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Palaeoenvironmental reconstructions by stable isotopes of Middle Miocene gastropods of the Central Paratethys

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Abstract

The stable isotopes of carbon and oxygen were used to provide information of mixing of marine and freshwater and subsequently used to determine palaeosalinities. In the Middle to Late Miocene St. Margarethen “Zollhaus” section (Upper Sarmatian “Mactra Zone”/Pannonian), a succession of three gastropod assemblages indicates changing environmental conditions from a limnic-fluviatile to littoral mudflat and a sublittoral marine environment. Several shells of the main representatives of the three assemblages [*Potamides hartbergensis* (Hilber), *Granulolabium bicinctum* (Brocchi), *Potamides disjunctus* (Sowerby)], and additionally shells of *Lymnaea* sp., a typical freshwater gastropod, and *Pomatias conicus*, a terrestrial gastropod, were taken for stable isotope analyses. Oxygen and carbon isotope data of the freshwater endmember are distinctively lower ($\delta^{18}\text{O} \sim -4.5\%$ / $\delta^{13}\text{C} \sim -9\%$) than of the marine endmembers ($\delta^{18}\text{O} \sim -2.2\%$ / $\delta^{13}\text{C} \sim -2.3\%$). In contrast to the expected intermediate isotopic composition between the freshwater and marine environment, the shells of supposed brackish environments have higher $\delta^{18}\text{O}$ values than the shells of the marine environment. These higher $\delta^{18}\text{O}$ values are explained by evaporation, which affected the protected areas of riverine to lacustrine environments and small pools on mudflats, formerly considered to be the habitats of the brackish assemblages. Thus, the oxygen and carbon isotope data extend the already existing palaeoenvironmental information.

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1. Introduction

Investigations of stable isotope ratios of carbon and oxygen on carbonate shells are a powerful tool for the reconstruction of palaeoenvironmental parameters.

Though the Paratethys underwent distinct changes in environmental conditions forced by palaeogeographical changes, the use of stable isotopes on Miocene fossils of the Paratethys has been rather scarce (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). The Badenian/Sarmatian (Middle Miocene regional stages) boun-

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dary marks a distinct change in faunal communities where nearly all stenohaline groups such as corals, echinoids and planktic foraminifera, became extinct. The same scenario is observed in the molluscan fauna, which is devoid of pectinids, strombids or other stenohaline taxa. The closure of the marine connection of the Paratethys is the main factor, which caused an isolation of the Paratethys fauna from the Mediterranean bioprovince. This geodynamic process coincided with a drastic change in water chemistry within the Paratethys (Rögl, 2001). Traditionally, a decrease in salinity is advocated as cause for the biotic changes (Papp, 1954). Recently, however, an increase in alkalinity of the water body as trigger for the faunistic collapse has been put forward (Pisera, 1995, 1996). Especially during the Middle Sarmatian, occurrence of ooliths and small biohermal carbonate bodies indicate normal marine conditions and contradict the brackish water scenario (Harzhauser and Piller, 2001).

The use of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values to provide information on mixing of marine and freshwater, and therefore inferring palaeosalinities, has long been tested (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). Commonly freshwater has lower $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values than marine water, whereas brackish water systems show intermediate isotopic ratios. But the relationship between salinity and isotopic composition is often more complicated: oxygen isotope values of carbonates are controlled by temperature and $\delta^{18}\text{O}$ of the ambient water. Evaporation may enrich water in ^{18}O , if it has a long residence time in hydrologically restricted settings (Swart et al., 1989; Hudson et al., 1995; Hendry and Kalin, 1997), and therefore lead to higher $\delta^{18}\text{O}$ values than typically expected for a specific setting. As freshwater dilution as well as evaporation can lead to depletion in $\delta^{13}\text{C}$ in surface waters, the interpretation of $\delta^{13}\text{C}$ values of carbonate samples for inferring paleosalinities may also be equivocal (Patterson and Walter, 1994; Swart et al., 2001).

The molluscan fauna of the Upper Sarmatian section of St. Margarethen “Zollhaus” has been recently investigated by Harzhauser and Kowalke (2002). They interpreted a succession of three gastropod assemblages as an indication of changing environments from a limnic-fluvial to a brackish-

littoral to a marine-littoral environment. These three assemblages were named after their main representatives as “*Potamides hartbergensis* assemblage”, “*Granulolabium bicinctum* assemblage” and “*Potamides disjunctus* assemblage”. The assumed palaeoenvironmental changes are connected with changes in palaeosalinities. If differences in the environmental parameters, like temperature and salinity, existed between the three assemblages, these should be reflected in oxygen and carbon isotope signatures of carbonate shells of representatives of the three assemblages. Lowest $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values would be expected for the limnic-fluvial environment, as freshwater typically has lighter isotope values than marine water. If oxygen and carbon isotopes behaved conservatively in the seawater–freshwater mixing zone, shells from the brackish-littoral setting should yield intermediate values between the freshwater and marine endmember. The use of oxygen and carbon isotope analyses should therefore provide a test of the proposed palaeoenvironmental interpretation based on a taxonomic uniformitarian approach.

2. Geological setting

The Late Sarmatian/Pannonian section at St. Margarethen “Zollhaus” (Burgenland, Austria) is an exploited gravel pit located in the Neogene Eisenstadt-Sopron Basin. This small basin of about 20×20 km size is interpreted to represent a satellite basin of the Vienna Basin (Steininger, 1991) (Fig. 1).

Recently a 30-m-thick section has been exposed comprising two sedimentary units of the Sarmatian (Middle Miocene) and Pannonian (Late Miocene). Based on the occurrence of Sarmatian *Maetra vitaliana* (d’Orbigny) and the characteristic composition of the mollusc fauna, a dating to the Upper Sarmatian ecostratigraphic “*Maetra* Zone” (zonation sensu Papp, 1954) (Fig. 2) is allowed. It is represented by gravels, marly sands and scattered detritic limestones, whereas the Pannonian consists of sand and silt. The Sarmatian part of the section yields only deposits which can be correlated with the *Maetra* Zone of the Vienna Basin ecostratigraphic mollusc zonation. Short lived outcrops in the base of the current outcrop proved the existence of sands, which already represent the preceding *Ervilia* Zone. Due to the lack of drilling

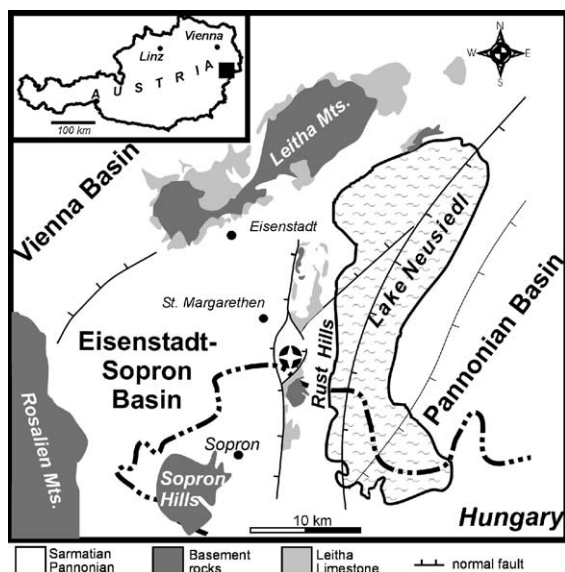


Fig. 1. Location of the St. Margarethen/Zollhaus section in the Eisenstadt-Sopron Basin (Schmid et al., 2001).

data, the exact thickness of the Sarmatian strata in this part of the Eisenstadt-Sopron Basin is unknown.

The entire section is described in detail by Harzhauser and Kowalke (2002) and Harzhauser et al. (2002). In this work, however, special focus is given to a layer, which shows a distinct succession of gastropod assemblages (Fig. 3).

3. Gastropod assemblages and palaeoecological constraints

The analysed shells derive from a short sequence of about 40 cm thickness (Fig. 3). Sedimentologically distinct layers yield three ecologically defined successive assemblages, represented by a lacustrine stage, a marine mudflat stage, and a Sarmatian-marine littoral stage. They were named by Harzhauser and Kowalke (2002) after the predominating potamidids the *Potamides hartbergensis*, the *Gran-*

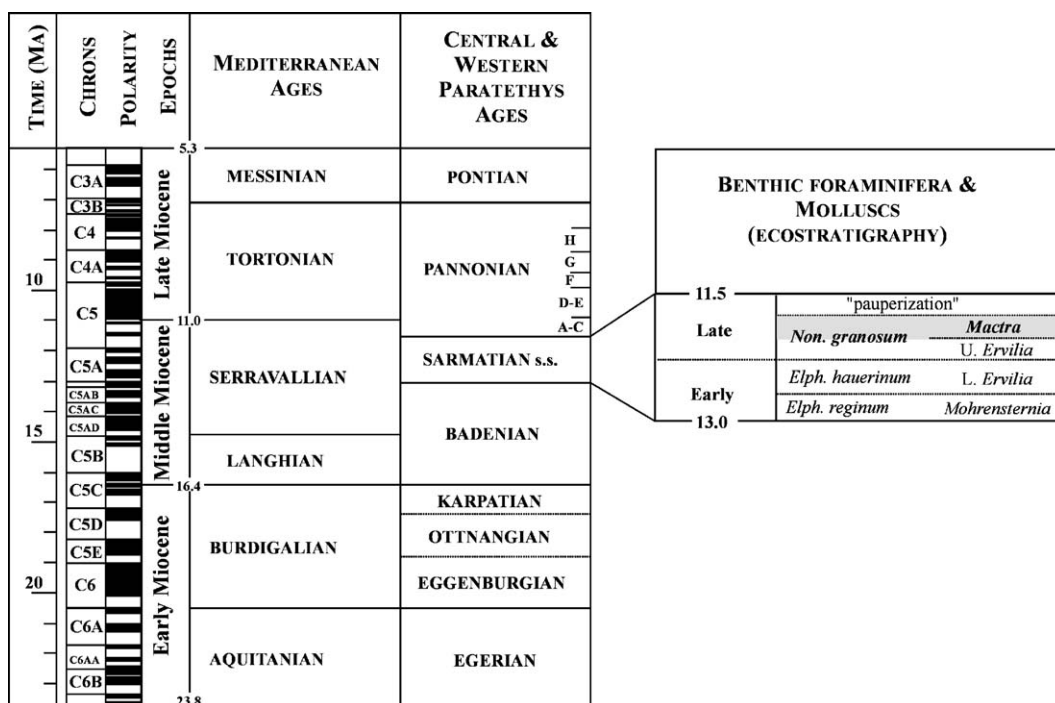
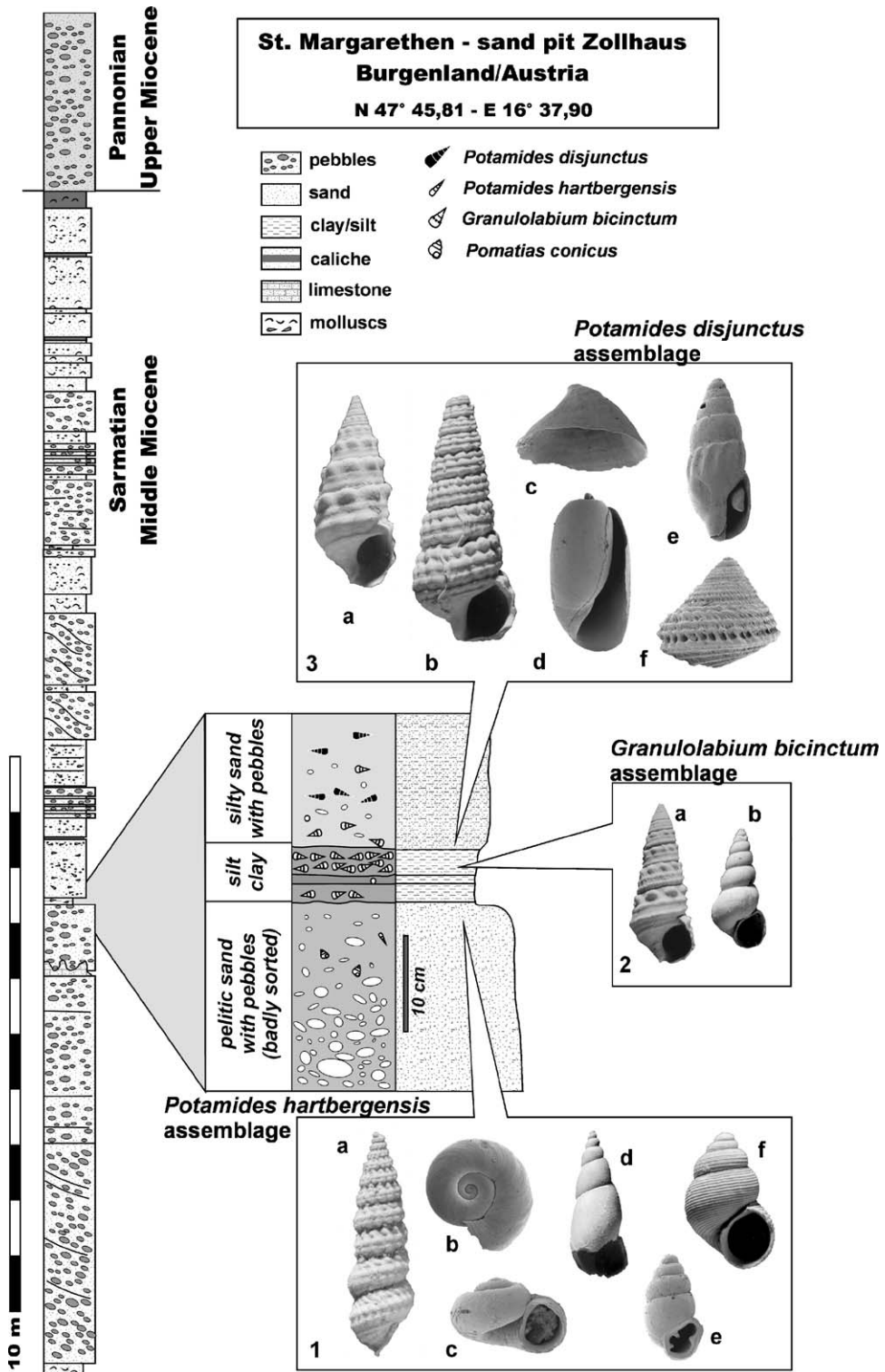


Fig. 2. Stratigraphic correlation chart of the Central and Western Paratethys with the Mediterranean.



ulolabium bicinctum and the *Potamides disjunctus* assemblages.

The lowest marly silt layer was settled by the “*Potamides hartbergensis* assemblage” consisting mainly of *P. hartbergensis* (Hilber), and abundant freshwater gastropods (lymnaeids and planorbids) as well as terrestrial gastropods (carychiids). This mixed assemblage was therefore interpreted by Harzhauser and Kowalke (2002) to have settled in a rather protected riverine to lacustrine environment which developed within the deltaic complex bordering the Sarmatian Sea. *P. hartbergensis*, however, cannot be interpreted as inhabitant of pure freshwater environments, and point to local or temporary development of ponds within the delta plain, suitable for this potamidid.

The succeeding “*Granulolabium bicinctum* assemblage” is characterised by a nearly monospecific mass occurrence of *G. bicinctum* (Brocchi) within a marly silt or clay. It is interpreted as having been formed during a minor transgressive phase during the expansion of the sea within the *Maetra* Zone. This relative sea level rise allowed the establishment of vast mudflats on the flat delta plain in the Eisenstadt-Sopron Basin. The fossil mudflat containing the *G. bicinctum* assemblage can be traced throughout the gravel pit and displays an extension of approximately 500 m². The basal layer of this mudflat deposit yields masses of *Hydrobia frauenfeldi* and *Hydrobia* cf. *stagnalis*. Soon after, the hydrobiids are replaced by monospecific *G. bicinctum* assemblages yielding excellently preserved shells. This internal succession of hydrobiids to *Granulolabium* assemblages seems to reflect the gradual shift from the upper intertidal zone to the lower intertidal zone.

The uppermost gastropod assemblage (“*Potamides disjunctus* assemblage”) is characterised by *P. disjunctus* (Sowerby), *Acteocina lajonkaireana* (Basterot), *Gibbula buchi* (Dubois), *Gibbula podolica* (Dubois), *Jujubinus turricula* (Eichwald), *Granulolabium bicinctum* (Brocchi) and *Acmaea soceni* (Jekelius). This assemblage is bound to a depositional

transition from the littoral to very shallow sublittoral, linked with a shift in lithofacies from silts and clays towards marly silts and marly sands with scattered pebbles. The sediments are interpreted as representing more or less normal marine conditions, based on the occurrence of various archaeogastropods, columbellids and opisthobranch gastropods, which shun brackish water environments. The freshwater influx had obviously ceased.

Thus, *Granulolabium bicinctum* occurs in two different assemblages. Nevertheless, its shell morphology seems to be strongly affected by the environment. Specimens from the mudflats are small, glossy, thin-shelled and poorly sculptured. In contrast, those from the “marine” *Potamides disjunctus* assemblage are robust, thick shelled and develop a conspicuous ornamentation. This observation is an important evidence that the specimens deriving from the marly sand overlying the mudflat are elements of the *P. disjunctus* assemblage rather than reworked shells from the *G. bicinctum* assemblage.

Potamidid and batillariid gastropods are perennial animals but exact data on the life span of recent representatives of these littoral animals are poor. By comparing with modern relatives (Yamada, 1982; Houbrick, 1991; Tojo and Ohno, 1999; Nishihira, 1983) life ages for the sampled gastropods may be deduced.

4. Materials and methods

Well preserved gastropods were used for stable isotope investigations. For detecting diagenesis, samples were analysed for their shell mineralogy and microstructures with X-ray diffraction analyses and scanning electron microscopy (SEM). At least three shells of *Potamides hartbergensis*, *Granulolabium bicinctum* from the *G. bicinctum* assemblage as well as from the *Potamides disjunctus* assemblage and *P. disjunctus* were chosen for X-ray diffraction and SEM

Fig. 3. St. Margarethen/Zollhaus section: enlarged part shows the layers from which the gastropod shells for stable isotope measurements were taken with their specific gastropod assemblages; (1) typical representatives of the *Potamides hartbergensis* assemblage: (a) *P. hartbergensis* (Hilber), (b) *Gyraulus vermicularis* (Stoliczka), (c) *Valvata pseudoadeorbis* Sinzov, (d) *Stagnicola* cf. *bouilleti* (Michaud), (e) *Carychium pachychilus* Sandberger, (f) *Pomatias conicus* (Klein); (2) typical representatives of the *Granulolabium bicinctum* assemblage: (a) *G. bicinctum* (Brocchi), (b) *Hydrobia frauenfeldi* (Hörnes); (3) typical representatives of the *Potamides disjunctus* assemblage: (a) *G. bicinctum* (Brocchi), (b) *P. disjunctus* (Sowerby), (c) *Acmaea soceni* Jekelius, (d) *Acteocina lajonkaireana* (Basterot), (e) *Mitrella agenta* (Harzhauser and Kowalke), (f) *Gibbula buchi* (Dubois) (after Harzhauser and Kowalke, 2002).

analyses. Mineralogical composition of the shells was analysed with a Bruker D8 Discover ($\text{CuK}\alpha_1$) with General Area Detector Diffraction solutions (GADDS). It is possible to investigate single points on a sample with this X-ray diffractometer. Therefore, three to five analyses on each shell on different whorls were made without destroying the shells. Multiple analyses on each shell should provide information about variations in shell mineralogy within one shell. For SEM analyses shell fragments from the aperture were used. The same shells which were investigated for diagenesis were chosen for stable isotope measurements: five shells of *G. bicinctum* of the *G. bicinctum* assemblage, five *P. hartbergensis* of the *P. hartbergensis* assemblage, three *P. disjunctus* and five *G. bicinctum* of the *P. disjunctus* assemblage. In addition, two specimens of *Lymnaea* sp. as representative of typical freshwater gastropods, three specimens of *Hydrobia* sp. from the basal layer of the mudflat and two specimens of *Pomatias conicus* as a terrestrial snail were analyzed. For the *G. bicinctum*, *P. hartbergensis* and *P. disjunctus* shells, at least six samples from each shell from the aperture to the apex were drilled with a 0.8-mm drill. Multiple samples from the shells were taken in order to estimate the range of isotopic values within one shell. For *Hydrobia* sp., *Lymnaea* sp. and *P. conicus*, whole specimens were crushed, and the powder used for isotope analyses. Whole shells were used because of the small size of each single shell. To compare these different types of samples, also mean values of the multiple samples from the other shells were used for interpretation. Samples were reacted 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 Geology and Palaeontology, University of Graz. Repeated measurements of 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 against VPDB.

5. Results

5.1. Shell structure and mineralogy

The shell mineralogy was determined using X-ray diffraction techniques. In most of the samples only aragonite was found. Although in a few samples

calcite might be present, comparison of isotopic results of the pure aragonitic shells with shells containing traces of calcite indicated no differences in the isotopic composition. SEM investigations performed on the samples also confirmed the aragonitic composition. As aragonite is a relatively unstable phase and easily converts to calcite during diagenesis, the results of these two methods show that all samples are nearly unaffected by diagenesis and provide strong evidence that stable isotope values are primary and can be used for palaeoenvironmental analyses.

5.2. Oxygen isotopes

Intrashell variability in $\delta^{18}\text{O}$ is distinct between the different assemblages (Fig. 4): within the *Potamides hartbergensis* assemblage gastropods show low variability of at most 1‰. In the *Granulolabium bicinctum* assemblage, intrashell changes are higher with values around 1.6–2.5‰. In the *Potamides disjunctus* assemblage, no differences in the intrashell variability between the two species are discernible: *G. bicinctum* and *P. disjunctus* show fluctuations of about 0.5–1.4‰.

In addition to the mean values of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of each measured shell, bulk data of the shells of *Lymnaea* sp., *Hydrobia* sp. and *Pomatias conicus* are given in Table 1.

In the *Potamides hartbergensis* assemblage, $\delta^{18}\text{O}$ values range from -1.3‰ to 2.0‰ , in the *Granulolabium bicinctum* assemblage from -3.2‰ to 0.5‰ . The *Hydrobia* sp., which settled the mudflats first, show values from -2.4‰ to -1.2‰ . In the *Potamides disjunctus* assemblage, $\delta^{18}\text{O}$ values vary from -3.1‰ to 0.4‰ . The freshwater gastropods *Lymnaea* sp. exhibit values of -5.1‰ and -4.2‰ , and shells of the terrestrial snails yielded data from -3.0‰ to -1.9‰ .

5.3. Carbon isotopes

Intrashell variability in $\delta^{13}\text{C}$ is approximately the same in nearly all specimens, ranging from 0.5‰ to 2.0‰ (Fig. 4). No distinct difference between the assemblages is observable, but two of the measured specimens show extreme high variability. One shell from *Granulolabium bicinctum* of the *G. bicinctum* assemblage and one shell of *G. bicinctum* of the

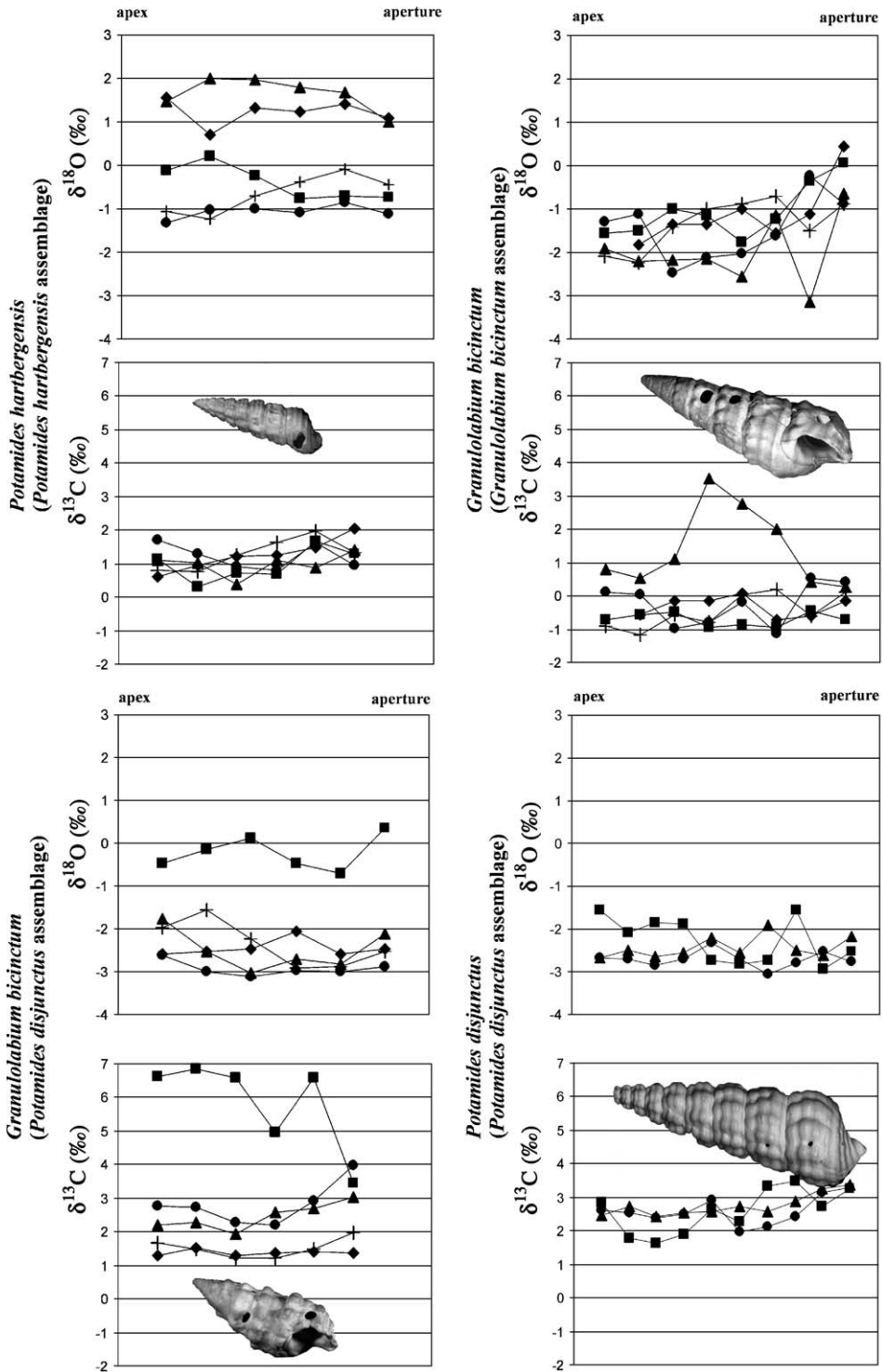


Fig. 4. Stable isotope profiles from the apex to the aperture of the shells of the different gastropod assemblages.

Table 1
Mean $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in ‰ and standard deviations of the gastropod shells

Assemblage	Species	Number of samples/shell	$\delta^{18}\text{O}$ (‰)	$\delta^{13}\text{C}$ (‰)
	<i>Pomatias conicus</i>	bulk	-3.0	-6.4
	<i>Pomatias conicus</i>	bulk	-1.9	-5.6
	<i>Lymnaea</i> sp.	bulk	-5.1	-7.6
	<i>Lymnaea</i> sp.	bulk	-4.2	-10.0
<i>Potamides hartbergensis</i>				
	<i>Potamides hartbergensis</i>	n=6	-0.4 (±0.4)	1.0 (±0.4)
	<i>Potamides hartbergensis</i>	n=6	-1.1 (±0.1)	1.2 (±0.4)
	<i>Potamides hartbergensis</i>	n=6	1.7 (±0.3)	1.0 (±0.3)
	<i>Potamides hartbergensis</i>	n=6	-0.7 (±0.4)	1.3 (±0.4)
	<i>Potamides hartbergensis</i>	n=6	1.2 (±0.3)	1.3 (±0.4)
<i>Granulolabium bicinctum</i>				
	<i>Granulolabium bicinctum</i>	n=8	-1.1 (±0.6)	-0.7 (±0.2)
	<i>Granulolabium bicinctum</i>	n=8	-1.5 (±0.7)	-0.3 (±0.6)
	<i>Granulolabium bicinctum</i>	n=8	-2.0 (±0.7)	1.4 (±1.1)
	<i>Granulolabium bicinctum</i>	n=8	-1.3 (±0.5)	-0.5 (±0.5)
	<i>Granulolabium bicinctum</i>	n=7	-1.1 (±0.7)	-0.3 (±0.3)
	<i>Hydrobia</i> sp.	bulk	-1.2	-0.3
	<i>Hydrobia</i> sp.	bulk	-2.4	0.7
	<i>Hydrobia</i> sp.	bulk	-1.9	-0.8
<i>Potamides disjunctus</i>				
	<i>Granulolabium bicinctum</i>	n=6	-0.2 (±0.4)	5.8 (±1.2)
	<i>Granulolabium bicinctum</i>	n=6	-2.9 (±0.2)	2.8 (±0.6)
	<i>Granulolabium bicinctum</i>	n=6	-2.5 (±0.4)	2.5 (±0.4)
	<i>Granulolabium bicinctum</i>	n=6	-2.4 (±0.5)	1.5 (±0.3)
	<i>Granulolabium bicinctum</i>	n=6	-2.5 (±0.2)	1.4 (±0.1)
	<i>Potamides disjunctus</i>	n=10	-2.3 (±0.5)	2.6 (±0.6)
	<i>Potamides disjunctus</i>	n=10	-2.7 (±0.2)	2.6 (±0.4)
	<i>Potamides disjunctus</i>	n=10	-2.4 (±0.2)	2.8 (±0.3)

Potamides disjunctus assemblage have intrashell variabilities of 3.2‰ and 3.4‰, respectively.

In the *Potamides hartbergensis* assemblage, $\delta^{13}\text{C}$ values range from 0.3‰ to 2.0‰, in the *Granulolabium bicinctum* assemblage from -1.1‰ to 3.5‰, and in the *Potamides disjunctus* assemblage from 1.6‰ to 6.8‰. The three shells of *Hydrobia* sp. showed values between -0.8‰ and 0.7‰. Bulk analyses of two shells of *Lymnaea* sp. exhibit values of -7.6‰ and -10.0‰, and the two shells of *Pomatias conicus* of -5.6‰ and -6.4‰ (Table 1).

6. Discussion

The excellent preservation of metastable aragonite in shells has been used to argue that the isotopic composition is also primary. Additionally, molluscs are considered to precipitate their shells in isotopic equilibrium (Grossman and Ku, 1986; Cornu et al., 1993). So it may be reasonably assumed that the isotopic composition of the analyzed aragonitic gastropod shells reflects the interplay of the general conditions (e.g. global climate), influencing the isotopic composition of the ambient water and local palaeoenvironmental parameters (e.g. temperature and salinity).

The main controlling factors of $\delta^{18}\text{O}$ values in gastropod shells are temperature and the $\delta^{18}\text{O}$ of the ambient water. Freshwater $\delta^{18}\text{O}$ values are primarily controlled by the isotopic composition of the rainwater. In contrast, $\delta^{13}\text{C}$ values of marine and freshwater gastropods are influenced by a multitude of factors, e.g., upwelling, seasonal productivity, diet, living mode, growth rate, reproductive status (Geary et al., 1992 cum lit.; Bonadonna et al., 1999).

Eocene marine molluscs from the Paris Basin and England show high intra-annual or intrashell variations in $\delta^{18}\text{O}$ between winter and summer of about 2.5‰ and 3.0‰, while $\delta^{13}\text{C}$ values vary by about 2.5‰ in the Paris Basin and up to 4.0‰ in England (Andreasson and Schmitz, 1996; Purton and Brasier, 1997). Samples from this work, as shown in Fig. 4, exhibit similar intrashell variabilities, probably reflecting seasonal temperature changes during their lifetime.

In palaeoenvironmental isotope studies, it can be difficult to distinguish between the effects of local temperature and salinity on account of the $\delta^{18}\text{O}$ signal

in gastropod shells. General palaeoenvironmental and climatic conditions for Sarmatian environments in the Central Paratethys can be inferred from new results by Piller and Harzhauser (2002). Tropical to subtropical conditions are assumed, based on the occurrence of small carbonate platforms with thick oolite sequences and limestones with abundant larger miliolid foraminifera. Bryozoan-foraminiferan build-ups formed bioconstructions of up to 20m width in the Eisenstadt-Sopron Basin during the *Maetra* Zone. On land, a semi-arid climate is indicated by the occurrence of calcrete formations (Piller and Harzhauser, 2002). These evidences also point to rather uniform warm temperature conditions in the marginal areas. Hence, it can be safely assumed that changes in salinity and water composition are more likely the cause of the variations in the $\delta^{18}\text{O}$ values between the assemblages than temperature.

The possibility to differentiate marine from freshwater environments by means of investigations of oxygen and carbon isotopes is based on the generally contrasting $\delta^{18}\text{O}$ values of seawater ($\sim 0\text{‰}$ SMOW) and freshwaters ($< -5\text{‰}$), and differences in $\delta^{13}\text{C}$ in dissolved inorganic carbon (DIC) between seawater ($\sim 0\text{‰}$ PDB) and freshwaters (generally lower $\delta^{13}\text{C}$ values). But the simple mixing between a saline

marine water and a less saline, generally isotopically depleted freshwater, used for proxy estimations of palaeosalinities, may be masked by other factors (e.g. evaporation) influencing the stable isotope composition of the mixing components (Swart et al., 1989, 2001; Patterson and Walter, 1994; Hudson et al., 1995; Hendry and Kalin, 1997; Holmden et al., 1997).

The isotope data of shells of the freshwater molluscs from St. Margarethen can be used to estimate the $\delta^{18}\text{O}$ composition of the freshwater endmember. Present members of the genus *Lymnaea* are typical freshwater gastropods which tolerate salinities lower than 0.3–0.7 ppt (Schmitz and Andreasson, 2001). The *Lymnaea* sp. from St. Margarethen show the lowest isotope values in $\delta^{18}\text{O}$ as well as in $\delta^{13}\text{C}$. A mean $\delta^{18}\text{O}$ value of -4.7‰ and a mean $\delta^{13}\text{C}$ value of -8.8‰ are consistent with a freshwater environment (Fig. 5).

The *Potamides disjunctus* assemblage was considered to be a marine assemblage in a shallow littoral setting. Normal marine conditions can be inferred from the gastropods in this assemblage, which do not occur in brackish environments. Isotopic composition of *P. disjunctus* and *Granulolabium bicinctum* shells from this assemblage show great similarities. The mean $\delta^{18}\text{O}$ value of the three *P. disjunctus* shells is

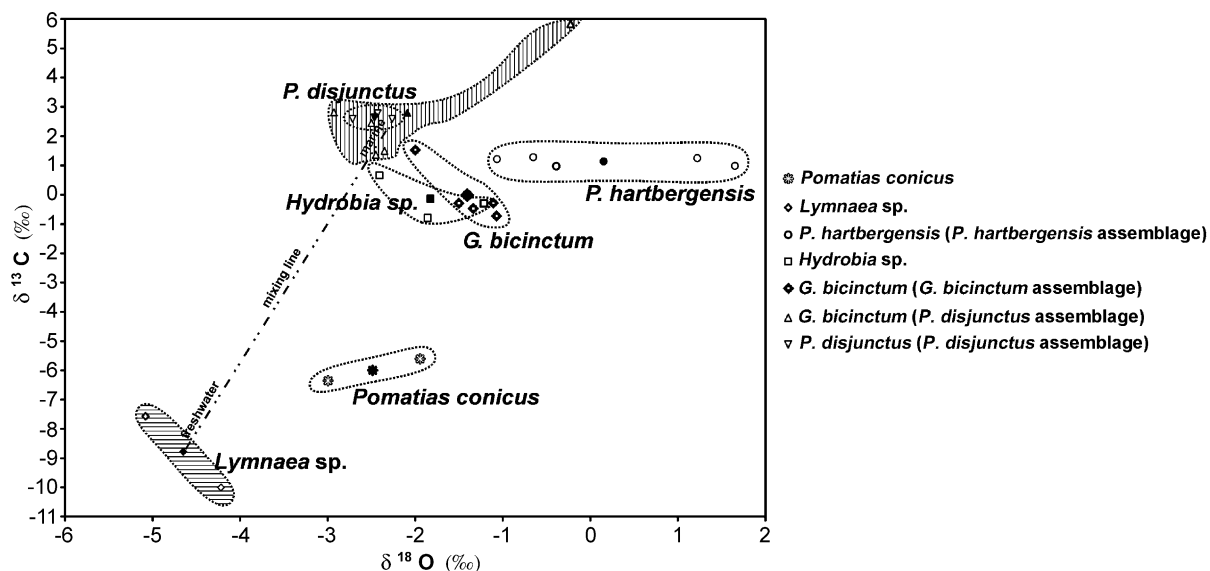


Fig. 5. Plot of the mean values of the stable isotope data of each measured gastropod shell. Open symbols are mean values of single shells, full symbols are mean values of each genus in one assemblage. Different gastropod assemblages can be clearly distinguished and their inferred environmental conditions are shown.

–2.1‰ and 2.8‰ for $\delta^{13}\text{C}$, respectively, while the *G. bicinctum* shells yielded a mean $\delta^{18}\text{O}$ value of –2.6‰ and a mean $\delta^{13}\text{C}$ value of 2.1‰, excluding one shell with anomalous high isotope values. As this shell shows no obvious differences in its mineralogy and shell structure, these anomalous positive oxygen and carbon isotope values have to remain unexplained by now.

In general, the mean $\delta^{18}\text{O}$ value of –2.6‰ for the *Potamides disjunctus* assemblage seems a little bit low for a marine environment. For example, isotope data of three marine *Conus* shells of the Miocene of northern Florida yielded an average $\delta^{18}\text{O}$ of –1.0‰ (Kobashi et al., 2001). But it is highly questionable if the Eisenstadt-Sopron Basin is comparable to an open oceanic environment. Though major ice sheet expansions around 14 Ma raised $\delta^{18}\text{O}$ of the seawater (Lear et al., 2000; Zachos et al., 2001), $\delta^{18}\text{O}$ estimates of seawater for the Late Middle Miocene are lower than 0‰ SMOW, which is today's worldwide oceanic average (Epstein and Mayeda, 1953). Local environmental conditions may have influenced the $\delta^{18}\text{O}$ of the seawater of this small satellite basin of the Vienna Basin, leading to even more reduced $\delta^{18}\text{O}$ values. Therefore comparison of the results with isotopic data from open oceanic localities might be inadequate. Unfortunately, only few stable isotope data of Sarmatian molluscs from the Central Paratethys are available for comparison (Geary et al., 1989; Matyas et al., 1996). Carbon and oxygen isotopic ratios of melanopsids from the Pannonian Basin system seem to indicate a shift in salinity of the Pannonian Lake from brackish towards freshwater environments during the Late Miocene (Geary et al., 1989). However, the selected gastropod genus *Melanopsis* inhabits mainly freshwater environments of riverine and deltaic ecosystems, as can be inferred from data provided by Van Damme (1984), Glaubrecht (1993), Heller and Sivan (2000), Heller et al. (1999) and Mienis (1983). Even if the endemic species of Lake Pannon might have settled also coastal areas adjacent to riverine systems, a considerable influence of the water chemistry should be expected. Hence, one may suppose that *Melanopsis* is a critical candidate for isotopic studies as it might have settled rather similar freshwater influenced habitats throughout the Mio-

cene, instead of having recorded the real water chemistry of the lake.

Sarmatian shells of *Cardium* and *Cerastoderma* from the Pannonian Lake show a wide range of isotope ratios ($\delta^{18}\text{O}$ from –2.6‰ to –0.2‰/ $\delta^{13}\text{C}$ from 1.0‰ to 1.9‰), but these data were obtained without differentiating between littoral and sublittoral elements (Matyas et al., 1996). Due to the then current assumption that the Sarmatian sea was a brackish environment, these authors interpreted the data as pointing to brackish conditions. But also some Badenian shells deriving from an undoubted fully marine environment showed similar isotopic compositions, especially $\delta^{18}\text{O}$ values are in the same range (–2.5‰ to –1.2‰), whereas $\delta^{13}\text{C}$ values of the Badenian shells are generally lower (–2.9‰ to 2.3‰). These inconsistencies could only be explained by considerations of a salinity and oxygen isotope mass balance for a closed or nearly closed lake (Matyas et al., 1996).

The mean $\delta^{18}\text{O}$ value of the *Potamides disjunctus* assemblage is in the range of the data from Geary et al. (1989) and Matyas et al. (1996), while the mean $\delta^{13}\text{C}$ value is a little bit higher. As the carbon isotopic composition of mollusc shells is influenced by several factors, and vital effects for $\delta^{13}\text{C}$ in gastropod shells cannot be excluded (Romanek and Grossman, 1989; Wefer and Berger, 1991), $\delta^{13}\text{C}$ signals are more complicated to interpret. New data of the Late Sarmatian reject the slowly freshening brackish basin and propose, at least for the Late Sarmatian, normal marine, even partly hypersaline conditions (Piller and Harzhauser, 2002).

In spite of the relatively low $\delta^{18}\text{O}$ data, which can be explained by slightly reduced $\delta^{18}\text{O}$ values of seawater in the Eisenstadt-Sopron Basin, the *Potamides disjunctus* assemblage can be considered as marine because of evidences from palaeofaunal considerations.

Differentiation between the freshwater endmember, represented by the *Lymnaea* sp., and the marine *Potamides disjunctus* assemblage, is evident in $\delta^{18}\text{O}$ as well as in $\delta^{13}\text{C}$ (Fig. 5). Intermediate values would have been expected for brackish water fossils. But as shown in Fig. 5, the *Potamides hartbergensis* and the *Granulolabium bicinctum* assemblages do not align along this simple mixing line. The *G. bicinctum* shells show similar values as the *Hydrobia*

sp. The mean $\delta^{18}\text{O}$ values are -1.8‰ for *Hydrobia* sp. and -1.4‰ for *G. bicinctum*. These values are slightly higher than the mean values for this species of the *P. disjunctus* assemblage. The shells of *P. hartbergensis* exhibited the most extraordinary values. In addition to the fact that the mean $\delta^{18}\text{O}$ value of the *P. hartbergensis* assemblage is the highest of the measured groups with 0.2‰ , the mean values of each shell span a range from -1.1‰ to 1.7‰ , which is quite a large variation within a group. But the range of $\delta^{13}\text{C}$ values for the five *P. hartbergensis* shells is small ($1.0\text{--}1.3\text{‰}$). Therefore, this environment must have provided special conditions. Such a wide range of $\delta^{18}\text{O}$ and an enrichment against the freshwater–marine mixing environment can be caused by high evaporation rates. Similar conditions, where high evaporation rates lead to an enrichment of $\delta^{18}\text{O}$ in brackish bay water, are documented from the Florida Bay (Lloyd, 1964; Swart et al., 1989) and the Lower Miocene of the Mainz Basin (Rothe et al., 1974).

The originally supposed conditions for the *Potamides hartbergensis* assemblage were a protected riverine to lacustrine environment which easily could experience higher evaporation rates within small ponds or pools leading to the high $\delta^{18}\text{O}$ values. A similar situation can be assumed for the *Granulolabium bicinctum* assemblage, which is interpreted to have settled on mudflats. A high evaporation level inferred from the isotope data of the *P. hartbergensis* assemblage fits well to the frequent calcrete formation, as observed at the section St. Margarethen (see Fig. 3), as well as in other Upper Sarmatian outcrops of the Vienna Basin and the Styrian Basin. At least short phases of hypersaline conditions have been predicted by Jámboř (1978) and Halmaj (1998), based on evaporite intercalations in the Sarmatian deposits of the Hungarian Zsambek Basin and Zagyva Valley and the Transylvanian Basin in Rumania.

7. Conclusion

Ecological interpretation of molluscan assemblages in the St. Margarethen “Zollhaus” section predicted a change from a limnic-fluvial to a brackish-littoral to a marine-sublittoral environment. This interpretation is

slightly modified in light of oxygen and carbon isotope data.

Based on the palaeofaunal evidence in combination with the isotopic results the *Potamides disjunctus* assemblage is considered as the marine endmember. The *P. disjunctus* assemblage shows distinctively higher $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values as compared to the freshwater endmember, represented by *Lymnae* sp. The *Potamides hartbergensis* assemblage, originally interpreted as representing a protected riverine to lacustrine environment, shows the highest $\delta^{18}\text{O}$ values. In addition, the shells of the *Granulolabium bicinctum* assemblage, and the shells of *Hydrobia* sp., both settling on the mudflat, also show higher $\delta^{18}\text{O}$ values than the marine *G. bicinctum* and *P. disjunctus* shells, but lower values than the *P. hartbergensis* shells. These data seem at first to contradict the original interpretation, where it was considered that freshwater influx decreased from the environment represented by the *P. hartbergensis* assemblage to the mudflat until fully marine conditions were reached. However, evaporation may have led to an enrichment in ^{18}O which affected especially the small protected areas of riverine to lacustrine environments of the *P. hartbergensis* assemblage or small pools on the mudflats, settled by *Hydrobia* sp. and the *G. bicinctum* assemblage, which were only flooded sporadically. Thus, the oxygen and carbon isotopic data provide a palaeoenvironmental insight not readily apparent from the study of the gastropod assemblages alone.

At least during the Upper Sarmatian *Maetra* Zone, gastropods from a freshwater, a brackish and a shallow sublittoral environment yielded distinctively different isotope signatures. The classical brackish water scenario for the Sarmatian (Papp, 1954) is not supported by these data. Furthermore the data of the *Potamides hartbergensis* assemblage and from the mudflat assemblage point to considerable evaporation during the Late Sarmatian.

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