

# Nonmarine Ostracoda as proxies in (geo-)archaeology – A review

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## Abstract

Ostracods as bioindicators are extremely useful for reconstructing palaeoenvironment and palaeoclimate and can also indicate the provenance of sediments and materials, for example, in studies on ancient commercial networks. Ostracods are small crustaceans that live in almost all aquatic habitats, both natural and man-made. Due to their calcitic carapace, they have high fossilization potential, and their use in geoarchaeology has been steadily increasing during the last decades. Their small size needs mean that only small volumes of sediment samples are needed, and species-specific ecological tolerances and preferences allow detailed palaeoenvironmental reconstructions. Typical methods of their application are palaeoecological analyses of associations based on ecological information and taphonomy, morphometric variability and stable isotope and chemistry analyses of their shells. The present paper aims to present an overview of applications of non-marine ostracods in (geo-)archaeological research, recommending sampling and analytical techniques for addressing archaeological research questions on palaeoclimate, habitat and landscape changes, water availability and quality, land use and other anthropogenic impacts, the provenance of materials and commercial networks to promote the application of Ostracoda in geoarchaeology/environmental archaeology.

## KEYWORDS

environmental archaeology, geoarchaeology, nonmarine, Ostracoda (Crustacea), palaeoclimate, Quaternary

## 1 | INTRODUCTION

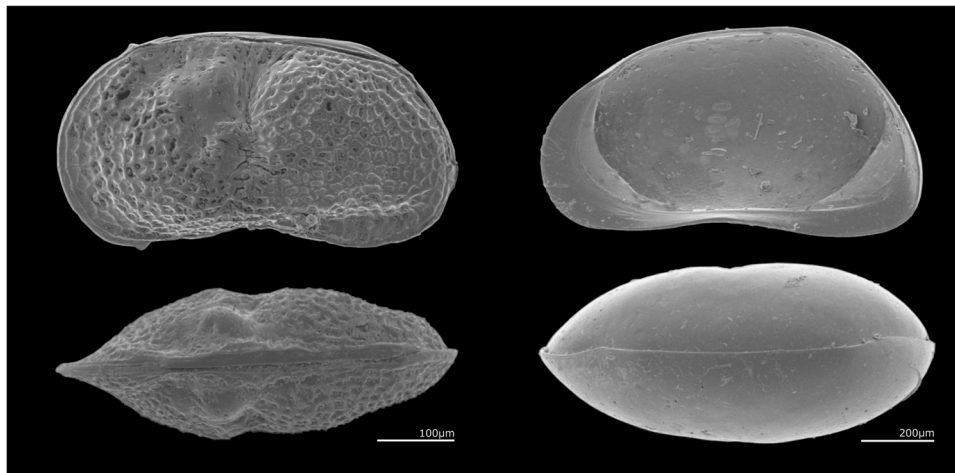
Ostracoda (seed shrimps) are small crustaceans, mostly 0.5–2 mm in length, living in almost all types of water bodies (Griffiths & Holmes, 2000). Their body is enclosed by two valves, mineralized with low-Mg calcite (Figure 1). These valves are easily preserved in sediments and allow the identification of species and even ontogenetic stages (Figure 2). The fossil record of ostracods reaches

back to the Ordovician (Rodríguez-Lazaro & Ruiz-Muñoz, 2012). Ostracods occur in the oceans, estuaries and continental waters (Frenzel & Boomer, 2005), with an estimated 20,000 species today and at least double that amount of fossils (D. A. Horne et al., 2012). Nonmarine habitats include lakes and ponds, streams and rivers, springs and swamps and even groundwater (Meisch, 2000). The highest density and diversity are found in lakes and ponds, that is, standing or slowly flowing waters. However, waters with low ion

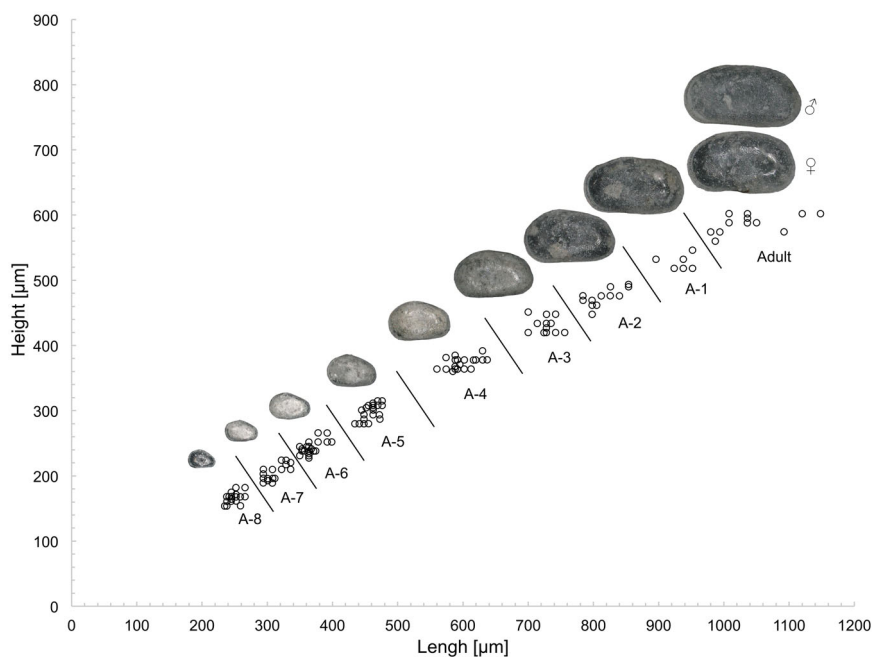
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**FIGURE 1** Adult examples of two recent ostracod species from the huge lake Tangra Yumco on the Tibetan Plateau. Left: The ornamented *Limnocythere inopinata* (Baird, 1843) in external view of a left valve and a dorsal view of two valves still articulated. Right: The smooth shelled *Candona candida* (Müller, 1776) with an internal view of a right valve and a dorsal view of two valves still articulated. Scale: 0.5 mm.



**FIGURE 2** The ontogenic stages of *Cyprideis torosa*, a brackish water ostracod, sampled from the early Holocene palaeolake of Tayma, Saudi Arabia. Measurements were taken from a single sample to avoid high morphological variances, except for the measurements of adult valves, due to the overall very low numbers of adults.

concentrations and low pH are problematic for ostracods because of their calcitic shell (Ruiz et al., 2013). There are only a few ostracod species in such waters, and the fossil record is destroyed chiefly by dissolution. The opposite is true for carbonate-rich lacustrine deposits, where ostracod shells may form a dominant part of the sand-sized sediment fraction.

The tiny size of ostracods allows high numbers in small sample volumes; for example, from sediment cores or sediment attached to artefacts, diversity is mostly higher than for macrofossils, and preservation is often better because transport results in lower levels of damage.

The presence of indicator species, the species composition of assemblages, morphological variability or chemical and isotopic

signatures of their valves document living conditions and anthropogenic impacts through time. These indications can be very specific and quantitative or summarize several environmental factors and show trends. The temporal resolution may range from centuries over decades and years (e.g., Palacios-Fest, 1994) or even seasonal effects (e.g., Palacios-Fest, 1997) depending on the investigated taxonomic groups and methodology. Another interesting aspect of using microfossils in geoaerchaeological studies is provenance analysis. They may indicate locations or regions of origin because of their specific distribution in space and time, thus enabling reconstruction of trade connections, exchanges or distributions, mobility/migration and settlement shifts (e.g., Quinn, 2008, 2013; Wilkinson, 2017; Wilkinson et al., 2016, 2017).

Many environmental factors can be evaluated and reconstructed based on (sub)fossil ostracods. These are salinity (e.g., Frenzel et al., 2010; Mischke, Almogi-Labin et al., 2014; Mischke et al., 2007) and water chemistry (e.g., De Deckker & Forester, 1988; Mischke et al., 2012; Wansard & Mezquita, 2001), water and air temperature (e.g., D. A. Horne et al., 2012; Pint, Schneider et al., 2017; Viehberg, 2006), precipitation/evaporation balance via lake-level reconstruction (e.g., Alivernini et al., 2018; Mischke et al., 2005; Pérez et al., 2011), organic pollution and oxygen deficiency (e.g., Boomer & Attwood, 2007; Mezquita et al., 1999; Rosenfeld & Ortal, 1982), habitat structure and disturbance (Higuti et al., 2010; Malmqvist et al., 1997; Marmonier et al., 1994), turbulence of the ambient water (e.g., Boomer et al., 2003), land use effects and sedimentation rate (e.g., Allen & Dodson, 2011; Cohen, 2000), tsunamis and storm floods (e.g., Engel et al., 2013), periodicity of a water body or spring proximity (e.g., Pint et al., 2015).

Most methods of ostracod-based palaeoenvironmental reconstruction are either palaeoecological approaches or shell chemistry investigations, including stable isotope analysis. Because ostracods are growing by moulting, the chemical and stable isotopic signature of a shell represents a snapshot of the ambient water composition. Palaeoecological approaches are diverse (Table 1). A fast but rough method is to rely on indicator species (or taxa) reflecting specific conditions or influences such as increased salinity or oxygen deficiency (e.g., Geiger, 1993; Pint et al., 2012). More detailed and reliable results are produced by evaluating the proportion of ecologically classified groups of taxa over a series of samples, either over time or along a transect (De Deckker & Forester, 1988; Frenzel, 2019; Frenzel et al., 2010). However, this method does not provide quantitative reconstructions of environmental variables despite requiring taxa counts within the samples. Quantitative reconstructions of environmental variables are possible by the mutual tolerance method comparing known ecological tolerances of a set of living species using the overlap of these ranges as reconstruction (e.g., D. J. Horne et al., 2012). Transfer functions are more sophisticated in producing quantitative reconstructions with error estimations (e.g., Mezquita et al., 2005; Mischke et al., 2007). They, however, require large training data sets for the regions investigated; such data sets are available only for a limited number of regions. Some species react via changes in morphology like forming nodes or changing the ornamentation and shape of the valves or sieve pores (e.g., Bodergat et al., 1991; Boomer et al., 2017; Frenzel et al., 2017, 2012; Yin et al., 2001). These environmentally induced morphological changes can be used for palaeoenvironmental reconstructions. Shell chemistry approaches use trace element or stable isotope signatures of ostracod shells for reconstructing past salinity, water chemistry, redox conditions, temperature, and so forth (Börner et al., 2013; Holmes & Chivas, 2002; Holmes & De Deckker, 2012). Taphonomical data provide additional information about the depositional environments (Boomer et al., 2003). A more detailed overview of all these methods is given in Griffiths and Holmes (2000), Frenzel et al. (2010) and D. A. Horne et al. (2012). This article will present an overview of the state of nonmarine ostracods in (geo-)archaeological research, highlighting applications and methods that are already well used and promoting the further use of ostracod proxies in this field.

## 2 | APPLICATIONS

### 2.1 | A short history of ostracod-based palaeoenvironmental reconstructions

The history of ostracod research in a palaeo-science context started with descriptions of fossil taxa in the early 19th century, with the first stratigraphic investigations appearing around 50 years later (Hartmann, 1966). Their usefulness in geological, especially biostratigraphic research, made them one of the classical groups of micropalaeontology.

Quaternary palaeoecological studies are especially useful for the geoarchaeological context, and many of them answer overlapping research questions in palaeoclimatology, palaeolimnology, pollution records and archaeology. While the first studies on Quaternary ostracods reach back to the mid-19th century (Jones, 1850), these merely listed species without systematic attempts to reconstruct the palaeoenvironments. After some rare studies applying ostracods in analysing Quaternary environments (Griffiths & Holmes, 2000 and review therein), there was an initial phase of Quaternary studies in the 1960s and the 1970s that has continued up to the present day. Today, the study of ostracods is a standard technique in Quaternary palaeolimnology. Studies on nonmarine ostracods are more numerous than those on marine ostracods (Frenzel & Boomer, 2005). There are, however, several geoarchaeological studies involving marginal-marine ostracods (review in Mazzini et al., 2021; and Pint & Frenzel, 2022); especially meaningful are those on ancient harbours (e.g., Goiran et al., 2014; Marriner et al., 2005; Rossi et al., 2015). Geoarchaeological studies based on non-marine ostracods are more numerous today, as we will show below. Nevertheless, their potential is still estimated as under-utilized (e.g., Kenward, 2009).

The first paper on non-marine ostracods in a geoarchaeological context was a record by R.W. Meyrick published by Buckland in 1978 (Griffiths & Evans, 1992). Since then, the number of studies has increased considerably over the decades (Figure 3), and non-marine ostracods were also noticed outside of ostracodology as proxies in archaeology (Branch et al., 2014; Mazzini et al., 2015; Palacios-Fest, 2018). The main fields covered remained constant for many years: reconstruction of climate and aquatic habitats, water availability and salinity, water levels, anthropogenic impacts like habitat disturbance, eutrophication and other pollution or erosion due to agriculture and the provenance of materials. A review of those research questions is presented in the following sections.

### 2.2 | Palaeoclimate and palaeoenvironmental studies on continental archaeological sites

Human occupation of a site depends, amongst others, on climatic and environmental conditions, and the requirements for the inhabited environments changed concurrently with human evolution and increasing social complexity. Through palaeoenvironmental studies, ostracods from archaeological sites can provide information of

**TABLE 1** An overview of the different palaeoenvironmental proxies based on ostracods and the corresponding methods, compiled from Griffiths and Holmes (2000), Boomer et al. (2003), Frenzel and Boomer (2005), Frenzel et al. (2010), D. J. Horne et al. (2012), D. A. Horne et al. (2012), Holmes and De Deckker (2012), Börner et al. (2013) and own experience in ostracod analysis.

Proxies	Methods	
Salinity	Morphological variation	Valve ornamentation Sieve pore analysis in <i>Cyprideis torosa</i>
	Relative abundance	Indicator species, ecological groups, transfer functions
	Mutual Ostracod Salinity Range (MOSR)	Indicator species (based on present-day ecological ranges; Pint, Schneider et al., 2017)
	Stable isotope analysis	$\delta^{18}\text{O}$
	Trace elements	Mg/Ca (Sr/Ca)
Water chemistry/pH	Relative abundance	Indicator species
Temperature	Relative abundance	Indicator species, ecological groups, transfer functions
	Mutual Climate Range (MCR)	Delorme method (analogue MCR; based only on components of a fossil assemblage that coexist today) Mutual temperature range (nonanalogue MCR; based on all species in a fossil assemblage, e.g., MOTR)
	Trace elements	Mg/Ca, Sr/Ca, Ba/Ca, Li/Ca
	Stable isotope analysis	$\delta^{18}\text{O}$ , potentially clumped isotopes
Productivity/nutrients	Abundance	Indicator species, total ostracod abundance, relative abundances of ecological groups
	Stable isotope analysis	$\delta^{13}\text{C}$
	Trace elements	Trace metals (Cd, Ba, Zn, ...)
Oxygenation	Abundance	Indicator species, relative abundances of ecological groups
	Trace elements	U/Ca
Water depth	Relative abundance	Transfer functions
	Taphonomy	Adult/juvenile ratio, valve/carapace ratio
Water source	Trace elements	$^{87}\text{Sr}/^{86}\text{Sr}$ , $^{143}\text{Nd}/^{144}\text{Nd}$
Environmental stress	Abundance	Valve/carapace ratio, ecological groups, diversity
Energy regime/post-mortem transport	Abundance	Adult/juvenile ratio
Habitat structure	Abundance	Indicator species, relative abundances of ecological groups

relevance for human mobility/migration and living conditions at temporary or permanent settlements. They can be used to determine the attractiveness of territories in a climatic sense, such as convenient temperatures or (drinking) water availability. For these aims, specific reconstruction methods, such as the Mutual Ostracod Temperature Range (MOTR developed by Horne, 2007; see Benardout, 2015; Daniel & Frenzel, 2010; Holmes et al., 2010), conductivity transfer functions (Mischke, Almogi-Labin et al., 2014; Mischke et al., 2010) or stable isotope analysis of ostracod shells (e.g., Anadón & Gabàs, 2009; Escobar et al., 2010; Palacios-Fest, 1994, 1997), have been applied. The following sections present examples of the most common methods in geoarchaeological studies

(Figure 4). Most common, however, is the usage of ostracod assemblages and their indicator species for more general palaeoecological indications, often as part of multiproxy palaeoclimate and palaeoenvironment studies (e.g., Bates et al., 2008; Griffiths, 1998; Mazzini et al., 2016).

### 2.2.1 | General palaeoenvironment/landscape reconstructions

During the Palaeolithic, mobility patterns and occupational territories of the smaller hunter-gatherer societies were strongly dependent on

suitable climatic and environmental conditions, such as the availability of drinking water and food (Carbonell et al., 2008).

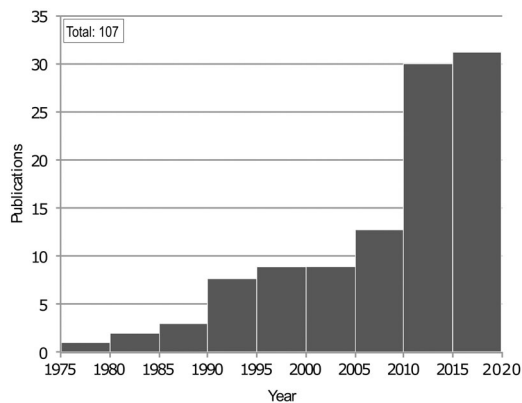
For example, at several sites in the United Kingdom, ostracod assemblages were used to reconstruct the environments and to characterize the nature of freshwater sources in the area, for example, a slow-flowing river with adjacent marshlands during the

late Middle Pleistocene (for an overview of geological time scales, see Figure 5) interglacial site at Purfleet in Essex (Schreve et al., 2002), small permanent groundwater-fed ponds at the Boxgrove site in West Sussex (Holmes et al., 2010; Roberts & Pope, 2009; Whatley & Haynes, 1986; Whittaker & Parfitt, 2017) or shallow groundwater-fed ponds with minor fluvial input in the White Peak in Derbyshire (Taylor et al., 1994).

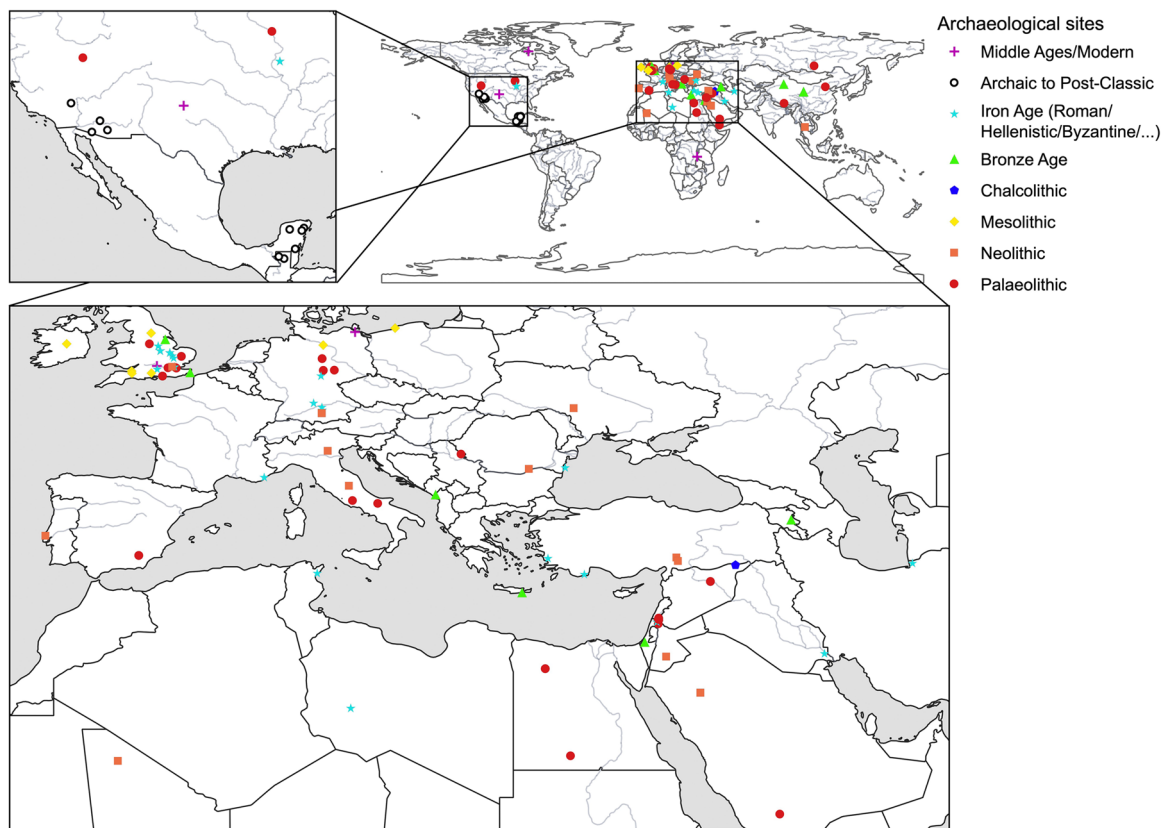
At the Youfangbei Locality, North China, a small Middle Palaeolithic flake industry in the Nihewan Basin of Yangyuan County, Hebei Province, ostracods and bivalves indicated a wetland environment on a river terrace, and showed a climatic change from a dry-warm to a cold-wet environment around the end of the last interglacial (Zhao et al., 2021).

Ostracods from a sediment core were also used to reconstruct the environmental history since the Late Glacial of Lake Ochaul, in the Upper Lena region of Eastern Siberia, known for its Palaeolithic, Mesolithic, Late Neolithic and Iron Age archaeological sites. The ostracod assemblages indicate lake-level changes, but show that the lake never dried out and, therefore, were in all likelihood an important source of water and hunting ground for hunter-gatherers (Kobe et al., 2021).

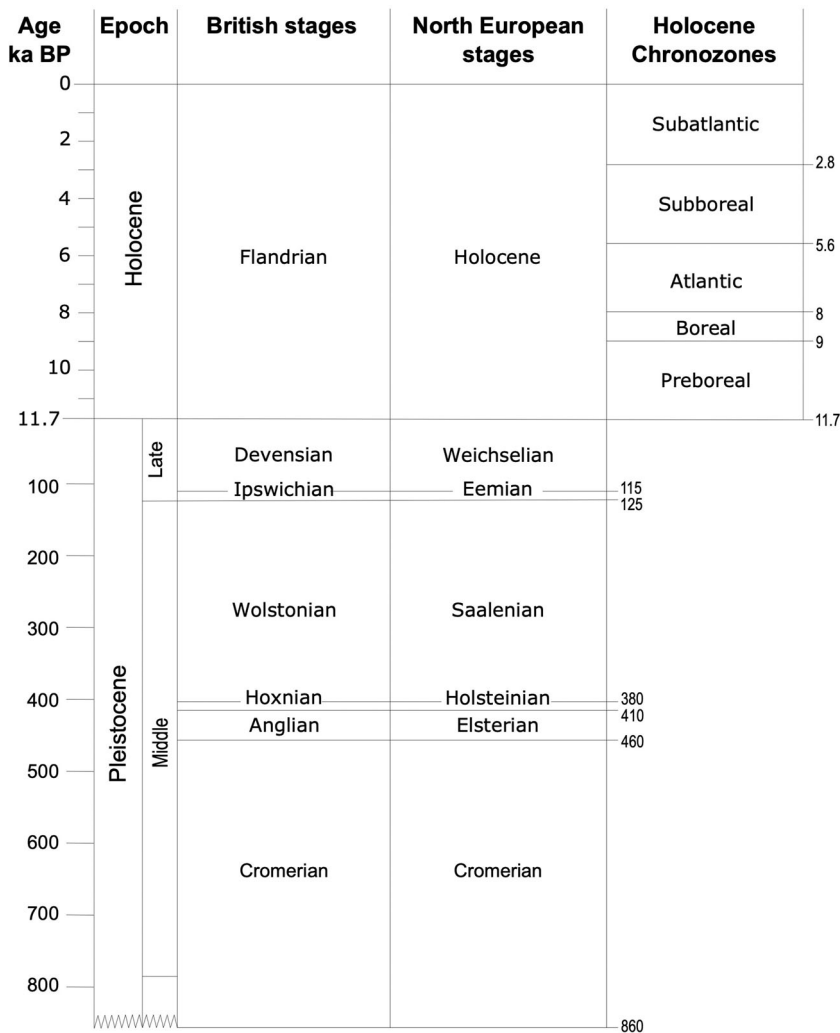
The settlement at the Lower Palaeolithic Deer excavation area of the archaeological site of Medzhibozh 1 in western Ukraine was, as indicated by ostracod assemblages in alluvial sediments, located in a



**FIGURE 3** An overview on the number of publications on archaeological case studies using ostracods as a proxy, in 5-year intervals, showing the increase in the geoarchaeological use of ostracods since 1975.



**FIGURE 4** World map showing the distribution of archaeological sites where ostracods were used as proxies and the rough archaeological periods of these sites. As can be seen, most of the sites are situated in Europe and the Near East, and some in northern Africa and Central America. [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 5** Overview of geological time scale with North European stages and British stages, and Holocene Chronozones. Ages are taken from Georgopoulou et al. (2015) and references therein.

floodplain environment with slowly flowing water, either a part of a deeper floodplain channel or a coastal zone (Dykan, 2014; Stepanchuk & Moigne, 2015).

In the Anagni basin in central Italy, abundant tool industries and fossils indicate favourable conditions for the Lower Palaeolithic hominin occupation of the area, which developed when large lacustrine basins and alluvial plains started to progressively shallow and temporarily emerged. This was seen in a combination of ostracod and palynological records and facies analysis (Florindo et al., 2021).

Ostracod abundances and taphonomic factors (abrasions, iron stains and calcium carbonate infillings) were used in the study of the Palaeo-American Gail Stone Site in Wisconsin, USA, where they, together with an aeolian lag deposit, indicated that the Palaeo-Americans deposited artefacts on a low terrace surface (Newman, 2001).

In the arid southern Great Basin, eastern California and Nevada, USA, prehistoric human occupations seem to be linked to episodic lake high-stands in the Ivanpah basin. Spaulding et al. (2021) concluded with remote imagery and several excavations that pluvial palaeolakes must have existed for decades or centuries in the Ivanpah basin during the Holocene. The freshwater ostracod

*Limnocythere ceriotuberosa* indicated cold, freshwater conditions and, therefore, a large, open lake rather than a paludal habitat.

The development of marshlands in connection with a shallow lake in the Lake Bonneville Basin in western Utah's Great Salt Lake Basin was thought to have attracted human occupations. The lake's formation, which was indicated by ostracod species as cold and fresh, was concurrent with the long-term use of the basin between 13,000 and 9500 cal. yrs. BP (Palacios-Fest et al., 2021).

Possible human adaptations to extreme environments and environmental changes are also of interest, for example, in European Early Mesolithic settlements and their landscapes, where the deglaciation of the Scandinavian ice sheet during the Late Pleistocene provided new space for these hunter-gatherers (see Zvelebil, 2008; and references therein). For example, the palaeoenvironments that attracted Mesolithic settlements during the post-glacial colonization of Ireland were analysed through ostracods in the calcareous tufa deposits at Newlands Cross in County Dublin. The assemblages indicated no large bodies of standing or flowing water, but apparently a small spring producing a weak flow of water, as the fauna was dominated by spring-dwelling species and a few species found in damp waterlogged ground (Preece et al., 1986). More Holocene tufa

deposits correlating with Mesolithic settlements in the Test Valley, Hampshire, UK, were described by Davies and Griffiths (2005). Ostracods reflected the hydrological conditions and showed that these tufas were groundwater-fed systems that covered considerable areas of the major river valley, in contrast to the other, usually spring-fed, tufa systems in the United Kingdom.

Environmental changes were also important at the transition from the Mesolithic to Neolithic and were noted both in the Holocene of the Polish lake site of Dąbki and at Queens Sedgemoor in Somerset, UK. At Dąbki, silting up of the lake and subsequent development of more lake shore vegetation worsened the accessibility of the lake shore (Laschke et al., 2015), while in Queens Sedgemoor, the whole lake environment changed to a raised bog (Hill et al., 2017, 2016). At the nearby UK localities Moorland House and Saltmoor near the River Parrett, brackish water ostracod species indicated a connection to the coast. The Parrett valley was therefore interpreted as an estuarine environment with strong tidal action and likely used for foraging by Mesolithic groups, but not for their camps (Wilkinson et al., 2021).

In the Neolithic, the development of farming and permanent settlements was influenced by environmental characteristics (e.g., Berger & Guilaine, 2009; Fowler et al., 2015 and references therein), which is reflected in many of the palaeoenvironmental studies using ostracods as proxies. Diverse wetland environments with fluvial activity were typical choices for settlement locations during the Neolithic. In the Eastern Mediterranean in Turkey, the Domuztepe site seems to have been established in the Late Neolithic. Ostracods indicated permanent or semipermanent freshwater bodies with still or slowly flowing open water, while the lithostratigraphy also shows episodes of enhanced fluvial influence (Gearey et al., 2011).

A similar environment was also reconstructed at the Olympic Park Site in London, UK. Here, the environmental history was described in an extensive study, including the use of ostracod assemblages, from the Neolithic floodplain to alluviation in the Iron Age, shallow-water environments in the Bronze Age, to marshy still water environments in the Early Saxon period (Grant et al., 2012).

At the archaeological site Hareer's Tells in Basrah City, in southern Iraq, ostracods displayed marsh to fluvial environment for a long time after the Neolithic until the Sasanian and Kassite periods (Pournelle et al., 2019).

At the palaeolake, Haijad in the Central Sahara that was occupied during the Neolithic, morphological changes of ostracods reflected cycles of disturbances in the carbonate balance, which correspond to low-amplitude climatic cycles (Carbonel, 1991).

Even the accessibility of sites has been investigated through ostracod analysis. Ostracods from the Grotta del Lago cave in Italy showed that it was only accessible at low lake levels during the Atlantic (cf. Figure 5), which correlated with the time of human occupation (Taliana et al., 1996).

With the technological development during Ancient and Post-classical history, research moreover focuses on the increasing human impact on the environment (cf. Ruiz et al., 2013). In the Levant, Chalcolithic to Early Bronze Age settlements at the eastern

tributaries in the Upper Khabur basin in Syria were, however, still dependent on humid phases and water accessibility. There, a steady flow of water in the tributaries was demonstrated by the ostracod assemblages, while today, they run dry during summer (Deckers & Riehl, 2007).

At the Bronze Age Crabble Paper Mill site in Dover, UK, ostracods from tufa springs were studied to reconstruct the palaeoenvironments. While the site was assigned to the 'burned mounds' sites that are always located adjacent to water bodies, the ostracods indicated that the tufa springs were much less developed and extensive than similar springs, such as the complex tufa pools at The Grove site near Watford (Bates et al., 2008).

With Bronze to Iron Age finds in the overlying clay pits, tufa deposits in the Ancholme Valley in Lincolnshire, UK, were also analysed for their ostracod fauna. For the three sites in the valley, the assemblages only reflected small local changes in the depositional environments. All assemblages were relatively similar and dominated by spring-dwelling species (Preece & Robinson, 1984).

In Turkey, the palaeoenvironmental history from the Lycian to the Late Roman periods for the city area of Limyra in SW Anatolia was studied using ostracods. Freshwater ostracods indicated a lacustrine environment in a sheltered area, probably a former lake in the Finike plain. In the mid-1st millennium (Late Roman Period), the lake started silting up, river channels evolved and people settled in the area, which later became the city of Limyra (Stock et al., 2020).

Ostracods have been used to reveal the palaeoenvironmental history, for example, at a Roman bridge in Fréjus, France, that today is located far from any rivers. The ostracods showed a transition from a river mouth setting to a closed lagoon with increasingly fresh water during the Roman times, and finally, a fully continental setting with subsequent desiccation (Allinne et al., 2006).

## 2.2.2 | Salinity

### Morphological variation

Salinity reconstructions based on ostracod analyses are relatively well used in geoarchaeological studies. However, analyses of morphological variations have not been considered much yet, as the methodology is relatively new. An example, using sieve pore analysis in *Cyprideis torosa* amongst other proxies, are the studies on the palaeolake of Tayma in north-western Saudi Arabia to identify humid periods that favoured Neolithic settlements. The ostracods indicated an early Holocene saline, but permanent lake with substantial seasonal hydrological variations (Brückner et al., 2013; Engel et al., 2012, 2017; Pint et al., 2011; Pint, Engel et al., 2017).

### Relative abundance

It is much more common to use ostracods as salinity proxy through the relative abundance of indicator species and ecological groups or conductivity transfer functions relying on ostracod assemblages.

In arid regions like the Levant, palaeoclimate studies have been especially relevant for periods when human settlement was

associated with humid phases. The Hula Basin in Israel yields archaeological sites that are important for understanding the hominins' route out of Africa through the Levant. Thus, ostracodological studies have aimed at defining water bodies, vital for humans, and the correlation between artefact-rich layers and ostracod data, even providing new arguments for the migration out of Africa repeatedly occurring in waves (Kalbe et al., 2015; Mischke, Ashkenazi et al., 2014; Rosenfeld et al., 2004). Further, ostracods from a permanent freshwater palaeolake in southern Arabia demonstrated a climate suitable for human occupation with a window for dispersal along the southern dispersal route into Asia between 75 and 10.5 ka (Rosenberg et al., 2011).

For reconstructing the climate in the Levant, ostracods from Israel and Jordan were used to develop a conductivity transfer function enabling the reconstruction of salinity as a proxy for precipitation/evaporation balance and suitability of water bodies as sources of drinking water for humans. This was demonstrated by analysing ostracod data from the Early to Middle Pleistocene Acheulian Gesher Benot Ya'aqov site from the Hula Basin and the Late Pleistocene Ohalo site in the Sea of Galilee, indicating changes in salinity that reflect climatic changes (Mischke, Almogi-Labin et al., 2014; Mischke et al., 2010).

Also, in the Hula valley, ostracods from the Jordan River Dureijat archaeological site were analysed for palaeoenvironmental reconstruction. They indicated a relatively large lake with probably slightly colder water temperatures than today. The lake was permanent, but probably with seasonal fluctuations, and the conductivity transfer function of Mischke, Ashkenazi et al. (2014) suggested strictly fresh water. Further ostracod taxa indicated that in a much younger sample, from the Late Holocene, the freshwater near-shore setting changed into a lake more similar to the modern-day Sea of Galilee (Eypórsdóttir, 2019; Valdimarsson, 2017).

Besides providing information about the suitability of a territory for early humans and thus indicating possible routes for early dispersals, ostracods have also been used to explain early human adaptations. At the Early Pleistocene Barranco León site in southern Spain, which is one of the most important sites for the human evolution and early occupation in Europe, ostracod assemblages, stable isotopes and trace elements indicated that the human occupation took place when the marginal zone of the adjacent lake was characterized by an oligohaline to mesohaline through-flow open lacustrine system, fed by groundwater and meteoric stream water. The section yielding archaeological remains was deposited during water-level changes with corresponding erosion and redeposition, as reflected by a high abundance of imbricated ostracod valves, and the tools are thus not *in situ* (Anadón & Gabàs, 2009; Anadón et al., 2003; De Marfà, 2007).

Another example is ostracods from the natural springs from the desert oasis El Kowm at Middle to Late Pleistocene sites in Syria, which show periods of brackish water when the landscape was steadily occupied by humans, leading to the consideration that early hominines were able to adapt to brackish drinking water resources in the eastern Mediterranean deserts (Kalbe & Jagher, 2014; Kalbe et al., 2016; Le Tensorer et al., 2007).

For the famous Ceprano human calvarium found on a Middle Pleistocene floodplain environment in the Campogrande area in Italy, ostracods were used for a palaeoenvironmental reconstruction. They added detailed information about the presence of oligo- to mesohaline travertines and spring pools with high concentrations of Ca and Mg at the site (Biddittu et al., 2020).

The interglacial ostracod fauna found in the sediments of the Middle Palaeolithic Geiseltal area in Neumark-Nord, Germany, was markedly different from other Eem Age (cf. Figure 5) ostracod assemblages, as it, for example, included species that today are restricted to Africa. The ostracod assemblage indicated an increase in salinity in the water body, probably due to increased evaporation during a climatic change (Fuhrmann & Pietrzeniuk, 1990; Mania, 1992).

Ostracods were used in a multi-proxy study from a saline wetland in 'Nagla Lu', Xizang, southern Tibetan highlands, which shows a continuous fire record attributed to humans since the Last Glacial Maximum. Freshwater species showed that the catchment of the area was less arid at the end of the Last Glacial Maximum than it is today due to higher winter precipitation (Miehe et al., 2021).

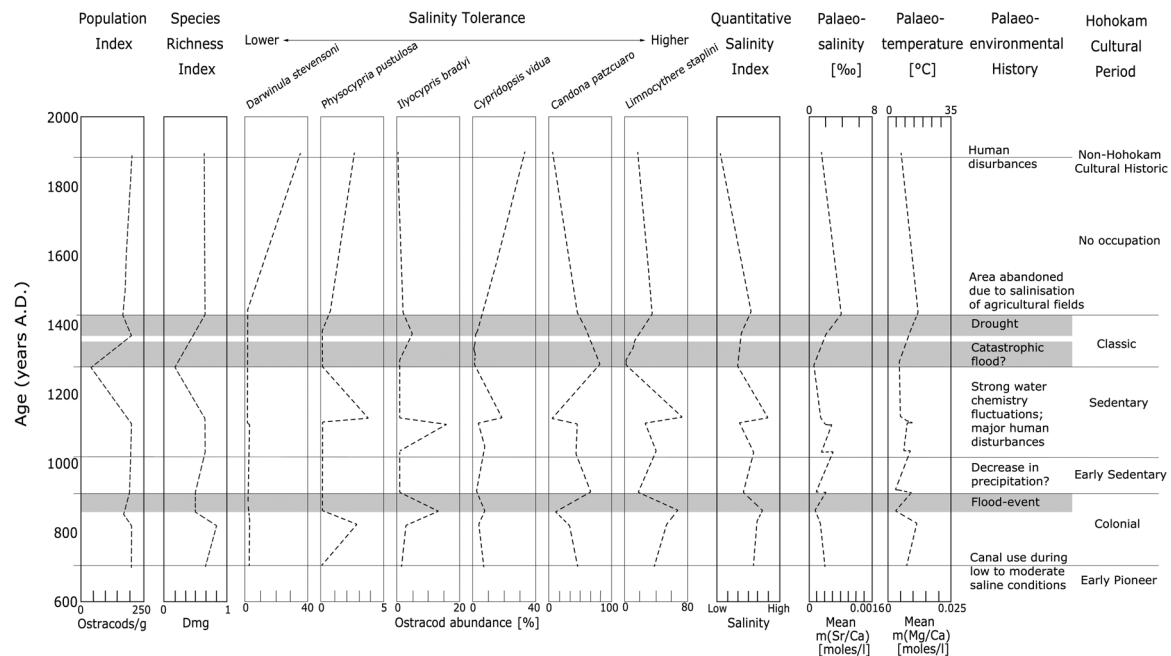
The human occupation of arid areas like the Levant after the dispersal out of Africa was still strongly dependent on the accessibility to water during the Neolithic. Mischke et al. (2015) studied ostracods from the Al Jafr Basin in Jordan, known for Neolithic to Bronze Age settlements, using the conductivity transfer function developed by Mischke, Ashkenazi et al. (2014). They demonstrated an environment of permanent shallow ponds with rich aquatic vegetation and large wetland areas with slow-flowing streams, which may have attracted the human settlement.

Similarly, in the Dhamar Highlands in Yemen, humid periods were identified by analysing ostracod abundances, with the aim of connecting to earlier studies in southern Arabia and the Dhamar Highlands about Neolithic settlements during the Holocene humid period. The first humid period was found to have commenced probably during the Late Pleistocene and lasted to about 7430–7310 cal yr. BP, and a second, possibly concordant with the Bronze Age, around 3900–3690 cal yr. BP (Mohammed & Keyser, 2021; Mohammed et al., 2018).

In Anatolia, Turkey, ostracods from the palaeolake Sağlık were used to show that the Neolithic Halaf culture first settled in the Kahramanmaraş Valley during a wetter period in the mid-Holocene and persisted into a drier period (Sekeryapan et al., 2020).

In the persistently more humid climates of Europe, ostracods have also been used to characterize the environmental attractiveness of an area for human settlement. For example, Lord et al. (2011) studied the settlement history at Rio Sizandro in Portugal, which was continuously evident since the Bronze Age from archaeological findings, while Neolithic findings in this area are rare. The ostracods show that after the post-glacial sea-level maximum, the area was a freshwater-dominated habitat-diverse environment, consistent with rich fish and mollusc faunas, and it would thus have been attractive for humans. Similarly, based on the high number of Neolithic to Chalcolithic sites, the palaeolake Gorgana at the Lower Danube





**FIGURE 6** Ostracod data from the Hohokam irrigation canals in central Arizona, and the corresponding interpretation of the palaeoenvironmental history and human occupational history. The displayed ostracod data are the number of ostracod valves per gram of sediment (Population Index), the number of different species found (Species Richness Index), the relative abundance of six ostracod species as indicator species for salinity tolerance and a thereof derived quantitative salinity index, the palaeosalinity based on trace elements (Sr/Ca) and the palaeotemperature based on trace elements (Mg/Ca). The shaded areas show major palaeoenvironmental events that are reflected in the different ostracod proxies. Modified from Palacios-Fest, (1994, 1997).

Valley in Romania appears to have been an attractive environment for human settlement. In a multiproxy study of the lake, most of the ostracods found were cosmopolitan species, but they still indicated a stable lacustrine environment, which accords with the high availability of resources like fish and molluscs (Nowacki et al., 2019).

#### Stable isotope analysis

Humid periods have been identified in the Neolithic wetland sites in Unfriedshausen and Pestenacker-Nord in southern Germany, based on ostracod taxa and stable oxygen and carbon isotope signatures from shells of abundant species. These data showed that climatic changes lead to larger permanent water bodies, which, in earlier research, were discussed as having attracted the possibly contemporaneous human settlement (Janz & Matzke-Karasch, 2001; Mayr et al., 2015).

The oldest archaeological finds from the Qinghai Lake Basin, China, date back to ca. 15 ka. Rhode et al. (2010) argue, in a geoarchaeological study including ostracods, that the cold and dry last glacial maximum (LGM) environment would have been very unfavourable in the area, but if older sites may exist, they may now be underwater and 4–6 km offshore.

At Lake Bafa in western Turkey, the transition from a marine environment to a lagoon and finally to a freshwater lake during the Late Bronze Age to Roman/Hellenistic was recorded with ostracod assemblages and stable isotope analysis of ostracods. This environmental transition was concurrent with changes in human settlement, transport and perhaps even cult activities (Akçer-Ön et al., 2020).

At an archaeological site at the Upper West Amarillo Creek Valley, Texas, USA, ostracod abundances, indicator species, stable isotopes and quantitative indices, such as a salinity index, were used to trace the Medieval Climatic Optimum and the transition into the Little Ice Age. They showed no evidence of anthropogenic impact, but permanent water would have been available through most of the documented history of the area that may have affected human settlements and seasonal movements (Palacios-Fest, 2010).

#### Trace elements

Mg/Ca and Sr/Ca are convenient proxies for salinity reconstructions. In the Bir Tarfawi-Bir area in the southwestern desert of Egypt, humid intervals are associated with Middle Palaeolithic artefact concentrations. Ostracods were abundant in two palaeolakes, and Mg/Ca ratios from their shells indicated a semi-arid environment with permanent water and high calcite precipitation, similar to travertine deposits. The water of the lakes was hence thought to derive from nearby springs or short streams (De Deckker & Williams, 1993).

Palacios-Fest (1994) analysed the palaeohydrochemistry in ostracods from irrigation systems of the pre-Columbian Hohokam culture that settled in the arid lowlands of the Southwest of North America. Mg/Sr and Sr/Ca values were used to infer two major climatic events that caused two major floods and one drought (Figure 6).

#### Mutual ostracod salinity range

Ranges with reconstructed maximum and minimum salinity values can be displayed with the Mutual Ostracod Salinity Range

(MOSR) (Pint, Schneider et al., 2017). The method is strongly dependent on the presence of index species with narrow salinity tolerance ranges, but has a better coverage of species in comparison to conductivity transfer functions that rely on large training data sets.

Krahn et al. (2021) used several ostracod proxies for their palaeoenvironmental reconstructions of the Lower Palaeolithic site of Schöningen in Lower-Saxony, Germany. While their transfer function shows high error ranges due to the low numbers of valves, the reconstructed salinities are still within the ranges indicated by the MOSR. Hence, the ostracod valves in Schöningen reflect increased salinities due to groundwater input in contact with a nearby salt structure, increased nutrients and lake-level variations (Krahn et al., 2021; Tucci et al., 2021).

### 2.2.3 | Temperature

#### Relative abundance

Temperature reconstructions with ostracod proxies are, similar to salinity reconstructions, often based on the relative abundances of indicator species and ecological groups.

At the Hoxnian (cf. Figure 5) Beeches Pit site in Suffolk, UK, palaeoenvironmental reconstructions based on ostracods and other proxies showed that human occupation took place during a middle Pleistocene interglacial in closed deciduous woodlands at small permanent pools and tufa springs. While the adaptation of early humans to extreme environments like glacial maxima or dense interglacial woodlands often has been debated, the occupation at Beeches Pit persisted into the subsequent cool phase, which the change in ostracod assemblage could demonstrate (Benardout, 2015; Preece et al., 2007).

In past River Thames channels at Syon Park in Brentford, correlating stratigraphically to the Late Palaeolithic settlements of the area, ostracods seem to indicate a thaw episode during the Last Glacial Maximum, as the species found are today associated with summer tundra pools in periglacial environments (Corcoran et al., 2012).

The environmental transition from the late Last Glacial to post-glacial at Lough Boora, one of the oldest Mesolithic sites in Ireland, was reconstructed based on ostracod assemblages. They showed a transition from a lake with carbonate sedimentation and poorly developed vegetation to a cool-temperate shallow lake with a swampy littoral zone and abundant lower plants (Griffiths, 1998).

The late Pleistocene–Holocene climatic transition was also seen in ostracods from a lake at the famous Early Mesolithic Star Carr site in North Yorkshire, UK. Late-glacial ostracod faunas reflected a calcareous, relatively deep lake with a low trophic state and temperatures, while ostracods from a Holocene sample showed the onset of warming, leaching and a shift in depositional regime (Holmes & Griffiths, 1998).

The Holocene environmental change also favoured human settlement at the Elbe river valley in Germany, where ostracods in a comprehensive multiproxy study were used for quantitative

temperature reconstructions, showing a temperature rise of 4–6°C in the early Preboreal (cf. Figure 5), and describing a diverse landscape structure that was thought to have attracted human settlement (Turner et al., 2013).

Holarctic ostracod species were found in Late Quaternary lacustrine sediments from a dry lake basin in the south-eastern Carpathian Basin, which were unfortunately not datable, but could provide implications for the Palaeolithic sites in this area. For example, information about the palaeoenvironment was obtained from the temperature optimum of the dominating species *Candona neglecta*, 4°C, during its final moulting time in spring, and juveniles that tolerate up to about 20°C (Zeeden et al., 2021).

#### Mutual Climate Range

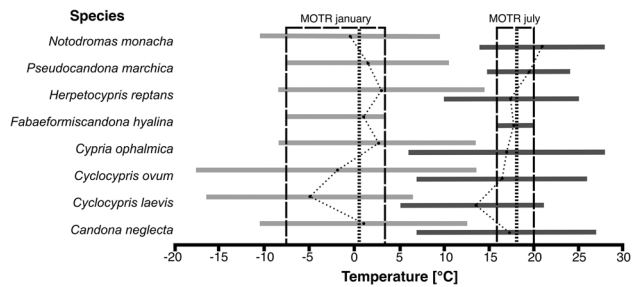
Temperature reconstructions using Mutual Climate Range methods can be used to display air temperature ranges, based on only those components of a fossil assemblage that coexist today (the Delorme Method developed by Delorme et al., 1976; see also D. A. Horne et al., 2012), or more usually based on all species in a fossil assemblage (MOTR developed by Horne, 2007; see also D. A. Horne et al., 2012; D. J. Horne et al., 2012).

MOTR has been used to discuss the human adaptations at different hominin sites during the climate changes in the Middle Pleistocene. While the Holsteinian (cf. Figure 5) Bilzingsleben site in Germany showed only slightly higher temperatures than modern day (Daniel & Frenzel, 2010; Diebel & Pietrzeniuk, 1980) (Figure 7), MOTR from the Hoxnian (cf. Figure 5) Beeches Pit site in Suffolk, UK, further showed that the human occupation not only took place during an interglacial but also continued into a succeeding cold phase (Benardout, 2015). Other Middle Pleistocene sites in the UK, like the Hoxnian (cf. Figure 5) Dierden's Pit site in Swanscombe and the Cromerian (cf. Figure 5) Boxgrove hominine site in West Sussex (Figure 8), suggested summer temperatures similar to modern values, but slightly colder winter temperatures and thus a stronger seasonality (Holmes et al., 2010; White et al., 2013; Whittaker & Parfitt, 2017).

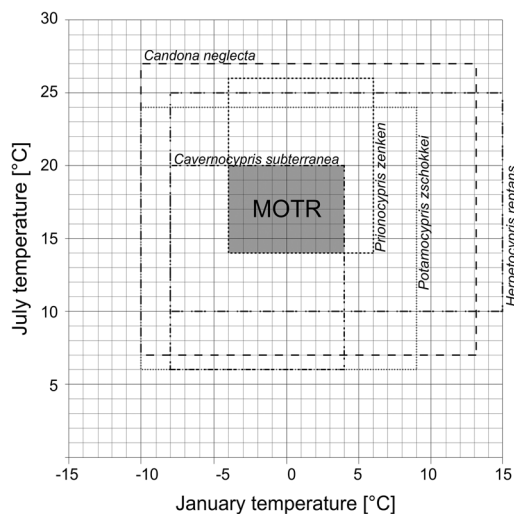
An attempt to prove cooling with MOTR after an interglacial failed for the Lower Palaeolithic archaeological site Schöningen, Lower-Saxony, Germany, as only a few ostracod valves were found in most samples, and the occurring species had a wide tolerance (Tucci et al., 2021).

### 2.2.4 | Radiocarbon dating

Radiocarbon dating has been shown to work on ostracod valves to some extent, but the valves of these water-dwelling animals have a reservoir effect similar to aquatic molluscs, and many adult valves are needed for one measurement because of their light weight. In geoarchaeological studies, ostracod valves have, therefore, rarely been used for this purpose, even if dating is an important issue in palaeoenvironmental studies of archaeological sites. Rhode et al. (2010) used ostracods for radiocarbon dating relatively successfully for their study of the environmental history of the Quinghai Lake Basin in China during the LGM. Similarly, Akçer-Ön et al. (2020)



**FIGURE 7** The Mutual Ostracod Temperature Range (MOTR) for the Middle Pleistocene site Bilzingsleben, Germany, for January ( $-7^{\circ}$  to  $4^{\circ}\text{C}$ ) and July ( $16$ – $20^{\circ}\text{C}$ ). The horizontal dashed lines show the calculated average temperatures ( $0.5^{\circ}\text{C}$  for January,  $18^{\circ}\text{C}$  for July). Redrawn from Daniel and Frenzel (2010).



**FIGURE 8** A different way to display the Mutual Ostracod Temperature Range (MOTR), for the Middle Pleistocene Boxgrove hominin site, UK, with the January temperatures on the y-axis and July temperatures on the x-axis. The grey area displays the MOTR, where all species overlap. Redrawn from Holmes et al. (2010).

performed radiocarbon dating on ostracods in one of their samples of the geoarchaeological study on Lake Bafa in Turkey, and the results agree well with radiocarbon dates on other materials.

### 2.3 | Landscape changes by human activity

Anthropogenic landscape changes became especially prevalent after the Neolithic Revolution with the beginning of agricultural land use and herding, which required more extensive cultivated areas. Land use by humans induced modification of natural landforms, such as deforestation for agricultural and pastoral purposes or trampling caused by herding at drinking sites, which directly or indirectly can be detected with ostracods.

Ostracod assemblages can possibly trace the Neolithic transition to agriculture and the dispersal of useful plants. McKenzie and

Moroni (1986) presented specific ostracod faunas from Italian rice fields. They argued that several species were brought to Italy by people within the past 10,000 years with rice seed exchanges and/or seeds and cuttings of other useful plants, as there is no fossil evidence of these genera or species in the pre-Holocene faunas of Europe.

At the Khok Phanom Di site in central Thailand, ostracod species of the genera *Stenocypris* and *Cypridopsis* that today are common in South-East Asian continental aquatic environments, such as rice fields, have been found, indicating a high likelihood for rice fields in the surrounding areas of the site. Further, the assemblage indicated that the site was located near an estuary with a low-lying marshy hinterland, with access to local ponds with fresh water (McKenzie & Higham, 1991).

Ostracods can indicate human activity, for example, by displaying discharge fluctuations in a stream caused by higher erosion rates in connection with deforestation. For example, ostracods from the barrage-tufa dammed fluvial systems in the White Peak in Derbyshire, UK, were used to show discharge fluctuations and especially lower flow rates after 7400 BP, which are difficult to explain by climate change. This is clearly before forest clearance of the surrounding area around 5000 BP, and the fluctuations were hence assumed to be a combination of changes in effective precipitation, variations in tufa precipitation and thus ponding, changes in water quality, increasing prevalence of macrophyte vegetation and a transition to thermophilous woodlands with higher runoff rates (Taylor et al., 1994). In contrast, human modification of the landscape since the Late Mesolithic was presumably the reason for the transition of a freshwater lake to a raised bog at Queens Sedgemoor, Somerset, UK, as shown by a multiproxy study of the palaeoenvironment including ostracods (Hill et al., 2017, 2016).

Anthropogenic activity was also revealed in the palaeoenvironment at the Early Celtic site on the mountain Ipf in Baden-Württemberg, Germany, by correlating periods of soil erosion and settlement history. Further, the palaeoenvironments of the site were reconstructed with ostracods, showing open standing water, followed by aridification and a transition from a marsh to a spring brook (Fischer et al., 2011).

Eutrophication of a lake can be detected with ostracods, as in Lake Coba on the Yucatan Peninsula, Mexico, at a time when the lake was at its deepest. This eutrophication was probably a result of agricultural forest clearance by early urbanization and development of farming villages at the lake during the Late Preclassic and Early Classic periods (ca. 600 BC–600 AC) and was demonstrated with ostracod assemblages and stable isotope ratios, combined with, for example, diatom and pollen analyses (Whitmore et al., 1996).

Besides assemblages and isotope data, Fleury et al. (2015) included ostracod abundances in their study of sediments from the Laguneta Tuspán in Guatemala as evidence of Mayan land use. The ostracod abundance was especially low in the thick layers of the so-called Maya Clay, which relates to increased erosion due to intensive land use. High erosion rates may have resulted in a decrease of ostracods due to dilution of densities by high sedimentation rates and

deterioration of living conditions by high suspension loads and oxygen depletion in the lake. This also resulted in a reduction of the photosynthesis activity, which is reflected in a decrease in oxygen-sensitive ostracod species and  $^{13}\text{C}$  depletion in the valves.

Palaeoclimatic studies have often attempted to explain the so-called Mayan collapse, as their swidden and wetland field agriculture depended on the climatic conditions. In northern Belize, this collapse happened at around 1000 AD, where ostracod assemblages from the Laguna de Cocos on Albion Island reflect a falling lake level coincident with a decline in agricultural activity (Bradbury et al., 1990).

Oxygen isotopes from ostracods from other Mayan sites on the Yucatan Peninsula also indicate a consistently dry climate and the driest mean conditions in the last 3000 years during the Terminal Classic Period (ca. 910–990 AD) (Escobar et al., 2010). However, environmental changes may also have been caused by changes in agricultural strategies and urbanization, as seen around two centuries before the general Mayan Collapse in the Petén area on the central Yucatan Peninsula. The abandonment of lakeshores due to urbanization was demonstrated by ostracod data, which showed recovery to more natural conditions and decreasing erosion rates (Fleury et al., 2015).

Alin (2001) and Palacios-Fest et al. (2005) studied ostracods and other fossils from Lake Tanganyika sediment cores. The associations indicated distinct faunal turnover and a decrease in abundance caused by deforestation in the 19th and early 20th centuries.

The importance of humidity for agriculture was also seen in Bronze Age Harappan Civilization at Lake Quinghai in China.  $\delta^{18}\text{O}$  values showed a minimum phase of increased humidity from ca. 11.6 to 9.4 cal ka BP, followed by a gradual decline in the mean annual temperature. The increasing aridity and dryness may have led to more efficient agricultural practices in the beginning and the eventual collapse of the Harappan Civilization between 3.5 and 3 cal ka BP (Leipe et al., 2014; Lister et al., 1991).

High erosion rates in connection with the reduction of woody vegetation were also seen in the Upper Khabur Basin in Syria around the 9th century AD, resulting in the aggradation of the floodplain. Deckers and Riehl (2007) attempted to include ostracods in their interpretation of the geomorphology of the basin, which presumably was partly human-influenced, but unfortunately, too few ostracods were sampled.

Deforestation may, besides increased erosion rates, also lead to increasing water yield, as the evapotranspiration will be reduced by a reduction in woodland and lead to the formation of wetlands or transformation of wetlands into lakes. The deepening of the lake Shkodra in northern Albania around 1200 cal yrs. BP, recorded by a change in the ostracod assemblage, may be a result of such an increased water yield by deforestation, or it could result from changes in the drainage pattern of the connected Buna and Drini rivers (Mazzini et al., 2016).

At a former Early Celtic fortress site at the Ipf mountain in Baden-Württemberg in Germany, Fischer et al. (2011) noticed successive soil erosion and changes in the ostracod assemblage through agricultural activity after the 6th century AD.

Furthermore, a decrease in the ostracod diversity can be used to determine the scale of anthropogenic influence. In Lake Sevan in Armenia, Holocene ostracod assemblages have been shown to be much more diverse compared to subrecent and recent assemblages, which is thought to be a result of the high anthropogenic activity in the area in the last decades. However, ostracods indicated that the lake inundated the Bronze Age landscape during more humid climate conditions. In addition, a major volcanic episode probably dammed an adjacent river, and the high lake levels remained until the early 20th century (Wilkinson, 2020; Wilkinson & Gulakyan, 2010).

This was also seen, for example, in Haarhausen, a Germanic site that shows a significant Roman influence (second half of the 3rd century AD), in Thuringia, Germany, where ostracods were analysed in two profiles: one from a stagnant lake with a swampy shoreline and one from a smaller marsh with proximity to a spring. Differences in the ostracod and mollusc assemblages and diversities from both profiles showed that the small marsh profile comprised evidence for anthropogenic influence, indicating that the settlement only extended towards the small marsh and not to the lake (Keding et al., 1995).

## 2.4 | Water use and water works

Ostracods can be used to detect past water works and water use. Ancient irrigation systems, anthropogenic dammed fluvial systems, water storages, lacustrine harbours or moats are examples of water works that affect non-marine environments and have been analysed through ostracods.

Anthropogenic-caused lake-level variations that seem to contradict the climatic history may be investigated with ostracods. For example, ostracods from the Holocene of Boston Lake in Tibet do not display the general trend towards aridity since 4500 cal yrs. BP. This trend is seen in several other records in the area. The variations may thus be a result of human impact on the hydrological balance as they improved their irrigation and channel systems (Wünnemann et al., 2006).

Human activity in the Prehistoric Hohokam irrigation systems in central Arizona, USA, was reconstructed thoroughly using ostracods and other methods. Analyses of Mg/Ca and Sr/Ca ratios and trace element data were applied to trace the human-impact hypotheses for environmental change in the irrigation system, showing that the records of water chemistry in the ostracods changed in accordance with human activity by agricultural practices (Palacios-Fest, 1994) (Figure 6). As the ratios can be used for temperature and salinity estimates, they suggested a seasonal opening of the Hohokam canals in the Phoenix area between late winter and early summer before the monsoon season (Palacios-Fest, 1997).

Ostracods from the irrigation systems of the Early Agricultural Period in southeastern Arizona were studied to determine the environmental history and human activity. The ostracod assemblages displayed the transition from opportunistic (diversion of episodic flows after storms) to functional (carefully timed diversions of

perennial flows) canal operation between 3000 and 2400 yrs. BP, which implies an increasing complexity of the social structure. From 2800 to 2500 yrs. BP, the farmers began to control the water input into the canals, as variations in the ostracod assemblage indicate alternating intervals of salinization and freshwater input that fits with the opening of a headgate (Palacios-Fest et al., 2001).

In a water storage reservoir of the Hohokam in the Sonoran Desert in southwestern Arizona, ostracods and other biological remains showed that the reservoir could store water all the year so that desert settlements, contrary to earlier beliefs, could be used permanently (Bayman et al., 2004).

Irrigation-based agriculture during the expansion of the Chinese empire in the Han Dynasty caused a significant reduction and probably a near desiccation of the lake Lop Nur in the eastern part of the Tarim Basin, NW China. Geological evidence, including ostracods, indicated the change from a perennial large and brackish to a saline lake until ca. 2000 years ago, and the water inflow in Lop Nur was probably controlled mainly by the intensity of farming activities in the lake's catchment after the Han Dynasty (Liu et al., 2016; Mischke et al., 2020, 2019).

Non-marine ancient harbours have also been analysed through ostracods, such as the Magdala Harbour in the Sea of Galilee, Israel, which was surrounded by areas of intensive agriculture during the Hellenistic and Roman/Byzantine periods. The ostracods showed the transition from a preharbour beach to the harbour basin and that the harbour area was presumably protected artificially, which is seen in an increase of organic matter and alkali enrichment in the ostracod valves, a decrease in water energy and a change in salinity (Lena et al., 2017; Rossi et al., 2013, 2015).

On the Danube Delta in Romania, at the Roman fortress of Halmyris, ostracods were used to identify the presence of a fluvial channel north of the settlement of Halmyris, which was navigable throughout the occupational periods, from the Getic/Greek to the Roman period, and could have been used as a natural harbour (Giaine et al., 2019).

In the Roman sewer systems from Church Street, York, UK, two bottom-dwelling ostracod species were found that further indicated that the sewer systems contained shallow and not necessarily clear water, with low salinity and little or no living plant material. The water was probably moving only slowly enough to keep it from stagnating (Buckland, 1976).

Ostracods have also been found in high diversity in the medieval town moat of Greifswald in Germany, where they indicated high productivity and moderate eutrophication of the water because of human activity. The assemblage further showed that the flow direction in the moat presumably was dominantly into the river Ryck, while saline water from the Baltic would only be introduced at flood events (Frenzel et al., 2004).

In the Canadian Arctic, the Sadlermiut used small, shallow ponds to clean and prepare their subsistence harvest. A sediment analysis including ostracods of a freshwater pond close to the archaeological site 'Native Point' on Southampton Island, Nunavut, showed fundamental changes in the ostracod adult/juvenile ratios, species

richness and frequency because of eutrophication. The anthropogenic influence was seen since the arrival of the Sadlermiut around 1250 CE and is still visible (Viehberg et al., 2021).

## 2.5 | Provenance studies

Ostracods found in, for example, pottery or building material can be useful in indicating provenance, thus distinguishing between locally produced and imported materials, thus pointing to trading and exchanges, or distributions, mobility/migrations and settlement shifts (see Quinn, 2008, 2013; Quinn & Day, 2007a; Wilkinson, 2017; Williams et al., 2016, 2017). In this section, fossil marine ostracods will also be considered, as the ostracod-bearing materials may originate from very different settings than where they were sampled.

Quinn and Day (2007b) review microfossil assemblages in ancient ceramics for provenance studies, also mentioning the use of ostracods. As archaeological ceramic samples for micropalaeontological or petrological purposes are often studied using thin sections with  $\times 25$ –400 magnification under a light microscope, ostracods cannot usually be determined on a species level, which reduces their applicability. Separation of the valves from the ceramic pieces is, in contrast with other microfossils, impossible, but the presence of ostracods can still be useful for narrowing the provenance area. This was, for example, the case in Day et al. (1999), where the epigraphy, typology and fabric of a sherd from the Bronze age site of Tel Haror in the Negev Desert, Israel, indicated a provenance from Crete. The sherd contained volcanic clasts and ostracods, which were taxonomically not identified, but narrowed the provenance area to only a few sites with similar pottery compositions on the central south coast near the Myrtos valley. This indicated that the sherd was produced in this area and provided evidence for a trading connection between the Levant and Crete during the Middle Bronze Age.

The presence or absence of ostracods was also crucial for a provenance study of clays in Garamantian ceramics from Jarma, south-west Libya. The different number of ostracods in specific red on white painted ware showed that it was both traded, as it, in contrast to local clays, contained ostracods, but that it also was imitated, as demonstrated by the absence of ostracods (Leitch et al., 2016).

The high abundance of ostracods in the sherds of Mediterranean amphorae from the Gulf of Hammamet, Tunisia, has been suggested as a primary determining feature of this production site, which can be used to distinguish it from other African amphorae (Capelli & Bonifay, 2014).

The *Cardium* imprinted ceramics from the Neolithic potteries of the Bug-Dniester culture in Ukraine also contain ostracods. These were similar to other Late Neolithic ceramics from the Bug-Dniester in forms, usage of identical stamps and in ornamentation methods and motifs, but differed in having *Cardium* seashell imprints like the *Cardium* Pottery of the eastern Adriatic and containing ostracods. The production site may, therefore, to some extent have been in close relations with or under the influence of the Eastern Adriatic *Cardium*

Pottery Culture, which had access to *Cardium* shells and materials containing ostracods. The ceramics may therefore be expected to have been produced at harbour sites and on the seashore of the Black Sea and transported along the west coast of the Black Sea into the Bug-Dniester area (Toykailo, 2012).

Ostracods in ceramics can also be used for firing temperature reconstruction based on physical alteration. This was shown in ceramics from the Sasanian archaeological site Qizlar Qal'eh, Iran, where Early Cretaceous and Quaternary ostracods and other microfossils suggested that the material was derived from alluvial sediments taken from an adjacent site north-west of the Gorgan River plain, and the altered internal ultra-structures of the shells indicated firing temperatures of 650–850°C (Daghmehchi et al., 2015).

Ostracod studies have also determined the provenance of other materials such as microfossils in Roman mosaics and sculpture material from Friedberg and Unterbaar, Germany. Here, the microfossils of black mosaic stones containing ostracods were assigned to local sediments, while other microfossils were derived from other regional sources, which showed that the combination of local and regional sources for the mosaic stones was common (Flügel, 1999).

Wilkinson et al. (2008) showed that it might be possible in some cases to identify ostracod species from mosaics as they were able to define two species in the chinks of Roman mosaic stones at Silchester, UK, but as these were long-ranging taxa, they provided no detailed biostratigraphic information.

Provenance studies of building materials have also sometimes focused on microfossils, including ostracods. One example is the building material from the late Iron Age of the Burrough Hill fort, which had its source in a local Pleistocene till, based on the identical microfossil signature (Wilkinson et al., 2013; Williams et al., 2015). The same was the case for ceramics from Burrough Hill fort, and Wilkinson et al. (2017) showed that, based on the microfossil signature, ceramics from Romano-British sites in England were also derived from nearby sources.

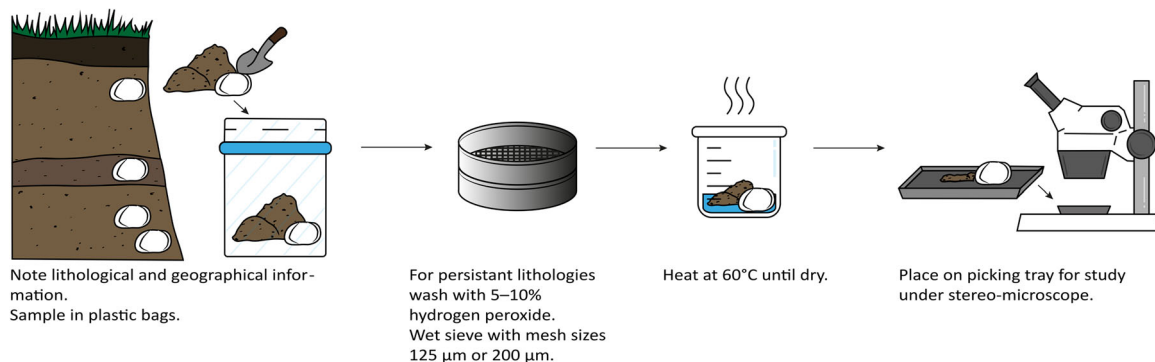
Wilkinson et al. (2010) applied microfossils, including ostracods, in a study of more recent building material from an English Civil War (mid-17th century) bastion at Wallingford Castle in Oxfordshire and

showed that it also derived from a nearby source. They conclude that microfossils can be applied to a wide range of provenance studies for classical to modern building materials.

### 3 | METHODS FOR SAMPLING AND LAB ANALYSES

Samples for extracting ostracods could be taken from any sediments representing a modern or former aquatic environment. Thus, they could derive from outcrops, land surfaces and sediment cores. From the latter, a sample distance of 10 cm is a usual minimum. For outcrop and surface samples, a weight of up to 50 g is recommended. The material should be kept wet before sieving if possible. A high clay and organic matter content, typical for lake, lagoonal and harbour sediments, can be dispersed by sodium pyrophosphate before sieving. More lithified sediments such as limestones can be treated with 5%–10% hydrogen peroxide. Mesh widths of the sieves should be 0.2 and 0.125 mm. If chemical analysis of the shells is required, the samples should be washed with demineralized water to avoid chemical overprinting of tap water. After careful drying in an oven at a maximum temperature of 60°C, the ostracods can be picked with a small brush or needle and collected in microcells using a stereomicroscope (Figure 9). A comprehensive description of the processing of ostracod samples from archaeological sites is given by Griffiths et al. (1993).

For species identification, classification literature is necessary. An overview of recent freshwater species of the world is given by Karanovic (2012), while regional literature such as books on regional ostracod faunas like, for example, Meisch (2000) or Fuhrmann (2012) for central Germany, or Henderson (1990) for Great Britain, is necessary as taxonomic references. A minimum of 300 individuals is recommended for statistically significant species abundances and for the use of mutual range methods. Multivariate statistics such as principal component analysis (PCA) and cluster analysis can be applied to compare samples and identify potential driving factors. Shell chemistry of ostracod valves comprises analyses of stable



**FIGURE 9** The process of sampling and sample processing: The sample is placed in a plastic bag to keep it moist; if necessary, it is processed with hydrogen peroxide to disintegrate the sediment, then sieved with water on mesh sizes 125 and 200 µm and dried at 60°C before ostracods can be picked under a low-power stereo-microscope. [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

isotopes, trace elements and radiocarbon dating. One of the most common species whose shell chemistry is well understood is *C. torosa* and, is therefore easily comparable with other studies. To investigate the preservation state of the valves, which is very important to indicate reworking and erosional processes, a scanning electron microscope or a high-resolution light microscope can be used.

## 4 | CONCLUSIONS

Ostracods have been proven to be good tools for palaeoenvironmental reconstructions and have, especially for this reason, increasingly been used in archaeological research. There are various options for their use as palaeoenvironmental proxies, and thus their application in geoarchaeological studies has increased in the last decades.

The widespread occurrence and species richness of ostracods in fresh water open many options for their use in palaeo-studies involving aquatic sediments. In non-marine geoarchaeological studies, the palaeoenvironmental and palaeoclimatic information from ostracods has been of particular interest. In studies of Palaeolithic sites, ostracod analyses were particularly valuable for identifying humid periods and evaluating human migrations or adaptations based on climatic or environmental reconstructions. In studies of Neolithic sites, climatic changes and changes in human living strategies can be reconstructed. Also, the environmental histories of areas with human occupation and the environmental suitability of areas for human settlements have been analysed. In more recent times, climatic changes affecting land and water use, like, for example, the Mayan swidden and wetland field agriculture, and the human impact on the environment, reflected by, for example, soil erosion or aridification, are interpreted using ostracod proxies. Tracing and analysis of land use based on ostracod analysis may be detected through eutrophication events, but are mostly indirectly shown through, for example, deforestation and connected higher erosion rates and thus discharge fluctuations in streams. Water works like canals and dams can be detected through ostracod analyses, but the ostracods also help reconstruct such structures' usage, potentially even with a seasonal chronological resolution.

Palaeoenvironmental interpretations are often based on palaeoecological analysis, using indicator species or assemblages that are easy and reliable to reconstruct past environments. Relative abundances of indicator species and assemblages have been shown to display palaeoecological trends connected, for example, to the settlement history of an area as nonquantitative reconstructions. MOTR and transfer functions for palaeosalinity have been used in several geoarchaeological studies, as these can provide a quantitative reconstruction when the available data sets are big enough. For shell chemistry, especially Mg/Ca and Sr/Ca ratios have often been used, as they have provided more precise information on palaeosalinity or palaeotemperature. Stable isotope analysis of  $\delta^{18}\text{O}$  in ostracod valves can be used as a palaeosalinity proxy instead of Mg/Ca or conductivity transfer functions in hydrologically closed basins, especially where no species-rich association and no modern training

data sets are available, while  $\delta^{13}\text{C}$  can be used for the analysis of the productivity or nutrient availability.

However, the mutual use of the different palaeoenvironmental proxies based on non-marine ostracods in geoarchaeological studies has still more perspectives. Other trace elements, such as trace metals (e.g., Cd, Ba, Zn), U/Ca ratios or  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios, have not or only rarely been used in the geoarchaeological context, but could provide further information about the palaeoenvironment of a water body, such as the productivity, oxygenation and water source. Ostracods have been used for radiocarbon dating in very few geoarchaeological studies, but with a successful outcome where enough material was available.

Ecologically induced morphological changes like size differences, nodes or sieve pore variations in the valves of some species have been proven to be useful tools and additions to nonquantitative species and assemblage analyses for a more detailed palaeoenvironmental reconstruction, and they could be considered for many archaeological studies involving aquatic sediments.

Fossil ostracod associations can also be analysed taphonomically. For example, the adult/juvenile ratio or the valve/carapace ratio can provide information on the water depth, sedimentation rate, energy regime of the water body or environmental stress.

The use of ostracods for provenance studies of many building materials or ceramics is less beneficial, as ostracods are usually damaged when attempting to extract them from the matrix. However, their mere occurrence is easy to recognize in thin sections and can play an important role in tracing the provenance of the material.

This overview of geoarchaeological studies, which all in some way used non-marine ostracods, gives an idea of the applicability of ostracod proxies for various (geo-)archaeological research questions. At the same time, it also displays the sparsity of detailed nonmarine ostracod studies at archaeological sites, which, regarding the state of research and development of new and better ostracod proxies, may further increase in the coming years.

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