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Small-scaled environmental changes: indications from stable isotopes of gastropods (Early Miocene, Korneuburg Basin, Austria)

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Abstract The Korneuburg Basin, with mainly upper Lower Miocene (Karpatian) sediment filling, is divided by the Mollmannsdorf–Obergänsersdorf Swell into two sub-basins characterised by different environmental settings. Paleoecological data indicate a marine northern part and a mainly estuarine southern part. Nevertheless, short-termed marine incursions from the north allowed marine faunas (ostracods, molluscs, and echinoids) to temporarily settle the southern part of the basin. The carbon and oxygen isotopic composition of gastropod shells from these different environmental settings were investigated. Highest $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values are found in *Turritella* shells from the northern part of the basin, and in *Turritella* shells from layers interpreted as a marine incursion in the south. Generally, components of the mudflat fauna (*Tympanotonos cinctus*, *Granulolabium bicinctum*, *Terebralia bidentata*, and *Ocenebra crassilabiata*) have slightly lower isotope values. Considerable freshwater influx in the southern part is documented by abundant freshwater genera such as *Melanopsis*, which show low carbon and oxygen isotope values. Data of identical taxa, especially *Turritella* and *Granulolabium*, reflect a trend from higher isotope values at the marine northern part to slightly lower values in the mainly estuarine southern part of the basin. Differences in $\delta^{18}\text{O}$ between the marine and the estuarine assemblages are interpreted to be caused by changes in salinity and isotopic composition of ambient water rather than by temperature. Paleotemperature estimates derived from oxygen isotope data are in good agreement with existing

paleoclimatic proxies for the Korneuburg Basin. Hence, an annual range of the sea-surface temperature from 13 to 26°C can be predicted within that protected basin.

Keywords Stable isotopes · Gastropods · Paleoecology · Paleoclimate · Salinity

Introduction

A widely applied method to reconstruct paleoenvironmental parameters is the actualistic approach of comparing fossil taxa with modern close relatives, or by comparing fossil assemblages with living counterparts. This uniformitarian approach, however, bears considerable risks and should therefore be supported by physical and chemical techniques. In addition to the paleoecological data derived from autecological and synecological analyses, biogenic carbonates can provide paleoenvironmental information, which is recorded in their chemical and isotopic composition. The oxygen isotopic composition of fossil molluscs can yield quantitative information about paleoenvironmental conditions, as molluscs are considered to precipitate their shells in near oxygen isotopic equilibrium (Grossman and Ku 1986; Cornu et al. 1993). $\delta^{18}\text{O}$ values of gastropod shells are a function of both temperature and the $\delta^{18}\text{O}$ of ambient water, which is related to salinity through processes of evaporation and freshwater dilution. $\delta^{13}\text{C}$ values in carbonate shells are mainly related to the isotopic composition of the dissolved inorganic carbon, but vital effects may lead to non-equilibrium fractionation.

As each method has its advantages, its drawbacks and limits in resolution, a combination of different independent methods can yield a more detailed paleoenvironmental interpretation.

The Korneuburg Basin, with deposits of mainly Karpatian (Early Miocene) age, shows a complex interplay of marine and coastal-terrestrial conditions. Although the geology and paleoecology of the Korneu-

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burg Basin has been intensively studied in the last years (Sovis and Schmid 1998, 2002), geochemical data are still missing. Generally, only few isotope studies have been performed 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).

The Korneuburg Basin yields one of the most diverse mollusc faunas known from the Karpatian of the Central Paratethys. In total, 162 gastropod species and 65 bivalve species are reported by Harzhauser et al. (2002b), Binder (2002), Ctyroký (2002), and Zuschin et al. (2004).

To test the detailed reconstruction of the paleoecology of the Korneuburg Basin, based on the distribution and composition of the Karpatian fauna and flora (Harzhauser et al. 2002b), we performed a stable isotope study on several gastropod samples from different environments. The paleotemperature estimates derived from the oxygen isotope data are compared with existing paleoclimatic proxies for the Korneuburg Basin.

Geological setting

The Korneuburg Basin is part of the Central Paratethys. This intracontinental sea, along with the Mediterranean Sea, formed as new marine realms during the Late Eocene as a heritage of the Tethys Ocean (Harzhauser et al. 2002a). Especially during the Miocene, the Paratethys area underwent distinct paleogeographical changes [see Rögl (1998a) for a detailed synthesis]. Consequently, the reorganisation and the repeated opening and closing of marine pathways caused fundamental changes in environmental conditions, which is reflected in the manifold fossil communities. Within that setting, the small, asymmetric Korneuburg Basin formed as a pull apart basin within the Alpine–Carpathian thrust belt during late Alpine movements (Wessely 1998).

The SSE–NNE elongated Korneuburg Basin (Fig. 1) was about 20 km long. The maximum width was 7 km, but in the northern part it narrowed to about 1.5 km. The basin was divided into two depocenters by a swell in the area of Obergänserndorf–Mollmannsdorf. The southern part of the basin was about 600 m deep, while the northern depocenter attained a depth of only 400 m.

In the northern part, the Waschberg Zone formed the margin and the base of the basin, while in the southern part the Flysch Zone delimited the basin. These Alpine–Carpathian nappes are underlain by the autochthonous basement, formed mainly by Upper Cretaceous and Jurassic units, and finally by the crystalline of the Bohemian Massif (Malzer et al. 1993). At the eastern margin, except for its northernmost part, faults are lacking, but on the western border the basin subsided along the Schlieffberg Fault. The considerable increase of sediment thickness towards this western fault zone bears witness to synsedimentary tectonic activity during Karpatian time.

Sedimentation started during the Eggenburgian (Lower Burdigalian), but the main basin fill is represented by Karpatian sediments (Upper Burdigalian). Most of the Karpatian Basin fill is lithostratigraphically united in the Korneuburg Formation. This depositional sequence is represented mainly by grey to yellow marly silt and fine to medium sand. Rarely, gravel and boulders occur near the Flysch Zone. A second lithological unit is formed by clayey marls with intercalated diatomites (“Diatomeenschiefer mit Fischresten”), which are exposed in the northern part of the basin near Großbrüßbach.

The Karpatian deposits of the Korneuburg Basin are dated into the latest Early Miocene (Fig. 2). The correlation of mammal remains with paleomagnetic data allowed a dating into the early mammal zone MN 5, spanning a time of about 16.5–16.7 My (Daxner-Höck 1998; Harzhauser et al. 2002b).

A more detailed introduction into the geology, paleoecology and the history of investigation of the Korneuburg Basin was presented by Wessely (1998) and Harzhauser (2002).

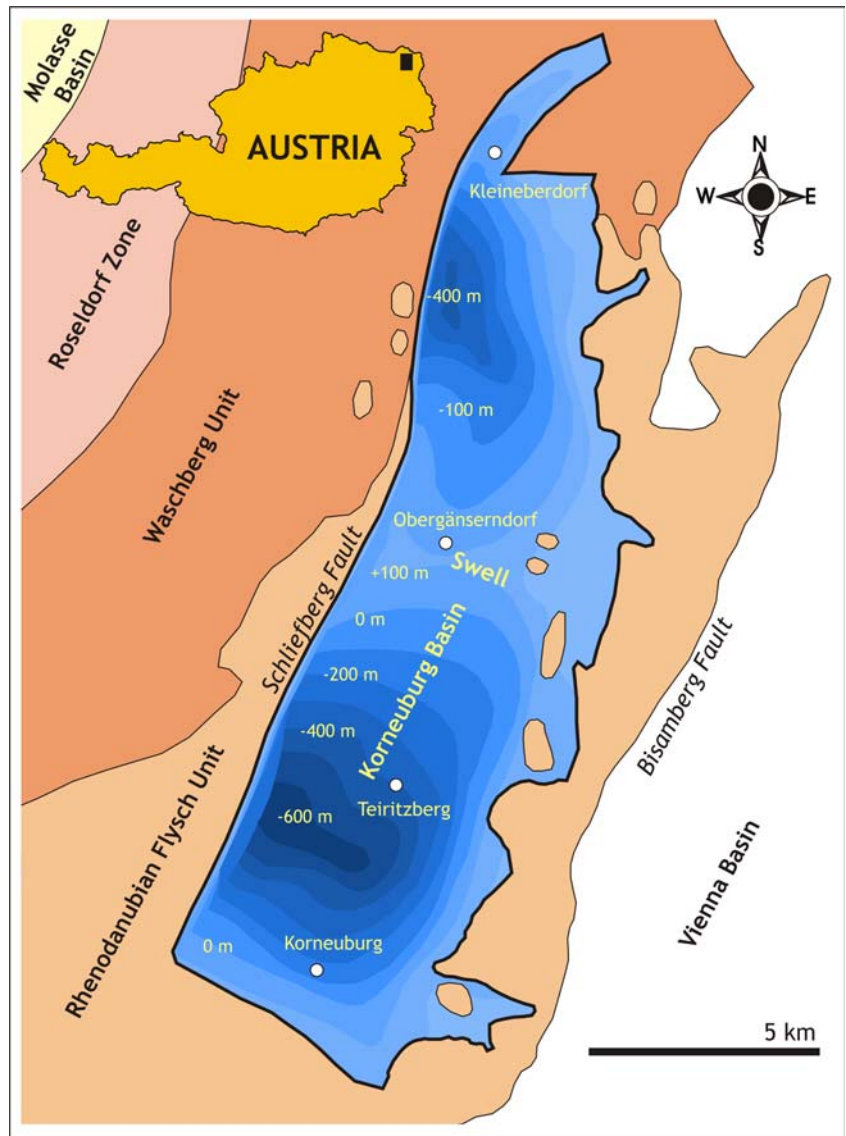
Paleoecology and paleogeography

Paleomagnetic investigations by Scholger (1998) suggest a southern position of the Korneuburg Basin in the Early Miocene with a hypothetical paleolatitude of 34°N. Furthermore, the author proposed a counterclockwise rotation of the basin by 22° since the Karpatian.

During the Karpatian, the Korneuburg Basin was situated in a protected position, having been largely isolated from the open Paratethys Sea. In a contemporary development in the neighbouring Vienna Basin, limnic/fluvial environments of a meandering river system were established on a slightly NE inclined fluvial plain (Weissenböck 1995). This depositional environment is evidenced by sandstones with intercalations of pelites and scattered fine conglomerates of the Aderklaa Formation. The distinct fluvial input along the eastern margin of the Korneuburg Basin in the area of the Obergänserndorf–Mollmannsdorf Swell suggests that the influence of the meandering river system of the Vienna Basin reached farther into the north than proposed in earlier studies (e.g. Seifert in Sauer et al. 1992). A connection to the marine realm therefore existed only along the northern tip, where the Paratethys Sea extended into the Alpine–Carpathian Foredeep. This situation is also reflected in the internal facies patterns.

The two sub-basins show differences in their two depositional environments. In the northern, predominantly marine part, shallow marine settings of 20–30 m water depth (Rögl 1998b) formed, with scattered corals inhabiting the silty to sandy bottom. In contrast, the southern basin, separated from the marine northern basin by the Obergänserndorf–Mollmannsdorf Swell, was characterised by estuarine settings. The Kleinebersdorf

Fig. 1 Location and generalized simplified geological map of the Korneuburg Basin (isobathes within the basin refer to thickness of Karpatian basin fill; after Wessely 1998). Two depocenters divided by a swell zone in the area of Obergänsersdorf are developed. A connection to the Paratethys Sea was established in the northeastern part of the basin



section, located north of the swell (Fig. 1), reflects a strong marine influence. The gastropod fauna yields many sublittoral, carnivorous, and infaunal species. A complex marine ecosystem with sponges, corals, and various echinoderms is predicted, based on the predators *Triphora perversa*, *Architectonica simplex*, *Zonaria dermatygdaloides*, *Ficopsis burdigalensis*, *Ficus cingulata*, and *Phalium (Semicassis) miolaevigata*. The littoral zone is well documented by mudflat-dwelling batillariid and potamidid gastropods such as *Granulolabium bicinctum*, *Terebralia bidendata*, and *Tympanotonos cinctus*. The same environment was settled in the northern part of the basin by very large populations of the giant turritellid *Turritella gradata*.

Corals, such as *Porites* and *Balanophyllia*, are also recorded from Kleinebersdorf (Kleemann 2002). The northern part of the basin is therefore interpreted as a marine embayment with connection to the Central Paratethys Sea.

In the southern part of the basin, tidal mudflats with extensive oyster biostromes, composed largely of the giant *Crassostrea gryphoides*, developed along large parts of the coasts. The wetland system of the southern Korneuburg Basin is interpreted as a small, narrow estuary, which was bordered by rather abrupt tectonic margins (Harzhauser et al. 2002b). Small-scale fluctuations of the relative sea level, however, caused repeated marine floodings in the southern basin.

The investigated gastropod samples from the southern Korneuburg Basin derive from Teiritzberg and Rückersdorf (Fig. 1). Generally, the assemblages from the Teiritzberg section point to a strong estuarine influence. Considerable freshwater influx is documented by abundant freshwater genera such as *Melanopsis*, *Stagnicola*, and *Theodoxus*, as well as by freshwater fishes such as *Aphanius* and *Carassius* (Reichenbacher 1998; Schultz 1998). However, several layers document short-termed marine incursions, allowing marine

Fig. 2 Late Oligocene to Late Miocene geochronology and biostratigraphy; *grey bar* displays the time classification of the investigated gastropods from the Korneuburg Basin (after Harzhauser et al. 2002b)

Time (Ma)	Chronos	Polarity	Epochs	Mediterr. Ages	Central & Western Paratethys Ages	Eastern Paratethys Ages	Calcareous Nanno - Zones	Mammal - Zones	Planktic Foraminifera - Zones
5.3	C3A		Late Miocene	MESSINIAN	PONTIAN	PONTIAN	NN11	MN13	M14
	C3B							MN12	b
	C4							MN11	M13
	C4A			TORTONIAN	PANNONIAN	MAEOTIAN	NN10	MN10	a
	C5						NN9b	MN9	
	C5A						NN9a/8		M12 (N15)
	C5AB						NN7	MN 8-7	M11-M8 (N14-N11)
	C5AC			SERRAVALLIAN	SARMATIAN	Bessarabian	NN6		
	C5AD								M7 (N10)
	C5B								M6 (N9)
	C5C			LANGHIAN	BADENIAN	TARKHANIAN	NN5	MN5	M5 (N8)
	C5D								M4 (N7)
	C5E								M3 (N6)
	C6		Early Miocene						M2 (N5)
	C6A								
	C6AA								
	C6B								M1 (N4)
	C6C								a
	C7		Oligocene						MP 28-30
	C8			CHATTIAN	EGERIAN	KALMYKIAN	NN1	MP27	P22
							NP25	MP24	

ostracods, molluscs and echinoids to settle in the southern part of the Korneuburg Basin (Harzhauser et al. 2002b). These ingressions are also reflected by the occurrence of marine rays and sharks.

The best-preserved paleoecosystem of the southern Korneuburg Basin is represented by extensive *C. gryphoides* biostromes; they became established in the mixohaline shallow subtidal to lower intertidal zone of the estuarine bay. This giant euryhaline oyster formed vast colonies, giving shelter to numerous species that depended directly or indirectly on that ecosystem. Laterally, these oyster biostromes frequently graded into mudflats. The investigated shells of *T. cinctus*, *G. bicinctum* and *T. bidendata*, as well as *Ocenebra crassilabiata*, derive from these laterally changing settings. Based on the thanotocoenoses, we predict a preference of *T. cinctus* and *O. crassilabiata* for the *Crassostrea* biostromes, whereas *G. bicinctum* is by far most abundant within the mudflat settings. *T. bidendata* occurs in thanotocoenoses of both paleoenvironments, but is more frequent in mudflat assemblages. The interplay of short-termed marine floodings versus freshwater discharge within an estuary is also reflected in the changing composition of the turrnellid assemblages: the pelites of the littoral zone bear numerous specimens of *T. gradata*, whereas *Turritella bicarinata* is most frequent in shallow sublittoral silt and sand. Both species seem to have been adapted to fluctuating salinities based on the co-occurring mollusc fauna. In contrast, *Turritella bellardii* is exclusively found in marly silt in presumably sublittoral settings. Scattered occurrences of planktonic foraminifera within these layers furnish evidence of an increased marine influence (Harzhauser et al. 2002b).

Materials and methods

Well-preserved gastropod specimens from Kleinebersdorf, Rückersdorf, and Teiritzberg of the Korneuburg Basin were used for the stable isotope investigations (Table 1). The samples were investigated for their shell mineralogy and microstructures by X-ray diffraction and scanning electron microscopy (SEM) to detect diagenetic recrystallisation. The mineralogical composition of the shells was analysed with a Bruker D8 Discover diffractometer with General Area Detector Diffraction Solutions (GADDS). This instrument allows single points on a sample to be investigated without destroying the shells. For SEM analyses, shell fragments from the aperture were used. The same shells, which were investigated for diagenesis, were chosen for stable isotope measurements: specimens were sampled in ontogenetic sequence from apex to aperture with a 0.3 mm drill.

In total, 234 samples from 22 shells were analysed for stable isotopes. Sample density depended on the size of each shell, but at least six samples from each shell were measured. In most turrnellid shells, two samples per whorl were collected. A similar sampling strategy, one sample per whorl, has been used for recent turrnellids by Allmon et al. (1992), and Jones and Allmon (1995). Multiple samples from the shells were taken in order to estimate the range of isotopic values within one shell. Samples were reacted with 100% phosphoric acid at 70°C in a ThermoFinnigan Kiel II automated reaction system and measured with a ThermoFinnigan Delta Plus isotope-ratio mass spectrometer at the Institute of Earth Sciences, University of Graz. Repeated measurements of

Table 1 Oxygen and carbon isotope ranges and mean values of aragonitic gastropod shells from the Korneuburg Basin

Locality (species)	Samples/shell (n)	$\delta^{18}\text{O}$ (‰ versus VPDB)			$\delta^{13}\text{C}$ (‰ versus VPDB)		
		Min.	Max.	Mean (SD)	Min.	Max.	Mean (SD)
Kleinebersdorf							
<i>T. gradata</i>	17	-2.0	-0.3	-1.5 (± 0.5)	1.0	3.0	2.1 (± 0.5)
<i>T. gradata</i>	13	-1.9	0.1	-1.3 (± 0.5)	0.9	2.1	1.6 (± 0.3)
<i>T. gradata</i>	12	-1.7	0.2	-1.2 (± 0.6)	1.1	1.9	1.4 (± 0.2)
<i>G. bicinctum</i>	14	-1.9	-0.2	-1.2 (± 0.5)	-0.6	1.3	0.6 (± 0.5)
<i>G. bicinctum</i>	13	-2.0	-0.4	-1.3 (± 0.4)	-0.9	1.3	0.5 (± 0.6)
<i>G. bicinctum</i>	8	-2.1	-1.2	-1.5 (± 0.3)	-0.6	0.9	0.3 (± 0.4)
<i>O. crassilabiata</i>	6	-1.9	-1.2	-1.7 (± 0.2)	0.4	1.1	0.8 (± 0.2)
Teiritzberg							
<i>T. gradata</i>	16	-3.1	-2.2	-2.8 (± 0.2)	0.6	2.0	1.3 (± 0.4)
<i>T. gradata</i>	12	-3.6	-0.8	-2.8 (± 0.7)	1.0	1.9	1.5 (± 0.2)
<i>T. bicarinata</i>	12	-1.0	0.5	-0.1 (± 0.5)	1.0	3.5	2.4 (± 0.8)
<i>T. bellardii</i>	10	-1.4	-0.7	-1.1 (± 0.2)	2.0	3.1	2.4 (± 0.3)
<i>T. bellardii</i>	7	-1.4	-0.9	-1.1 (± 0.2)	2.5	3.0	2.8 (± 0.2)
<i>O. crassilabiata</i>	9	-1.3	0.8	-0.5 (± 0.6)	2.1	3.1	2.4 (± 0.3)
<i>O. crassilabiata</i>	8	-2.1	-0.2	-1.2 (± 0.6)	0.2	2.0	1.2 (± 0.5)
<i>T. bidentata</i>	12	-2.9	-1.1	-2.3 (± 0.5)	-1.8	-0.4	-1.1 (± 0.5)
<i>T. cinctus</i>	11	-2.1	0.1	-1.2 (± 0.7)	-2.6	-0.1	-1.5 (± 0.8)
<i>Melanopsis impressa</i>	6	-9.5	-7.0	-8.7 (± 0.9)	-5.0	-2.9	-4.2 (± 0.7)
<i>Melanopsis impressa</i>	9	-9.0	-7.9	-8.7 (± 0.4)	-6.4	-5.0	-6.1 (± 0.4)
Rückersdorf							
<i>G. bicinctum</i>	8	-3.2	-0.8	-2.3 (± 0.7)	-1.5	0.0	-0.7 (± 0.5)
<i>G. bicinctum</i>	15	-2.4	-1.2	-1.8 (± 0.4)	-1.8	0.1	-1.0 (± 0.6)
<i>G. bicinctum</i>	10	-2.8	-1.1	-1.9 (± 0.5)	-1.8	-0.2	-1.0 (± 0.6)
<i>T. bidentata</i>	6	-2.7	-0.3	-1.3 (± 0.7)	-2.3	-0.4	-1.6 (± 0.7)

NBS-19 and an internal laboratory standard yield a standard deviation of 0.1‰ for both $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$. Values are given in permil relative to V-PDB.

Results

Shell mineralogy

The shell mineralogy was determined using X-ray diffraction techniques. In all samples, only aragonite was found. SEM investigations performed on the samples also confirmed the aragonitic composition. As aragonite is metastable and easily converts to calcite during diagenesis, the results show that all samples are nearly unaffected by diagenesis. The results also provide strong evidence that stable isotope values are primary and can be used for paleoenvironmental analyses.

Oxygen and carbon isotopes

The results of the oxygen and carbon isotope measurements are listed in Table 1.

Kleinebersdorf

The three shells of *T. gradata* show similar $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values; $\delta^{18}\text{O}$ values range from -2.0 to 0.2‰, and $\delta^{13}\text{C}$ values from 0.9 to 3.0‰. Samples from three shells of *G. bicinctum* show $\delta^{18}\text{O}$ values of -2.1 to -0.2‰ and $\delta^{13}\text{C}$

values of -0.6 to 1.3‰. *O. crassilabiata* yields results comparable to the shells of *G. bicinctum*, with $\delta^{18}\text{O}$ values from -1.9 to -1.2‰, and $\delta^{13}\text{C}$ values of 0.4 to 1.1‰.

Teiritzberg

Seven different gastropod species from various environmental settings were measured from the locality Teiritzberg.

Shells of *T. bellardii* show $\delta^{18}\text{O}$ values from -1.4 to -0.7‰, and $\delta^{13}\text{C}$ values from 2.0 to 3.1‰. The shell of *T. bicarinata* yields $\delta^{18}\text{O}$ values from -1.0 to 0.5‰, and $\delta^{13}\text{C}$ values of 1.0 to 3.5‰, while $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of the two shells of *T. gradata* are lower, -3.6 to -0.8 and 0.6 to 2.0‰, respectively. The two shells of *O. crassilabiata* show a small overlapping range only in $\delta^{18}\text{O}$: one shell yields values from -1.3 to 0.8‰, the second from -2.1 to -0.2‰. $\delta^{13}\text{C}$ values of the two shells are not consistent. The shell with higher $\delta^{18}\text{O}$ values shows also higher $\delta^{13}\text{C}$ values from 2.1 to 3.1‰, in contrast to 0.2 to 2.0‰ of the second shell. $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of *O. crassilabiata* fall into the range of the Turritellidae. In contrast, *T. cinctus* and *T. bidentata* differ remarkably from the other investigated shells of Teiritzberg in their $\delta^{13}\text{C}$ values, with a range from -0.1 to -2.6‰. Although their $\delta^{13}\text{C}$ values are quite consistent, $\delta^{18}\text{O}$ values of *T. cinctus* are higher (-2.1 to 0.1‰) than those of *T. bidentata* (-2.9 to -1.1‰). *Melanopsis impressa* shells yield the lowest $\delta^{18}\text{O}$ (-9.5 to -7.0‰) and $\delta^{13}\text{C}$ values (-6.4 to -2.9‰).

Rückersdorf

One shell of *G. bicinctum* shows a prominent variation in $\delta^{18}\text{O}$ values from -3.2 to -0.8‰ . The other two shells of *G. bicinctum* yield similar values but within smaller ranges. $\delta^{13}\text{C}$ values of the three shells are quite consistent (-1.8 to -0.2‰). The $\delta^{18}\text{O}$ values of the *T. bidentata* shell range from -2.7 to -0.3‰ , indicating no distinct difference in comparison to the shells of *G. bicinctum*; $\delta^{13}\text{C}$ varies from -2.3 to -0.4‰ .

Discussion

Paleoenvironment

Oxygen and carbon isotopes have been used to differentiate between marine, brackish and freshwater environments (Keith and Weber 1964; Keith et al. 1964; Keith and Parker 1965; Stanton and Dodd 1970; Mook 1971; Dodd and Stanton 1975; Anderson and Arthur 1983; Hudson et al. 1995; Hendry and Kalin 1997). The feasibility of differentiating these environments by investigating oxygen and carbon isotopes is based on the generally contrasting $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of seawater and freshwater. While today's marine water shows $\delta^{18}\text{O}$ values around 0‰ SMOW and $\delta^{13}\text{C}$ around 2‰ PDB (Kroopnick 1980), freshwater can exhibit a wide range of isotope compositions, although $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values are commonly distinctly lower. Brackish water systems usually show intermediate isotopic ratios. Here, however, the relationship between salinity and isotopic composition is often more complicated: for example, $\delta^{18}\text{O}$ in the seawater–freshwater mixing zone can be strongly influenced by evaporation, depending on the water residence time and climate. Areas with long water residence times, for example lagoons or pools, can be characterised by high evaporation rates leading to high $\delta^{18}\text{O}$ values (Holmden et al. 1997).

Paleoenvironmental reconstructions based on oxygen and carbon isotope data of mollusc shells are only useful if the isotopic values reflect the conditions during carbonate formation. The preservation of the original aragonitic shell material is good evidence for a primary isotope signal. Significant intra-shell variability in the stable isotope values is also an indication that shells have retained their primary geochemical signature (Tripathi et al. 2001). Furthermore, molluscs are considered to precipitate their shells in oxygen isotopic equilibrium (Grossman and Ku 1986; Cornu et al. 1993). Thus, it is reasonable to assume that the oxygen isotopic composition of the analysed aragonitic gastropod shells indicates the Late Karpatian environmental conditions of the Korneuburg Basin. The main controlling factors of $\delta^{18}\text{O}$ in gastropod shells are temperature and the $^{18}\text{O}/^{16}\text{O}$ ratio of ambient water, which is related to climatic conditions and salinity. In contrast, $\delta^{13}\text{C}$ values are influenced by a multitude of factors, e.g., upwelling, productivity, diet, living mode, growth rate (Geary et al.

1992 cum lit.; Allmon et al. 1992; Bonadonna et al. 1999).

Among gastropod genera, recent as well as fossil Turritellidae have been studied by stable isotopes (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, mainly shallow infaunal or epifaunal, most commonly in waters less than 100 m deep. They prefer normal marine salinities, but several species tolerate lower salinities (Allmon 1988). Stable isotope investigations of recent specimens support their usefulness as isotopic indicators for environmental parameters. Thus, fossil turritellids have been used for stable isotope investigations to determine paleoenvironmental conditions (Andreasson and Schmitz 1996).

Data on life spans and growth rates are available for only few recent species and are mainly based on stable isotope profiles. *Turritella gonostoma* is reported to grow by about 14–17 whorls (70–110 mm) in 1.5 years (Allmon et al. 1992). Pliocene *Turritella apicalis* and *T. gladeensis* show higher growth rates of about 18–20 whorls per year (Jones and Allmon 1995). Recent *T. cingulata* and its supposed Pleistocene ancestor *T. cingulatifformis* exhibit growth rates of about ten whorls in 2 years (Teusch et al. 2002). No detailed age estimation is available for the three species of *Turritella* analysed in this study. Based on the overall shape of giant and extremely thick-shelled *T. gradata* (measuring up to 150 mm in height), a life span of at least 1.5–2 years is predicted. A shorter life span is expected for the small-sized *T. bellardii*, which usually does not exceed 25 mm in height.

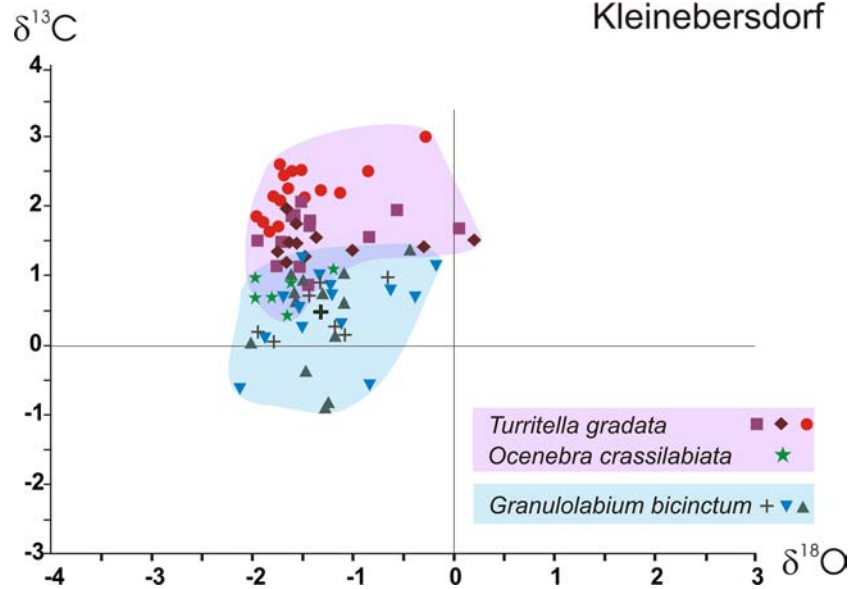
$\delta^{18}\text{O}$ values for the three specimens of *T. gradata* from Kleinebersdorf are comparable (Fig. 3). Their maximum variance in $\delta^{18}\text{O}$ differs slightly from shell to shell (between 1.7 and 2.0‰). These ranges are in good agreement with isotope results from other fossil as well as recent *Turritella* specimens (Allmon et al. 1992, 1994; Jones and Allmon 1995; Andreasson and Schmitz 1996, 2000; Teusch et al. 2002). Allmon et al. (1992), and Jones and Allmon (1995) demonstrated that the seasonality of water temperature is well documented in the $\delta^{18}\text{O}$ signal of the Turritellidae shells by a sampling density of about two samples per whorl. As the sampling density in the *Turritella* shells of the Korneuburg Basin is similar, these specimens probably also reflect the maximum isotopic range.

The samples from the other two gastropod genera measured from Kleinebersdorf show $\delta^{18}\text{O}$ values comparable to those of the *Turritella* shells: the three *G. bicinctum* shells yield a minimum value of -2.1‰ ; their maximum isotope values are slightly lower than for the *Turritella* shells, with 0.9, 1.6, and 1.7‰. $\delta^{18}\text{O}$ values of *O. crassilabiata* are in the same range as the other shells, but the maximum and minimum values differ by only 0.7‰.

Isotope data of the Teiritzberg samples yield a large range of values due to their origin from different envi-

Kleinebersdorf

Fig. 3 Oxygen and carbon isotope data of gastropod shells from Kleinebersdorf. *Blue* and *purple fields* indicate different life habitats in the marine environment. The probably exclusively mudflat dwelling browsing *Granulolabium* specimens concentrate in the purple field whilst the less vagile *T. gradata* specimens are supposed to have settled the lower littoral to shallow sublittoral zone. The intermediate position of the carnivorous *Ocenebra* might point to a tendency to avoid the extreme habitats still acceptable for *Granulolabium*



ronmental conditions (Fig. 4). Some specimens reflect estuarine conditions (*T. gradata*), others marine ingressesions (*T. bellardii*/*T. bicarinata*). $\delta^{18}\text{O}$ values of the *Turritella* shells from the marine ingressesions range from

-1.4 to 0.5‰ . The narrow range of $\delta^{18}\text{O}$ values in *T. bellardii* (0.7 and 1.1‰) may reflect the lack of a complete annual cycle due to a shorter life span, as inferred from their small size (12 mm). In contrast,

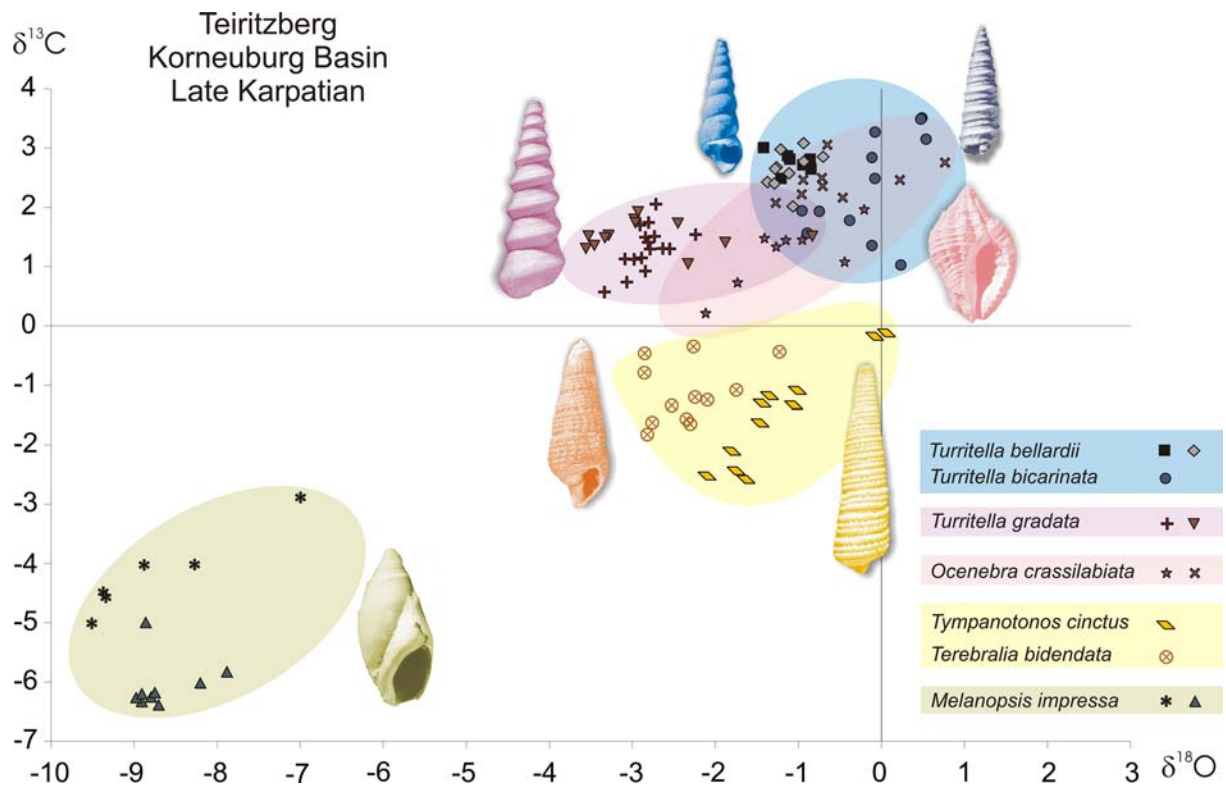


Fig. 4 Oxygen and carbon isotope data of gastropod shells from Teiritzberg; *coloured fields* group different environmental conditions and life habitats of the analysed gastropod shells (*blue field* rather stable marine environment; *purple field* estuarine and/or littoral environment; *yellow field* estuarine mudflat environment, *green field* riverine freshwater environment). Within the turritellids

the gradient from the euryhaline *T. gradata* via an intermediate position of *T. bellardii* towards the more stenohaline *T. bicarinata* is obvious. The observed co-occurrence of *T. gradata* and *T. bicarinata* in some layers might thus result from short environmental fluctuations and a subsequent low-grade time averaging

T. gradata from Teiritzberg is supposed to have settled in an estuarine setting and reveals lower $\delta^{18}\text{O}$ values of -3.6 to -0.8‰ . $\delta^{18}\text{O}$ values of one shell of *O. crassilabiata* are in the range of *T. bellardii* and *T. bicarinata*, indicating that the shell derives from a marine ingress layer. The second *O. crassilabiata* shell, as well as the *T. cinctus* shell has intermediate values between the marine *Turritella* shells and the *Turritella gradata* shells. $\delta^{18}\text{O}$ values of *T. bidendata* are comparable with those of *T. gradata*. The low oxygen values (-7.0 to -9.5‰) of two *Melanopsis impressa* shells point to a freshwater origin of these shells and are comparable to isotope data of modern *Melanopsis* shells (Reinhardt et al. 2003).

The faunal composition of the Rückersdorf deposits, south of the Obergänsersdorf–Mollmannsdorf Swell, yielded a shallow marine nearshore gastropod assemblage with various euryhaline species (Harzhauser 2002). *G. bicinctum* shells from Rückersdorf show lower $\delta^{18}\text{O}$ values than *G. bicinctum* shells from the more marine Kleinebersdorf section. Isotope results of *T. bidendata* are comparable to the data of the mudflat fauna of Teiritzberg.

T. gradata shells from Kleinebersdorf reveal $\delta^{13}\text{C}$ values from 0.9 to 3.0‰ , with intra-shell differences ranging from 0.8 to 2.0‰ . In general, shells of the same

genera show similar values, but *G. bicinctum* and *O. crassilabiata* yield lower values than *Turritella* (Fig. 3).

$\delta^{13}\text{C}$ values from the shells in Teiritzberg reflect a similar pattern as $\delta^{18}\text{O}$. The highest $\delta^{13}\text{C}$ values are measured in the *Turritella* shells from the marine ingressions, ranging from 1.0 to 3.5‰ . In contrast, *T. gradata* reveals $\delta^{13}\text{C}$ values from 0.6 to 2.0‰ . The two *O. crassilabiata* shells show different $\delta^{13}\text{C}$ values; the shell with higher $\delta^{18}\text{O}$ values reveals higher $\delta^{13}\text{C}$ values while the second *O. crassilabiata* shell has values in the range of the *T. gradata* shells. $\delta^{13}\text{C}$ values of *T. bidendata* and *T. cinctus* are much lower (-2.6 to -0.1‰) than those of *T. gradata*. The very low $\delta^{13}\text{C}$ values (-2.9 to -6.4‰) of the *Melanopsis impressa* shells are typical for a freshwater environment. *G. bicinctum* shells from Rückersdorf show lower $\delta^{13}\text{C}$ values than *G. bicinctum* shells from the more marine Kleinebersdorf section.

Paleoenvironmental interpretation of the $\delta^{18}\text{O}$ values is complicated because of an interplay between the temperature and the $\delta^{18}\text{O}$ of the ambient water, which is related to salinity. Although $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values generally differ between marine, brackish and freshwater, specific environments cannot be inferred from absolute δ -values. The *Turritella* shells from Kleinebersdorf show a range of $\delta^{18}\text{O}$ values from -2.1 to 0.2‰ and relatively

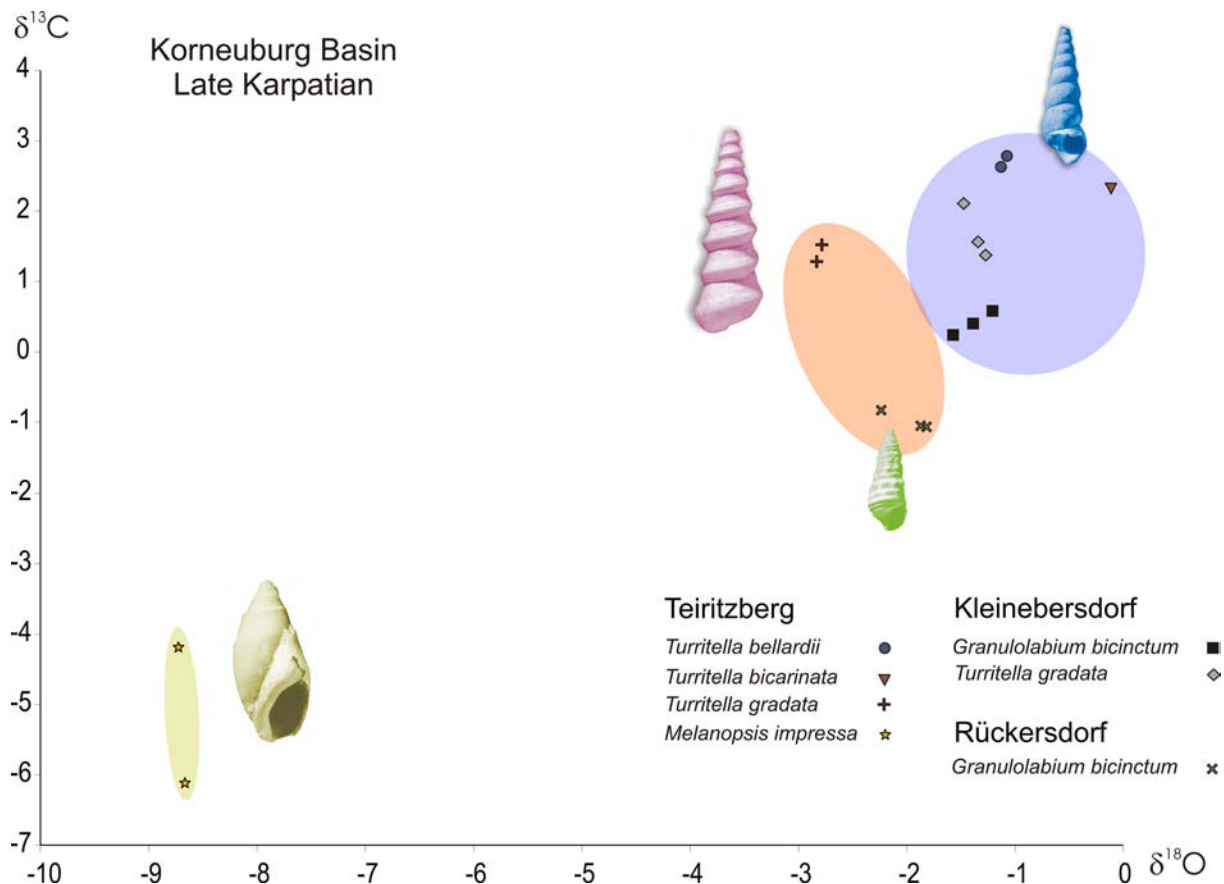


Fig. 5 Mean oxygen and carbon values of *Turritella*, *Granulolabium*, and *Melanopsis* shells from the Korneuburg Basin showing highest isotope values for shells from marine environments (blue field), intermediate values for estuarine environments (orange field) and very low values for freshwater environments (green field)

high $\delta^{13}\text{C}$ values (0.9–3.0‰) arguing for a marine environment. This interpretation is supported by the occurrence of sponges, corals and echinoids. The oxygen values of the mollusc shells from the marine incursions in Teiritzberg show values consistent with the isotope results of the *Turritella* shells from Kleinebersdorf, whereas the lower $\delta^{18}\text{O}$ values of the *T. gradata* shells from Teiritzberg point to a more estuarine environment. The lower $\delta^{18}\text{O}$ values of this assemblage reflect changes in salinity rather than temperature. The wide range of values in the Teiritzberg shells support the interpretation of changing environmental conditions.

In contrast to oxygen isotope values, $\delta^{13}\text{C}$ signals are generally more complicated to interpret because many more factors influence the carbon isotopic composition of mollusc shells. For $\delta^{13}\text{C}$ of gastropod shells vital effects are common (Romanek and Grossman 1989; Wefer and Berger 1991), but microhabitat effects may also lead to these differences.

The differences in $\delta^{13}\text{C}$ values probably reflect the habitat preferences of the mudflat-dwelling potamidids and may also be related to metabolic effects. Metabolic processes, with the incorporation of respiration-derived carbon, lead to $\delta^{13}\text{C}$ values in mollusc carbonate shells that are lower than expected for equilibrium with seawater bicarbonate (Wefer and Berger 1991; Hickson et al. 2002). Recent results from field studies on bivalve carbonate shells also suggest that metabolic effects may vary between individuals (Owen et al. 2002).

Considering oxygen and carbon isotope values together and comparing the data of the same species or genera, mainly *Turritella* and *Granulolabium*, the isotope data indicate a distinction between the northern and the southern part of the basin, confirming the interpretation of a northern marine and a southern mainly estuarine environment (Fig. 5).

Paleoclimate indications

In marine environments without seasonal changes in salinity, intra-shell variability in $\delta^{18}\text{O}$ can confidently be ascribed to temperature changes. However, precise temperatures can only be reconstructed if reliable oxygen values for seawater are available. But even with an incomplete knowledge of seawater $\delta^{18}\text{O}$, the maximum and minimum $\delta^{18}\text{O}$ values of shells can be used to approximate the range of water temperatures. Factors influencing the range of the variability in the intra-shell $\delta^{18}\text{O}$ record are seasonal shell cessation and salinity changes. As seasonal variations of salinity certainly occur in estuarine-influenced environments, the interpretation of the data is potentially complicated. Seasonal salinity changes should be stronger within the estuary, and weaker within the marine setting with a connection to the open sea. Only the oxygen isotope data from those *Turritella* that require normal salinities (from the marine part of the Korneuburg Basin) have been used for paleotemperature calculations. Assuming a constant

salinity year-round, $\delta^{18}\text{O}$ ranges of the three *T. gradata* specimen of Kleinebersdorf indicate temperature variations of around 8–9°C, calculated using the equation given by Böhm et al. (2000). We cannot exclude a seasonal cessation of shell growth, which would reduce the variability in the intra-shell $\delta^{18}\text{O}$ record: the calculated temperature range therefore actually represents a minimum estimate.

Generally, a $\delta^{18}\text{O}$ value of seawater of around -1.0‰ is assumed for the Miocene climatic optimum (Shackleton and Kennett 1975; Savin et al. 1975; Lear et al. 2000), but it is not clear how accurately open marine values for the Miocene reflect the isotopic composition of Karpatian seawater in the restricted Korneuburg Basin.

In using isotopic analyses of the marine carbonate shells from the Korneuburg Basin to reconstruct the paleoenvironment and paleoclimate, it is important to consider the isolated position of the basin. Therefore, the oxygen isotope composition of the seawater should be characterised by local environmental conditions. Today the worldwide average of $\delta^{18}\text{O}$ is 0‰ SMOW (Epstein and Mayeda 1953), although the value of the Baltic Sea, for example, is lower due to significant addition of meteoric water (Förstel 1983). Alternatively, evaporation can enrich $\delta^{18}\text{O}$ of seawater. Thus, the Mediterranean Sea has an average value of $+1\text{‰}$ and the Red Sea an even higher one (Craig 1966). A similarly raised $\delta^{18}\text{O}$ level might be expected for the Paratethys Sea during the Late Karpatian due to the occurrence of evaporites in the Sol'ná Baňa Formation of the East Slovakian Basin (Karoli et al. 1997). On the other hand, freshwater discharge within the protected estuary of the Korneuburg Basin suggests lowered $\delta^{18}\text{O}$ values within this part of the basin.

Assuming a seawater $\delta^{18}\text{O}$ value of -1.0‰ (V-SMOW), the calculated temperatures from the $\delta^{18}\text{O}$ values of the marine *Turritella* shells of Kleinebersdorf and Teiritzberg are in the range of approximately 13–26°C for the shallow sea. As good paleoclimatic and temperature estimates are available for the Karpatian Korneuburg Basin, we can compare calculated temperatures from isotope analyses with these climate proxies. Based on the distribution of thermophilic ectothermic vertebrates, a subtropical climate with a minimum mean annual temperature (MAT) of 17°C, and a minimum cold month temperature (CMT) ranging from at least 3°C to about 8°C were derived (Böhme 2003). Meller (1998) predicted a subtropical climate with a MAT above 14°C and an annual precipitation of about 2000 mm based on fruits and seeds. Among the gastropod fauna in the Korneuburg Basin, stenothermic elements are represented by *Strombus* (*Lentigo*) *bonelli* and *Melongena cornuta*. The modern descendant *Strombus* (*Lentigo*) *latus* is found along the tropical western African shore, with its distribution restricted to the 15/16°C minimum sea surface temperature (SST) isotherm (data from Meco 1977). A quite similar minimum SST proxy of about 14–16°C is derived from *Melongena*

coronata (Harzhauser et al. 2002b). The climatic requirements of the fish fauna support a transitional area between the warm temperate and tropical belt (Schultz 1998; Reichenbacher 1998). The minimum temperature value of 13°C calculated by oxygen isotope data are in good agreement with the above-mentioned paleobotanical and paleozoological climate proxies. Paleotemperature estimations for the northern marine part of the Korneuburg Basin, calculated with the mean $\delta^{18}\text{O}$ value of -1.0‰ (V-SMOW) for seawater at that time, provide results that fit very well with other climate proxies. Nevertheless, the assumed $\delta^{18}\text{O}$ value for the seawater in the Korneuburg Basin probably represents local environmental conditions, e.g. minor variations in salinity, rather than global ones.

Conclusion

Based on paleontological data of different faunas and floras, an integrated paleoecological model for the Korneuburg Basin has been developed (Harzhauser et al. 2002b): the basin is separated by the Obergänsersdorf–Mollmannsdorf Swell into a northern part with marine conditions and a southern part displaying a mainly estuarine setting. Nevertheless, short-termed marine incursions, documented by marine ostracods, molluscs, echinoids, rays, and sharks are evident in the sediment successions south of the swell. The oxygen and carbon isotope analyses of gastropods from three sections (Kleinebersdorf, Teiritzberg, and Rückersdorf) with different environmental conditions support the paleoecological interpretation. The isotope data of *Turritella* and *Granulolabium* specimens reflect a trend from the northern marine part with higher oxygen and carbon values to the southern estuarine part with lower values, although the differences in isotope values between the environmental settings are rather small. The very low oxygen and carbon isotope values of the shells of the freshwater gastropod *Melanopsis impressa* clearly indicate freshwater conditions.

Oxygen isotope data of marine gastropod shells can be used to estimate paleotemperatures. As rather good paleotemperature proxies for the Korneuburg Basin are available, oxygen isotope values of the marine *Turritella* shells are compared to these approaches. Assuming a $\delta^{18}\text{O}$ value of -1‰ for the oxygen composition of the Karpatian seawater, which is a worldwide average value for the late Early Miocene, temperature estimates range from 13 to 26°C for the shallow-water environment. This calculated temperature range is in good agreement with other paleontological climate models, pointing to a subtropical climate with minimum water temperatures of 13–16°C.

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