Silent witnesses

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Summary

8.1 Objective and research questions

The overall objective of our research was to examine the potential of freshwater mussel shell chemistry as a proxy for past river conditions, in order to reconstruct late Holocene river dynamics in the Rhine-Meuse delta. This objective was addressed in three steps: (1) a monitoring experiment in which mussels were kept in cages in both rivers for a period of 1.5 years; (2) the analysis of shells from both rivers, collected during the 20th century; (3) the analysis of late Holocene shells from the Rhine-Meuse delta.
Key questions were:

1. Are seasonally changing stable oxygen and carbon isotope ratios of ambient water recorded in growth increments of unionid freshwater mussels? Which ecological parameters influence the accuracy of bivalve shell $\delta^{18}O_{ar}$ and $\delta^{13}C_{ar}$ values as proxy systems in the Meuse and Rhine rivers? Are the differences in composition between the Meuse (rain-fed) and the Rhine (rain-fed/meltwater), as reflected in stable oxygen isotopic values of the water, recorded in unionid shells?
2. Can we establish models for interannual and intraseasonal growth rates from stable oxygen and carbon isotope chemistry of river water and equivalent sclerochronological shell records?
3. What is the empirical relation between measured $\delta^{18}O_w$ values and river discharge? Can we use this relation to reconstruct past $\delta^{18}O_w$ values and link these to measured river discharge values? Can extremely low and high discharge events be recognised in the reconstructed $\delta^{18}O_w$ and discharge records?
4. What information can unionid $\delta^{18}O_{ar}$ records provide about past river development and the climate during the late Holocene? Can centennial to millennial scale late Holocene climatic variations be recognised in unionid $\delta^{18}O_{ar}$? What were the effects of late Holocene climate change on seasonal (summer) $\delta^{18}O_w$ values and related river conditions (i.e. Alpine meltwater input, Meuse summer droughts)?

8.2 Unionids as recorders of seasonal $\delta^{18}O_w$ and $\delta^{13}C_{DIC}$ values

Unionid species living in the Rhine and Meuse rivers, precipitate skeletal aragonite in oxygen isotopic equilibrium with ambient water. Seasonal patterns in shell $\delta^{18}O_{ar}$ values are a result of seasonal variation in both ambient water $\delta^{18}O_{w}$ values and temperature. Freshwater bivalve $\delta^{18}O_{ar}$ records can therefore serve as a proxy for past river $\delta^{18}O_{w}$ values, in relation to discharge seasonality and river dynamics.

Shells from the rivers Rhine and Meuse differ significantly in bulk $\delta^{18}O_{ar}$ values, accurately reflecting the difference of $\delta^{18}O_{w}$ values between the two rivers (rainwater/meltwater versus rainwater only). These bulk $\delta^{18}O_{ar}$ values can be applied to determine if an ancient river channel was fed by the Rhine, by the Meuse, or by both.

River $\delta^{13}C_{HCO3-}$ has a seasonal cycle with low values in winter and spring. Abruptly rising values in early summer are caused by preferential removal of ^{12}C from the DIC pool by phytoplankton photosynthesis. This seasonal $\delta^{13}C_{HCO3-}$ cycle is accurately recorded in the $\delta^{13}C_{ar}$ values of growth increments of unionid shells.

Freshwater bivalve $\delta^{13}C_{ar}$ records can potentially serve as a proxy for past primary productivity, although other parameters (e.g. input of metabolic carbon or CO_2 exchange with atmosphere) will probably affect $\delta^{13}C_{ar}$ as well.

8.3 Interannual and intraseasonal growth

Knowing that unionid bivalves faithfully record both $\delta^{18}O_{w}$ and $\delta^{13}C_{HCO3-}$, we can reconstruct interannual and intraseasonal growth. The seasonal $\delta^{18}O_{ar}$ records of the unionids we studied show a truncated sinusoidal pattern with narrow peaks and wide troughs, caused by a combination of temperature fractionation and winter growth cessation. This record can be applied to reconstruct accurate interannual growth rate variation. In the first 2 to 3 years of their life both *Unio pictorum* and *U. tumidus* grew relatively fast. In later years, growth slowed down considerably. Such an ontogenetic growth decrease is common in unionids, and has been observed in previous studies as well (Ravera and Sprocati, 1997; Christian et al., 2000; Anthony et al., 2001).

Based on a correlation of intraseasonal $\delta^{18}O$ and $\delta^{13}C$ variation in ambient water and shells, a growth model is constructed which indicates non-linear growth of these unionids. Onset and cessation of growth of unionid freshwater mussels are induced by water temperature, whereas intraseasonal growth rates are a result of primary productivity (food availability).

8.4 Linking $\delta^{18}O_w$ values to river discharge

If $\delta^{18}O_{ar}$ values are to be used as a proxy for past river discharge, we first need to characterise the relation between river discharge and $\delta^{18}O_w$ values. In the Meuse this is a logarithmic relationship, which allows reconstruction of past discharge from reconstructed $\delta^{18}O_w$ values. Low discharge episodes during summer are recorded in the shells. Summer high discharge events cannot be reconstructed from shell $\delta^{18}O_{ar}$ records, because the predictive power of $\delta^{18}O_w$ values with respect to discharge is limited for the normal to high discharge situation due to the logarithmic nature of the relation between the two.

For the Rhine no significant relation between discharge and $\delta^{18}O_w$ values could be found. Quantitative reconstruction of past $\delta^{18}O_w$ values and discharge from unionid $\delta^{18}O_{ar}$ values is therefore not possible. However, extremely large Alpine meltwater pulses might be detected by their very low $\delta^{18}O_w$ values.

8.5 The Holocene

The final step towards reconstruction of past river dynamics using unionid shell chemistry as a proxy, is the actual analysis of late Holocene shells.

All shells have average, minimum and maximum $\delta^{18}O_{ar}$ values within the range of recent specimens. This suggests that meltwater amounts and severity of droughts during the climatic intervals studied (Subboreal, Roman Warm Period and Medieval Warm Period) were similar to the present day. It is likely that possible centennial to millennial scale climate variations between the time intervals studied are too subtle to readily be recognised in these records. Due to the considerable amount of noise in the $\delta^{18}O_{ar}$ records, introduced by large interannual and intraseasonal environmental variation in these rivers, these shells are more suitable for studying seasonal to decadal scale environmental variability.

Two medieval shells show decadal-scale variation in reconstructed $\delta^{18}O_w$ values, with a period of ~ 7-10 years. These possibly reflect NAO variability, which is strongly linked to European spring-summer atmospheric circulations and related river runoff. In order to draw firm conclusions about late Holocene variability in river dynamics, a larger number of shells, comprising many seasons, need to be analysed. The apparent detection of NAO-variability is particularly tantalising and calls for more research on Medieval Warm Period freshwater mussels, especially on species with a long lifespan.

8.6 Final outcome and outlook

This study investigates unionid shell chemistry as a proxy for past river dynamics and is one of the first combining a monitoring experiment and analysis of recent specimens with their application on late Holocene material. We demonstrated that three species of *Unio* faithfully record their environment with respect to both stable oxygen and carbon isotopes, making them a useful tool in palaeoclimate research.

The combination of different high-resolution chemical records within a single shell enabled us to construct preliminary models for interannual and intraseasonal growth.

The spatial and temporal heterogeneity of the river environments studied here introduces a considerable amount of noise to the background climate signal. This means that both local circumstances as well as significant intraseasonal environmental variation can obscure a lower frequency climate-related signal in these shells. In comparison to most freshwater systems, in the marine realm, both water temperature and $\delta^{18}O_w$ tend to be less variable within and between seasons. Therefore, sclerochemical records of freshwater shells are more complicated to interpret than their marine counterparts, hampering the straightforward interpretation of stable isotope records from subfossil Unionidae.

To minimise these problems, several directions of research can be pursued. First of all it is necessary to analyse a sufficient number of shells ($> \sim 10$) from a given climate interval, in order to capture the full range of interannual variability.

Furthermore, in order to better match certain parts of the shell with the corresponding time frame within the growing season, there is need for accurate intraseasonal and interannual growth models. Noteworthy work on these subjects has been done by Goodwin et al. (2003), De Ridder et al. (2004) and De Brauwere et al. (2008) and is still ongoing (Beelaerts et al., 2009). With respect to intraseasonal growth, Goodwin et al. (2009) achieved promising results with a numerical model based on predicted and measured $\delta^{18}O_{ar}$ values (MoGroFunGen).

Interannual growth is briefly addressed in chapter 4 (Versteegh et al., 2009). Growth increment size appears to decrease with shell length logarithmically as was previously described in *Unio mancus* and *Anodonta cygnea* (Ravera and Sprocati, 1997). In addition, differences in growth strategy have been found between species and between reservoirs (Christian et al., 2000). We have strong indications that growth strategies differ between time intervals en between reservoirs in the species studied here. More work is desirable on these subjects as well.

Reconstructions of past environmental variability might be greatly improved by using multiple proxies within one organism (Schöne and Surge, 2005; Schöne et al., 2006). For example, $\delta^{18}O$ values as well as certain trace element records might be influenced by (and serve as a proxy for) temperature. When these are also influenced by other factors, a temperature reconstruction based on one proxy alone might be highly uncertain, whereas a reconstruction considering all proxies at once will have much smaller associated errors (Bauwens et al., 2009). Furthermore, another approach to determine past river discharge is by salinity reconstructions derived from $\delta^{18}O$, $\delta^{13}C$ and Ba/Ca records in estuarine bivalves (Gillikin et al., 2006a; Gillikin et al., 2006b). Combining these records with freshwater bivalve $\delta^{18}O_{ar}$ values can strengthen reconstructions of palaeo-discharge.

Providing the above suggestions are met to a sufficient degree, stable isotope records of archaeological shells can serve as a proxy for reconstructing past river dynamics and possible droughts and meltwater fluxes. These reconstructions are much needed for validation of models predicting the impact of climate change in the Rhine-Meuse delta (Cohen and Lodder, 2007; Ward, 2009).