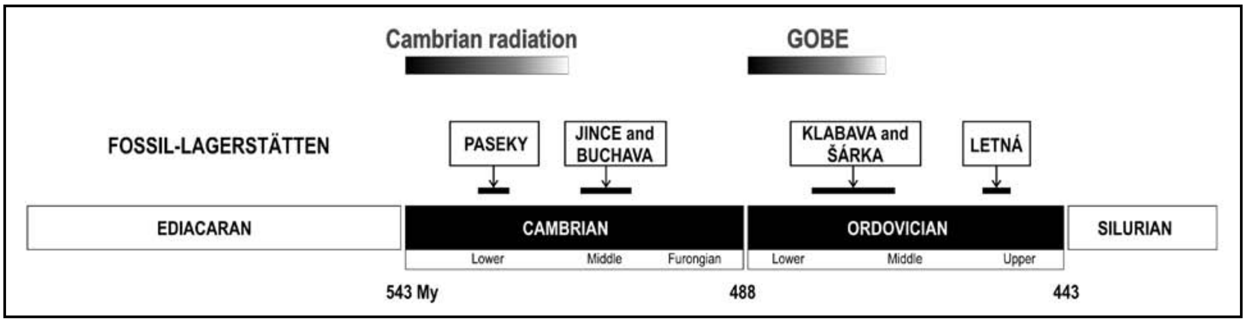

Fig. 1: Time frame of the studied Fossil-Lagerstätten (GOBE = Great Ordovician Biodiversification Event).

- feeding on carcasses of diverse skeletal fauna and the associated trace fossils were documented (Fatka et al. 2009b, 2011c, Fatka – Szabad 2011a, b),
- bitten and malformed agnostids were studied (Fatka et al. 2009a),
- feeding on carcasses of diverse soft-bodied fauna and the associated trace fossils were analyzed (Mikuláš 2001, Mikuláš et al. 2011),
- fodinichnial association – new type of trilobite mortichnia is defined by Fatka – Szabad (2011b),
- exceptionally preserved hyolithids as well as numerous articulated hyolithids feeding in situ are documented (Fatka et al. 2008, Valent et al. 2009, 2011a, b).

3. ***Klabava and Šárka formations (Lower – Middle Ordovician; Floian – Darriwilian)***

Published data on Lower Ordovician fossil taxa have been compiled by Kraft – Kraft (2000) and references therein. Data on Lower and Middle Ordovician primary producers were summarized by Fatka (1993), knowledge on the skeletal fossils was recently compiled for brachiopods and trilobites – Mergl (2002, 2004) and Budil et al. (2007), Mergl et al. (2007, 2008); graptolites – Kraft – Kraft (1999), Kraft – Mergl (1979) and ichnofossils – Mikuláš (1993, 1995, 1998). The brachiopod and trilobite assemblages were established and/or discussed (Mergl 2002, Mergl et al. 2007, 2008, Servais et al. 2008, Fatka – Mergl 2009).

Soft parts and other kinds of exceptionally preserved fossils are known in numerous samples of worms – Kraft – Mergl (1989), Harvey et al. 2010, agnostids – Slavíčková – Kraft (2001), and trace-fossils – Bruthansová – Kraft (2003). Some other discoveries were studied in detail within the grant GAČR 205/09/1521:

- bitten trilobites (Budil et al. 2010),
- exceptional sponge-radiolarian assemblage (Mergl – Duršpek 2006),
- echinoderm Lagerstätten (Lefebvre 2007, Lefebvre – Fatka 2003),
- soft parts of hyolithids (Valent – Kraft 2009).

4. ***Letná Formation (Upper Ordovician)***

Revision and description of new findings of the enigmatic arthropods were published (Rak 2009, Rak et al. 2009, Ortega-Hernández et al. 2010); the brachiopod and trilobite assemblages were recently re-evaluated (Servais et al. 2008, Fatka – Mergl 2009). Some of exceptionally preserved trilobites were also studied (Fatka et al. 2011).

Summary

All the five lithostratigraphic units, the Paseky Member, Jince, Buchava, Klabava, Šárka and Letná formations contain exceptionally preserved fossils and represent taphonomic windows of the Konservat-Lagerstätten type in several levels. Such levels offer an extraordinary possibility to study early Cambrian to Upper Ordovician ecosystems in the classical Barrandian area using earlier inaccessible data.

Study and evaluation of fossils collected from such Lagerstätten could provide very important information for reconstruction of the complex benthonic and in some cases planktonic parts of food web following the Precambrian/Cambrian agronomic revolution and the subsequent development associated with the GOBE (Global Ordovician Biodiversification Event).

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BRAND NEW GEOCHEMICAL DATA TOOLKIT *(GCDKIT 3.0)* – IS IT WORTH UPGRADING AND BROWSING DOCUMENTATION? (YES!)

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Key words: igneous rocks, geochemistry, graphics, software, Windows

Abstract

The freeware Geochemical Data Toolkit (www.gcdkit.org) is a flexible R-language package designed for handling, recalculation and plotting of whole-rock geochemical data from igneous and metamorphic rocks. The current version, GCDkit 3.0, was released in September 2011 and developed in the brand new R 2.13.0 for Windows. The release addresses some stability issues and improves the appearance of the plots. Apart from several new diagrams and plugins, it brings principal conceptual changes. The first is the internationalization – it introduces dictionaries, serving for the translation of classification diagrams. Czech and French localizations are provided as an example. Moreover, the system enables editing plates of multiple plots, in a manner previously available only for some of the stand-alone plots. Lastly, most of the commands can be invoked in batch mode, thus further speeding up otherwise tedious processing of large data files.

Meskimen's Law: There's never time to do it right, but there's always time to do it over.

GCDkit – an overview of the existing system

The GeoChemical Data toolkit, or in short *GCDkit*, is a comprehensive software package released some eight years ago to meet the growing demand for a potent tool capable of efficient handling, recalculation and plotting of whole-rock geochemical data from crystalline rocks (Erban et al. 2003; Janoušek et al. 2003, 2005, 2006). In its development, we have opted for the Windows version of the freeware R language (*http://www.r-project.org*), which in itself provides a rich environment for data analysis, graphics and software development. The *GCDkit* is thus a R-package tailored to meet specific needs of igneous geochemist, with the immense wealth of generic R functions within the easy reach.

The *GCDkit* not only offers a graphical user interface front-end to the (fraction of) powerful statistical and graphical functions built in R, but also provides a number of specialized tools designed specifically for igneous geochemistry. Available are core routines for effortless import, modification, searching, subsetting, classification, plotting and output of the geochemical data. Thanks to the *RODBC* package (Ripley – Lapsley 2010), it is possible to directly import from Excel, Access and DBF files, as well as the data formats used by the geochemical packages such as *NewPet* (Clarke et al. 1994), *IgPet* (Carr 1995), *MinPet* (Richard 1995) and *PetroGraph* (Petrelli et al. 2005). Moreover, imported can be the data from popular WWW-based databases such as *GEOROC* (*http://georoc.mpch-mainz.gwdg.de/georoc*) and *PETDB* (*http://www.petdb.org*).

The *GCDkit* comes with a wealth of built-in publication quality plots that can be exported into a number of data formats (including PostScript, PDF, WMF, JPG, PNG and BMP). The available graphs include user-defined binary, ternary and multiple binary diagrams (such as Harker plots), spiderplots as well as a wide palette of classification and geotectonic discrimination diagrams.

Most of the plots are defined as templates for *Figaro* – a set of graphical utilities for R, developed by C. Farrow and implemented in *GCDkit*. *Figaro* provides a means to create figure objects, which contain both the data and methods to make subsequent changes to the plot. So, for example, the title or its colour can be altered and any changes are automatically made visible. *Figaro* objects currently permit zooming and scaling of the diagrams, editing of the text, font, size and colour of the main title, secondary title and axis labels; colour, size and symbol for the data points; colour, type and width of the lines. Thus *Figaro* provides a degree of interactive editing before committing to hardcopy. Thanks to this approach, new diagram templates can be added in a rather simple way.

The templates can be used also as a basis for classification. The general classification algorithm, based on the R package *sp* (Pebesma et al. 2011) looks for the name of the polygon within the diagram, into which the rock analysis falls according to its x–y coordinates. Moreover, *GCDkit* comes with tools for identification of data points on binary/ternary plots and spiderplots. There is a function for interactive labelling of individual analyses (typically by sample names but other labels can be specified).

The system is easy to expand by means of the so-called plugins that provide a simple method of adding effortlessly new items to the menus of *GCDkit*.

Exactly three years elapsed since the last version (2.3) of GCDkit for R 2.7.0 has been released. Meanwhile, Windows Vista and then Windows 7 became widespread, and R reached version 2.13, bringing about some stability issues and thus also necessary amendments. The new *GCDkit 3.0*, released in September 2011, not only tackles

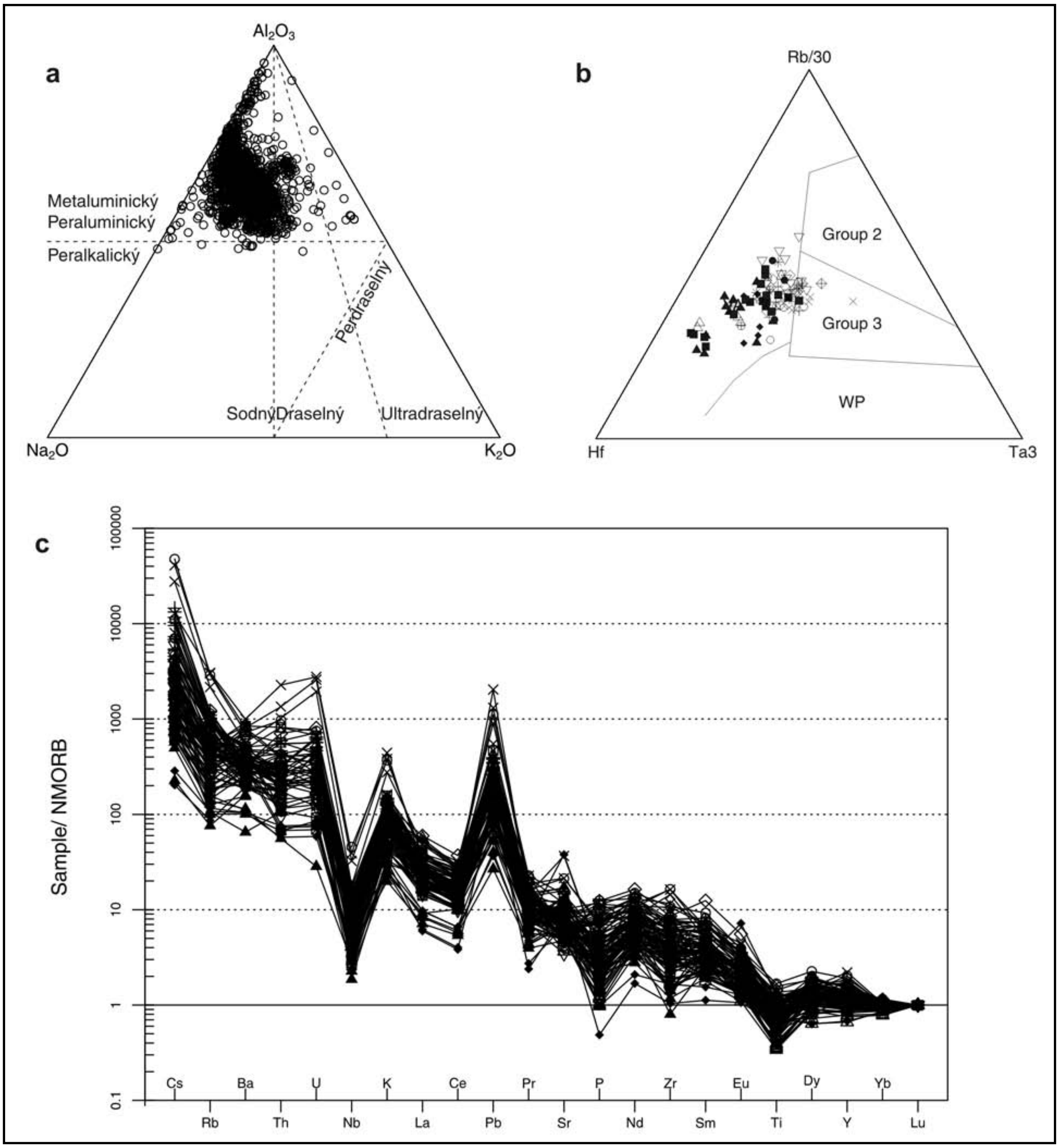

Fig. 1: Examples of diagrams newly introduced by *GCDkit* 3.0. a – Ternary plot Na_2O–Al_2O_3–K_2O (mol. %); b – Ternary diagram Hf–Rb/30–Ta×3, serving for classification of collisional granites (after Harris et al. 1986); c – Double normalized spiderplot [by NMORB composition after Sun – McDonough (1989) and then adjusted so that the normalized Lu contents equal unity].

these problems, but also introduces a number of new features, some indeed revolutionary, as summarized bellow.

Added functionality in the new release

Like in the previous releases, several new graphs have been implemented. For instance, the ternary plot of Na_2O–Al_2O_3–K_2O (mol. %) can support an assessment of the balance of alumina and the two alkali oxides (fig. 1a). Modern and robust multivariate diagrams based on major- and minor-element oxides (Verma et al. 2006) or trace elements (Agrawal et al. 2008) facilitate the determination of geotectonic setting for (ultra-) basic rocks. The collision-related alkaline granites can be distinguished from calc-alkaline and peraluminous suites on the basis of the diagram after Sylvester (1989). Ternary plot Hf–Rb/30–Ta×3, proposed by Harris et al. (1986), serves for classification of collisional granites (fig. 1b).

Function *spider2norm* produces double normalized spider plots (fig. 1c). Their aim is to eliminate effects of fractional crystallization, looking solely on the source characteristics (Thompson et al. 1983; Pearce et al. 2005; Pearce – Stern 2006). This double normalization is also newly implemented in spider boxplots. Moreover, spiderplots have a more sophisticated appearance, as they allow a choice of several styles of labelling x axis (e. g., rotated and/or offset labels) and extra tick marks on the y axis (fig. 1c).

Of interest to granite geochemists may be the brand new plugin implementing the thermometer of Jung – Pfänder (2007). As shown by Sylvester (1998), the Al_2O_3/TiO_2 ratio in the granitic magmas increases with the rising temperature of the crustal anatexis, reflecting most likely the decreasing stability of Ti-bearing phases. Jung – Pfänder (2007) compiled the available experimental data and defined a set of regression formulae for several types of protoliths.

Wedge diagrams and concentration ratio plots (Ague 1994) became an integral part of the *isocon.r* plugin in order to expand the range of tools available for assessing mass balance during open-system processes such as metasomatism, partial melting, migmatization or metamorphism.

In the statistics, arguably the most useful additions represent the function for printing ranges of selected geochemical parameters in individual groups of samples (*summaryRangesbyGroup*) and the so-called strip box-plots – i. e. stripplots of selected parameter for individual data groups, each underlain by a boxplot. Optionally also a second variable can be portrayed by variable size of the plotted circles.

Brand new concepts and future development

More importantly, *GCDkit 3.0* brings several new concepts. Firstly, the so-called *plates*, i. e. collections of two or more stand-alone plots, have been introduced (fig. 2). In the previous versions the graphical output system behaved in two contrasting ways: there was a wide range of *Figaro*-based retouching tools for individual diagrams (editing, zooming, point identification etc.), whereas composite plots made of two or more diagrams were static,

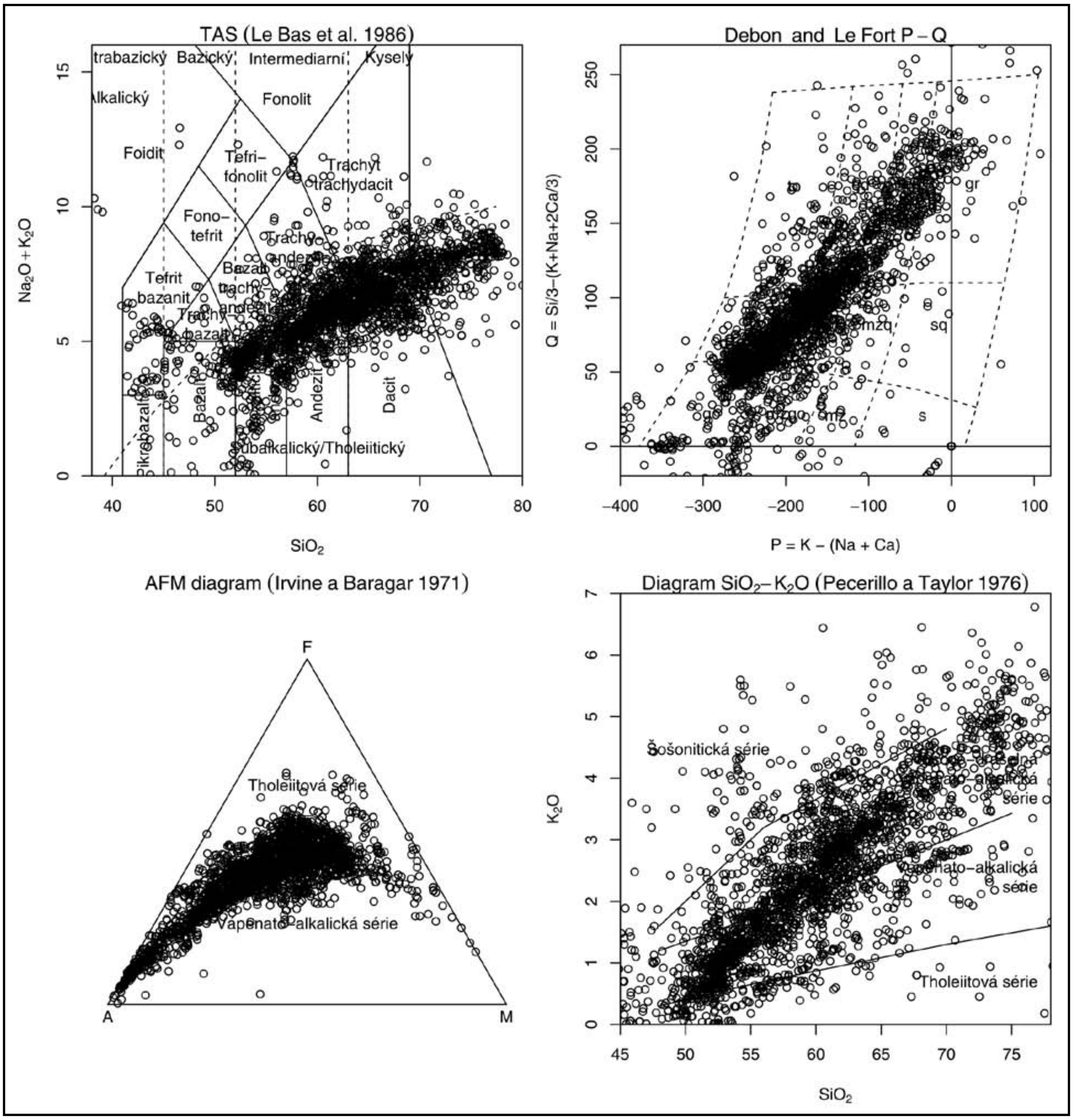

Fig. 2: A user-defined plate featuring several classification diagrams. The data set represents ~ 4000 analyses of Andean arc-related igneous rocks from the GeoRoc database.

virtually 'dead'. These involved for instance Harker plots, or diagrams using the same *Figaro* template plotted repeatedly for each of the groups ("Multiple plots by groups" – function *figMulti*), defined e. g. according to the petrographic type. The plates are designed to overcome this weakness/inconsistency. Of course, plates can be fully user-defined and comprise any mixture of Figaro-compatible plots, e. g., binary plots, ternary plots, classification diagrams or spiderplots.

From the plate already plotted, a single plot can be selected by graphical cursor and subsequently edited in a manner previously available exclusively to stand-alone Figaro-compatible plots. Moreover, properties of the whole plate/all its diagrams can be changed simultaneously. For instance, the whole plate can be set to black and white, the font size of axis labels can be altered, scaling of the common axis on Harker plots, or the minima of all y axes of binary plots set to 0.

The second issue addressed by the new version of *GCDkit* is internationalization. As the first step, available is a choice of several languages to label the classification plots (so far English, Czech and French only; e. g. figs 1–2) using built-in dictionaries that ensure that further languages can be introduced, quickly and efficiently. English remains the master language so the dictionary is actually built as a list of paired terms *English – [further language]*.

The new version also enables persistent system options to be set, implementing an easy-to-use graphical user interface (GUI). The options are subsequently saved to a permanent configuration file.

Last but least, *GCDkit 3.0* has been redesigned so that most functions are not only accessible via pull-down menus, but can run fully in an interactive regime or even in a batch mode, without the potentially pestering dialogues. This means efficiency for repetitive recalculations/plotting tasks involving several distinct datasets, and a possibility for automation by external programs. The help pages contain more examples that can run directly, illustrating the main concepts, and that also represent numerical recipes that can be incorporated into user-defined macros/programs.

The current release represents an important step ahead in our effort to separate the *GCDkit* functionality (algorithms) from the user dialogues (interface). Such a move should, in longer perspective, enable development of alternative interfaces, e. g., to the World Wide Web, large database systems or built using operation system-independent languages such as Java or Tcl/Tk. Our aim is to release ultimately Linux and Macintosh versions of *GCDkit* and thus expand the number of its potential users.

Conclusions

The *GCDkit 3.0* offers a number of new features and should fix the stability problems of the previous release. It is developed primarily for Windows Vista/7. We have decided to stop the support for Windows 95/98/ME and warn the users that on Windows 2000 and XP the system may become unstable, especially if many graphical windows or complex plates are being opened. The package can be downloaded from the new website at *http://www.gcdkit.org*.

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REVIEW OF GROUNDWATER RESOURCES

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Key words: Czech Republic, hydrogeological survey, groundwater resources

Abstract

Assessment of groundwater resources was an integral part of the regional hydrogeological survey of Czechoslovakia and later the Czech Republic performed in the period 1966–1990. Meanwhile, methods of investigation and conditions of groundwater recharge have changed. Therefore, the former values of groundwater resources are now older than 20–30 years and their actual relevance is very problematic. The Czech Geological Survey has proposed the project called Review of Groundwater Resources, which reflected a rated review of the former results and should comply with the requirements of the water balance according the Czech Water Act and characterization of quantitative status of the groundwater bodies according the European Water Framework Directive. This project includes 56 hydrogeological zones which should be newly reviewed.

The groundwater flow (baseflow) presents a part of the total surface water discharge ranging between 15 to 50 percent of it, and therefore it is an important part of the environment as well as conditions for the public water supply and for ecosystems depending on groundwater. Besides, the estimation of groundwater resources is necessary to comply with the legislative requirements. First, the Czech Water Act No. 254/2001 established in Art. 22 the National Water Balance. The balance should be performed annually with groundwater resources being an integral part of it. Second, the Water Framework Directive 2000/60/EC has introduced the 6-year period for the water-policy planning which requires periodical revisions of the quantitative status of the groundwater bodies.

The systematic assessment of groundwater resources originated from results of the nationwide regional hydrogeological survey performed during the period 1966–1990. The investigation covered the prevailing part of the important hydrogeological structures, namely the Bohemian Cretaceous Basin (Herčík et al. 2003) and the Neogene basins in southern Bohemia. The presumed survey of the Quaternary fluvial deposits could not be realized. An overview of the completed tasks has been presented by Kadlecová et al. (2009).

Evaluations of groundwater resources were an integral part of the survey tasks defined by the instructions of the special governmental committee (Commission for Classification of the Mineral Resources – KKZ). The evaluations were due to be approved by this Committee which verified and ratified the final value. Up to this date, 86 of the records of the Committee are still valid. The regional survey in the territory of the former Czechoslovakia and later the Czech Republic was organized on the basis of hydrogeological zoning. The first version has been constructed in combination with the hydrogeological map at a scale 1: 500 000 in 1965, later reviewed according with results of the regional survey at a more detailed scale 1 : 200 000 in 1973 and 1986. The present version of 2005 of hydrogeological zoning used the GIS technology depicting 3 layers of zones at the scale 1: 50 000, and is now available either on CD (Olmer et al. 2006) or at web sites <*heis.vuv.cz*> <*voda.gov.cz*>. The hydrogeological zones reflect both the geological genetic characteristics and the area of groundwater flow, and are described in the interconnected tables (fig. 1).

The regional hydrogeological survey was performed during a period of 25 years. Meanwhile, techniques of investigation and methods of groundwater evaluation and balances have been developed. Furthermore, conditions of groundwater recharge and both long-time and seasonal flow regime have been affected due to abstractions and climate changes. These facts led to several efforts to prove the actual relevance and/or validity of the former results and to continue and fulfill the original goals. A real step presented the study by Kadlecová et al. (2010) which prepared proposals for a new phase of a general review of groundwater resources, reflecting the governmental resolution (sine 2007) and using the chance to gain a support of funding by The Operational Programme Environment.

The preparatory study was based on a specific analysis (Herrmann 2008) rating the former results and actual needs as well, taking into account:

- availability, level and relevance of the groundwater resources values being introduced in the water balance presented by the Czech Hydrometeorological Institute (CHMI),
- groundwater abstractions over 1 mill. m^3 per year,
- poor or failing quantitative status of the groundwater body,

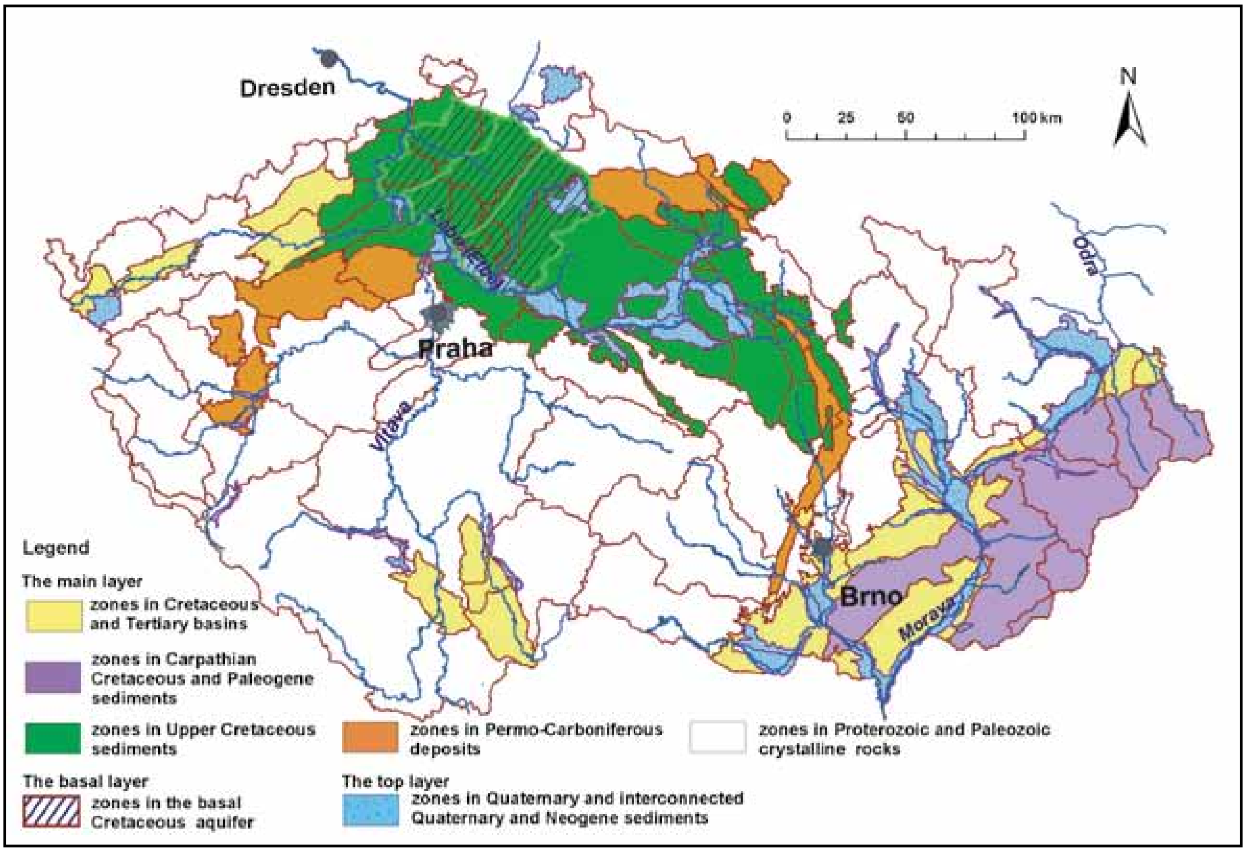

Fig. 1: Hydrogeological zones of the Czech Republic.

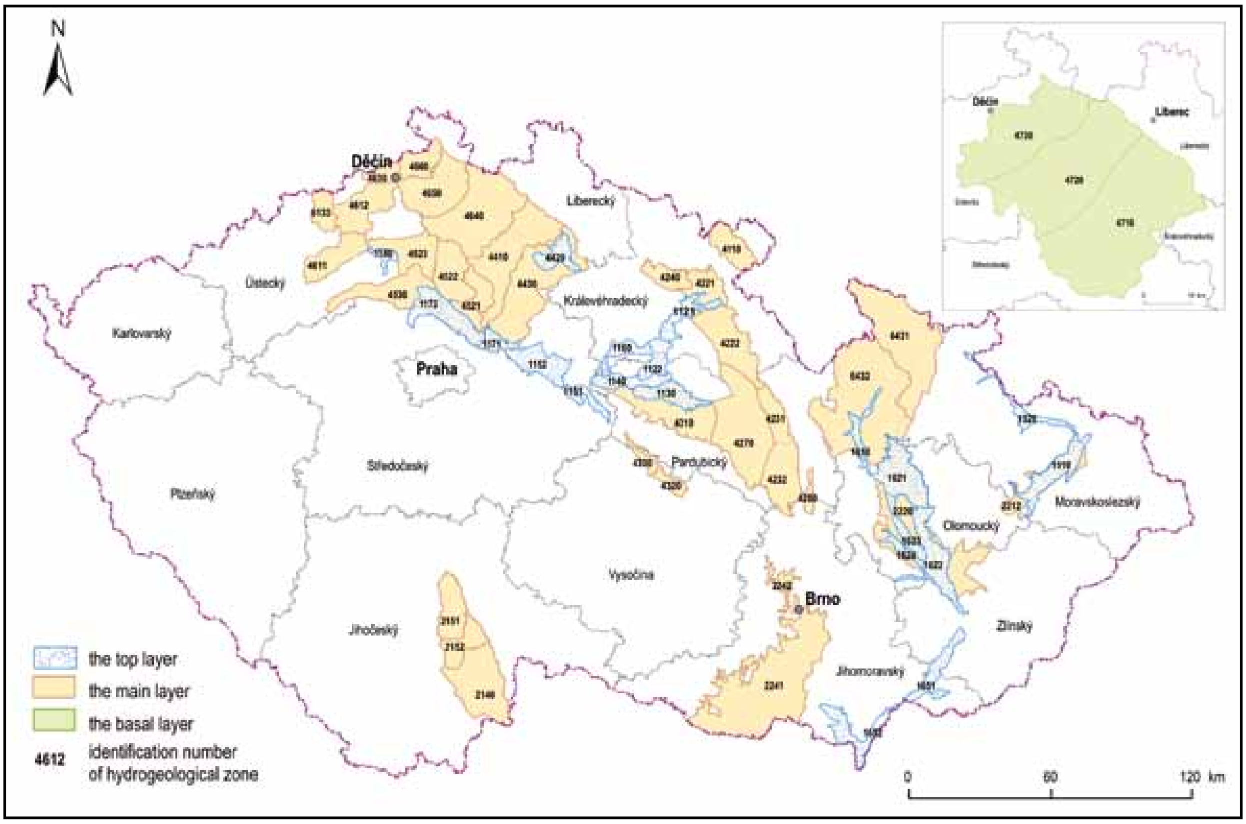

Fig. 2: Hydrogeological zones proposed for the review.

ID HGR	název hydrogeologického rajonu (HGR)	the name of the hydrogeological region	area km^2
1121	Kvartér Labe po Hradec Králové	Quaternary of the Labe River downstream to Hradec Králové	146.1
1122	Kvartér Labe po Pardubice	Quaternary of the Labe River downstream to Pardubice	127.8
1130	Kvartér Loučné a Chrudimky	Quaternary of the Loučná and Chrudimka Rivers	181.9
1140	Kvartér Labe po Týnec	Quaternary of the Labe River downstream to Týnec	146.9
1151	Kvartér Labe po Kolín	Quaternary of the Labe River downstream to Kolín	88.1
1152	Kvartér Labe po Nymburk	Quaternary of the Labe River downstream to Nymburk	238.6
1160	Kvartér Urbanické brány	Quaternary of the Urbanice Gate	105.1
1171	Kvartér Labe po Jizeru	Quaternary of the Labe River downstream to the Jizera River	88.7
1172	Kvartér Labe po Vltavu	Quaternary of the Labe River downstream to the Vltava River	293.8
1180	Kvartér Labe po Lovosice	Quaternary of the Labe River downstream to Lovosice	57.8
1510	Kvartér Odry	Quaternary of the Odra River	262.9
1520	Kvartér Opavy	Quaternary of the Opava River	124.7
1610	Kvartér Horní Moravy	Quaternary of the upper Morava River	92.2
1621	Pliopleistocén Hornomoravského úvalu – severní část	Plio-Pleistocene of the Upper Moravian Graben – northern part	356.8
1622	Pliopleistocén Hornomoravského úvalu – jižní část	Plio-Pleistocene of the Upper Moravian Graben – southern part	289.1
1623	Pliopleistocén Blaty	Plio-Pleistocene of the Blata River	99.7
1624	Kvartér Valové, Romže a Hané	Quaternary of the Valová, Romže and Haná Streams	84.2
1651	Kvartér Dolnomoravského úvalu	Quaternary of the Lower Moravian Graben	168.2
1652	Kvartér soutokové oblasti Moravy a Dyje	Quaternary of the Morava and Dyje Rivers confluence area	216.8
2140	Třeboňská pánev – jižní část	Třeboň Basin – southern part	551.1
2151	Třeboňská pánev – severní část	Třeboň Basin – northern part	260
2152	Třeboňská pánev – střední část	Třeboň Basin – middle part	202.2
2212	Oderská brána	Odra Gate	307.2
2220	Hornomoravský úval	Upper Moravian Graben	257.2
2241	Dyjsko-svratecký úval	Dyje-Svratka Graben	1 460.8
2242	Kuřimská kotlina	Kuřim Basin	80.1
4232	Ústecká synklinála v povodí Svitavy	Ústí n. Orl. Syncline in the Svitava River catchment	358
4240	Královédvorská synklinála	Dvůr Králové Syncline	145.3
4270	Vysokomýtská synklinála	Vysoké Mýto Syncline	799.9
4280	Velkoopatovická křída	Cretaceous of the Velké Opatovice area	49.6
4310	Chrudimská křída	Cretaceous of the Chrudim area	595.8
4320	Dlouhá mez – jižní část	Dlouhá mez – southern part	65.7
4330	Dlouhá mez – severní část	Dlouhá mez – northern part	60.3
4530	Roudnická křída	Cretaceous of the Roudnice area	405.8
4611	Křída Dolního Labe po Děčín – levý břeh, jižní část	Cretaceous of the lower Labe River downstream to Děčín, left-bank – southern part	280.1
4612	Křída Dolního Labe po Děčín – levý břeh, severní část	Cretaceous of the lower Labe River downstream to Děčín, left-bank – northern part	331.8
4630	Děčínský Sněžník	Děčínský Sněžník	97.7
4640	Křída Horní Ploučnice	Cretaceous of the upper Ploučnice River	833
4650	Křída Dolní Ploučnice a Horní Kamenice	Cretaceous of the lower Ploučnice and upper Kamenice Rivers	481.4
4660	Křída Dolní Kamenice a Křinice	Cretaceous of the lower Kamenice River and the Křinice Stream	180.3
4720	Bazální křídový kolektor od Hamru po Labe	Cretaceous basal aquifer between Hamr and the Labe River valley	1 339.7
4730	Bazální křídový kolektor v benešovské synklinále	Cretaceous basal aquifer of the Benešov Syncline	948.9
4521	Křída Košáteckého potoka	Cretaceous of the Košátecký Stream	337.6
4522	Křída Liběchovky a Pšovky	Cretaceous of the Liběchovka and Pšovka Streams	335.2
4523	Křída Obrtky a Úštěckého potoka	Cretaceous of the Obrtka and Úštěcký potok Streams	309
4110	Polická pánev	Police Basin	214
4221	Podorlická křída v povodí Úpy a Metuje	Cretaceous of the Orlické hory (Mts.) piedmont in the catchments of the Úpa and Metuje Rivers	252.5
4222	Podorlická křída v povodí Orlice	Cretaceous of the Orlické hory (Mts.) piedmont in the Orlice River catchment	434.5
4231	Ústecká synklinála v povodí Orlice	Ústí n. Orl. Syncline in the Orlice River catchment	176.3
4410	Jizerská křída pravobřežní	Cretaceous of the Jizera River, right-bank part	685
4420	Jizerský coniak	Coniacian of the Jizera River	152.2
4430	Jizerská křída levobřežní	Cretaceous of the Jizera River, left-bank part	899.5
4710	Bazální křídový kolektor na Jizeře	Cretaceous basal aquifer in the Jizera River catchment	1 881.8
6133	Teplický ryolit	Rhyolite of the Teplice Spa area	134.4
6431	Krystalinikum severní části Východních Sudet	Crystalline of the northern part of the Eastern Sudeten	922.9
6432	Krystalinikum jižní části Východních Sudet	Crystalline of the southern part of the Eastern Sudeten	1 422.8

Tab. 1: Hydrogeological zones proposed for the review.

- importance of the groundwater unit resulting from the River basin management plans,
- other water management problems.

All of the 152 hydrogeological zones of the Czech Republic were investigated after the mentioned points and ordered according to urgency and necessity of a new review.

A new digital hydrogeological map of the Czech Republic is performed in the frame of the VaV Project (No. SP/2e1/07) representing a base in the project: Review of the Groundwater Resources.

The Czech Geological Survey has presented the project "Review of the Groundwater Resources" (Ident. No. 1559996). Expenses of investigating all of the rated zones was shared after a unified method (Kadlecová et al. 2010). The selection has been made in accordance with the results of the above mentioned preparatory study and rating analysis and with the expected limit of the funding, i. e. 25 000 EURO. The final term for this task is given by 2015. The proposal of the actual phase of the review respected both the results of rating and the financial limit, and thus the list of the selected hydrogeological zones has been closed by the number 56 (fig. 2, tab. 1).

The goals of the proposal of reviewing the hydrogeological and water management conditions have been described as „Activities", which at the same time are defining the partial items for the selection procedures:

1. inventory, selection and analysis of archive records, delimitation of aquifers,
2. values of resources implemented in the quantitative status of groundwater bodies,
3. actualization of archive records by remote sensing, geophysical and field investigation,
4. testing of aquifers by hydrogeological boreholes,
5. hydrogeological conceptual modeling,
6. hydrological modeling,
7. hydraulical modeling,
8. quantitative status of groundwater bodies, hydrochemical modeling,
9. protection of groundwater and on water depending ecosystems,
10. summary,
11. publicity, web.

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DIAMONDS IN THE BOHEMIAN MASSIF – EVIDENCE FOR ULTRAHIGH-PRESSURE METAMORPHISM

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Key words: diamond, ultrahigh-pressure metamorphism, high-pressure granulite, Bohemian Massif

Abstract

Diamond and coesite were discovered in high-pressure granulites of the north Bohemian crystalline basement in the Eger Crystalline Complex and České středohoří Mts. Diamonds, confirmed by micro-Raman spectroscopy, occur as 5–10 µm-sized inclusions in kyanite and garnet as well as in accessory zircon. Coesite was identified within kyanite enclosed in garnet. Diamond and coesite form at pressures above 4 and 3 GPa, respectively, and the presence of these two minerals in the continental crust indicates ultrahigh-pressure metamorphic conditions reached only during a continental subduction deep into the mantle. Preservation of coesite in felsic-intermediate crustal rocks is a rather unique phenomenon due to its very limited metastable survival within exhumed terranes. Importantly, the north Bohemian crystalline basement represents only the fifth accepted location worldwide where diamond has been documented in situ in the continental crust rather than in mantle rocks such as peridotites. Our discovery also strongly supports the previously questioned Bohemian provenance of macroscopic diamonds, found in the České středohoří Mts. area in the 19th and 20th century.

Introduction

High-pressure granulites represent a major rock type of the internal domain of the Variscan crystalline basement in Europe, including the easterly-located Bohemian Massif. The unusual association of these crustal high-pressure granulites and mantle garnet peridotites recording apparently very contrasting peak pressures is a common but until now not fully understood phenomenon. It has been demonstrated that the peak mineral assemblages of predominant felsic, Saxony-type granulites, comprising garnet, kyanite, mesoperthitic feldspar and quartz, formed at ultra-high (~ 1000 °C) temperatures and plot in the eclogite facies field as defined by experimental studies on both acid and basic rock compositions (O´Brien – Rötzler 2003, Kotková 2007). We searched for evidence for ultrahigh-pressure (UHP) metamorphism of the high-pressure granulites, which would provide explanation for the apparently high thermal gradients needed for granulite formation as well as the granulite-garnet peridotite association. The north Bohemian crystalline basement was selected as a study area due to the lack of high temperature-medium pressure overprint in these granulites implying high exhumation and cooling rates (Kotková et al. 1996, Zulauf et al. 2002), the presence of garnet peridotites and also historical diamond finds in the area (Schafarik 1870, Ježek 1927).

Geological context

The high-pressure granulites along with migmatites and various gneisses constitute the crystalline basement of north Bohemia traditionally attributed to the Saxothuringian Zone of the Bohemian Massif. Granulites are exposed in the erosional window along the Eger (Ohře) River – in the Eger Crystalline Complex (ECC; ohárecké/oherské krystalinikum), and make up to several hundred meters thick sections with associated garnet peridotites in the drill-cores in the České středohoří Mts. basement (Kopecký – Sattran 1966, Kotková 1993, Kotková et al. 1996, Zulauf et al. 2002, Mlčoch – Konopásek 2010). Although the exposure in the area is poor due to voluminous alkaline volcanism as well as sedimentation associated to a large extent with the Cenozoic Eger Rift formation, sufficient material comprising both felsic and intermediate high-pressure granulites is available.

Methods and sample description

Polished thin sections of granulites were examined using transmitted and reflected light microscopy. Raman spectra for minerals were acquired using a confocal Raman spectrometer (LabRam HR: Horiba Jobin Yvon) at the Institut für Erd- and Umweltwissenschaften, Universität Potsdam.

We investigated both felsic and intermediate granulites from drill-cores in the České středohoří Mts. basement (T7 and T38 boreholes, located at Staré, and T21 located at Měrunice) and from granulite outcrops in Stráž nad Ohří, ECC. Granulites contain the high-pressure mineral assemblage garnet-kyanite-quartz-mesoperthite (felsic rocks) and garnet-clinopyroxene-feldspar-quartz (intermediate rocks).

Felsic granulite (T7 borehole, Staré; fig. 1A)

The rock is banded, consisting of the light part poor in biotite and dark irregular biotite-rich zone several millimetres thick with weak preferred orientation of biotite. Garnet (1–2 mm in diameter) and kyanite (mostly elongated grains 0.5–1mm long) porphyroclasts are surrounded by a fine-grained matrix composed of quartz, perthitic K-feldspar and subordinate secondary plagioclase with heterogeneous grain size (up to 0.3 mm) and lobate grain

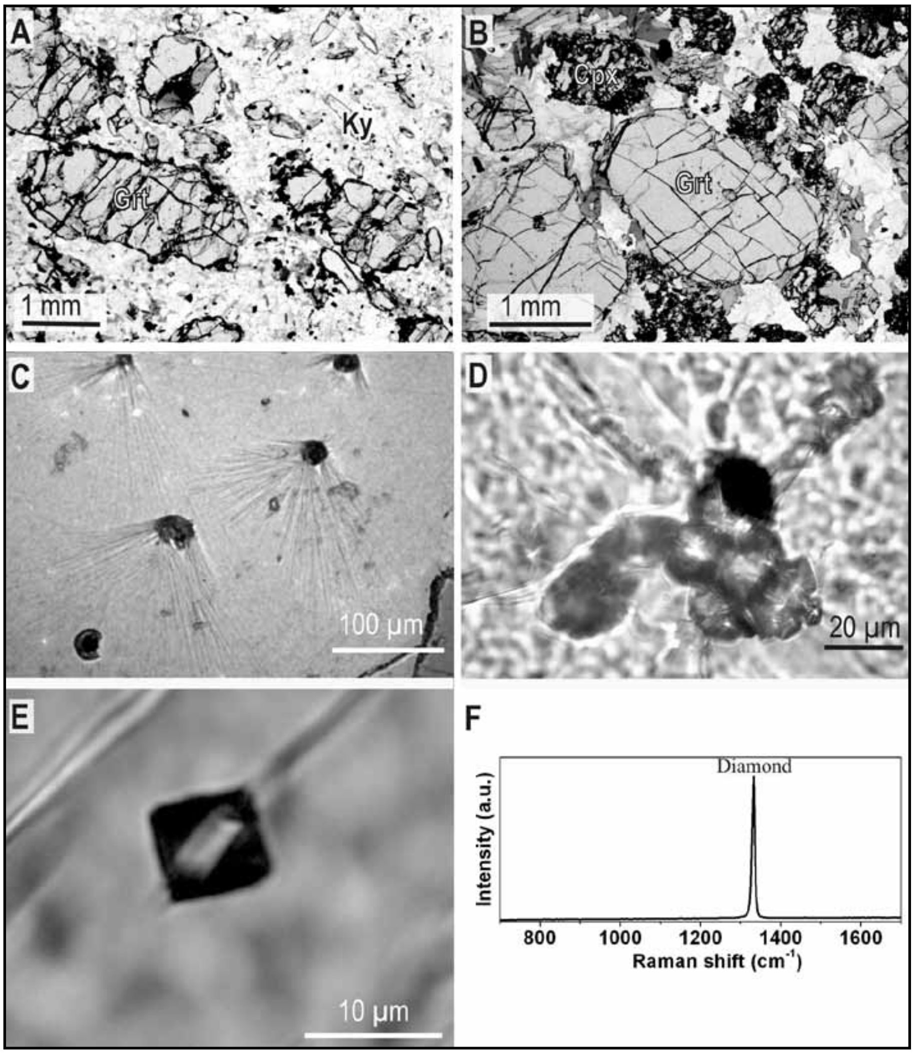

Fig. 1: A – felsic granulite, T7 borehole, České středohoří Mts. (PPL); B – intermediate granulite, T38 borehole, České středohoří Mts. (PPL); C – polishing scratches from diamond protruding from the thin-section, intermediate granulite, Stráž nad Ohří, ECC (reflected light); D – diamond cluster in garnet, intermediate granulite, T38 borehole (PPL); E – diamond enclosed in kyanite, T7 borehole, České středohoří Mts. (PPL); F – Raman spectrum of a diamond enclosed in garnet, T7 borehole, České středohoří Mts.

boundaries. The majority of kyanite grains show preferred orientation subparallel to that of the biotite banding. Biotite is disseminated in the matrix and forms discontinuous (continuous in the dark part) rims on garnets. Accessory phases are zircon, rutile, apatite, graphite and ore minerals (mainly pyrite), occurring as inclusions within major rock-forming minerals as well as in the rock matrix.

Intermediate granulite (T38 borehole; fig. 1B)

Garnet and clinopyroxene porphyroclasts occur within a rather equigranular fine-grained (grain size up to 0.4 mm) matrix, consisting of plagioclase and quartz. Whereas rounded to slightly elongated garnets are large, reaching 1–2.5 mm in diameter, clinopyroxene grains are as a rule smaller (0.5–1 mm), elongated, showing weak preferred orientation. Biotite occurs in clusters up to 0.5 mm in size, located within the matrix or rimming the garnet grains. Pyroxene grains feature irregular boundaries and are in places replaced by other phases, mainly amphibole. Accessory phases are zircon, rutile, apatite, ilmenite and graphite. The latter mineral occurs exclusively as inclusions in garnet and pyroxene.

Results

Micro-diamonds were discovered as 5–30 µm sized inclusions in garnet and kyanite in felsic granulites and in garnet and zircon in intermediate granulites. They are located below the surface of the sample or protrude from the thin section. Radiating polishing scratches from fragments of the grains that were broken off represent one of the prospecting tools for the diamonds (fig. 1C). Diamonds within garnet commonly have ragged surfaces, are sub-rounded, occur in clusters (fig. 1D), and appear with graphite, apatite, rutile, quartz and carbonate minerals, whereas diamond in kyanite forms well-defined single octahedra with only minor associated graphite (fig. 1E). Confocal micro-Raman analysis of these grains yielded an isolated peak at around 1332–1333 cm^{-1} characteristic of diamond (Ramaswami 1930; fig. 1F). Coesite with characteristic peak at about 521cm^{-1} has been identified as an inclusion in kyanite itself completely enclosed in garnet in a felsic granulite sample containing also polycrystalline quartz aggregates within garnet (Kotková et al. 2011).

Discussion and conclusions

Although the discovery of diamond in pyrope-bearing gravels in northern Bohemia in 1869 (Schafarik 1870) represented a sensation both in scientific and layman circles as the first reliable diamond find in Europe, its Bohemian origin was immediately questioned. It was assumed that a diamond from East India had become mixed up with the north Bohemian pyrope in the polishing workshop (Nature 1870). A second diamond was found in 1927 (Ježek 1927). Intensive diamond prospecting in the 1950´and 1960´ focused on Tertiary volcanic breccias, especially those containing pyrope xenocrysts, and considered as possible diamond host rocks analogous to kimberlites (Kopecký et al. 1967). No diamond was found during these works, and despite later studies of the two diamond grains failing to exclude endogenous as opposed to impact diamond genesis (Bouška et al. 1993), the origin of the Bohemian diamond still remained unexplained. Discovery of coesite, and diamond, in metamorphic rocks of crustal origin only 25 years ago (see Liou et al. 2009 and references therein) led to recognition of ultrahigh-pressure metamorphism as a product of deep subduction of the crust into the mantle. In the Bohemian Massif the deeply subducted rocks were returned to the surface but in other cases, such as in Eastern Australia (Barron et al. 2008) the subducted crust, still at depth, acts as the source for diamonds, including macroscopic (average 0.25 carat) grains, transported by younger alkali basalts. This newly recognised process in Earth sciences, ultrahigh pressure metamorphism, provides a new possibility for diamond formation following on from our gradually acquired understanding of sedimentary (redeposited, placer), mantle (garnet peridotite, garnet pyroxenite, transported by kimberlite) and impact diamond origins.

Our discovery of diamond and coesite in high-pressure granulites of north Bohemian crystalline basement has the following implications:

- it ranks the studied terrane on the short list of world localities (i. e. Kokchetav Massif in Kazakhstan, Saidenbachtal in German Erzgebirge, Rhodope Massif in Greece and the Qinling Mts. in China, see Liou et al. 2009) where diamond was documented in situ in the continental crustal rather than in mantle rocks,
- it represents the first robust evidence for UHP conditions in a major Variscan crustal rock type, allowing to envisage a larger UHPM unit involving the Saidenbach area where the rare, exotic diamond-bearing garnet-phengite gneisses occur (Nasdala – Massonne 2000),
- it strongly supports the Bohemian provenance of the macroscopic diamond found in previous centuries,
- it shows, that the ultra-high temperatures above 1 000 °C, deduced for the HP granulites and questioned by some authors (see O´Brien 2008), are realistic as the thermal gradients required under UHP conditions are not extreme,
- deep subduction and rapid exhumation (Matte 1998, Willner et al. 2002, Massonne – O´Brien 2003), rather than homogeneous crustal thickening (Schulmann et al. 2008) are required to explain the ultra-high metamorphic pressure and granulite-garnet peridotite association characteristic of the internal zone of the European Variscan belt.

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THE PIENINY KLIPPEN BELT – STRUCTURE, EVOLUTION AND POSITION IN THE CARPATHIAN TECTONIC FRAMEWORK

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Key words: Pieniny Klippen Belt, Mesozoic, Palaeogene, structural evolution

Abstract

The current tectonic research in the western and eastern Slovakian parts of the Pieniny Klippen Belt (PKB) has revealed some important differences between these two segments. The western PKB segment is characterized, in addition to the presence of ubiquitous Oravic units, by a broad incorporation of frontal elements of the Central Carpathian Fatric cover nappe system (Manín, Klape, Drietoma nappes). These are overstepped by still synorogenic, Gosau-type Senonian–Palaeogene basins. On the contrary, the northern and eastern PKB parts are dominated by the Oravic complexes representing an independent, originally intra-Penninic palaeogeographic element. Though strongly affected by Miocene along-strike wrench movements, several PKB sectors still preserve original fold-and-thrust structures that developed sequentially in a piggy-back manner during the Late Cretaceous to Early Eocene times. Timing of these thrust events is facilitated by the presence of syntectonic sediments in the footwalls of thrust sheets, as well as by overstep complexes sealing older structures. The syntectonic sediments typically include olistostromes and huge olistolites derived from the overriding nappe fronts. In such a way, three principal Oravic units have been recently defined in the eastern Slovakian PKB – the Šariš, Subpieniny and Pieniny nappes.

Introduction

Owing to the picturesque landscape and tectonic peculiarities, the Pieniny Klippen Belt (PKB) is considered as the most conspicuous regional zone of the Western Carpathians. It forms a narrow (merely several km), but lengthy (up to 600 km) stripe that separates the External Western Carpathians (EWC – Flysch Belt, Tertiary accretionary wedge) from the Central Western Carpathians (CWC – Cretaceous basement/cover nappe stack). The PKB involves predominantly Jurassic, Cretaceous and Palaeogene sediments with variable lithology and intricate internal structure. During almost two centuries of intense research, these have been differentiated into numerous lithostratigraphic and tectonic units of originally distant palaeogeographic provenances, hence witnessing excessive shortening and dispersal within this restricted zone. The purpose of this paper is to present briefly some new results and ideas developed during the recent investigations focussed on structural evolution of zones along the EWC/CWC boundary, i. e. the PKB and adjacent units. Our results partially, or even completely in some cases, contradict the previous views. In particular, new opinions concern the relations of the klippen to surrounding rocks, as well as the number and hierarchy of tectonic units incorporated into the PKB edifice (e. g. Plašienka – Jurewicz 2006, Froitzheim et al. 2008, Schlögl et al. 2008, Plašienka – Mikuš 2010). The inferred internal structure and relationships of the PKB to the neighbouring zones is illustrated by a series of cross-sections (fig. 1).

Structure of the Pieniny Klippen Belt

Several large-scale tectonic systems are partly or fully incorporated and/or closely juxtaposed to the PKB (fig. 1). From bottom to top (and generally from N to S), these are the Magura Nappe, Biele Karpaty Superunit, Oravic Superunit (PKB sensu stricto), elements of the CWC Fatric nappe system and overstepping complexes.

The large Magura Nappe of the EWC Flysch Belt (Senonian–Oligocene, predominantly flysch lithologies) is in a contact with PKB in north-western and eastern Slovakia. In the Middle Váh Valley, the PKB directly contacts the Bystrica Subunit, which otherwise occupies a central position in the Magura Belt. This contact is purely tectonic and relatively young, and has a character of oblique slip dextral/reverse fault zone. It indicates backthrusting, since the PKB units are overturned towards the S (fig. 1C). In the Orava region and further east in eastern Slovakia, the PKB neighbours the Oravská Magura-Krynica Unit, which is dominated by the Eocene Magura-type sandstones (fig. 1A, B). In eastern Slovakia, the outermost PKB Šariš Unit overrides the innermost elements of the Krynica Unit terminated by the Oligocene to Lower Miocene deposits (Oszczypko et al. 2010, Plašienka – Mikuš 2010).

The Biele Karpaty Superunit is the innermost element of the SW part of the EWC Flysch Belt where it is put next to and partly underlies the outer elements of the PKB. It is characterized by a special composition (rich carbonate material in clastic formations), restricted stratigraphic extent (Cretaceous–Lower Eocene; Švábenická et al. 1997, Potfaj 1993) and very low thermal and deformational reworking (Hrouda et al. 2009). It consists of several thrust sheets, the two higher being in a direct contact with the PKB (fig. 1E, F).

Oravic Superunit

The Oravic Superunit (known also as the “Pieninic” units or “Pienides” in older literature – e. g. Andrusov (1974) or PKB s. s. – Maheľ 1980) embraces the typical PKB units of their own, which are characterized by the peculiar “klippen tectonic style” (block-in-matrix struc-

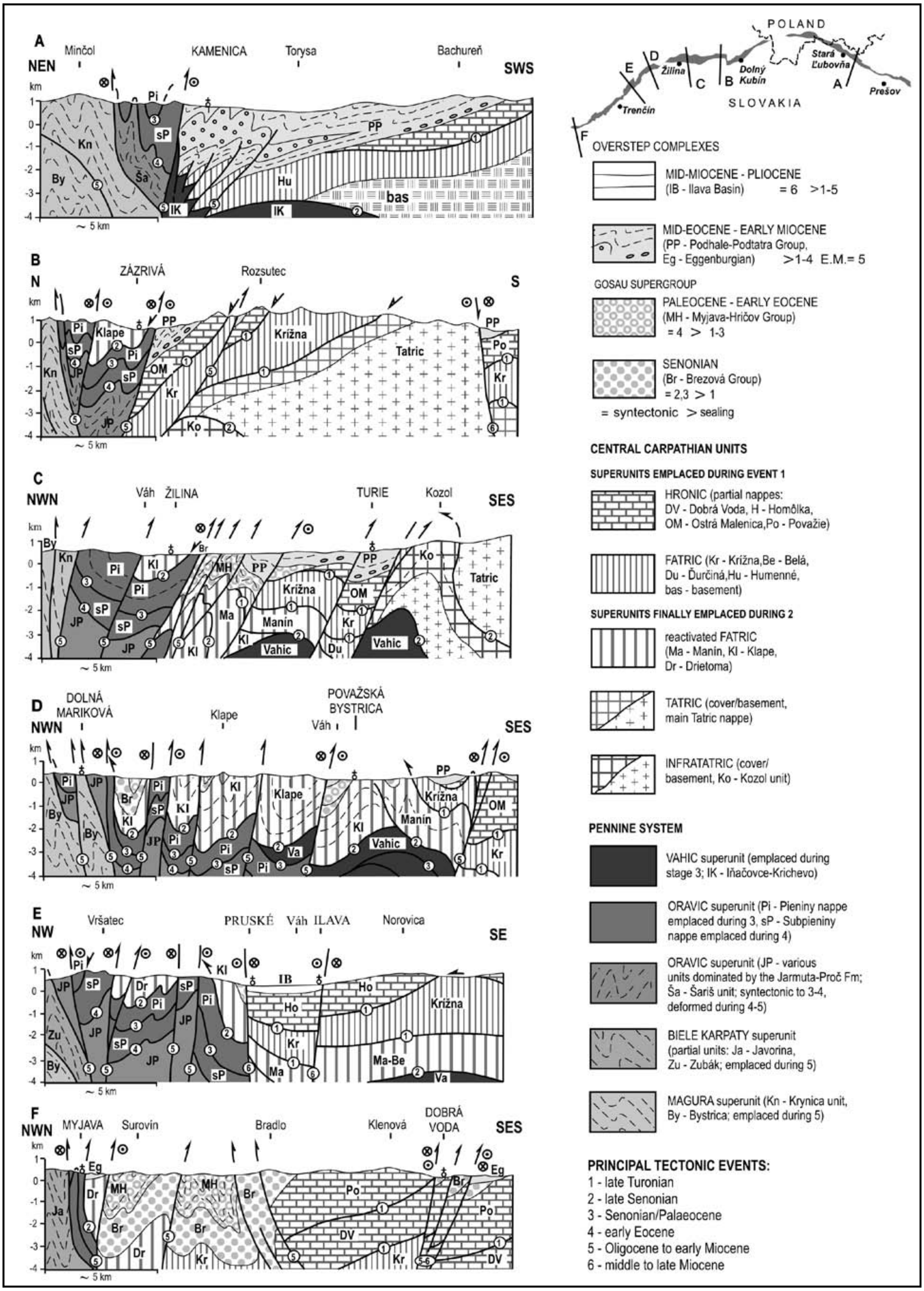

Fig. 1: Cross-sections across the PKB showing relationships of its principal units.

ture). The lowermost element of the eastern PKB s. s. is represented by the recently defined Šariš Unit (Plašienka – Mikuš 2010; fig. 1A), which was formerly considered to be a part of the "klippen mantle" (e. g. Stráník 1965). It consists of varied Upper Jurassic to Upper Cretaceous pelagic sediments followed by Maastrichtian–Lower Eocene, deep marine, pelagic (variegated shales) and clastic (turbidites, mass-flows) deposits. The latter are known as the Jarmuta and/or Proč Fm. and involve also chaotic olistostrome bodies (Milpoš Breccia) with olistolites dominantly derived from the overlying Subpieniny Nappe. These have been mostly considered as klippen, i. e. tectonic inliers until now. However, already Nemčok recognized their sedimentary character (Nemčok 1980, Nemčok et al. 1989). The overriding Czorsztyn-type units form a system of imbricated thrust sheets. Their disintegrated fronts pass into mass-flows inserted within and above the Jarmuta–Proč flysch, thus indicate close sedimentary and tectonic relationships between the Šariš and overlying units.

For the higher nappe sheet of the PKB, we come back to the old Uhlig's term Subpieniny Nappe (Uhlig 1907). This includes the most widespread Czorsztyn Succession, as well as the Pruské, Niedzica, Czertezik and similar "transitional" successions derived from the Czorsztyn Ridge and its slopes. Lithology and stratigraphy of these successions were described in detail in numerous papers (e. g. Birkenmajer 1977, 1986). On the other hand, we do not ascribe a tectonic independence to these local successions as Birkenmajer did (see also Książkiewicz 1977). The Subpieniny Nappe has a stable structural position, but it is strongly imbricated, or even disintegrated internally. The youngest sediments of the Czorsztyn-type successions are the Upper Senonian Jarmuta-type calcareous sandstones overlain by olistostrome breccias (Gregorianka Breccia – Nemčok et al. 1989). These breccias only contain material derived from the still higher Pieniny Nappe. The Subpieniny Unit is characterized either by imbricated thrust stacks and duplexes, or by a "mature" klippen style with small blocky klippen composed of massive Middle–Upper Jurassic limestones embedded within a soft matrix of Upper Cretaceous marls.

The highermost Oravic tectonic unit of the PKB – the Pieniny Nappe – includes several differing lithostratigraphic successions as well (Pieniny s. s., Kysuca-Branisko, Podbiel-Orava, Nižná). The Pieniny Nappe is strongly folded and imbricated, but generally continuous. It overlies the Subpieniny Unit, but in places directly the Šariš Unit. Usually it forms the southernmost zone of the eastern PKB. In the western PKB part, it is dominated by the basinal Kysuca Succession. The eastern part is ranged to a still more deep-basinal Pieniny Succession, which is usually detached at the base of Middle/Upper Jurassic radiolarites.

All the Oravic units are characterized by an independent palaeogeographic position around the Middle Penninic swell known as the Czorsztyn Ridge, which was a continental ribbon separated by oceanic domains from the Central Carpathian (Austroalpine) plate to the south and from the North European Platform to the north (South Penninic-Vahic and North Penninic-Rhenodanubian-Magura Oceans, respectively – e. g. Plašienka 2003). Unlike the pre-Senonian Austroalpine units, the Oravic Superunit involves more-or-less continuous Jurassic–Cretaceous stratigraphic successions reaching as late as the Early Eocene in the most external zones.

Fatric Superunit

The "non-Oravic" units of the CWC-Austroalpine provenance incorporated into the PKB are generally ranged to the Fatric Superunit (Krížna and related nappes – cf. fig. 1). These are widespread in the western PKB part, especially in its broadest Púchov sector, where they occur in a superposition over the Oravic units within the southeastern zone of the PKB designated as the "Periklippen Belt" by Maheľ (1980). Three large units compose the "non-Oravic" Periklippen zone. The Drietoma Unit, which comprises the Upper Triassic (Carpathian Keuper Fm.) – Cenomanian, chiefly basinal succession, predominates in the SW part of the PKB (Hók et al. 2009). It shows close structural links to the overlying CWC nappe systems – the Fatric Krížna Nappe and Hronic Nedzov Nappe, as well as to the Albian–Cenomanian synorogenic flysch with "exotic" conglomerates. The latter provide a link to the huge Klape Unit, which prevails in the Middle Váh Valley. This is composed of about a thousand metres thick mid-Cretaceous wildflysch complex (the Klape Flysch) with big olistolites of Jurassic carbonates (e. g. the spectacular Klape Klippe – Marschalko 1986). In the Považská Bystrica area, the belt of the Klape Unit is up to 15 km wide, composed of four to five juxtaposed subunits divided by antiformal strips of the underlying Kysuca Unit and/or synforms of the overstepping Gosau sediments (fig. 1D). These Klape subunits are considered to represent strike-slip duplexes, accumulation of which caused exceptional broadening of the PKB in the Púchov sector (Schlögl et al. 2008).

The SE-most component of the Periklippen Belt is the Manín Unit. Its Lower Jurassic–Cenomanian sequence (including the characteristic Urgon-type platform limestones) closely relates to the ridge-type successions of the Fatric Superunit (e. g. the Belá Unit in the Strážovské vrchy Mts – Maheľ 1978). However, many authors prefer the Tatric affiliation of the Manín Unit (e. g. Rakús – Hók 2005). The Manín Unit is dominated by the mid-Cretaceous hemipelagic and flysch formations, older stiff limestones build several large "klippen", which are in fact brachyanticlines (Manín and Butkov Hills). Contrary to earlier views, the Senonian sediments in the Klape and Manín Zone are supposed to represent a post-nappe, Gosau-type cover (fig. 1D; cf. Salaj 2006). The mid-Cretaceous flysch of the Manín Unit is from the SE overridden by the frontal elements of the typical Fatric Krížna Nappe.

The "non-Oravic" units participate to a lesser extent in the eastern PKB structure compared to the western one. The large, composite Haligovce Klippe in the Slovak Pieniny Mts is usually correlated with the Manín Unit. This is mainly based on distinct facies similarities (e. g. the Urgon-type limestones), the high structural position above the Oravic units, as well as on overstepping Palaeogene rocks analogous to the "Periklippen" Myjava-Hričov Group. The Haligovce Unit also contains Middle Triassic carbonates –

otherwise unusual feature for the PKB. Further east, a few km SW of the PKB proper, a structural elevation of the Humenné Mts occurs, which is composed of typical Fatric elements (Krížna Nappe). The Humenné Unit is strongly imbricated with SW-verging system of backthrusts, i. e. it occupies a position in the SW limb of the PKB transpressional structural fan (fig. 1A).

Overstep complexes

In western Slovakia, the southern boundary of the PKB against the CWC is followed by deformed Palaeocene–Lower Eocene sediments known as the "Periklippen Palaeogene" (Myjava-Hričov Group – fig. 1). In the westernmost part of the PKB and CWC (Malé Karpaty Mts), these build the upper part of the Gosau Supergroup (including the Senonian Brezová Group) in a situation analogous to the position of Gosau sediments in the Northern Calcareous Alps (NCA, e. g. Wagreich – Marschalko 1995). Gosau sediments in the NCA and Malé Karpaty Mts are interconnected through the "Giesshübl Syncline" drilled in the substratum of the Neogene Vienna Basin (e. g. Wessely 1992).

In general, the Gosau-type Brezová and Myjava-Hričov Groups are characterized by pelagic marls and calcareous flysch formations with a frequent shallow-water biogenic detritus and Maastrichtian–Palaeocene reef-derived olistolites. In the eastern PKB part, the Magura vs. PKB tectonic contact is sealed by the Middle Eocene–Oligocene sediments of the Údol (Ujak) Succession, which is composed of Middle–Upper Eocene variegated shales, Globigerina marls, menilite shales and Oligocene calcareous flysch of the Malcov Formation (see Oszczypko et al. 2005 for details). These formations exhibit close facies relationships to the southward adjacent, coeval sediments of the Central Carpathian Palaeogene Basin (CCPB). However, the PKB and the CCPB are separated by a younger, steep oblique dextral backthrusts there (fig. 1A).

Tectonic evolution

Superposition of the PKB nappe units was strongly modified by post-Oligocene deformation, but it is still well recognizable in several places. The structural position, age range of included sedimentary successions and the inferred age and composition of coarse-grained synorogenic clastic deposits reveal that the stacking of the PKB units progressed from the mid-Cretaceous emplacement of the Fatric nappes followed by sequentional overthrusting of the Oravic units. The Pieniny Unit overrode the Subpieniny around the Cretaceous/Palaeogene boundary. Then the thrusting propagated northwards throughout the Palaeocene–Lower Eocene (Subpieniny + Pieniny over Šariš) and terminated by the local Lower Miocene thrusting of the Šariš Unit and the overlying nappe and overstepping complexes above the inner Magura elements (fig. 1). This compressional tectonic scenario was interrupted by the Middle/Late Eocene extension followed by Oligocene subsidence. Renewed compression/transpression and wrench faulting then occurred during the Lower Miocene. In spite of this complicated tectonic history, the data about the post-depositional thermal history indicate that the PKB sediments were never buried to considerable depths, and all the deformation occurred in the brittle field. For this reason it is assumed that shallow thrusting did not generate a significant burial and the PKB units must have always occupied a high structural position. This would indicate a prevailingly footwall-propagating, "piggy-back" mode of thin-skinned thrusting.

The Lower Miocene transpressional event generated the final form of the PKB that is restricted to a large-scale bivergent, positive "flower" structure indicated by the surface structural data, as well as by the seismic reflection profiles and deep drillings (Plašienka et al. 2008). The flower is usually centred by a generally vertical zone of the PKB, in which strike-slipping prevailed (fig. 1). The along-strike wrench movements led to the formation of the typical "klippen" tectonic style caused by pervasive brittle faulting that destructed earlier fold-and-thrust structures (Ratschbacher et al. 1993, Kováč – Hók 1996).

Summing up, the overall tectonic scenario for the PKB includes piggy-back mode of forward thrusting, formation of a fold-and-thrust belt capped by synorogenic sedimentary basins and some out-of-sequence thrusting as the principal tectonic processes during the Late Cretaceous and earliest Palaeogene, followed by Eocene extension and Oligocene–Lower Miocene dextral transpression responsible for the steepening and narrowing of the PKB that acquired its final structural style.

Conclusions

The new facts and ideas about the structure and evolution of the PKB can be delineated in the following points:

1. The Subpieniny (Czorsztyn) Unit is neither autochthonous, nor the lowermost element of the PKB structure – it is underlain by the newly defined Šariš Unit in eastern and by the Biele Karpaty Unit in western Slovakia.
2. The Šariš Unit includes pelagic Cretaceous sediments followed by coarsening-upward Maastrichtian–Lower Eocene synorogenic deep-marine clastics (Jarmuta/Proč Fm.), consequently the "Klippen Belt Palaeogene" does not represent the "klippen mantle", but constitutes a structurally independent unit.
3. The overthrust processes in the PKB Oravic units are registered by synorogenic tectono-sedimentary breccias in several units and stratigraphic levels, thus they enable stratigraphic dating of tectonic events.
4. The breccias often carry blocks of particularly the Czorsztyn-type Jurassic limestones – a significant fraction of "klippen" is in fact represented by olistolites.
5. In several sectors of the PKB, relics of early fold-thrust structures may be identified – the PKB originally corresponded to a broad, but thin imbricated fold-thrust sheet covering a considerable southern portion of the EWC accretionary wedge that developed during the Palaeogene.
6. The long-termed tectonic deformation processes were repeatedly accompanied by deposition of synorogenic and followed by overstepping formations that partly

seal older structures, but which were deformed later together with their substratum.

7. An important extensional event affected the PKB and adjacent zones during the Eocene, which was likely related to an extensional collapse of overthickened rear parts of the developing EWC accretionary wedge and followed by Oligocene subsidence.
8. The "klippen tectonic style" (block-in-matrix) resulted from the Lower Miocene transpressional deformation and disintegration of the original fold-thrust structures.

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THE EYES OF BOHEMIAN TRILOBITES

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Abstract

There are trilobites of the Bohemian area, which belong to the best preserved in the world. Their compound eyes were first studied in detail by Hawle and Corda in 1847, but especially by Barrande (1852, 1872), whose original observations are still of great value. More recently both holochroal and schizochroal eyes have been documented from Bohemian material, their visual fields plotted, growth geometry established, and thin-sections and polished surfaces used for determining the internal structure of the lenses. Modern physiological methods have great potential for determining the nature of the light environment to which even extinct animals were adapted, and thus have an important bearing on their ecology. The use of the eye parameter, which can be determined from the diameter and angle between adjacent lenses is discussed here. This approach, along with further detailed structural investigations should allow many new insights to accrue over the next few years.

Introduction

When Barrande (1846, 1852, 1872) published his comprehensive work on Central Bohemian trilobites, he took great care also to describe and illustrate details of eye morphology in his extraordinarily beautiful and precise drawings. While these drawings were made by his artist, Mr. Josef Fetters, Barrande supervised him at every stage, and the eyes are shown in the greatest detail observable in that time. Although trilobite eyes had been subsequently illustrated on Swedish material by Lindström (1901) it was not until the 1960s that the structure of the lenses, and other aspects of eye morphology were investigated, and this was based to a great extent on superbly preserved Silurian and Devonian material from Bohemia. Sometimes this is re-crystallised, but this is not always so, and thus Clarkson (1968) using polished surfaces and thin-sections of the eyes of *Reedops* showed that the intralensar bowls discussed and illustrated by Lindström were original components of the lenses and not diagenetic artefacts. Likewise in *Ananaspis fecunda* a sublensar capsule was recognised for the first time (Clarkson 1969) and such structures have been abundantly confirmed since. Ordovician *Ormathops* from Bohemia was used in studies of the generation and packing of lenses and distribution (Clarkson 1971) and many other Bohemian eyes have been illustrated, and their visual fields set out graphically (Clarkson 1973, 1975, 1997). Of the trilobite eyes illustrated in six plates by Clarkson (1975), three-quarters were from Bohemia, using material stored in British collections. Moreover, *Dalmanitina* eyes were used by Clarkson & Levi-Setti (1975) in investigations of lens-function. Budil and colleagues published articles about Middle Devonian Bohemian trilobite eyes (e. g. Budil 1996, 1999, Budil – Hörbinger 2007), but there remains scope for further studies on how they may have functioned, what their internal structure may have been, and what these eyes could tell us about the light environments to which these eyes were adapted – and thus their owners – the trilobites of the Prague Basin.

In many of the trilobites of the Barrandian area, the eyes are exceptionally well preserved, as good as, or better than, any in the world. They are all compound eyes, like those of arthropods such as insects or crustaceans living today. Functionally, the visual organs of trilobites are almost certainly of, or at least base on the so-called apposition type, still present in most diurnal arthropods of the present day, such as bees, dragonflies and many crustaceans active during the day. More evolved types, such

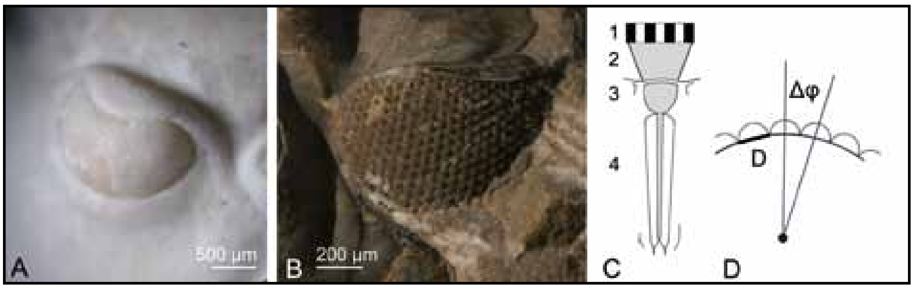

Fig. 1: Principles of compound eyes in trilobites: A – Holochroal eye of *Gerastos (Longiproetus) glandiferus glandiferus*; B – Schizochroal eye of *Dalmanites* sp.; C – Functional principle of an apposition eye: contrast distribution of the environment (1) inside the visual field of the ommatidium (2) is focused by the dioptric apparatus (3) onto the central rhabdom, which is part of the sensory cells (4); D – Explanation of the parameters: Δφ opening angle of the visual unit (ommatidium), D lens diameter, aperture.

Fig. 2: Holochroal eyes: A – Moulting of *Pricyclopyge binodosa* (Salter 1859); B – Facetted eyes of *P. binodosa*; C – Pattern of the facets of the compound eye of *P. binodosa*.

as the different kinds of superposition eyes (neural superposition eyes and all kinds of optical superposition eyes), compound eyes adapted to poorer light conditions, are not known before Jurassic times (Gaten 1998).

There are two main functional types in trilobite eyes. The holochroal eye (fig. 1 A, fig. 2), is composed of up to several thousands of units which can make up a compound eye, with densely packed round or hexagonal facets (fig. 2 B, C). A second type arose in the suborder Phacopina in the Early-Middle Ordovician, where the lenses remain separated from each other. The lenses are remarkably larger than in holochroal eyes (sometimes larger than 1 mm), and normally are less numerous. This type is called schizochroal eye (fig. 1 B, fig. 3). It has been shown recently by x-ray tomography that the schizochroal eyes of the Devonian trilobites

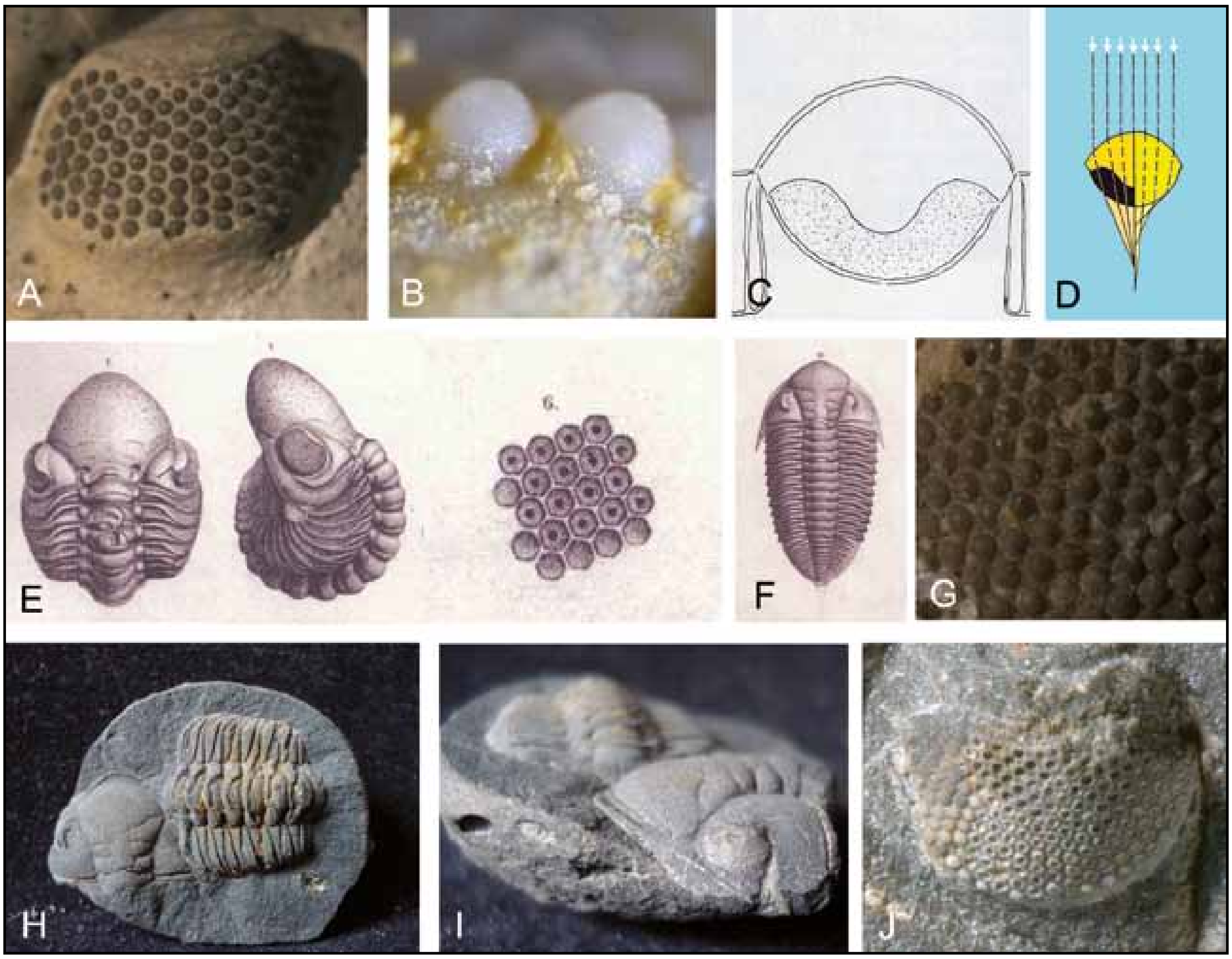

Fig. 3: Schizochroal eyes: A – Schizochroal eye of *Chotecops auspex*; B – Lens doublet of a small Bohemian phacopid trilobite; C – Schematic drawing of the lens doublet, the functional structure of a phacopid lens (after Levi-Setti 1975); D – Functioning of the lens doublet: right side: the rays at the periphery of the lens are focused at a different point from those which enter more centrally, thus the image will be blurred. Left side: the aplanic interfaces focuses all rays into one point, thus it results a sharp image; E – *Reedops cephalotes* (Hawle & Corda 1847) enrolled. In the center of the lenses the third internal structure, the core, is illustrated (Barrande, 1852, pl. 20, figures 1., 2., 6., as *Phacops cephalotes* Cor.); F – *Dalmanitina socialis* (Barrande, 1852), (Barrande 1852, pl. 26, fig. 16., as *Dalmanites socialis*); G – Visual surface of *Dalmanites* sp. (unknown locality, Silurian); H, I – *Ormathops atava*; J – Eye of specimen in H and I..

Geesops schlotheimi (Bronn 1835) from the German Trilobitenfelder/Gees show an internal structure identical to that of the apposition eyes of modern diurnal arthropods, although most previous models proposes a retinal eye. Because the schizochroal eye very probably originated by paedomorphosis (Clarkson – Zhang 1991) from an holochroal ancestror the holochroal eye ought to have the same functional structure, being an apposition eye too.

Methods of analysis of fossilised eyes and their chances of prospects for further insights

The apposition compound eye is composed of independent repetitive units, separated physically and functionally. Each unit, the so-called ommatidium (fig. 1 C), consists of a dioptric apparatus, which focuses the incident light onto a light-guiding structure, the so-called rhabdom, which is part of the sensory cells and contains the visual pigments. The energy of the entering rays changes the stereometric form of the visual pigment molecules and causes, in consequence, a low electrical signal, which can be processed by the nervous system of the arthropod. Because all the light captured inside the opening angle of the ommatidium is combined inside of the rhabdom, all contrasts inside the visual field of one facet is averaged to a single mean light intensity. Thus, an individual ommatidium does not transmit a complete image of the environment, but just a single point. The images from all the ommatidia form a mosaic-like image, in the same way that a pixel contributes to a computer graphic. The more pixels are available, the higher is the acuity of vision (at least in the first approxiamtion, other parameters may be taken into consideration too, but those are rather secondary). In modern arthropods like in certain dragonflies, but also in trilobites (for example among the Cyclopygidae), several thousands of "pixels" per eye are established. This performance of a compound eye is comparably low with regard to human camera lens eyes with several millions of sensory cells, but the circumspectant view at all times and into three dimensions is one of the great advantages of the compound eye system.

Modern physiology has developed advanced tools to describe the performances of apposition compound eyes, such as acuity (Snyder 1977, 1979, Snyder et al 1977, Horrdige 1977) and sensitivity (Land 1981). They have been applied to many recent forms, to characterise and to compare them (for an overview see Land 1981, Land & Nilsson 2002). Recently these methods have been used for diverse arthropods belonging to the Chengjiang Fauna and also for trilobites (Schoenemann – Clarkson 2010, 2011 a, b, c, McCormick – Fortey 1998).

A higher sensitivity gives an ability to live under poorer light conditions, in other words a crepuscular life style or at greater depth. This depends normally on a sufficient size of the facets, because larger lenses can capture more light than smaller ones. A high acuity however demands for as many visual units as possible, and thus in the limited space of a compound eye, they should be as small as possible. Thus, adapted to the light conditions of their environment, there results in compound eyes a "conflict" between the demands of acuity and sensitivity. As a result there is a compromise between highest acuity at threshold perception of light and the need to gather as much light as possible. This theoretical concept has led to the development of the so-called eye parameter p, characterising this compromise. When the facets are hexagonal: $p_{hex} = \frac{1}{2}.D.\Delta\varphi.\sqrt{3}$ [µm rad].D Lens diameter, the greater D the higher the sensitivity, because the more light can be yielded per unit, $\Delta\varphi$ opening angle of the visual unit (fig. 1 D), the smaller the angle, the finer the pattern of scanning of the surrounding and the higher is the acuity, Snyder (1977, 1979), Snyder et al 1977, Horridge (1977). Horridge (1977) investigated the eye parameter of many arthropods and showed how the eye parameter can be a useful tool for assigning the arthropods, in terms of the design of their compound eyes, to light environments to which they are adapted. This technique has been successfully used many since (for overview see Land 1981).

Using these methods of modern physiology it has been shown that of the more than half a billion year old fossilised *Isoxys* from the Chengjiang Fauna there exist two forms – one living close to the shore, and another one in deeper areas of the sea (Schoenemann – Clarkson 2010). Estimation of the eye parameter made it possible for McCormick and Fortey (1998) in a detailed analysis to assign the Ordovician telephinid trilobite *Carolinites killaryensis utahensis* to be pelagic, while *Pricyclopyge bindosa* was interpreted as mesopelagic. These theoretical tools have not yet been used further to characterise the environments to which Bohemian trilobites were adapted, but such an approach would undoubtedly be worth while, as will be shown here subsequently.

The eyes of Bohemian trilobites

Bearing in mind these principles, it seems appropriate to give a general preliminary characterisation of Bohemian trilobite vision, for even the outer shape, as the way to "wear" an eye, indicates much about a trilobite´s life-style. Holochroal eyes in particular reflect the mode of life of their owners. Most similar to the eyes of the predatory dragonflies are the impressive eyes of the Ordovician Cyclopygidae, which likewise possess several thousands of facets, small enough to indicate a diurnal, light adapted life-style. The compact and strong shape of their bodies indicate a powerful, free-swimming trilobite (fig. 2 A), and the high acuity of the eye allows the assumption that these trilobites were pelagic predatory arthropods, orientating themselves visually and so capturing their prey. This assumption is strengthened by the convergence and fusion of the lateral eyes anteriorly among in pricyclogidids. Finally *Ellipsotaphrus* possesses functionally just a single eye, panoramic and highly acute. Other impressive examples are among the remopleurid *Amphitryon*, body shaped like a modern jet fighter, and equipped with a highly resolving view in a wide ranging visual field (but offering only narrow, sub-horizontally oriented strip of closely packed sub-hexagonal ommatidia with very limited possibility to see dorsally and, especially, ventrally).

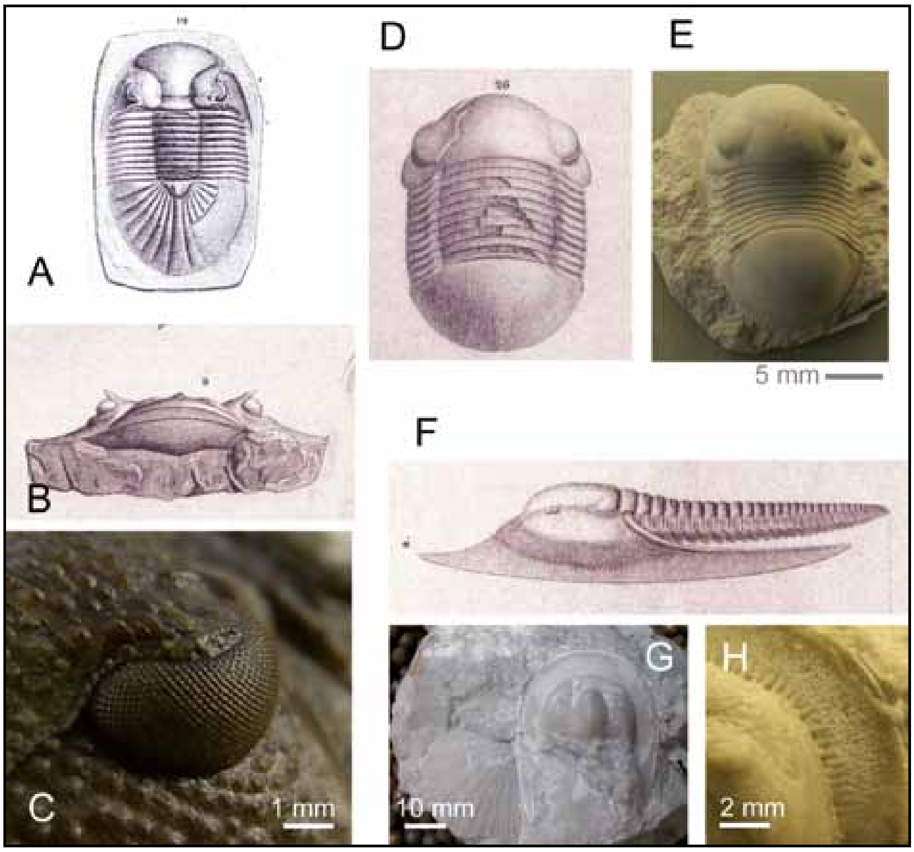

Fig. 4: Special adaptations and eye reduction: *Scabriscutellum (S.) caelebs caelebs* (Barrande, 1852, pl. 46, fig. 19, *Bronteus caelebs* (Barr.); B – Frontal view of *Radioscutellum intermixtum* (Hawle & Corda 1847) (Barrande 1852, plate 45, fig. 9., as *Bronteus palifer* Beyr.); C – Holochroal eye of *Scutellum geesense* Rud. & E. Richter 1956 (Middle Devonian, Germany); D – *Liolalax bouchardi* (Barrande, 1846), (Barrande, 1852, pl. 34, fig. 26., as *Illaenus bouchardi* Barr.) ; E – *Bumastus* sp.; F – *Bohemoharpes (Unguloharpes) ungula ungula* (Sternberg 1833) (Barrande 1852, pl. 9, fig. 2., as *Harpes ungula* Stern.) ; G, H – *Lioharpes venulosus* (Hawle & Corda, 1847). Note the delicate pores of cephalic rim.

Other holochroal eyes, with hundreds of fine delicate lenses can be found amongst the proetid and illaenid trilobites (fig. 4 A–E). These indicate a high acuity but they also require a high light intensity to function, thus a diurnal life-style not too far from the well lit water surface. Many of these eyes are covered by a kind of lid, the so-called palpebral lobe, which protects the eye from flickering light downwelling from the water surface, and thus concentrating the view mainly to the wide lateral horizon enabling the detection of possible predators. However, many of Bohemian illaenids are blind. The scutelloids show an impressive compound eye, each rather with a remarkable field of view, in a similar way. In the scutelloids the lenses may be slightly larger, however, indicating also that they were adapted to poorer light conditions. So, for example *Paralejurus campanifer* comes from the peri-reef environment, on the other hand, *Paralejurus brongniarti* from deeper part of the basin; a closer investigation of their visual systems would be of worth.

Besides the few pelagic probably predatory trilobites mentioned before, the detection of predators is a primary task for the facetted eyes of trilobites, and an effective facility for the detection of motion is one of the great advantages of this system. A temporal change in the pattern of light distribution across the facets indicates a moving object in the environment, and this detection is the finer the smaller are the facets. For small organisms especially it may be advantageous to have set the visual field onto long stalks, because the angle over the ground for scanning the horizon may be enlarged (Zeil et al. 1986, Zeil – Hemmi 2006). This principle is appropriate for example for the delicate forms of acidaspids, especially *Miraspis mira* (Barrande 1852, fig. 5 A). Notably, when coupled with an ability for enrollment, stalked eyes may enable such trilobites to see over the margins of their own bodies, as in *Cyphaspis* and allied genera (Barrande, 1852, plate 18) (fig. 5 D, E).

The need for detecting predators, social partners or simply to orientate optically may be of less importance in certain habitats and may lead to reduced compound eyes like the holochroal eyes of *Agraulos ceticephalus* (fig. 5 H, I); especially when other sensory organs may overtake the orientation function or help to find adequate food. This may be true especially for the harpetids, gliding over the ground with their wide cephalic margins, equipped with thousands of fine pores (fig. 4 F–H), which in our view may be traces of tiny chemosensory organs. The eye is reduced to 2 (*Bohemoharpes vittatus*) or 3 facets. Because they contribute, as explained before, just 3 “pixels”, and thus are unable to form any image, they may have functioned just as light detectors, informing the trilobite about the state of the day or may have given rough and limited information about moving patterns in the environment. The relatively large size of the lenses indicates again an adaptation to darker environments.

Blindness is regarded to be secondary in trilobites, and blind trilobites like *Conocoryphe sulzeri* (fig. 5 G) or the elegant forms of *Ampyx* (fig. 5 B, C) are restricted to a benthic habitat, probably with poor light conditions.

The schizochroal eye, which is represented only in the suborder Phacopina, originated from the holochroal eye probably paedomorphically (Clarkson – Zhang 1991). The lenses of the Silurian dalmanitids as in many geologically younger phacopids, show a highly differentiated internal structure, which is not as yet completely understood. The impressive schizochroal eyes like those of *Dalmanites*

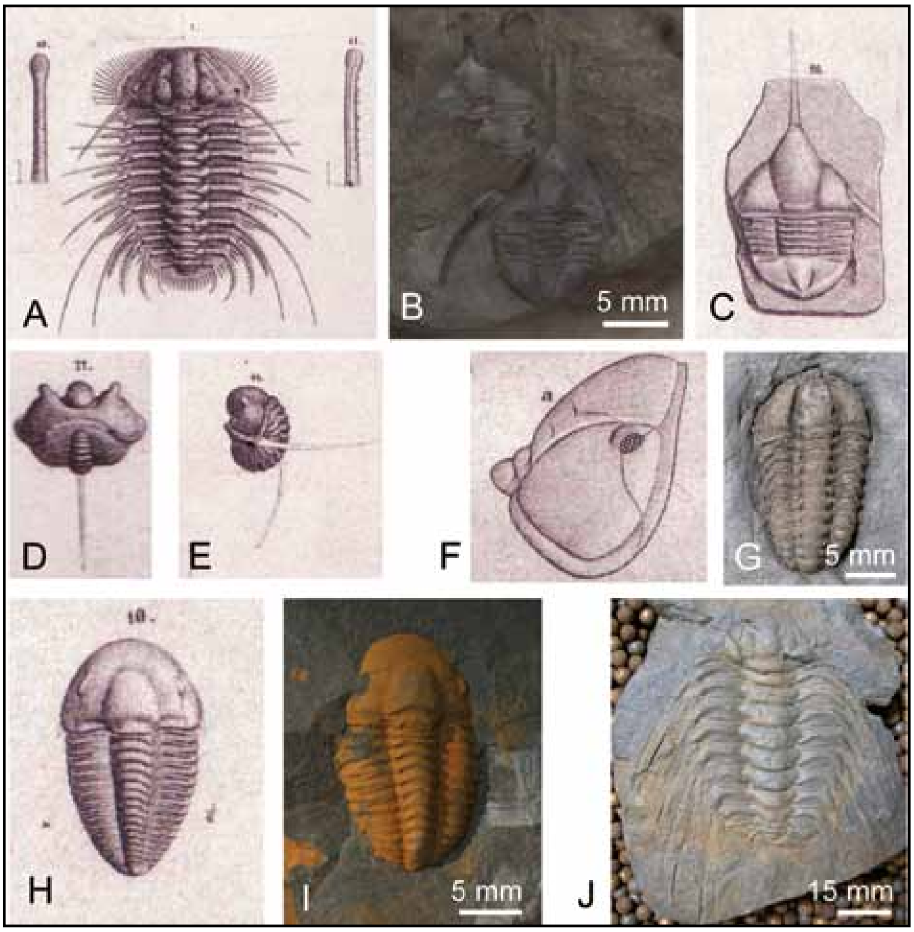

Fig. 5: Special adaptations and eye reduction: Stalked eyes of *Miraspis mira* (Barrande 1852, pl. 39, figures 1., 10., 11., as *Acidaspis mira* Barr.); B – *Ampyx nasutus* Dalman 1827, a blind trilobite (Ordovician, Morocco); C – *Lonchodomas porthlocki* (Barrande 1846) (Barrande 1852, pl. 30, fig. 26., as *Ampyx porthlocki* Barr.); D, E – *Cyphaspis barrandei* (Hawle & Corda 1847), (Barrande 1852, pl. 18, figures 43., 44., as *Cyphaspis barrandei* Cord.) enrolled, looking over the margins of the body; F – Eye reduction in schizochroal eyes *Deckmannites volborthi* (Barrande 1852) (Barrande 1982, pl. 3, fig. 26., as *Phacops volborthi* Barr.); G – *Conocoryphe sulzeri sulzeri* (Schlotheim 1823), a blind trilobite; H, I – *Agraulos (A.) ceticephalus* (Barrande, 1846), (Barrande 1852, as *Arionellus ceticephalus* Barr.); J – *Selenopeltis* sp., a huge ground-living trilobite.

(fig. 3 F, G) or Ormathops (fig. 3 H–J), have a wide field of view, and their almost spherical lenses remain close to each other,even if not as close as in holochroal eyes. It was shown by Clarkson and Levi-Setti in 1975, that the lenses of Bohemian *Dalmanitina socialis* Barrande 1852 are actually lens-systems (fig. 3 C), consisting of two parts, which under certain conditions allow a sharp focusing, even without spherical aberration (fig. 3 D). This sophisticated system suggested an underlying retina, able to form real images. In other phacopid trilobites, like the Middle Devonian *Geesops schlotheimi* (Bronn 1835), from the German Trilobitenfelder in Gees, it has been shown however, by x-ray tomography, made in Bonn, the sublensar elements were of apposition type, which represents the oldest traces of sensory cells known so far (Schoenemann – Clarkson 2011c).

In some phacopid trilobites even a third internal structure exists, a central more or less drop-like shaped core, which may act as an additional internal lens or may have some other optical function. This core can already be seen in the precise drawings of Barrande´s *Reedops cephalotes* (Barrande 1852, plate 20) (fig. 3 E). These structures occasionally have been discussed as diagenetical, but it could be shown that they are primary structures (Lee et al. 2007).

However sophisticated the visual system of phacopid trilobites may have been, eye reduction can be observed also in Bohemian phacopid trilobites, as in the comparably small but robust *Denckmannites volborthi*, which possesses small eyes, with less than 20 facets within each (fig. 5 F). Because the lenses are orentated anteriorly and the reduction starts in the posterior part of the eye, this eye could still well protect the trilobite by vision or to help to unearth prey. To see movements outside still would be possible, but the acuity of vision became rather low.

In this short article only a few of the different kinds of eyes in the Bohemian trilobite fauna have been discussed here, along with a general overview of physiological principles, which should help in understanding them further. There is scope for so much more work to be undertaken on the superbly preserved eyes of Bohemian trilobites, and it is highly likely that their exceptional quality will allow many new insights to accrue over the next years.

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Various xenoliths enclosed in amphibole-biotite granodiorite of the Central Bohemian Plutonic Complex; quarry Solopysky (3 km W of Sedlčany, 16 km NW of Monínec). Photo: F. V. Holub, 2002.

Praenucula applanans (Barrande, 1881) from the Šárka Formation (Middle Ordovician), two valves of articulated specimen (Osek near Rokycany). Length of the valves 10 mm. Photo: M. Steinova, 2010.

Contact of a minette dyke (dark) intruding pinkish biotite granite of the Central Bohemian Plutonic Complex near its NW border. Roadcut at Milín (SE of Příbram, 35 km WNW of Monínec). Photo: F. V. Holub, 2005.

Spherical orbicule (6 cm in diameter) formed by a core made up of a subhedral crystals of cordierite, replaced by secondary minerals (chlorite, muscovite), and rimmed by radially oriented oligoclase crystals. Dyke of orbicular granite, Sedlec. Photo: D. Buriánek, 2002.

Famous palaeontological locality Háj near Zahořany (left) belongs to very important localities of the Letná Formation (Upper Ordovician, Sandbian, Prague Basin). At this locality, many important fossil findings have been gathered, including this complete specimen of *Selenopeltis buchi* with edrioasteroids attached to the dorsal exoskeleton (right). Such findings document commensal behaviour of these organisms. Length of sample 14 cm (longer size). Photos: P. Čáp, 2006 – locality Háj near Zahořany and P. Budil, 2010 – *Selenopeltis buchi*.

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