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Geodynamic impact on the stable isotope signatures in a shallow epicontinental sea

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ABSTRACT

Analyses were made of a mollusc-based meta dataset of 859 $\delta^{13}C$ and $\delta^{18}O$ data of Miocene nearshore settings in the European Paratethys Sea and its descendant Lake Pannon. The observed trends document a strong tie to geodynamics, which are largely decoupled from Miocene open ocean isotope curves. Semi- to fully enclosed, initially marine water bodies such as the Paratethys Sea are prone to switching seawater isotope signatures because they respond rapidly to changes in the evaporation/precipitation ratio. Two phases of positive deviations of oxygen isotope values of water (relative to the modern ocean value, SMOW) occurred during the Middle Miocene; both were initiated by tectonic constrictions of the seaways and became amplified by global warming and regionally decreasing precipitation. With the final disintegration of the Paratethys, the marine isotope signatures vanish. Instead, the observed isotope trends suggest a comparably simple system of an alkaline lake with steadily declining salinity. The 'ocean-derived' Paratethys Sea may thus act as a key for understanding isotope trends in epicontinental seas.

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Introduction

The marine Miocene deposits of Central Europe are a heritage of the Paratethys Sea (Fig. 1). During its maximum extent this sea spread from the Rhône Basin in France towards Inner Asia. As a northern satellite sea of the Western Tethys (= Proto-Mediterranean) it originated during the latest Eocene and Early Oligocene due to the rising Alpine island chains, which acted as geographical barriers (Rögl, 1998). The Central Paratethys existed throughout the Early and Middle Miocene. Already during the latest Middle Miocene, marine connections to adjacent seas were strongly narrowed. Finally, at 11.6 Ma, the western part of that sea became isolated within the Pannonian Basin system and Lake Pannon formed (Magyar *et al.*, 1999). In this evolving system, severe changes in the composition of the Paratethyan nearshore faunas were triggered by climatic and geodynamic developments (Harzhauser *et al.*, 2003). The latter are indicated by repeated isolation events with highly endemic faunas (Rögl, 1998).

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Methods, samples and study area

1.

As no generally accepted standard procedure of sample treatment prior to isotope analyses exists, we avoided any pre-treatment (e.g. roasting) of the shells to exclude any artificial alteration. Multiple samples were taken in ontogenetic sequence from apex to aperture with a 0.3-mm drill. Very small shells were crushed. All samples were reacted with 100% phosphoric acid at 70 °C in a Thermo-Finnigan Kiel II automated reaction system and measured with a Thermo-Finnigan Delta Plus isotope-ratio mass spectrometer at the Institute of Earth Sciences, University of Graz. Repeated measurements of NBS-19 and an internal laboratory standard yielded a standard deviation of 0.1‰ for both $\delta^{18}O$ and $\delta^{13}C$. Values are given in permil relative to V-PDB. The shell mineralogy and microstructures were investigated by XRD (X-ray diffraction) and SEM (Scanning Electron Microscopy) to detect diagenetic alteration (see Latal *et al.*, 2004, 2006a for techniques, methodology and exemplary SEM photographs).

As no alteration in the original shell material was detected we assume that no modification of the original isotope composition occurred. This is an essential assumption, because molluscs generally precipitate their shells in oxygen isotope equilibrium or near equilibrium (Grossman and Ku, 1986). Accordingly, oxygen and carbon isotope data may be applied for paleoenvironmental and paleotemperature reconstructions. $\delta^{18}O$ values in gastropod shells are mainly controlled by the temperature and $\delta^{18}O$ of the ambient water, whereas $\delta^{13}C$ values are influenced by a multitude of factors, e.g. upwelling, seasonal productivity, diet, living mode, growth rate, reproductive status (Geary *et al.*, 1992 and references therein; Bonadonna *et al.*, 1999). Global climate is one of the main factors that influence the oxygen isotope value of seawater in open oceans, whereas local environmental conditions are more important in marginal seas or coastal areas. Freshwater $\delta^{18}O$ values are primarily controlled by the isotopic composition of the rainwater.

2.

In total, 859 $\delta^{13}C$ and $\delta^{18}O$ data were measured in gastropod and bivalve shells from the Central Paratethys Sea and Lake Pannon. Fluvial and lacustrine taxa (e.g. *Melanopsis*, *Lymnaea*, *Unio*, *Margaritifera*) provide data for the freshwater endmembers and are used to discriminate between marine, brackish and purely freshwater values. The samples were collected in the

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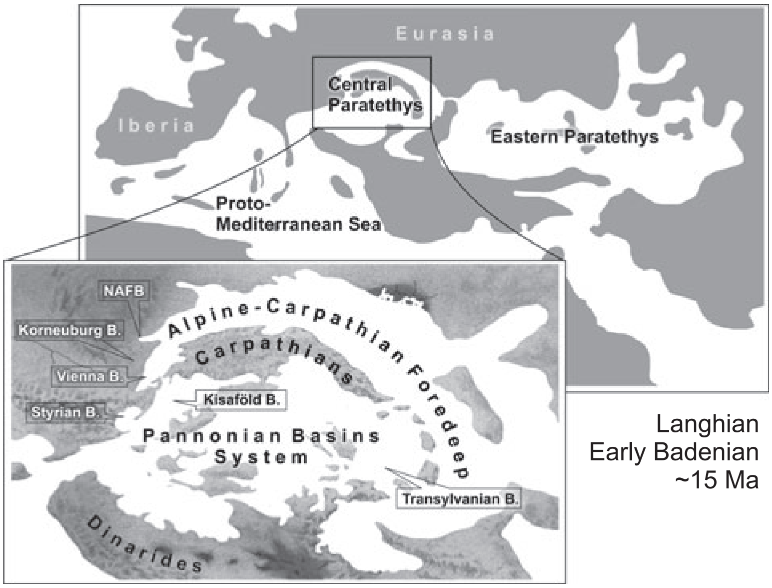

Fig. 1 Paleogeography of the circum-Mediterranean area during the early Middle Miocene (early Badenian, Langhian) based on Rögl (1998). The insert map presents the area studied and shows the position of the basins mentioned in the text (NAFB = North Alpine Foreland Basin). The Korneuburg Basin was already dry land in the reconstructed time slice. Data from the Hungarian Kisaföld Basin and the Rumanian Transylvanian Basin are from Geary *et al.* (1989) and Mátyás *et al.* (1996).

North Alpine Foreland Basin and the Pannonian Basin System (Vienna B., Korneuburg B., Styrian Basin; Fig. 1). Additional literature data are derived from the Hungarian and Rumanian part of the Pannonian Basin system (Kisaföld B., Transylvanian B.; Fig. 1). Nine time slices have been selected: ~20 Ma (Eggenburgian), ~16.5 Ma (late Karpatian), ~15 Ma (early/middle Badenian), ~14 Ma (late Badenian), ~12.5 Ma (early Sarmatian), ~12 Ma (late Sarmatian), ~11.5 Ma (early Pannonian), ~11–10 Ma (middle Pannonian), ~9–6 Ma (late Pannonian) (Fig. 2). Usually, serial samples per specimen were obtained by microdrilling. The same method was applied by all cited earlier studies. In the following, the number of samples is indicated as n and the number of shells as s.

The dataset (n = 37, s = 3) of the oldest samples is derived from littoral gastropod species (one batillariid; two muricids) of lower Lower Miocene (= Eggenburgian) deposits. The second dataset (n = 234, s = 22) comes from upper Lower Miocene (= Karpatian) deposits published by Latal *et al.* (2006a) and includes littoral (batillariid, potamidid, ocenebrid) and sublittoral (turritellid) gastropods. For the lower Middle Miocene (= Badenian), 175 measurements (s = 22) were collected, supplementing published data from Latal *et al.* (2006b) and Mátyás *et al.* (1996). A broad range of taxa was measured, including littoral batillariids and potamidids, shallow sublittoral turritellids, nassariids, naticids, etc. and deeper sublittoral thyasirid bivalves. The late mid-Miocene Sarmatian is covered by 235 (s = 32) measurements taken from Latal *et al.* (2004), Piller and Harzhauser (2005), Geary *et al.* (1989), Mátyás *et al.* (1996) and new analyses. Littoral potamidids and batillariids along with hydrobiids are represented along with shallow marine cardiids. The Late Miocene (= Pannonian and 'Pontian') data are based on 178 (s = 69) measurements derived from bivalves published in Harzhauser *et al.* (2007) and 87 measurements (bivalves and gastropods) from Geary *et al.* (1989) and Mátyás *et al.* (1996). Coastal faunas are represented by melanopsid gastropods and various dreissenids; sublittoral environments are covered by cardiids and the endemic dreissenid *Congeria*.

The entire dataset with detailed taxonomic, paleoenvironmental and geographic information and references is available online (http://www/Content.Node/forschung/geologie/mitarbeiter/pdfs/Harzhauser_et_al_TerraNova.xls).

Results

Miocene nearshore isotope values are plotted within a stratigraphic frame in Fig. 2. To avoid a bias by data lumping, the analysed taxa were separated according to their environmental requirements. Consequently, pure freshwater dwellers tend to be separated from the marine taxa by their usually lower $\delta^{13}C$ and $\delta^{18}O$ values. This trend is more obvious for $\delta^{13}C$ than for $\delta^{18}O$ values. During the early Late Miocene, however, the freshwater oxygen values of unionid bivalves are equal to or greater than those of littoral taxa of Lake Pannon. An aberrant Pannonian pattern is also evident from the average $\delta^{18}O$ values of sublittoral taxa. These steadily increase from the Early Miocene to the Middle Miocene, with an early Sarmatian maximum of +1.74‰ at ~12.5 Ma. After a strong $\delta^{18}O$ decrease during the late Sarmatian (~12 Ma) with a rather negative value of −1.2‰, a slight increase is evident again during the early Pannonian (~11.5–10.5 Ma) coinciding with the formation of Lake Pannon. Afterwards, a continuous decrease sets in. A generally similar trend is reflected by $\delta^{13}C$ average values. A focus on the maximum $\delta^{13}C$ values reveals an excursion at ~12 Ma during the Sarmatian. This positive peak of +6.8‰ contrasts with Early to Middle Miocene carbon maxima between +3 and 4‰. The distribution pattern of the stable isotope values is best visualized in frequency diagrams based on 799 $\delta^{18}O/\delta^{13}C$ measurements (Fig. 3). They document a shift of the $\delta^{18}O$ maximum from the Karpatian to the Badenian towards the heavy tail, while the $\delta^{13}C$ frequency curves lack a distinct shift. During the Sarmatian and Pannonian, the $\delta^{18}O$ maxima switch back to values comparable with the Karpatian ones. A marked shift towards negative values for both stable isotopes does not occur before the late Pannonian.

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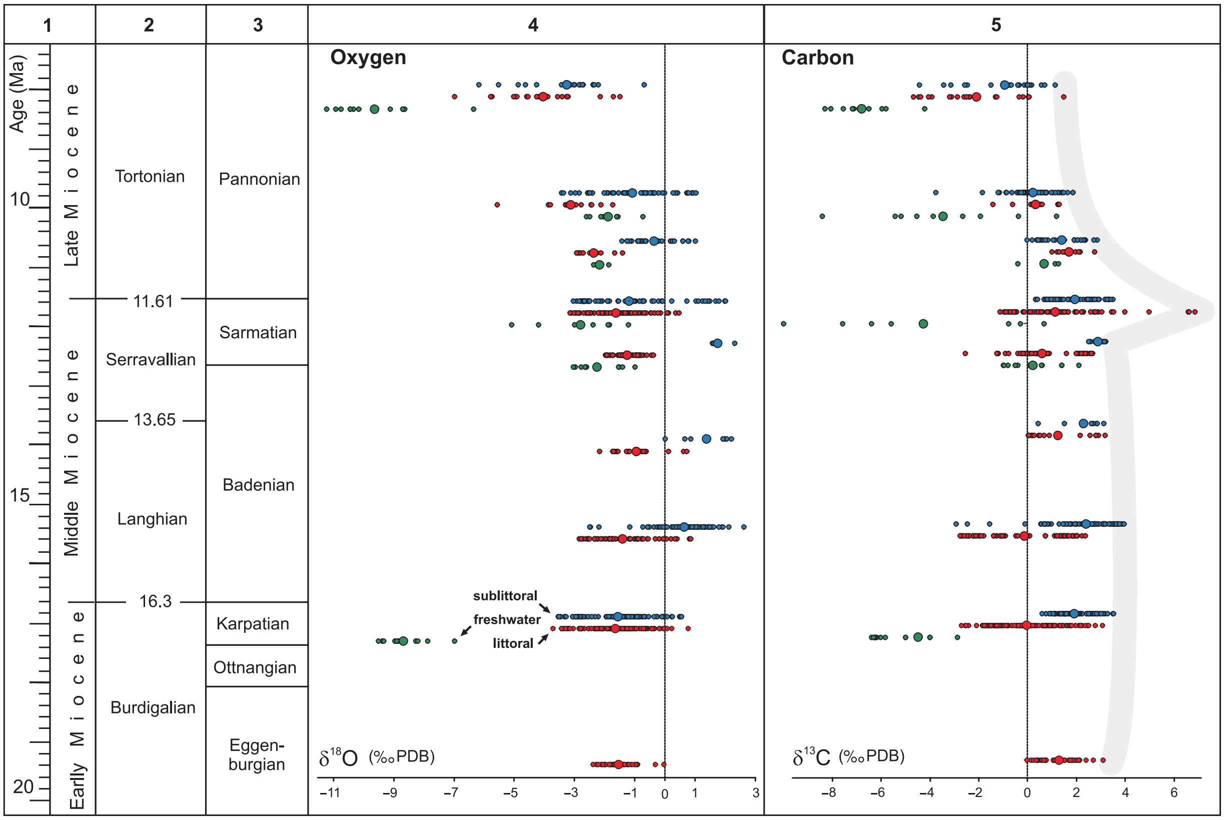

Fig. 2 Stratigraphic correlation between the Mediterranean and Paratethys with isotope data. 1: ages and epochs, 2: Mediterranean standard stages, 3: regional stages for the Central Paratethys Sea (compiled from Rögl, 1998; Harzhauser and Piller, 2004), 4 and 5: 859 $\delta^{18}O$ and $\delta^{13}C$ measurements from marine and freshwater molluscs (see text for references); vertical position corresponds to the approximate stratigraphic age. Green circles represent freshwater taxa, red circles littoral taxa, blue circles shallow sublittoral species; larger circles in each row represent the average value. The grey line in column 5 indicates the maximum $\delta^{13}C$ values.

Discussion

1.

A clear weakness of the 'holistic' approach is the inhomogeneity of the available data per time slice. Nonetheless, some general trends seem to be robust. Oxygen isotope values of extant shallow marine molluscs have maxima between −2 and +1‰ (Goodwin *et al.*, 2001; Rodriguez *et al.*, 2001; Keller *et al.*, 2002; Kobashi and Grossman, 2003; Reinhardt *et al.*, 2003). More negative values due to freshwater influx by river runoff or seasonal increases in precipitation are also commonly described (e.g. Rodriguez *et al.*, 2001; Kobashi and Grossman, 2003; Schöne *et al.*, 2003). Most of our data range well within that reference framework. Nevertheless, strongly changing average values throughout the Miocene (Fig. 4) suggest a complex system of driving forces. A pronounced positive shift in $\delta^{18}O$ values of about 1.4‰ occurs at the Early/Middle Miocene boundary. This shift cannot be explained solely by temperature differences. The early influence of the Middle Miocene climate optimum (MMCO) (Zachos *et al.*, 2001; Shevenell *et al.*, 2004) is already reflected in the late Early Miocene terrestrial fauna (Böhme, 2003) and by a northward migration of thermophilic mollusc taxa along with a marked increase in gastropod diversity along Paratethyan coasts (Harzhauser *et al.*, 2003). Minimum SSTs (Sea Surface Temperature) for the Karpatian have been estimated at around 14 °C (Latal *et al.*, 2006b) and from 15 to 17 °C for the early Badenian based on mollusc (Harzhauser *et al.*, 2003) and planktic foraminifers (Gonera *et al.*, 2000). Hence, both time intervals display fairly similar SSTs. The recorded shift can therefore only be explained by a switch of the isotope composition of the ambient seawater.

2.

A $\delta^{18}O$ of the open ocean seawater of *c.* −1.0‰ is indicated for the Middle Miocene climatic optimum by Lear *et al.* (2000). Our data suggest that this open ocean value cannot be uncritically adopted for epicontinental seas such as the Paratethys. Calculating the proxy data-based minimum SSTs against the measured $\delta^{18}O$ values of the mollusc carbonate (Grossman and Ku, 1986) indicates an isotopically negative seawater system (∼−1‰) in the Early Miocene and a positive one (∼+1‰) in the Middle Miocene (Fig. 4). This change is considered to be geodynamically induced

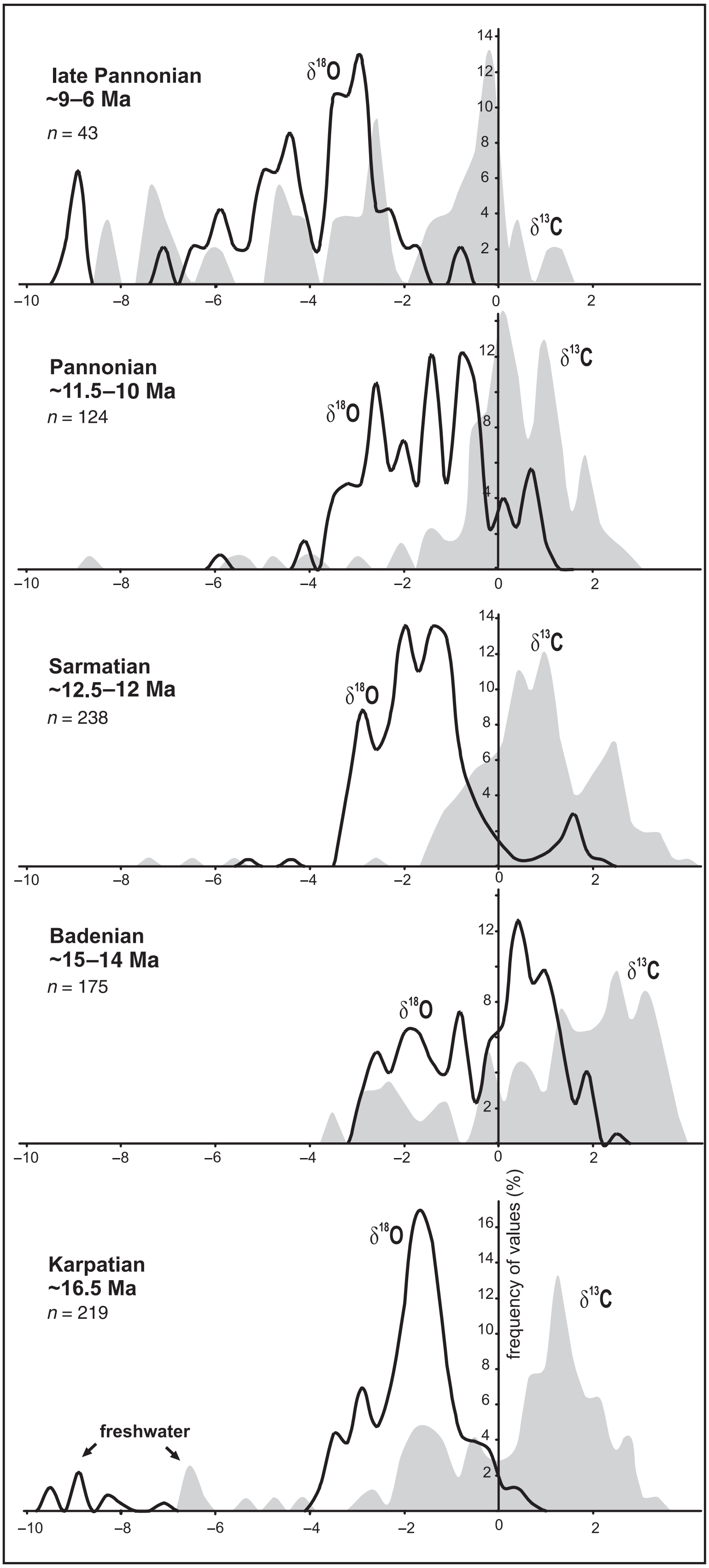

Fig. 3 Frequency diagrams of observed $\delta^{18}O$ and $\delta^{13}C$ values in five Miocene time series (black line: 0.3 intervals; grey background: smoothed curve, 0.6 intervals; frequencies are given in %). In both stable isotopes, the Badenian is characterized by unusually high data value frequencies in the heavy field. Thereafter, a clear shift towards negative values is evident, culminating in the late Pannonian. This trend is briefly interrupted by the erratic maximum during the Sarmatian. Another unique pattern occurs in the Pannonian carbon diagram, which displays a very abrupt frequency break between 0 and −1‰.

and climatically enforced. During that time, the Paratethyan basins transformed from west–east-trending deep-water basins towards shallow intra-mountain basins (Rögl, 1998). A highly structured archipelago sea was formed with decreasing connections to the open ocean. In addition, the high precipitation during the Karpatian (2000 mm year^{-1}; Meller, 1998) was replaced by less humid conditions and increasing seasonality (Böhme, 2003). Thus, similar to the modern Red Sea or Persian Gulf, the oxygen isotope composition of this semi-enclosed sea shifted towards positive values, amplified by the high temperatures of the MMCO. The reverse trend during the late Badenian and the early Sarmatian was initiated by the mid-Miocene climate transition, as suggested by the decline of the reef systems (Pisera, 1996) and surface water cooling (Baldi, 2005). The calculated $\delta^{18}O$ values of the early Sarmatian seawater might have additionally been influenced by the ingression of eastern Paratethyan waters after the re-connection with the Asian part of the Paratethys. The renewed positive peak during the late Sarmatian again reflects geodynamic and climatic interplay. A short warming phase, as indicated by the global curve of Zachos *et al.* (2001), is reflected in the Paratethys by a highly productive Sarmatian carbonate factory in the subtropical climate (Piller and Harzhauser, 2005). The sea became completely sealed and was thus prone to evaporation, which shifted the $\delta^{18}O$ values to around +1‰ (Fig. 4). These evaporation effects are emphasized by a characteristic peak of very heavy

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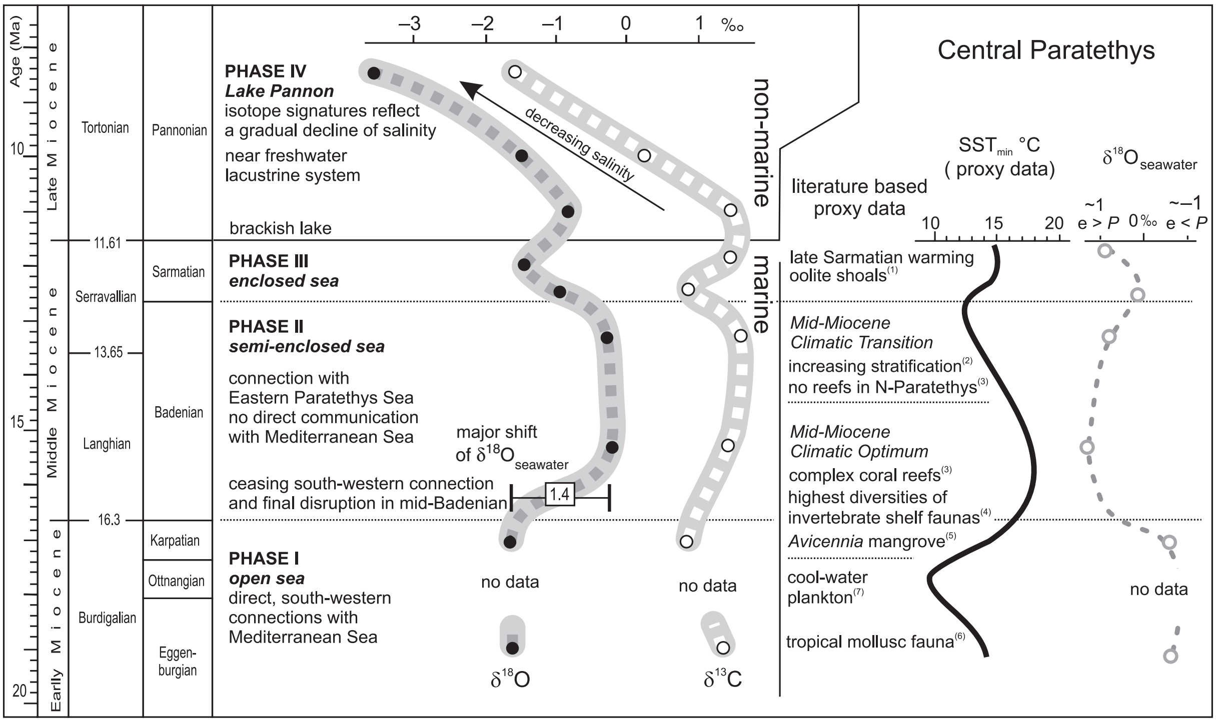

Fig. 4 Stable isotope trends (average values) and proxy data based on minimum sea surface temperatures (1: Piller and Harzhauser, 2005; 2: Baldi, 2005; 3: Pisera, 1996; 4: Harzhauser *et al.*, 2003; 5: Meller, 1998; 6: Mandic *et al.*, 2005; 7: Rögl, 1998). These paleo-environmental estimations are based on fossil floras (5), foraminifers (1, 7), molluscs (1, 2, 4, 6) and sedimentological data (1, 2, 3); no isotope data have been integrated to avoid circular reasoning. Calculating the recorded mollusc δ^{18}O against the estimated SST_{min} according to the standard equations (e.g. Grossman and Ku, 1986; Böhm *et al.*, 2000) allows the deviation of δ^{18}O of Paratethyan surface waters to be predicted. A major shift towards heavy oxygen isotope values during the Badenian is related to a positive δ^{18}O water value; evaporation *e* exceeds precipitation *p*. A similar transformation occurred from the early to the late Sarmatian, culminating in partly hypersaline coastal waters. Nearly identical δ^{18}C values in the late Sarmatian Paratethys and the preceding non-marine Lake Pannon suggest an alkaline start for that freshwater system.

oxygen isotope values, pointing to even hypersaline waters in coastal areas (Latal *et al.*, 2004*)*. The increasing trend of δ^{13}C maxima during the Sarmatian fits well to a lowered sea level accompanied by advanced evaporation in coastal areas. Indeed, the Sarmatian maximum extension of the Paratethys Sea occurred during the early Sarmatian, whilst the late Sarmatian with oolite shoals corresponds to a lowered sea level (Harzhauser and Piller, 2004). These conditions would support a better vertical mixing, promoting surface productivity, and in turn would increase the δ^{13}C value (Li and Ku, 1997). Again, geological data support this scenario: laminated marls of the early Sarmatian point to a stratified water body, whereas carbonate sedimentation of the late Sarmatian lacks evidence for pronounced stratification (Piller and Harzhauser, 2005).

3.

The onset of Lake Pannon corresponds to a parallel decrease in both stable isotope trends. This simply seems to reflect gradual freshening of the lake water, which started as a brackish remnant of the Paratethys Sea. Increasing freshwater discharge soon turned the lake into a near-freshwater system. Fossil-water analyses of well-logs support this interpretation (Mátyás *et al.*, 1996). The abrupt decline towards negative values is unique in the entire dataset. Nevertheless, a dominant carbon regime supported still rather high values between −0.5 and + 1‰. A brackish water scenario, as calculated from the oxygen values, cannot explain the high δ^{13}C values. In modern lake systems such high δ^{13}C values strongly correlate with elevated pH values. This would yield a pH value of 9–10 for the initial Lake Pannon based on the empiric data plot of Bade *et al.* (2003). Lake Pannon would thus have started as an alkaline lake.

Conclusions

The Paratethyan isotope patterns reflect a severe impact by an interconnected system of geodynamics and regional climate. The resulting trends are often decoupled from global isotope curves and are bound to the considerable fluctuations of the isotope composition of the Paratethys Sea. First constrictions of the seaways in the Middle Miocene are reflected immediately by a major positive shift in oxygen isotope values. That trend was positively amplified by the global warming of the mid-Miocene Climate Optimum and by a decrease in humidity on the regional scale. The cooling during the Miocene climate deterioration led to a swing back towards balanced values, which attain nearly

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0‰ deviation from the SMOW in the early Sarmatian, probably due to the influx of water with negative δ^{18}O and δ^{13}C values from the eastern Paratethys. A second sealing of the connections, coinciding with a short-termed warm interval and a lowered sea level in the late Sarmatian, caused a second phase with positive δ^{18}O and δ^{13}C values for Paratethyan waters. Widespread ooid formation at that time hints at increased alkalinity, which fits well to the coeval peak in δ^{13}C maxima in molluscs from littoral settings. The final disintegration of the sea is followed by the formation of Lake Pannon. The aberrant, positive δ^{18}O and δ^{13}C values of the early lake stage suggest elevated salinity in a brackish lake and a rather high alkalinity. Both factors may account for the big faunal turnover at that time, which gave rise to a fully endemic mollusc radiation. During all these phases a straightforward calculation of SST, based only on the mollusc isotopes, is impossible without independent proxy data.

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References

Bade, D.L., Carpenter, S.R., Cole, J.J., Hanson, P.C. and Hesslein, R.H., 2003. Controls of δ13C-DIC in lakes: geochemistry, lake metabolism, and morphometry. *Limnol. Oceanogr.*, **49**, 1160–1172.

Baldi, K., 2005. Paleoceanography and climate of the Badenian (Middle Miocene, 16.4-13.0 Ma) in the Central Paratethys based on foraminifera and stable isotope (δ^{18}O and δ^{13}C) evidence. *Int. J. Earth Sci.*, **95**, 119–142.

Böhm, F., Joachimski, M.M., Dullo, W.C., Eisenhauer, A., Lehnert, H., Reitner, J. and Wörheide, G., 2000. Oxygen Isotope fractionation in marine aragonite of coralline sponges. *Geochim. Cosmochim. Acta*, **64**, 1695–1703.

Böhme, M., 2003. The Miocene Climatic Optimum: evidence from ectothermic vertebrates of Central Europe. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **195**, 389–401.

Bonadonna, F.P., Leone, G. and Zanchetta, G., 1999. Stable isotope analyses on the last 30 ka molluscan fauna from Pampa grassland, Bonaerense region, Argentina. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **153**, 289–308.

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

Geary, D.H., Brieske, T.A. and Bemis, B.E., 1992. The influence and interaction of temperature, salinity, and upwelling on the stable isotopic profiles of strombid gastropod shells. *Palaios*, **7**, 77–85.

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

Goodwin, D.H., Flessa, K.W., Schöne, B.R. and Dettman, D.L., 2001. Cross-calibration of daily growth increments, stable isotope variation, and temperature in the Gulf of California Bivalve Mollusk *Chione cortezi*: implications for paleoenvironmental analysis. *Palaios*, **16**, 387–398.

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

Harzhauser, M. and Piller, W.E., 2004. Integrated stratigraphy of the Sarmatian (Upper Middle Miocene) in the western Central Paratethys. *Stratigraphy*, **1**, 65–86.

Harzhauser, M., Mandic, O. and Zuschin, M., 2003. Changes in Paratethyan marine molluscs at the Early/Middle Miocene transition – diversity, paleogeography and paleoclimate. *Acta Geol. Pol.*, **53**, 323–339.

Harzhauser, M., Latal, C. and Piller, W.E., 2007. The stable isotope archive of Lake Pannon as a mirror of Late Miocene climate change. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **249**, 335–350.

Keller, N., Del Piero, D. and Longinelli, A., 2002. Isotopic composition, growth rates and biological behaviour of *Chamelea gallina* and *Callsita chione* from the Gulf of Trieste (Italy). *Mar. Biol.*, **140**, 9–15.

Kobashi, T. and Grossman, E.L., 2003. The oxygen isotopic record of seasonality in *Conus* shells and its application to understanding late middle Eocene (38 Ma) climate. *Palaeontol. Res.*, **7**, 343–355.

Latal, C., Piller, W.E. and Harzhauser, M., 2004. Paleoenvironmental reconstruction by stable isotopes of Middle Miocene Gastropods of the Central Paratethys. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **211**, 157–169.

Latal, C., Piller, W.E. and Harzhauser, M., 2006a. Small-scaled environmental changes: indications from stable isotopes of gastropods (Early Miocene, Korneuburg Basin, Austria). *Int. J. Earth Sci.*, **95**, 95–106.

Latal, C., Piller, W.E. and Harzhauser, M., 2006b. Shifts in oxygen and carbon isotope signals in marine molluscs from the Central Paratethys around the Lower/Middle Miocene transition. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **231**, 347–360.

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

Li, H.-C. and Ku, T.-L., 1997. δ^{13}C-δ^{18}O covariance as a paleohydrological indicator for closed-basin lakes. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **133**, 69–80.

Magyar, I., Geary, D.H. and Müller, P., 1999. Paleogeographic evolution of the Late Miocene Lake Pannon in Central Europe. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **147**, 151–167.

Mandic, O., Harzhauser, M., Steininger, F. and Roetzel, R., 2005. RCMNS 2005 Excursion C: Miocene of the Eastern Alpine Foredeep – the Bohemian Massive Southeastern Margin. *Nat. Hist. Mus. Excursion Guides*, **46**, 1–53.

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

Meller, B., 1998. Karpo-Taphocoenosen aus dem Karpat des Korneuburger Beckens (Unter-Miozän; Niederösterreich). *Beitr. Paläontol.*, **23**, 85–121.

Piller, W.E. and Harzhauser, M., 2005. The Myth of the Brackish Sarmatian Sea. *Terra Nova*, **17**, 450–455.

Pisera, A., 1996. Miocene reefs of the Paratethys: a review. *SEPM*, **5**, 97–104.

Reinhardt, E.G., Fitton, R.J. and Schwarcz, H.P., 2003. Isotopic (Sr, O, C) indicators of salinity and taphonomy in marginal marine settings. *J. Foramin. Res.*, **33**, 262–272.

Rodriguez, C., Flessa, K.W., Tellez-Duarte, M.A., Dettman, D.L. and Aliva-Serrano, G.A., 2001. Macrofaunal and isotopic estimates of the former extent of the Colorado River estuary, Upper Gulf of California, Mexico. *J. Arid Environ.*, **49**, 183–193.

Rögl, F., 1998. Palaeogeographic considerations for Mediterranean and Paratethys Seaways (Oligocene to

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Miocene). *Ann. Naturhist. Mus. Wien*, **99A**, 279–310.
Schöne, B.R., Flessa, K.W., Dettman, D.L. and Goodwin, D.H., 2003. Upstream dams and downstream clams: growth rates of bivalve mollusks unveil impact of river management on estuarine ecosystems (Colorado River Delta, Mexico). *Estuar. Coast. Shelf Sci.*, **58**, 715–726.
Shevenell, A.E., Kennett, J.P. and Lea, D.W., 2004. Middle Miocene Southern Ocean cooling and Antarctic cryosphere expansion. *Science*, **305**, 1766–1770.
Zachos, J., Pagani, M., Sloan, L., Thomas, E. and Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science*, **292**, 686–693.

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