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Paleoecology of the Upper Eocene–Lower Oligocene Malcov Basin based on the calcareous nannofossils: a case study of the Leluchów section (Krynica Zone, Magura Nappe, Polish Outer Carpathians)

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Abstract: During the period of ca. 20 Ma (Middle Eocene–Chattian) the Leluchów Succession of the Magura Basin passed through drastic changes of sedimentary condition and paleobathymetry from well oxygened red shales with *Reticulofragmium amplectens*, deposited beneath CCD, red *Globigerina* oozes, to oxygen depleted organic-rich menilite-type shales and finally to flysch deposition of open marine conditions. The biostratigraphic and lithostratigraphic scheme is well established with the Leluchów Marl Member — Zones NP19–20 to NP22 (Late Eocene–Early Oligocene), Smereczek Shale Member, Zone NP23 (Early Oligocene) and the Malcov Formation s.s., Zone NP24 (Early–Late Oligocene). The aim of the paper is to present the quantitative analyses as the basis for paleoecological changes in the Magura Basin during the Late Eocene–Late Oligocene period. The changes manifest themselves through a decrease in the water temperature and progressing eutrophication. Species typical of brackish water conditions and restricted to the Paratethys region were identified from the NP23 Zone.

Key words: Late Eocene–Oligocene, Western Carpathians, Magura Nappe, Krynica Zone, Malcov Formation, paleoecology, biostratigraphy, calcareous nannoplankton.

Introduction

The Eocene and Oligocene were periods of major change in ocean circulation and global climate. Starting from the Middle Eocene through to the Late Oligocene several paleoclimatic events have been identified by paleontological and geochemical data. The main episodes include:
— The Middle Eocene Climatic Optimum (MECO) warming event at ~40 Ma (Bohaty & Zachos 2003; Jovane et al. 2007);
— Late Eocene warming interval at ~36 Ma (Bohaty & Zachos 2003);
— Oi-1 event at ~34 Ma (Miller et al. 1991; Wei et al. 1992; Aubry 1992; Zachos et al. 1996; Persico & Villa 2004; Coxall et al. 2005);
— The warming episode in the Late Oligocene at ~26 Ma (Miller et al. 1987; Zachos et al. 2001; Villa & Persico 2006; Pekar et al. 2006).

According to Miller et al. (2009) the Eocene-Oligocene transition is characterized by 3 main episodes: (1) 2 °C deep-water cooling and a drop in sea level of ca. 25 m (EOT-1, 33.80 Ma); (2) a deep-water cooling and minor drop in sea level (EOT-2, 33.63 Ma), (3) a deep-water cooling of 2 °C and a drop in sea level of 80±25 m (Oi-1, 33.45 Ma). The initiation, as well as the continuous growth of ice on Antarctica could have been the result of gradual global cooling coupled with the uplift of continental areas even situated away from Antarctica.

Understanding the relationship between the Central Carpathian Paleogene Basin, Pieniny Klippen Belt and the Magura Nappe is important for establishing a better understanding of the paleogegraphy and paleotectonic evolution of the Outer Carpathians. The first steps in this direction were made by Książkiewicz & Leško (1959), who correlated Upper Eocene–Oligocene deposits in the Pieniny Klippen Belt to the southern part of the Magura Nappe. This study was followed by Leško & Samuel (1968) who suggested the existence of a Late Eocene-Oligocene seaway connection between the Magura and Central Carpathian Paleogene Basin via the Pieniny Klippen Belt.

Stráník & Hanzlíková (1968) described several transitional facies (Ujak, Kremna, Lackovce and Inovce) between the Central Carpathian Paleogene, Pieniny Klippen Belt and Magura basins. Traditionally the Oligocene Malcov Formation has been regarded as a typical transitional facies between the Magura, Pieniny Klippen Belt and Central Carpathian Paleogene basins. In Poland the best exposures of the Malcov Formation are known from the Leluchów section (Birkenmajer & Oszczypko 1989; Oszczypko-Clowes 2001; Oszczypko et al. 2005; Oszczypko & Oszczypko-Clowes 2010). This section, located along the Polish-Slovak boundary, is directly linked with the Lubotin–Plaveč–Ujak (Udol) — tectonic depression, which is filled with Upper Eocene–Oligocene deposits of the Pieniny Klippen Belt (Nemčok 1990). The Leluchów section records the transition from the Magura Formation, a typical lithofacies of the Magura Basin to the Malcov Formation — a typical lithofacies of the Pieniny Klippen Belt and the Central Carpathian Paleogene Basin.

Previous work

Exposures of variegated marls, menilite-type shales and Krosno-type beds in Leluchów have been studied for a long time and are discussed in several papers (Książkiewicz & Leško 1959; Świdziński 1961; Leško & Samuel 1968; Książkiewicz 1977). The first detailed description of these beds was provided by Blaicher & Sikora (1967). In 1989 Birkenmajer & Oszczypko described the Leluchów section as transitional from the Magura Formation (Middle Eocene) to the Malcov Formation (Upper Eocene–Oligocene) of the Ujak Succession. Thin-bedded flysch and red shales containing *Reticulophragmium amlectens* were attributed to the Mniszek Shale Member. At the same time variegated marls and menilite-type shales were included in the Leluchów Marl Member and Smereczek Shale Member, respectively. In the lower part of the Leluchów Marl the dominating arenaceous Middle/Late Eocene foraminifera were discussed by Malata in Oszczypko et al. (1990). Towards the top of the marls the amount of planktonic foraminifera increases and is typical for the *Globigerina* Marls (Late Eocene–Oligocene, see Malata in Oszczypko et al. 1990). In the Smereczek Shale Member foraminifera were not found. Higher up in the section (marly mudstones with sandstone intercalations) the foraminiferal assemblage is dominated by poorly preserved planktonic foraminifera with admixtures of benthic forms and reworked older foraminifera (Malata op.cit.). The litho- and calcareous nannoplankton biostratigraphy of the Malcov Formation in the Leluchów sections A and B were studied by Oszczypko-Clowes (1996, 1998, 1999, 2001, see also Oszczypko et al. 2005; Oszczypko & Oszczypko-Clowes 2010). As a result the Leluchów Marl Member is assigned to Zones NP19–20, 21 and 22, the Smereczek Shale Member to Zone NP23, and the Malcov lithofacies to Zone NP24.

According to dinocyst studies, Gedl (1999, 2004) placed the Eocene/Oligocene boundary in the upper part of the Leluchów Marl Member.

Studied section

The Leluchów section (Krynica Zone) is situated on the right bank of the Smereczek Stream, which is the right confluence of the Poprad River (Figs. 1, 2) close to the Polish-Slovak border (Fig. 2). The main section (A) of the Malcov Formation is located along the creek near the tourist path, close to the Greek-Catholic Church (Fig. 2) and the studied section (B) is situated 500 m NE of the church (Fig. 2).

The lowest part of the Leluchów section crops out along the Leluchów-Muszyna road, and consists of south dipping, thick bedded (0.4–2.5 m) muscovite sandstones and conglomerates of the Piwniczna Sandstone Member of the Magura Formation (?Lower–Middle Eocene, see Birkenmajer & Oszczypko 1989; Oszczypko et al. 1990; Oszczypko & Oszczypko-Clowes 2010). In 2001 the uppermost portion of the Piwniczna Sandstone Member was drilled in hydrogeological borehole P-8, 200 m depth (Figs. 2, 3). The core material displays light grey and dark grey, muscovite rich, thick-bedded sandstone and fine conglomerates (Fig. 4) with layers (0.5–6 m thick) of grey, non-

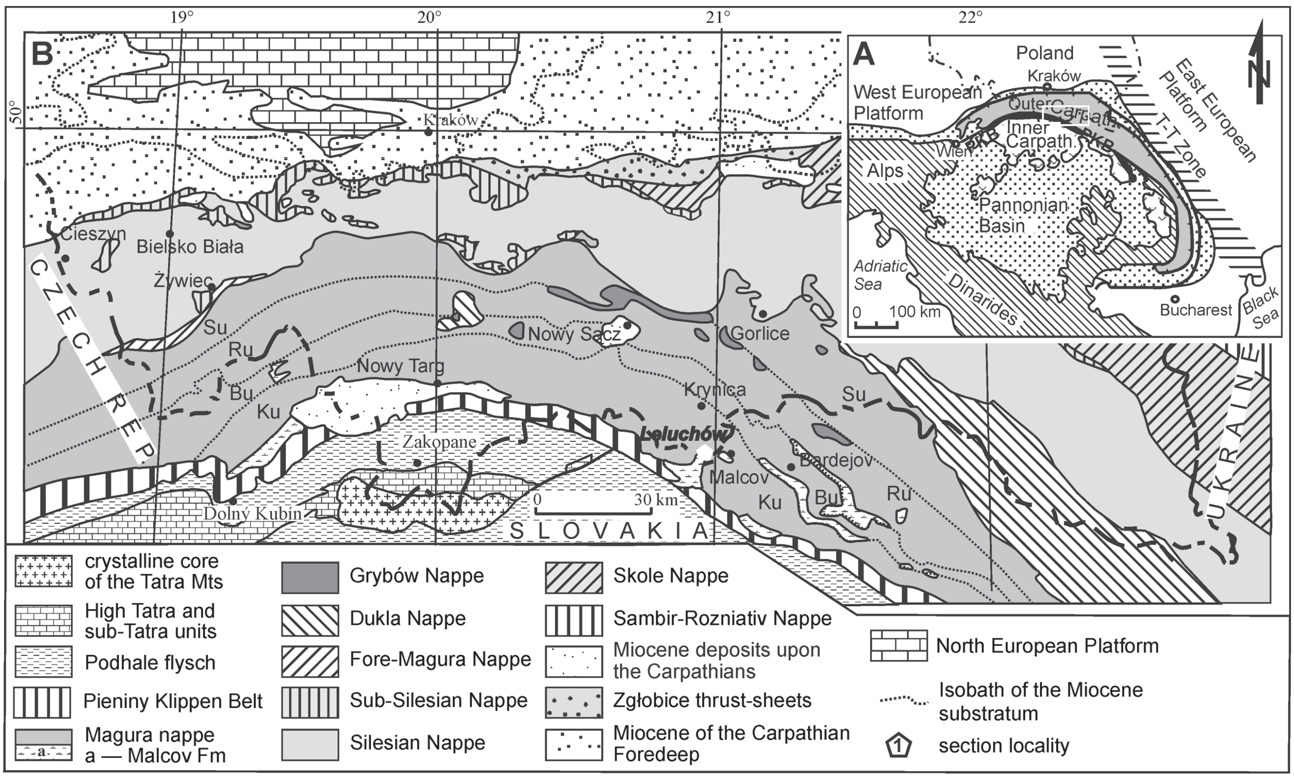

Fig. 1. A — Simplified tectonic scheme of the Alpine-Carpathian orogens (based on Picha 1996). **B** — Geological map of the Polish Carpathians (based on Żytko et al. 1989, modified), with location of studied areas.

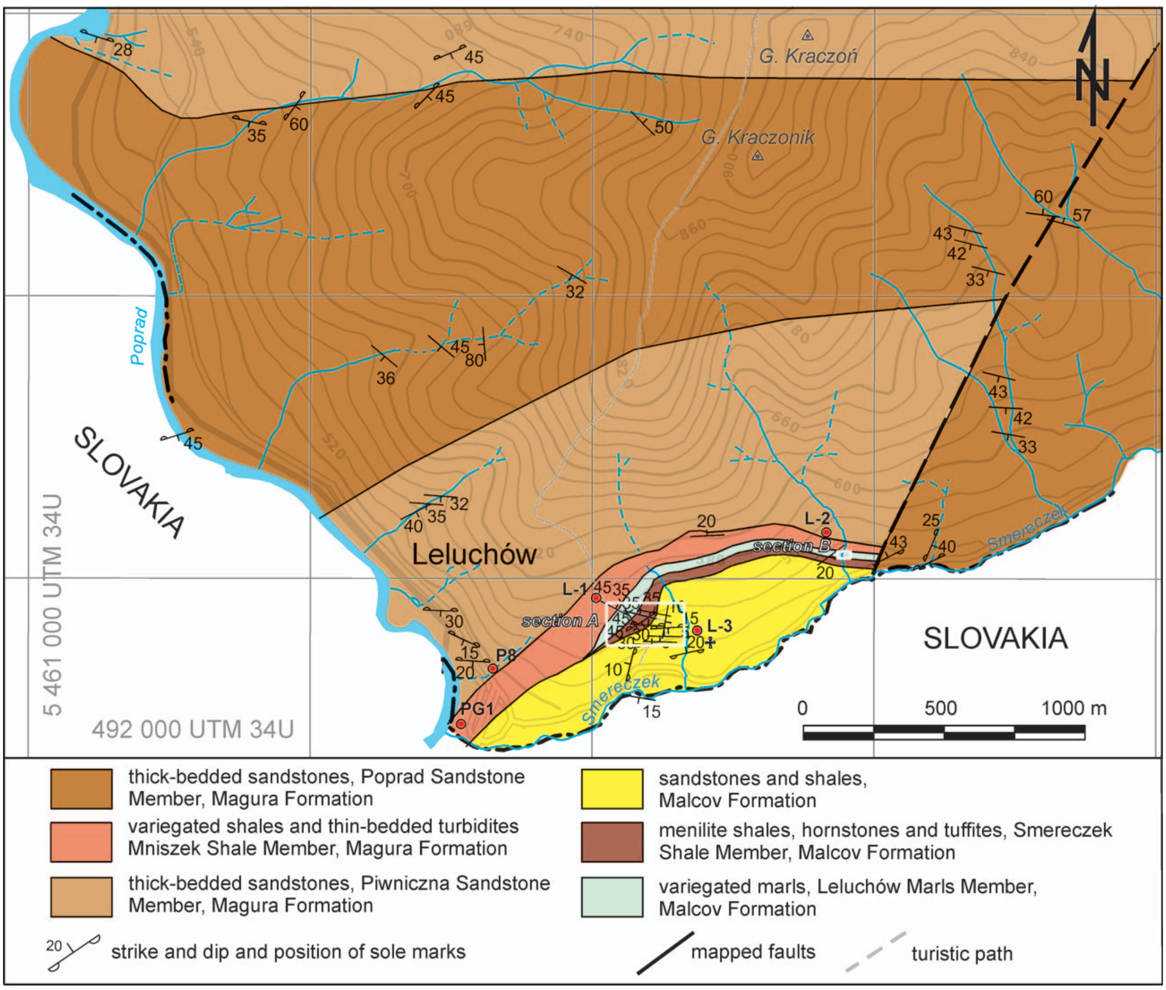

Fig. 2. Geological map of Leluchów area (based on Oszczypko & Oszczypko-Clowes 2010, and Neścieruk et al. 2010).

calcareous shales with intercalations of thin- to medium-bedded sandstones. The sandstones are very hard (siliceous cement) and fractured. The Piwniczna sandstone was also cored in 2009, in borehole L-3 (Figs. 2, 4). In 2005, in borehole PG-1, ca. 100 m south of borehole P-8, red shales were pierced at a depth of 15.5–27.0 m, and more recently in borehole L-1 (Fig. 2, see also Nescieruk et al. 2010). The first time these red shales with *Reticulophragmium amplectens* were found by Blaicher & Sikora (1967) in the BS excavation (Fig. 2). The thin-bedded flysch and red shales from Leluchów were regarded by Birkenmajer & Oszczypko (1989) and Oszczypko et al. (1990) as the Mniszek Shale Member of the Magura Formation (Middle Eocene). The Magura Formation grades upwards into the Malcov Formation. The Malcov Formation was divided by Birkenmajer & Oszczypko (1989) into three members: the Leluchów Marl Member, Smereczek Shale Member, and Malcov lithofacies. The exposures (A, B) of the Leluchów Marl Member, also known as the Sub-Menilite Globigerina Marls, are at least 6.5 m thick. The basal part (2.5 m thick) of the member is represented by grey-greenish marls with numerous calcite veins, covered by a 4 m thick unit of red and olive marls. The red marls contain burrows of *Planolites*, *Chondrites* and *Thalassinoides* (see Leszczyński 1997). Taking into account the results from borehole L-1 (Figs. 2, 3) the thickness of the grey-greenish marly shales can be up to 45 meters. The Leluchów Marl Member is covered by the ca. 20 m thick Smereczek Shale Member, a dark, bituminous, non-calcareous, menilite-like shale (see Blaicher & Sikora 1967). The lower part of this member contains thin intercalations of marly shales (sample 39/98/N), a few 1–2 cm thick tuffite intercalations, and a thin (2–5 cm) intercalation of cherts as well as two thin intercalations of detrital *Bryozoa–Lithothamnium* limestones (see Oszczypko-Clowes 2001; Oszczypko & Oszczypko-Clowes 2010). The upper part of the member is developed as Menilite Shale with black non-calcareous, bituminous shales, with intercalations of coarse-grained, thick-bedded sandstones. In this part of the section, thin layers of marly shales were recognized (sample 38/98/N). The black shales are covered by a 10 m packet of coarse-grained, muscovite rich, thick-bedded sandstones of the Magura type with intercalations of green marly claystones and medium-bedded sandstones with Tabc Boumas intervals (Fig. 3). The uppermost, flat-laying part of the section consists of the Krosno-like facies: dark grey marly shales with intercalations of thin-bedded, cross-laminated calcareous sandstones (Birkenmajer & Oszczypko 1989; Oszczypko-Clowes 2001; Oszczypko & Oszczypko-Clowes 2010).

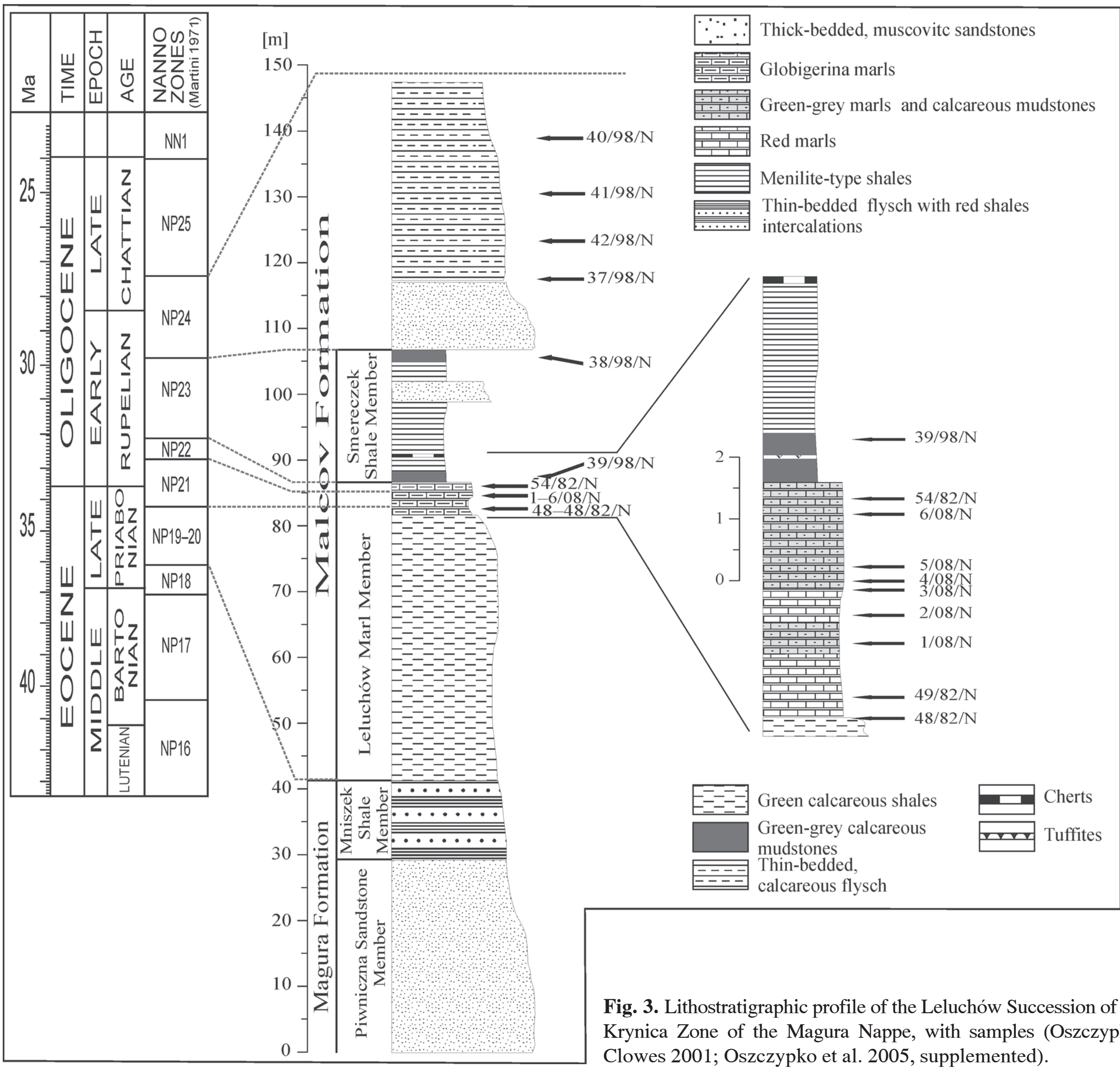

Fig. 3. Lithostratigraphic profile of the Leluchów Succession of the Krynica Zone of the Magura Nappe, with samples (Oszczypko-Clowes 2001; Oszczypko et al. 2005, supplemented).

Methods

Sixteen samples were examined for calcareous nannofossil content (Figs. 2, 3). Samples labelled as x/98/N were collected and first published by Oszczypko-Clowes (1996, 1998, 1999, 2001), while samples labelled as x/82/N were obtained from Ewa Malata. Additionally new samples from the Leluchów Marl Member (x/08/N) were collected.

All samples were prepared using standard smear slide techniques for the light microscope (LM). The investigation was carried out using Nikon — Eclipse E 600 POL, scope at a magnification of 1000× using parallel and crossed nicols. Specimens photographed using the LM are illustrated in Figs. 5–6.

The taxonomic frameworks of Perch-Nielsen (1985), Aubry (1984, 1988, 1989, 1990, 1999) and Bown (1998 and references therein) have been followed. Quantitative analyses were performed by counting 300 specimens on each slide. In order to analyse and calculate the percentage abundance of autochthonous and allochthonous assemblages the authors accepted the 5 % range of error. The nominal values are presented in Table 1. The paleoecological analyses were performed on autochthonous assemblages. Abundances were calculated for individual species with an error range of 0 % — the total amount of autochthonous species in each of the slides is equal to 100 %. The nominal values as well as percentages are also presented in Table 1.

The biostratigraphic analyses, using the standard zonation of Martini (1971) proved the results obtained through earlier research (Oszczypko-Clowes 2001; Oszczypko et al. 2005), and are summarized in Table 1. Additional samples (1/08/N–6/08/N) from the Leluchów Marl Member were assigned to *Ericsonia subdisticha* Zone (NP21). The zone assignment is based on a continuous range of *Ericsonia formosa*, following the disappearance of *Discoaster saipanensis* and *Discoaster barbadiensis*.

The paleoecological analysis is based on quantitative results and it takes into account three major factors (temperature, trophism and salinity) controlling coccolithopores biogeography.

Fig. 4. Photographs of the typical Eocene-Oligocene rocks of the Ujak Facies, Krynica Zone of the Magura Nappe at Leluchów: figs. 1–3. Core material of the thick-bedded sandstones of the Piwniczna Member (Middle Eocene) of the Magura Formation, Leluchów borehole P-8 (Fig. 2). **1** — Grey-blue, very coarse sandstone to 4 mm granule conglomerate (+HCl), depth 26–26.30 m. **2** — Grey-blue very coarse-grained to granule conglomerate; depth 32.0–35.5 m, grey-blue fine- to medium-grained sandstones with vertical fracture, with Fe dioxide, depth 31.0–32.0 m. **3** — Grey-blue medium-grained sandstone, depth 75.5–76.5 m and, grey-blue, medium- to coarse-grained, non-calcareous sandstones, depth 76.5–77.5 m. 4 — Red *Globigerina* marls of the Leluchów Marl Member of the Malcov Formation, Leluchów, section A. **5** — Olive marls of the Leluchów Marl Member of the Malcov Formation, Leluchów, section A. **6** — Thick-bedded Magura type sandstone at the top of the Smereczek Shale Member, Leluchów, section A. **7** — Medium-bedded, fine-grained sandstone and marly shales of the Malcov lithofacies, Leluchów, section A.

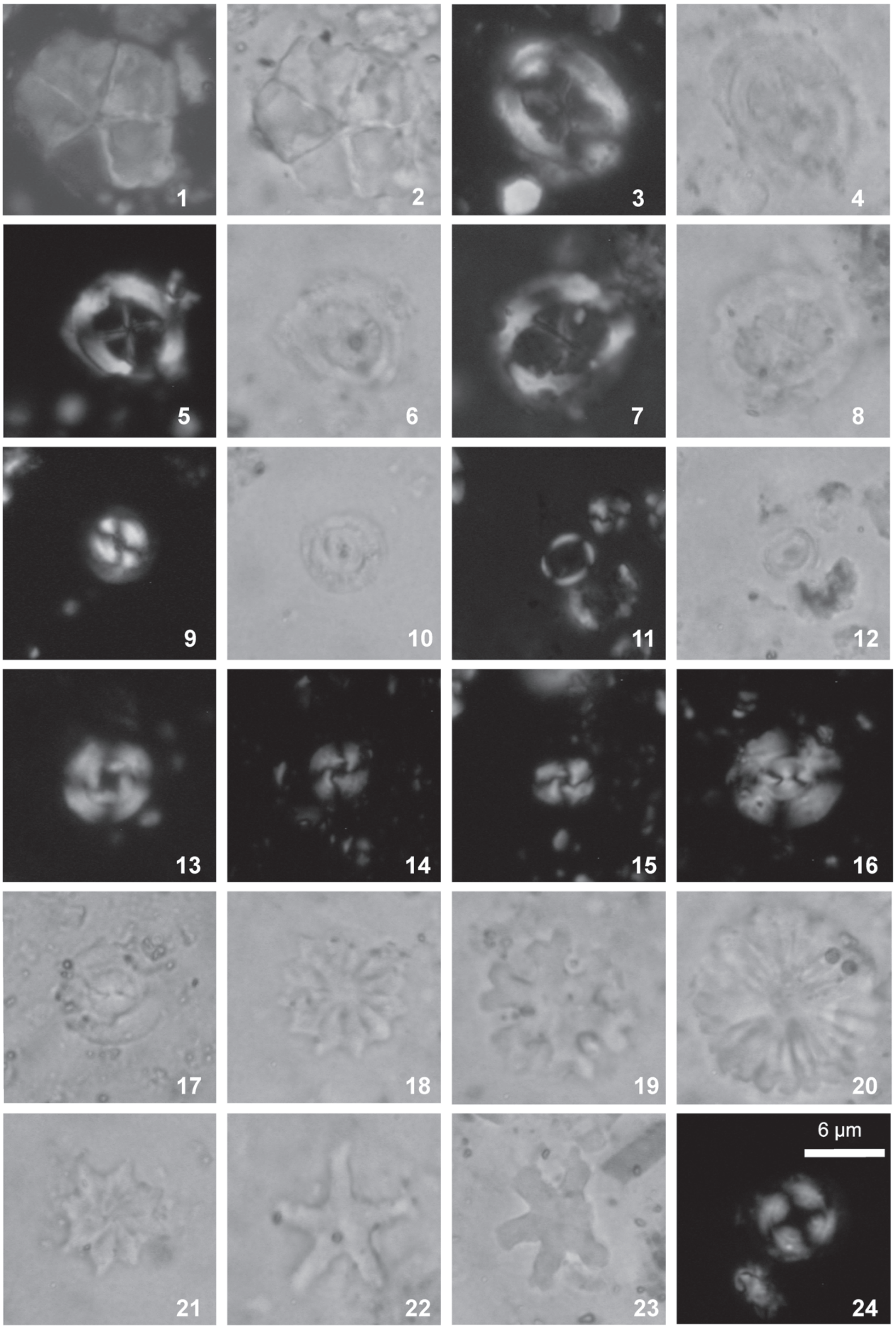

Fig. 5. LM microphotographs from Leluchów section A (scale bar is the same for all photographs). **1, 2** — *Braarudosphaera bigelowii* (sample 37/98/N), 1 — crossed nicols, 2 — parallel nicols. **3, 4** — *Chiasmolithus grandis* (sample 41/98/N), 3 — crossed nicols, 4 — parallel nicols. **5, 6** — *Chiasmolithus medius* (sample 38/98/N), 5 — crossed nicols, 6 — parallel nicols. **7, 8** — *Chiasmolithus oamaruensis* (sample 48/82/N), 7 — crossed nicols, 8 — parallel nicols. **9, 10** — *Coccolithus pelagicus* (sample 2/08/N), 9 — crossed nicols, 10 — parallel nicols. **11, 12** — *Coronocyclus nitescens* (sample 3/08/N), 11 — crossed nicols, 12 — parallel nicols. **13** — *Cyclicargolithus abisectus* (sample 41/98/N). **14** — *Cyclicargolithus floridanus* (sample 39/98/N). 15 — *Cyclicargolithus floridanus* (sample 5/08/N). **16, 17** — *Dictyococcites bisectus* (sample 39/98/N), 16 — crossed nicols, 17 — parallel nicols. **18** — *Discoaster barbadiensis* (sample 48/82/N), parallel nicols. **19** — *Discoaster deflandrei* (sample 42/98/N), parallel nicols. **20** — *Discoaster multiradiatus* (sample 37/98/N), parallel nicols. **21** — *Discoaster saipanensis* (sample 49/82/N), parallel nicols. **22** — *Discoaster tanii* (sample 6/08/N), parallel nicols. **23** — *Discoaster tanii nodifer* (sample 4/08/N), parallel nicols. **24** — *Ericsonia formosa* (sample 1/08/N), crossed nicols.

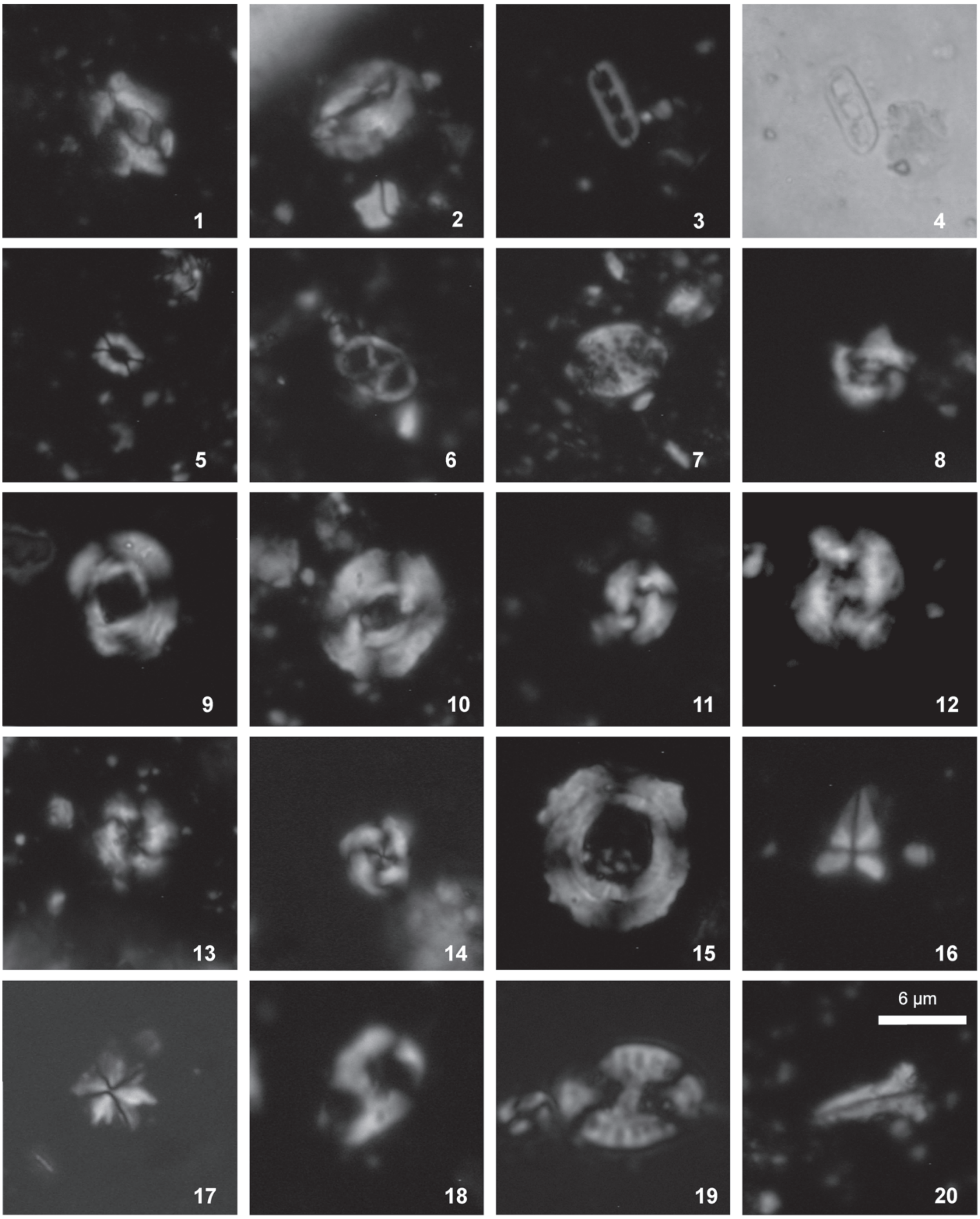

Fig. 6. LM microphotographs from Leluchów section A (scale bar is the same for all photographs). **1** — *Helicosphaera bramlettei* (sample 5/08/N) crossed nicols. **2** — *Helicosphaera compacta* (sample 41/98/N), crossed nicols. **3, 4** — *Isthmolithus recurvus* (sample 54/82/N), 3 — crossed nicols, 4 — parallel nicols. **5** — *Lanternithus minutus* (sample 6/08/N), crossed nicols. **6** — *Neococcolithes dubius* (sample 42/98/N), crossed nicols. **7** — *Pontosphaera multipora* (sample 39/98/N), crossed nicols. **8** — *Reticulofenestra callida* (sample 3/08/N), crossed nicols. **9** — *Reticulofenestra dictyoda* (sample 48/82/N), crossed nicols. **10** — *Reticulofenestra hillae* (sample 1/08/N), crossed nicols. **11, 12** — *Reticulofenestra lockerii* (sample 38/98/N), crossed nicols. **13** — *Reticulofenestra ornata* (sample 37/98/N), crossed nicols. **14** — *Reticulofenestra reticulata* (sample 48/82/N), crossed nicols. **15** — *Reticulofenestra umbilica* (sample 49/82/N), crossed nicols. **16** — *Sphenolithus radians* (sample 42/98/N), crossed nicols. **17** — *Sphenolithus dissimilis* (sample 42/98/N), crossed nicols. **18** — *Transversopontis fibula* (sample 39/98/N), crossed nicols. **19** — *Transversopontis pulcheroides* (sample 41/98/N), crossed nicols. **20** — *Zygrhablithus bijugatus* (sample 49/82/N), crossed nicols.

Table 1: Nominal and percentage (in italics) distribution of calcareous nannoplankton in the Leluchów section. Reworked species in grey, x- species too rare to be included in count.

	Leluchów Marl Mb																		Smereczek Shale Mb				Malcov lithofacies							
Zone	NP19–20				NP21												NP22		NP23				NP24							
Sample	48/82/N		49/82/N		1/08/N		2/08/N		3/08/N		4/08/N		5/08/N		6/08N		54/82/N		39/98/N		38/98/N		37/98/N		42/98/N		41/98/N		40/98/N	
sample abundance	H		H		VH		VH		VH		VH		VH		VH		H		M		M		M		H		H		H	
nannofossil preservation	M		M		G		G		G		G		G		G		G		M		M		M		M		M		M	
Braarudosphaera bigelowii			x								1	*0.34*									2	*0.90*	3	*1.30*	x					
Chiasmolithus grandis																							1				1			
Chiasmolithus medius									x		x		x		x						x		x		x		x		1	
Chiasmolithus oamaruensis	1	*0.34*																							1					
Chiasmolithus sp.	2								x		2														x		2			
Coccolithus pelagicus	53	*18.28*	82	*27.80*	79	*26.33*	75	*25.25*	66	*22.92*	122	*41.22*	78	*26.00*	34	*11.53*	44	*14.81*	56	*21.71*	51	*22.87*	65	*28.26*	72	*31.44*	34	*16.59*	65	*32.34*
Coronocyclus nitescens	8	*2.76*	3	*1.02*	2	*0.67*	x		2	*0.69*					1	*0.34*	2	*0.67*	x						2	*0.87*	3	*1.46*		
Cyclicargolithus abisectus																							5	*2.17*	10	*4.37*	11	*5.37*	6	*2.99*
Cyclicargolithus floridanus	4	*1.38*	31	*10.51*	61	*20.33*	91	*30.64*	110	*38.19*	47	*15.88*	70	*23.33*	89	*30.17*	81	*27.27*	41	*15.89*	50	*22.42*	46	*20.00*	56	*24.45*	68	*33.17*	44	*21.89*
Dictyococcites bisectus	83	*28.62*	73	*24.75*	64	*21.33*	47	*15.82*	42	*14.58*	66	*22.30*	87	*29.00*	27	*9.15*	77	*25.93*	99	*38.37*	76	*34.08*	77	*33.48*	45	*19.65*	44	*21.46*	57	*28.36*
Dictyococcites sp.	x		2	*0.68*	6	*2.00*	2	*0.67*	4	*1.39*	11	*3.72*	9	*3.00*	7	*2.37*	4	*1.35*	x		7	*3.14*	4	*1.74*	12	*5.24*	22	*10.73*	14	*6.97*
Discoaster barbadiensis	5	*1.72*	2	*0.68*					x												6		1		2		6		11	
Discoaster deflandrei	x		x		x				1	*0.35*											x		x		1	*0.44*	x		2	*1.00*
Discoaster lodoensis																					2		x		3		x		1	
Discoaster multiradiatus	3		2																				3		x		4		2	
Discoaster saipanensis	x		1	*0.34*			x		x												2		x		3		x		2	
Discoaster sp.	4	*1.38*	6	*2.03*	x		1	*0.34*			x								1		9		6		3		15		14	
Discoaster tanii	1	*0.34*	1	*0.34*	3	*1.00*									2	*0.68*					1		2		4		3		9	
Discoaster tanii nodifer			x						x		1	*0.34*									3		2		1		5		6	
Ericsonia fenestrata					x		1	*0.34*			x		x		3	*1.02*	x		x				x		x					
Ericsonia formosa	4	*1.38*	7	*2.37*	11	*3.67*	5	*1.68*	1	*0.35*	2	*0.68*	x		x				13		25		18		17		16		21	
Ericsonia subdisticha					11	*3.67*	12	*4.04*	9	*3.13*	14	*4.73*	16	*5.33*	2	*0.68*			x		x				x					
Helicosphaera bramlettei													1	*0.33*							1	*0.45*			x		x		1	*0.50*
Helicosphaera compacta			x										x		1	*0.34*			2	*0.78*					x		3	*1.46*	2	*1.00*
Isthmolithus recurvus	x		x		9	*3.00*	5	*1.68*	3	*1.04*	1	*0.34*			2	*0.68*	7	*2.36*	10				2		5		3		3	
Lanternithus minutus					x		2	*0.67*			x		x		91	*30.85*	47	*15.82*	3	*1.16*	x		x		x					
Neococcolithes dubius																					1				2					
Pontosphaera multipora															1	*0.34*			2	*0.78*					x					
Reticulofenestra callida									4	*1.39*	3	*1.01*	1	*0.33*																
Reticulofenestra dictyoda	15	*5.17*	10	*3.39*	4	*1.33*	3	*1.01*	2	*0.69*			3	*1.00*					6				4				11		5	
Reticulofenestra hillae	26	*8.97*	4	*1.36*	x		2	*0.67*	4	*1.39*			1	*0.33*	4	*1.36*	x				12		3		4		5		7	
Reticulofenestra lockerii																			19	*7.36*	15	*6.73*	11	*4.78*	3	*1.31*	2	*0.98*		
Reticulofenestra ornata																			22	*8.53*	11	*4.93*	7	*3.04*	11	*4.80*	10	*4.88*	x	
Reticulofenestra reticulata	2	*0.69*	x								x		2	*0.67*	3	*1.02*	2	*0.67*	5		2		3		4		1		x	
Reticulofenestra umbilica	84	*28.97*	67	*22.71*	36	*12.00*	36	*12.12*	29	*10.07*	1	*0.34*	3	*1.00*	x		3	*1.01*			4		19		15		20		13	
Sphenolithus dissimilis																							3	*1.30*	5	*2.18*	2	*0.98*	4	*1.99*
Sphenolithus moriformis	x		5	*1.69*	14	*4.67*	14	*4.71*	11	*3.82*	15	*5.07*	22	*7.33*	3	*1.02*	15	*5.05*	4	*1.55*	8	*3.59*	8	*3.48*	11	*4.80*	4	*1.95*	5	*2.49*
Sphenolithus predistentus					x																									
Sphenolithus radians																					1				2					
Sphenolithus spiniger			2		x		x		3		2																			
Transversopontis fibula																			1	*0.39*	x									
Transversopontis pulcher													x		6	*2.03*	x		2	*0.78*			1	*0.43*	1	*0.44*				
Transversopontis pulcheroides																	3	*1.01*							x		1	*0.49*	1	*0.50*
Tribrachiatus orthostylus			x																						1					
Zygrhablithus bijugatus	x		1	*0.34*	x		1	*0.34*	x		12	*4.05*	7	*2.33*	19	*6.44*	12	*4.04*	7	*2.71*	2	*0.90*	x		x		1	*0.49*		
Cretaceous species	5		1				3		9						5		3		7		9		6		4		3		4	
Sum	300		300		300		300		300		300		300		300		300		300		300		300		300		300		300	

Each of these factors was analysed separately in the case of nannnofossil autochthonous assemblages from Leluchów section.

Calcareous nannofossils preservation

The most widely used method is a visual assessment of the state of preservation of the assemblage based on the degree of etching and/or calcite overgrowth observed during light- or electron-microscopy (Roth & Thierstein 1972; Roth 1973; Bown & Young 1998). For the purpose of this work the criteria proposed by Roth & Thierstein (1972) were used namely: VP — very poor, etching and mechanical damage is very intensive, specimens mostly in fragments; P — poor, severe dissolution, fragmentation and/or overgrowth; the specific identification of specimens is difficult; M — moderate, etching or mechanical damage is apparent but majority of specimens are easily identifiable; G — good, little dissolution and/or overgrowth; diagnostic characteristics are preserved, the specimens could be identified to species level without any “trouble”.

Species diversity and abundance

Estimates of the nannofossil abundance for individual samples (Table 1) was established using the following criteria: VH — very high (>20 specimens per 1 field of view), H — (10–20 specimens per 1 field of view), M — moderate (5–10 specimens per 1 field of view), L — low (1–5 specimens per 1 field of view), VL — very low (<5 specimens per 5 fields of view).

Results

The preservation of calcareous nannofossils is moderate (m) or predominantly moderate to good (m–g) in all investigated samples (Table 1). Nannofossils show minor etching and minor to moderate overgrowth. Good and moderate preservation of nannofossils indicates that little carbonate dissolution has occurred in these sediments.

During quantitative analyses of the calcareous nannoplankton assemblages, 44 species were identified. The percentage of autochthonous and reworked species in individual samples was calculated (Fig. 7). To distinguish reworked from in-place nannofossil, the biostratigraphical range of species, was used.

The most common autochthonous species are: *Coccolithus pelagicus*, *Cyclicargolithus floridanus*, *Dictyococcites bisectus*, *Dictyococcites* sp., *Sphenolithus moriformis* and *Zygrhablithus bijugatus*.

Other autochthonous species, which occur irregularly in the samples are: *Braarudosphaera bigelowii*, *Discoaster deflandrei*, *Helicosphaera bramlettei*, *Helicosphaera compacta*, *Pontosphaera multipora*, *Transversopontis pulcher*, *Transversopontis pulcheroides*, *Sphenolithus predistentus* and *Sphenolithus radians* (see Table 1).

The highest numbers of reworked species (13.3 %–31.35 %; Fig. 7) were observed in samples taken from thin-marly intercalations in the Smereczek Shale Member (39/98/N and 38/98/N) and Malcov lithofacies (37/98/N, 42/98/N, 41/98/N and 40/98/N). Samples from the Leluchów Marl Member are characterized by a very low level of reworking, which does not exceed 3.80 %, (sample 3/08/N).

The percentage of reworked species is clearly associated with lithology (Fig. 7). The lowest number (0 %–3.80 %) of reworked species was recorded in samples from the marly facies of the Leluchów Marl Member. Turbidite facies of the Malcov lithofacies are characterized by increased reworking, reaching 31.35 % in sample 40/98/N, located in the uppermost part of the studied section.

Allochthonous specimens include (samples: 40/98/N, 41/98/N, 42/98/N, 37/98/N, 38/98/N, 39/98/N) *Chiasmolithus medius*, *Discoaster barbadiensis*, *Discoaster lodoensis*, *Discoaster saipanensis*, *Discoaster* sp., *Discoaster tani*, *Discoaster tani nodifer*, *Ericsonia formosa*, *Isthmolithus recurvus*, *Neococcolithes dubius*, *Reticulofenestra dictyoda*, *Reticulofenestra hillae*, *Reticulofenestra reticulata*, *Reticulofenestra umbilica* and undivided Cretaceous species.

The quantitative analyses of autochthonous assemblages from section A allowed the authors to observe a constant decrease in the diversity of species. The sequence of extinction is as follows: *Discoaster barbadiensis* and *Discoaster saipanensis* (Zone NP19–20), *Ericsonia for-*

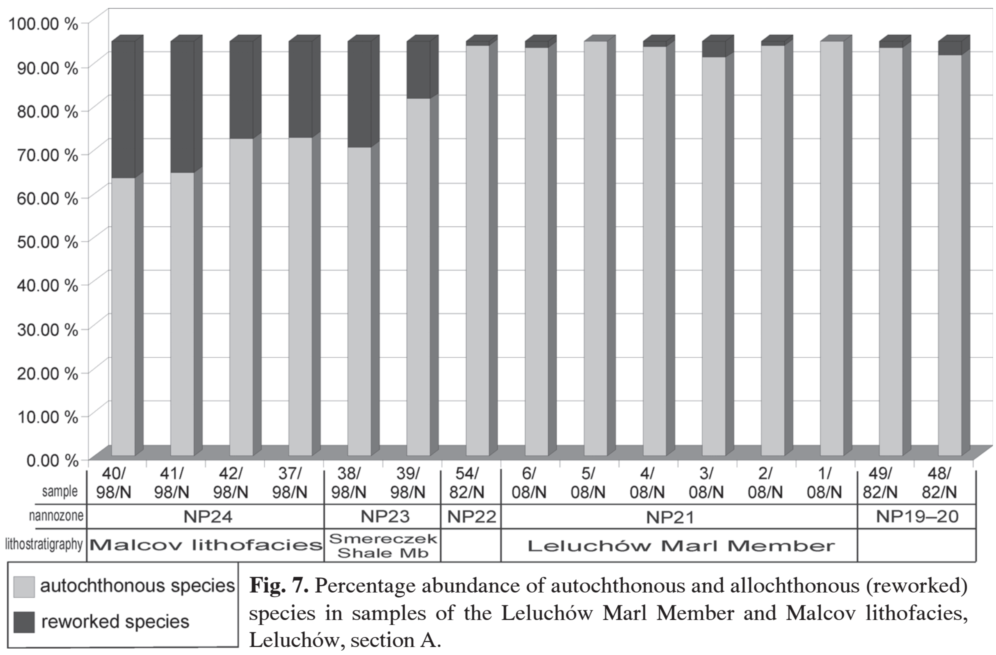

Fig. 7. Percentage abundance of autochthonous and allochthonous (reworked) species in samples of the Leluchów Marl Member and Malcov lithofacies, Leluchów, section A.

mosa (Zone NP21), *Chiasmolithus oamaruensis*, *Discoaster tanii*, *Discoaster tanii nodifer*, *Isthmolithus recurvus*, *Reticulofenestra dictyoda*, *Reticulofenestra umbilica*, *Reticulofenestra hillae*, *Reticulofenestra reticulata* (Zone NP22), *Ericsonia fenestrata*, *Ericsonia subdisticha* and *Lanternithus minutus* (Zone NP23). At the same time the first evolutionary appearance takes place in the Zone NP23 (*Reticulofenestra ornata*, *Reticulofenestra lockerii* and *Transversopontis fibula)* and in the Zone NP24 — *Cyclicargolithus abisectus*.

Paleoecology

Temperature. Temperature is one of the most important factors determining the nannofossil distribution in sedimentary basins. Wei & Wise (1990) grouped Paleogene calcareous nannofossils according to their temperature preferences. In addition this work takes into account more recent papers studying Paleogene calcareous nannofossil paleoecology in areas of the Southern Ocean (e.g. Wei et al. 1992; Bralower 2002; Persico & Villa 2004; Villa & Persico 2006; Villa et al. 2008) and mid-latitude oceans (Agnini et al. 2006; Gibbs et al. 2006). Taking into account the results of Wei & Wise (1990 and references therein) and Villa et al. (2008 and references therein), it is possible to differentiate three main temperature based, ecological groups:

1. Typical warm-water species are: all species from the genera *Discoaster*, *Helicosphaera*, *Sphenolithus* and *Ericsonia formosa*.

2. Temperate-water species are *Cyclicargolithus floridanus*, *Cyclicargolithus abisectus*, *Dictyococcites bisectus*, *Dictyococcites scrippsae* and *Reticulofenestra umbilica*.

3. Cold-water species include *Chiasmolithus*, *Ericsonia fenestrata*, *Ericsonia subdisticha*, *Isthmolithus recurvus*, *Lanternithus minutus*, *Reticulofenestra daviesii*, *Reticulofenestra callida*, *Reticulofenestra clatrata*, *Reticulofenestra lockerii* and *Reticulofenestra ornata*.

And finally there is a group of nannofossils, whose biogeography do not depend on geographical latitude: all species belonging to genera *Blackites* and *Rhabdosphaera*, as well as *Reticulofenestra reticulata* and *Zygrhablithus bijugatus*.

In the Leluchów section the Late Eocene assemblages (Zones NP19–20 and NP21) (Fig. 8, Table 1) are dominated by *Coccolithus pelagicus*, *Dictyococcites bisectus*, *Cyclicargolithus floridanus*, *Reticulofenestra umbilica* and *Ericsonia formosa*. All of these species, except for *Ericsonia formosa*, prefer temperate-water temperatures (Wei & Wise 1990; Villa et al. 2008). The percent abundance of temperate water species varies from 82 % up to 88 % (Fig. 9; Table 2). The only warm-water taxa are *Discoaster barbadiensis*, *Discoaster deflandrei*, *Discoaster saipanensis*, *Dicoaster tanii*, *Discoaster tanii nodifer*, *Ericsonia formosa*, *Helicosphaera compacta* and *Sphenolithus moriformis* (see Wei & Wise 1990; Villa et al. 2008) which are present, but never abundant. The warm-water species constitute less than 9 % of the association (Fig. 9; Table 2). Most of these species last occurred during the latest Eocene and earliest Oligocene. The highest number of warm-water species was observed in sample 1/08/N (Figs. 3, 9; Table 2).

Sample 6/08/N is characterized by an increase in the percentage of cold-water taxa (a 26.88 % increase when compared to sample 3/08/N), and a drop in temperate water taxa by 23.63 %. This change is mostly due to a decrease in percent abundance of *Coccolithus pelagicus* (from 26 % to 11.53 %) and *Dictyococcites bisectus* (from 29 % to 9.15 %) (Fig. 9; Table 2). The cooling trend is apparent in sample 6/08/N, which has an increased abundance of *Lanternithus minutus* (30.85 %). Additionally sample 6/08/N is characterized by the lowest percentage of warm-water taxa in this section and does not exceed 2.03 % (Fig. 9; Table 2).

The Early- and Middle Oligocene assemblages are again dominated by temperate water species. Starting with sample

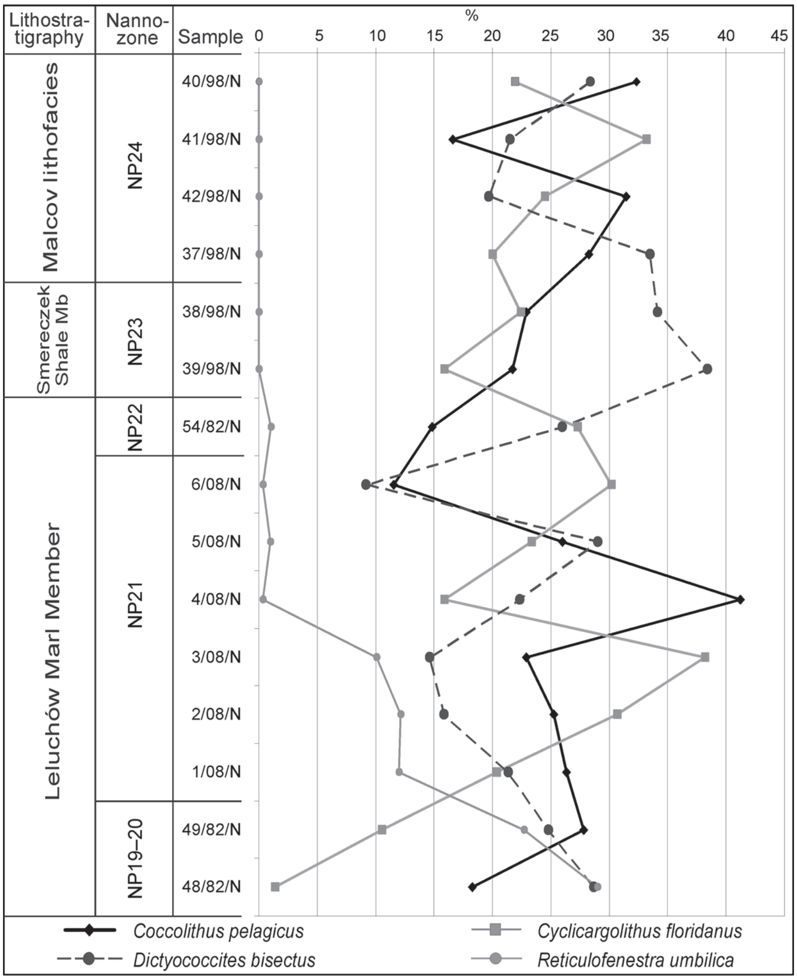

Fig. 8. Percent abundance of the four most numerous autochthonous species, Leluchów, section A.

Table 2: Percent abundance of main paleoecological groups.

	Leluchów Marl Mb									Smereczek Shale Mb		Malcov lithofacies			
	NP19–20		NP21						NP22	NP23		NP24			
	48/82/N [%]	49/82/N [%]	1/08/N [%]	2/08/N [%]	3/08/N [%]	4/08/N [%]	5/08/N [%]	6/08/N [%]	54/82/N [%]	39/98/N [%]	38/98/N [%]	37/98/N [%]	42/98/N [%]	41/98/N [%]	40/98/N [%]
	TEMPERATURE														
Cold-water species	0.34	0.00	3.67	5.05	4.51	5.74	5.67	32.54	15.82	17.05	11.66	7.83	6.11	5.85	0.00
Temperature water species	86.90	88.14	82.00	85.52	88.54	87.50	85.67	62.03	75.08	78.68	83.41	85.65	85.15	87.80	92.54
Warm-water species	4.83	7.46	9.33	6.73	4.51	6.42	7.67	2.03	5.05	2.33	4.93	6.09	7.42	4.39	6.97
Other	7.93	4.41	5.00	2.69	2.43	0.34	1.00	3.39	4.04	1.94	0.00	0.43	1.31	1.95	0.50
	SALINITY														
Fully marine species	48.62	65.76	77.67	79.80	81.94	92.57	91.00	92.54	96.63	82.17	87.00	83.48	85.59	84.39	92.04
Species tolerating salinity fluctuation	0	0	0	0	0	0	0	2	1	1	1	2	0	0	0
Endemic species	0	0	0	0	0	0	0	0	0	9	5	3	5	5	0
	TROPHIC RESOURCE														
Eutrophic species	30.34	36.27	43.67	48.15	54.17	46.28	57.67	81.36	75.42	68.60	66.37	62.17	58.95	76.59	60.70
Oligotrophic species	55.52	58.98	48.33	44.11	38.19	47.64	35.33	14.92	22.22	24.03	26.91	33.04	39.74	22.44	39.30
Other	14.14	4.75	8.00	7.74	7.64	6.08	7.00	3.73	2.36	7.36	6.73	4.78	1.31	0.98	0.00

54/82/N there is a constant growth in the content of temperate water species. A drop in cold-water species is always compensated by an increase in temperate water species, which is especially clearly visible in samples 3/08/N, 5/08/N, 53/82/N and 41/98/N (Fig. 9; Table 2). The amount of warm-water taxa is low and constitutes no more than 9 % (sample 42/98/N), though it does show a growing trend (Fig. 9; Table 2). The youngest assemblage (sample 40/98/N) is characterized by the lowest possible content of cold-water species (0 %) and the highest content of temperate water species (92.54 %) (Fig. 9; Table 2).

Trophic resources. Although, temperature has always been regarded as a prime factor in controlling the distribution of calcareous nannofossils, trophic resources can also play a major role in the distribution and abundance pattern of Paleogene *coccolithopore* (Aubry 1992; Krhovský et al. 1992; Villa et al. 2008). The fluctuation in nutrient availability during the Paleogene was delineated through observation of the relationship between planktonic and large benthic foraminiferal assemblages and oceanic paleochemistry (Boresma et al. 1987; Hallock et al. 1991). According to these authors during the Early Eocene oligotrophy in euphotic waters expanded in open oceans and marginal seas. This was followed by increasing eutrophication and a loss of oligotrophic habitats during the Middle and Late Eocene, result-

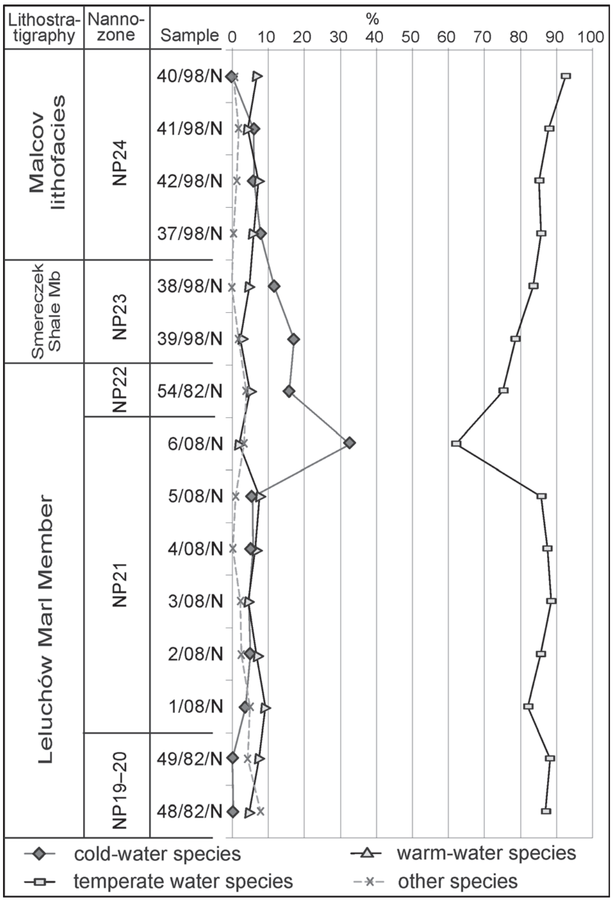

Fig. 9. Percent abundance of taxa with different temperature preferences, Leluchów, section A.

ing in a maximum concentration of the trophic resources continuum (TRC, Hallock 1987) in the Early Oligocene.

In the Late Eocene–Oligocene, calcareous nannoplankton assemblages preferring an eutrophic environment were represented by *Braarudosphaera bigelowii*, *Chiasmolithus oamaruensis*, *Chiasmolithus* sp., *Cyclicargolithus abisectus*, *Cyclicargolithus floridanus*, *Dictyococcites bisectus*, *Dictyococcites* sp., *Lanternithus minutus*, *Pontosphaera multipora*, *Reticulofenestra ornata*, *Transversopontis fibula*, *Transversopontis pulcher*, *Transversopontis pulcheroides*, *Zygrhablithus bijugatus* (Aubry 1992; Krhovský et al. 1992; Villa et al. 2008).

All autochthonous species were classified either as oligotrophic, eutrophic or "other". The later group is composed of mesotrophic species or taxa whose nutrient level preferences are not yet known. As the percent abundance of these group is very low (on average no more than 6–7 %) it can be excluded from the analyses.

A major change in the composition of nannoplankton assemblages, involving a shift in dominance from oligotrophic to eutrophic genera, occurred in the Late Eocene and Early Oligocene (from 27.87 % in the sample 48/82/N to 70.93 % of the sample 54/82/N) (Fig. 10; Table 2).

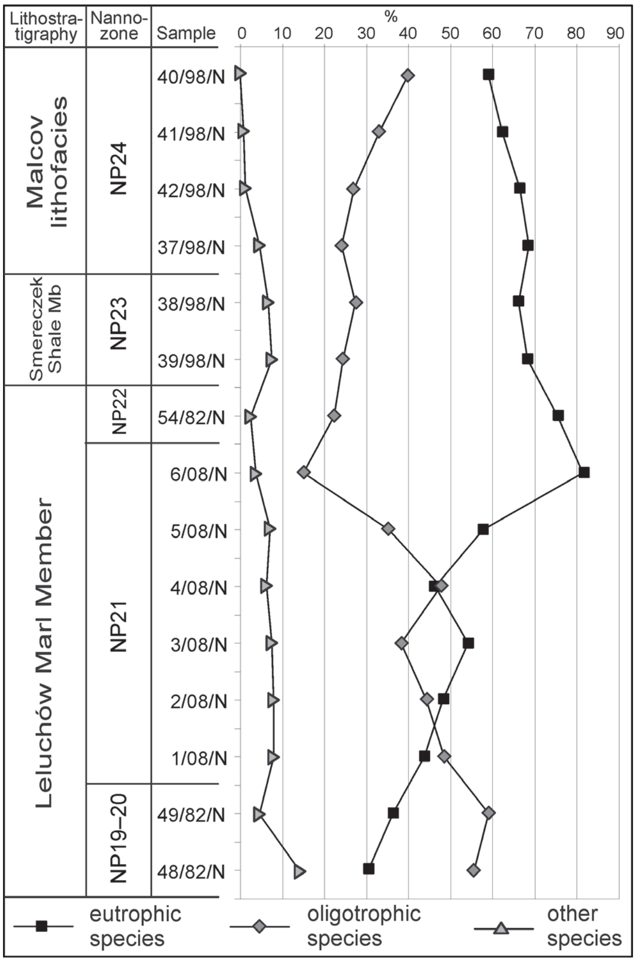

Fig. 10. Percent abundance of taxa with different trophic preference, Leluchów, section A.

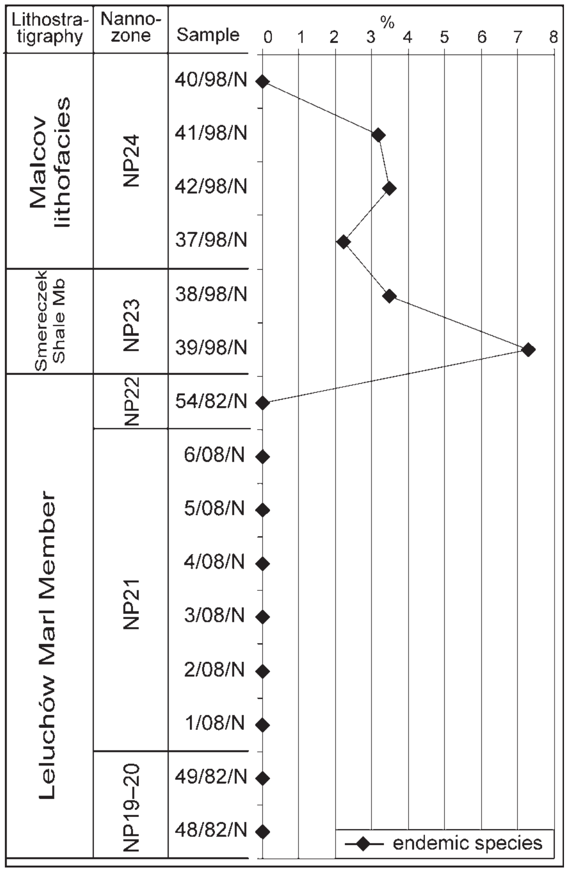

Fig. 11. Percentage abundance of taxa with different salinity preference, Leluchów, section A.

Only in the case of sample 4/08/N is the amount of eutrophic and oligotrophic species almost similar (respectively 46.28 % and 47.64%) (Fig. 10; Table 2). The highest amount of eutrophic species (81.36 %) was observed in sample 6/08/N. From this position there is a visible increase of nearly 25 % of oligotrophic species (Fig. 10; Table 2), though the assemblage is still dominated by eutrophic species.

Salinity. Taking into account the salinity preferences of certain species, Nagymarosy & Voronina (1992) distinguished the endemic nannofossil assemblage, which is characterized by the presence of *Reticulofenestra ornata*, *Transversopontis fibula* and *Transversopontis latus*. The above mentioned association is strictly characteristic for Zone NP23 for the brackish-water environments and limited to the Paratethys only.

Both *Reticulofenestra ornata* and *Transversopontis fibula* occur for the first time in sample 39/82/N and they constitute 9 % of the total autochthonous assemblage (Fig. 11; Table 2). *Transversopontis fibula* is very rare and does not exceed 0.5 %. The occurrence of *Reticulofenestra ornata* varies from 8.63 % in sample 39/82/N to 3.04 % in sample 37/82/N, it is absent from sample 40/98/N (Fig. 11; Table 2). All the other samples contain nannofossil assemblages indicative of open ocean conditions and are characterized by the presence of *Dictyococcites bisectus*, *Coccolithus pelagicus*, *Cyclicargolithus floridanus*, *Ponthosphaera multipora*, *Sphenolithus moriformis*, *Isthmolithus recurvus*, *Zygrhablithus bijugatus*, *Lanternithus minutus* (see also Nagymarosy & Voronina 1992).

Discussion

During the Late Eocene through Early Oligocene, drastic changes in paleogeography and paleoecology also took place in Southern Europe. This was connected with the transformation of the Western Tethys into the Central Paratethys. This transformation was initiated in the nannoplankton Zones NP21/22 and resulted in long lasting anoxic bottom conditions and the deposition of black shales (see Schulz et al. 2005). In the Carpathian sedimentary area, this was recorded by the replacement of pelagic *Globigerina* Marls with menilite bituminous shales. These paleoenviromental changes took place mainly in the northern external part of the Carpathian Flysch Basin (Skole, Sub-Silesian/Silesian and Dukla sub-basins) and are collectively known as the Terminal Eocene Event (Van Couvering et al. 1981; Švábenická et al. 2007). To a lesser extent these changes took place in the Transylvanian and Central Carpathian Paleogene basins (Soták et al. 2001; Soták 2010), and to a very small extent also in the Magura Basin (Oszczypko-Clowes 1998, 2001).

The Late Eocene-Oligocene assemblages of calcareous nannoplankton from the Leluchów section are highly dominated by temperate water species. The number of warm-water taxa starts to decrease at the beginning of Zone NP21 (the latest Eocene) and this is accompanied by an increase in cold-water taxa (Fig. 12). The uppermost part of Zone NP21 is characterized by a maximum of cold-water taxa and this is accompanied by the lowest content of temperate water taxa.

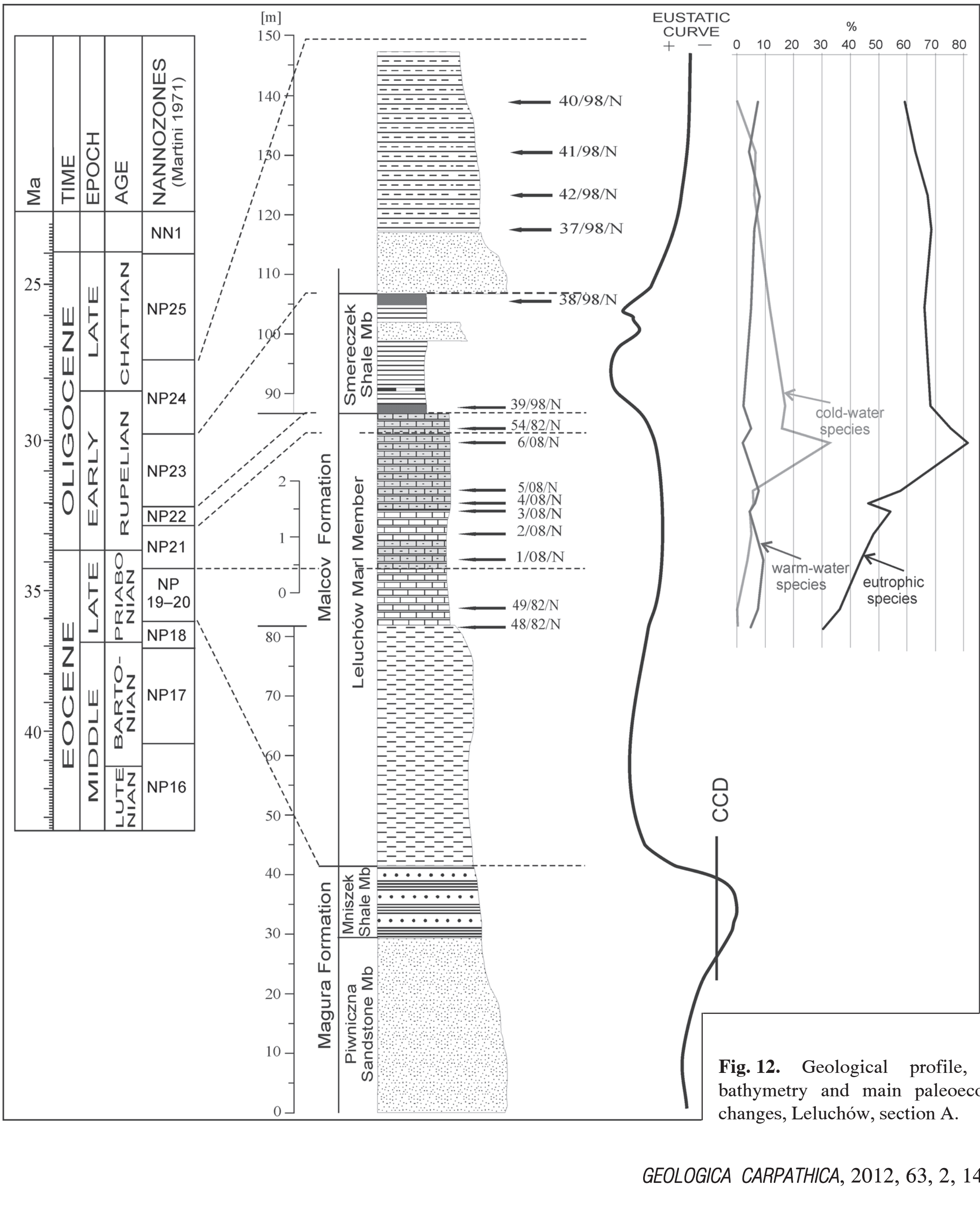

Fig. 12. Geological profile, paleobathymetry and main paleoecological changes, Leluchów, section A.

The same sample has the highest level of eutrophic species and the lowest amount of oligotrophic species. This event can most likely be correlated with the Oi-1 event, which in the Leluchów embayment of the Magura Basin reflects a progressive eutrophication rather than a cooling of sea water. In a well-stratified water column, nannoplankton are typically diverse (e.g. Hallock 1987). In a less well-mixed water column, nannoplankton diversity is lower, and mesotrophic or more opportunist, eutrophic taxa are dominant.

Increased nutrient concentration was a prime factor controlling the biogeographic distribution of calcareous nannoplankton (Fig. 12), and the extinction of species in the Early Oligocene Malcov embayments in the Magura Basin (see Oszczypko & Oszczypko-Clowes 2009).

The increase of nutrients within the uppermost part of the Leluchów Marl Member and Smereczek Shale Member were confirmed by Gedl (2004) on the basis of analysis of dinocysts.

The presence of *Reticulofenestra ornata* and *Transversopontis fibula* in the assemblages from the Smereczek Shale Member in the Leluchów section reflects the freshwater run-off and inflow of freshwater carrying a large amount of organic matter. However, organic material is not so prominent as what was recorded in the Ždánice-Pouzdřany Unit — Chert Member and Dynów Marl of the Menilite Formation (Krhovský 1981a,b; Krhovský et al. 1992; Krhovský & Djurasinovič 1993; Švábenická et al. 2007), Central Carpathian Paleogene Basin (Soták 2010) as well as in NW Transylvania — bituminous marls and shales of the Bizuşa and Ileanda units and bituminous cherts, marls and shales of the Menilite and Lower Dysodile formations (Melinte 2005; Melinte-Dobrinescu & Brustur 2008).

According to Nagymarosy & Voronina (1992) *Reticulofenestra ornata* and *Transversopontis fibula* are characteristic of brackish-water environments and are limited to Paratethys only. The presence of this assemblage is characteristic for the upper part of Zone NP23. This event is associated with the complete isolation of the Paratethys (Báldi 1980; Rusu 1988; Rögl 1998) suggesting that the southern part of the Magura Basin was only partially isolated from the Mediterranean realm at this time.

The Malcov lithofacies represents the nannofosil Zone NP24. This sand-rich deposition of lithofacies was induced with the mid-Oligocene glacio-eustatic regression (see Soták 2010). The Malcov lithofacies, of the uppermost part of the Leluchów section, (sample 40/98/N) is characterized by the disappearance of the last cold-water taxa, a growth in abundance of warm-water taxa and an increased amount of reworked species. This could suggest the beginning of a warming episode in the Late Oligocene (Chattian). This episode can be traced through the Carpathians in the Czech Republic (Krhovský 1981a,b; Krhovský et al. 1992; Krhovský & Djurasinovič 1993; Švábenická et al. 2007), Poland (Oszczypko-Clowes 2001; Oszczypko & Oszczypko-Clowes 2009) and finally in Romania (Melinte 2005; Melinte-Dobrinescu & Brustur 2008). The Malcov lithofacies represents a broader connection in the southern part of the Magura Basin with post-nappe Pieniny Klippen Belt and Central Carpathian Paleogene basins (Soták et al. 2001; Soták 2010). In the Magura Basin, as a result of the Illyrian vertical movement (see Leško & Samuel 1968), the Malcov lithofacies locally overlapped Magura-type sandstones with an angular unconformity.

Conclusion

1. The short Leluchów section records transitional Late Eocene-Oligocene facies between the forearc CCP Basin located on the upper plate, the partly sub-merged Pieniny Klippen Belt suture zone, and the Magura Basin, as the inner part of the foreland-basin on the descending slab of the European Plate.

2. The surface-water regimes of Early Oligocene Magura Basin is characterized by eutrophic populations preferring high-nutrient levels and well-mixed surface waters.

3. The nannofossil assemblages are highly dominated by temperate water and eutrophic species, which is evidence for progressive eutrophication rather than a cooling of sea water.

4. The endemic Paratethyan species suggesting the freshwater inflow were observed in samples from the Smereczek Shale Member.

5. During the deposition of the Leluchów Marls the activity of turbiditic currents drastically decreases. That is manifested in an extremely low number of reworked nannoplakton species.

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APPENDIX
Nannofossil taxa mentioned in the text, in alphabetical order of genus names

Braarudosphaera bigelowii (Gran & Braarud, 1935) Deflandre, (1947)
Chiasmolithus grandis (Bramlette & Riedel, 1954) Radomski, (1968)
Chiasmolithus medius Perch-Nielsen, (1971)
Chiasmolithus oamaroensis (Deflandre *in* Deflandre & Fert, 1954) Hay, Mohler & Wade, (1966)
Coccolithus pelagicus (Wallich, 1877) Schiller, (1930)
Coronocyclus nitescens (Kamptner, 1963) Bramlette & Wilcoxon, (1967)
Cyclicargolithus abisectus (Müller, 1970) Wise, (1973)
Cyclicargolithus floridanus (Roth & Hay *in* Hay et al., 1967) Bukry, (1971)
Dictyococcites bisectus (Hay, Mohler & Wade, 1966) Bukry & Percival, (1971)
Discoaster barbadiensis Tan, (1927)
Discoaster deflandrei Bramlette & Riedel, (1954)
Discoaster lodoensis Bramlette & Riedel, (1954)
Discoaster multiradiatus Bramlette & Reidel, (1954)
Discoaster saipanensis Bramlette & Riedel, (1954)
Discoaster tanii Bramlette & Riedel, (1954)
Discoaster tanii nodifer (Bramlette & Riedel, 1954) Bukry, (1973b)
Ericsonia fenestrata (Deflandre & Fert, 1954) Stradner *in* Stradner & Edwards, (1968)
Ericsonia formosa (Kamptner, 1963) Haq, (1971)
Ericsonia subdisticha (Roth & Hay *in* Hay et al., 1967) Roth *in* Baumann & Roth, (1969)
Helicosphaera bramlettei Müller, (1970)
Helicosphaera compacta Bramlette & Wilcoxon, (1967)
Isthmolithus recurvus Deflandre *in* Deflandre & Fert, (1954)
Lanternithus minutus Stradner, (1962)
Neococcolithes dubius (Deflandre *in* Deflandre & Fert, 1954) Black, (1967)
Pontosphaera multipora (Kamptner, 1948) Roth, (1970)
Reticulofenestra callida (Perch-Nielsen, 1971) Bybell, (1975)
Reticulofenestra dictyoda (Deflandre *in* Deflandre & Fert, 1954) Stradner *in* Stradner & Edwards, (1968)
Reticulofenestra hillae Bukry & Percival, (1971)
Reticulofenestra lockerii Müller, (1970)
Reticulofenestra ornata Müller, (1970)
Reticulofenestra reticulata (Gartner & Smith, 1967) Roth & Thierstein, (1972)
Reticulofenestra umbilica (Levin, 1965) Martini & Ritzkowski, (1968b)
Sphenolithus moriformis (Brönnimann & Stradner, 1960) Bramlette & Wilcoxon, (1967)
Sphenolithus predistentus Bramlette & Wilcoxon, (1967)
Sphenolithus radians Deflandre *in* Grassé, (1952)
Sphenolithus spiniger Bukry, (1971)
Transversopontis fibula Gheta,
Transversopontis pulcher (Deflandre *in* Deflandre & Fert, 1954) Perch-Nielsen, (1967)
Transversopontis pulcheroides (Sullivan, 1964) Báldi-Beke, (1971)
Tribrachiatus orthostylus Shamrai, (1963)
Zygrhablithus bijugatus (Deflandre *in* Deflandre & Fert, 1954) Deflandre, (1959)