GEOLOGICA CARPATHICA, APRIL 2010, 61, 2, 129–145 doi: 10.2478/v10096-010-0006-3

Upwelling conditions in the Early Miocene Central Paratethys Sea

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(Manuscript received June 3, 2009; accepted in revised form October 2, 2009)

Abstract: Evidence for regional upwelling conditions in the Central Paratethys Sea is presented for mid-Burdigalian (early Ottnangian) times. The oceanographic phenomenon is detected in clay-diatomite successions along the steep escarpment of the Bohemian Massif in the eastern North Alpine Foreland Basin. Interpretations are based on a multi-proxy data-set including published sedimentological and paleontological data, newly performed stable isotope measurements ($\delta^{18}O$, $\delta^{13}C$) of foraminifers and bulk sediment samples, and analyses of dinoflagellate cyst assemblages. The revealed stable isotope values of planktonic foraminifers point to upwelling: low $\delta^{13}C$ values indicate strong mixing of surface waters with rising nutrient-rich waters, high $\delta^{18}O$ values reflect cool sea surface temperatures (SST). Temperature calculations give SSTs ranging from 10–14 °C. Cool SSTs and high productivity are additionally supported by bulk sediment analyses. Assemblages of dinoflagellate cysts indicate a distal-shelf environment with nutrient-rich waters. Westerly winds and tidal currents are discussed as potential driving forces behind the local upwelling event. As mid-Burdigalian geography favoured strong current patterns in the Central Paratethys as documented in the sedimentary record from the Rhône Basin to Hungary upwelling might have been a more common phenomenon in this epicontinental sea than currently known.

Key words: Early Miocene, Central Paratethys, upwelling, foraminifers, dinoflagellates, stable isotopes.

Introduction

Coastal upwelling areas represent regions of the highest primary productivity in the world's oceans. Warm surface water currents caused by prevailing winds along a steep shore are forced offshore due to the Coriolis effect triggered by Earth's rotation. The surface waters are replaced by rising cold bottom waters bringing up high amounts of nutrients which are usually stored at the sea floor (Summerhayes et al. 1995). The richness in nutrients triggers blooms of phytoplankton, providing the basis of a simple food web consisting of zooplankton, fish swarms, sharks, whales and sea birds (Lange et al. 1997; Granata et al. 2004). Much research has been done on the causes and consequences of coastal upwelling. By using many different techniques of oceanography, studies have revealed detailed information about food webs, hydrodynamics, sedimentation and biogeochemistry (e.g. Lange et al. 1997; Nave et al. 2001; Granata et al. 2004; Diz & Francés 2008; Salgueiro et al. 2008). It happens that coastal upwelling can be triggered by different hydrodynamic conditions. Besides wind patterns, tidal currents (e.g. Lee et al. 1997) and topography (e.g. Oke & Middleton 2000) have been discovered as potential driving and amplifying agents.

The information collected from extant upwelling sites is used to trace back their history by documenting changes in primary productivity and water temperature and thus in upwelling intensity. These efforts have been quite successful especially for the Pleistocene and have revealed links between changes in upwelling and global climate patterns (e.g. Faul et al. 2000; Snyder et al. 2003; Nicholson et al. 2006). However, detecting upwelling sites in vanished seas is still a great challenge. Efforts from different disciplines of earth sciences to find traces of upwelling in the geological record have shown that this goal can only be achieved by a multiproxy approach combining various techniques of investigation (Peterson et al. 1995).

On the basis of sedimentological and micropaleontological analyses, coastal upwelling has been repeatedly suggested for the Early Miocene (mid-Burdigalian, early Ottnangian) Central Paratethys Sea along the south-eastern margin of the Bohemian Massif (Řeháková 1992, 1993, 1994, 1996; Mandic et al. 2005; Roetzel et al. 2006). Based on this hypothesis the present study offers new data from dinoflagellate cyst assemblages and geochemical measurements on foraminifers and bulk sediment samples to address the question of coastal upwelling in the area. The variety of proxies revealed by this and previous studies will contribute to an integrated case study concerning upwelling events in the Central Paratethys accompanied by a discussion of their paleoceanographic plausibility.

Geological setting

The early Ottnangian (mid-Burdigalian) Central Paratethys paleogeography

The investigated outcrops are situated in the North Alpine Foreland Basin of Austria and comprise Early Miocene sediments of the vanished epicontinental Central Paratethys Sea (Roetzel et al. 1999b). The Central Paratethys came into existence around the beginning of the Oligocene when the rising Alpine chains triggered a reorganization of paleo(bio)geographic patterns within the ancient Tethys Ocean (Rögl 1998; Harzhauser & Piller 2007). Each of the resulting Mediterranean, Central Paratethys and Eastern Paratethys Seas underwent a history of its own. Thus, a regional stratigraphic scheme was developed for each of them (see Piller et al. 2007 for details). Based on lithostratigraphy and biostratigraphic evaluation of calcareous nannoplankton, diatoms, silicoflagellates and foraminifers, the outcrops of this study are all regarded as belonging to the early Ottnangian (mid-Burdigalian; Fig. 1) (Roetzel et al. 2006; Rupp et al. 2008).

In the late Eggenburgian (ca. 19 Ma) a rapid transgression connected the Western Paratethys again with the Central Paratethys which led to the establishment of a new marine pathway via the Alpine Foreland Basin into the Rhône Basin (Fig. 2). This narrow connection is called the Burdigalian Seaway and persisted throughout the early Ottnangian (Rögl 1998). Sedimentation during the early Ottnangian was mainly siliciclastic resulting in deposition of the characteristic sandy/silty "Schlier" (Harzhauser & Piller 2007). Widespread tidal-influenced deposits from Eggenburgian to early Ottnangian are reported from the area of the Burdigalian Seaway (Homewood & Allen 1981; Allen & Homewood 1984; Allen et al. 1985; Faupl & Roetzel 1987, 1990; Keller 1989; Tessier & Gigot 1989; Krenmayr 1991; Schaad et al. 1992; Martel et al. 1994; Salvermoser 1999; Bieg 2005). A frequent occurrence of diatomites is documented for the North Alpine Foreland Basin of Lower and Upper Austria and the Carpathians (Kotlarczyk & Kaczmarska 1987; Kotlarczyk 1988; Roetzel et al. 2006). Carbonate deposits like the bryozoan-corallinacean limestones of the Zogelsdorf Formation in Lower Austria are scarce (Piller et al. 2007).

This paleogeographic situation changed distinctly during the late Ottnangian, when the seaways ceased and brackish lakes developed in parts of the North Alpine Foreland Basin and in the Carpathian Foredeep (Rögl 1998).

Regional geology

In the study area along the south-eastern margin of the Bohemian Massif, Paleozoic rocks are overlain by Lower Miocene marine nearshore sediments and a Pleistocene-Holocene cover. The geological situation of this area is shown in detail on the Austrian geological map GÖK22 Hollabrunn (Roetzel et al. 1998; Fig. 3) and has been described by Roetzel (1994, 1996, 2004) and Roetzel et al. (1999a).

The crystalline upland of the Bohemian Massif is bordered against the Miocene sedimentary area in the east by the prominent Diendorf fault zone, which is formed by NE-SW-running subparallel dislocations with sinistral strike-slip character (Roetzel 1996). The morphological slope consists of several steep scarps, numerous spurs and frequent inselberg-like bedrock elevations scattered across the foreland (Roštínský & Roetzel 2005). Close to the main faults, both the crystalline rocks and the bordering sediments of the foredeep are heavily sheared and tectonically displaced.

The crystalline rocks of this area are mostly Paleozoic granites and metamorphic rocks overlain by Lower Miocene (upper Eggenburgian) nearshore sands and gravels of the Burgschleinitz Formation. Above an erosional contact, sandy shallow marine limestones of the Zogelsdorf Formation (lower Ottnangian) were deposited, which laterally and vertically pass into deep-water pelitic sediments of the Zellerndorf Formation. Drillings in this area show a thick-

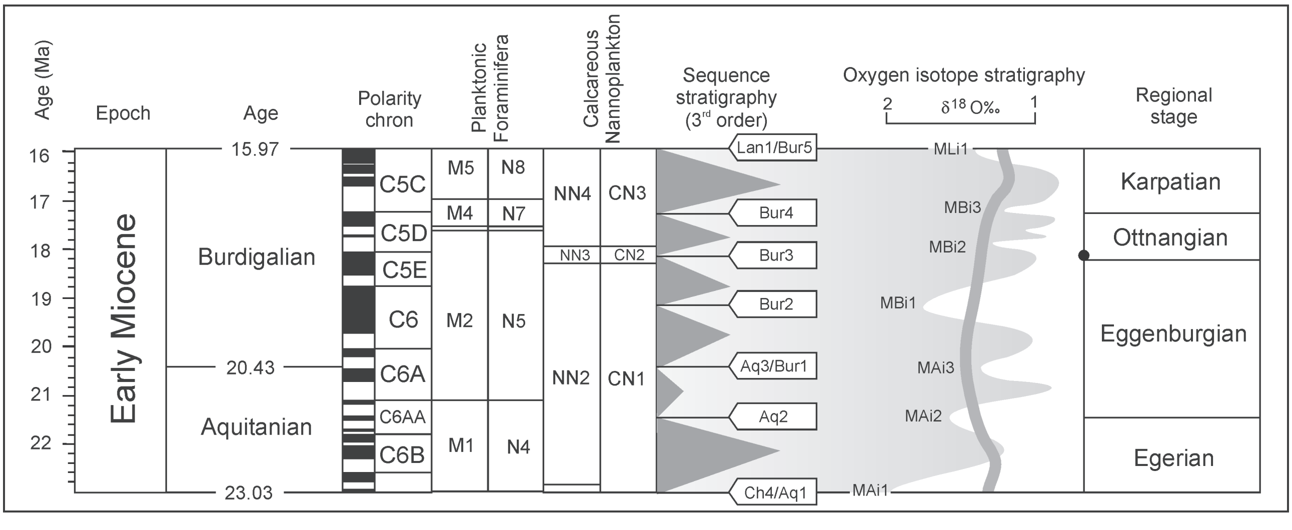

Fig. 1. Lower Miocene stratigraphy for the Paratethys based on Piller et al. (2007). Black dot indicates stratigraphic position of the studied sections. Geochronology, geomagnetic polarity chrons, biozonations of planktonic foraminifers and calcareous nannoplankton after Lourens et al. (2004), sequence stratigraphy and sea-level curve after Hardenbol et al. (1998) and oxygen isotope stratigraphy after Abreu & Haddad (1998).

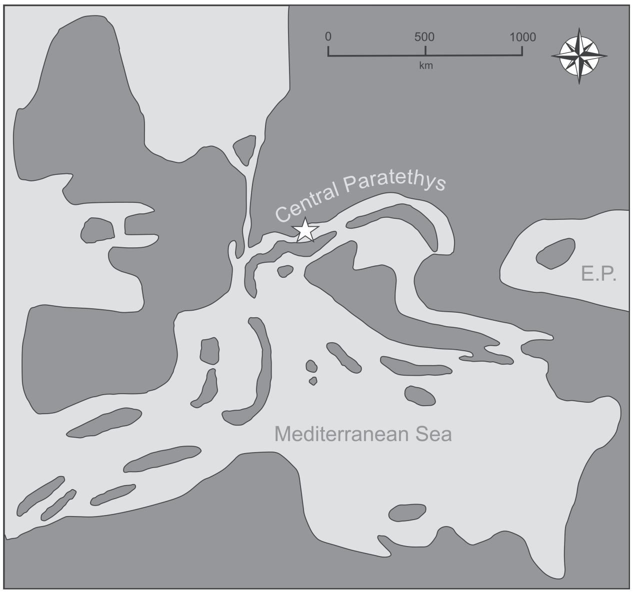

Fig. 2. Paleogeographic sketch-map for the early Ottnangian circum-Mediterranean area based on Rögl (1998). The asterisk indicates the study area. **E.P.** = Eastern Paratethys.

ness of the pelites of about 25–100 m above the Zogelsdorf Formation (Raschka 1912; Roetzel 1994, 1996). In the surroundings of Limberg, Niederschleinz, Oberdürnbach, and Parisdorf, very close to the Diendorf fault scarp, finely laminated diatomites of the Limberg Member are intercalated with the upper part of the Zellerndorf Formation, laterally thinning out towards the east (Roetzel 1996; Roetzel et al. 1999b). In the area of Limberg–Parisdorf the diatomites are at most 5–7.5 m thick. The overlying pelites of the Zellerndorf Formation consist of finely laminated and thin-bedded, bluish-grey, light- and dark-brown, mostly non-calcareous and smectitic silt-clays. They show calcareous layers only immediately above the base of the Zogelsdorf Formation and near the top above the Limberg Member. The Zellerndorf Formation is discontinuously overlain by Lower-Middle Miocene marine and freshwater sediments covered by Pleistocene loess. Most of these formations east of the Diendorf fault are affected by intensive horst-graben tectonics (Fig. 3b).

Studied sites

As the succession of the Zellerndorf Formation and the intercalated Limberg Member from the three investigated outcrops has been described in detail in several earlier studies (e.g. Roetzel et al. 1999b, 2006 and Mandic et al. 2005) only a brief characterization of the localities is given here. Their geographic position and logs are shown in Figs. 3 and 4.

The small natural outcrop Niederschleinz is located in a small ditch NW of the chapel of Niederschleinz. It exposes the transition from pelites into the diatomites and is regarded as representing a more distal facies of the Zellerndorf Formation (Řeháková 1996; Roetzel 1996; Roetzel et al. 2006). Sample NI 1 was taken here (BMN 716906/384548).

The Parisdorf diatomite pit is located 2.5 km ESE of Maissau and about 400 m SE of Parisdorf. It belongs to the Wienerberger AG and is still in use. Diatomites are exposed at the base, followed by pelites of the Zellerndorf Formation. Pelites of the Zellerndorf Formation below the diatomites are known from drillings and the surroundings of the pit which are poor in fossils (Roetzel et al. 1999b). The Neogene sediments are covered by Pleistocene deposits. A detailed characterization of the sediments and tectonics is given in Roetzel et al. (1999b, 2006).

For this study, samples PA 1–PA 8 were taken from the pelites above the diatomites in the eastern part of the pit (BMN 715067/380930–BMN 715075/380937). Additionally, samples from earlier collections (1987, 1994) by R. Roetzel were used for geochemical measurements: Sample 67-1 was taken in the eastern part of the pit about 80 cm above the diatomite. Samples PAR-4 and PAR-5 are from the northern part at about 3.7 m and 7.5 m above the diatomite and have been studied for sedimentology and micropaleontology (calcareous nannoplankton, foraminifers, diatoms, silicoflagellates) by Roetzel et al. (2006). Their relative position to samples PA 1–PA 8 is shown in Fig. 4.

The abandoned Limberg quarry is located NE of the railway station, south of the road to Straning near the Taubenberg hill. Similar to the Parisdorf pit, the finely stratified diatomites of the Limberg Member are exposed at the base, followed by the pelites of the Zellerndorf Formation. There is a sharp contact between them with a distinct change of colour. The greyish pelites are poorly stratified, and their base is non-calcareous. Carbonate content increases upsection and calcareous concretions occur irregularly. The benthic foraminifer *Bathysiphon* is found frequently on the bedding planes. Strong tectonic deformation such as in Parisdorf does not appear. For this study, samples LI 1–LI 5 were taken from the pelites of the Zellerndorf Formation (BMN 716025/384618).

Material and methods

Dinoflagellates

Samples PA 1–PA 8 from Parisdorf and LI 1–LI 5 from Limberg were processed according to standard palynological techniques (Green 2001). A total of 12 rock samples, each weighing 20–30 g, were cleaned, crushed and treated with 38% HCl (cold) to remove carbonates and 48% HF (cold) for two days to remove silicates. The samples were rinsed to neutrality between each step and sieved through a 20 µm nylon sieve (after ultrasonic treatment for 30 seconds). No heavy liquid separation or oxidation treatment was applied. The residue was washed and stained with Safranine "O". Glass slides were prepared from each sample using glycerin jelly and were sealed with nail polish. At least two slides were scanned at a magnification of 400× for the productive samples using a Carl Zeiss microscope (Axioplan 2) fitted with a Leica digital photo camera DFC230. The first 250 dinocyst specimens of each slide were counted and identified to species level whenever possible. Additionally, observations and photographs were made by using a DSM 982 Gemini SEM, operating at a working voltage of 10 to 15 kV.

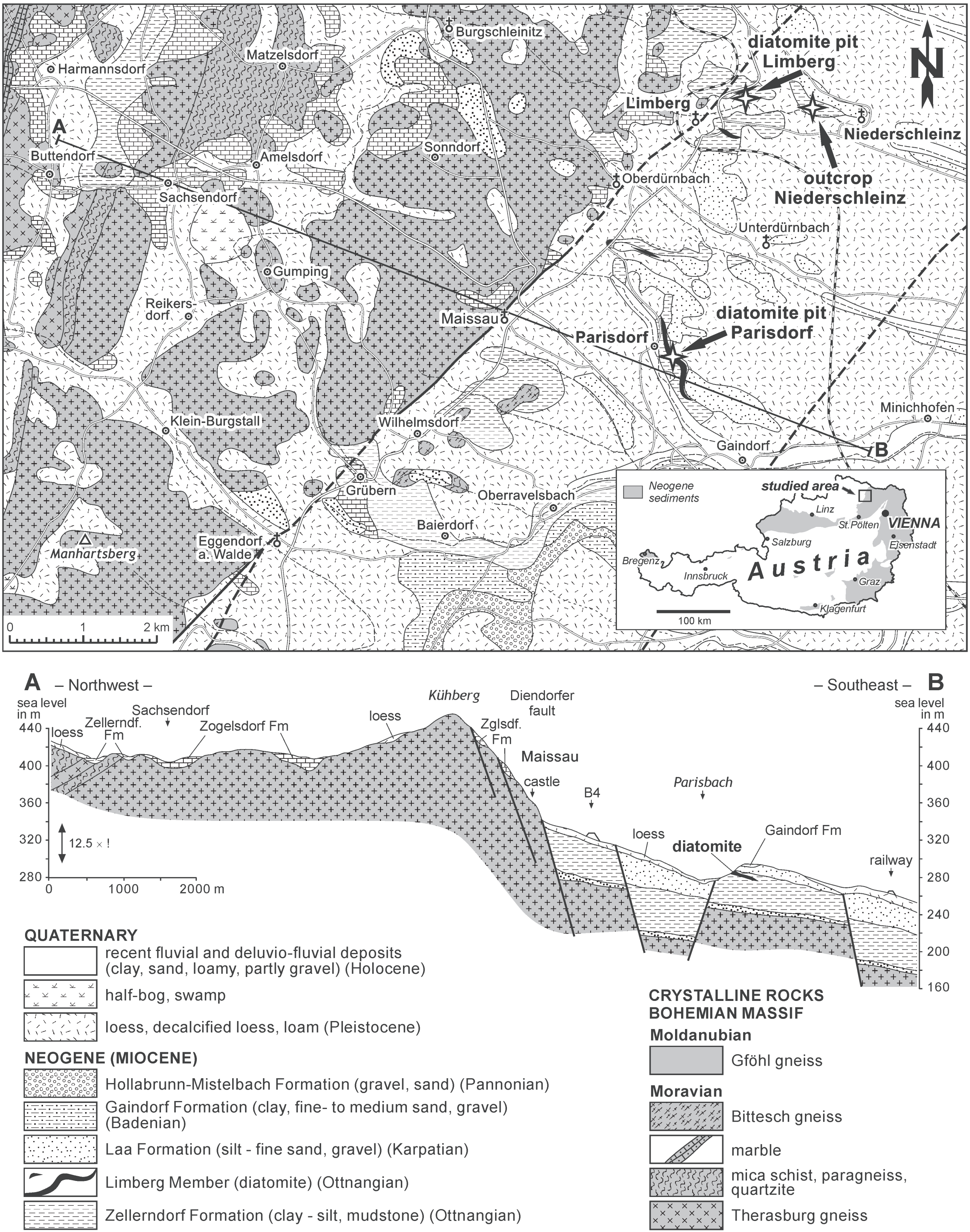

Fig. 3. Geological map (**A**) and cross-section (**B**) of the study area. Arrows in (A) indicate the studied sections Parisdorf, Niederschleinz and Limberg. Modified from Roetzel et al. (2006).

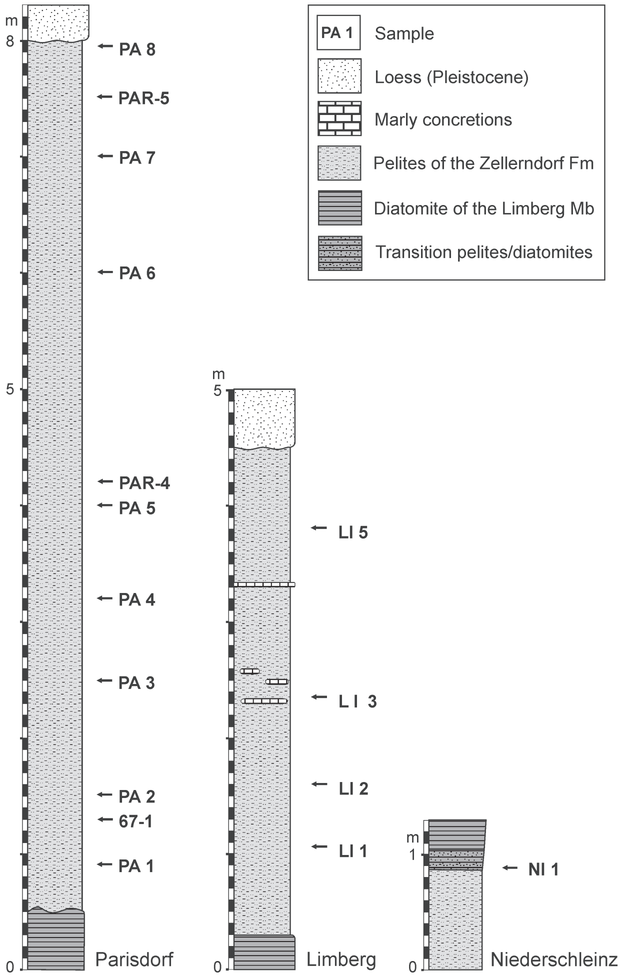

Fig. 4. Logs of the studied sections Parisdorf, Limberg and Niederschleinz.

Stable isotopes

Sample preparation

All samples were dried at 35 °C. 100g of each sample were soaked in diluted H_2O_2 as earlier studies have shown that H_2O_2 does not alter the isotopic composition of foraminiferal tests (Ganssen 1981). Samples were then wet sieved under running water and separated into four size-fractions: 63–150 µm, 150–300 µm, 300–600 µm and >600 µm. The sieved fractions were first put into deionized water and then in undenatured Ethanol.

Thereafter the washed samples were dried at 35 °C again, clean tests of the chosen planktonic and benthic foraminifers were picked from fractions 63–150 µm and 150–300 µm of samples NI 1, PA 1–PA 3 and PAR-4. Between 18 and 55 tests were selected for each measurement, depending on particular species and size. Selected specimens from all the investigated samples were studied under the SEM to exclude a possible influence of diagenesis. All the other samples yielded no (PA 4–PA 8, LI 2, LI 3) or badly preserved and/or diagenetically altered (LI 1, LI 5, PAR-5) specimens.

Isotopic composition of bulk sediment samples PA 1–PA 8, PAR-4, PAR-5, 67-1, LI 1–LI 3 and LI 5 was measured twice for each sample. Therefore sediment of each sample was crushed and homogenized in a mortar.

To compare the revealed bulk sample signal, 24 samples (OS 1–24) from the Ottnangian stratotype section Ottnang-Schanze in Upper Austria have been processed in the same way and were included in the analysis. These sediments are dated to early Ottnangian and are described in Rögl et al. (1973) and Rupp et al. (2008).

Selected foraminiferal species

As mixed-layer dwelling *Globigerina bulloides* is commonly used for isotopic analysis it seemed reasonable to pick closely related *Globigerina lentiana* and *Globigerina praebulloides* from all suitable samples (Fig. 5). Additionally, *Globigerina ottnangiensis* was picked from sample PAR-4.

Besides globigerinids, mass occurrences of small microperforate tenuitellids characterize the samples (Roetzel et al. 2006). Although not commonly used in isotopic studies and thus expected to be difficult to interpret, specimens of *Tenuitella clemenciae* were picked from sample PA 1 in order to provide additional planktonic data.

Selecting benthic foraminifers was limited by the fact that the samples usually contained very small specimens showing high species diversity but low total numbers. Thus, only infaunal species *Bulimina striata striata*, *Melonis pompilioides*, *Myllostomella advena*, *Myllostomella recta*, *Pullenia bulloides* and *Siphonodosaria consobrina* were picked from samples NI 1 and PAR-4. Although their isotopic signal was expected to be influenced by synsedimentary pore water, a comparison of the two samples should be possible after careful consideration of vital effects.

Stable isotope measurements

Isotopic analyses on foraminifers and bulk sediment samples from NI 1, PA 1–PA 8 and LI 1–LI 5 were performed at the Institute of Earth Sciences at the University of Graz, using an automatic Kiel II preparation line and a Finnigan MAT Delta Plus mass spectrometer. Samples were dried and reacted with 100% phosphoric acid at 70 °C. Analytical precision, based on replicate analysis of international standards NBS-19 and NBS-18 and an internal laboratory standard is better than 0.08 ‰ for $\delta^{18}O$ and 0.04 ‰ for $\delta^{13}C$. Results are reported in conventional δ notation relative to the Vienna Pee Dee Belemnite standard (VPDB) in ‰ units.

Foraminifers from NI-1 and PAR-4 as well as the bulk sediment samples from Ottnang-Schanze were measured for $\delta^{13}C$ and $\delta^{18}O$ values at the Joanneum Research in Graz. The setup of the analytical system combines a continuous-flow isotope-ratio mass spectrometer (Finnigan DeltaplusXP) with a ThermoFinnigan GasBench II equipped with a CTC Combi-Pal autosampler. A comparable experimental setup has been used in other studies (Spötl & Vennemann 2003). The samples and two international reference materials (NBS-19, IAEA-CO-8) were simultaneously analysed by using the phosphoric acid method at a T = 75 °C. The isotope values of the samples are

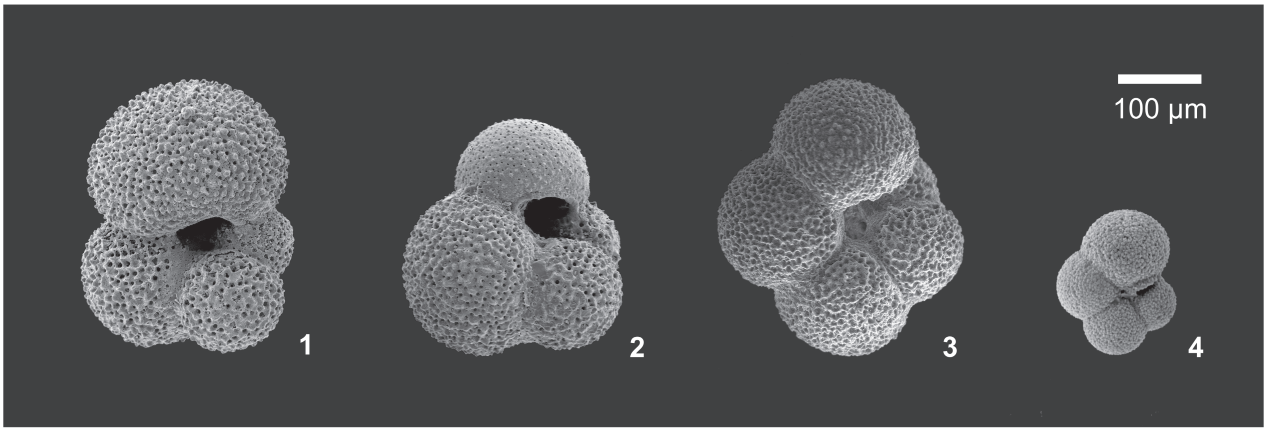

Fig. 5. Studied planktonic foraminifers. **1** — *Globigerina praebulloides*, sample PA 1, 450×; **2** — *Globigerina lentiana*, sample PA 1, 250×; **3** — *Globigerina ottnangiensis*, sample PAR-4, 250×; **4** — *Tenuitella clemenciae*, sample PA 1, 400×.

given relative to the VPDB-standard (Coplen 1996). For replicate measurements of different aliquots of samples the overall error of reproducibility is <0.15 ‰ (VPDB) for both δ^{13}C and δ^{18}O values.

Results

Dinoflagellates and other palynomorphs

The investigated samples PA 8 from Parisdorf and all Limberg samples revealed dinoflagellate cysts (Table 1). The dinoflagellate cysts are well preserved but the assemblages are rather poor and dominated by few taxa. The samples mainly consist of *Cleistosphaeridium* spp. together with common occurrences of *Lingulodinium machaerophorum*, *Operculodinium centrocarpum*, *Lejeunecysta* spp. and *Brigantedinium* spp.

Besides dinocysts, other palynomorphs have been encountered in samples PA 8 and LI 1–LI 5 consisting of sporomorphs (*Pinus*, *Cathaya*, *Abies*, *Picea*, *Acer*) and the prasinophycean chlorophyte *Pterospermella*. In samples LI 1 and LI 2 organic wall morphotypes resembling *Glomus* have been found in considerable numbers (Fig. 6.9–12). All other samples are barren of palynomorphs.

Table 1: Dinoflagellate cysts and other palynomorphs revealed from the studied Limberg (LI) and Parisdorf (PA) samples. The first 250 specimens were counted from each sample. Abundant (a): >20; common (c): 5–20; rare (r): 2–4; single (s): 1.

Species	Samples				
	PA 8	**LI 1**	**LI 2**	**LI 3**	**LI 5**
Cleistosphaeridium spp.	a	a	a	a	a
Lingulodinium machaerophorum	c		c	c	a
Spiniferites/Achomosphaera spp.		r		r	r
Lejeunecysta spp.	c		c	r	
Brigantedinium spp.			s	c	
Operculodinium centrocarpum		s	r		c
Trinovantedinium sp.			s		
Pentadinium laticinctum		s			r
Pterospermella spp.				r	c
Pollen	a	a	a	c	a
Fungal spores	c	a	c	c	c

Stable isotopes

Foraminifers

The results for all 19 measurements are summarized in Table 2. δ^{18}O values for all planktonic foraminifers are negative and vary between −1.46 ‰ and −0.56 ‰. With respect to globigerinids, *G. lentiana* always shows slightly higher values than *G. praebulloides* of the same test size and sample (mean offset: +0.12 ‰ for fraction 150–300 µm; +0.09 ‰ for fraction 63–150 µm). *G. ottnangiensis* shows significantly lower values in sample PAR-4 than *G. praebulloides*. *T. clemenciae* revealed the highest value (−0.76 ‰) within sample PA 1.

δ^{13}C values for planktonic tests are also negative in all samples ranging from −1.52 ‰ to −0.03 ‰. *G. lentiana* shows on average slightly lower values in their δ^{13}C signal than *G. praebulloides* of the same test size and sample values (mean offset: −0.29 ‰ for fraction 150–300 µm; −0.05 ‰ for fraction 63–150 µm). An offset between larger and smaller tests in *G. lentiana* (mean: +0.13 ‰) and *G. praebulloides* (mean: +0.34 ‰) can be observed for all the samples. *T. clemenciae* shows the highest value (−0.8 ‰) within sample PA 1.

With respect to benthic foraminifers, *Siphonodosaria consobrina* from sample NI 1 revealed the only positive values in all measured species and thus shows highest values in both δ^{18}O and δ^{13}C (0.72 ‰ and 0.47 ‰). *Myllostomella recta* occurs in both samples and shows the most negative δ^{18}O and δ^{13}C values of all benthic species. A significant offset of at least −1 ‰ for both values from all other benthic species is documented. The intra-specific offset in *M. recta* between samples NI 1 and PAR-4 is −0.29 ‰ in δ^{18}O and −1.02 ‰ in δ^{13}C.

Bulk samples

Bulk samples for Parisdorf show negative δ^{18}O values ranging from −5.81 ‰ to −2.57 ‰ (Table 3). Whereas samples PA 1–PA 7, PAR-4, PAR-5 and 67–1 range within a mean offset of 1.2 ‰ without showing a clear trend, sample PA 8 differs at least in one measurement very distinctly.

The δ^{13}C-record for the bulk samples revealed values ranging from −0.99 ‰ to +0.09 ‰ for Parisdorf. Samples

Table 2: δ^{18}O and δ^{13}C values of the planktonic and benthic foraminifers measured within the present study. All isotopic values are given in ‰ VPDB.

Locality	Sample	Species	Grain-size fraction	No.	δ^{18}O	δ^{13}C
Planktonic foraminifers						
Parisdorf	PA 1	*Globigerina lentiana*	150–300	27	–1.36	–1.50
		Globigerina praebulloides	150–300	25	–1.43	–1.22
		Globigerina lentiana	63–150	45	–0.99	–1.52
		Globigerina praebulloides	63–150	55	–1.08	–1.40
		Tenuitella clemenciae	63–150	46	–0.76	–0.80
	PA 2	*Globigerina praebulloides*	63–150	50	–1.46	–1.35
	PA 3	*Globigerina lentiana*	150–300	30	–0.67	–0.9
		Globigerina praebulloides	150–300	30	–0.95	–0.84
		Globigerina lentiana	63–150	34	–0.72	–1.15
		Globigerina praebulloides	63–150	50	–0.81	–1.18
	PAR-4	*Globigerina ottnangiensis*	150–300	30	–1.40	–0.32
		Globigerina praebulloides	150–300	40	–0.56	–0.03
Benthic foraminifers						
Niederschleinz	NI 1	*Bulimina striata striata*	150–300	35	–0.28	–0.35
		Melonis pompilioides	150–300	19	–0.48	–0.34
		Myllostomella recta	63–150	33	–1.82	–1.39
		Pullenia bulloides	150–300	20	–0.45	–1.07
		Siphonodosaria consobrina	150–300	25	0.72	0.47
Parisdorf	PAR-4	*Myllostomella advena*	63–150	42	–1.16	–1.46
		Myllostomella recta	63–150	51	–2.11	–2.41

Table 3: δ^{18}O and δ^{13}C values of the bulk samples measured within the present study. All isotopic values are given in ‰ VPDB.

Locality	Sample	δ^{18}O	δ^{13}C
Parisdorf	PA 1	–3.5	–1.09
	PA 2	–3.3	–0.53
	PA 3	–2.65	–0.65
	PA 4	–3.12	–0.53
	PA 5	–3.08	–0.35
	PA 6	–2.77	0.03
	PA 7	–2.88	–0.37
	PA 8	–4.5	–3.79
	PAR-4	–3.01	–0.79
	PAR-5	–3.73	–2.72
	67–1	–3.11	–0.44
Limberg	LI 1	–3.47	–0.89
	LI 2	–2.22	0.37
	LI 3	–4.08	–3.69
	LI 5	–6.9	–8.55
Niederschleinz	NI 1	–3.12	–0.54
Ottnang–Schanze	OS 1	–4.79	–0.08
	OS 2	–5.31	–0.2
	OS 3	–5.11	0.4
	OS 4	–4.83	0.02
	OS 5	–4.81	0.06
	OS 6	–5.1	–0.25
	OS 7	–4.93	0.22
	OS 8	–4.83	0.12
	OS 9	–4.95	0.26
	OS 10	–5.13	–0.16
	OS 11	–3.96	0.32
	OS 12	–4.84	0.27
	OS 13	–5.15	0.57
	OS 14	–4.64	0.69
	OS 15	–4.63	0.68
	OS 16	–5.24	0.5
	OS 17	–4.98	0.19
	OS 18	–4.76	0.34
	OS 19	–5.11	0.17
	OS 20	–5.47	0.32
	OS 21	–4.42	0.57
	OS 22	–4.53	0.51
	OS 23	–4.8	0.46
	OS 24	–4.71	0.36

PAR-5 and PA8 yielded the lowest values, the later was aberrantly low (−8.55 ‰).

Niederschleinz revealed values similar to Parisdorf ranging from −33 ‰ to −91 ‰ for δ^{18}O and −62 ‰ to −46 ‰ for δ^{13}C.

The samples from Ottnang-Schanze show values from −5.47 ‰ to −3.96 ‰ (mean: −4.88 ‰) and δ^{13}C values ranging from −0.25 ‰ to +0.69 ‰ (mean: +0.26 ‰).

Discussion

Dinoflagellates

Recent upwelling areas are known to be dominated by heterotrophic dinoflagellates which feed on the highly abundant diatoms (e.g. Zonneveld et al. 2001; Sprangers et al. 2004). Frequent taxa reported from areas of seasonal coastal upwelling include *Brigantedinium* spp., *Operculodinium centrocarpum*, *Lingulodinium machaerophorum* and different *Spiniferites* species (De Vernal & Marret 2007), all of which are present in the samples of this study.

Several studies have shown that the presence of *Lingulodinium machaerophorum* in shelf sediments correlates with nutrient enriched waters (e.g. Wall et al. 1977; Dale 1996; Targarona et al. 1999). In the current study, the occurrence of *L. machaerophorum* is in some samples positively correlated with the abundance of protoperidinioid dinoflagellate cysts as *Lejeunecysta*, *Brigantedinium* and *Trinovantedinium* which also indicate elevated nutrient levels (e.g. Wall et al. 1977; Bujak 1984; Lewis et al. 1990; Powell et al. 1990).

The dominant taxon in the studied assemblages is *Cleistosphaeridium*. Although common in the fossil record, the paleo-autecology of this genus is still poorly understood. According to Brinkhuis (1994) and Sluijs et al. (2005) high numbers of *C. placacanthum*, *C. ancyreum* and *C. diversispinosum* suggest a distal shelf environment.

An estimation of sea-surface temperatures is not possible as the encountered dinocysts occur over a very broad range of temperatures. For example, recent *L. machaerophorum* is a temperate to tropical, euryhaline species present in regions where water-temperature ranges from –1.5 °C winter SST to 29.1 °C summer SST (Marret & Zonneveld 2003).

Some specimens of *Lingulodinium machaerophorum* with reduced processes (Fig. 6.2–3) have been revealed from the lower part of the Limberg section. The occurrence of such morphotypes has often been linked to reduced salinity (Head et al. 2005; Head 2007). However, a major change in salinity seems unlikely for the studied sections as the stable isotope data clearly contradict this idea by showing no distinct trend.

Other palynomorphs

Pollen of *Pinus*, *Cathaya*, *Abies*, *Picea* and *Acer* as well as fungal spores of *Glomus* have been encountered in the studied samples (Table 1). Given the idea of a distal upwelling setting as indicated by dinoflagellate cysts and mass occurrences of planktonic foraminifers (Roetzel et al. 2006), their occurrence appears enigmatic at first. However, palynological studies have shown that pollen grains can be transported by winds and ocean currents dozens of kilometers off the coast (e.g. Hooghiemstra et al. 2006). As strong winds and current patterns are dominant features of upwelling sites, an aeolian transport of the herein revealed pollen seems most likely. Input by river-transport can be excluded as freshwater indicators like the algae *Pediastrum* are absent in all samples (whereas marine prasinophyceaean algae are present) and no river sediments are known from the study area.

Recent *Glomus* is associated with plant roots and synonymized with the fossil fungal spore *Palaeomyces*. The uncompressed nature, clustering and abundance of arbuscular mycorrhizal hyphae preserved in the association together with the outcrop situation strongly point to a post-depositional origin of these fungal spores.

Planktonic foraminifers

Stable isotope values of globigerinid foraminifers as indicator for coastal upwelling

Surface waters in upwelling areas show a characteristic isotopic signal (e.g. Steens et al. 1992; Wefer et al. 1999; Peeters et al. 2002): high δ^{18}O values reflect low temperatures, low δ^{13}C values result from strong mixing with cold nutrient-rich deeper waters depleted in ^{13}C. This characteristic isotopic composition should be reflected in tests of organisms which calcify in such an environment. A number of studies have shown this with recent and fossil foraminifers (e.g. Faul et al. 2000; Peeters et al. 2002).

The results of the globigerinid foraminiferal tests in the present study show values that are in good agreement with coastal upwelling: δ^{18}O values vary between –46 ‰ and –56 ‰, δ^{13}C ratios range from –1.52 ‰ to –0.03 ‰. When the data are plotted together with Miocene to recent data of the same or closely related species (Vergnaud-Grazini 1978; Šutovská & Kantor 1992; Pearson et al. 1997; Faul et al. 2000; Peeters et al. 2002; Báldi 2006), a relation with upwelling areas is obvious (Fig. 7). This plot also shows that in fact the carbon isotope values are the main indicator for upwelling as they point to mixing of the surface water with nutrient rich bottom water. Temperature is known to be one of the most important factors for the distribution of foraminifers (Schiebel & Hemleben 2005). Therefore, tests of the same species from different areas should provide similar δ^{18}O values. Fig. 7 shows this effect for *G. praebulloides* from our Ottnangian samples and the samples of non-upwelling areas in the Central Paratethys, the Mediterranean and the Atlantic seas (Vergnaud-Grazini 1978; Šutovská & Kantor 1992; Pearson et al. 1997).

Low δ^{13}C ratios can also be caused by freshwater input of nearby rivers. This is very unlikely for the present case as there is no evidence of an ancient river in the sedimentary record around the study area. Additionally, the fresh water influx would distinctly lower oxygen isotope values.

Sea surface temperatures

As δ^{18}O ratios are mainly determined by water temperature, they can be used to calculate absolute water temperatures. The classic notation for this purpose was defined by Epstein et al. (1953) based on molluscs. Up to now, several equations for tests of different benthic and planktonic foraminifers were developed (see Bemis et al. 1998 for a summary). The notation of Shackleton (1974) based on uvigerinids has become the most popular:

$$T = 16.9 - 4.38x(\delta^{18}O_c - \delta^{18}O_w) + 0.1x(\delta^{18}O_c - \delta^{18}O_w)^2 \qquad (1)$$

where T is temperature in °C, $\delta^{18}O_c$ the composition of the shell carbonate and $\delta^{18}O_w$ is the composition of the water in which the carbonate was precipitated.

Species specific vital effects result in offsets in the isotopic composition of the test compared to the surrounding water (e.g. Peeters et al. 2002). The problem with extinct foraminifers is that the influence of vital effects on their shell composition remains unknown. One possibility to deal with this problem is an actualistic approach.

The globigerinids used in this study, *Globigerina lentiana* and *Globigerina praebulloides*, are both closely related to *Globigerina bulloides* (Kennett & Srinivasan 1983). Therefore, the use of the equation developed by Bemis et al. (1998) seems more reasonable for calculating water temperatures from these species:

$$T = 13.2 - 4.89x(\delta^{18}O_c - \delta^{18}O_w) + 0.27x(\delta^{18}O_c - \delta^{18}O_w)^2 \qquad (2)$$

All temperature equations take into account the δ^{18}O composition of the surrounding seawater ($\delta^{18}O_w$). Today the sea-

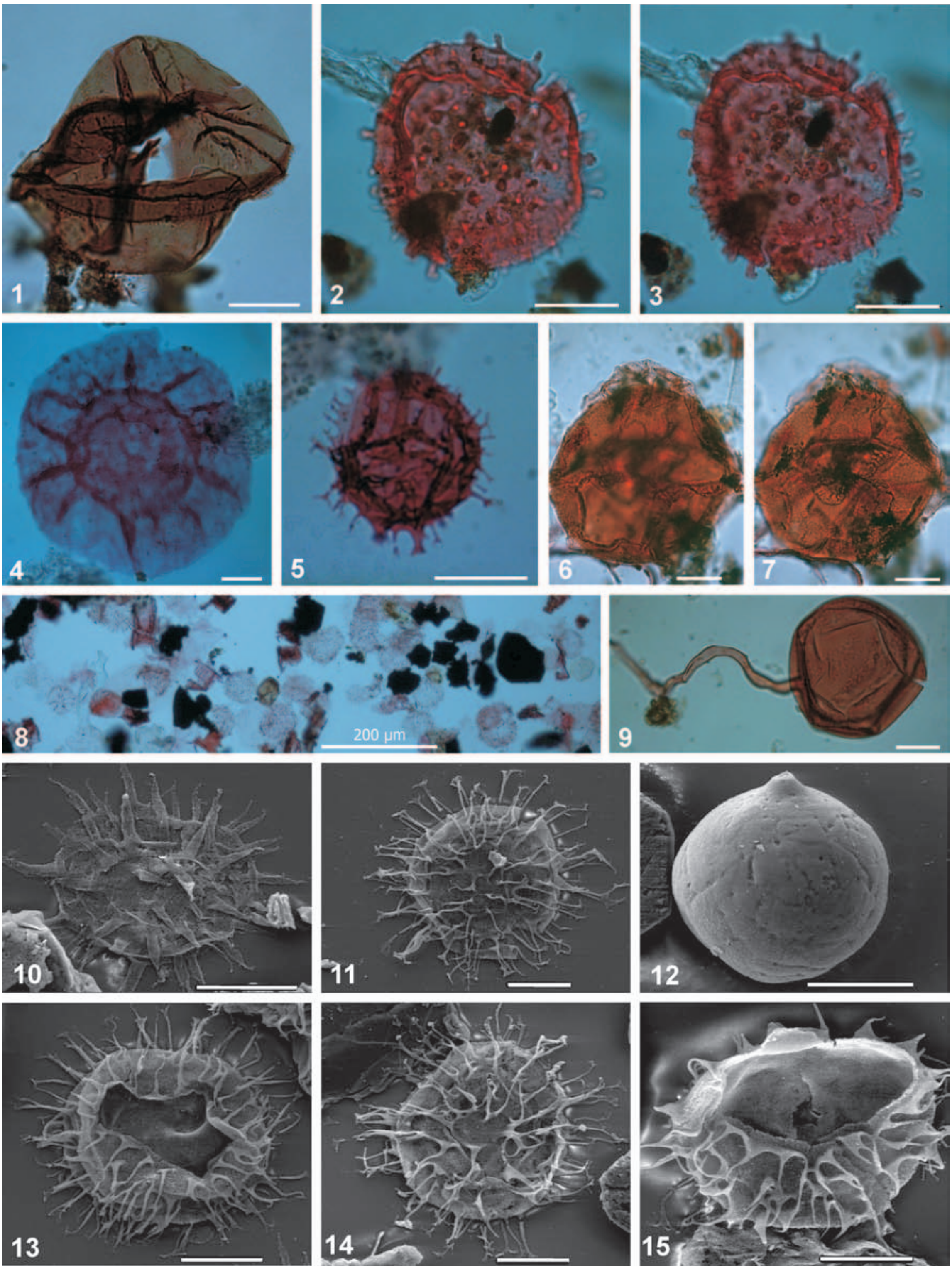

Fig. 6. Dinoflagellate cysts and fungal spores. Photomicrographs are bright field (1–9) and scanning electron microscope (10–15); scale bar is 20 µm except where noted: **1** — *Lejeunecysta paratenella*; dorsal view, sample LI 2; slide B; England Finder T45. **2–3,10** — *Lingulodinium machaerophorum*; 2–3 — uncertain orientation of the same specimen with short processes (bulbous); different foci; sample LI 2; slide B (2–3); uncertain orientation of specimen with long processes; sample PA 8 (10). **4** — *Pterospermella* sp., sample LI 3, slide B, England Finder K38. **5** — *Spiniferites* sp., sample LI 3, slide B, England Finder S34/4. **6–7** — *Pentadinium laticinctum*, sample LI 1, slide C, England Finder S51, ?ventral view different foci. **8** — Clusters of *Cleistosphaeridium* spp.; sample PA 8; slide B. **9, 12** — *Glomus* spp., sample LI 1; slide B; England Finder J39 (9) and SEM from sample PA 8 (12). **11** — *Cleistosphaeridium diversispinosum*; uncertain orientation; sample PA 8. **13–14** — *Cleistosphaeridium ancyreum*; specimen in apical view (9) showing the archeopyle; sample PA 8 (9) and uncertain orientation of specimen from sample PA 8. **15** — *Cleistosphaeridium placacanthu*m; oblique apical view; sample PA 8.

water has a mean $\delta^{18}O$ composition of 0 ‰ (SMOW), but this value can vary locally due to evaporation or mixing with fresh water. For example, a $\delta^{18}O_w$ of +1 ‰ is reported for the Mediterranean (Pierre 1999) and +2 ‰ for the Red Sea (Craig 1966). Thus, $\delta^{18}O_w$-values are not the same for all oceans and they are not constant in time. Lear et al. (2000) suggest a globally averaged $\delta^{18}O_w$ of ca. −1 ‰ for the Early Miocene based on Mg/Ca ratios of benthic foraminifers. Harzhauser et al. (2007) showed that this value is in good agreement with Early Miocene mollusc data from the Central Paratethys. As all results of this study are given relative to VPDB, the $\delta^{18}O_w$ value has to be converted to VPDB by −0.27 ‰ according to Hut (1987).

Based on these assumptions, temperature estimates for globigerinid species vary between 10–14 °C for an assumed $\delta^{18}O_w$ of −1 ‰ in most samples from the Parisdorf section which is in good accordance with reported estimates based on microfaunal assemblage composition (Table 4; Roetzel et al. 2006).

For reasons of comparison, temperatures were also calculated with the commonly used equation established by Shackleton (1974). The resulting values exceed the calculations based on Bemis et al. (1998) by 3–4 °C and clearly contradict all other proxies (Table 4). As this equation has been derived from benthic uvigerinids, its application to planktonic foraminifers seems inappropriate.

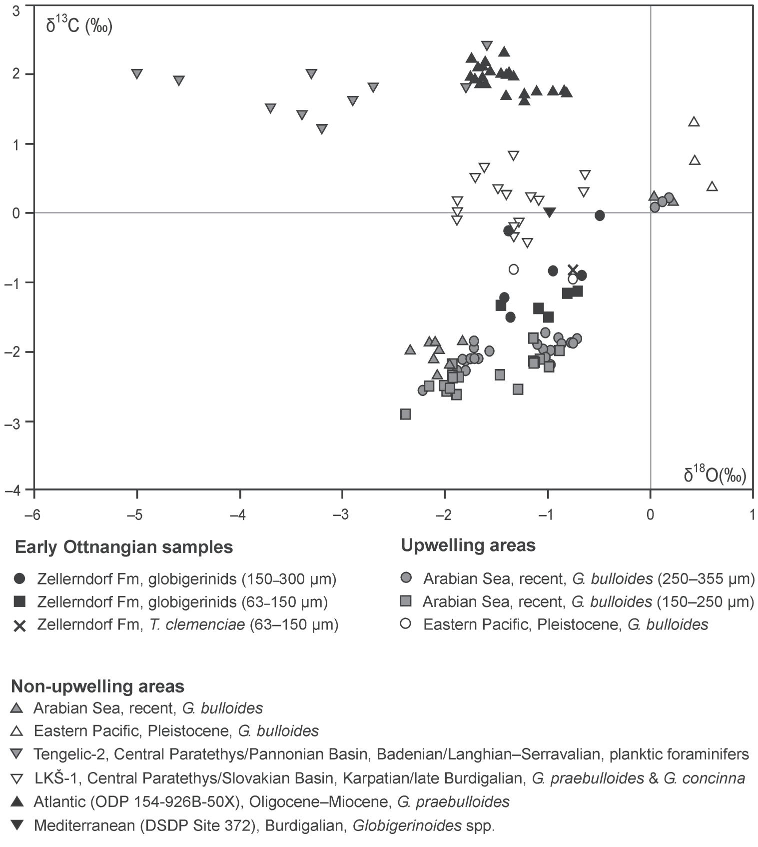

Fig. 7. $\delta^{18}O$ vs. $\delta^{13}C$ plot of the globigerinids (*Globigerina lentiana*, *G. ottnangiensis*, *G. praebulloides*) from the Ottnangian samples compared to data-sets from recent upwelling and non-upwelling areas. Numbers in brackets give sieved fraction in µm; isotopic values are given in ‰ VPDB. Data for Arabian Sea from Peeters et al. (2002), Eastern Pacific from Faul et al. (2000), Tengelic-2 (Hungary) from Báldi (2006), LKŠ-1 (Slovak Basin) from Šutovská & Kantor (1992), DSDP-data (Mediterranean) from Vergnaud-Grazini (1978) and ODP-data (Atlantic) from Pearson et al. (1997).

Depth habitats

As water temperature decreases with depth, $\delta^{18}O$ data can be used to determine depth habitats for different species of foraminifers (Niebler et al. 1999). In the present study, *Tenuitella clemenciae* from sample PA 1 shows the highest values (−0.76 ‰; mean offset to all globigerinids from the Parisdorf section: +0.46 ‰; mean offset to globigerinids with test size 0.063 µm: +0.28 ‰) indicating that this species lived deeper in the water column than the globigerinids. This corresponds well with published data of recent tenuitellids (Li et al. 1992, 1999).

Benthic foraminifers

As benthic foraminifers occupy ecological niches on and within the sediment their geochemical signal is influenced by the pore-water circulating in the sediment. This “microhabitat-effect” has been documented in countless studies and can alter the $\delta^{13}C$ signal significantly compared to the $\delta^{13}C$ of bottom water dissolved inorganic carbon ($\delta^{13}C_{DIC}$; e.g. Mackensen et al. 2000; Fontanier et al. 2006). Additionally, as in planktonic foraminifers, the geochemical signal in benthic foraminifers is altered by diverse vital effects. Thus, a summary of the current knowledge on the geochemistry and ecology of the benthic species referred to in this study is given in Table 5 together with the corrected isotopic values for the different benthic foraminifers and for *Globigerina praebulloides* from this study.

For sample NI 1, the corrected values fit quite well, especially for the $\delta^{18}O$ values. Assuming that the corrected $\delta^{18}O$ values for *B. striata striata*, *M. pompilioides* and *P. bulloides* (mean: −0.07 ‰) represent bottom water conditions we can assume a correction factor of +1.75 ‰ for *Myllostomella recta* resulting of −0.36 ‰ for sample PAR-4. The slight offset of +0.45 ‰ to the corrected *G. praebulloides*-value of the same sample indicates a low temperature gradient and strong mixing of the water column. Applying the above-mentioned equation of Shackleton (1974) based on *Uvigerina* (which is supposed to be in equilibrium with bottom waters) calculations suggest 11–12 °C bottom water temperature for Niederschleinz and 13 °C for Parisdorf (Table 4).

The ecological preferences of the investigated taxa clearly point to high productivity in the upper water-column: e.g. *Melonis* and *Bulimina* are regarded as “high-productivity” taxa (Caralp

Table 4: Temperature calculations from tests of the planktonic foraminifers *Globigerina lentiana* and *G. praebulloides* and benthic foraminifers based on the equations of (1) Shackleton (1974) and (2) Bemis et al. (1998). A value of −1 ‰ is assumed for $\delta^{18}O_w$ according to Harzhauser et al. (2007). For details see text.

Sample	Species	Grain-size fraction	$\delta^{18}O$	T (°C) [1]	T (°C) [2]
Planktonic foraminifers					
PA 1	*Globigerina lentiana*	150–300	–1.36	17	14
PA 1	*Globigerina praebulloides*	150–300	–1.43	18	14
PA 1	*Globigerina lentiana*	63–150	–0.99	16	12
PA 1	*Globigerina praebulloides*	63–150	–1.08	16	12
PA 2	*Globigerina praebulloides*	63–150	–1.46	18	14
PA 3	*Globigerina lentiana*	150–300	–0.67	14	10
PA 3	*Globigerina praebulloides*	150–300	–0.95	16	12
PA 3	*Globigerina lentiana*	63–150	–0.72	15	11
PA 3	*Globigerina praebulloides*	63–150	–0.81	15	11
PAR-4	*Globigerina praebulloides*	150–300	–0.56	14	10
Benthic foraminifers					
NI 1	*Bulimina striata striata*	150–300	–0.18	12	–
	Melonis pompilioides	150–300	0.02	11	–
	Pullenia bulloides	150–300	–0.05	12	–
PAR-4	*Myllostomella recta*	63–150	–0.36	13	–

Table 5: Microhabitat effect of the stable isotope composition of the studied benthic foraminifers and *Globigerina praebulloides* as revealed by different studies. In case of more than one correction value a mean value was calculated. Asterisks indicate estimates based on the genus level. Only large tests of *G. praebulloides* were used except for sample PA 2. References: (1) Naidu et al. (2004); (2) Mackensen et al. (2000); (3) McCorkle et al. (1990); (4) Grossman (1987).

Species	$\delta^{18}O–\delta^{18}O_{eq}$	$\delta^{13}C_{DIC}$	Sample	$\delta^{18}O_{corr}$	$\delta^{13}C_{corr}$	Ref.
Globigerina praebulloides	+0.25 *		PA 1	–1.68	–	1
			PA 2	–1.71	–	
			PA 3	–1.20	–	
			PAR-4	–0.81	–	
			LI 1	–2.53	–	
Bulimina striata striata	–0.1 *	–0.8 *	NI 1	–0.18	–	2, 3
Melonis pompilioides	–0.5	–0.3	NI 1	+0.02	–0.04	4
Pullenia bulloides	–0.4		NI 1	–0.05	–	4

1989; Murray 2006; Smart et al. 2007). As the studied foraminifers are the most abundant benthic species within the samples their stable isotope signals seem to be reliable and in good accordance with a proposed upwelling setting.

The bulk sample record

Recent studies have shown that bulk sediment signal roughly reflects the isotopic composition of coccoliths and thus gives additional information about surface water conditions (e.g. Minoletti et al. 2001; Kováčová et al. 2008). Influence of meteoric and pedogenic diagenesis is reflected in aberrantly light isotope values (Armstrong-Altrin et al. 2009). Thus, Parisdorf samples PAR-5 and PA 8 as well as all Limberg samples are excluded from analysis.

For the Lower Austrian study area the remaining samples show rather similar values without a distinct trend (mean values: −3.05 ‰/−0.52 ‰; Fig. 8). Compared to Ottnang-Schanze with mean values of −4.88 ‰ and +0.26 ‰, both signals show a clear offset (+1.75 ‰ for $\delta^{18}O$/−0.78 ‰ for $\delta^{13}C$; Fig. 9). The higher $\delta^{18}O$ and lower $\delta^{13}C$ thus point to lower SSTs and higher bioproductivity for Parisdorf and Niederschleinz.

The multi-proxy approach

Only a multi-proxy approach can lead to a reliable identification of upwelling events in the sedimentary record (Peterson et al. 1995). Consequently, all available data from the herein studied sections shall be discussed in particular for coastal upwelling (see Table 6 for a summary).

Upwelling conditions for the Zellerndorf Formation and the diatomitic Limberg Member were originally suggested on the basis of microfossil analyses (Řeháková 1994, 1996; Mandic et al. 2005; Roetzel et al. 2006): assemblages of calcareous nannoplankton, diatoms, silicoflagellates, sponge spicules and foraminifers point to a nutrient-rich, highly productive environment. SST-estimates range from 10–15 °C. The isotopic data revealed in the present study fit very well with these proxies.

Referring to paleobiogeography, Roetzel et al. (2006) pointed out that the composition of foraminiferal communities in the study area differs clearly from the common early Ottnangian assemblages described from Upper Austria (Rupp et al. 2008) and Bavaria (Wenger 1987) indicating special oceanographic conditions.

On the macrofossil level, palm leaves (Berger 1955), fish (Bachmayer 1974), insects (Bachmayer 1974), birds (Bachmayer 1980), crabs (Bachmayer 1983) and bladder wrack (Mandic et al. 2005) have been documented for the Limberg Member from different localities in Lower Austria. Plant debris and fish teeth have been reported from the Zellerndorf Formation in the Parisdorf pit (Mandic et al. 2005). With respect to environmental conditions, the high number of fish remains (scales and teeth as well as whole specimens) indicates a very productive setting attracting fish swarms. Layers

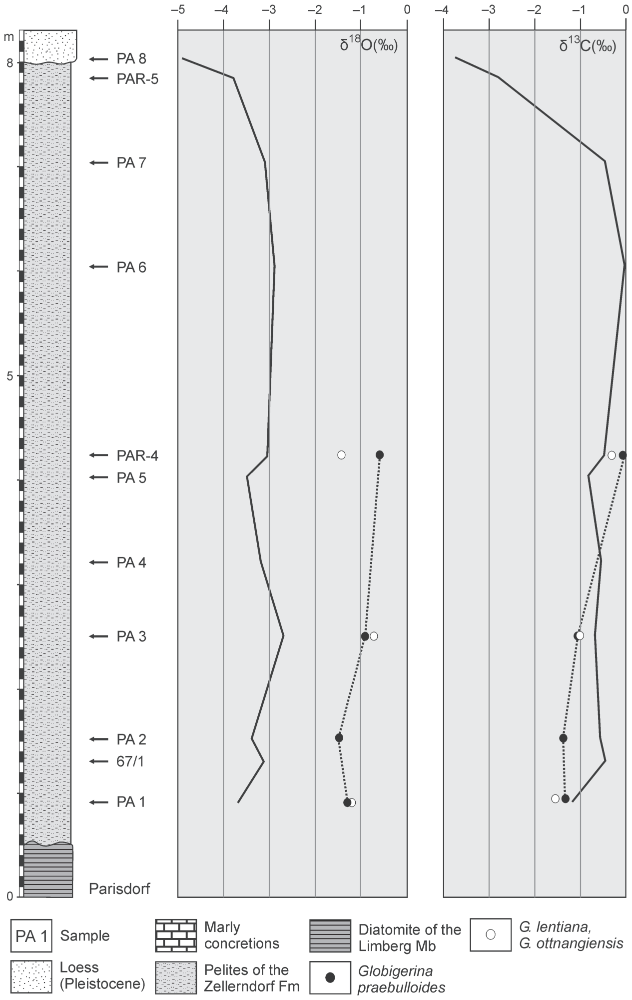

Fig. 8. Trends in $\delta^{18}O$ and $\delta^{13}C$ revealed from bulk samples (solid lines) and planktonic foraminifers for the Parisdorf section. Dotted line shows trend for *Globigerina praebulloides.*

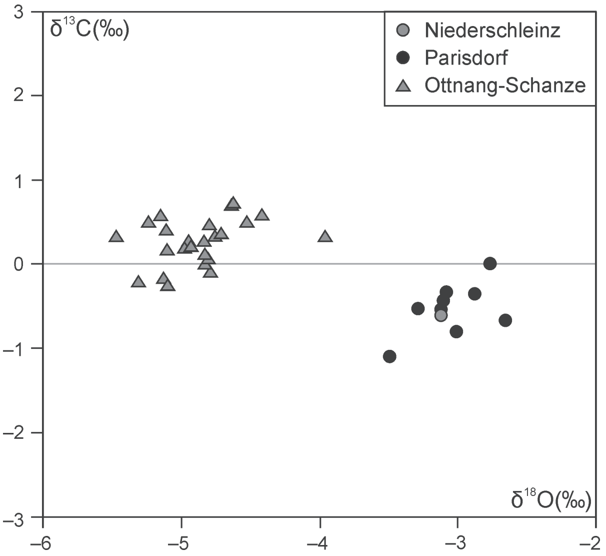

Fig. 9. Comparison of $\delta^{18}O$ and $\delta^{13}C$ for bulk sediment samples from Lower and Upper Austria. Note that the samples PAR-5 and PA 8 and all Limberg samples are not included due to diagenesis.

with masses of fish scales are also a typical feature in coeval well-cores and point to a widespread phenomenon (personal observation F. Rögl). Two brachyuran specimens assigned to the family Geryonidae by Bachmayer (1983) are also of interest, since extant species of this family are known as deep-sea crabs living on the shelf break and continental slope down to depths of 3800 m (Jones et al. 2003). Some geryonid species have been described from upwelling areas off Baja California (*Pleuroncodes planipes*) and Angola (*Geryon maritae*) (Walsh et al. 1974; Bianchi 1992).

Based on the faunal and floral data, upwelling is assumed for the pelites as well as for the intercalated diatomites. Concerning the change in sedimentation, sedimentological data presented by Roetzel et al. (1999b) suggest that the input of volcanic ash further amplified the bloom of diatoms leading to a further boost in primary productivity by bringing additional silica in the system and thus resulting in the deposition of the diatomites (Mandic et al. 2005; Roetzel et al. 2006).

The driving agent

Having a handful of proxies available suggesting upwelling along the south-eastern margin of the Bohemian Massif during the early Ottnangian, the fit with the paleogeographic and paleoceanographic framework has to be discussed. At first thought an upwelling setting in the narrow epicontinental Central Paratethys Sea seems unlikely. Today, the most prominent coastal upwelling areas are situated along the coasts of Africa, South America, Australia and the Arabian Peninsula providing a steep continental slope of several thousand meters (Summerhayes et al. 1995). This was not the case in the shallow Central Paratethys as Roetzel et al. (2006) suggest a deep sublittoral environment for the Lower Austrian study area. However, they point out similarities in topography: the steep paleocoast along the Bohemian Massif triggered by the Diendorf fault resembles the steep continental slope on a smaller scale (Fig. 3). The modern upwelling in the narrow Santa Barbara Channel along the coast of California might serve as an analogue (Lange et al. 1997; Hendershott & Winant 1996): restricted by a chain of islands, it reaches depths of approximately 500 m at its deepest part in the Santa Barbara Basin.

Given a suitable topography a driving force behind the suggested upwelling is still in question. Two main agents have been identified to trigger extant upwelling (e.g. Lee et al. 1997; Oke & Middleton 2000): tidal currents and prevailing winds producing surface currents. Sea floor and basin topography can further amplify these currents. Both scenarios can be applied to the Early Miocene Central Paratethys.

(1) In most cases upwelling is a wind-driven phenomenon. Thus, as suggested by Roetzel et al. (2006), prevailing westerly winds blowing parallel to the ancient coastline along the Bohemian Massif might thus have induced surface currents resulting in the coastal upwelling setting (Fig. 10A).

(2) Widespread meso- to macrotidal deposits are documented throughout the Central Paratethys during early-mid Burdigalian ranging from the French, Swiss and German Molasse (Homewood & Allen 1981; Allen & Homewood 1984; Allen et al. 1985; Keller 1989; Tessier & Gigot 1989; Lesueur et al. 1990; Schaad et al. 1992; Martel et al. 1994; Salvermoser

Table 6: Synopsis of all available sedimentological, biogenic and geochemical data reported in literature and in this study for the Zellerndorf Formation and the Limberg Member. References: (1) Roetzel et al. (2006); (2) Mandic et al. (2005); (3) Roetzel et al. (1999); (4) Řeháková (1996, 1994, 1993, 1992); (5) Bachmayer (1983, 1980, 1974). For more references and a detailed discussion see text.

Proxy	Remarks	Reference
1) Sediment		
diatomites and pelites of the Zellerndorf Fm	diatomites finely laminated; commonly known from upwelling areas	1, 2, 3, 4
2) Biota		
foraminifers	planktonics point to cold, nutrient-rich surface waters; blooms of cold-water tenuitellids; benthics depend on high organic flux from surface waters	1, 2
diatoms	frequent occurrence of *Thalassionema nitzschioides* characteristic of nutrient-rich, high productive areas; absence of shallow-water benthic taxa	1, 2, 4
calcareous nannoplankton	blooms of *Coccolithus pelagicus* with an optimal growth temperature of 2–12 °C	1, 2
silicoflagellates	frequent occurrence of cold and temperate taxa	1
dinoflagellates	neritic, nutrient-elevated environment	this study
macrofossils	fish, deep-sea crabs; insects, birds, palm leaves, bladder wreck	2, 5
3) Geochemistry		
$\delta^{18}O$ and $\delta^{13}C$ from planktonic and benthic foraminifers	rather high $\delta^{18}O$ values and low $\delta^{13}C$ values point to cold, nutrient-rich environment and low water-column stratification	this study

1999; Bieg 2005) via the Austrian North Alpine Foreland Basin (Faupl & Roetzel 1987, 1990; Krenmayr 1991) to the North Hungarian Bay (Sztanó 1994, 1995; Sztanó & De Boer 1995). These strong tidal currents supposedly amplified by the narrow paleogeography of the region are considered as possible driving forces for Paratethyan upwelling (Fig. 10B).

The paleogeography of the Early Miocene Central Paratethys with its narrow, long-stretched foreland basins favoured amplification of current patterns during phases of open connections to the Mediterranean (Allen et al. 1985; Bieg 2005). Such conditions existed several times from Egerian to early Ottnangian giving a time frame for possible upwelling events (Rögl 1998; Harzhauser & Piller 2007). Massive diatomites intercalated with pelites, commonly seen as indicator of upwelling conditions (Wagner 1998; Mandic et al. 2005), are not only known from the localities of this study. Time equivalent Early Miocene diatomites are also reported from the Carpathian Foredeep in Moravia and Poland (Kotlarczyk & Kaczmarska 1987; Kotlarczyk 1988; Picha & Stráník 1999). The widespread distribution of diatomites in the Early Miocene of the Central Paratethys might indicate that upwelling events were more common in the Central Paratethys than currently known.

Conclusions

A multi-proxy data-set from diatomite-clay successions in the North Alpine Foreland Basin of Lower Austria consisting of sedimentological and paleontological data from earlier

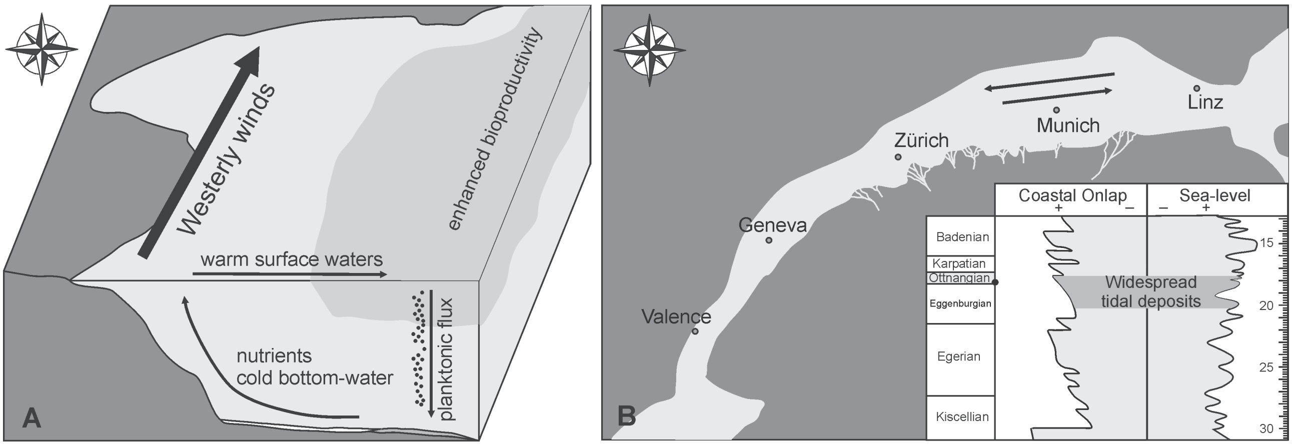

Fig. 10. Illustrations for the two discussed upwelling scenarios. **A** — Upwelling driven by prevailing westerly winds. **B** — Upwelling driven by meso- and macroscale tidal currents. For details see text.

studies, stable isotope analyses of foraminiferal shells and bulk sediment samples as well as dinoflagellate assemblages indicate upwelling conditions along the margin of the Bohemian Massif in the Central Paratethys during mid-Burdigalian times. Planktonic foraminifers examined for their isotopic composition show low $\delta^{13}C$ values and rather high $\delta^{18}O$ values, being remarkably consistent with data from recent upwelling areas. Temperature calculations based on globigerinids revealed sea surface temperatures from 10 to 14 °C. Low SSTs and high productivity are supported by the bulk sample record. Benthic foraminifers point to a low temperature gradient and strong mixing of the water column. Dinoflagellate assemblages indicate a highly productive, distal environment. The influence of NE trade winds and strong tidal currents are discussed as potential driving agents of the herein studied upwelling site. Coeval mid-Burdigalian deposits with marine diatomites are widespread in the Paratethys Sea from Austria and Moravia up to Poland. The local upwelling setting along the steep coast of the Bohemian Massif might thus reflect a characteristic hydrodynamic and/or wind regime along the Paratethyan coasts between ca. 19–18 Ma.

Acknowledgments: We want to thank Albrecht Leis (Joanneum Research, Graz) for carrying out part of the isotopic measurements. We are grateful to Fabrizio Lirer (Istitutio per l'Ambiente Marino Costiero, Naples, Italy), Michal Kováč (University of Bratislava, Slovakia), Andrea Kern (University of Vienna), Andreas Kroh and Oleg Mandic (both Natural History Museum Vienna) for many helpful discussions. Martin Head (Brock University, St. Catharines, Canada) and Lilian Švábenická (Czech Geological Survey, Prague) are thanked for constructive comments which helped to improve the paper. Franz Topka (Natural History Museum Vienna) is thanked for assisting with the fieldwork. Financial support for this study was provided by the Commission for the Palaeontological and Stratigraphical Research of Austria (Austrian Academy of Sciences).

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Appendix

Faunal reference list of the identified foraminifers and dinoflagellate cysts. Taxonomy of the Foraminifera follows Cicha et al. (1998) and Roetzel et al. (2006), dinoflagellate cyst nomenclature is based on Fensome et al. (2008). Descriptions and representative illustrations can be found in the same publications.

Foraminifera

Bulimina striata striata D'Orbigny 1837
Globigerina lentiana Rögl 1969
Globigerina ottnangiensis Rögl 1969
Globigerina praebulloides Blow 1959
Melonis pompilioides (Fichtel & Moll 1798)
Myllostomella advena (Cushman & Laiming 1931)
Myllostomella recta (Palmer & Bermudez 1936)
Pullenia bulloides (D'Orbigny 1826)
Siphonodosaria consobrina (D'Orbigny 1846)
Tenuitella clemenciae (Bermudez 1961)

Dinoflagellate cysts

Achomosphaera ramulifera (Deflandre) Evitt 1963
Cleistosphaeridium ancyreum (Cookson & Eisenack) Eaton et al. 2001
Cleistosphaeridium diversispinosum Davey et al. 1966 emend. Eaton et al. 2001
Cleistosphaeridium placacanthum (Deflandre & Cookson) Eaton et al. 2001
Lejeunecysta paratenella (Benedek 1972) Artzner & Dörhöfer 1978
Operculodinium centrocarpum (Deflandre & Cookson) Wall 1967 s.l.
Pentadinium laticinctum Gerlach 1961 emend. Benedek et al. 1982