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Centennial- to decadal scale environmental shifts in and around Lake Pannon (Vienna Basin) related to a major Late Miocene lake level rise

Mathias Harzhauser ^{a,*}, Andrea Kern ^b, Ali Soliman ^{c,d}, Klaus Minati ^e, Werner E. Piller ^c, Dan L. Danielopol ^e, Martin Zuschin ^b

^a Natural History Museum Vienna, Geological-Paleontological Department, Burgring 7, A-1010 Vienna, Austria

^b University Vienna, Department of Paleontology, Althanstrasse 14, A-1090 Vienna, Austria

^c Institute of Earth Sciences, Graz University, Heinrichstrasse 26, A-8010 Graz, Austria

^d Department of Geology, Faculty of Science, Tanta University, Tanta 31527, Egypt

e Commission of the Stratigraphical and Palaeontological Research of Austria, Austrian Academy of Sciences, Heinrichstrasse 26, A-8010 Graz, Austria

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ABSTRACT

A detailed ultra-high-resolution analysis of a 37-cm-long core of Upper Miocene lake sediments of the longlived Lake Pannon has been performed. Despite a general stable climate at c. 11–9 Ma, several high-frequency oscillations of the paleoenvironments and depositional environments are revealed by the analysis over a short time span of less than 1000 years. Shifts of the lake level, associated with one major 3rd order flooding are reflected by all organisms by a cascade of environmental changes on a decadal scale. Within a few decades, the pollen record documents shifting vegetation zones due to the landward migration of the coast; the dinoflagellate assemblages switch towards "offshore-type" due to the increasing distance to the shore; the benthos is affected by low oxygen conditions due to the deepening. This general trend is interrupted by smaller scale cycles, which lack this tight interconnection. Especially, the pollen data document a clear cyclicity that is expressed by iterative low pollen concentration events. These "negative" cycles are partly reflected by dinoflagellate blooms suggesting a common trigger-mechanism and a connection between terrestrial environments and surface waters of Lake Pannon. The benthic fauna of the core, however, does not reflect these surface water cycles. This forcing mechanism is not understood yet but periodic climatic fluctuations are favoured as hypothesis instead of further lake level changes. Short phases of low precipitation, reducing pollen production and suppressing effective transport by local streams, might be a plausible mechanism. This study is the first hint towards solar activity related high-frequency climate changes during the Vallesian (Late Miocene) around Lake Pannon and should encourage further ultra-high-resolution analyses in the area.

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1. Introduction

At about 11.6 Ma a glacio-eustatic sea-level drop caused the final disintegration of the central and south–eastern European Paratethys Sea, and Lake Pannon formed in the Pannonian basin system (Magyar et al., 1999b; Harzhauser et al., 2004; Piller et al., 2007; Harzhauser and Mandic, 2008). In its initial phase, Lake Pannon was an alkaline brackish water system (Harzhauser et al., 2007). During the Late Miocene and Pliocene the lake was gradually freshening and gave rise to a spectacular endemic evolution of benthic organisms (Müller et al., 1999). During its maximum extent, at 10.5–10.0 Ma, it covered an area of c. 290,000 km² and achieved a water depth of several hundred meters in its central parts (Magyar et al., 1999b; Harzhauser and Mandic, 2008, Fig. 1). This study deals with the coastal vegetational

E-mail address: mathias.harzhauser@nhm-wien.ac.at (M. Harzhauser).

dynamics over a very short interval of roughly 800 yr coinciding with this phase of lake level high stand. During the last years, the overall development of Lake Pannon along its western shores was revealed by geophysical studies such as well-log analyses and 3D seismic studies (Kosi et al., 2003, Harzhauser et al., 2004). These studies permitted the correlation of surface outcrops and revealed the Hennersdorf section as one of the few outcrops that provide insight into the environmental shifts during one of the major transgressions of Lake Pannon (Harzhauser and Mandic, 2004). Therefore, several up to 40 cm-long drill cores have been taken at the opencast pit Hennersdorf 1, is supposed to cover one of the most severe transgressive pulses of the Middle Pannonian Lake Pannon.

The vegetation surrounding Lake Pannon is fairly well known and was described in numerous papers dealing with plant fossil assemblages or palynological records (e.g.: Hofmann and Zetter, 2005; Bruch et al., 2006; Kvaček et al., 2006; Jiménez-Moreno et al., 2008 and references therein). Several vegetational zones have been deciphered by Kovar-Eder et al. (2002), Kvaček et al. (2006) and Jiménez-Moreno

^{*} Corresponding author. Fax: +43 1 52177 459.

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Fig. 1. Geographic position of the investigation area; the maximum extension of Lake Pannon is indicated in insert 1 according to Magyar et al. (1999b). Insert 2 displays the exact position of the Hennersdorf section and of the key-well Eichhorn 1 which is used as calibration for Late Miocene sedimentation by Harzhauser et al. (2004) and Lirer et al. (2007). Seismic data indicate a close position of the Hennersdorf section to a southern deltaic body, which might have influenced the influx of terrestrial material. The proximity of the core to the shore and low-mountains of the Eastern Alps is indicated in insert 3. The shoreline was established in a distance of about 4–6 km from the sampling point. Mid-altitudes areas in a distance of c. 8 km [this paleogeographic sketch is based on geological mapping, revealing the coveal coastlines of Lake Pannon (e.g.: Brix, 1980; Papp, 1951; Richarz, 1921) and seismic data, showing the transition into the basinal settings (e.g.: Jirícek and Seifert, 1990 and various unpublished reports of the OMV-AG). Elevation models as discussed by Kuhlemann (2007). Dunkl et al. (2005) and Kvaček et al. (2006) allow a careful estimation of the adjacent hinterland].

et al. (2008): shores and adjacent wetlands were characterised by hydrophytic floras comprising *Potamogeton*, *Ceratophyllum*, *Decodon* and *Trapa* but also by halophytic elements among the Amaranthaceae and Chenopodiaceae. Swamps and riparian forests were dominated by Taxodiaceae along with Myricaceae, Nyssaceae, *Alnus*, *Ulmus*, and *Rhus*. Mixed mesophytic forests with *Carya*, *Quercus*, *Fagus*, *Picea*, *Abies*, *Pinus* and *Tsuga* developed along the hills of the Alpine– Carpathian mountain chain. Above 1000 m altitude, a mid-altitude deciduous and coniferous mixed forest developed with *Fagus*, *Betula*, *Cathaya*, *Cedrus* and *Tsuga* whereas *Abies* and *Picea* formed forests in high altitudes. As seen from geological mapping and seismic studies, the Late Miocene paleorelief of the Eastern Alps along the margin of the Vienna Basin favoured the development of all these vegetational zones in a radius of less than 15 km of the studied section (Fig. 1) except for the high altitude zone.

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For the middle Pannonian–the covered interval studied herein–the data suggest a warm temperate, permanently humid Cfa type climate (humid subtropical) with warm summers and mild winters (mean annual temperatures ~15–18 °C, coldest month temperature of ~4–8 °C). Annual precipitation of 1100–1300 mm was moderately seasonal with highest values during the summer (Bernor et al., 2003; Bruch et al., 2004, 2006; Jiménez-Moreno et al., 2008).

2. Materials

2.1. Hennersdorf section and age model

The lithology and sedimentary environment of the Hennersdorf section were described by Harzhauser and Mandic (2004) and Harzhauser et al. (2004). The section is situated close to Hennersdorf in the central Vienna Basin, c. 10 km south of the city of Vienna (Fig. 1) and exposes a section of c. 14 m of pelites (Fig. 2). The blue-green marls, clays and silty clays of this area are widespread throughout the Vienna Basin and belong to the up to 340-m-thick Záhorie Member of the Bzenec Formation (Harzhauser et al., 2004). The base of the opencast pit at Hennersdorf is composed of a few metres of blue-grey clay and silt with in situ clusters of the dreissenid bivalve Congeria subglobosa Partsch, 1836. This unit is terminated by a 3-5 cm-thick bivalve coquina, (=He 4 in Harzhauser and Mandic, 2004). This marker bed underlies approximately 8 m of green-blue-grey clays and silty clays intercalated by numerous thin layers made up of masses of predominantly articulated bivalves [Sinucongeria primiformis (Papp, 1951)]. The top of the Hennersdorf section is represented by about 7-8 m of yellow-grey clay and silt that is virtually barren of macrofossils except for a coquina bed (=He 1 in Harzhauser and Mandic, 2004).

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Fig. 2. Age model of the Pannonian sedimentary sequences according to Harzhauser et al. (2004) and Lirer et al. (2007) based on geophysical data of the Eichhorn 1 well. The surface outcrop Hennersdorf is correlated with a short interval within the Pannonian Zone E, which encompasses one of the major transgressions of Lake Pannon (shaded area). The overall transgressive character is also indicated by the gamma-log data of the lower part of the Hennersdorf section. The investigated core (shaded area) penetrates a coquina layer that was used here as marker bed. The photograph of the core illustrates the position of the samples and summarizes the lithology and macrofossil content.

The section comprises parts of the Middle Pannonian Mytilopsis czjzeki Zone, the Lymnocardium schedelianum Subzone (mollusc zonation after Magyar et al., 1999b) and the Spiniferites paradoxus Zone (dinoflagellates; Magyar et al., 1999a). The magnetostratigraphic dating of the Hennersdorf section allowed its correlation with chron C5n (Magyar et al., 1999a). Based on the age model of Harzhauser et al. (2004), an approximate age of 10.5 Ma is suggested for the deposits. Astronomical tuning of the Late Miocene depositional sequences of the Vienna basin by Lirer et al. (2007) allows an even more detailed age determination (Fig. 2). Based on cross correlations with well logs, the Hennersdorf section is supposed to represent an interval of less than 100 kyr (Fig. 2). Herein, we focus exclusively on a 37-cm-thick core from the base of the section, including the coquina marker bed He 4. Most recent astronomical-tuning-based estimations of the sedimentation rate in the Miocene of the Vienna Basin range from 0.45 mm/yr (Badenian; Hohenegger et al., 2007) to 0.64 mm/yr (Pannonian; based on age model of Lirer et al., 2007).

2.2. Core

The 37-cm-thick core of 10 cm-diameter was taken at N 48° 06′ 04.65'' E 16° 21′ 10.91″, in the lower part of the section covering the marker layer He 4 (Fig. 2). It starts with a 3-cm-thick unit of silt and clay with heavy bioturbation (overlying a cross-bedded silt to fine-sand part, which is not covered by our core). Above follow 3–3.5 cm of clay with very rare shell fragments, which are bioturbated from the overlying coquina. This coquina (He 4) is a 3–5 cm-thick unit of shell hash

consisting mainly of strongly fragmented dreissenid and lymnocardiid bivalves. The uppermost part of the coquina is formed by 1 cm of clay with well preserved but disarticulated dreissenid bivalves (*Congeria, Mytilopsis*). Usually the left and right valves are still in a close position and the shells are deposited with the convex-side down. The upper part of the core comprises homogenous silty clay and is almost barren of macrofossils, with the exception of a single thin shell pavement consisting of articulated dreissenids (*Sinucongeria*) at 19 cm.

Based on the above mentioned sedimentation rates of 0.45–0.64 mm/yr, the 37-cm-thick core might span ~570 yr to ~830 yr. In respect to the paleogeographic position of the section at the western border of Lake Pannon a rather high sedimentation rate can be assumed suggesting that the lower limit of the age estimation is more realistic.

2.3. Interpretation of the coquinas

The coquina He 4 was described by Harzhauser and Mandic (2004) as a within-habitat assemblage, which formed in place and lacks traces of transport. The high fragmentation rate seems to be linked to bioturbation and was additionally supported by shell-stability-decline due to a long-time exposure on the lake floor. Oxygenation on the lake bottom was high enough to maintain life and to facilitate some bioturbation. The uppermost part of the coquina is characterised by disarticulated but well preserved shells indicating a change of the environment. The convexside down position of the shells and the close position of the left and right valves point to a quiet-water deposition. After death, the shells simply keeled over following their low balance point close to the umbos.

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 Table 1

 Data sheet with a list of selected taxa used for statistical analysis

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0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		Elangaceae	$\begin{array}{c} 0.0\\ 0.2\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\$
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		рлэсыла	0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		Celtis	$\begin{array}{c} 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0$
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		Rutaceae	$\begin{array}{c} 0.0\\ 0.5\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\$
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		radmabiupiJ	$\begin{array}{c} 0.3\\ 0.5\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0$
0	0	0	0	0	0	0	0	0	0	0	0	0	-	0		Suphobiaceae	0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		muilyisia	0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		รมชานอเมอ รถนเน่นชา	$\begin{array}{c} 0.0 \\$
0	0	0	1	0	0	0	0	-	0	0	0	0	0	0		nmag	
0	-	0	0	0	0	0	0	0	0	0	0	0	0	0		nur	
	0	0	0	0	0	0	0	0	0	0	0	0	0	0		Dilit	
0		0	0	0	0	0	0	0	0	0	0	0	0	0		Compositae	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
-	1	0	0	0	0	-	0	0	0	0	0	0	0	0		Mvrica	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		ովել	
0	0	0	2	0	0	0	0	0	0	0	0	0	0	0		96936dtne16mA\.siboqon9d2	
0	0	-	0	0	0	0	0	0	0	0	0	0	0	0		<i>віпттози</i> ∃	0.0 0.5 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0	0	0	-	-	-	0	0	0	0	0	-	5	0	0		swords	$\begin{array}{c} 0.3\\ 0.5\\ 0.2\\ 0.6\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0$
0	0	2	0	0	0	0	0	0	0	0	0	0	0	0		Ericaceae	$\begin{array}{c} 0.3\\ 0.2\\ 0.2\\ 0.3\\ 0.3\\ 0.3\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0$
0	-	0	0	0	-	0	0	0	0	0	0	0	0	0		sunigrad	$\begin{array}{c} 0.6 \\ 0.2 \\ 0.0 \\$
-	0	0	0	0	0	0	0	0	0	0	-	-	-	0		σικονα	$\begin{array}{c} 1.4 \\ 0.5 \\ 0.7 \\ 0.7 \\ 0.8 \\ 0.3 \\ 0.0 \\$
0	0 0	0 0	0 1	0 0	0 0	0	0 0	0	1	0	0	0 0	0 0	0 0		DSSKN	$\begin{array}{c} 0.6 \\ 0.5 \\ 0.3 \\ 0.3 \\ 0.3 \\ 0.0 \\$
0	0	-	5	0	0	0	0	0	0	0	0	1	0	0		əsmlaq	$\begin{array}{c} 0.0\\ 1.4\\ 1.2\\ 1.9\\ 0.3\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0$
0	4	-	4	0	-	-	0		-	0	2	0	0	-		sup[3n]	$\begin{array}{c} 1.7\\ 0.5\\ 0.6\\ 0.8\\ 0.4\\ 0.0\\ 0.0\\ 0.2\\ 0.2\\ 0.0\\ 0.0\\ 0.0\\ 0.0$
0	0	1	-	0	0	0	0	0	0	0	0	0	0	0		snulA	$\begin{array}{c} 1.7\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0.0\\ 0$
1 0	1 0	1 3	3 1	0 0	0 0	0 2	0 1	0 1	0 0	0 0	0 1	05	0 1	0 2		Acer	0.0 0.0 0.0 0.4 0.4 0.0 0 0.0 0 0.0 0 0.0
-	0	-	2	0	0	0	0	0	2	0	0	7	2	0		nibradloga	2.0 1.1 1.2 1.2 1.2 1.7 1.7 1.7 1.7 1.7 0.4 0.4 0.4 0.0 0.0
1 3	04	1 2	2 2	0 1	3 1	2 0	8 4	1 1	1	2 0	0 2	0 1	0 0	0 0		scindopitys	1.11 1.11 1.12 1.12 1.12 1.13 1.13 1.13
e	-	7	0	-	-	0	-	-	0	-	0	4	0	0		unuvsuvds	2.6 2.3 2.3 2.3 2.3 2.3 2.3 2.7 2.2 2.2 2.2 2.0 0.0 0.0 0.0 0.0 0.0 0.0
-	1	ŝ	4	0	2	ŝ	2	2	2	ŝ	5	ŝ	2	0		snan-	
-	ŝ	-	2	0	5	ŝ	-	0	5	0	0	01	0	0		1.096696	0 0 7 1 0 8 0 7 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	9	8	9 1	е С	1 2	4	5		80	0	1	1	۳ 	ی در		concol	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
4	7	00	2	0	2	5	6	4	0	2	-	7	-	-		shung]	8 2 2 3 4 4 7 7 5 5 2 1 2 8 8 2 2 3 4 4 7 7 5 5 2 2 2 8 8 2 9 9 9 9 9 9 9 9 9 9 9 9 9 9
10	4	4	4	-	5	2	ŝ	ŝ	ŝ	5	2	9	ŝ	0		Бегосатиа	0 0 1 0 0 7 0 0 0 0 0 0 0 0 0 0 0 0
2	ŝ	2	00	ŝ	4	8	-	4	9	ŝ	11	6	4	8		כסנאס	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
16	~	11	20	0	9	4	17	14	6	6	6	12	4	2		Quercus	0.000 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
80	8	5	1 10	0	9 6	9 0	6 (7 16	12	1 10	3 16	7 13	14	15		ngusT	6 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5
3	3 16	3	1 14	ŝ	19	116	5 2(7 2.	80	1	4 18	4 17	1 6	4		esoseiboxeT	66. 67. 67. 66. 66. 66. 66. 66. 66. 66.
1 29	3 33	7 15	34	5 5	8 20	0 25	3 25	4 27	1 26	9.3	9 24	1 44	2 39	8 43		Picea	0.6 3.5 6.8 6.8 6.8 6.8 6.8 6.8 6.8 6.8 6.8 6.8
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38	45	46	60	4	38	5.2	20	5,	99	22	3 66	5	52	56	S		0.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1
107	121	111	124	29	87	146	142	127	135	158	105	158	66	132	LAGE	Cathava	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
															CEN	snuid	33. 33. 33. 33. 33. 15. 33. 33. 33. 33. 33. 33. 33. 33. 33. 3
45	47	4 8 4 9	51	52 53	55	57	59	61 62	63	65	67	69	3 7 8	73	PER	səldme2	27 23 23 33 39 29 29 29 29 29 29 29 20 20 20 20 20 20 20 20 20 20 20 20 20

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Table	e 1 (con	ntinue	(p:	ļ			ļ																							ļ					ļ			ļ										
PERC	ENTAG	ES																																														
səldme2	sunig	רמווימאמ	Picea Picea	non t	DENE	Quercus	כמואט	Ρέενοςαιγα	snmlU	Poaceae	snSvJ	muinpgrade	syityobnitys	nibradlegaA	Acer	sunlA	รแซเซิก(esmise	DSSÁN	DVOM92	Ericaceae	svoky	ріпттоэиЯ	96936d1n676mA/.eiboqon9d2	DydAL	Myrica	setizoqmoD	niliT	Betula	Carpinus orientalis	muilytaid	96926idonqu'i Liquidamber	Rutaceae	Celtis	Γοπίτετα	esosgnela	Plantago	xiln2	syiiqirbidga	siləmamaH	sozojduiAs	Vitis	2011 xajj	snyy	рләрәң	тиЛупдоітуМ	Βίαέγςαιγα	
%																																																
29	34.7	9.6 1	10.2 5	9.6 1.	4.0 1.	9 2.	9 2.2	3.2	0.3	1.0	1.6	0.6	1.9	1.3	1.3	0.3	0.3	0.0	0.0	.3 0	.6 0.	3 0.0	0.3	3 0.3	0.0	0.3	0.0	0.3	0.3	0.0	0.0	0.0	0.0.0	0.0.	0 0.0	0 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	
31	26.0 1.	5.3 1	16.5 10	0.3	9.5 3.	7 2.	1.4.1	4.1	2.1	1.7	0.4	0.0	0.4	0.8	0.4	1.2	0.0	0.0	0.4 (0.00	.0 0.	0 0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.4	0.0	0.0	0.0	0.0	0 0.0	0 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
8	40.4 1	1.7	16.0 10	0.2	8.6 2.	. 0	2.5	2.2	0.6	1.2	9.0	0.3	0.6	0.3	0.3	0.3	0.0	0.0	0.0	0.3	0.0	3 0.0	0.0	0.3	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.3 0	0.0	0.0	0 0.0	0 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
35	34.6 11	0.0	8.6 11	3.3 1	8.6 5.	0 2.	1 2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0. 0. 0. 0.	0 0.0 4 1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 0.0	0.0.0.0	0.0	0.0	0.0 0	0.0	0.0	0.0	0.0	0.0	0.0	0 0	0.0	0.0 0	0.0	0.0	
39	36.9	9.8 1	8.4 10	0.3	8.9 4.	5 3.	5 1.4	0.3	0.3	0.8	1.1	0.3	1.1	0.3	0.0	0.6	0.6	0.0	0.0	0.0.0	0 0	0 0.6	5 0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 0	0.0.0.	.0 0.	0 0.0	0.0.0	0.0 0	0.0	0.0	0.0	0.0	0.0	0.0	0 0.0	0.0	0.0	0.0	
41	34.8	7.8 1	17.7 12	2.3	8.7 4.	2 2.4	1 1.8	2.7	1.2	0.3	3.3	0.3	0.3	0.0	0.0	0.6	0.0	0.6	0.3 (0.0.0	.0 0.	3 0.0	0.0 (0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0 0	0.0.0.	.0 0.	0 0.0	0 0.0	0.0 0	0.0	0.0	0.0	0.0	0.0	0.0	0 0.0	0.0	0.0	0.0	
43	40.2 10	0.0 2	20.0 12	2.7	7.3 1.	5 2.0	1.5	0.5	0.2	0.0	0.2	0.5	0.5	0.7	0.2	0.0	0.2	0.5	0.0	0.0.0	.0 0.	5 0.0	0.0 0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0 0	0.0.0.	.0 0.	0 0.0	0 0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0 0.0	0.0 (0.0	0.0	
45	31.8 1	1.3 1	18.2 8	8.6	9.8 2.	4 4.	3 2.1	3.0	1.2	0.6	2.1	0.3	0.3	0.9	0.3	6.0	0.3	0.3	0.0	0 0.0	.0 0.	0 0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3 0	0.0.0.	.3 0.	0 0.0	0 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
47	33.9 1.	3.4 2	21.8	9.2	4.5 2.	2 2.	2.1.4	::	2.0	1.4	1.7	0.8	0.3	0.3	0.0	1.1	0.0	0.3	0.0	0.0	.1 0.	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3 0	0.3 0.	0.0	3 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
51	34.5 16	6.7 1	2.5 9	9.5	3.9 2.	8 0.0	22	1.1	0.6	1.1	1.7	0.6	1.1	0.0	0.6	0.6	0.6	0.8	0.3 0	0.3 0.	1 0.0	5 U.C	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0.0	0.0	0.0	3 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
53	38.2 18	8.4 1	9.7 6	5.6	3.9 0.	0 0.	3.9	1.3	0.0	0.0	3.9	0.0	0.0	1.3	0.0	1.3	0.0	0.0	0.0	0.0.0	.0 0.	0 0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0 0	0.0.	.0 0.	0 0.0	0 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0 0.0	0.0	0.0	0.0	
55	35.8 1	5.6 1	15.6 8	8.2	7.8 2.	5 2.	5 1.6	0.8	0.8	1.6	0.8	2.1	0.8	0.4	1.2	0.4	0.0	0.0	0.0	0.0.0	4 0.4	0 0.0	0.0 0	0.0	0.4	0.0	0.4	0.0	0.0	0.0	0.0	0.0 0	0.0.0.	.0 0.	0 0.0	0 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0.0	0.0	0.0	0.0	
57	41.0 10	6.0 1	19.7 7	2.0	4.5 1.	7 1.	1 2.2	0.6	1.4	0.3	1.1	0.8	0.8	0.0	0.6	0.0	0.0	0.0	0.6 (0.0.0	.3 0.	0 0.0	0.0 0	0.0 (0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3 0	0.0.0.	.0 0.	0 0.0	0 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
59	38.8 1.	4.5 1	17.2 6	5.8	5.5 2.	5 4.0	5 0.3	1.4	2.5	1.4	1.4	0.3	0.5	0.3	0.8	1:1	0.0	0.0	0.3 (0.0.0	0.0	0 0.0	0.0 0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 0	0.0.0.	0 0	0 0.0	0 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0 0.0	0.0	0.0	0.0	
61	37.4 1	5.3 1	12.9 7	6.7	7.9 4.	7 4.	1 1.2	1.5	1.2	0.6	2.1	0.0	1.5	0.3	0.3	0.3	0.0	0.0	0.3 (0.0.0	.3 0.	0 0.0	0.0 0	0.0 (0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 0	0.0.0.	.0 0.	0 0	3 0.0	0.0	0.0	0.0	0.0	0.0	0.0	.0 0.	0 0.0	0.0	0.0	0.0	
63	38.9 1	9.9 1	14.7 7	7.5	2.3 3.	5 2.	5 1.7	1.4	0.0	1.4	2.3	0.6	1.4	0.0	0.3	0.3	9.0	0.0	0.0	0 0.0	.3 0.	0 0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 0	0.0.0.	.0 0.	0 0.0	0 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
65	45.4 10	6.4 1	14.1 10	0.6	3.2 2.	9 2.	5 1.4	0.6	0.6	0.6	0.0	0.0	0.9	0.3	0.6	0.0	0.0	0.0	0.0	0.0.0	.0 0.	0 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0.0.	0.0	0 0.0	0 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
6	34.1 20	0.8 1	12.3	9.1	5.7 5.	0 5	3.5	1.6	0.3	2.2	0.3	0.0	1.6	0.0	0.0	0.6	0.0	0.0	0.3	0 0.0	.6 0.	0 0.0	0.0	0.3	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0 0.0	0 0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
69	35.0 19	2.2	5 2 14		4.1 3.	7 7	777 6	0 -	1.1	0.1	1.1	7.0	1.0	0.1	0.0	7.0	0.7	0.0		0 0.0	0.0	7 0.0		7.0 0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0 0.0	0.0				0.0	0.0	0.0	0.0					0.0	0.0	
23	37.7 1(6.0 2	2.3 12	53	1.1 4.	3 0.6	5 23	0.0	0.3	6.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 0	0.0 0.	0.0.	0 0.0	0.0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Num	bers are	e tota	al coun	nts (s	hadec	l are.	I repi	esen	ts the	e coq	luina	inte	rval																																			

Bioturbation is low in this part of the core. At that time, this part of Lake Pannon was below wave base, which was situated at c. 15 m (Korpás-Hódi, 1983). Thereafter, very calm conditions were established; bioturbation is absent and mollusc settlement was reduced to the short-lived *Sinucongeria* pavements. This coquina-type represents boom-&-bust populations formed by 1–2 generations of highly opportunistic *r*-strategists. Iron-sulphides in the sediment within the bivalves point to low oxygen levels on the lake bottom and especially in the sediment. These periodically occurring census assemblages reflect very short periods of favourable conditions within a generally hypoxid lake bottom environment (Harzhauser and Mandic, 2004). Within the core, only one of these pavements is recorded.

3. Methods

For sample acquisition, we used a coring device consisting of a 50 cm-long and 10 cm-diameter plastic tube fitted within a steel mantle with a sharp ring-cutter at the lower extremity. The tube was rammed into the sediment with a motor pulse-hammer. The obtained core was cut lengthwise into two halves and further sliced into 5 mm thick sediment layers. For ostracod analysis we extracted 20 cubic cm from each layer, which were further treated with H_2O_2 and sieved with a 125, 250 and 500 μ m mesh-size sieves. From 66 samples studied for ostracods only 5 were barren (Table 1). We counted and identified to generic level all the ostracods in those samples in order to achieve abundance data (Table 1).

For palynological data 74 samples were studied out of the core (dinoflagellates and pollen samples are identical). They were dried and weighed and two Lycopodium clavatum tablets were added to each sample. Then, they were treated with cold HCl (34%) to remove carbonates. After washing with distilled water, the samples were treated with HF (48%) and cold HCl to fully remove silicates and colloids. The residue was sieved at 125 µm and 10 µm and divided into two portions. One portion was ultrasonicated (c. 15-30 s) and resieved at 20 µm for dinoflagellate cysts analysis. A slight oxidation with diluted HNO3 was applied for a few seconds to some samples very rich in organic matter. The residue was washed and stained with Safranine O. Slides were prepared from each sample using glycerin jelly and were sealed using nail polish. The slides were scanned at 400× and 300 dinocyst specimens were counted and identified to species level when possible. Similarly, for the study of pollen at least 150 specimens have been counted (excluding Pinus and Pinaceae). Exceptions are the samples 15, 19, 17, 35 and 53, which yielded extremely few pollen grains. To overcome this obstacle of uneven counts we used percentages for most of the analyses. For ostracods and dinoflagellates, all samples have been studied, for pollen analysis every second sample. This sample density warrants a resolution roughly on decadal level for dinoflagellates and ostracods whereas the pollen analysis achieves a resolution of 2-3 decades.

4. Results

4.1. Ostracoda

A total of 2136 valves were counted from the 250 and 500 µm fractions for this analysis including 453 *Cyprideis*, 501 *Hemicytheria*, 1067 *Lineocypris/Caspiolla*, 40 *Amplocypris* and 75 *Loxoconcha* (Table 1). Additional but very rare ostracod taxa identified in the samples are presented in Table 2.

Only a few specimens of the main groups and rare loxoconchids and leptocytherids occur in the lower part of the core. The few candonids belong to the genus *Caspiolla*, with very thin valves and an elongated posterior shape. Both the cytherids and the candonids show a first peak within these first centimetres of the core where the sediment shows minor evidence of bioturbation (Fig. 2). It is followed by a drop in population densities and a reincrease just below the coquina (Table 1). The preservation of the valves is not very good, especially of *Lineocypris* valves that are partly decalcified and present a milky appearance as described by Danielopol et al. (1986).

Within the coquina, the number of valves increases strongly. However, in the middle of the coquina, a drop in their relative abundances and a sharp decline from layer 17 upwards was observed. Adult valves of the two large species *Lineocypris* aff. *reticulata* and *Amplocypris* sp. (length: 0.9–1.5 mm) are very abundant in the first 3 cm of the coquina. Both have strongly calcified walls. The highest numbers of loxoconchids occur within this part of the core. The preservation of the valves is very good, especially those of the cytherids. Only few valves are slightly broken, but many are blackened.

The upper part of the core, starting with sample 17, is characterised by very low abundances of ostracods and are mainly represented by juveniles of cytherids, candonids and rare leptocytherids. The large *Amplocypris* sp. and the *Loxoconcha* species are not present anymore. The preservation of the candonids in this part of the section is poor; the valves are decalcified and deformed, carapaces of juveniles are crushed, and many valves are broken.

4.2. Dinoflagellate cysts

Dinoflagellate cysts are well preserved but the assemblage is rather poor and dominated by few taxa (Table 3). The assemblage consists mainly of Spiniferites/Achomosphaera [mostly S. bentorii (Rossignol) Wall and Dale, 1970; 60% of the total counts], Impagidinium [mostly I. sphaericum (Wall, 1967; 23%] and Batiacasphaera hirsuta Stover, 1977 (12%). The remaining 5% are contributed by Selenopemphix, Brigantedinium, Pyxidinopsis psilata (Wall et al.) Head, 1994, Nematosphaeropsis and few other taxa such as Operculodinium, Dapsilidinium, Lingulodinium and Polysphaeridium. In addition to the dinoflagellate cysts, there is a considerable occurrence of freshwater algae e.g. Pediastrum and Botryococcus as well as fungal spores. Generally, the dinocyst assemblages in the core can be divided into a lower part (samples 1-13) and an upper part (samples 14-73) including the coquina (Fig. 3). The lower part is characterised by high abundances of Batiacasphaera hirsuta (39-55%), Spiniferites/Achomosphaera (34-46%) and Pediastrum. Impagidinium is less abundant and shows a slight increase from 4% to 15%

Table 2

Ostracod taxa identified in the Hennersdorf core (det. D.L.D.) The taxonomic system here adopted follows largely those used by Sokač (1972), Meisch (2000) and/or Gross (2004)

Superfamily Cytheroidea Baird, 1850 Family Cytherideidae Sars, 1925 Genus Cyprideis Jones, 1857 Cyprideis obesa (Reuss, 1850) Family Hemicytheridae Puri, 1953 Genus Hemicytheria Pokorný, 1955 Hemicytheria folliculosa (Reuss, 1850) Family Loxoconchidae Sars, 1925 Genus Loxoconcha Sars, 1866 Loxoconcha aff, granifera (Reuss, 1850) Loxoconcha aff. rhombovalis Pokorný, 1952 Family Leptocytheridae Hanai, 1957 Genus Amnicythere Devoto, 1965 Amnicythere sp. Genus Euxinocythere Stancheva, 1968 Euxinocythere sp. Superfamily Cypridoidea Baird, 1845 Family Cyprididae Baird, 1845 Genus Amplocypris Zalányi, 1944 Amplocypris sp. Family Candonidae Kaufmann, 1900 Genus Lineocypris Zalányi, 1929 Lineocypris aff. reticulata (Méhes, 1907) Lineocypris aff. trapezoidea (Zalányi, 1929) Genus Caspiolla Mandelshtam, 1960 Caspiolla sp. 1 Caspiolla sp. 2 Caspiolla sp. 3

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Table 3

List of dinoflagellate cysts recorded in the samples; a statistical analysis of the taxa not mentioned in Table 1 will be given elsewhere

Achomosphaera ramulifera (Deflandre,) Evitt, 1963
Achomosphaera argesensis Demetrescu, 1989
Achomosphaera cf. A. fenestra Kirsch, 1991
Batiacasphaera hirsuta Stover, 1977
Batiacasphaera sphaerica Stover, 1977
Cordosphaeridium minimum (Morgenroth) Benedek, 1972
Dapsilidinium pastielsii (Davey and Williams) Bujak et al., 1980
Habibacysta tectata Head et al., 1989
Impagidinium sphaericum (Wall) Lentin and Williams, 1981
Impagidinium spongianum Süto-Szentai, 1985
Labyrinthodinium truncatum Piasecki, 1980
Lejeunecysta spp.
Lingulodinium machaerophorum (Deflandre and Cookson) Wall, 1967
Melitasphaeridium choanophorum (Deflandre and Cookson) Harland and Hill, 1979
Nematosphaeropsis sp.
Operculodinium centrocarpum (Deflandre and Cookson) Wall, 1967
Polysphaeridium zoharyi (Rossignol) Bujak et al., 1980
Pyxidinopsis psilata (Wall and Dale) Head, 1994
Selenopemphix brevispinosa Head, Norris and Mudie, 1989
Selenopemphix conspicua (de Verteuil and Norris) Louwye, Head & De Schepper, 2004
Selenopemphix nephroides Benedek emend. Bujak in Bujak et al., 1980
Spiniferites bentorii (Rossignol) Wall and Dale, 1970
Spiniferites galeaformis Süto-Szentai, 1994
Spiniferites lazus Reid, 1974
Spiniferites membranaceus (Rossignol) Sarjeant, 1970
Spiniferites nodosus (Wall) Sarjeant, 1970
Spiniferites paradoxus (Cookson and Eisenack) Sarjeant, 1970
Spiniferites tengelicensis Süto-Szentai, 1982
Spiniferites virgulaeformis Süto-Szentai, 1994

within that part of the core. This interval is characterized by a considerable amount of reworked dinoflagellate cysts, e.g. *Distatodinium*, *Homotryblium* and *Deflandrea*. The sample interval 13–15 is marked by a distinct break; *Batiacasphaera hirsuta* drops strongly to values around 1.7%–6.7% whereas *Impagidinium* and *Spiniferites/Achomosphaera* display a parallel trend towards higher values. The latter predominates and comprises c. 60% of the total dinoflagellate spectrum of the upper core. Slight decreases in *Spiniferites* abundance are limited to the samples 27, 36 and 61 where the decline of *Spiniferites* is compensated by short spikes of *Impagidinium*.

4.3. Pollen

52 pollen taxa have been identified in the studied samples (Table 1, Fig. 3) and Pinus, Cathaya, Abies and Picea are the most abundant palyno-genera. Taxodiaceae, Tsuga, Carya, Pterocarya, Quercus and Acer are important constituents as well, whereas all other taxa are rare and usually represent less than 5% of the spectra. The pollen spectra represent 4 basic groups (Fig. 4): The dominating group, represented by Pinus, Cathaya, Abies and Picea, shows high to moderate abundances in samples 1-14 representing the lower part of the core and a basal part of the coquina. Within the coquina, sample 15 coincides with a total breakdown of abundance in this group. Thereafter, a gradual but slightly oscillating recovering phase is evident up to sample 35, which is followed by a rather stable high-abundance phase. Taxodiaceae, Quercus, Acer and Fagus display peaks in abundance at different times within the coquina interval. Especially the Taxodiaceae are the sole dominating group in the low pollen concentration sample 15. All these taxa comprise only low or moderate amounts in the pre- and post-coquina samples. Carya, Pterocarya, Poaceae and Sparganium are represented by low percentages (never higher than 10%) and reach their higher abundance within the coquina, becoming rare in the upper part of the core. The diversity of the samples is strongly fluctuating as well (Fig. 4). There are 4 important episodes of low pollen concentrations with less than 5 recorded taxa at samples 15, 27, 35 and 53. These events separate 4 cycles of moderate diversities with ~20-30 taxa and a fifth high-diversity cycle with 32-39 taxa in the lower part of the core (samples 1-13).

5. Discussion

The data set gives insight into 3 different environments in the Lake Pannon area: lake bottom conditions are reflected by the ostracod and mollusc faunas, surface water conditions are indicated by the dinoflagellates and the terrestrial habitats are at least partly manifested by the pollen record.

5.1. The lake bottom

The fluctuation of the relative abundances of the ostracod groups points at a dynamic benthic system. A first peak of ostracods occurs in



Fig. 3. Comparison of total counts of pollen, dinoflagellates and ostracods. Five cycles are evident in the pollen concentration curve. The lower three minima are also reflected by 3 blooms of *Impagidinium* within the dinoflagellate assemblages. In contrast, the lower minimum is opposed by a frequency maximum of ostracods.

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Fig. 4. Percentage-based pollen diagrams for the most important constituents of the pollen-assemblages. Shaded areas indicate low-concentration samples (light grey) and coquina interval (dark grey). A strong decline of mid-to high altitude elements is evident in the basal part of the coquina, where Taxodiaceae, *Quercus* and *Acer* predominate. The upper part of the core reflects a gradual increase of bisaccate pollen and a decline of wetland taxa. The poor correlation of low pollen concentrations intervals with major shifts in the percentage ratios in the upper core suggest processes such as climatically induced reduced transport of non-bisaccate pollen during these short episodes rather than a real change of vegetation.

the bioturbated lower part of the core (at c. 7 cm; Fig. 3). The abundance of loxoconchids and leptocytherids as well as the appearance of slightly decalcified candonid valves point to a photic benthic habitat at a shallow depth not far from the wave base line, with submerged macrophytes. This is the common environment colonised by loxoconchids with well developed eye tubercles and leptocytherids (Bonaduce et al., 1975; Kamiya, 1992; Cronin et al., 2005). *Loxoconcha* aff. *granifera* with its strong reticulated valves is most probably an epibenthic species like *Hemicytheria folliculosa* and *Cyprideis obesa* whereas *Loxoconcha* aff. *rombovalis* and the two leptocytherids are probably phytophilous species. The low numbers of *Caspiolla* suggest a poorly oxygenated environment (dysoxic sensu Tyson and Pearson, 1991) with only 0.2–2 mg/l dissolved oxygen.

A highly diversified ostracod assemblage develops during the formation of the lower part of the coquina, pointing to an improvement of the benthic habitat. Still submerged macrophytes could have covered the bottom of the lake, offering suitable life conditions. Most of the species display an increase of population-size. All the species probably required conditions similar to related extant species such as *Cyprideis torosa* Jones 1850 (Hermann and Heip, 1982) and *Cytherissa lacustris* Sars, 1863 (Geiger, 1990). Thus, abundance, large size and strength of the calcified valves of *Cyprideis obesa*, *Hemicytheria folliculosa*, *Lineocypris* aff. *reticulata*, *Loxoconcha* aff. *granifera* and *Amplocypris* sp. suggest a generally euoxic habitat with more than 2–3 mg/l dissolved oxygen at the sediment-water interface. However,

close to the decaying molluscs of the coquina, anoxic micro-habitats developed where iron sulphides were produced as indicated by the high number of blacked ostracod valves (Danielopol and Handl, 1990).

In the upper part of the coquina (sample 17), a distinct change of the ostracod assemblage occurs. The abundances drop strongly and Amplocypris and Loxoconcha disappear, pointing to a loss of macrophytes and the development of a eutrophic bottom system. The lake bottom at the core-section is now below wave base within the hypolimnion, probably due to a rise of the lake level. A near-permanent suboxic environment (dissolved oxygen concentrations below 0.2 mg/l) established. An intense microbial respiration at the sediment-water interface increased the carbon dioxide concentration, respectively the production of slightly acidic water at and in the surficial sediment, causing decalcification of the candonid valves (Danielopol and Casale, 1990). Interestingly, in the post-coquina section of this core, a single dreissenid pavement does not coincide with any abundance peak of ostracods. Obviously, the short episode of hypolimnion oxygenation, which promoted the development of 1-2 generations of Sinucongeria, did not allow the ostracods to recolonise the site. One explanation might be that the ecological window for an ostracod resettlement remained closed due to the filter potential of dreissenid boom-&-bust populations. These might have removed the ostracod larvae from the water by filter feeding (Strayer et al., 1996). This hypothesis, however, is weakened by the fact that all recorded ostracods in the core lack swimming antennal setae during their life cycles. Maybe, the ostracods

were simply unable to recolonise the depauperated sediments within less than 10–20 years because of their low movement capacity and because the environment remained unsuitable for them (e.g. still high concentrations of hydrogen sulphide in the upper sediment layers). This scenario is derived from the observations on *Cytherissa lacustris* which has very low displacement rates of 3 m/year in mesotrophic sediment conditions of Lake Mondsee (Danielopol et al., 1990; Geiger, 1990) compared to swimming species, such as *Cypria opthalmica*. As the motility behavior of *C. torosa* is comparable with that of *Cytherissa lacustris* (D.L.D. personal observations) the resettlement calculations might also be suitable for the related Lake Pannon *Cyprideis obesa*.

5.2. Surface waters

The dinoflagellates suggest a major change in paleoenvironments by the simultaneous decline of *Batiacasphaera hirsuta* and a bloom of *Spiniferites* and *Impagidinium* from sample 14 upwards. *Impagidinium* is an indicator for offshore conditions in marine settings and points to oligotrophic environments (Dale, 1996; Marret and Zonneveld, 2003). It covers a wide range of temperatures but usually has a low tolerance for lowered salinities (Edwards and Andrle, 1992; Rochon et al., 1999). Thus, the high number of *Impagidinium* in the brackish environment of Lake Pannon suggests that some species are less stenohaline (Marret et al., 2004).

A rise in the lake level, which would result in a landward shift of the coast would thus be a realistic scenario to explain the sudden increase of *Impagidinium* spp. This interpretation is supported by the near-disappearance of the coastal and lagoonal *Batiacasphaera hirsuta*, which is recorded in Paratethyan embayments often in association with pollen of a swamp flora (Gedl and Worobiec, 2005). Comparable patterns of *Batiacasphaera* decline and *Impagidinium* take-over have been reported also from marine transgressions in the Miocene of the Carpathian Foredeep (Gedl, 1996, 1998) and decadal scale responses of *Impagidinium* to sea-level rises are documented for Holocene deposits of the Caspian and Aral seas (Marret et al., 2004; Sorrel et al., 2006).

Spiniferites, as a neritic genus, profited from the lake level rise and roughly parallels the *Impagidinium* trend by strongly increasing abundances starting at sample 14. Despite the general high levels of *Impagidinium* and *Spiniferites* in samples 14–73, at least 3 events of opposite trends are recorded at samples 27, 36 and 61 (Fig. 3). These events are marked by strong *Impagidinium* peaks that are counterbalanced by *Spiniferites* lows. In contrast, the *Spiniferites* blooms at samples e.g. 21, 26, and 60 coincide with strongly declining *Impagidinium* values. These patterns point to further oscillations of the lake environment on a decadal scale. The short *Spiniferites* blooms may be linked to increased nutrient concentrations and/or warming of the surface water (Harland, 1983; Turon, 1984; Zonneveld, 1995). *Impagidinium* blooms might reflect short-term lake level oscillations and/or phases of increasing oligotrophy due to decreasing input of nutrients by rivers and wind.

5.3. The shore and the hinterland

The paleoecological analysis of the pollen assemblage follows the categories used by Bertini (2001), Jiménez-Moreno et al. (2005), Jiménez-Moreno (2006), Kloosterboer-van Hoeve et al. (2006) and Kvaček et al. (2006). The pre-coquina part of the core is dominated by *Pinus, Cathaya, Picea* and *Tsuga*. In addition, *Carya, Pterocarya*, Poaceae, Taxodiaceae and Cupressaceae are frequent constituents of the spectra. Many other generally less frequent elements such as *Sparganium–Typha, Nyssa, Zelkova, Ginkgo*, Palmae, Chenopodiaceae and Amaranthaceae display their highest occurrence in this part of the core. This assemblage, with Taxodiaceae, *Typha, Nyssa* and *Sparganium*, is interpreted to reflect the wetland flora of the swamps and marshes around Lake Pannon in c. 5–6 km distance of the core (Fig. 1). A mixed mesophytic forest with *Pinus, Cathaya, Tsuga, Quercus* and

Ulmus covered the adjacent low- and mid-altitude areas of the margin of the Vienna Basin. *Picea* and *Abies*, although often considered as indicators for high-altitude areas above 1800 m (Jiménez-Moreno et al., 2008), are considered to have been elements of this forest type as well, as such high mountainous areas did not exist in the Eastern Alps within a radius of c. 250 km (although they might have been transported by rivers over a long distance).

The onset of the coquina coincides with a major break in the pollenfrequency patterns. The otherwise predominating Pinus, Cathaya, Abies and Picea drop to very low percentages whereas Taxodiaceae and Quercus take-over. The Taxodiaceae spike and the accompanying Quercus and Acer spikes, however, are not caused by a marked increase in real pollen number but only a result from the low pollen concentration and the resulting disappearance of most other taxa. Carya, Pterocarya, Poaceae and Sparganium co-occur throughout the coquina interval but display a declining trend. In contrast, Pinus, Cathaya, Abies and Picea show a gradual increase in abundance within the coquina after the collapse in sample 15. This implies a decrease in allochthonous elements and a better representation of par-autochthonous coastal elements in the spectra during the formation of the coquina. A simple spreading of Taxodiaceae can be ruled out, as their overall frequency does not change significantly. Moreover, the represented time span of a few decades was probably too short to have allowed the growth of a new taxodiacean swamp. The mechanism that triggered this strange pattern could have been the reduced pollen input from the hinterland during a transgression which would have resulted in a landward shift of vegetation zones. Moreover, during the initial very rapid transgression (sample 15), the shallow marshland would have been drowned. Considering the rather narrow belt of lowlands between the Eastern Alps and the shores of Lake Pannon, the extension of the lake would have greatly reduced the wetlands. This would have resulted in the gradual decline of reed taxa, whereas the trees represented by Taxodiaceae could have kept up with a moderate lake level rise.

Above the coquina, the gymnosperms attain up to 93% in the pollen spectra and the angiosperms drop from c. 40% in the lower part of the core to 6%. Hinterland taxa, such as Pinus, Cathaya, Abies and Picea account for more than 80% of the total palynoflora. Reed taxa and elements from the low lands become rare and the Taxodiaceae are constantly decreasing to nearly insignificant levels. This development might be linked to a loss of wetlands due to a rise of the lake level in a moderately steep escarpment with narrow local vegetational zones. A general landward shift of the coast is indicated by the overall increase of bisaccate pollen, which can be transported over longer distances and can swim longer on the water-surface (Hopkins, 1950; Traverse and Ginsburg, 1966; Heusser and Balsam, 1977). This shift of the spectra is also evident in the percentage-based cluster analysis and total counts-based nMDS analysis (Fig. 5). Samples of the wetlandelement dominated lower part of the core are clearly separated from the samples of the upper core.

This simple scenario, however, does not explain the pollen concentration cycles (Fig. 3) which are separated by 4 outstanding samples of low pollen concentrations and low numbers of taxa. The lowermost break down is twofold (samples 15, 19) and corresponds to the above described taxodiacean high. In contrast, the upper 3 low-pollen concentration events (samples 27, 35, 53) coincide with lowered Taxodiaceae/Cupressaceae values but are unreflected by the other taxa in terms of percentages. A simple taphonomic bias due to poor preservation, can be ruled out based on the rich dinoflagellate assemblages of these samples. A potential trigger-mechanism could have been minor floodings which reduced the spreading of parautochthonous coastal material, whilst the relation between hinterland pollen did not change significantly. As these low-concentration samples are not separated in the percentage-based cluster analysis we rather interpret these phases as climate signals which caused a reduced transport of non-bisaccate pollen. Such a mechanism could be a reduced fluvial influx and/or a lowered wind transport.

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Fig. 5. The cluster analyses based on pollen percentages (left) and the nMDS plot based on total counts of pollen and dinoflagellates (right) both separate the samples of the lower part of the core (pre-coquina) very clearly from the upper samples. This separation is interpreted to reflect the major reorganisation of the local vegetational zones due to the transgression of Lake Pannon. Low concentration samples are separated in the total count nMDS plot but do not separate in the percentage-based cluster analysis aside from those within the coquina. [nMDS_(Euclidean) is based on *Pinus, Cathaya, Picea, Tsuga, Abies,* Taxodiaceae, *Carya, Engelhardia, Juglans,* Poaceae, *Quercus, Acer,* Chenopodiaceae, *Sparganium,* spores, *Batiacasphaera, Spiniferites* and *Impagidinium*].

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5.4. Lake-hinterland interference

The above described data suggest a depositional environment close to the coast for the lower part of the core. Wetlands with Taxodiaceae and reed formed a broad coastal belt and eutrophic dinoflagellates bloomed in surface waters. Lake bottom conditions were suboptimal and promoted only small numbers of ostracods. Nevertheless, the lake bottom was close to the wave base and bioturbation occurs. Some phytal cover close to the depositional area supported the development of Loxoconcha. Thereafter, within a few decades, a first distinct rise of the lake level occurs. This transgression is also reflected in geophysical data in various well logs in the Vienna Basin (Fig. 2). Immediately, the dinoflagellate assemblage changes towards "offshore" assemblages with Impagidinium and Spiniferites. Few metres below wave base, the bottom was now suitable for dreissenid settlement and soon a coguina formed which was strongly affected and altered by bioturbation. The reduced input from the shore is also reflected by a rather low abundance of pollen grains. The mollusc shells accumulated without getting covered by sediment. This exposure supported the physico-chemical shell destabilisation and the subsequent fragmentation. Simultaneously, ostracods experienced an increase of micro-habitats, resulting in booming frequencies. Along the shores, the rising water table caused a reduction of the wetland areas as the close mountainsides hindered a simple shift of vegetation zones. Moreover, the transgression favoured the preservation and accumulation of bisaccate pollen grains, which are more suitable for a longer transport.

After a short pause of lake level rise, reflected in the coquinaformation which thus represents a "Mid-Cycle Condensed Shellbed" sensu Abbott (1997), the transgression continued. This deepening caused a transition from oxygenated to hypoxic bottom conditions and the ostracod populations strongly declined. The breakdown of the ostracod acme is not paralleled in the dinocysts-record as the transgressive trend is reflected by rising *Impagidinium* values and lowering of *Batiacasphaera hirsuta* occurrences. Within the mollusc fauna, a take-over by rather thick-shelled specialists such as *Congeria* took place before the deteriorating conditions finally killed even these specialists. Finally, the formation of the coquina ends and the bottom conditions pass into largely inhabitable hypoxic environments with near-zero values of ostracods. Thus, the second transgressive pulse seems to have closed the ecological window for the benthic life. In total, both episodes of lake level comprise only c. 50–100 years.

Later, single mixing events were utilised by dreissenid boom-&-bust populations which vanished after few years as the low-oxygenated hypolimnion developed again. Thereafter, the marshland areas were largely reduced and a small fringe of Taxodiaceae swamps was opposed



Fig. 6. Power spectra performed on percentage data of selected pollen taxa and for the total diversity (based on changing pollen concentrations). Weak peaks are developed at 2–3 cm and between 7–8 and 10 cm. (the data analysis package PAST was used for analysis; http://folk.uio.no/ohammer/past/).

by a predominating mixed mesophytic forest covering the mid-altitudes of the Eastern Alps.

Two *Impagidinium* peaks (coupled with declining *Spiniferites* values) at samples 27 and 36 coincide with extremely low pollen concentrations. A third *Impagidinium* peak at sample 61, however, does not coincide with the pollen concentration curve (Fig. 3). The first two peaks might simply be a result of two minor floodings. This explanation would imply a subsequent lowering of the water table immediately after the transgressions. Nevertheless, the periodicity and duration of the blooms rather suggest a connection to climate. Thus, short periods of lowered precipitation and consequently decreased nutrient input would favor the development of *Impagidinium* on the costs of *Spiniferites*. Such decrease in nutrients is also indicated by low numbers of the heterotrophic dinocysts *Selenopemphix* and *Brigantedinium*. This scenario would also explain the generally lower amount of pollen influx and the shift towards wind-derived bisaccate pollen.

5.5. Cycles and forces

Drill cores and geophysical data of several basins within the Pannonian Basin document the influence of 100 kyr and 400 kyr eccentricity cycles on the sedimentary record of Lake Pannon (Juhász et al., 1999; Harzhauser et al., 2004; Lirer et al., 2007). Benthic life in Lake Pannon was discussed to have also been influenced by smaller scaled cycles such as precession, which have periodically allowed pioneer taxa to settle the deeper part of the lake (Harzhauser and Mandic, 2004). Moreover, the oscillations of Lake Pannon have been deciphered so far only on a large scale (Kosi et al., 2003; Harzhauser et al., 2004; Lirer et al., 2007). The herein studied interval is far too short to represent any of these Milankovitch cycles. Recently, several sub-Milankovitch signals, which are independent from global glaciation effects, have been detected in Neogene lake sediments. Kloosterboer-van Hoeve et al. (2006) documented ~10, ~2.5 and ~1.5 ka periodicities related to variations in solar activity in Early Pliocene pollen records from Greece. Multi-decadal to centennial variability of the Gleissberg (~80, 140-110 yr) and Suess (~250-200 yr) cycles of solar activity modulated the sedimentary record in a Pleistocene maar lake in Southern Africa (Garcin et al., 2006 and references therein). Even Schwabe cycles of solar activity (10-12 yr) are deciphered from Holocene lake deposits (Theissen et al., 2008). Unfortunately, the age model of the studied core is not tight enough to allow a clear identification of such cycles. Power spectra of Pinaceae, Tsuga, Cathaya, Pterocarya and Picea, display peaks at 2-3 cm and 7-8 cm. However, those peaks are below the 95% confidence level (Fig. 6). The power spectrum for the pollen concentration related total pollen diversity has an additional peak close to 10 cm. Based on the assumed sedimentation rates of ~0.5 mm/yr the lower values around 2-3 cm would correspond to a frequency of c. 40-60 yr and the higher values (7-8 cm) would span periodicities from c. 140-160 yr and roughly 200 yr for the concentration cycles. Obviously, the large error bars of our calculations preclude a direct correlation with solar activity cycles such as the Gleissberg cycles and needs further studies, which cannot be performed on the short analysed core.

6. Conclusions

The fairly homogenous climate proxies for the Late Miocene between 10–9 Ma around Lake Pannon suggest rather stable conditions for this interval (Bernor et al., 2003; Bruch et al., 2004; 2006, Harzhauser et al., 2007). Consequently, climate reconstructions focused on developments from ten thousands to millions of years. Our data, however, furnish evidence that at least one of the major transgressive events in Lake Pannon comprised a staccato of smaller floodings on a near-decadal scale. Due to the very sensitive response of different groups of organisms, these individual pulses can be clearly recognised by ultra-high resolution sampling and an integrated paleoecological analysis. This complex

pattern would not be resolved based solely on the autecological interpretations of one group of organisms and would remain hidden by more typical sampling distances of 10–30 cm. The larger–lake level related–pattern is further modulated by smaller iterative events of low pollen concentrations. These events and some of the vegetational elements could suggest a modulation of the overall stable humid climate by external factors such as solar activity.

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