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Ostracoda from inland waterbodies with saline influence in Central Germany: Implications for palaeoenvironmental reconstruction

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ABSTRACT

As a necessary precursor to reconstructing the palaeoenvironmental conditions likely to be temporarily influenced by salt bearing ground waters, modern sites of Central Germany, known from the literature to be continental salt water localities, were investigated for their ostracod faunas. Analysing their associations enables the test of several methods in palaeoenvironmental analysis based on ostracods. In total, 54 ostracod taxa are documented. One species, *Microdarwinula zimmeri*, is new for the area. Interesting is the historical occurrence of *Cyprideis torosa* and *Cytheromorpha fuscata*, typically regarded as indicators of brackish water. The draining of wetlands has led to the disappearance of many former inland salt sites so that only a few of the sampled water bodies still show slightly elevated salinity (oligohaline range). The most important factors for the distribution of ostracod associations are groundwater influence, turbidity and ecological stability, whereas the type of dominating ions is of lesser importance because of time-averaging using taphocoenoses from surface sediments in our study. The relative proportion of ecological groups of ostracods appears to be the best tool for reconstructing past habitat types. The newly established Ostracod Permanence Index and Ostracod Turbulence Index allow the recognition of the influx of ground and surface waters, perennial habitats and flowing waters. A test of the Mutual Ostracod Temperature Range (MOTR) method demonstrates its capability to reconstruct, with a precision of +/−2 °C, the mean July and January air temperatures for the time interval 2002–2012. Additionally, the study contributes to the poorly known Recent distribution of ostracods in Central Germany.

1. Introduction

Ostracoda, small bivalved crustaceans, are one of the microfossil groups best suited for reconstructing past continental environments. For such purposes, ecological and distribution data are needed. However, studies on Recent ostracods in the German federal states of Thuringia and Saxony-Anhalt are very rare, despite numerous investigations on Pleistocene Ostracoda by Pietrzeniuk, Diebel and Fuhrmann (e.g. Diebel and Pietrzeniuk, 1969, 1977, 1978a, 1978b, 1984; Fuhrmann, 2008, 2013). The aim of the present study is 1) to test ostracods as indicators of habitat types and 2) to establish baseline distributional data for the modern ostracod fauna from Central German localities previously reported to have salt water influence. Our analysis includes the test of 3) the Mutual Ostracod Temperature Range (MOTR) method for palaeoclimate reconstruction. The study prepares palaeoenvironmental reconstructions based on Holocene ostracod associations in Central Germany.

2. Study area

In Central Germany, alternating sequences of Triassic sandstone and limestone reflect the oscillation between shallow sea and terrestrial fluvial sedimentation in the Thuringian Basin during the Permian and Triassic. Jurassic and Cretaceous as well as Tertiary strata are rarely preserved today. The larger central part of the Thuringian Basin is covered by Triassic rocks whereas sediments of the Permian, including Zechstein evaporites, are only exposed at its margin. Numerous sinkholes formed due to the dissolution of Permian and Triassic evaporites (Seidel, 2003; Wirth, 2008). After the silting up or artificial draining of the lakes covering the depressions in historical times, large reed flats with small relict water bodies developed. Although most of these water bodies contain salinities less than 2 psu today, halophytic plants still grow on the salt bearing soil in many places (Westhus et al., 1997). The 23 sites

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investigated in this study are situated in the Thuringian Basin and its surroundings (Fig. 1).

The modern climate in Germany is generally humid, however, large parts of Central Germany are characterised by relatively dry conditions resulting from the rain shadow caused by the Harz Mountains. The annual precipitation is 450–500 mm/year (Fabig, 2007). Annual air temperature fluctuations are characterised by strong seasonality in the temperate climate zone. Mean values of −0.5 °C for January and 17.5 °C for July are published for the period 2002–2012 in Jena, south-eastern Thuringian Basin (weather station of the Max Planck Institute for Biogeochemistry, Jena).

3. Material and methods

We carried out a sampling campaign in the Thuringian Basin and adjacent areas (see Supplementary data) from summer 2006 to late spring 2007 complemented by samples from the former Süsser See and Bindersee taken in 2004. Additionally, more detailed collections were carried out around Bilzingsleben and in the area of Bad Kösen–Groß Heringen in summer 2010 as well as the Pennickental at Jena in summer 2011. Data from Altenburg (Fuhrmann, 2010) and the Plothener fish ponds sampled in spring 2012 by Gemeinhardt and Frenzel (2014) as well as older material from Erfurt and Bad Kösen probably taken in 1966/68, from Siebleben taken in 1969 and from Bilzingsleben taken in 1978/79 (material from the Diebel & Pietrzeniuk ostracod collection in the Museum für Naturkunde Berlin) complete our data set. Those older collections are stored dried in micropalaeontological slides. The valves were identified and counted by us for adding the data to our modern training set. During our sampling campaign in 2006 and 2007, conductivity, pH and temperature of the water were measured using a multiprobe WTW 340i and the habitats were characterised. The sampling was carried out exclusively in shallow waters (<1 m water depth) reflecting the small size of the majority of water bodies. Many of the 23 sites were sampled at multiple stations covering different habitat types and almost all stations were sampled only one time resulting in 77 modern samples in total (compare Fig. 1 and Supplementary data).

Water quality analyses included ion chromatography (Dionex DX-120) for anions and ICP-OES (Varian 725 ES) for cations. After transformation of ionic masses into equivalent masses, the percentages of the main ions were calculated and used for chemical classification of water bodies.

Ostracods were sampled with a hand net (ca. 0.1 mm) by scraping the uppermost 1–2 cm of the surface sediment. The 100–200 ml sample was washed through a 200 μm sieve. Ostracod carapaces and valves were picked from the dry residues using a wetted fine-tipped brush. Ostracods were counted and identified relying on Meisch (2000) and Fuhrmann (2013). Valves recognisable as reworked through abrasion or corrosion marks were excluded from analysis. For most samples, it was not possible to identify individuals that were still living during sampling due to the use of material from various collections. Therefore, we decided to use total associations instead.

The software package PAST (Hammer and Harper, 2005) served for statistical analyses. A PCA on samples containing at least 50 valves each was carried out in order to identify associations and groups of samples bound to habitat types and environmental factors respectively. This PCA is based on 62 of the 77 samples and untransformed relative abundances of 36 ostracod species after excluding species present in less than three samples or never exceeding 5% of the association of each sample. Before analysis, the matrix was tested on highly correlated (>| ± 0.9|) variables using Spearmen's Rank Correlation as recommended by Backhaus et al. (2010). The MOTR method uses calibrated temperature ranges determined from a combination of species distributions and an interpolated climate model in a Geographical Information System (Horne, 2007; Horne and Mezquita, 2008). The calibrated

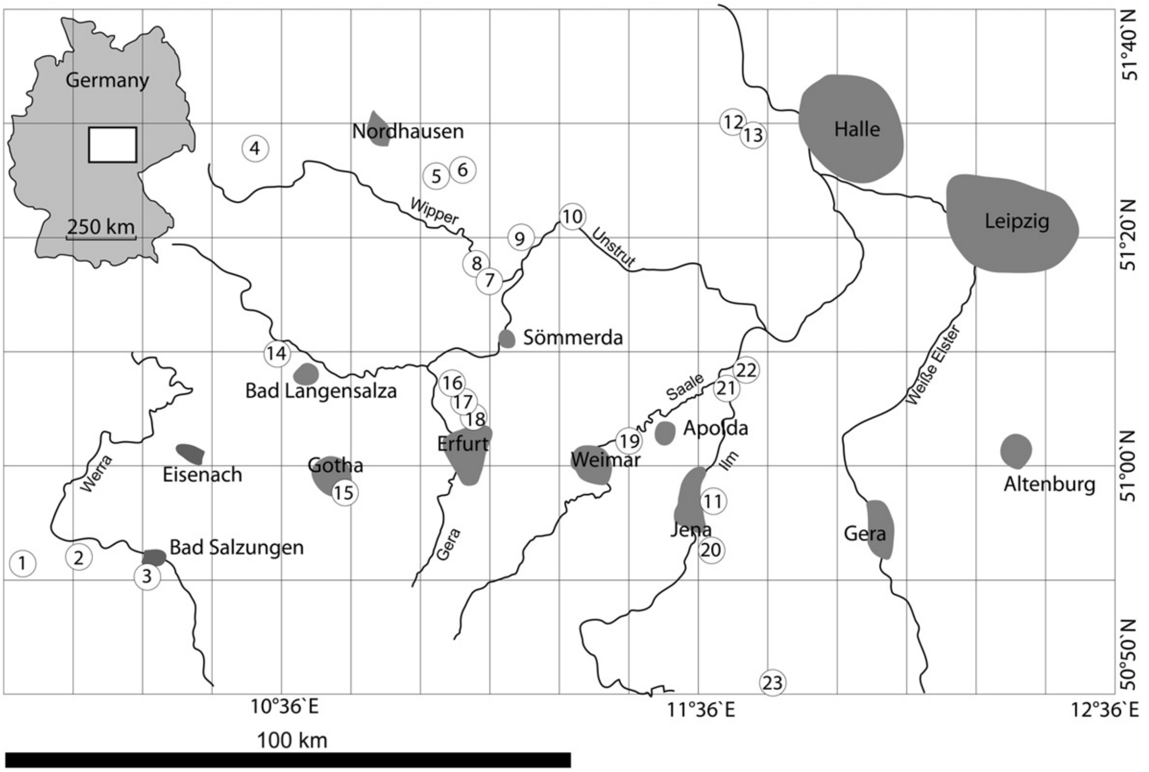


Fig. 1. Map of the investigated sites in Central Germany. The numbers indicate the studied modern localities; number of sampled stations are bracketed: 1 — Unterbreizbach (1); 2 — Merkers (1); 3 — Etmarshausen (1); 4 — Kraja (1); 5 — Numburger Quellen (1); 6 — Stausee Kelbra (1); 7 — Kindelbrück (4); 8 — Bilzingsleben (13); 9 — Esperstedt (2); 10 — Solequelle Artern (1); 11 — Fürstenquelle Jena (2); 12 — Süsser See (2); 13 — Bindersee (3); 14 — Grossengottern (2); 15 — Siebleben (2); 16 — Hasslebensee (2); 17 — Alperstedter See (1); 18 — Stotternheimer See (1); 19 — Oßmannstedt; 20 — Pennickental (7); 21 — Groß Heringen (3); 22 — Bad Kösen (9); and 23 — Plothener fish ponds (2).

ranges used herein are based on OMEGA (Ostracod Metadatabase of Environmental and Geographical Attributes; Horne et al., 2011, 2012). As a test of its performance, the MOTR method is applied to the Recent sites of the Thuringian Basin comparing its temperature estimations with measured January and July temperatures. The Ostracod Permanence Index was calculated using the percentage of species living in permanent waters divided by the sum of species living in permanent and temporary waters. The Ostracod Turbulence Index is defined as the ratio of turbulent and streaming water preferring species (mesorheophilic + polyrheophilic) and calm water preferring species (rheophobic + oligorheophilic) not counting rheoeuryplastic species. Both indices rely on ecological classifications given by Meisch (2000) and Fuhrmann (2013). The ecological classification of main species is given in Table 1.

Quantitative distribution data are to be added to the NODE (Nonmarine Ostracod Distribution in Europe) database (Horne et al., 1998) which contributes to OMEGA. The ostracod material collected in this study will be archived in the museum Mauritianum in Altenburg, Thuringia.

4. Results

4.1. Water bodies

We exclusively sampled shallow waters, because all Recent aquatic habitats affected by salt water brines in Central Germany are small water bodies. Most sampled habitat types were ponds (natural and man-made) and streams. However, there is a remarkable proportion of spring-fed waters (Table 1). Despite preferentially sampling sites reported in literature as saline influenced, only a few showed elevated salinity (oligohaline range). Salinity ranges from 0.1 to 1.8 with a median of 0.5. The majority of the studied waters is SO_4^{2-}-dominated (Table 1).

4.2. Ostracoda

37 ostracod species were identified in 65 samples from 23 sites in Thuringia and southern Saxony Anhalt (Table 1, Plate I, Appendix A). The most frequent and abundant species include *Candona candida*, *Candona neglecta* and *Ilyocypris bradyi* (Table 1). True brackish water species are *Cyprideis torosa*, which occurs in a few sites, and *Cytheromorpha fuscata* found in one site with low numbers only; however, both species are represented exclusively by empty valves. All valves of *C. torosa* are representing the smooth (not noded) form. Semiterrestrial ostracod species such as *Microdarwinula zimmeri* and *Scottia pseudobrowniana* were found in the Bilzingsleben area in high abundance.

Most ostracod species found are either present in a few samples or widely scattered over habitat types. Thus, associations indicative for selected habitats are hardly recognisable. Only the helocrenic species *Fabaeformiscandona brevicornis* and *Cryptocandona vavrai* are limited to spring-fed waters. Taxa preferring turbulent water are present in almost all samples in large numbers. Perennial forms are rare and mostly limited to temporary water bodies, the littoral zone of lakes and ponds and in ditches. Despite their indication of perennial waters, forms of permanent waters mostly co-occur with them in such samples. *Scottia pseudobrowniana*, a semi-terrestrial species (Meisch, 2000), is limited to fen and spring sites. Taxa of lakes and ponds are widely scattered over all habitats, their highest diversity (>3 species), however, is found in lake and pond samples only (Table 1).

In the present study we tested the MOTR method by applying it to combined Recent ostracod assemblage of 35 species for which a reliable calibration set exists (Horne and Mezquita, 2008). The reconstruction was obtained by integrating records from all studied 65 samples and 23 sites in the Thuringian Basin. The result indicates a mean July air temperature range of +16 to +20 °C and a mean January air temperature range of −1 to +2 °C (Fig. 2).

5. Discussion

A grouping of the studied inland water bodies was done based on its ionic composition with a focus on ionic dominances (Table 1). Two main groups of anionic composition may be distinguished: Cl^-- and SO_4^{2-}-dominated waters. To explain the origin of these ions, a groundwater contact to NaCl- or $CaSO_4$-bearing sediments underground is assumed in most cases. NaCl is typical for evaporites of Zechstein strata underground but can also occur in Triassic sediments (Seidel, 2003; Wirth, 2008). In the case of $CaSO_4$-dominated water, sediments from outcrops in addition to that from the underground are also possible sources. Gypsum-rich sediments occur frequently in Permian and Triassic formations and may lay on the surface.

The list of ostracod species found in our material comprises all taxa frequently found in Quaternary sediments of Central Germany associated with *Cyprideis torosa* (Pint et al., 2012). The only exceptions are *Limnocytherina sanctipatricii* and *Cytherissa lacustris* which are absent from our Recent material. Both species are known to prefer cold water (Meisch, 2000), hence they are more typical for glacial or transitional climatic conditions or the deep water of oligotrophic lakes and are not expected for our Holocene interglacial shallow water associations. Remarkable is the occurrence of living *Microdarwinula zimmeri* in a fen sample at Bilzingsleben, a species previously known from sites south of the Alps only (Fuhrmann, 2013).

Principle Component Analysis (PCA) on ostracod distribution over samples shows only two species and a few samples with high loadings onto the first two axes (Fig. 3). The first axis explains only 16.4%, the second one 11.0% of the variance of data. This finding points to a heterogeneous data set and a multitude of factors influencing ostracod distribution. Examining loadings of samples reveals waters dominated by $CaSO_4$ on the right side and those dominated by NaCl on the left side of the diagram. *Candona candida* shows the highest loading on axis 1, hence is typical for $CaSO_4$-rich waters in our data set. *Heterocypris salina* characterises the other side of the first axis, which fits its characterisation as preferring NaCl-rich waters (Meisch, 2000). The second axis may be explained by its being negatively impacted by flowing water. Whereas four species preferring flowing water (*Ilyocypris bradyi*, *Prionocypris zenkeri*, *H. salina*, *Candona neglecta*) are grouped at the lower end of the second axis, the highest loadings are associated with *Potamocypris zschokkei* which prefers stagnant waters (Meisch, 2000). The placing of samples within the PCA is reflecting our interpretation of the two axes as well.

Surprisingly, presence/absence distribution of species does not allow the discrimination of habitat types (Table 1). A possible explanation for this circumstance is the lack of differentiation of living and dead individuals in parts of our data set. Due to this, samples are time-averaged tentatively containing subfossil material or maybe even allochthonous specimens in rare cases. As Westhus et al. (1997) report, and we have noticed in many locations, many salt water sites known from older literature were drained and converted into areas for agriculture after the Second World War. Hence, we could find a low number of sites with elevated salinity only and many smaller water bodies have disappeared and were replaced by reed areas (Ried). Biasing effects of sampling season are assumed to be marginal because of analysis of total associations comprising assemblages of probably some years.

Taxa given in Meisch (2000) and Fuhrmann (2013) as helocrenic occur not only in springs and spring influenced water bodies, but also in streams, fens and in some of the ponds (Table 1). The presence of helocrenic ostracod species in other than spring-fed water bodies may be caused by seepage in or close to such waters not recognised by us during field work. We assume therefore more species than only *Fabaeformiscandona brevicornis* and *Cryptocandona vavrai* as documented by our study to be indicator-species for spring impact. We decided to use the proportion of helocrenic species and also the proportion of cold water species within the associations to investigate its proxy value assuming that the sampled springs have constant low water temperatures

Table 1

Distribution of modern Ostracoda in surface samples from Central Germany. Species never exceeding 2% in any sample or occurring in less than two samples are omitted. The remaining are sorted based on ecology (Meisch, 2000; Fuhrmann, 2013). Samples listed according to water type and salinity range, which are derived from the measured conductivity. The dominate anion and cation are listed if they were measured. Samples from the oligohaline range and *Cyprideis torosa* as the only true brackish water species present in numbers are shaded. The relative abundance of ostracod taxa is given by dominance values following Engelmann (1978): full circle = eudominant (≥32%), three quarter circle = dominant (≥10%), half circle = subdominant (≥3.2%), quarter circle = recedent (≥1.0%) and empty circle = (present with <1.0%).

Locality (site number)	Coordinates		Ecology	Helocrenic								Meso- to polyrheophil								Perennial					S	Permanent					Lakes and ponds										Environment				
	Nord	East	Sample	*Psychrodromus olivaceus*	*Ilycypris inermis*	*Fabaeformiscandona brevicornis*	*Cryptocandona vavrai*	*Fabaeformiscandona breuli*	*Potamocypris zschokkei*	*Eucypris pigra*	*Cavernocypris subterranea*	*Ilyocypris bradyi*	*Prionocypris zenkeri*	*Candona candida*	*Limnocythere inopinata*	*Potamocypris unicaudata*	*Ilyocypris gibba*	*Cyclocypris ovum*	*Pseudocandona rostrata*	*Pseudocandona sucki*	*Physocypria kraepelini*	*Fabaeformiscandona fabaeformis*	*Cyprois marginata*	*Potamocypris arcuata*	*Scottia pseudobrowniana*	*Candona neglecta*	*Cypridopsis vidua*	*Cyprideis torosa*	*Pseudocandona marchica*	*Herpetocypris reptans*	*Heterocypris salina*	*Cyclocypris laevis*	*Plesiocypridopsis newtoni*	*Sarscypridopsis aculeata*	*Heterocypris incongruens*	*Darwinula stevensoni*	*Cypria ophtalmica*	*Cypris pubera*	*Pseudocandona albicans*	*Notodromas monacha*	Water type			Salinity	Chemistry
8	51°17,440'	11°03,560'	DP-Bilz-8	●	●	○	○	◔				◔		◑				◑								◔											◑		◔		Spring	Discharge	Permanent	Freshwater	no data
8	51°17,440'	11°03,560'	DP-Bilz-1	●	◔	◕	◑							○								○			●				◑			○					○		◔						
8	51°16,605'	11°03,561'	DP-Bilz-2	●	◑	◔			◑			◑										◑			◑				○			◑							◔						
7	51°15,816'	11°04,600'	DP-Bilz-11			◑						○		○				◕								●											◕		◑						
11	50°54'56.98"	10°16'22.64"	Fü-1						●					◑																			◑				◔								SO_4^{2-}; Ca^{2+}
22	51°7'44.56"	11°43'9.98"	J.Berg		◑					●				◕												◕													◑				?		
21	51°6'9.13"	11°40'14.52"	ABKL7							◔	●		◑	◑	○																														
21	51°6'9.13"	11°40'14.52"	Bahnd								●		◑	◑		◔																													
22	51°7'49.10"	11°43'24.19"	ABKL4							◑		◕	◕	●	◕											◕																		Oligohaline	Cl^-; Na^+
22	51°7'49.10"	11°43'24.19"	Quelle							◑		◕	◕	●	◕											◑																			
19	51°0,999'	11°25,593'	B9						◑			◕				●	◕										◑								◕							Standing	P.?		SO_4^{2-}; Ca^{2+}
19	51°0,998'	11°25,598'	B1/2						◑			◑				●											◕				○				◕										
5	51°25'39.91"	10°57'47.05"	Nu-2									◔				○		○													●				◕						Spring influenced			Freshwater	Cl^-; Na^{2+}
3	50°48'06.68"	10°16'22.64"	Et-1						◑			◕			●												◑				◔														
9	51°19'22.63"	11°10'28.39"	Esp-3									●		◕			◔	◑					○	○			◕				◕	◔	◑		◑										Cl^-; Na^+
11	50°49'50.46"	10°07'36.38"	Fü-2									●		◔		◑	●							○		◔					○														SO_4^{2-}; Ca^{2+}
8	51°15,816'	11°04,600'	Grü-1											○				◕								◕		●									●								
8	51°17,440'	11°03,560'	DP-Bilz-9	◔								○		◕				◑								◕						○					●								no data
8	51°17,328'	11°03,608'	Bilz-1	◑	◔							◔	●												◔	◕			◔										○			Flowing			
7	51°15,816'	11°04,600'	DP-Bilz-7	◑	◑	◑		◔				◕	◕				○	◑				○			◔	◕													◔						
22	51°7'49.10"	11°43'24.19"	ABKL5		◑					◑		◑	◕	●	◕											◕											◑				Spring			Olig.	Cl^-; Na^+
22	51°7'49.10"	11°43'24.19"	Saale		◔					◑		◑	◕	●	◑	◑										◕					◔						◑								
21	51°06,279'	11°40,107'	ABKL11							◔	◑	◕	◕	●	◑											◑											◔		◑						SO_4^{2-}; Ca^{2+}
22	51°6'16.36"	11°40'6.55"	ABKL9							○	◕	◕	◕	●	◑											◔											◔		○						
22	51°7'38.86"	11°43'6.21"	ABKL6		◕					◑		◕	◕	◕												◕											◔		◑						
22	51°7'38.86"	11°43'6.21"	Kalkw.		◕					◑		◕	◕	◕		◔										◕						◔					◔		◑						
22	51°7'44.56"	11°43'9.98"	ABKL3		◑					●				◕												◕													◔						

4	51°27'03.57"	10°30'51.07"	Kra-1						◔			◑	●	◔			◑		◕							◕					◔		◔								Stream		Permanent	Freshwater	
8	51°16,965'	11°04,330'	Bilz-12				◔					◑			◕			◔								◑				◑	●														no data
8	51°17,328'	11°03,608'	DP-Bilz-4	◕	◑	○						◔	●	○					○							◑			◔			◔													
7	51°15,829'	11°04,682'	DP-Bilz-6	◕	◑							◕	◕	◔			◕									◑					●														
8	51°16,128'	11°04,083'	Bilz-10		○							●	◕	○												◑				◔	◕				◕										
1	50°48'59.00"	9°58'49.98"	Br-1									●	◔	●						◔						○																			Cl^-; Na^{2+}
20	50°54,385'	11°37,896'	P3	◕	◕	◔		◕	◑	◕				○				○											◕																SO_4^{2-}; Ca^{2+}
20	50°54,355'	11°37,630'	P5.1	◔	○				●																																Pond	Standing			
9	51°20'46.55"	11°10'50.48"	Esp-1									◔	◕	◑												◕	○				◑										Ditch				Cl^-; Na^+
16	51°06'06.97"	11°00'01.92"	Haß-4											●			◕	◑		◔																								Oligohaline	SO_4^{2-}; Ca^{2+}
16	51°06'06.97"	11°00'50.29"	Haß-5									◑		●			◑																												
14	51°08'33.29"	10°35'22.35"	Gros-7											●				◑			◕																●								no data
14	51°08'33.29"	10°35'22.35"	Gros-6											○	◔		●	◕	◔				◔			◕						◑													
13	51°29'12.29"	11°29'12.29"	1018-1												◕	◕												◕								●					Lake or pond				Cl^-; Na^+
13	51°29'12.29"	11°29'12.29"	1018-3												◑	●										◔	◔	◑			◑					◕	◕								
13	51°29'12.90"	11°43'24.20"	Rol-1									◑			◑	◑	◔		◑	◑						◑	◕	◕	◑		◑		◑				◔			◔					
17	51°04'28.86"	11°02'21.97"	Alp-1									◕	◑	◕	◑	◔		◔									◕				◕	◑		◑			◕							Freshwater	SO_4^{2-}; Ca^{2+}
6	51°25'36.54"	10°58'13.11"	Ke-1													◔								◑			◔	◑			◕	◔	●		◔			◕	○						
12	51°29'43.65"	11°40'21.41"	Sü-1									◕		◔	◑			◕	◕	◕						◑	◑	◑			○	◑	○												Cl^-; Na^+
12	51°29'55.99"	11°39'44.10"	1017-1									◔		◑	◕	◑							○			◑	◔	○			○					●									
18	51°02'56.08"	11°03'29.29"	St-1									●	◕	◔			◑	◑		◔								◔					◑	◕	◔										SO_4^{2-}; Ca^{2+}
15	50°56'07.87"	10°45'46.81"	Sieb-Grei											○	◔					◔		◔	●								◔	◕						◕		○			Perennial		SO_4^{2-}; Mg^+
16	51°05'47.33"	11°00'50.29"	Haß-3									◑		◕	◕		●			○	◑						◑					○					◑								SO_4^{2-}; Ca^{2+}
16	51°05'47.33"	11°00'50.29"	Haß-2									◕		●				◔		○							●					◑													
20	50°54,396'	11°37,950'	P2		◕				●	◕		○		●						○																									
20	50°54,388'	11°37,953'	P2.1		◑				◕	○		○		●						○																									
2	50°49'38.67"	10°07'12.49"	Me-1									○		◑						◔						●					●				◔										SO_4^{2-}; Na^+
23	50°39,310'	11°45,631'	SRT 1											●							◑						○						○				○								SO_4^{2-}; Ca^{2+}
23	50°38,927'	11°45,695'	SGT 2											●			◕				◕					○										●									
15	50°56'07.87"	10°45'46.81"	Sieb-2									◑		◔	◕	◕	◑	◔					◑	◑		◕	◔				◕	◑	○			○									SO_4^{2-}; Mg^+
20	50°54,390'	11°37,458'	P6.1	◕	●					◔		◕		◔																															SO_4^{2-}; Ca^{2+}
20	50°54,390'	11°37,458'	P6	◕	●			◔	◑					◔				○																					◔						
8	51°17,226'	11°03,668'	DP-Bilz-10									◕						◔													◔			●					◑						no data
8	51°16,124'	11°06,526'	Bilz-3									◔		◕	○	◔		◕									◕									◕	◕			◔					
7	51°15,879'	11°04,734'	Bilz-7		◔							●		◑	◑			◕								◑	◑		◔	◔	◔	◔								◕					
8	51°17,340'	11°03,661'	Bilz-2	◑		◕								◔				◑				◑			◑				●			◑							◔		Fen	Flow.			
8	51°17,340'	11°03,661'	DP-Bilz-3	◕	◔	◕	◔					◔		○				◔				◑			◕	◑			◕		◔	◑		◔					○						
20	50°54,371'	11°37,835'	P4						◑	●								●																								S.			SO_4^{2-}; Ca^{2+}

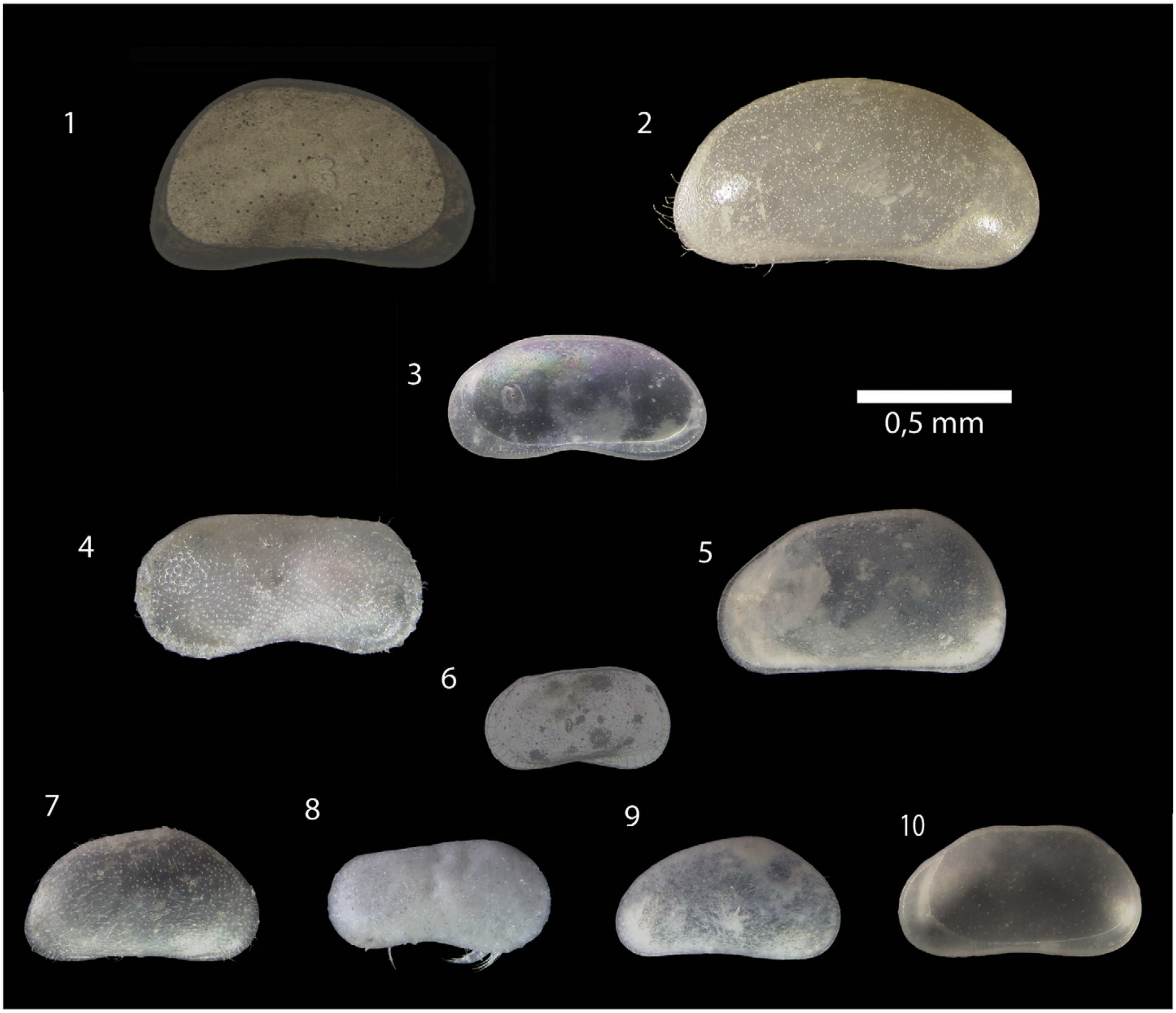


Plate I. Selected ostracods found in modern surface sediments of Central Germany: 1: *Fabaeformiscandona brevicornis*; 2: *Psychrodromus olivaceus*; 3: *Candona candida* 4: *Ilyocypris inermis*; 5: *Pseudocandona marchica*; 6: *Limnocythere inopinata*; 7: *Potamocypris zschokkei*; 8: *Ilyocypris bradyi*; 9: *Potamocypris unicaudata*; 10: *Pseudocandona albicans*. All specimens are from Pennickental at Jena, except *L. inopinata* and *C. candida* from Stausee Kelbra.

thus being favoured by cold water taxa. A mutual high proportion of helocrenic and cold water taxa is indeed characteristic for clearly spring influenced habitats (Fig. 4). Furthermore, all samples without documented spring influence do not contain any helocrenic ostracod species. On the other hand, there are some spring samples without helocrenic taxa — in fossil samples like those the groundwater influence would not be detectable by ostracod analysis alone.

The general presence of ostracod species preferring turbulent waters, even in standing water bodies, is not surprising if considering the shallow water depth of all sampling sites. Waves and currents triggered by wind create turbulence in shallow waters — most of our samples come from less than 30 cm water depth. For discriminating flowing waters from other habitats by using the Ostracod Turbulence Index (OTI = relative abundance of rheophobic and oligorheophilic species within the sum of those and meso- to polyrheophilic species) and for checking the reliability of the Ostracod Permanence Index (OPI = relative abundance of species occurring in permanent waters only within the sum of those and others preferring perennial waters) we cross-plotted both indices. We expected a high OTI and OPI for rivers and other flowing waters and a high OTI and low OPI for the very shallow water of the littoral zone in standing waters. Except for one spring-fed brook, all ostracod associations from flowing waters plot above a value of 90% of the Ostracod Turbulence Index (Fig. 5) illustrating its value as current proxy. Several other associations plot into the same field of the diagram in Fig. 5, mainly springs. Ostracod associations from perennial waters and the littoral zone of stagnant permanent waters probably temporary falling dry due to lake level variability can only be found at values of the Ostracod Permanence Index <12% (Fig. 5). There are, however, ostracod associations from permanent waters that can be found as well. As our data show, flowing waters may be identified in the fossil record by an OTI of >90% and a consideration of the OPI is not necessary for this. Identifying temporary waters or the littoral zone of standing permanent waters with a fluctuating water level requires a low OPI, in our data set <12%, but a high diversity of species attributed by Meisch (2000) and Fuhrmann (2013) to lakes and ponds may help to distinguish such samples.

The brackish water indicator *Cyprideis torosa* (Pint et al., 2012) occurs in five localities, one time together with another brackish water

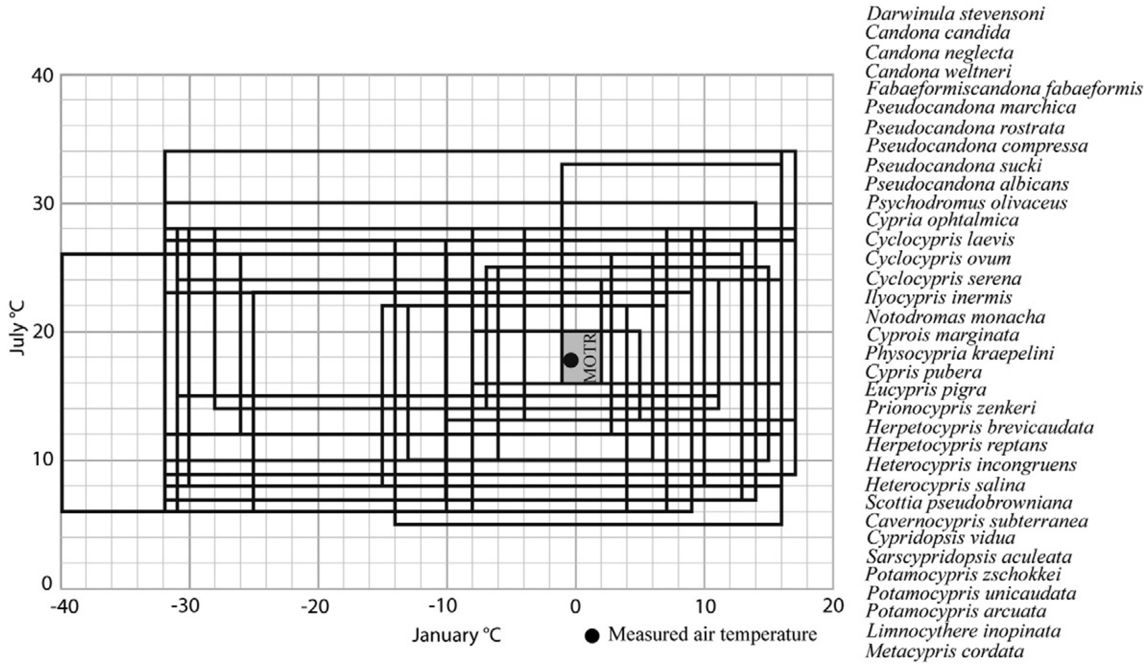


Fig. 2. Mutual Ostracod Temperature Range (MOTR) of recent sites of the Thüringer Basin with calibrations based on Horne and Mezquita (2008) and updates from OMEGA, December 2011. The black lines represent the temperature range of each species listed here. Only species for which a reliable calibration set exists (Horne and Mezquita, 2008) are used for the MOTR.

ostracod, *Cytheromorpha fuscata* (Frenzel et al., 2010). Both species are considered to represent a salinity >0.5 psu, while the single presence of the un-noded form of *C. torosa* may signify even higher salinity (Frenzel et al., 2012). *C. torosa* is known to be wide-spread in Quaternary athalassic brackish waters of Central Germany (Pint et al., 2012) and forms stable and long-living populations in larger salty inland waters as it is known for *C. fuscata* as well (Salziger See, Wennrich, 2005). Four of the seven studied localities yielding this indication were, however, freshwater sites during sampling (Table 1). We know for some of these water bodies (Süßer See, Stotternheim) that they were brackish in the recent past and assume all those *C. torosa* and *C. fuscata* valves to be subfossil. This seems to be the case for the very few freshwater literature records of *C. torosa* as well (Pint et al., 2012). Hence, they are interpreted to reflect past salinity values. *Heterocypris salina* occurs throughout the covered salinity range and does not show an indicator value for brackish water as already stressed by Meisch (2000) and Fuhrmann (2013).

Analysis of water chemistry preferences indicates *Psychrodromus olivaceus*, *Fabaeformiscandona brevicornis*, *Pseudocandona marchica*, *Ilyocypris inermis* and *Potamocypris zschokkei* as typical for Ca-dominated waters (Fig. 6). *Ilyocypris gibba* and *Potamocypris unicaudata* are characteristic species for SO_4-dominated and *Heterocypris salina*, *Limnocythere inopinata* and *Prionocypris zenkeri* for Cl-dominated water. *Heterocypris incongruens* and *Cypridopsis vidua* do not occur in Ca-dominated water in our material and their absence could support the identification of Ca-dominated water in reconstructions.

The test of the MOTR method (Horne, 2007), using an aggregated species assemblage for the region, satisfactorily reproduced the

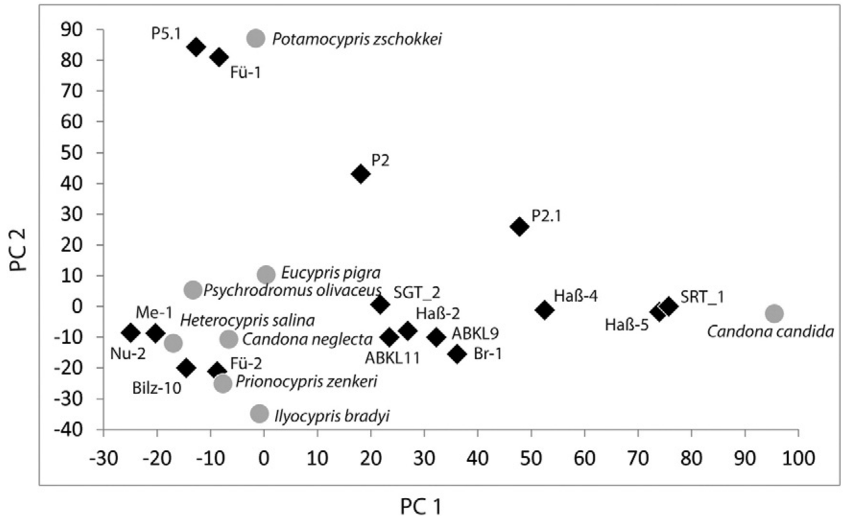


Fig. 3. Principle Component Analysis (biplot) of 62 modern samples and 36 associated ostracod species from the Thuringian Basin. The first axis, reflecting water chemistry, explains 16.4% and the second 11.0% of the variance. $CaSO_4$-dominated waters are found at high loadings and NaCl-dominated waters at low loadings on the first component. Only species with loadings higher than +20 and lower than −20 (sites); higher than +10 and −10 (species) are labelled.

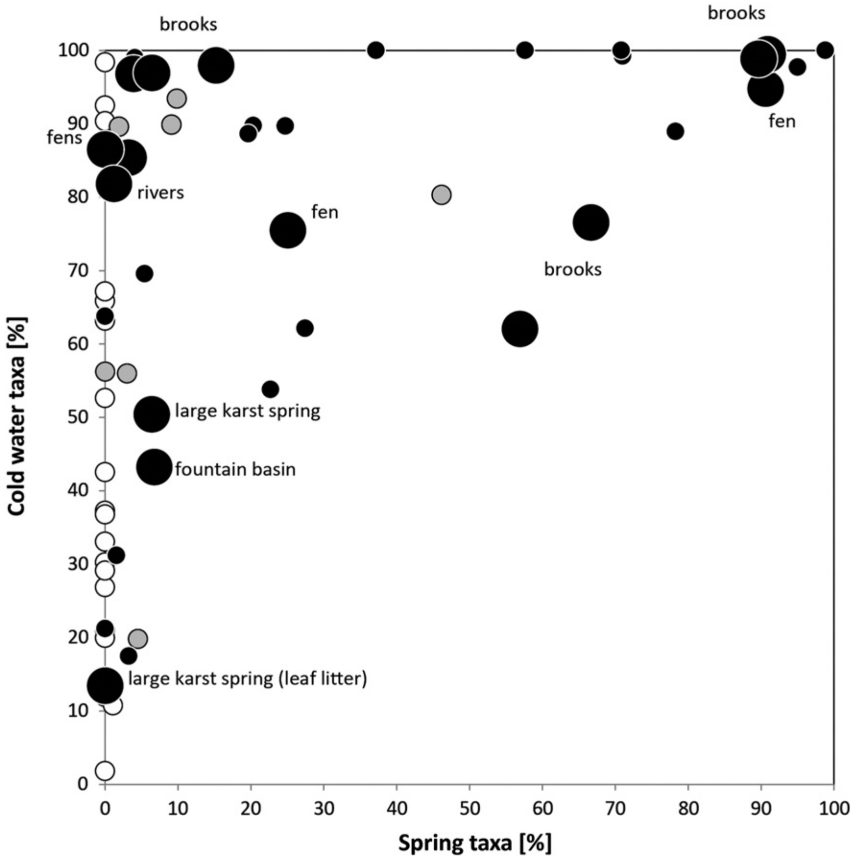


Fig. 4. Cross-plot of relative abundances of ostracod species occurring often in springs versus cold-stenothermal species based on ecological classifications by Meisch (2000) and Fuhrmann (2013). The habitat types are indicated by large black circles for sites immediately in front of a groundwater discharge, small black circles for sites close to a spring, small grey circles for sites with assumed spring influence and white circles for other sites without spring influence. Text within the diagram refers to springs (large black circles) and gives further habitat details.

present-day mean July and January air temperatures to within +/−2 °C. This is consistent with measured air temperatures for the region of these sites (July +17.5 °C, January −0.5 °C, Weather Station of the Max Planck Institute for Biogeochemistry, Jena, 2002–2012). This demonstrates very well its potential for palaeotemperature reconstructions. However, it is worth noting that no single site in the Thuringian Basin dataset contained all 35 species; MOTR analyses based on less diverse assemblages from individual sites would not yield such a precise, closely-constrained result, although even very broadly reconstructed temperature ranges would still enclose the true values. Moreover, inspection of Fig. 2 shows that obtaining a narrow-ranging reconstruction is not necessarily reliant on the presence of stenothermal taxa (i.e. with narrow calibrated ranges) but can also be obtained from the mutual overlap of the wide temperatures ranges of more or less eurythermal taxa. The MOTR method, as with all mutual climatic range methods, tends to provide greater precision with higher numbers of taxa.

6. Conclusions

The distribution analysis of living ostracods is compulsory to gain ecological data needed for palaeoenvironmental analysis. Total associations not differentiating between living and dead specimens hampers the interpretation of species autecology, however, it allows water type comparisons with fossil associations. A purely qualitative approach in analysing ostracod associations from potential inland brackish water sites is of limited use for palaeoenvironmental analysis because of its low habitat and water chemistry discrimination. Quantitative analyses relying on proportions of ecological groups show a much better discrimination performance. By using the proportion of helocrenic taxa, the Ostracod Permanence Index and the Ostracod Turbulence Index, the recognition of groundwater inflow, current of flowing waters and perennial habitats is possible in most cases. In addition, *Scottia pseudobrowniana* and *Microdarwinula zimmeri* may be used as indicators for semi-terrestrial habitats. The occurrence of subfossil *Cyprideis torosa* and *Cytheromorpha fuscata* in surface sediments indicates a historical salinity change for those water bodies caused by land amelioration. *Heterocypris salina* alone is not a reliable brackish water indicator. For the reconstruction of mean monthly air temperature, the precision and utility of the MOTR method has been demonstrated by means of a test on the modern ostracod fauna of Central Germany.

7. List of ostracod taxa

Candona angulata Müller, 1900
Candona candida (O.F. Müller, 1776)
Cando na neglecta Sars, 1887
Candona weltneri Hartwig, 1899
Candonopsis kingsleii (Brady & Robertson, 1870)
Cavernocypris subterranea (Wolf, 1920)
Cryptocandona vavrai Kaufmann, 1900
Cyclocypris laevis (O.F. Müller, 1776)
Cyclocypris ovum (Jurine, 1820)
Cypria ophtalmica (Jurine, 1820)
Cyprideis torosa (Jones, 1850)

The present specimens are all smooth shelled, i.e. without nodes, and are therefore assigned as *Cyprideis torosa* f. *littoralis* sensu Brady, 1868.

Cypridopsis vidua (O.F. Müller, 1776)
Cypris pubera O.F. Müller, 1776

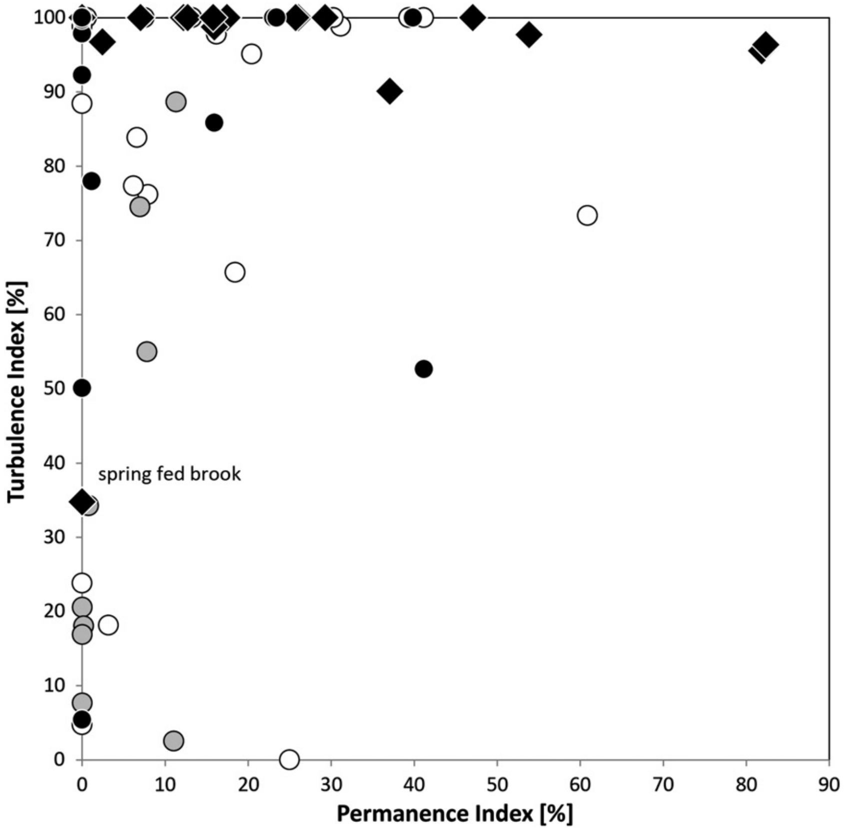
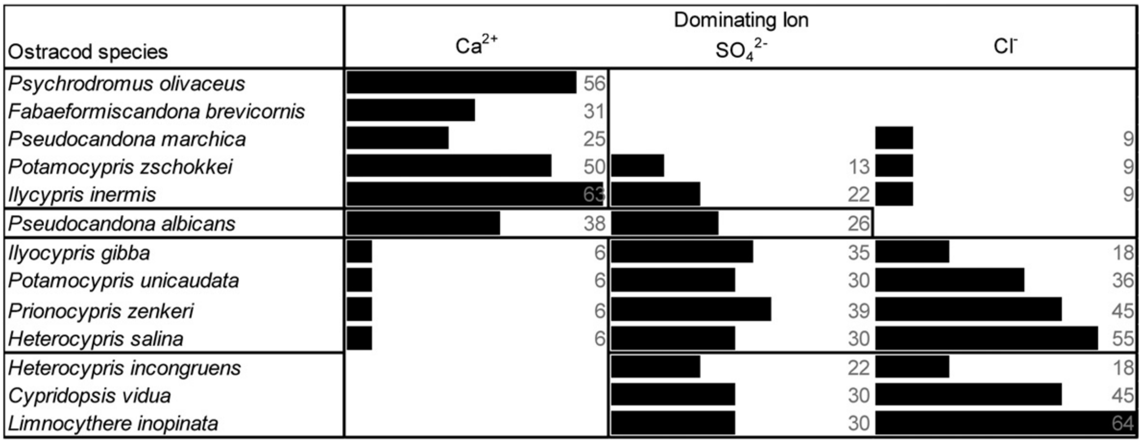


Fig. 5. Ostracod Permanence Index (relative abundance of species occurring in permanent waters only within the sum of those and others preferring perennial waters) compared to Ostracod Turbulence Index (relative abundance of rheophob and oligorheophilic species within the sum of those and meso- to polyrheophilic species). The ecological classification of species is based on Meisch (2000) and Fuhrmann (2013). The habitat types are indicated by black diamonds for flowing water, black circles for springs, small grey circles for the littoral of standing water bodies and perennial waters and white circles for other habitat types. The only flowing water site with a low Ostracod Turbulence Index is marked.

Cyprois marginata (Straus, 1821)
Cytheromorpha fuscata (Brady, 1869)
Darwinula stevensoni (Brady & Robertson, 1870)
Eucypris pigra (Fischer, 1851)
Eucypris virens (Jurine, 1820)
Fabaeformiscandona breuili (Paris, 1920)
Fabaeformiscandona brevicornis (Klie, 1925)
Fabaeformiscandona fabaeformis (Fischer, 1851)
Herpetocypris brevicaudata Kaufmann, 1900
Herpetocypris reptans (Baird, 1835)
Heterocypris incongruens (Ramdohr, 1808)
Heterocypris salina (Brady, 1868)
Ilyocypris bradyi Sars, 1890
Ilyocypris gibba (Ramdohr, 1808)
Ilyocypris inermis Kaufmann, 1900
Ilyocypris sp.



Ostracod species	Dominating Ion: Ca^{2+}	SO_4^{2-}	Cl^-
Psychrodromus olivaceus	56		
Fabaeformiscandona brevicornis	31		
Pseudocandona marchica	25		9
Potamocypris zschokkei	50	13	9
Ilycypris inermis	63	22	9
Pseudocandona albicans	38	26	
Ilyocypris gibba	6	35	18
Potamocypris unicaudata	6	30	36
Prionocypris zenkeri	6	39	45
Heterocypris salina	6	30	55
Heterocypris incongruens		22	18
Cypridopsis vidua		30	45
Limnocythere inopinata		30	64

Fig. 6. Steadiness (black scales and grey numbers) of ostracod species occurrence in waters of different dominating ions. Rare and ubiquitous species are omitted. Groups with similar preferences of water chemistry are separately framed.

Ilyocypris sp. could not be assigned to a species given in Meisch (2000). The marginal zone of the left valve of this species is smooth without ripplets.

Ilyocypris species were identified using valve size, morphology (marginal spines and nodes) and the presence and degree of marginal ripplets in the posterior-ventral part of the left adult valves sensu Van Harten (1979) and Janz (1994).

Limnocythere inopinata (Baird, 1843)
Metacypris cordata Brady & Robertson, 1870
Microdarwinula zimmeri (Menzel, 1916)
Nannocandona faba Ekman, 1914
Notodromas monacha (O.F. Müller, 1776)
Physocypria kraepelini G.W. Müller, 1903
Plesiocypridopsis newtoni (Brady & Robertson, 1870)
Potamocypris arcuata (Sars, 1903)
Potamocypris fallax Fox, 1967
Potamocypris fulva (Brady, 1868)
Potamocypris smaragdina (Vávra, 1891)
Potamocypris unicaudata Schäfer, 1943
Potamocypris zschokkei (Kaufmann, 1900)

Potamocypris species were identified based on articulated valves. If separated and juvenile valves were not distinguished, they appear in our counts as *Potamocypris* spp.

Prionocypris zenkeri (Chyzer & Toth, 1858)
Pseudocandona albicans (Brady, 1864)
Pseudocandona compressa (Koch, 1838)
Pseudocandona marchica (Hartwig, 1899)
Pseudocandona rostrata (Brady & Norman, 1889)
Pseudocandona sucki (Hartwig, 1901)

The five *Pseudocandona* species, especially *P. marchica* and *P. rostrata* are hard to distinguish. For juvenile specimens it is even impossible. Therefore, we assign all specimens to *Pseudocandona* spp. for quantitative analyses and give qualitative distribution data only for the species.

Psychrodromus olivaceus (Brady & Norman, 1889)
Sarscypridopsis aculeata (Costa, 1847)
Scottia pseudobrowniana Kempf, 1971
Trajancypris clavata (Baird, 1838)

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.palaeo.2014.07.042.

References

Backhaus, K., Erichson, B., Plinke, W., Weiber, R., 2010. Multivariate Analysemethoden. Springer Lehrbuch, pp. 1–583.

Brady, G.S., 1868. On the crustacean fauna of the salt marshes of Northumberland and Durham. Nat. Hist. Trans. Northumberland 3, 120–136.

Diebel, K., Pietrzeniuk, E., 1969. Ostrakoden aus dem Mittelpleistozän von Süßenborn bei Weimar. Paläontol. Abh. (A) 3, 367–788.

Diebel, K., Pietrzeniuk, E., 1977. Ostrakoden aus dem Travertin von Taubach bei Weimar. Quartärpaläontologie 2, 119–137.

Diebel, K., Pietrzeniuk, E., 1978a. Die Ostrakodenfauna aus den jungpleistozänen (weichselkaltzeitlichen) Deckschichten von Burgtonna in Thüringen. Quartärpaläontologie 3, 207–221.

Diebel, K., Pietrzeniuk, E., 1978b. Die Ostrakodenfauna des eeminterglazialen Travertins von Burgtonna in Thüringen. Quartärpaläontologie 3, 87–91.

Diebel, K., Pietrzeniuk, E., 1984. Jungpleistozäne Ostrakoden aus Sedimenten der Parkhöhlen von Weimar. Quartärpaläontologie 5, 285–319.

Engelmann, H.D., 1978. Zur Dominanzklassifizierung von Bodenarthropoden. Pedobiologia 18, 378–380.

Fabig, I., 2007. Changing precipitation leeward of the Harz Mts. — indicators of a regional climate change. Hercynia N.F. 40, 33–39.

Frenzel, P., Keyser, D., Viehberg, F.A., 2010. An illustrated key and (palaeo) ecological primer for recent to postglacial Ostracoda (Crustacea) of the Baltic Sea. Boreas 39, 567–575.

Frenzel, P., Schulze, I., Pint, A., 2012. Noding of *Cyprideis torosa* valves (Ostracoda): a proxy for palaeosalinity? Int. Rev. Hydrobiol. 4, 314–329.

Fuhrmann, R., 2008. Die Ostrakoden- und Molluskenfauna des Auelehmprofils Zeitz (Landkreis Burgenland) und ihre Aussage zum Klima sowie zur Landnutzung im jüngeren Holozän Mitteldeutschlands. Mauritiana 20 (2), 253–281.

Fuhrmann, R., 2010. Die Ostrakodenfauna der Gießwasserbehälter ausgewählter Friedhöfe Mitteldeutschlands mit Beschreibung von *Potamocypris altenburgensis* sp. nov. (Crustacea: Ostracoda). Mauritiana 21, 95–107.

Fuhrmann, R., 2013. Atlas quartärer und rezenter Ostrakoden Mitteldeutschlands. Altenburger Naturwiss. Forsch. 15, 1–320.

Gemeinhardt, C., Frenzel, P., 2014. Vergleichende Untersuchungen zur Ostrakodenfauna intensiv und ökologisch bewirtschafteter sowie renaturierter Fischteiche im Dreba-Plothener Teichgebiet, Südostthüringen. Mauritiana 25, 127–143.

Hammer, Ø., Harper, D.A.T., 2005. Paleontological Data Analysis. Blackwell Publishing, Malden, Oxford, Carlton.

Horne, D.J., 2007. A Mutual Temperature Range method for Quaternary palaeoclimatic analysis using European nonmarine Ostracoda. Quat. Sci. Rev. 26, 1398–1415.

Horne, D.J., Mezquita, F., 2008. Palaeoclimatic applications of large databases: developing and testing methods of palaeotemperature reconstruction using nonmarine ostracods. Senckenb. Lethaea 88, 93–112.

Horne, D.J., Baltanas, A., Paris, G., 1998. Geographical distribution of reproductive modes in living non-marine ostracods. In: Martens, K. (Ed.), Sex and Parthenogenesis: Evolutionary Ecology of Reproductive Modes in Non-marine Ostracods. Backhuys, Leiden, pp. 77–99.

Horne, D.J., Curry, B.B., Delorme, L.D., Martens, K., Smith, A.J., Smith, R.J., 2011. OMEGA: the Ostracod Metadatabase of Environmental and Geographical Attributes. Joannea Geol. Paläontol. 11, 80–84.

Horne, D.J., Curry, B.B., Mesquita-Joanes, F., 2012. Mutual climatic range methods for Quaternary ostracods. In: Horne, D.J., Holmes, J.A., Rodriguez-Lazaro, J., Viehberg, F. (Eds.), Ostracoda as Proxies for Quaternary Climate ChangeDev. Quat. Sci. 17, 65–84.

Janz, H., 1994. Zur Bedeutung des Schalenmerkmals, Marginalrippen' der Gattung *Ilyocypris* (Ostracoda, Crustacea). Stuttg. Beitr. Naturkunde Ser.B 206, 1–19.

Meisch, C., 2000. Crustacea: Ostracoda. In: Schwoerbel, J., Zwick, P. (Eds.), Süßwasserfauna von Mitteleuropa. 8 (3). Spektrum Akademischer Verlag, Heidelberg, Berlin, pp. 1–522.

Pint, A., Frenzel, P., Fuhrmann, R., Scharf, B., Wennrich, V., 2012. Distribution of *Cyprideis torosa* (Ostracoda) in Quaternary athalassic sediments in Germany and its application for palaeoecological reconstructions. Int. Rev. Hydrobiol. 4, 330–355.

Seidel, G., 2003. Geologie von Thüringen. Schweizerbart, Stuttgart, pp. 1–601.

Van Harten, D., 1979. Some new shell characters to diagnose the species of the *Ilyocypris gibba-biplicata-bradyi* group and their ecological significance. In: Krstić, N. (Ed.), Taxonomy, Biostratigraphy and Distribution of Ostracodes. Proceedings of the 7th International Symposium on Ostracodes, pp. 71–76.

Weather Station of the Max Planck Institute for Biogeochemistry, Jena, 2002–2012. http://www.bgc-jena.mpg.de/wetter/.

Wennrich, V., 2005. Die spätweichselglaziale und holozäne Klima- und Umweltgeschichte des Mansfelder Landes/Sachsen-Anhalt, abgeleitet aus Seesedimenten des ehemaligen Salzigen Sees. (Ph.D. thesis) Universität Leipzig.

Westhus, W., Fritzlar, F., Pusch, J., van Elsen, T., Anders, C., 1997. Binnensalzstellen in Thüringen — Situation, Gefährdung und Schutz. Naturschutzreport, Thüringer Landesanstalt für Umwelt. 12, pp. 1–193.

Wirth, J., 2008. Stein- und Kalisalze. In: Bachmann, G.H., Ehling, B.-C., Eichner, R., Schwab, M. (Eds.), Geologie von Sachsen-Anhalt, Schweizerbart, Stuttgart, pp. 506–519.