Available online at www.sciencedirect.com

SCIENCE DIRECT®

Palaeogeography, Palaeoclimatology, Palaeoecology 231 (2006) 347–360

PALAEO

www.elsevier.com/locate/palaeo

Shifts in oxygen and carbon isotope signals in marine molluscs from the Central Paratethys (Europe) around the Lower/Middle Miocene transition

Christine Latal *, Werner E. Piller, Mathias Harzhauser

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

Received 19 November 2004; received in revised form 3 August 2005; accepted 30 August 2005

Abstract

Stable isotope data of mollusc shells from two adjacent time slices (Karpatian/Badenian) from the Central Paratethys were investigated to detect differences in environmental parameters and to depict shifts in the isotope signature of the Paratethyan seawater around the Early/Middle Miocene transition. Altogether seventeen different gastropod species and one bivalve species from the Karpatian (Korneuburg Basin) and the Badenian (Northern Alpine Foreland Basin) were selected. Representatives of various ecological guilds yielded different isotope patterns, especially in $\delta^{13}C$, reflecting different original habitats or nutrition. Although molluscs precipitate their shells in oxygen isotopic equilibrium, we preferred to compare isotope data of shells of the same genus of the family Turritellidae from the Karpatian and Badenian. The Badenian *Turritella* shells from the Northern Alpine Foreland Basin yielded distinctly higher $\delta^{18}O$ and $\delta^{13}C$ values than the respective Karpatian shells from the Korneuburg Basin. As the main factors controlling $\delta^{18}O$ values in gastropod shells are temperature and $\delta^{18}O$ of the water during precipitation, the differences between the oxygen isotope data of the two time slices can only be explained by these factors. Good independent palaeotemperature proxies exist for the Early to Middle Miocene of Central Europe; they do not indicate a significant temperature variation. Therefore, different $\delta^{18}O$ values of the seawater in the different basins of the Central Paratethys must be responsible for the contrasting $\delta^{18}O$ values. When calculated with commonly assumed $\delta^{18}O$ seawater values for the Miocene Badenian, *Turritella* shells indicate too cold temperatures. These data clearly document the danger of palaeotemperature interpretations based solely on stable isotopes. As smaller and marginal marine settings such as the Paratethys Sea can be seriously influenced by regional differences in the isotope composition of the seawater, only a thorough, consistent control by other climate proxies (e.g. palaeoecology of molluscs, as in this study) allows a sensible interpretation.

Keywords: Stable isotopes; Molluscs; Palaeotemperature; Early and Middle Miocene; Central Paratethys

1. Introduction

During the late Eocene and early Oligocene, new marine realms–the Mediterranean Sea and the Paratethys–were formed. The development of the Paratethys from the Oligocene to the Miocene was mainly influenced by regional geotectonic events and global sea level fluctuations, leading to alternating marine and non-marine phases in the region. Especially during the Miocene, marine seaways with the Indian Ocean in the East, and with the Mediterranean Sea and the Atlantic Ocean in the West, opened and closed repeatedly, producing significant environmental changes. Distinct changes in

---

* Corresponding author.
E-mail address: christine.latal@uni-graz.at (C. Latal).

0031-0182/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.palaeo.2005.08.008

the fossil communities reflect these variations in environmental parameters (changing basin geometries, subsidence, water depth, water chemistry, climate, salinity, etc.). These ancient environmental parameters are often reconstructed in a uniformitarian approach by comparing fossil taxa and assemblages with living relatives. Biogenic carbonate shells offer, based on their chemical and isotopic composition, an additional record of environmental parameters. Oxygen and carbon isotope studies on mollusc shells are widely used for estimations of marine and nearshore palaeoenvironmental conditions (Purton and Brasier, 1997; Andreasson and Schmitz, 1998; Tripati and Zachos, 2002). Nevertheless, only few stable isotope data have been published on Miocene fossils of the Paratethys (Geary et al., 1989; Sutovska and Kantor, 1992; Matyas et al., 1996; Durakiewicz et al., 1997; Hladilova et al., 1998; Gonera et al., 2000; Bojar et al., 2004; Latal et al., 2004, in press).

In this study we focus on the late Early and the early Middle Miocene of the Central Paratethys to compare two adjacent time slices with quite different faunistic inventory. The investigated faunas are separated in time by the Karpatian/Badenian (Early/Middle Miocene) boundary, which coincides with a significant sea level drop (Haq et al., 1988; Hardenbol et al., 1998). A frequently observed hiatus in sedimentation, traceable throughout the Central Paratethys (Rögl et al., 2002), and a changing tectonic regime in the entire Alpine–Carpathian area (Kováč et al., 2004), followed by an extensive marine transgression during the early Middle Miocene (Lower Badenian), accentuate this interval. This major palaeogeographic and oceanographic phase might also be reflected by considerable differences in the isotope composition of the seawater. This study compares stable isotope data of marine gastropod shells of Karpatian age from the Korneuburg Basin with those

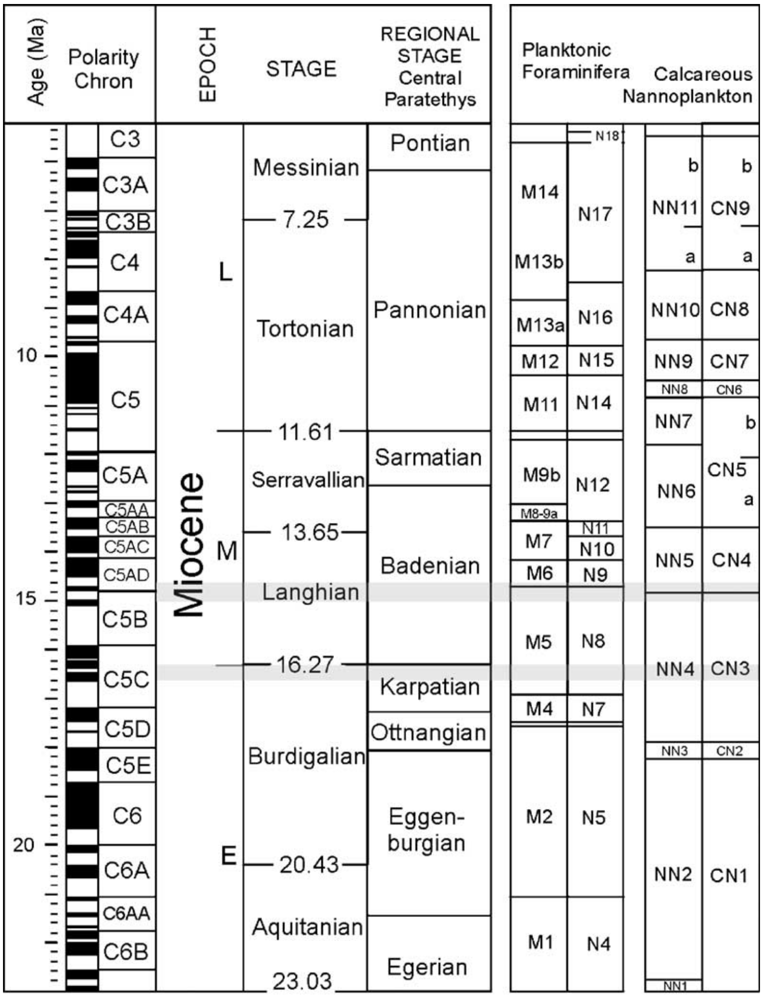

Fig. 1. Late Oligocene to Late Miocene geochronology and biostratigraphy (according to Gradstein et al., 2004).

of Early Badenian age from the Northern Alpine Foreland Basin in order to detect differences in environmental parameters between these two time spans (Fig. 1) and to depict shifts in the overall isotope signature of the Paratethys Sea.

2. Geological setting and palaeoecology

2.1. Data set 1: Korneuburg basin—Karpatian

The Early Miocene molluscs were derived from the Korneuburg Formation in the Korneuburg Basin (Fig. 2). The faunas consist exclusively of shallow-water, nearshore assemblages living under the changing conditions of an estuary (Harzhauser et al., 2002). The formation of the asymmetric Korneuburg Basin resulted from pull apart effects within the Alpine–Carpathian thrust belt during late Alpine movements (Wessely, 1998). The SSE–NNE elongated basin is about 20 km long and attains a maximum width of 7 km, but is strongly narrowed in its northern extension. A central swell separates a southern part of the basin of about 650 m depth from a shallower northern one with about 350 m depth. Sedimentation started during the Eggenburgian (~Early Burdigalian), but the main basin fill is represented by Karpatian deposits (~Late Burdigalian). Karpatian sediments are mainly represented by grey to yellow marly silt and fine to medium sand.

During the Karpatian, the basin was strongly cut off from the open Paratethys Sea. The adjacent Vienna Basin was largely covered by a fluvial-deltaic system which prograded from the south. A connection to the marine realm was only present along the northern tip, where the Paratethys Sea extended into the Alpine–Carpathian Foredeep (Harzhauser and Wessely, 2004).

In the northern part of the basin, shallow marine settings of 20–30 m water depth formed where scattered corals inhabited the silty to sandy bottom. The southern basin was characterised by estuarine settings and tidal mudflats with extended *Crassostrea* bioherms. Along the seaward fringe a low-diversity Mediterranean *Avicennia* mangrove was present. Brackish marshes, shallow lakes, oxbows and rivers developed as the typical wetland types of the southern Korneuburg Basin. A diverse mammalian fauna derived from the swamps

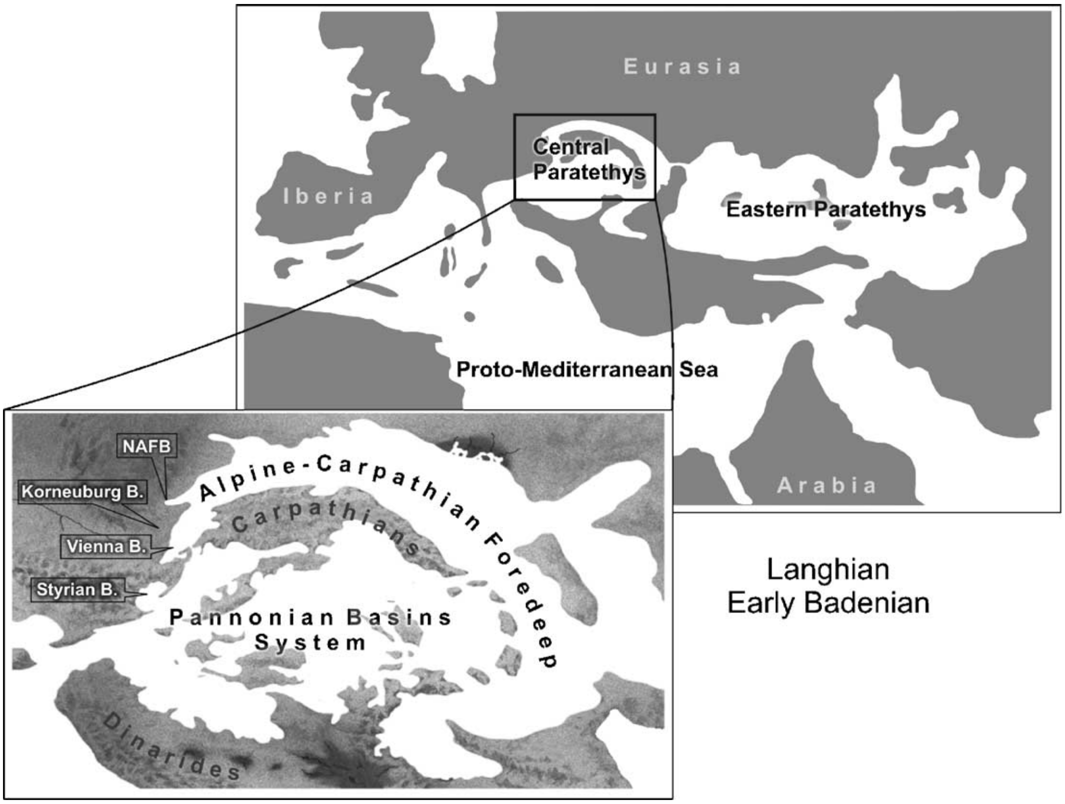

Fig. 2. Palaeogeography of the circum-Mediterranean area during the early Middle Miocene (early Badenian, Langhian) based on Rögl (1998a,b) and Popov et al. (2004). The insert-map presents the area studied and shows the position of the basins mentioned in the text. Note that the Korneuburg Basin was already dry land in the reconstructed time-slice.

and forests. Freshwater influx is documented by molluscs and aquatic vertebrates, such as the fishes *Esox* and *Barbus* or the turtle *Trionyx* (Harzhauser et al., 2002 and references therein). Recently obtained stable isotope data of gastropods from the Korneuburg Basin support the existing palaeoecological interpretation of a northern part with marine conditions, and a southern part dominated by an estuarine environment (Latal et al., in press).

Böhme (2003) proposed a subtropical climate with a minimum mean annual temperature (MAT) of 17 °C, based on the living requirements of crocodiles and cordylid lizards. The winter months were probably frost free; the minimal cold month temperature (CMT) should have ranged from at least 3 °C to about 8 °C. Based on the temperature requirements of the mollusc fauna, a minimum sea surface temperature (SST) of 14–16 °C was discussed by Harzhauser et al. (2002).

2.2. Data set 2: Northern Alpine Foreland Basin (NAFB)—Badenian

The NAFB–often referred to as the Molasse Basin–formed as part of the Alpine–Carpathian Foredeep as a W–E trending trough in front of the prograding nappes of the Alpine orogen (Fig. 2). It is delineated to the north by the passive margin of the Variscan Bohemian Massif and in the south by the overriding Rhenodanubian Flysch-Helvetic nappes of the Alpine–Carpathian thrust front. The width of the Austrian part of the NAFB, which is about 300 km long, ranges from 5 to 50 km. From the late Eocene up to the present, the Alpine orogeny took place and the foreland basin formed. The present basin is only a narrow remnant of the original basin. Tectonic activities within the thrust sheets and lateral movements of the basement along the western flank of the Bohemian Massif are still ongoing (Wagner, 1996).

During the Oligocene and Early Miocene, deep marine conditions prevailed. With the beginning of the Middle Miocene, rather shallow marine environments established up to about 14 Ma, when Middle Miocene uplift caused the sea to retreat from west to east. The fauna investigated in this study settled the NAFB during this late marine phase. The shells were collected in the siliciclastic deposits at the Grund section, the type locality of the Grund Formation. The Grund Formation (Lower Badenian) has been the aim of various taxonomic studies since the late 19th century, but detailed sedimentological and taphonomic studies have only been conducted recently (Harzhauser et al., 2003b; Roetzel and Pervesler, 2004; Zuschin et al., 2001, 2004). According to Ćorić et al. (2004), the investigated part of the Grund Formation belongs to the regional Early Badenian Lower Lagenidae Zone, being an age-equivalent of the Langhian. The entire succession is dated as the foraminifera “Zone with *Praeorbulina glomerosa circularis*” and as nannoplankton zone NN5 by Rögl et al. (2002), pointing to an absolute age ranging between 15.0 and 14.8 Ma [according to the zone calibrations of Gradstein et al. (2004)].

The mollusc assemblage occurs in highly diverse and densely packed tempestitic shell beds. The shells are abraded and were transported from agitated shallow-water habitats into a somewhat deeper pelitic, dysaerobic environment with monospecific *Thyasira* assemblages in life position (Zuschin et al., 2001, 2004).

3. Material and methods

The selection of representatives of various ecological guilds was expected to yield differences in isotope patterns due to their original (micro)habitats. In a next step, the resulting eco-patterns of each time-slice can be compared to reveal overall shifts between the Early and the Middle Miocene environments.

Ten Badenian gastropod and one bivalve species and eight Karpatian gastropod species were used for stable isotope measurements. In total, 36 specimens were measured. The measurements from the Korneuburg Basin (Karpatian) and the resulting intra-basin palaeoecological interpretations have already been discussed in Latal et al. (in press). Shells from Grund were treated in the same way as samples from the Korneuburg Basin (Latal et al., in press). Shell preservation state was determined by X-ray diffraction and scanning electron microscopy. X-ray diffraction was performed on a Bruker D8 Discover with GADDS (General Area Detector Diffraction Solutions). Several points on each shell were investigated non-destructively. For stable isotope analyses, the shells were sampled with a 0.3-mm drill in ontogenetic sequence from the apex to aperture. Sample density depended on shell size. Oxygen and carbon isotope measurements were performed by reaction of the samples with 100% phosphoric acid at 70 °C in a Finnigan Kiel II automated reaction system, and measured with a Finnigan Delta Plus isotope-ratio mass spectrometer at the Institute of Earth Sciences, University of Graz. Measurements of NBS-19 and an internal laboratory standard yielded a standard deviation of 0.1‰ for both $\delta^{18}O$ and $\delta^{13}C$. Isotope data are given in ‰ relative to VPDB.

4. Results

This chapter describes only results of the molluscan shells from Grund; the results from the Korneuburg Basin have already been presented in Latal et al. (in press).

Shell mineralogy: X-ray diffraction was used to determine shell mineralogy and to detect diagenesis. Only aragonite is present in the shells. As all shells are originally built up of metastable aragonite, which easily converts to calcite during diagenesis, the results show that all samples are unaffected. The mineralogical results point to primary stable isotope values, so that palaeoenvironmental conditions can be deduced from the isotope signals in the gastropod shells.

Oxygen and carbon isotopes: Ten different mollusc taxa were investigated. Of these, the batillariid gastropod *Granulolabium bicinctum* inhabited littoral mudflats. All other gastropods, such as *Turritella eryna*, *Acteon* sp., *Nassarius schoenni*, *Nassarius* sp., *Tudicla rusticula*, and *Capulus ungaricus* probably preferred littoral to shallow sublittoral habitats. Only the chemosymbiotic bivalve *Thyasira michelottii* is thought to have occupied the somewhat deeper sublittoral zone (Zuschin et al., 2001, 2004).

Sample density in the shells of *T. eryna* followed the sampling regime of Allmon et al. (1992) and Jones and Allmon (1995) for recent turritellids. The oxygen and carbon isotope curves for the *T. eryna* shells, sampled in detail, are shown in Fig. 3. The intrashell variability of oxygen isotopes in the three shells is 1.4‰, 2.2‰ and 3.3‰, and $\delta^{18}O$ values range from −0.7‰ to 2.6 ‰ (Table 1). Each shell shows a distinct isotope pattern. The two shells with the largest ranges in $\delta^{18}O$ values exhibit weak cyclicities (Fig. 3a,b). The third shell (Fig. 3c) yields the most scattered oxygen isotope data. Carbon isotope profiles in the three *T. eryna* shells are more alike, although the third shell again shows a scattered carbon isotope signal. $\delta^{13}C$ values range from 1.9‰ to 4.0‰. The three shells show no correlation between $\delta^{18}O$ and $\delta^{13}C$ values, but the first and second shells show, starting from the apex, a decrease in $\delta^{13}C$ which shifts to an increase in the last three to four whorls.

Six to eight samples were measured from each *G. bicinctum* shell. $\delta^{18}O$ values range from −2.0‰ to 0.8‰, with a slightly higher intrashell variability than the *Turritella* shells. Compared to the *Turritella* shells, $\delta^{18}O$ values are about 1.0‰ lower in the *Granulolabium* shells. The $\delta^{13}C$ values, however, differ distinctly within the species: one shell shows quite low values of −0.5‰ to 0.7‰, whereas the other two shells range between 0.7‰ and 1.9‰.

Acteon sp., *N. schoenni* and *Nassarius* sp. yield comparable $\delta^{18}O$ values, ranging from 0.1 to 1.5‰, while *T. rusticula* has lower values (−0.1 to 0.6‰). $\delta^{18}O$ values of *C. ungaricus* lie in a small range between 1.3‰ and 1.6‰: this small intrashell variability reflects the smaller number of samples taken from each shell. Nevertheless, all these samples yield $\delta^{18}O$ values in the range of the *T. eryna* shells.

Carbon isotopes of the various gastropod shells show a greater variability. $\delta^{13}C$ values in the *T. rusticula*, *Aporrhais pespelecani*, *N. schoenni* and *Nassarius* sp. shells are comparable to those of *G. bicinctum*, while *Acteon* sp. and *C. ungaricus* yield slightly higher values.

A quite different isotope pattern was determined for the bivalve *T. michelottii* shell. Though $\delta^{18}O$ values are in the range of the *T. eryna* shells (1.1–2.0‰), $\delta^{13}C$ is very low compared to the measured gastropod genera (−3.5‰ to 0.3‰).

5. Discussion

5.1. Seasons and temperature

When the effects of diagenesis on shell chemistry are negligible, oxygen and carbon isotopes of fossil mollusc shells can yield valuable palaeoenvironmental information. The gastropod species examined in this study have aragonitic shells. The preservation of the relatively unstable aragonitic phase provides strong evidence for predominantly unaltered isotope values. Studies of extant aragonitic gastropods indicate that these organisms precipitate shells in oxygen equilibrium or near equilibrium (Grossman and Ku, 1986). Recently, Lécuyer et al. (2004) have shown that the oxygen isotope composition of various mollusc shells from littoral open marine environments, as well as from mangroves, yield good records of the ambient water temperature. Thus, oxygen and carbon isotope data may be applied for palaeoenvironmental and palaeotemperature reconstructions. Environmental factors and metabolic processes control the isotopic composition of mollusc shells; for $\delta^{18}O$ the main factors are temperature and the $\delta^{18}O$ of the water during precipitation, whereas for $\delta^{13}C$, in addition to metabolic processes, the carbon isotope composition of dissolved inorganic carbon (DIC) plays an important role. Though some studies show a constant offset of shell $\delta^{13}C$ from the equilibrium $\delta^{13}C$ values of DIC (e.g. Dettman et al., 1999; Abell and Hoelzmann, 2000; Kaandorp et al., 2003), $\delta^{13}C$ values of mollusc shells are still considered to yield good records of variations in $\delta^{13}C$ of DIC (Kaandorp et al., in press).

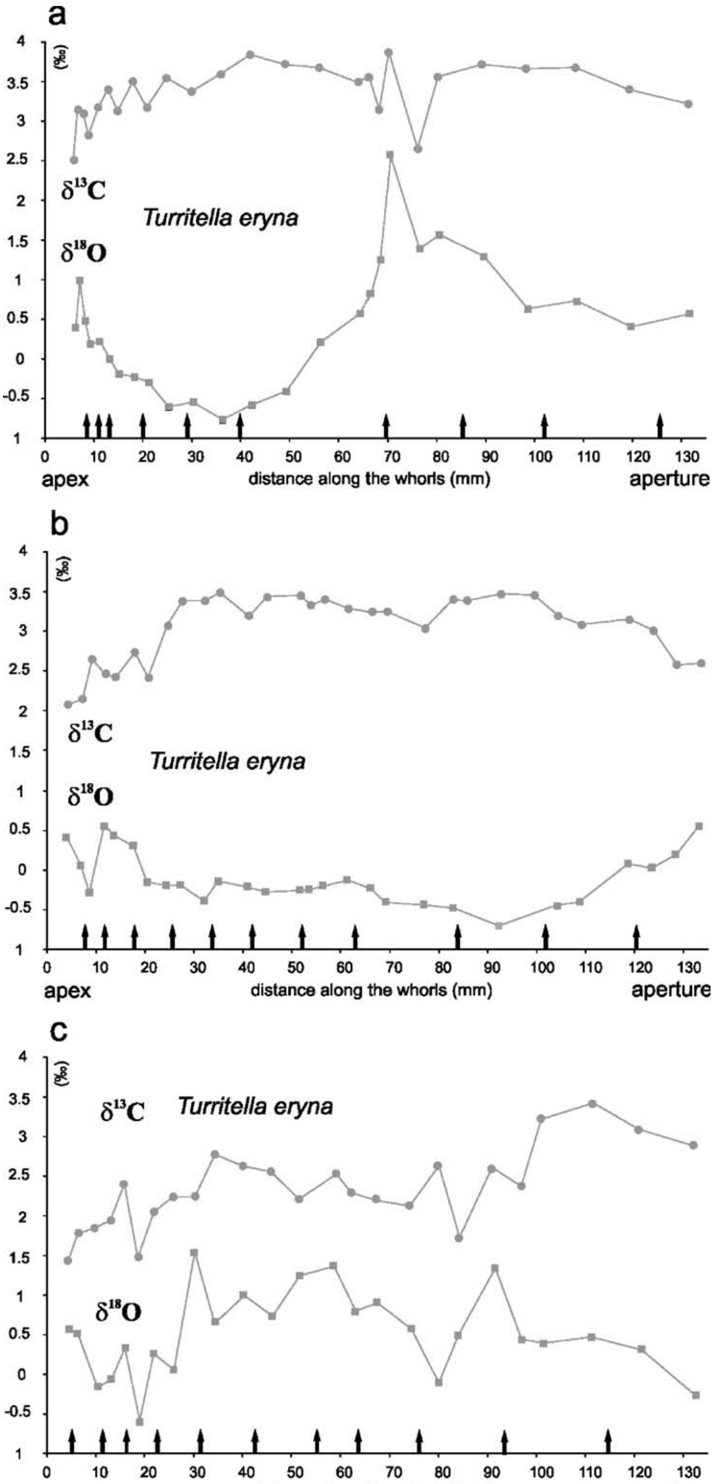

Fig. 3. Stable isotope profiles from apex to aperture of three *Turritella eryna* shells from the NAFB (black arrows indicate position of whorls).

Table 1
Oxygen and carbon isotope ranges and mean values of aragonitic mollusc shells from the NAFB

Taxon	Number of samples	$\delta^{18}O$ (‰ vs VPDB)				$\delta^{13}C$ (‰ vs VPDB)			
		Min.	Max.	Mean	Std.dev.	Min	Max.	Mean	Std.dev
Turritella eryna 1	30	−0.3	1.1	0.4	0.3	2.6	4.0	3.5	0.4
Turritella eryna 2	26	−0.7	2.6	0.4	0.8	2.5	3.8	3.3	0.3
Turritella eryna 3	25	−0.1	2.1	1.1	0.5	1.9	3.9	2.9	0.5
Granulolabium bicinctum	8	−1.8	0.8	−1.2	0.8	0.7	1.8	1.3	0.3
Granulolabium bicinctum	8	−0.3	0.8	−0.8	1.1	−0.5	0.7	−0.1	0.3
Granulolabium bicinctum	6	−1.7	0.3	−0.4	0.6	1.2	1.9	1.5	0.2
Capulus ungaricus	4	1.3	1.6	1.4	0.1	2.2	2.6	2.4	0.1
Tudicla rusticula	3	−0.1	0.6	0.4	0.3	−0.1	1.9	1.2	0.9
Aporrhais pespelecani	8	0.4	1.5	0.7	0.3	0.5	1.8	1.0	0.5
Nassarius schoenni	5	0.1	0.8	0.5	0.3	1.3	1.9	1.6	0.2
Nassarius sp.	6	0.5	1.3	0.9	0.3	0.8	2.1	1.6	0.4
Acteon sp.	6	0.3	1.5	0.7	0.4	2.4	2.8	2.7	0.1
Thyasira michelottii	4	1.1	2.0	1.5	0.3	−3.5	0.3	−2.4	1.4
Natica tigrina (bulk sample)				0.5				0.7	

The isotopic composition of seawater in open ocean environments is mainly controlled by global climate, whereas in marginal seas and coastal areas it may strongly be influenced by local environmental conditions. In palaeoenvironmental isotope studies, this requires considering the impact of the different factors on the isotope signals in carbonate shells. Isotope data of recent mollusc shells, as well as fossil ones, have been intensively studied for various purposes [e.g. reconstruction of marine palaeotemperatures and seasonality changes (Williams et al., 1982; Jones et al., 1983, 1989; Krantz, 1990; Klein et al., 1996; Kaandorp et al., 2003), detection of upwelling events (Killingly and Berger, 1979), estimations of ancient salinity (Geary et al., 1989)].

Among gastropods, several studies on recent Turritellidae indicate that stable isotope contents in their shells are good indicators for environmental parameters (Allmon et al., 1992, 1994; Jones and Allmon, 1995; Andreasson and Schmitz, 1996; Teusch et al., 2002). Recent Turritellidae live in a wide range of environments, but prefer normal marine salinities (Allmon, 1988). Generally, their mode of life is shallow infaunal or epifaunal. Recent turritellids show differences in their isotopic values related to their specific environment. In general, $\delta^{18}O$ ranges are quite large (1.1–2.7‰), and high $\delta^{13}C$ values up to 4.0–4.5‰ have been measured (Allmon et al., 1992; Teusch et al., 2002). Estimations on lifespan and growth rate in recent turritellids are mainly based on stable isotope profiles. A growth rate of about 14–17 whorls, corresponding to 70–110 mm, in 1.5 years is suggested for *Turritella gonostoma* (Allmon et al., 1992). Slightly higher growth rates of about 18–20 whorls per year were calculated for Pliocene *Turritella apicalis* and *Turritella gladeensis* (Jones and Allmon, 1995), whereas recent *Turritella cingulata* exhibit growth rates of about 10 whorls in 2 years (Teusch et al., 2002). Stable isotope investigations on fossil turritellids were also used to reconstruct palaeoenvironmental conditions (Andreasson and Schmitz, 1996, 2000; Teusch et al., 2002; Latal et al., in press).

Each of the three analysed *T. eryna* shells shows a distinct isotope pattern (Fig. 3). In fully marine environments, where salinity fluctuations are less pronounced, cyclic changes in $\delta^{18}O$ can be ascribed to annual temperature changes. The shell with the largest range in $\delta^{18}O$ values exhibits a clear cyclicity. This shell (Fig. 3a) is about 30 mm long and 12 whorls are present. Interpreting the cyclic $\delta^{18}O$ curve as representing annual temperature changes, a growth rate of about 10 whorls per year can be estimated for this shell. The second shell (Fig. 3b) is very similar in size, but oxygen isotope values show more scatter. The third shell (Fig 3c), which is only 21 mm long but has 13 whorls, yielded the most complicated $\delta^{18}O$ pattern. Up to the 5th whorl a scattered signal with a general trend to a minimum value of −0.1‰ is observable. The next samples show a continuous increase up to 2.1‰. Interpreting the oxygen signal from this point to the aperture is difficult because of the large scatter. Based on the oxygen isotope profile of the shell with the clear cyclicity, and on a comparison with the growth rates of recent turritellids, we assume a maximum age of 2–3 years.

The carbon isotope patterns of the three shells exhibit characteristics similar to the $\delta^{18}O$ patterns, but interpreting the $\delta^{13}C$ in gastropod shells is generally more difficult. The $\delta^{18}O$ and $\delta^{13}C$ values in the turritellid shells do not correlate, but the two larger shells show similar trends: a $\delta^{13}C$ decrease starting from the apex then shifts into an increase in the last three to four whorls. The smallest shell yields a quite different pattern. Although the shells are taken from the same horizon, each shell represents only one or a few years time of a single horizon. Particularly in shallow-water habitats, local environmental conditions can vary strongly within years. The observed differences in the oxygen and carbon isotope data of the three *T. eryna* shells may therefore be explained by local environmental changes within years.

Palaeotemperature reconstructions using oxygen isotope data of carbonate shells is only possible when the oxygen composition of the seawater is known. Nevertheless, assuming that the $\delta^{18}O$ variation in the *Turritella* shells is mainly due to annual temperature changes, the maximum and minimum $\delta^{18}O$ values indicate the minimum range of water temperatures. The largest range of $\delta^{18}O$ in the shells is 3.3‰, corresponding to a range of temperature of 14 °C, calculated by the equation of Böhm et al. (2000). The variability in the intrashell $\delta^{18}O$ record could have been minimized by seasonal shell cessation. On the other hand, the temperature range could be overestimated if lower salinities were associated with higher temperatures, and if salinity increased during the cold winter months.

5.2. The influence of feeding and habitat

With the exception of the *Granulolabium* and the *T. michelottii* shells, all other shells yield similar oxygen isotope values, though intrashell ranges of $\delta^{18}O$ values vary between the different gastropod genera (Fig. 4). As these gastropods prefer similar habitats, and they are assumed to incorporate oxygen isotopes in equilibrium with ambient seawater, no distinct difference of $\delta^{18}O$ values should be expected. The outliers probably reflect different habitat preferences. As discussed in Latal et al. (2004), the batillariid *Granulolabium* is a mudflat inhabitant and was therefore prone to changing salinities. Though growth cessation during the colder winter months cannot be excluded, it is more likely that evaporation and elevated temperatures during low tide caused these $\delta^{18}O$ signals.

In contrast, the $\delta^{13}C$ values differ greatly between the investigated species. The $\delta^{13}C$ signal in gastropod shells is influenced by several environmental and biological factors. Reinforcement or cancellation of these factors makes a meaningful interpretation of the $\delta^{13}C$ data very difficult. Feeding strategies, however, may provide some clues. One approach is to group ecological guilds along the gradient from low towards high

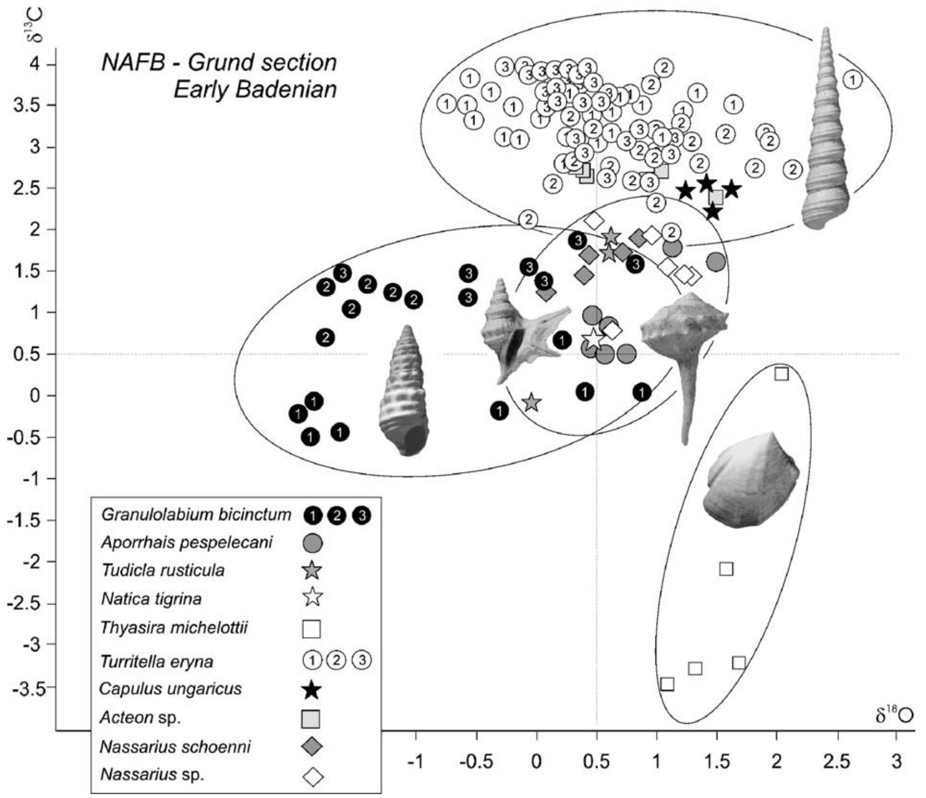

Fig. 4. Oxygen and carbon isotope data of Badenian mollusc shells from the NAFB.

δ^{13}C values. Though the net δ^{13}C of the food source may affect the soft tissue of molluscs more than the shell carbonate (Hendry and Kalin, 1997; Bottelo et al., 1980), the δ^{13}C of shell aragonite in pulmonate snails is a good record of diet (Stott, 2002).

Hence, lowest δ^{13}C values are detected in littoral mudflat inhabitants and freshwater taxa such as *Melanopsis* (Fig. 5). Like modern potamidids and batillariids, *Granulolabium* is interpreted to have lived as an epifaunal mudcreeper feeding on organic detritus and algae (see Latal et al., 2004 for discussion).

The “midfield” is occupied–though not exclusively–by carnivorous and scavenging taxa such as *Tudicla, Natica* and *Nassarius*. *Aporrhais* is also found in that field, but displays somewhat “disjunct” signals. Recent *Aporrhais* species are seasonal burrowers grazing on diatoms and decaying macroalgae (Roy, 1994). Changes in diet reflecting the seasonal change of mode of living have also been described by Roy (1994). The above-mentioned disjunct δ^{13}C pattern in the fossil *Aporrhai*s hints at a corresponding behaviour.

Finally, the third group, with highest δ^{13}C values, is represented by the turritellids *Capulus* and *Acteon*. Most turritellids are semi-infaunal suspension-feeders, although deposit-feeding species have also been described (Allmon, 1988). The epifaunal *Capulus* is also filter-feeding (Yonge, 1938). Only the carnivorous *Acteon* is an outsider within that “suspension-feeding group”, as acteonids are predators on polychaete worms (Yonow, 1989).

The extraordinarily low δ^{13}C of the *T. michelottii* shell could reflect its chemosymbiotic living mode (Zuschin et al., 2001) or locally low δ^{13}C values of the dysoxid muds because of decaying organic matter. This reveals isotope studies as a valuable tool to support suspected chemosymbiosis in the fossil record.

In conclusion, a gradient in δ^{13}C values from low towards high seems to reflect a gradual succession from deposit-feeding/browsing via carnivory/scavenging towards suspension-feeding. Obvious “outliers” such as the chemosymbiotic *Thyasira* point to highly specialised strategies or are influenced by locally low δ^{13}C values of their environment.

5.3. One sea–two waters?

The Karpatian and Badenian mollusc faunas from the Central Paratethys have recently been compared

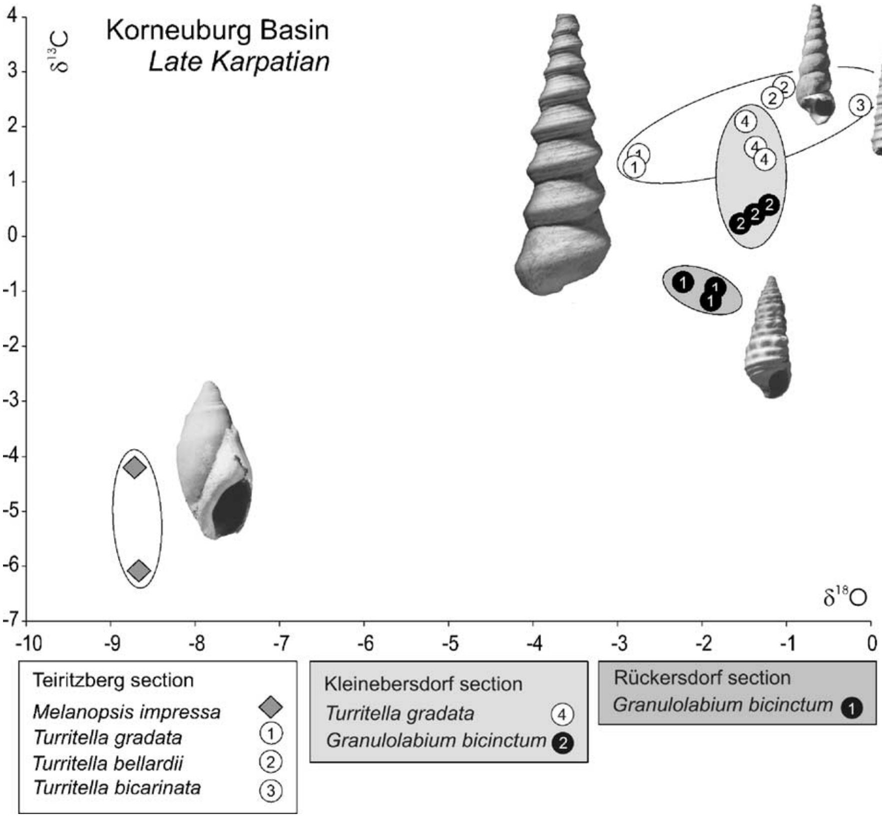

Fig. 5. Mean oxygen and carbon isotope data of Karpatian gastropod shells (from Latal et al., in press).

by Harzhauser et al. (2003a). These faunas are separated by a major drop in sea level at the Early/Middle Miocene transition (Haq et al., 1988; Hardenbol et al., 1998), followed by an extensive marine transgression. Both time slices are characterised by strong immigrations of molluscs from the adjacent Mediterranean Sea, resulting in a low percentage of endemism. The Middle Miocene assemblages show an even higher diversity due to a heavy wave of immigration. Furthermore, the Early/Middle Miocene climatic optimum is also reflected within the Middle Miocene fauna by a unique northward migration of thermophilic taxa (Harzhauser et al., 2003a). This strong Badenian transgression "inoculating" the Paratethys with new southern waters is expected to also be reflected in a shift of the isotopic composition of the seawater. To depict this change in the isotopic signature, we compared the congeneric taxa of the Karpatian (Fig. 5) and the Badenian. Although gastropods are considered to precipitate their shells in oxygen isotopic equilibrium, comparing the isotope data of shells of the same genus is preferable to comparing isotope data of different genera. The best data set was achieved within the turritellids (Fig. 6). The Badenian *Turritella* shells yield distinctly higher δ^{18}O and δ^{13}C values than the Karpatian shells. These differences may be related either to variations in the δ^{18}O of the seawater, or to changes in temperature. As noted above, oxygen isotope data of carbonate shells can be used to calculate reliable palaeotemperatures only if the oxygen isotope composition of the seawater in which the carbonate shells precipitated is known. This composition of the seawater still presents a great challenge in using isotopes for palaeotemperature estimations.

For the Early to Middle Miocene of Central Europe, good independent palaeotemperature proxies exist. In Central Europe a climatic optimum from the Eggenburgian to the Middle Badenian (20.0–13.6 Ma), with a peak in the Ottnangian and Karpatian, is inferred from the temporal distribution of thermophilic and dry-adapted lower vertebrates (Böhme, 2003). Palaeobotanical and palaeopedological proxies support the climatic scenario of a subtropical climate with frost-free winter months. Temperatures remained unchanged in the Lower and Middle Badenian, but seasonality was increasing (Böhme, 2003). Modern stenothermic gastropod relatives of the Korneuburg Basin fauna require minimum SSTs of about 14–16 °C (Harzhauser et al., 2002). Temperature requirements of the fish fauna support a transitional area between the warm temperate and tropical belt (Schultz, 1998, 2003; Reichenbacher, 1998). Slightly higher minimum SST isotherms of at least 16–18 °C can be assumed for the Badenian Paratethys, based on

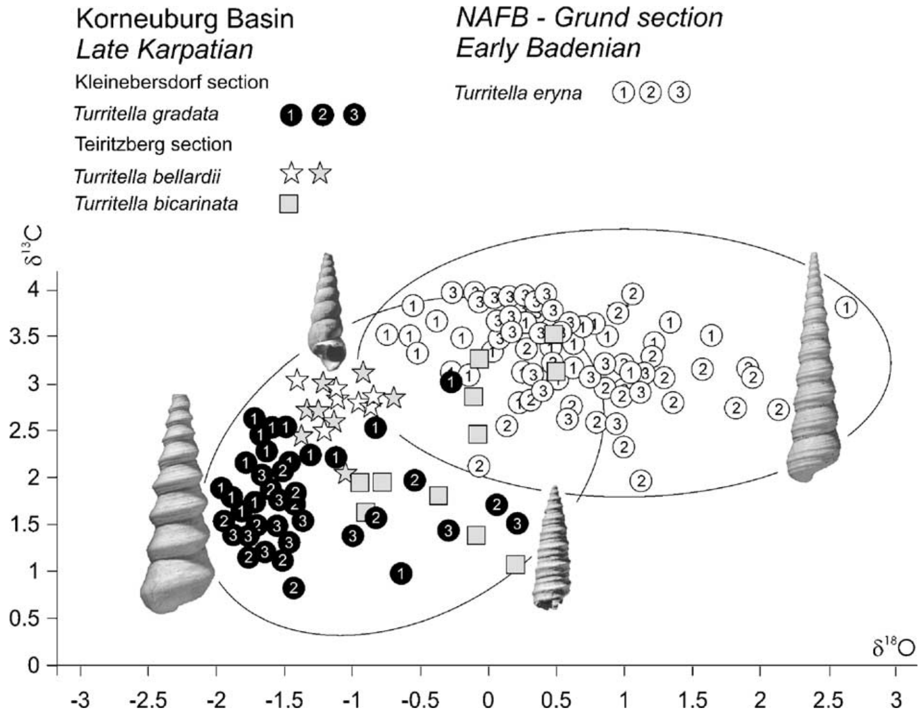

Fig. 6. Oxygen and carbon isotope data from Badenian *Turritella* shells from the NAFB, and compared to Karpatian isotope data from the Korneuburg Basin.

the occurrence of several strombid genera (Harzhauser et al., 2003a).

Today's seawater has a mean δ^{18}O composition of 0‰ SMOW, but δ^{18}O can vary significantly locally due to evaporation and mixing with freshwater. Marginal marine environments are strongly influenced by these factors. For example, the Mediterranean Sea has a value of +1‰, the more saline Red Sea around +2‰, and the Black Sea −3‰. An average δ^{18}O value of −1‰ SMOW is commonly assumed for the Early Miocene seawater because the Early–Middle Miocene transition was more or less ice-free (Lear et al., 2000).

Calculating temperatures from the oxygen isotope data of the *T. eryna* shells after the equation of Böhm et al. (2000), with an assumed δ^{18}O of −1‰ SMOW for the Miocene seawater, yields estimates from 4 to 19 °C. Compared to other palaeotemperature proxies, this estimate is much too low. Karpatian *Turritella* shells from the Korneuburg Basin, however, provided quite reliable temperatures from 13 to 26 °C with the same δ^{18}O value of −1‰ SMOW for the seawater (Latal et al., in press). Only when assuming a δ^{18}O of +1‰ SMOW for the seawater in the case of the Badenian *T. eryna* shells do the temperature estimates fall in the range of 13–28 °C, which fits with other palaeotemperature proxies (Fig. 7). This high δ^{18}O value for Badenian seawater in the Northern Alpine Foreland Basin was unexpected.

The differences between the results of the Badenian and Karpatian *Turritella* shells are striking but difficult to explain. As δ^{18}O values of the Badenian gastropod shells (NAFB) are high, diagenetic alteration–generally leading to lower isotope values–can be neglected as an influencing factor. The determination of aragonite as shell material also contradicts a diagenetic alteration here. The logical conclusion is an unusually high δ^{18}O value for the Miocene seawater in the NAFB, because proxies indicate a subtropical climate with high temperatures. The differences between the oxygen isotope data of the two basins may thus be explained by different local influences in each basin. As freshwater input and evaporation can significantly change oxygen isotope values of the seawater, these factors may have influenced the local values of δ^{18}O in each of these basins. The influence of freshwater in the restricted Korneuburg Basin may have lowered a generally higher δ^{18}O value of the Paratethyan seawater, whereas the seawater in the NAFB may have been enriched in ^{18}O by evaporation. Thus, without other temperature proxies, Badenian *Turritella* shells indicate too cold temperatures when calculated with commonly assumed δ^{18}O seawater values for the Miocene.

6. Conclusion

We present new carbon and oxygen data from well-preserved gastropod shells from the Central Paratethys. The Badenian data set from the NAFB comprises stable isotope data of various gastropod genera. Three *T. eryna* shells show a wide range of δ^{18}O values (−0.7–2.6‰). With the exception of *G. bicinctum* and the bivalve shell *T. michelottii*, all examined gastropod genera prefer similar normal marine habitats which is reflected in their similar oxygen isotope values. In contrast, carbon isotope values differ significantly between gastropod genera, probably because of different metabolic processes and differences in diet and microhabitat effects. Generally, lower δ^{13}C values seem to correlate with browsing and deposit-feeding, whilst relatively higher values correspond to suspension-feeding. The intermediate field is occupied by carnivorous and scavenging species. Extraordinarily low values, such as documented for the bivalve *Thyasira*, are

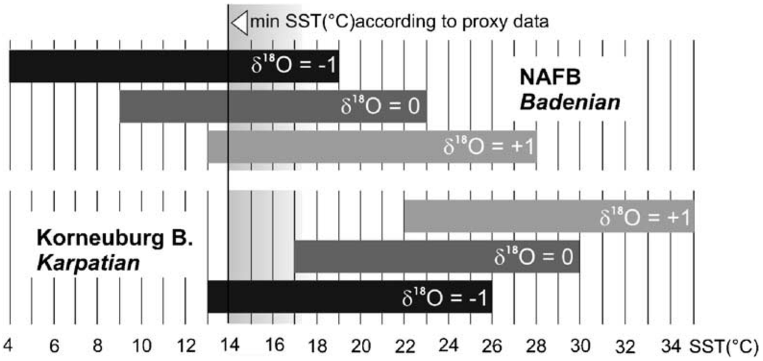

Fig. 7. Calculations of palaeotemperatures with different assumptions for δ^{18}O values of the palaeo-seawater for the Badenian NAFB and the Karpatian (Korneuburg Basin).

interpreted to reflect a chemosymbiotic mode of life.

Comparing these new data with stable isotope data of Karpatian gastropods from the Korneuburg Basin (Latal et al., in press) reveal remarkable features: Badenian *T. eryna* shells from the NAFB have generally higher $\delta^{18}O$ values. Thus, assuming a $\delta^{18}O$ value of −1‰ SMOW for the Early/Middle Miocene seawater, palaeotemperature estimates for the Badenian versus Karpatian turritellids from the Korneuburg Basin differ significantly (much lower for the Badenian). Other palaeotemperature proxies do not indicate such a temperature difference between these two time slices in the Paratethys. These contrasting results can only be explained by different $\delta^{18}O$ values of the seawater in the various basins of the Central Paratethys. This observation clearly documents that a palaeotemperature interpretation based solely on stable isotopes entails considerable risks, but that a combination of different independent methods (e.g. molluscan palaeoecology, as in this study) can yield a more detailed palaeoenvironmental interpretation. Stable isotope data of carbonate shells, especially in rather small and marginal marine settings such as those of the Paratethys Sea, can be seriously affected by regional differences in the isotopic composition of the seawater.

Acknowledgements

We thank F. Wesselingh and an anonymous reviewer for their very helpful critical comments. The study was supported by the Austrian Science Foundation [FWF, project “Stable Isotopes and changing Miocene palaeoenvironments in the East Alpine region” (P-14366 BIO) and project “Evolution Versus Migration: Changes in Austrian Marine Miocene Molluscan Palaeocommunities” (P-13745 BIO)].

References

Abell, P.I., Hoelzmann, P., 2000. Holocene palaeoclimates in northwestern Sudan: stable isotope studies on molluscs. Global and Planetary Change 26, 1–12.

Allmon, W.D., 1988. Ecology of recent turritelline gastropods (Prosobranchia, Turritellidae): current knowledge and paleontological implications. Palaios 3, 259–284.

Allmon, W.D., Jones, D.S., Vaughan, N., 1992. Observations on the biology of *Turritella gonostoma* valenciennes (Prosobranchia: Turritellidae) from the Gulf of California. The Veliger 35/1, 52–63.

Allmon, W.D., Jones, D.S., Aiello, R.L., Gowlett-Holmes, K., Probert, P.K., 1994. Observations on the Biology of *Moaricolpus roseus* (Quoy and Gaimard) (Prosobranchia: Turritellidae) from New Zealand and Tasmania. The Veliger 37/3, 267–279.

Andreasson, F.P., Schmitz, B., 1996. Winter and summer temperatures of the early middle Eocene of France from Turritella $\delta^{18}O$ profiles. Geology 24/12, 1067–1070.

Andreasson, F.P., Schmitz, B., 1998. Tropical Atlantic seasonal dynamics in the early middle Eocene from stable oxygen and carbon isotope profiles of mollusk shells. Paleoceanography 13/2, 183–192.

Andreasson, F.P., Schmitz, B., 2000. Temperature seasonality in the early middle Eocene North Atlantic region: evidence from stable isotope profiles of marine gastropod shells. Geological Society of America Bulletin 112/4, 628–640.

Böhm, F., Joachimski, M.M., Dullo, W.-C., Eisenhauer, A., Lehnert, H., Reitner, J., Woerheide, G., 2000. Oxygen isotope fractionation in marine aragonite of coralline sponges. Geochimica et Cosmochimica Acta 64, 1695–1703.

Böhme, M., 2003. The miocene climatic optimum: evidence from ectothermic vertebrates of Central Europe. Palaeogeography, Palaeoclimatology, Palaeoecology 195, 389–401.

Bojar, A.-V., Hiden, H., Fenninger, A., Neubauer, F., 2004. Middle Miocene seasonal temperature changes in the Styrian basin, Austria, as recorded by the isotopic composition of pectinid and brachiopod shells. Palaeogeography, Palaeoclimatology, Palaeoecology 203, 95–105.

Bottelo, A.V., Mandelli, E.F., Macko, S., Parker, P.L., 1980. Organic carbon isotope ratios of recent sediments from coastal lagoons of the Gulf of Mexico, Mexico. Geochimica et Cosmochimica Acta 44/3, 557–560.

Ćorić, S., Harzhauser, M., Hohenegger, J., Mandic, O., Pervesler, P., Roetzel, R., Rögl, F., Spezzaferri, S., Stingl, K., Švábenická, L., Zorn, I., Zuschin, M., 2004. Stratigraphy and correlation of the Grund formation in the molasse basin, northeastern Austria (Middle Miocene, Lower Badenian). Geologica Carpathica 55/2, 147–153.

Dettman, D.L., Reische, A.K., Lohmann, K.C., 1999. Controls on the stable isotope composition of seasonal growth bands in aragonitic fresh-water bivalves (Unionoidae). Geochimica et Cosmochimica Acta 63 (7/8), 1049–1057.

Durakiewicz, T., Gonera, M., Peryt, T.M., 1997. Oxygen and carbon isotopic changes in the Middle Miocene (Badenian) foraminifera of the Gliwice area (SW Poland). Bulletin of the Polish Academy of Sciences. Earth Science 45, 145–156.

Geary, D.H., Rich, J., Valley, J.W., Baker, K., 1989. Stable isotopic evidence of salinity change: influence on the evolution of melanopsid gastropods in the late Miocene Pannonian basin. Geology 17/11, 981–985.

Gonera, M., Peryt, T.M., Durakiewicz, T., 2000. Biostratigraphical and palaeoenvironmental implications of isotopic studies (^{18}O, ^{13}C) of middle Miocene (Badenian) foraminifers in the Central Paratethys. Terra Nova 12, 231–238.

Gradstein, F., Ogg, J., Smith, A. (Eds.), 2004. A Geological Time Scale. Cambridge University Press, pp. 1–589.

Grossman, E.L., Ku, T.-L., 1986. Oxygen and carbon isotope fractionation in biogenic aragonite: temperature effects. Chemical Geology 59, 59–74.

Haq, B.U., Hardenbol, J., Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level changes. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.S.C, Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea-level Changes: An Integrated Approach, Society of Economic Paleontologists and Mineralogists Special Publication, vol. 42, pp. 71–108.

Hardenbol, J., Thierry, J., Farley, M.B., Jacquin, T., de Graciansky, P.C., Vail, P.R., 1998. Mesozoic and Cenozoic Sequence Chronostratigraphic Framework of European Basins. In: Graciansky, P.-C., Hardenbol, J., Jacquin, T., Vail, P.R. (Eds.), Mesozoic and Cenozoic Sequence Stratigraphy of European Basins, SEPM, Special Publication, vol. 60, pp. 3–12.

Harzhauser, M., Wessely, G., 2004. The Karpatian of the Korneuburg Basin (Lower Austria). In: Brzobohatý, R., Cicha, I., Kovác, M., Rögl, F. (Eds.), The Karpatian—An Early Miocene Stage of the Central Paratethys. Masaryk University Brno, pp. 107–111.

Harzhauser, M., Böhme, M., Mandic, O., Hofmann, Ch.-Ch., 2002. The Karpatian (Late Burdigalian) of the Korneuburg basin—a palaeoecological and biostratigraphical synthesis. Beiträge zur Paläontologie 27, 441–456.

Harzhauser, M., Mandic, O., Zuschin, M., 2003a. Changes in Paratethyan marine molluscs at the Early/Middle Miocene transition: diversity, palaeogeography and palaeoclimate. Acta Geologica Polonica 53/4, 323–339.

Harzhauser, M., Daxner-Höck, G., Boon-Kristkoiz, E., Coric, S., Mandic, O., Miklas-Tempfer, P., Roetzel, R., Rögl, F., Schultz, O., Spezzaferri, S., Ziegler, R., Zorn, I., 2003b. Palaeoecology and biostratigraphy of the section Mühlbach (Gaindorf Formation, lower Middle Miocene, Lower Badenian, Austria). Annalen des Naturhistorischen Museums in Wien 104A, 323–334.

Hendry, J.P., Kalin, R.M., 1997. Are oxygen and carbon isotopes of mollusc shells reliable palaeosalinity indicators in marginal marine environments? A case study from the Middle Jurassic of England. Journal of the Geological Society, London 154, 321–333.

Hladilova, S., Hladikova, J., Kovac, M., 1998. Stable isotope record in miocene fossils and sediments from Rohoznik (Vienna Basin, Slovakia). Slovak Geological Magazine 4/2, 87–94.

Jones, D.S., Allmon, W.D., 1995. Records of upwelling, seasonality and growth in stable-isotope profiles of Pliocene mollusk shells from Florida. Lethaia 28, 61–74.

Jones, D.S., Williams, D.F., Arthur, M.A., 1983. Growth history and ecology of the Atlantic surf clam *Spisula solidissima* (Dillwyn) as revealed by stable isotopes and annual shell increments. Journal of Experimental Marine Biology and Ecology 73, 225–242.

Jones, D.S., Arthur, M.A., Allard, D.J., 1989. Sclerochronological records of temperature and growth from shells of *Mercenaria mercenaria* from Narragansett Bay, Rhode Island. Marine Biology 102, 225–234.

Kaandorp, R.J.G., Wesselingh, F.P., Vonhof, H.B., in press. Ecological implications from geochemical records of Miocene western Amazonian bivalves. Journal of South American Earth Sciences, Special Issue on Neogene Amazonia (published online).

Kaandorp, R.J.G., Vonhof, H.B., Del Busto, C., Wesselingh, F.P., Ganssen, G.M., Marmól, A.E., Romero Pittman, L., van Hinte, J.E., 2003. Seasonal stable isotope variation of the Amazonian fresh water bivalve *Anodontites trapesialis*. Palaeogeography, Palaeoclimatology, Palaeoecology 194, 327–342.

Killingly, J.S., Berger, W.H., 1979. Stable iostopes in a mollusk shell: detection of upwelling events. Science 205, 186–188.

Klein, R.T., Lohmann, K.C., Thayer, C.W., 1996. Bivalve skeletons record sea-surface temperature and δ^{18}O via Mg/Ca and ^{18}O/^{16}O ratios. Geology 24, 415–418.

Kováč, M., Barath, I., Harzhauser, M., Hlavaty, I., Hudackova, N., 2004. Miocene depositional systems and sequence stratigraphy of the Vienna Basin. Courier Forschungsinstitut Senckenberg 246, 187–212.

Krantz, D.E., 1990. Mollusk-isotope records of Plio-Pleistocene marine paleoclimate, U.S. Middle Atlantic Coastal Plain. Palaios 5, 317–335.

Latal, C., Piller, W.E., Harzhauser, M., 2004. Palaeoenvironmental reconstructions by stable isotopes of Middle Miocene gastropods of the Central Paratethys. Palaeogeography, Palaeoclimatology, Palaeoecology 211, 157–169.

Latal, C., Piller, W.E., Harzhauser, M., in press. Small-scaled environmental changes: indications from stable isotopes of gastropods (Early Miocene, Korneuburg Basin, Austria). International Journal of Earth Sciences.

Lear, C.H., Elderfield, H., Wilson, P.A., 2000. Cenozoic deep-sea temperatures and global ice volumes from Mg/Ca in Benthic Foraminiferal Calcite. Science 287, 269–272.

Lécuyer, C., Reynard, B., Martineau, F., 2004. Stable isotope fractionation between mollusc shells and marine waters from Martinique Island. Chemical Geology 213, 293–305.

Matyas, J., Burns, S.J., Müller, P., Magyar, I., 1996. What can stable isotopes say about salinity? An example from the late Miocene Pannonian Lake. Palaios 11, 31–39.

Popov, S.V., Rögl, F., Rozanov, A.Y., Steininger, F.F., Shcherba, I.G., Kováč, M., 2004. Lithological-Paleogeographic maps of Paratethys. 10 Maps Late Eocene to Pliocene. Courier Forschungsinstitut Senckenberg 250, 1–46.

Purton, L.M.A., Brasier, M.D., 1997. Gastropod carbonate δ^{18}O and δ^{13}C values record strong seasonal productivity and stratification shifts during the late Eocene in England. Geology 25/10, 871–874.

Reichenbacher, B., 1998. Fisch-Otolithen aus dem Karpat des Korneuburger Beckens. Beiträge zur Paläontologie 23, 325–345.

Roetzel, R., Pervesler, P., 2004. Storm-induced event deposits in the type area of the Grund Formation (Middle Miocene, Lower Badenian) in the Molasse Zone of Lower Austria. Geologica Carpathica 55, 87–102.

Rögl, F., 1998a. Palaeogeographic considerations for Mediterranean and Paratethys Seaways (Oligocene to Miocene). Annalen des Naturhistorischen Museums in Wien 99, 279–310.

Rögl, F., 1998b. Das Werden der Zentralen Paratethys im Tertiär. In: Schultz, O. (Ed.), Tertiärfossilien Österreichs. Goldschneck Verlag, pp. 10–11.

Rögl, F., Spezzaferri, S., Coric, S., 2002. Micropaleontology and biostratigraphy of the Karpatian-Badenian transition (Early-Middle Miocene boundary) in Austria (Central Paratethys). Courier Forschungsinstitut Senckenberg 237, 47–67.

Roy, K., 1994. Effects of the Mesozoic Marine Revolution on the taxonomic, morphologic, and biogeographic evolution of a group: aporrhaid gastropods during the Mesozoic. Paleobiology 20, 274–296.

Schultz, O., 1998. Die Knorpel- und Knochenfischfauna (excl. Otolithen) aus dem Karpat des Korneuburger Beckens (Niederösterreich). Beiträge zur Paläontologie 23, 295–323.

Schultz, O., 2003. The Middle Miocene Fish Fauna (excl. Otoliths) from Mühlbach am Manhartsberg and Grund near Hollabrunn, Lower Austria. Annalen des Naturhistorischen Museums in Wien 104A, 185–193.

Stott, L.D., 2002. The influence of diet and the δ^{13}C of shell carbon in the pulmonate snail *Helix aspersa*. Earth and Planetary Science Letters 195/3–4, 249–259.

Sutovska, K., Kantor, J., 1992. Oxygen and carbon isotopic analysis of Karpatian foraminifera from LKS borehole (Southern Slovakian Basin). Mineralia Slovaca 24, 209–218.

Teusch, K.P., Jones, D.J., Allmon, W.D., 2002. Morphological variation in turritellid gastropods from the pleistocene to recent of Chile: association with upwelling intensity. Palaios 17, 366–377.

Tripati, A., Zachos, J., 2002. Late Eocene tropical sea surface temperatures; a perspective from Panama. Paleoceanography 17/3, 1032–1046.

Wagner, L.R., 1996. Stratigraphy and hydrocarbons in the Upper Austrian Molasse Foredeep (active margin). In: Wessely, G., Liebl, W. (Eds.), Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe, EAGE Special Publications, vol. 5, pp. 217–235.

Wessely, G., 1998. Geologie des Korneuburger Beckens. Beiträge zur Paläontologie 23, 9–23.

Williams, D.F., Arthur, M.A., Jones, D.S., Healy-Williams, N., 1982. Seasonality and mean annual sea surface temperatures from isotopic and sclerochronological records. Nature 296/5856, 432–434.

Yonge, C.M., 1938. Evolution of ciliary feeding in the Prosobranchia, with an account of feeding in *Capulus ungaricus*. Journal of the Marine Biological Association of the United Kingdom 22, 377–380.

Yonow, N., 1989. Feeding observations on *Acteon tornatilis* (Linneaus) (Opisthobranchia: Acteonidae). Journal of Molluscan Studies 55, 97–102.

Zuschin, M., Mandic, O., Harzhauser, M., Pervesler, P., 2001. Fossil evidence for chemoautotrophic bacterial symbiosis in the thyasirid bivalve *Thyasira michelottii* from the middle miocene (Badenium) of Austria. Historical Biology 15, 123–134.

Zuschin, M., Harzhauser, M., Mandic, O., 2004. Taphonomy and paleoecology of the Lower Badenian (Middle Miocene) molluscan assemblages at Grund (Lower Austria). Geologica Carpathica 55/2, 117–128.