

CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY AND SEDIMENTARY ENVIRONMENT OF VALANGINIAN–HAUTERIVIAN RHYTHMITES (SILESIA NAPPE, POLISH CARPATHIANS)

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Abstract: The results of semi-quantitative and qualitative studies of nannofossil assemblages in dark to light grey, rhythmically bedded, calcareous mudstones of the Upper Cieszyn Beds, Silesian Nappe of the Outer Carpathians are presented. The vertical variation in the carbonate content of these mudstones and changes in the composition of nannofossil assemblages, as well as the Shannon diversity index (SI), result from humid-arid climate changes, driving the trophic conditions of surface waters and nannoplankton biocalcification. These changes were controlled by the variable influences of both the Tethyan and Boreal provinces. The light grey mudstones were deposited during the dominance of warm waters from the Tethyan realm and some nannoconids, typical of the warm, stratified water of lower palaeolatitudes, occur here. The dark grey mudstones represent influences of the Boreal province, indicated by the appearance of *Crucibiscutum* sp. and a generally higher biodiversity demonstrated by SI. Climatic changes affected the stratification of surface water, expressed also by different linear fits for pairs of SI, *Watznaueria barnesiae* and *Rhagodiscus asper*. On the basis of the presence of *Eiffellithus striatus*, *E. windii* and signals of both Tethyan and Boreal influences, the section studied represents the uppermost Valanginian–lowermost Hauterivian boundary interval, i.e., the upper part of the BC5/BC6 nannofossil zones, related to the *furcillata-radiatus* ammonite zones.

Key words: calcareous nannofossils, biostratigraphy, Lower Cretaceous, Silesian Nappe, Polish Carpathians, Tethyan-Boreal influences.

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INTRODUCTION

Valanginian–Hauterivian time is considered to mark major, climate-induced, environmental perturbations and the coldest interval during the Early Cretaceous, supposedly connected with the formation of the polar ice cap. Direct evidence for Early Cretaceous glaciations, such as clasts from seasonal ice rafting and glendonites or tillite, have been reported (e.g., Frakes *et al.*, 1995; Price, 1999; Alley and Frakes, 2003). McArthur *et al.* (2007) drew attention to the Late Valanginian and Early Hauterivian as the time of formation of the polar ice cap, which waned in the Late Hauterivian. The consequence of formation of the ice cap was a drop in sea level, postulated on a chart by Hardenbol *et al.* (1998) to have been as much as 90 m, or 50 m as claimed by Stoll and Schrag (1996), on the basis of sudden inputs of strontium, resulting from the emergence of the continental shelves.

The supposed formation of the polar ice cap was triggered by a global drop in palaeotemperature. On the basis of $\delta^{18}\text{O}$ data, taken from belemnite rostra, it was estimated as

about 10°C, dropping from 20°C in the Berriasian down to 10°C in the Early Hauterivian (Podlaha *et al.*, 1998). The early Late Valanginian *verrucosum* and *peregrinus* ammonite zones are considered to be a time of a cold sea surface, with a decline of about 4° (McArthur *et al.*, 2007). Isotopic data from Siberian sub-Arctic belemnites show the lowest temperatures in the Late Valanginian, coinciding with a fall in sea level and pulses of nutrient inputs, due to melting of the ice (Price and Mutterlose, 2004). Also oxygen and carbon isotope data, taken from belemnites and glendonites in Arctic Svalbard, point out cool palaeotemperatures (4–7°C), indicative of glacial, polar conditions in the Valanginian (Price and Nunn, 2010). Data from carbon-isotope studies of terrestrial plants also evidence a cool period or icehouse in the Late Valanginian (Gröcke *et al.*, 2005). However, the cooling trend of ocean bottom water, dropping from 15°C in late Early Valanginian to 11°C in the Late Valanginian–Early Hauterivian, was connected with a second-order rise in sea level, allowing for the displacement of cold, Boreal wa-

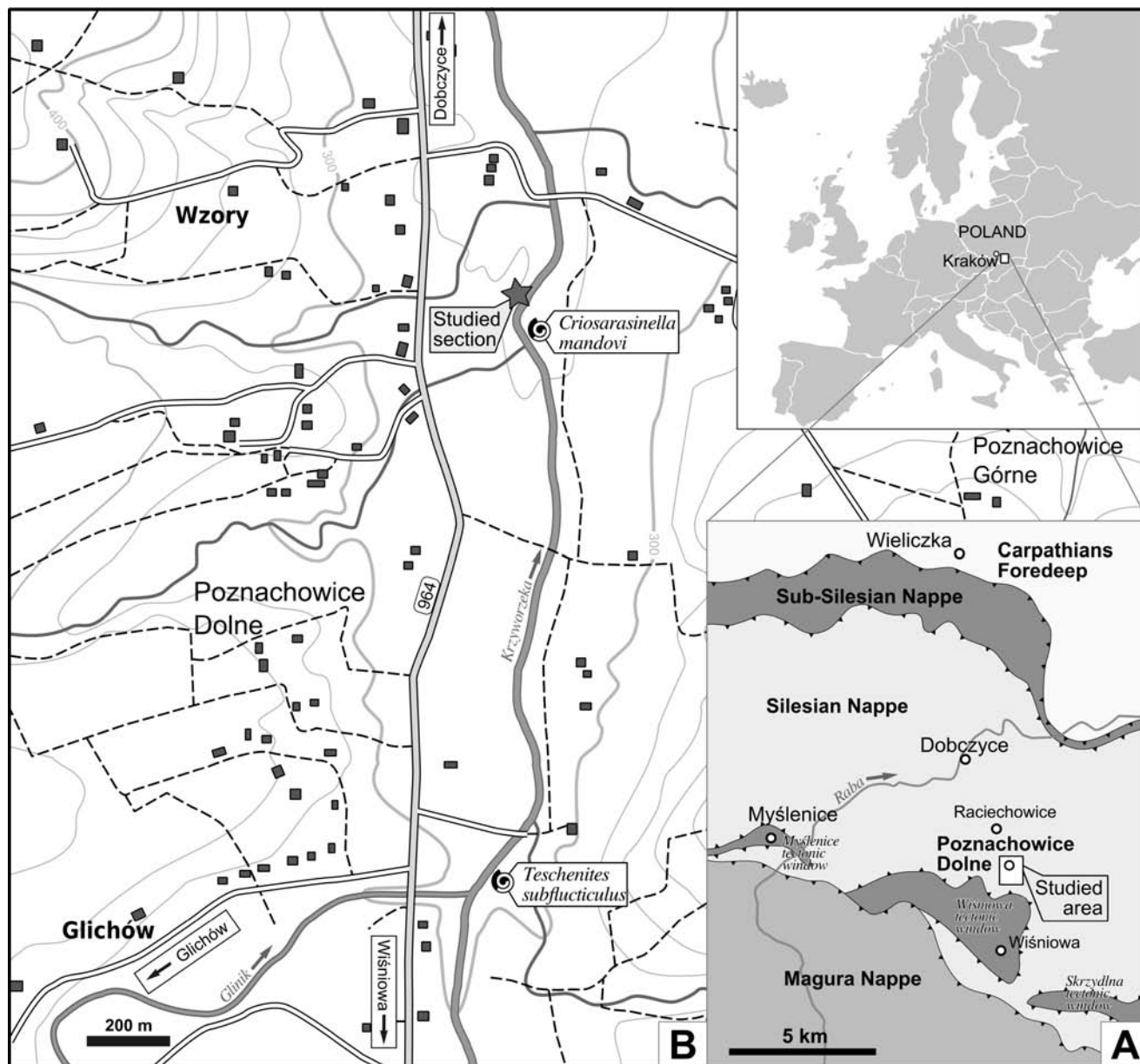


Fig. 1. Location maps of the area and section studied. **A.** Location of the area studied on the background of the geological sketch map (after Burtan, 1984). **B.** Detailed, topographic map with locations of the section studied and ammonite finds, described by Vašíček *et al.* (2010)

ters by warm Tethys ones (Van de Schootbrugge *et al.*, 2000). Vašíček and Michalík (1997) also noted a Boreal ammonite migration during the high stands of the *verrucosum* ammonite Zone (early Late Valanginian). They also referred to the Lower Valanginian *petransiens* and Lower Hauterivian *radiatus* ammonite zones as times of Boreal ammonite influences in the Silesian Basin in the Western Carpathians. The *verrucosum* ammonite Zone was also a time of Tethyan ammonite migration into both northern and southern, high latitudes (Kutek *et al.*, 1989; Kutek and Marcinowski, 1996; Aguirre-Urreta, 1998; Alsen, 2006).

Littler *et al.* (2011) presented evidence to the contrary, for warm sea-surface water that exceeded temperatures of 32°C in the palaeolatitudes 15°–20°N and reached about 26°C in the vicinity of palaeolatitude 53°S. Also Bornemann and Mutterlose (2008) concluded that an increase in

nutrient availability indicates enhanced upwelling, rather than cooling in the western Atlantic during the Valanginian. Recently, Barbarin *et al.* (2012), on the basis of oxygen isotopes from fish teeth, postulated that the Valanginian bottom water temperature ranged from 18.4 to 21.6°C at about 500–800 m in depth, in the subtropical zone of the Vocontian Basin (SE France). Furthermore, Jenkyns *et al.* (2012) demonstrated the elevated sea-surface temperatures at high latitudes during the Jurassic–Cretaceous “cold snaps”, which dropped down to the 25–26°C level during the coldest part of the Callovian–Oxfordian boundary. This may indicate the presence, if any, of continental ice-caps only in considerable areas of high altitude on Antarctica.

The Early/Late Valanginian was a time of a major shift of $\delta^{13}\text{C}$ called the Weissert Episode (Weissert and Erba, 2004; Föllmi *et al.*, 2006; McArthur *et al.*, 2007; Föllmi,

2012). It was accompanied or followed by enrichment in phosphorus and trace metals (Föllmi, 1995; Van de Schootbrugge *et al.*, 2003; Kuhn *et al.*, 2005). Despite the carbon isotope anomaly, the Weissert Episode was not entirely related to enhanced, marine, primary production and bottom anoxia in some regions (McArthur *et al.*, 2007; Westermann *et al.*, 2010). The Valanginian sediments of the Vocontian Basin were deposited on a well oxygenated bottom, under relatively stable, marine, palaeoenvironmental conditions (Kujau *et al.*, 2012). It cannot be excluded that, in contrast to other Mesozoic oceanic anoxic events, the Weissert Episode resulted in increased deposition of organic matter in marginal seas and on continents, combined with the demise of shallow-water carbonate platforms (Westermann *et al.*, 2010).

This was interpreted to be the result of the break-up of Pangaea and creation of new, continental rift basins (see Föllmi, 2012), including the Proto-Silesian rift basin, at the margin of the North European Platform. The break-up and rifting of Pangaea led to the submergence of the widespread carbonate platform, with the main phase referable to the Valanginian *verrucosum* to *radiatus* ammonite zones (Föllmi *et al.*, 1994; Weissert *et al.*, 1998; Föllmi *et al.*, 2006; Föllmi, 2012). This general scenario also is recorded in the Silesian Unit. The submergence of the carbonate shelf of the Proto-Silesian Basin also was postulated by Szydło and Jugowiec (1997, 1999). In conclusion, following the Proto-Silesian rifting, the Tithonian–Berriasian carbonate-rich Cieszyn Limestone Formation gave way to the dark Upper Cieszyn Shales in the Valanginian. The section studied represents this initial stage of this change.

The main goal of this study was to recognize the stratigraphy and palaeoenvironmental changes of the Upper Cieszyn Beds in the vicinity of Poznachowice (Silesian Unit) on the basis of calcareous nannofossil assemblages.

GEOLOGICAL SETTING

Palaeogeography and geological background

The section is located between the Raciechowice Anticline and the Wiśniowa Tectonic Window and represents the Silesian Unit succession (Fig. 1A) (Kuźniar 1923, 1924; Burtan, 1984). The Silesian Unit, the largest complex nappe of the Outer Carpathians, was folded and thrust northward during the Miocene and nowadays stretches out from Czech Republic through Poland to the Ukrainian Flysch Carpathians. It comprises a thick series of mainly flysch deposits, ranging from the Kimmeridgian up to the Lower Miocene. They accumulated in an oceanic rift or back-arc basin, located on thinned, continental crust of the North European Platform. The Late Jurassic–Early Cretaceous basin, named the Proto-Silesian or Severin–Moldavide Basin, was subdivided into several smaller basins during the Late Cretaceous, with the Silesian Basin (Silesian Unit) the largest one among them (e.g., Ślaczka *et al.*, 2006; Golonka *et al.*, 2008a).

In addition to the historical treatises by Staszic (1815), Push (1836), Hohenegger (1861) and Uhlig (1902), the stratigraphy and tectonic history of the Silesian Unit are known

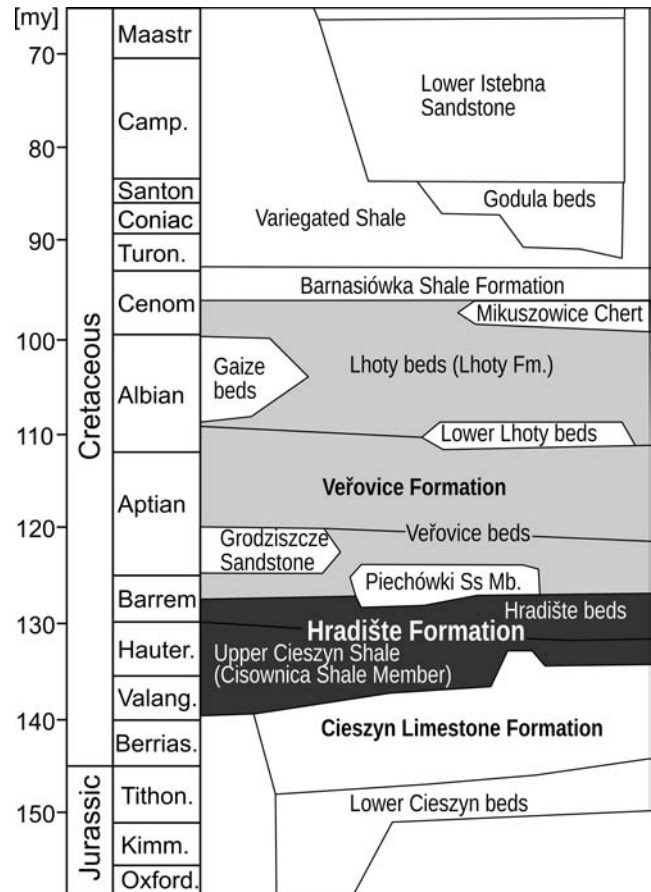


Fig. 2. Lithostratigraphic scheme of Silesian Nappe. Studied interval coloured in dark grey (after Vašíček *et al.*, 2010 and authors, cited therein)

from more recent papers by Kokoszyńska (1949), Gašiorowski (1962), Vašíček (1972, 1975, 2008), Burtan (1974, 1978, 1984) and Szymakowska (1981). Micropalaeontological studies of the Lower Cretaceous of the Silesian Unit by Geroch (1966), Olszewska (1997), Gedl (2001), Olszewska and Malata (2006), Olszewska *et al.* (2008), including nannofossil investigations by Szydło and Jugowiec (1997, 1999), Švábenická (2008), Svobodova *et al.* (2011) and Halásová *et al.* (2012), narrowed the age of the Upper Cieszyn Beds to the Valanginian–Hauterivian (Fig. 2). Nevertheless, according to Olszewska *et al.* (2008), sedimentation of the underlying Cieszyn Limestone already may have been completed at the end of the Valanginian, and therefore, sedimentation of the Upper Cieszyn Beds began at least in the Early Hauterivian. Recently, the discovery of two ammonites, *Criosarasinella mandovi* Thieuloy and *Teschinites subflucticulus* Reboulet, a few hundred meters from the section (Fig. 1B), indicated the uppermost Valanginian, i.e., *peregrinus* and *furcillata* ammonite zones, according to Reboulet *et al.* (2009) (*vide* Vašíček *et al.*, 2010).

The Upper Cieszyn Beds represent the lower part of the Hradište Formation, distinguished as the formal, lithostratigraphical unit, named as the Cisownica Shale Member, which is assigned to the Valanginian–Hauterivian (Golonka *et al.*, 2008b) and considered to be the oldest sedimentary rocks in the study area (Fig. 2).

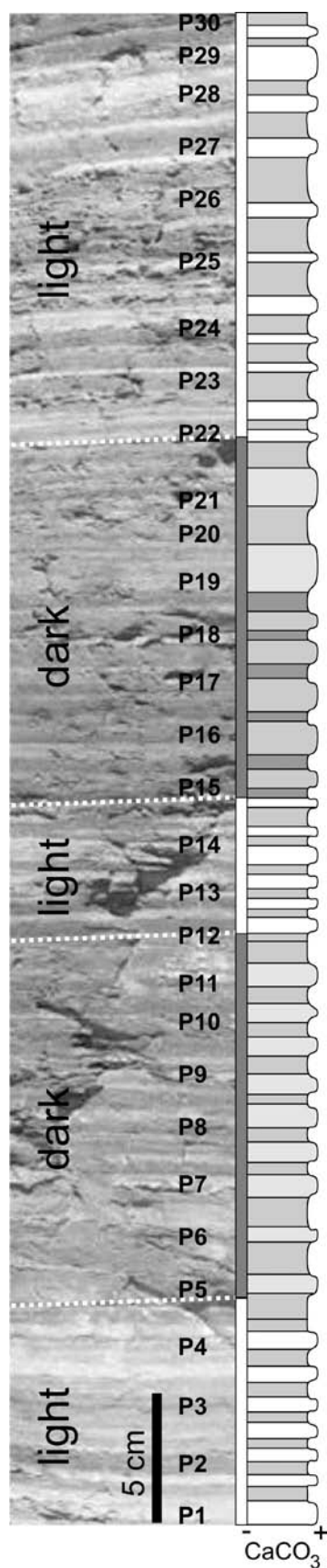


Fig. 3. Section studied, with location of rock samples indicated by sample numbers. Distinguished groups of light- and dark-coloured mudstones are separated by white, dotted lines. Shades of grey depend on assumed carbonate content

Characteristics of the section studied

The section of the Upper Cieszyn Beds is located in the western bank of the Krzyworzeka stream (coordinates: N49°49'56", E20°07'13"), in Poznachowice Dolne village, south from Dobczyce in the direction of Wiśniowa, along Road No. 964 (Fig. 1B). The section consists of alternating dark and light grey, thin-bedded (2–20 mm), laminated, carbonate mudstones, in places interbedded with thin (up to 5 mm) beds of fine-grained, calcareous sandstones. They dip almost vertically and frequently are cut by faults. The dark and light grey mudstones comprise regularly recurring groups of carbonate-rich beds (Fig. 3).

MATERIAL AND METHODS

Every 2 cm of the section, embracing 147 beds with three groups of light grey and two groups of dark grey mudstones respectively, were sampled for the present study (Fig. 3). This constitutes a record of 60 cm of the section with 30 rock samples, designated P1 through P30. Microscope slides were made, using the simple-smear slide technique (Bown and Young, 1998), and then examined under the light Nikon Eclipse E600 Pol microscope at a magnification of $\times 1000$.

The relative abundance (percentage) of calcareous nanofossils was determined on the basis of about 300 specimens, counted on a smear-slide (*vide* Bown and Young, 1998). In samples, where the total nanofossil abundance was at least less than 300 specimens, the percentage was calculated, with respect to all specimens available for analysis (Tab. 1). The heterogeneity or relationship of diversity and abundance of each of the taxa counted is given by the Shannon Index (SI) (Shannon and Weaver, 1949). Assemblages, dominated by one or a few taxa, tend to show low values of SI. In contrast, high SI value, characterize highly diversified assemblages. Moreover, regression analysis was performed for selected variables with continuous (or almost continuous) occurrence.

RESULTS

Calcareous nanofossils have been found in all of the slides examined and some of them are exemplified on Fig. 4. In general, they are poorly or moderately preserved and represent 29 taxa, belonging to 17 genera (Tab. 1). The calcareous nanofossil assemblages are dominated by *Watznaueria barnesiae* species, the percentage of which varies from 74% in sample P20 to 92% in sample P10. *Staurolithites mutterlosei*, *Staurolithites* spp., *Rhagodiscus asper*, *Retecapsa* spp. including *R. angustiforata*, *W. fossacincta* or *Zeugrhabdotus* spp. are also common (Tab. 1). However, rare but very distinctive occurrences of *Crucillipsis cuvillieri* and *Crucibiscutum* sp. were also noted (Fig. 4). The presence of *C. cuvillieri* is almost continuous, whereas *Crucibiscutum* sp. was found in samples P4 and P20, taken from the dark grey mudstone groups of strata (Fig. 3). *Crucibiscutum* sp., which was noted in the samples, differs

Table 1

Number of species, Shannon Index and abundances of calcareous nannofossils studied

No of samples	NOS	Shannon index	<i>Biscutum</i> sp.	<i>Calceolathina oblongata</i>	<i>Cretarhabdus conicus</i>	<i>Crucibiscutum</i> sp.	<i>Crucitripsis cavillieri</i>	<i>Cyclagelosphaera</i> sp.	<i>Diazomatolithus lehmannii</i>	<i>Eiffelolithus striatus</i>	<i>Eiffelolithus windii</i>	<i>Eiffelolithus</i> spp.	<i>Micrantholithus hoshultzei</i>	<i>Micrantholithus obtusus</i>	<i>Nannoconus</i> spp.	<i>Retecapsa angustiforata</i>	<i>Retecapsa surirella</i>	<i>Retecapsa</i> spp.	<i>Rhagodiscus asper</i>	<i>Rhagodiscus</i> sp.	<i>Speetonia colligata</i>	<i>Staurolithes erax</i>	<i>Staurolithes mutterlosei</i>	<i>Staurolithes</i> spp.	<i>Tubodiscus</i> spp.	<i>Watznaueria barnesiae</i>	<i>Watznaueria britannica</i>	<i>Watznaueria fossacincta</i>	<i>Zeugrhabdotus diplogrammus</i>	<i>Zeugrhabdotus embergeri</i>	<i>Zeugrhabdotus</i> spp.	
P30	15	2.414			0.5				0.5	0.5						0.5	0.5	0.9	0.9	0.9			3.7	4.1	0.5	82.1		1.8		0.9	1.8	
P29	16	1.962	0.3		0.3		0.3		0.6		0.3					0.6		2.5	0.3	0.3			0.3	1.5	0.3	86.5		5.2		0.3	0.3	
P28	17	1.92		0.3					0.3	0.3			0.3			0.3	0.9	0.9	1.2			0.3	1.2	1.7	0.3	88.4	0.9	1.7		0.3	0.9	
P27	20	2.256	0.3		0.3		0.8		0.5	0.3	0.3	0.5	0.3		0.3		0.3	1.3	1.5			0.3	2.6	2.8	0.5	84.8		1.3	0.3		1.0	
P26	15	2.129			0.9			0.9		0.4		0.9					0.9	2.2	1.3	0.4			0.9	2.2		85.8	0.4	2.2		0.4	0.4	
P25	14	2.026	0.5				0.5	0.5	0.5	0.5					0.5	0.5	1.5		1.0				1.0	1.0		85.7		5.9			0.5	
P24	3	1.822																								9.1		81.8		9.1		0.0
P23	16	1.7		0.3	0.3		0.3			0.3	0.3	0.6		0.3			1.2		1.2			0.3	0.3	0.6		90.5		3.0		0.3	0.3	
P22	15	2.101		0.3	1.2			0.6	0.9								0.9		2.4	0.6			0.3	0.6	0.3	85.5		2.9	0.3	0.3	0.9	
P21	15	2.414		0.3	0.9			0.3	1.7			0.3					1.5	0.9	2.9	0.6		0.3	0.6	2.3		81.4	0.3	5.8				
P20	14	3.021			1.4	0.5	0.5		0.5		0.5					0.5	0.5		8.7	3.2		0.5	3.2	2.7		74.0		3.7				
P19	13	2.029	0.3		0.9		0.6		0.0			0.3						1.8	0.9				0.3	1.5	0.3	85.5	0.3	5.1			2.1	
P18	7	2.552					1.6		3.2									4.8	1.6							3.2		75.8		9.7		
P17	14	2.204			0.3				0.6	0.3		1.5						2.5	1.5			0.3	0.9	2.2	1.2	84.6	1.8	1.8			0.3	
P16	13	1.964					0.3					1.5					0.9	2.2	2.5			0.3	0.6	1.8	1.2	87.1		0.9		0.3	0.3	
P15	11	2.016							0.7								0.7	0.7	1.3			0.7	0.7	1.3	2.0	85.2		6.0			0.7	
P14	11	2.072			0.3							0.6						1.5	4.0	3.4			0.3		0.3	84.6		2.8		0.6	1.5	
P13	11	2.182										0.9				0.3		2.1	2.1				0.9	1.5	0.9	83.9		4.2		1.5	1.5	
P12	17	2.589			0.9		0.5		0.5			1.4				0.5	0.5	1.9	0.5	4.2			1.9	2.3	0.9	81.2		0.9	0.5	0.5	0.9	
P11	8	2.713										4.8						4.8	2.4					2.4	4.8	76.2		2.4			2.4	
P10	9	1.555										1.5						1.5	0.7				0.7	0.7	0.7	92.0		0.7			1.5	
P9	17	2.066			0.3				0.3	0.3		1.8				0.3	0.6	0.9	0.9			0.3	0.6	1.8	0.6	86.8		2.2	0.3	0.6	1.2	
P8	9	2.16										0.0	1.1					1.1	3.2	1.1			1.1	2.2	6.5	82.8		1.1				
P7	19	2.24			0.3		0.3			0.5		2.7				0.3	0.5	1.9	2.9	0.5		0.3	0.8	0.8	0.3	84.9	0.3	0.5	0.3	0.8	1.3	
P6	15	2.392			1.5		0.3			0.3		1.2	0.3					2.7	5.5	0.3		0.6	0.9	1.5		82.0		0.6		0.6	1.5	
P5	11	2.518			1.0		2.0					1.0	1.0					2.0	4.9						5.9	1.0	79.4				1.0	1.0
P4	16	2.37			0.6	0.3	0.3				0.3	2.7					0.9	1.8	4.6	1.5			0.3	1.5	0.3	82.6		0.6		0.3	1.2	
P3	20	2.511	0.3		0.3		0.3		0.9	0.3		0.6	0.6		0.3	0.3		0.9	5.5		0.3	0.3		1.8	1.2	81.9		0.9	0.3	1.2	1.5	
P2	17	2.672	0.3		0.3				0.3			0.9	0.3				1.2	2.4	6.8	0.3		0.3	1.5	3.6	1.2	78.9		0.9		0.3	0.6	
P1	17	2.312		0.3	0.3		0.3		0.3	0.3		2.2				0.6	1.8	2.2	3.4	0.6		0.3	0.3	1.8	0.9	83.7		0.6				

from known species by having a wide, central area with an axial cross and narrow rim (Fig. 4B). Moreover, some rare appearances of nannoconids were noted in three samples P3, P25 and P27, taken from the groups of light grey mudstone strata.

The number of species in a sample (NOS) changes from 3 in sample P24 up to 20 in samples P3 and P27. The Shannon diversity index (SI) varies from 1.56 in sample P10 to 3.02 in sample P20.

The variables of the regression analysis, apart from SI and NOS, include *W. barnesiae*, *R. asper*, *Zeugrhabdotus* spp., *S. mutterlosei* and *Staurolithes* spp. (Tab. 2; Fig. 5).

The regression analysis shows a significant, strong correlation, i.e., $|r|$ above 0.5, only for three pairs of variables: SI vs. *W. barnesiae*, SI vs. *R. asper* and *W. barnesiae* vs. *R. asper*. Other pairs have zero to medium, linear fit.

Table 2

Correlation coefficient r for selected variables.

	NOS	SI	<i>W. barnesiae</i>	<i>R. asper</i>	<i>Zeugrhabdotus</i> spp.	<i>Staurolithes</i> spp.
Shannon index	0.1656					
<i>W. barnesiae</i>	0.2209	-0.9043				
<i>R. asper</i>	0.2068	0.6770	-0.5695			
<i>Zeugrhabdotus</i> spp.	0.0944	0.0547	0.0593	-0.0387		
<i>Staurolithes</i> spp.	-0.4241	0.1911	-0.439	0.0016	-0.2338	
<i>S. mutterlosei</i>	0.3128	0.3426	-0.1761	0.1553	0.01356	0.0517

$|r|$ values above 0.5 are in bold type

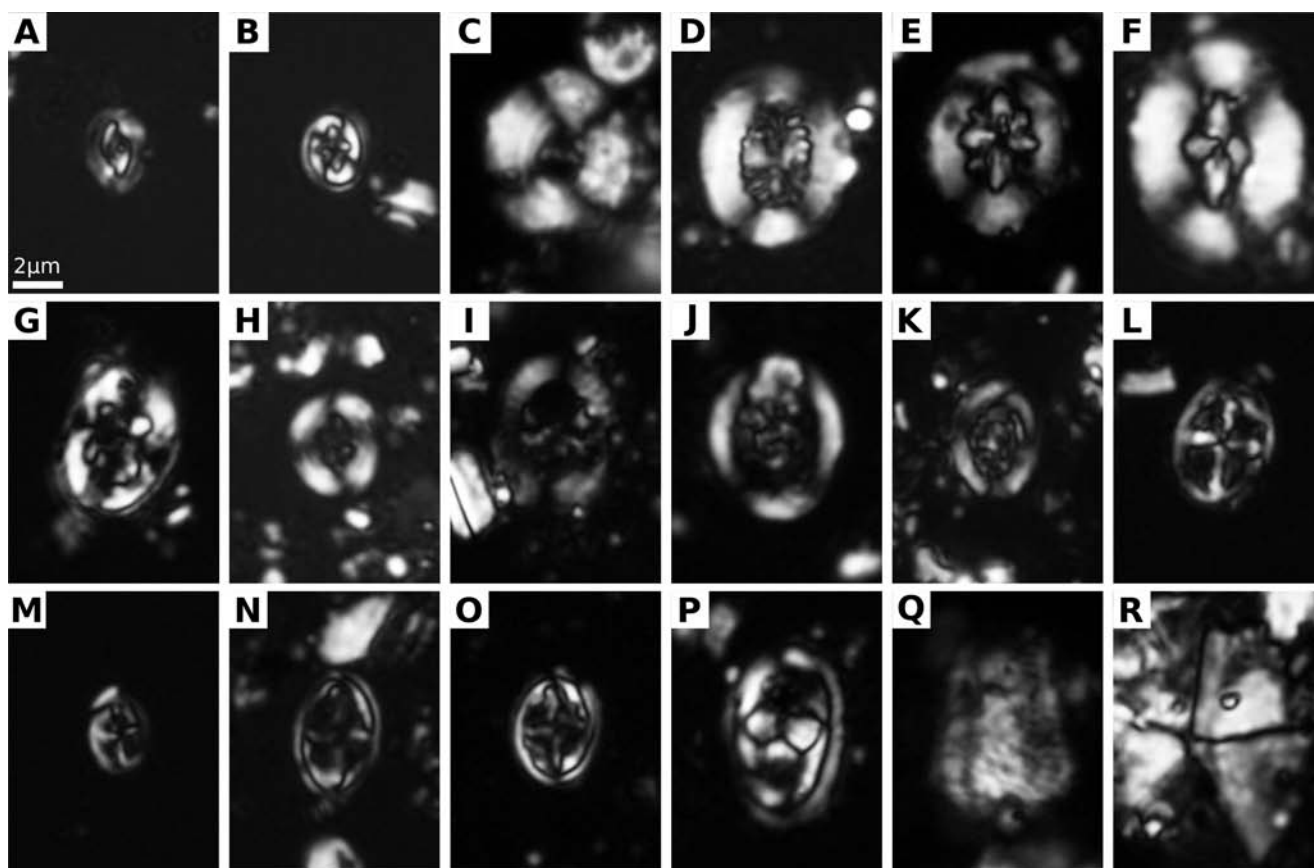


Fig. 4. Calcareous nannofossils in cross-polarised light. **A.** *Biscutum* sp., sample P25; **B.** *Crucibiscutum* sp., sample P20; **C.** *Watznaueria britannica*, sample P17; **D.** *Retecapsa surirella*, sample P14; **E.** *R. angustiforata*, sample P29; **F.** *Crucielipsis cuvillieri*, sample P18; **G.** *Eiffellithus striatus*, sample P25; **H.** *E. windii*, sample P20; **I.** *Speetonia colligata*, sample P3; **J.** *Rhagodiscus asper*, sample P21; **K.** *Rhagodiscus* sp., sample P30; **L.** *Staurolithites* sp., sample P24; **M.** *S. crux*, sample P6; **N.** *S. mutterlosei*, sample P30; **O.** *S. mutterlosei*, sample P8; **P.** *Zeugrhabdotus embergeri*, sample P3; **Q.** *Nannoconus* sp., sample P25; **R.** *Micrantholithus hoschultzii*, sample P8. The scale-bar is the same for the all photographs

DISCUSSION

Preservation of nannofossil assemblages

The susceptibility of calcareous nannofossils to dissolution during deposition and diagenesis depends on nannofossil structure (Steinmetz, 1994) and the presence of clays and organic matter in the deposit (Turchyn and DePaolo, 2011).

The taxon, most resistant to dissolution among those studied, is *Watznaueria barnesiae*. Fragile muroliths and placoliths, such as *Staurolithites crux* or *Biscutum constans*, are prone to dissolution (Hill, 1975; Thierstein, 1980; Roth and Bowdler, 1981; Bown and Young, 1998).

Roth and Bowdler (1981) concluded that assemblages with percentages of *Watznaueria* spp., exceeding 40%, may have been significantly changed by diagenesis. Alternatively, nannofossil assemblages dominated by *Watznaueria* may also be records of a pristine signal (e.g., Thomsen, 1989; Pittet and Mattioli, 2002). Such evidence is explained by the *r*-selected life strategy of that genus, which can be found in great abundance in the sediments of environments that were hostile for other taxa (e.g., Lees *et al.*, 2004). Moreover, the clays and/or organic matter in the sediment control the composition of the biogenic carbonates and,

consequently, the nannofossil assemblages (Pearson *et al.*, 2001; Turchyn and DePaolo, 2011).

Taking the above statement into account, one might expect a better preservational signal, i.e., higher diversity of assemblages, from the more clayey mudstone strata than from the carbonate-bearing, light grey mudstones. In general, such trend would be observed in the dark grey mudstone strata of the section, where the percentage of *W. barnesiae*, the most resistant species, is the lowest. Hence, the assemblages, strongly dominated by this species, reflecting diagenetic change, should occur in the light grey mudstone strata. In fact, the relationship between the percentage of *W. barnesiae* and the dark to light grey mudstone strata is not clear. The reason may be the amounts of clay and organic matter that are above the thresholds for significant dissolution of nannofossil calcite (*vide* Turchyn and DePaolo, 2011). Therefore, the percentage of *W. barnesiae* and assemblage diversity do not depend on carbonate content.

This can be evidenced by the $|r|$ value, counted for the *W. barnesiae* vs. NOS pair, which is 0.22, showing very little linear fit. Moreover, *W. barnesiae* is not associated with any other taxa, except for *R. asper*, a robust murolith, which also seems to be dissolution resistant. A few samples, with

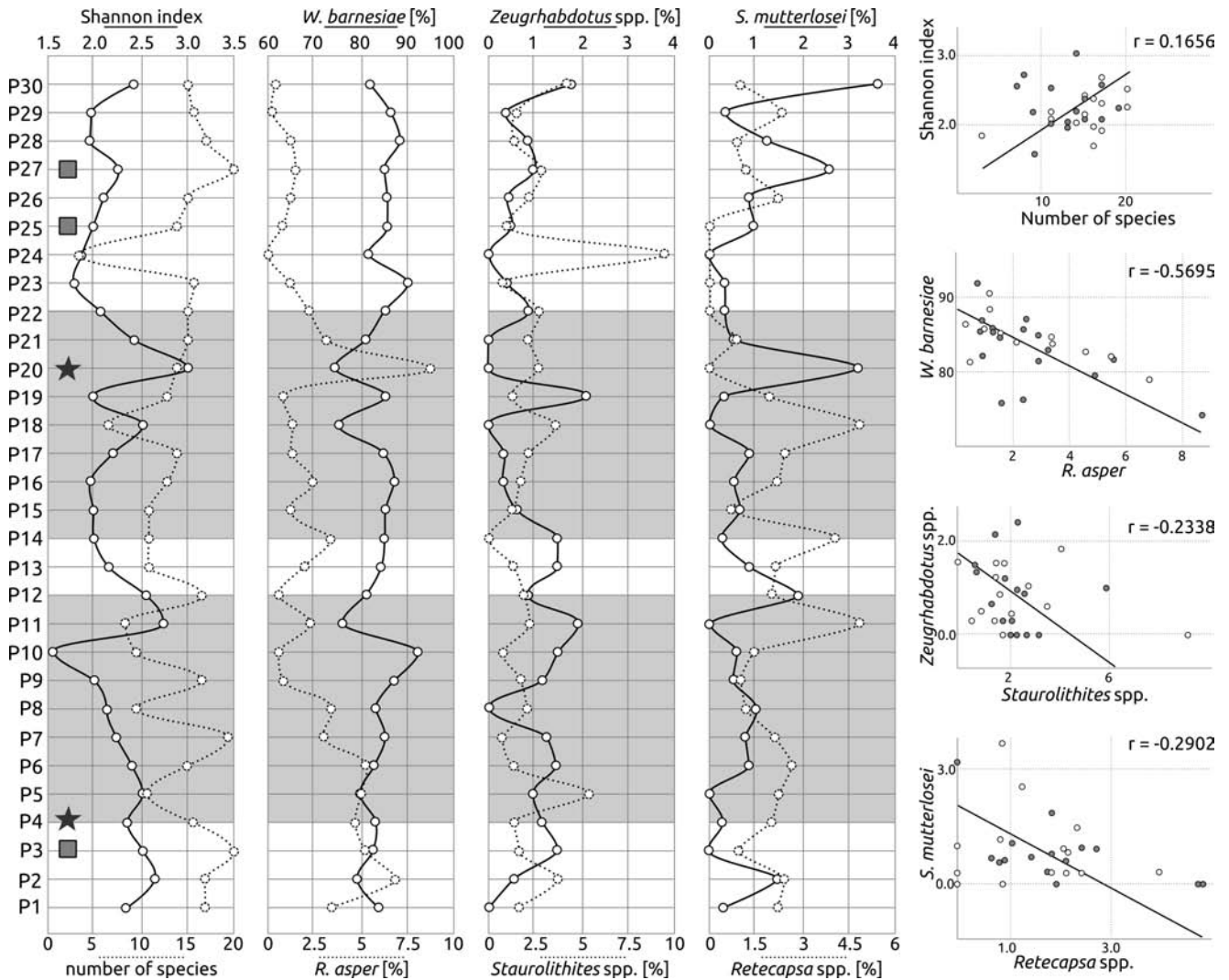


Fig. 5. Shannon Index, number of species, percentage of calcareous nannofossils and linear fits for selected variables. Stars: occurrences of *Crucibiscutum* sp., rectangles: occurrences of nannoconids. Dark-coloured mudstones are shown in shaded bands

an NOS below 10 taxa (P8, P10, P11, P18, P24), might be suspected of having undergone some diagenetic change, but the percentage of *W. barnesiae* exceeds 90% only in one of the above samples, P10. The next sample with a percentage of above 90%, P23, has 16 taxa. Furthermore, sample P18, with 7 taxa only, is the one with the lowest *W. barnesiae* percentage (75.8%).

With regard to the above considerations, we suppose that assemblages studied are not at all or only very little (e.g., sample P10) affected by diagenetic processes and may represent the primary composition.

Valanginian to Hauterivian calcareous nannoplankton ecology

The Early Cretaceous is known as a time of a globally widespread deposition of black shale, rich in organic matter. They used to be attributed to anoxic events, which in the Cretaceous are known as Oceanic Anoxic Events (OAE). Recently, it became apparent that OAEs are only one possible result of environmental changes. Therefore, the general

term, episodes of environmental changes (EECs), is more appropriate (Föllmi, 2012). Early Cretaceous EECs are defined by a specific carbon-isotope record and black, organic-rich deposits independently. These features may both indicate the occurrence of EECs, but only one of them may be diagnostic (Föllmi, 2012). The Valanginian EECs illustrate the above explanation.

Valanginian EECs had a major impact on the planktonic microfauna, especially the calponellid group, which nearly became extinct. This was connected to the plate-tectonic re-organization, but in the stratigraphic record, it is recognized as a biocalcification crisis.

The Valanginian biocalcification crisis may be characterized by a 65% reduction in nannofossil palaeofluxes. Despite the submergence of carbonate platforms, it may be triggered by a two- to three-fold increase in $p\text{CO}_2$, caused by major volcanic activity. The crisis was expressed in the pelagic realm by a decline in the abundance of nannoconids (nannoconid crisis) in calcareous nannofossil assemblages (Erba, 2004; Erba and Tremolada, 2004; Weissert and Erba, 2004). Lately, it was suggested that nannoconid abundance

shows a polyphase decline, with two stages of decrease interrupted by an increase in the abundance of *Nannoconus*. It seems to be related to temperature decrease and variability in nutrient supply. The nannoconid recovery occurred during the coldest period of the Valanginian cooling phase and was inferred to be connected to the input of more oligotrophic surface waters (Barbu and Melinte-Dobrinescu, 2008; Barbarin *et al.*, 2012). Moreover, palaeoclimatic changes probably were the cause of long-term trends (1–4 my), reflected in shifts from *Watznaueria* spp.-dominated assemblages in the Upper Barremian–Lower Valanginian to *Nannoconus* spp.-dominated assemblages in the Upper Valanginian (Melinte and Mutterlose, 2001).

The correlation coefficient indicates a strong dependence of SI and the percentage of *W. barnesiae*, as well as that of *R. asper*. These nannofossil species also have a strong negative correlation for their fit. The almost perfect linear fit of SI and *W. barnesiae* indicates that the occurrence of this species had a great influence on assemblage diversity (Tab. 2; Fig. 5). Obviously, this is caused by the high percentage of *W. barnesiae* and its dominance in the all samples. Nevertheless, the high, positive correlation of *R. asper* and SI indicates that *R. asper* is the species that is indicative of enhanced nannofossil diversity. Consequently, the correlation coefficient for the fit of *W. barnesiae* and *R. asper* has a strong, negative value. Both species are regarded as warm-water species (e.g., Perch-Nielsen, 1985; Mutterlose 1991, 1992). Moreover, *W. barnesiae* represents an *r*-selected life strategy, similar to that of the presently extant *Emiliana huxleyi*. Accordingly, it was dominant in palaeoenvironments hostile for other taxa (e.g., Street and Bown, 2000; Lees *et al.*, 2004; Lees *et al.*, 2005). Mutterlose and Kessels (2000) considered the *W. barnesiae*-*Nannoconus* sp.-*R. asper* assemblage to be typical for low-latitude, warm, and nutrient-poor surface waters, which may have corresponded to the modern, subtropical and tropical *Emiliana huxleyi*-*Gephyrocapsa oceanica* communities.

Nevertheless, the strong, negative correlation coefficient *r* for the *R. asper* vs. *W. barnesiae* pair indicates their different environmental preferences, in addition to their relationship to water temperature. Such observations were already reported by Thomsen (1989), for example, who found seasonal variations in *W. barnesiae* and *R. asper* abundance. Peaks in the abundance of these species occurred in different laminae, indicating different environmental connections. Hardas *et al.* (2012) found that increased water-column stratification during the Middle Cenomanian Event caused a distinctive decrease in the abundance of *R. asper*. This may be applicable in the present study, because of the peak in the occurrence of *R. asper* in sample P20 that coincides with the appearance of *Crucibiscutum* sp., high-latitude taxa, indicating the influence of cold water which mixed the surface-water column.

On the other hand, *W. barnesiae* has a very strong, negative correlation with SI, in contrast to *R. asper*, which has a strong, positive correlation with SI. This simply shows that *R. asper* is more abundant in samples with biodiversity that is higher, by comparison with those containing *W. barnesiae*. If SI is taken as a measure of trophic conditions, then higher biodiversity may indicate environments more hospi-

table to nannoplankton development than the environments of the poorly diversified assemblages, dominated by *W. barnesiae*.

In the material studied, the dominance of *W. barnesiae* probably reflects strong, oligotrophic conditions of a fully marine environment, with a stratified water-column, and the appearance of *R. asper* indicates slight changes, leading to less oligotrophic (mesotrophic?) conditions. Interestingly, the occurrence of the Tethyan nannoconids is connected with the dominance of *W. barnesiae*, which additionally supports the interpretation of a predominance of warm, stratified, oligotrophic waters (see Erba, 2004; Erba and Tremolada, 2004).

Nevertheless, finds of nannoconids were rare in the present study and, in general, reflect a Valanginian biocalcification crisis. Nannoconids were found only in those samples with supposedly higher carbonate contents i.e., the light grey mudstones of samples P4, P25 and P27. Some Tethyan taxa, such as *C. cuvillieri* and *C. oblongata* occur constantly throughout the section, but their abundances increase slightly within those intervals, where nannoconids occur (Tab. 1; Fig. 5). The alternation of the dark-and light-coloured mudstones, together with changes in the composition of nannofossils assemblages, may have been caused by humid-arid climate changes, driving the trophic conditions of surface waters and nannoplankton biocalcification, as postulated by Gréselle *et al.* (2011) and Föllmi (2012). The scenario inferred is as follows: a humid and contemporaneously cool climate, connected to sea-level fall caused the erosion of the inner shelf and restricted carbonate production (e.g., Brachert *et al.*, 2003). This intensified the weathering processes and the related input of nutrients into surface waters. As a result, oligotrophic, stratified surface waters of the arid period were mixed and transformed into less oligotrophic or mesotrophic environments. This is recorded by the dark-coloured mudstones, and an increase in SI and occurrences of *R. asper*. Accordingly, light-colored mudstone represents an arid and relatively warmer climate, with a stratified water column, evidenced by a decrease in SI, the predominance of *W. barnesiae* and occurrences of nannoconids.

Calcareous nannofossil biostratigraphy

A few nannofossil zonations are widely used for the Lower Cretaceous. Bown *et al.* (1998) proposed a new zonation for boreal assemblages and correlated it with the Tethyan NK zones of Bralower *et al.* (1989) and with the NC zones of Roth (1978, 1983), Bralower (1987) and Bralower *et al.* (1993), as well as with the CC zones of Sissingh (1977) (Fig. 6).

In addition to the above schemes, other nannofossil zonations have been proposed in the Carpathians. Melinte (1997) distinguished two main nannofossil groups, characterized by an influence of the Boreal or Tethyan realm. The lower part of the Lower Valanginian is defined by the occurrence of Tethyan and cosmopolitan nannofossils. The interval with the Lower/Upper Valanginian boundary shows a mixture of Tethyan and Boreal taxa. The upper part of the Upper Valanginian is characterized by Tethyan taxa. Me-

		Tethyan ammonite zones (Reboulet <i>et al.</i> , 2009)	(Vašiček <i>et al.</i> , 2010)	Boreal nannofossil zones (Bown <i>et al.</i> , 1998)	Nannofossil assemblage characterization (Švábenická, 2008; Svobodova <i>et al.</i> , 2011)						
130 [m.y.]	Hauterivian	<i>ohmi</i>	<i>T. subflucitulus</i>	BC11	<i>C. cuvillieri</i>						
		<i>balearis</i>		BC10							
		<i>ligatus</i>		BC9		BC-9	<i>T. septentrionalis</i> <i>R. cf. windleyae</i>	scarce nannoconids			
		<i>sayni</i>		BC8	<i>E. striatus</i>	BC8-9	<i>Eiffellithus striatus</i>	<i>P. plethoretus</i> <i>T. octiformis</i>	nannoconids		
		<i>nodosoplicatum</i>									
		<i>loryi</i>		BC7	<i>E. windii</i>	BC6-9	<i>Eiffellithus striatus</i>		nannoconids		
		<i>radiatus</i>		BC6		<i>Cruciellipsis cuvillieri</i>	<i>Braarudosphaera</i> sp.	nannoconids (rare)			
		135		Valanginian	<i>furcillata</i>	<i>C. mandovi</i>		<i>E. striatus</i>	BC4-5	<i>E. windii</i> , <i>S. colligata</i> , <i>C. cuvillieri</i>	nannoconids
					<i>peregrinus</i>		BC5				
					<i>verrucosum</i>		BC4	<i>Z. diplogrammus</i>	BC4b	<i>M. speetonensis</i> , <i>C. rothii</i> , <i>E. windii</i>	
<i>campylotoxus</i>											
140			<i>petransiens</i>				<i>E. windii</i>	BC4a	influx <i>S. colligata</i> , <i>C. cuvillieri</i> , <i>T. jurapelagicus</i>	no nannoconids	
								BC3b-4a	before influx <i>S. colligata</i>	scarce nannoconids	

Fig. 6. Stratigraphic position of interval studied – marked in dark grey colour. Bold, vertical lines indicate Boreal influences, recorded in Western Carpathians by Vašiček and Michalík (1997) in *radiatus* ammonite Zone and by Švábenická (2008) and Svobodova *et al.* (2011) in *campylotoxus-verrucosum* and *ligatus-balearis* ammonite zones

linte (1997) proposed a subdivision off the Valanginian into the following three interval nannofossil zones: *Retecapsa* (= *Cretarhabdus*) *angustiforata*; *Speetonia colligata* and *Calccalathina oblongata*. The *S. colligata* Zone also is subdivided into three subzones: *Reinhardtites fenestratus*; *Micrantholithus speetonensis* and *Diadorhombus rectus*, where the *M. speetonensis* nannofossil Zone is the total range taxon biozone.

Gaździcka in Dziadzio *et al.* (2004) proposed a zonation scheme for the Lower Cretaceous in central and SE Poland. The reason for the proposal of the new zonation was the specific nature of the nannofossil assemblages of the Polish Lowland, which excluded it from the use of the Tethys or Boreal zonations. This zonation introduced the PN 2 to PN 5 interval zones for the Valanginian and the lowermost Hauterivian, where the PN 4 and PN 5 had been defined previously by Mutterlose (1991). The PN 2 *Zeugrhabdotus diplogrammus* Zone represents the lowermost part of Valanginian and its lower boundary is defined by the FO of the index species. The definition of the lower boundary of the next PN 3 *Watznaueria barnesae* Zone seems to be questionable. This is defined by the appearance of a poorly diversified assemblage, dominated by the index species. A zone that is defined in this way is useless, because it might be connected to no time-related, environmental or preservational signal. Instead, the poorly diversified interval, dominated by *W. barnesiae*, may only characterize the upper part of the PN 2 *Zeugrhabdotus diplogrammus* Zone. The PN 3 *Watznaueria barnesae* Zone represents the upper part of the Lower Valanginian. The PN 4 *Eiffellithus striatus* Zone is defined by the FO of the index species, as well as the PN 5 *Conusphaera rothii*. The upper boundary of the PN 5 Zone is defined by the FO of the next index species,

Eprolithus antiquus. The PN 4 Zone represents the lower part of the Upper Valanginian, embracing the *verrucosum* ammonite Zone, and the PN 5 Zone represents the upper part of the Upper Valanginian and the lowermost part of the Hauterivian (Gaździcka in Dziadzio *et al.*, 2004).

In the present study, samples yielded stratigraphically important species, such as *E. windii* or *E. striatus*. The first occurrence of *E. striatus* defines the base of the CC4 Zone and is in the upper part of both the NK3B and BC5 zones. The next nannofossil species *Nannoconus bucheri* and *Lithraphidites bollii*, which first occur above this zone, were not found in the material. Thus, the upper limit of the age was taken from the last occurrence of *E. windii*, which was noted in the lower part of the NC4 Zone. The interval between the FO of *E. striatus* and the LO of *E. windii* is equivalent of the upper part of the Upper Valanginian and lower part of the Lower Hauterivian.

However, the Valanginian EECs, despite their triggering mechanism, also induced Boreal and Tethyan exchanges of fauna. The spread of Tethyan nannoplankton species into the Boreal realm of NW Europe was recorded in the earliest Late Valanginian, the Valanginian–Hauterivian boundary interval and Late Hauterivian (Mutterlose, 1992, 1993). These migrations may have some stratigraphic potential. The Early Cretaceous species *C. salebrosum* almost exclusively is known in high-latitudes of both hemispheres, particularly during the Valanginian to Hauterivian. This probably reflects a high-latitude thermal gradient, which may be amplified by a lowstand of the sea-level (Mutterlose and Kessels, 2000). Nevertheless, that species is often recorded in low latitudes in the early Late Valanginian *verrucosum* ammonite Zone together with other boreal taxa (Mutterlose, 1993; Melinte, 1997; Melinte and Mutterlose,

2001; Kessels *et al.*, 2006; Melinte-Dobrinescu and Jipa, 2007; Barbu and Melinte-Dobrinescu, 2008; Švábenická, 2008; Svobodova *et al.*, 2011). The *verrucosum* ammonite Zone seems to have been the time of the most conspicuous invasion of the Boreal taxa into the Tethys ocean realm. The next time of the Boreal nannofossil influences in the low latitudes was in the Early Hauterivian. Concluding, Boreal species, including *C. salebrosum*, can be found at low latitudes in the BC3-4 and BC6-8 nannofossil zones (Kessels *et al.*, 2006; Švábenická, 2008; Svobodova *et al.*, 2011). It is noteworthy that this nannofossil, reported earlier from the Wąwał section by Mutterlose (1993), was missed by Dzia-dzio *et al.* (2004) and probably as a result, they emphasized mainly Tethyan influences.

The environmental connections of *C. salebrosum* most probably can be extended to the entire genus *Crucibiscutum*. Accordingly, the appearance of *Crucibiscutum* sp. in samples of the present study is indicative of a high-latitude influence (Mutterlose and Kessels, 2000; Bown and Concheyro, 2004; Kessels *et al.*, 2006; Pauly *et al.*, 2012a, b).

In addition to the index nannofossil species used for definition of the BC zones, Švábenická (2008) and Svobodova *et al.* (2011) determined diagnostic nannofossil assemblages for each BC Zone, in terms of the influences of the Tethyan or Boreal provinces (Fig. 6). These specific assemblages could be used for stratigraphic purposes. Accordingly, the Boreal influences, indicated by occurrences of *M. speetonensis* and *Sollasites horticus*, characterize the upper part of the Lower Valanginian and BC4b nannofossil sub-Zone. This corresponds well to the *verrucosum* ammonite Zone, commonly referred to the time of invasion by distinct Boreal taxa into the Tethys ocean realm (e.g., Melinte, 1997; Vašíček and Michalík, 1997; Melinte and Mutterlose, 2001; Kessels *et al.*, 2006; Barbu and Melinte-Dobrinescu, 2008). The Upper Valanginian, i.e., the BC4-BC5 nannofossil zones, is characterized by the predominance of Tethyan nannofossil taxa, such as: *E. windii*, *R. asper*, *S. colligata* or *Cruciellipsis cuvillieri*, with minor additions of nannoconids. On the other hand, the rare occurrences of *Crucibiscutum* sp. in samples of the present study suggest some Boreal influences. These influences with invasion by high-latitude nannofossils, were recorded in the BC4b Zone, corresponding to the *verrucosum* ammonite Zone and the BC9 Zone of the Upper Hauterivian by Švábenická (2008) and Svobodova *et al.* (2011). However, the BC4b Zone is characterized by the presence of *Micrantholithus speetonensis* and *Conusphaera rothii*, which were not found in the samples of the authors. Moreover, the BC4b Zone occurs below the FO of *E. striatus*, found in samples of the present study and the BC9 Zone is above the LO of both *E. striatus* and *E. windii* and is characterized by taxa that are absent in section studied.

Nevertheless, Vašíček and Michalík (1997) noted some Boreal influences in the Outer Carpathians, also in the lowermost Hauterivian *radiatus* ammonite Zone. This fits well to the nannofossils record of the present account. Taking into account also the ammonite data, provided by Vašíček *et al.* (2010), it may be concluded that the section represents the BC5-BC6 zones boundary interval, i.e., the Valanginian/Hauterivian boundary (Fig. 6).

CONCLUSIONS

1. The assemblages of calcareous nannofossils studied are dominated by the following taxa: *W. barnesiae*. Common are *Retecapsa* spp., *R. asper*, *Staurolithites mutterlosei*, *Staurolithites* spp. and *Zeughrabdotus* spp.

2. Tethyan nannofossil taxa predominate in the material studied, but some uncommon Boreal species, i.e., *Crucibiscutum* sp., also were found.

3. *Rhagodiscus asper* and *W. barnesiae* represent different ecological strategies, despite their supposed association with warm surface water. The percentage of *R. asper* increases with increasing SI (correlation coefficient $r = 0.677$) and decreases with increasing percentages of *W. barnesiae* (correlation coefficient $r = -0.5695$).

4. The occurrence of some Tethyan nannoconids, increasing percentages of *W. barnesiae* in light grey mudstones, together with the appearance of *Crucibiscutum* sp. and increasing percentages of *R. asper* in dark grey mudstone, indicate different surface-water conditions during sedimentation. These resulted from humid-arid climate changes, driving the trophic conditions of surface waters and nannoplankton biocalcification.

5. Dark grey mudstones were deposited under the influences of the Boreal realm. In contrast, light grey mudstones reflect predominance of the influences of the Tethyan province.

6. On the basis of the presence of *Eiffellithus striatus*, *E. windii* and both Tethyan and Boreal influences, the section studied represents the Valanginian/Hauterivian boundary interval, i.e., the boundary of the BC5-BC6 zones, related to the *furcillata-radiatus* ammonite zones.

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