Oxygen isotope analyses of Equus teeth evidences early Eemian and early Weichselian palaeotemperatures at the Middle Palaeolithic site of Neumark-Nord 2, Saxony-Anhalt, Germany

Kate Britton1,2,*, Sarah Pederzani2,1, Lutz Kindler3, Wil Roebroeks4, Sabine Gaudzinski-Windheuser3, Michael P. Richards5 and Thomas Tütken6

1 Department of Archaeology, University of Aberdeen, St Mary’s Building, Elphinstone Road, Aberdeen, AB24 3UF, UK
2 Department of Human Evolution, Max Planck Institute for Evolutionary Anthropology, Deutscher Platz 6, 04103 Leipzig, Germany
3 MONREPOS Archaeological Research Centre and Museum for Human Behavioural Evolution, Römisch-Germanisches Zentralmuseum, Leibniz Forschungsinstitut für Archäologie, Schloss Monrepos, 56567 Neuweid/Rhein, Germany and Institute of Ancient Studies, Department of Pre- and Protohistorical Archaeology, Johannes Gutenberg-Universität Mainz, Schillerstrasse 11, 55116 Mainz, Germany
4 Faculty of Archaeology, Leiden University, P.O. Box 9514, 2300 RA Leiden, The Netherlands
5 Department of Archaeology, Simon Fraser University, 8888 University Drive, Burnaby, BC, Canada V5A 1S6
6 Arbeitsgruppe für Angewandte und Analytische Paläontologie, Institut für Geowissenschaften, Johannes Gutenberg–Universität Mainz, Germany
*Corresponding author (k.britton@abdn.ac.uk)

Highlights:

- Equus sp. enamel was sampled from Neumark-Nord 2 (find levels NN2/2b, 2/1c, 2/0)
- $\delta^{18}O_{PO4}$ data were generated in order to estimate mean annual air temperature (MAT)
- early Eemian (~121±5 ka) MAT estimates are ~9 °C, correlating with other proxies
- early Weichselian (~93±7 ka) MAT was ~6 °C, elevated compared to other proxies
- implications for archaeology and Neanderthal-environmental interactions are explored

Author contributions:

KB designed the study, conducted sampling, prepared the samples for analysis, conducted data analysis, and wrote first full draft of the paper. All the authors provided critical review and contributions to subsequent versions of the manuscript. SP assisted in data interpretation and literature review; LK performed species determination, aided sample selection/sampling and provided site information; WR and SG-W contributed materials and provided contextual information about the site/archaeology; MR contributed to study design and analytical tools and provided facilities; and TT contributed to study design, methodological development and contributed analytical tools and facilities.
Abstract

Here we present phosphate oxygen isotope ($\delta^{18}O_{PO4}$) data from horse (Equus sp.) tooth enamel (bioapatite) from the early Eemian and early Weichselian find levels at the archaeological site of Neumark-Nord 2, Germany. Based on the relationship between $\delta^{18}O_{PO4}$ of bioapatite, body water, local precipitation and air temperature, these data are used to reconstruct palaeoclimatic conditions contemporary to the different phases of Neanderthal activity at the site. Bulk enamel samples representing one year of growth were taken from horse teeth from early Eemian (NN2/2b [~121±5 ka], and NN2/1c) and early Weichselian (NN2/0; ~93±7 ka) find levels, and $\delta^{18}O_{PO4}$ values were then utilised to calculate $\delta^{18}O$ of local environmental water and mean annual air temperature (MATs) during these phases of MIS5. Results indicate that during the early Eemian MAT was ~9 °C, with some evidence of variability through time. Although ~3 °C lower, the calculated early Weichselian MAT exceeds that indicated by other local and regional climate proxy datasets, suggesting that Neanderthal activity may have been limited to more ameliorate phases of the early Weichselian in this area.

Keywords: Pleistocene; Paleoclimatology; Europe; Stable isotopes; Bioapatite; Phosphate; Neanderthal; Last Interglacial; Interstadial
1. Introduction

During the Pleistocene, global climatic fluctuations have resulted in successive glacial and interglacial periods. These climatic changes would have strongly influenced environmental conditions in northern and central Europe, with glacial advance and permafrost conditions during glacial maxima, the spread of forests during interglacials, and the predominance of tundra or steppic environments during intermediate periods (Ehlers et al., 2011; Fletcher et al., 2010; Rother et al., 2019; Stewart and Lonergan, 2011; Turner, 2000). These variations would have posed challenges for hominins, influencing the extent and nature of their activity in the landscape. In this sense, the investigation and characterisation of terrestrial palaeoclimates contemporary to the occupation of Palaeolithic archaeological sites can illuminate the adaptive capacities and strategies of Pleistocene hunter-gather groups subsisting in these landscapes. At the same time, such studies can also yield data relevant to our knowledge of past climate variation that can be factored into models of past and future climate change.

Ice core oxygen isotope data ($\delta^{18}$O) provide a high-resolution record of Middle and Late Pleistocene climatic change, confirming and refining climatic information obtained from deep-sea marine sediment cores (Brook and Buizert, 2018; Dahl-Jensen et al., 2013; Rasmussen et al., 2014; Seierstad et al., 2014). However, although these systems provide evidence of polar and global marine trends, the influence of these large-scale climatic and environmental changes in continental contexts varies geographically; this requires further characterisation in many regions and calls for the establishment of regional climatic records. Most notably, proxy or measurement-based studies on
geographical variation in $\delta^{18}$O of precipitation (directly related to local
palaeotemperature) are rare. The gaining of inland, region-specific data is
essential to the interpretation of human and animal responses to climatic
variations, as well as to the construction of a palaeoclimatic record within a fully
terrestrial framework. Such data are particularly important in understanding the
broader climatic context of expansion and contraction of the Neanderthal
geographic range (Hublin and Roebroeks, 2009) or that of early anatomically
modern human expansions into central and more northerly Europe during the
Late Pleistocene. The Neanderthal exploitation of semi-open or forested
interglacial environments has been particularly contentious (see Pop and
Bakels, 2015 and references therein), and thus environmental and temperature
reconstructions at archaeological sites unambiguously dating to the Eemian
interglacial (as well as at contrasting glacial sites) are particularly valuable.

Like today, the Last Interglacial, the Eemian (~121 to 109 ka in N-W Europe,
see Sier et al., 2015; Sier et al., 2011), was characterised by reduced terrestrial
ice volume relative to glacial periods and increased temperatures, recorded in
ice core data (EPICA community members, 2004) and a minimum in benthic
$\delta^{18}$O values in marine sediment cores (Lisiecki and Raymo, 2005). However,
the Eemian climate – both globally and locally – may have differed from the
current interglacial. A compilation of terrestrial and marine records indicates
global temperatures were ~1.5 °C warmer than in the mid- and late 20th century
AD (AD 1961-1990, see Turney and Jones, 2010). The maximum annual mean
warming is thought to have occurred in mid- and high- (Northern Hemisphere)
latitudes (Turney and Jones, 2010), associated with changes in vegetation
patterns and characterised by warm summer temperatures. However, spatial (and temporal) variation was likely high, and competing proxies have resulted in varying estimations at similar locales (see review in Turney and Jones, 2010).

There are a number of geochemical methods that can be used to reconstruct continental palaeotemperatures based on the oxygen isotope analysis of incrementally growing minerals and biominerals. These approaches include the analysis of geological archives such as speleothems (e.g. Drysdale et al., 2005; McDermott et al., 1999; Vansteenberge et al., 2019), as well as biogenic hard tissues including shells of bivalves or other molluscs (e.g. Goodwin et al., 2003; Latal et al., 2006; Schöne et al., 2004), or mammal bone and tooth (see review in Pederzani and Britton, 2019). These methods are based on the relationship between the oxygen isotope composition ($\delta^{18}O$) of these biominerals and the $\delta^{18}O$ of local environmental water (Iacumin et al., 1996; Kohn, 1996; Longinelli, 1984; Luz et al., 1984), which is related to the $\delta^{18}O$ of precipitation, reflecting local temperature and other factors (Clark and Fritz, 1997; Dansgaard, 1964; Gat, 1980; Yurtsever, 1975). The relationship between the $\delta^{18}O$ of local environmental water and (bio)mineral $\delta^{18}O$ values is mediated by the $\delta^{18}O$ of percolating ground water in the case of speleothems and body water in the case of vertebrate mineralised hard tissues. As homeothermic mammals have a metabolically-controlled, relatively constant body temperature (~37°C), bioapatite (a carbonated hydroxyapatite) precipitates in oxygen isotope equilibrium with body water at this temperature (Levinson et al., 1987; Longinelli, 1984; Luz et al., 1984). While there is a roughly linear relationship between ingested water and body water, this varies between different species.
However, fractionation factors have been established for a number of extant species, including horses (e.g. Delgado Huertas et al., 1995). Local processes such as water mixing, water movement, groundwater recharge and evaporation processes that occur in surface water bodies can all influence the oxygen isotope composition of environmental water (and, by inference, drinking water). However, broad correlations between groundwater, mean annual precipitation, and climate at specific locales are universally apparent (see review in Pederzani and Britton, 2019). Therefore, the oxygen isotope analysis of mammalian bioapatite can be useful in the reconstruction of past climatic conditions, specifically palaeotemperatures.

A number of recent studies have utilised oxygen isotope analysis of herbivore teeth in palaeoclimatological investigations, in order to reconstruct $\delta^{18}$O values of past precipitation, mean annual palaeotemperatures and seasonal temperature variations (palaeoseasonality). Studies have included analysis of both the carbonate (CO$_3$) and phosphate (PO$_4$) components of tooth enamel, using a range of different Pleistocene mammals (Arppe and Karhu, 2010; Bernard et al., 2009; Bryant et al., 1996; Bryant et al., 1994; Delgado Huertas et al., 1997; Fabre et al., 2011; Fricke et al., 1998a; Fricke et al., 1998b; Koch et al., 1989; Kovács et al., 2012; Skrzypek et al., 2011; Velivetskaya et al., 2016). The oxygen isotope analysis of small mammals has proven useful in palaeoecological terrestrial contexts, for example, in the Late Eocene (Grimes et al., 2004). However, the use of anthropogenically-derived (archaeofaunal) assemblages of larger mammals are particularly useful for reconstructing past climatic conditions at archaeological sites as these remains are normally the
direct product of human activity: thus, they can provide insights into that activity or the prevailing conditions, and can therefore generate terrestrial palaeoclimate proxy data near-synchronous to human site-use (see discussions in Britton, 2017; Pederzani and Britton, 2019). As obligate drinkers with significant daily water requirements, and taxa found in both glacial and interglacial faunal assemblages, equids may be particularly useful for mapping past $\delta^{18}$O precipitation patterns and palaeoclimate conditions.

Here, we present $\delta^{18}$O$_{PO_4}$ data of horse enamel (Equus sp.) from the Middle Palaeolithic site of Neumark-Nord 2, Germany, in order to investigate precipitation $\delta^{18}$O values and MAT in the early Eemian and Weichselian in this area of central Europe. Within the context of the rich archaeological and palaeoenvironmental record of Neumark-Nord 2, we seek to integrate these data with other archaeological data and palaeoclimatic proxies, and explore the potential and limitations of isotope zooarchaeological approaches in archaeological and palaeoclimatic studies.

2. The Site of Neumark-Nord 2, Germany

The site of Neumark-Nord 2 is located approximately 35 km west of Leipzig in Saxony-Anhalt, Germany (51°19'28"N, 11°53'56"E; Figure 1).
First discovered in the 1980s, this area of the Geisel valley contains two Eemian basins, rich in archaeological, botanical and faunal remains, and which infills cover the complete last interglacial cycle. These basins include the large lake Neumark-Nord 1 (NN1; approximately 24 hectares) and the adjacent shallow pool Neumark-Nord 2 (NN2; ~1.6 hectares) (Gaudzinski-Windheuser et al., 2018; Gaudzinski-Windheuser and Roebroeks, 2014; Kindler et al., in press; Mania et al., 2010; Mania et al., 1990; Meller, 2010). In 2003, excavations commenced at Neumark-Nord 2, initially focusing on the early Weichselian levels (NN2/0) and then on the interglacial find horizon (NN2/2b). Extensive excavations were carried out at Neumark-Nord 2 between 2004 and 2008,
yielding around 20,000 Middle Palaeolithic flint artefacts and around 120,000 faunal remains, dominated by warm-temperate species, specifically from the rich find level Neumark-Nord 2/2 (NN2/2, especially NN2/2b) (Gaudzinski-Windheuser et al., 2014; Kindler et al., 2014; Pop, 2014). Focusing on a profile section near the centre of the basin (HP7, Hauptprofil 7, or main profile 7), a recent multi-disciplinary study of Neumark-Nord 2 basin infill (Gaudzinski-Windheuser and Roebroeks, 2014) has produced detailed climatic and chronological proxy records (Figure 2). Results of these studies have shown that the archaeological find level NN2/2 (located to the north of HP7 and connected via an additional trench) dates to the early part of an interglacial (see Figure 2). The succession is constrained by the underlying diamicton, a glacial till of Late Saalian/Drenthe age (Eissman, 2002) and by the overlying Weichselian deposits, and attribution to the Eemian is clear from the pollen record and also from the positioning of the palaeomagnetic Blake Event in the Neumark-Nord 2 deposits (Bakels, 2014; Sier et al., 2015; Sier et al., 2011). Amino acid racemisation analysis of *Bithynia tentaculata* gastropod opercula at the site (Penkman in Sier et al., 2011) also suggest that the deposits are contemporaneous with those at the Amersfoort and Amsterdam basin in the Netherlands, the Eemian stratotype locality (e.g. Cleveringa et al., 2000; Van Leeuwen et al., 2000; Zagwijn, 1961). Thermoluminescence (TL) dating of heated flint artefacts from NN2/2b yielded a weighted mean age of 121±5 ka. Optically Stimulated Luminescence (OSL) on the overlying sands which contain the (archaeologically less rich) Neumark-Nord 2/0 (NN2/0) deposits gave a date of 93±7ka, confirming likely Weichselian placing in the climatostratigraphic framework (Richter and Krbetschek, 2014).
Figure 2: Stratigraphical subdivision and assignment of archaeological find levels in basin NN2 and its Weichselian cover sequence, showing the find levels adapted in this study, adapted from Pop and Bakels (2015: 77, Figure 5). Numbering of find layers and descriptive information after Hesse and Kindler (2014). Eemian vegetation succession (pollen zones) and water conditions from Pop and Bakels (2015). Thermoluminescence (TL) dates from Richter and Krbetschek (2014).

Sedimentological and soil micromorphological studies of the NN2 sections indicate a rapid infilling of the shallow basin with fine-grained calcareous silts, a near continuous process with very little evidence of soil formation during periods of non-deposition (Mücher, 2014). Malacological and botanical studies...
demonstrate that the shallow basin contained water most of the time, and characteristic laminations in deeper parts of the sequence are consistent with repetitive seasonal rainfall (Gaudzinski-Windheuser et al., 2014: 35). Pollen are well preserved in the Eemian deposits, with the small basin (90m NE-SW by 60m NW-SE at its largest extent, Hesse and Kindler, 2014) likely reflecting strictly local vegetation. Palynological data from HP7 demonstrate an interglacial succession that is typical for the Eemian interglacial in northern Europe (see Figure 2), the succession starting with Pollen Assemblage Zone (PAZ) I and ending with PAZ VI/VII, (cf. Menke and Tynni, 1984) at the top of the sections (Bakels, 2014; Pop and Bakels, 2015). Palynological analyses situate NN2/2 in the Quercus-Corylus phase of the Eemian, a vegetation phase that lasted ~1150 years (Bakels, 2014; Menke and Tynni, 1984), while the rich NN2/2b find material accumulated over a period of maximally 500 years. An additional archaeological find level NN2/1c overlies NN2/2 in the NN2 basin (see Figure 2), and can be positioned within the somewhat later Corylus phase of the Eemian interglacial, and is thus maximally 2,000 years younger than the NN2/2 assemblage (Bakels, 2014; Menke and Tynni, 1984).

Excavations in find complex NN2/2 (and especially of find-rich Level 2/2b) uncovered the remains of more than 154 large herbivores as well as ~18,000 lithic artefacts and abundant traces of the presence of fire (Pop et al., 2016). The faunal record is dominated by large sized mammals and typical of Eemian fauna; aurochs (Bos primigenius) and horse (Equus sp.), as well as medium sized cervids such as red deer (Cervus elaphus) and fallow deer (Dama dama geiselana). The assemblage also includes straight-tusked elephant (Elephas
antiquus) and rhinoceros (Stephanorhinus sp.), giant deer (Megaloceros giganteus), bear (Ursus sp.), lion (Panthera leo spelaea) and wolf (Canis lupus) (Kindler et al., in press). Bones show abundant traces of butchery and marrow extraction, indications that they are the product of hominin (Neanderthal) activity (Gaudzinski-Windheuser et al., 2014; Kindler et al., 2014). The diverse faunal assemblage, particularly of NN2/2b, likely reflects a diverse or mosaic landscape, with both open, forested and lacustrine habitats. A previous study of carbon and nitrogen stable isotope data from well-preserved bone collagen extracted from horse and bovid bone from archaeological find Level 2/2 suggests niche feeding differences between these species and further attest to the mosaic or semi-open environment at this time (Britton et al., 2012; Britton et al., 2014). Higher up in the sequence, in addition to lithic artefacts, a smaller amount (<5000 pieces) of highly fragmented, intensively weathered and abraded bone was uncovered from NN2/1c, with anthropogenic marks on some bone surfaces (Kindler et al., in press). Still higher up, at the base of the Weichselian loess sequence, the faunal assemblage from find complex NN2/0 comprised approximately 8,000 fragments, including the remains of equids, bovids and cervids, and limited other mammalian species, such as bear, beaver, and fox, along with micromammals and mollusc species (Wijnand, 2008). All three of the find levels discussed above (NN2/2b, NN2/1c and NN2/0) contained the remains of equids, including teeth.

The reconstruction of mean annual temperatures (MATs) at Neumark-Nord 2, making use of the abundant faunal record at the site, will provide valuable palaeoclimatic proxy data for this region and provide climatic context for the
Neanderthal exploitation of continental European interglacial (NN2/2b, NN2/1c) as well as early Weichselian (NN2/0) environments. Significantly, the bioapatite $\delta^{18}O_{PO_4}$ data from NN2/2b will be compared directly to other sources of site-specific palaeoclimate proxy evidence for the early Eemian, allowing the assessment of this approach. Given the sparsity of other palaeoclimatic evidence in find levels NN2/1c and NN2/0 (compared to NN2/2), data from these find levels will provide refined insights into prevailing MATs in the later early Eemian and in the early Weichselian, and thus a better context for the interpretation of hominin behaviours and Neanderthal adaptations in this region.

3. Materials and Methods

3.1 Sampling strategy

Due to high level of anthropogenically-induced fragmentation of the Neumark faunal assemblages, samples selected for analysis comprised mostly of loose horse (*Equus* sp.) cheek teeth. Horses were selected as they are obligate drinkers, and therefore more likely to record water-isotope inputs with a greater fidelity. Furthermore, ontogenetic development patterns on juvenile bones and teeth in the NN2/2 assemblage, as well as estimates for ungulate biomass production, suggest the perennial presence of horses in the vicinity of the lake basins during the first half of the Eemian (García-Moreno et al., 2015; Kindler et al., 2015; Kindler et al., in press; Smith et al., 2015). Their tissues, therefore, are more likely to reflect local drinking water values than potentially migratory species would. As lactate is enriched relative to body water in mammals, the second premolar (P2) and third molar (M3) were preferentially selected.
wherever possible as they form/mineralise post-weaning (Hoppe et al., 2004).

Furthermore, these teeth can be easily differentiated from other, earlier forming cheek teeth. In cases of poor physical preservation (i.e. where teeth were heavily fragmented), the tooth could not be identified but was also sampled in order to maximise sample size for each find level (see Table 1). While efforts were made to ensure duplicate samples were not taken (e.g. by maximising spatial distance between samples within levels), it is acknowledged that this sampling strategy could have resulted in multiple teeth originating from the same individuals.

Tooth samples were prepared for isotopic analysis in the Archaeological Chemistry Laboratories, Max Planck Institute for Evolutionary Anthropology (Department of Human Evolution), Leipzig, Germany. The buccal face of the anterior loph of each tooth was preferentially selected for sampling, and was mechanically abraded ahead of sampling using a tungsten carbide burr (NTI-Kahla, Germany) to mechanically clean external surfaces. Whole teeth were then ultrasonicated in double-distilled deionized water (Milli-Q®, 18.7 MΩ) for 5 minutes to remove any adhering powder residue and air dried prior to sampling.

In all teeth enamel was removed as powder using clean burrs, sampled to almost it's full depth (with care taken to avoid enamel directly at enamel-dentine junction and dentine itself), from an area of approximately ~1 cm (horizontal width) by ~3-3.5 cm (vertical height). This sampling area was selected to ensure that oxygen isotope data generated from each tooth were comparable and represented a full year of growth in each tooth and each individual selected
Horse teeth, like those of other hypsodont herbivores, form over an extended period, with tooth mineralization for individual teeth being between ~1.5 and ~2.8 years, depending on the tooth type (Hoppe et al., 2004: 362). While this can be advantageous during intra-tooth sampling (for the reconstruction of seasonality), this variability must be accounted for (and, ideally, removed) in ‘bulk’ sampling. A smaller sampling region would represent material formed over only a few months of the year introducing a seasonal bias in isotopic data and likewise would a sampling region spanning the full crown height (where it was considerably longer than 3.5 cm) and more than one year of growth. In the case of the M3 and P2, for example, ~3 cm and ~3-4 cm vertical height of enamel should be sampled respectively to ensure isotopic values roughly represent one year of isotopic inputs (Hoppe et al., 2004: 363). These estimates are consistent with empirical data from other oxygen isotope studies in equids (e.g. Bendrey et al., 2015; Sharp and Cerling, 1998; Trayler and Kohn, 2017).

3.2 Analytical protocols

Powdered enamel samples were prepared for phosphate oxygen isotope analysis following methods described in Britton et al. (2015), after Tütken et al. (2006) and based on O'Neil et al. (1994) and Dettmann et al. (2001: Appendix, GSA Data Repository item 20018). In brief, powdered samples (~10 mg) were pretreated with 30% hydrogen peroxide (H₂O₂; 40 µl/1 mg of enamel powder) at room temperature for 24 hrs, before being rinsed in Milli-Q ultrapure water (x4) and dried (24 hrs, 50 °C). Dried samples were dissolved in 0.8 ml 2M HF and agitated in solution for 24 hrs at room temperature. In each instance, the
resultant phosphate solution was separated from the CaF$_2$ residue and the indicator Bromothymol Blue (1 drop), was added to each sample (yellow: acidic solution). Samples were then neutralized using 25 % ammonia solution (NH$_4$OH) was added until a colour change (yellow to green) was observed (~180 µl). 0.8 ml of 2 M silver nitrate (AgNO$_3$) was then added to each sample, forming the yellow silver phosphate precipitate (Ag$_3$PO$_4$). The precipitate was separated by centrifugation, the liquid fraction was discarded, and the precipitate was rinsed 4x with Milli-Q water, and dried for 24 hrs at 50 °C. The silver phosphate was then weighed into silver capsules for oxygen isotope analysis. Aliquots of NBS 120c were also prepared alongside the samples. NBS 120c, although not certified for oxygen isotope values, is an international standard material commonly used in many laboratories as a reference material during phosphate oxygen isotope analysis as its composition and matrix is more similar to biogenic apatite than other reference materials (Chenery et al., 2010: 159).

Phosphate $\delta^{18}$O values were determined by CF-IRMS, measured with a Thermo-Fisher TC-EA connected to a Finnigan Delta Plus XL mass spectrometer, at the Department of Geochemistry, University of Tübingen, Germany. Mean values and standard deviations (1 s.d.) were provided by the analysing laboratory, calculated from the analysis of each sample in triplicate (Table 1). In some instances, these values were provided from duplicate measurements, due to sample size, sample loss, loss of sample integrity or through internal data quality control checks in Tübingen (for exceptions, see Table 1). Long-term laboratory reproducibility was reported as ± 0.3 ‰ (1 s.d.),
while mean reproducibility for the samples analysed in this study was ± 0.2 ‰ (1 s.d.) or better. Samples were calibrated to $\delta^{18}O_{\text{PO}_4}$ values using internal standards, including TU-1 ($\delta^{18}O_{\text{PO}_4} = 21.11$ ‰ V-SMOW); TU-2 ($\delta^{18}O_{\text{PO}_4} = 5.35$ ‰ V-SMOW) and 130-0.5-1 ($\delta^{18}O_{\text{PO}_4} = -1.13$ ‰ V-SMOW). Repeat analysis of NBS120c prepared alongside samples analysed here ($n=4$) gave a mean $\delta^{18}O_{\text{PO}_4}$ value of 21.40±0.52 ‰ (1σ), which is within error of the mean reported values from 19 previous publications (cited in Chenery et al. 2010: Table A3, 161; 21.7±0.5 ‰ (1σ)) although slightly lower than weighted mean value reported in a recent inter-laboratory calibration (21.79±0.15 ‰ (1σ); Halas et al., 2011: 582).

3.3 Conversion equations and air temperature estimates

The generation of estimated air temperature values ($^\circ$C) from mammalian skeletal bioapatite $\delta^{18}O$ is underlain by a number of assumptions (primarily based on local environmental and landscape hydrology, and the drinking behaviour of the species in question), and is contingent on the use of conversion equations, initially to estimate drinking water $\delta^{18}O$ (i.e. assumed local precipitation $\delta^{18}O$) and then to estimate local temperature. For example, although there is a primary relationship between air temperature and $\delta^{18}O$ of precipitation, there are also (temperature-related) variations with season, as well as variations with altitude and latitude, as well as amount effects (Clark and Fritz, 1997; Dansgaard, 1964; Gat, 1980; Rozanski et al., 1993; Yurtsever, 1975). There may also be other local processes such as water mixing, water movement, groundwater recharge and evaporation processes that occur in
surface water bodies, which can influence the oxygen isotope composition of drinking water (making it distinct from local precipitation values). A water source (related to local precipitation values) and use of that water source by an obligate drinker is also an assumption in-built to use of faunal isotopic compositions as estimators of palaeoclimatic variables (see discussion in Pederzani and Britton, 2019).

In order to convert bioapatite $\delta^{18}O_{\text{PO}_4}$ values to $\delta^{18}O$ values of that water source, various empirical regression equations have been proposed, including for horses (Bryant et al., 1994; Delgado Huertas et al., 1995; Sánchez Chillón et al., 1994). Such equations are required given that isotopic fractionation occurs in the body as water is metabolised, enriching the biomineral in the heavier isotope relative to drinking water. Species-specific conversion equations are necessary primarily due to inter-specific differences in water dependency, diet and physiology (Kohn, 1996; Kohn et al., 1996; Levin et al., 2006), although in-built within the application of these to archaeological materials is the assumption that fractionation factors established for extant animals are applicable to Pleistocene ones. Furthermore, error ranges in such conversion equations can be high, and it has been argued that, because of this, errors in the conversion of $\delta^{18}O_{\text{bioapatite}} - \delta^{18}O_{\text{water}}$ could hamper their application to archaeological provenance studies in some circumstances. For example, where the total environmental variation of groundwater or meteoric water for a specific country is relatively small, such as in the United Kingdom, errors on $\delta^{18}O_{\text{water}}$ estimates must be substantially smaller than this range to permit meaningful regional allocations of place of origin (see Pollard et al., 2011).
Further calibration equations are then required to convert $\delta^{18}O_{\text{water}}$ (‰) to air temperature estimates ($^\circ$C). Multiple regression equations have been calculated and published based on data sets from modern water isotope monitoring stations, with each potentially generating slightly different predicted temperature values for any given $\delta^{18}O_{\text{precipitation}}$ value. Furthermore, due to error estimates within these conversion equations, the $\delta^{18}O_{\text{bioapatite}}$ to $\delta^{18}O_{\text{precipitation}}$ to air temperature conversions required to infer palaeoclimate are prone to further error propagation (Pryor et al. 2014). It should be noted that the use of conversions that utilise modern water isotope data correlations with contemporary air temperature assume that atmospheric circulation and the factors that determine the distribution of rain in any particular region of study today were similar during the late Pleistocene, which may or may not be the case (Skrzypek et al., 2011: 484). It should be noted, however, that the study of old groundwaters appear to confirm the stability of the temperature-$\delta^{18}O_{\text{precipitation}}$ relationship overtime (e.g. Rozanski, 1985; Rozanski et al., 1992; Zuber et al., 2004). Furthermore, general circulation model-proxy comparison studies have indicated that the European atmospheric circulation patterns during the Eemian were broadly comparable to today (Kaspar et al., 2005).

In light of the above, the use of these methodologies is not without its caveats. However, given the potential of isotope zooarchaeological approaches as proxies for site-specific palaeoclimatic conditions from terrestrial contexts contemporary to human site use, their usefulness should not be disregarded. As part of this study, a number of sampling decisions and analytical steps were devised to maximise the quality of data generated and to characterise and
quantify potential errors. Firstly, the selection of an obligate drinker (horse) increases likelihood that isotopic inputs from those water sources are recorded with greater fidelity in mineralised tissue. Dental sampling strategies were employed incorporating the known formation and mineralisation process of extant horses, and in order to minimise the influence of seasonal bias in an incrementally-developed tissue when characterising MAT (see Section 3.1 above). Furthermore, the sampling of multiple individuals from the same levels (see Table 1) was undertaken to reduce population-level uncertainty when using conversion equations (Pryor et al., 2014). It should be noted however that the diachronic nature of our study at a single site permits measured \(\delta^{18}O_{\text{bioapatite}}\) values to be compared at the site without the use of conversion equations, providing temporal (albeit relative) insights into climatic change. However, in order to estimate palaeotemperatures, conversion equations must be employed. Here we use the most recently published conversion equation for \(\delta^{18}O_{\text{PO}_4} - \delta^{18}O_{\text{drinking water}}\) for horses (Delgado Huertas et al., 1995, eq. 8: 4304, and following Pryor et al. 2014):

\[
\delta^{18}O_{\text{PO}_4} = 0.71(\delta^{18}O_{\text{drinking water}}) + 22.60
\]

\(R^2 = 0.77\)

For temperature conversions, we utilise the recently published conversion dataset for Europe and an inverted forward fit regression (Pryor et al., 2014:100, and Appendix A. Supplementary data sheet Z2).

\[
\delta^{18}O_{\text{precipitation}} = 0.53T_{\text{mean}} - 13.74
\]

\(R^2 = 0.60\)

We calculate and report errors on the data conversion following Pryor et al. (2014: Appendix A. Supplementary data). We chose inverted forward fit
regression as it mirrors the causal dependencies inherent in the system ($\delta^{18}O_{\text{water}}$ is contingent on $T \degree C$, and not *vice versa*) but we acknowledge the current debate regarding the calculation of palaeotemperatures using oxygen isotope data from mammalian bioapatite (see Skrzypek et al., 2016) and that alternative approaches have their own merits. For example, the transposed fit approaches can introduce lower overall errors and can permit the incorporation of data from multiple species (and their species-specific $\delta^{18}O_{\text{PO}_4}$–$\delta^{18}O_{\text{water}}$ regression models) from the same site (Skrzypek et al., 2016; Skrzypek et al., 2011).

4. Results and Discussion

4.1 ‘Bulk’ oxygen isotope data and palaeotemperature estimations

Horse tooth enamel phosphate oxygen isotope data ($\delta^{18}O_{\text{PO}_4}$) from Neumark-Nord 2 are shown in Table 1 and Figure 3.

Table 1: Horse tooth enamel $\delta^{18}O_{\text{PO}_4}$ data from early Eemian (NN2/2b, NN2/1c) and early Weichselian (NN2/0) find levels at Neumark-Nord 2, Germany. † denotes where mean oxygen isotope values and standard deviations are calculated from duplicate rather than triplicate measurements. Sup. = maxillary, inf. = mandibular; sin. = left; dex. = right.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Stratigraphic Level</th>
<th>Tooth sampled</th>
<th>Mean $\delta^{18}O_{\text{PO}_4}$ (‰)</th>
<th>stdev (± 1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14466.1</td>
<td>NN2/0</td>
<td>P/M sup.</td>
<td>14.1</td>
<td>0.4</td>
</tr>
<tr>
<td>14467.1</td>
<td>NN2/0</td>
<td>P/M sup.</td>
<td>15.3</td>
<td>0.1</td>
</tr>
<tr>
<td>15339.1</td>
<td>NN2/0</td>
<td>P/M</td>
<td>15.0</td>
<td>0.2</td>
</tr>
<tr>
<td>15340.1</td>
<td>NN2/0</td>
<td>P/M</td>
<td>16.3</td>
<td>0.0</td>
</tr>
<tr>
<td>15341.1</td>
<td>NN2/0</td>
<td>P/M</td>
<td>15.2</td>
<td>0.1</td>
</tr>
<tr>
<td>15342.1</td>
<td>NN2/0</td>
<td>P/M</td>
<td>14.5</td>
<td>0.3</td>
</tr>
<tr>
<td>16755</td>
<td>NN2/0</td>
<td>P/M</td>
<td>17.8</td>
<td>0.0</td>
</tr>
<tr>
<td>16756</td>
<td>NN2/0</td>
<td>P/M</td>
<td>15.0</td>
<td>0.1</td>
</tr>
<tr>
<td>16757</td>
<td>NN2/0</td>
<td>P/M</td>
<td>14.7</td>
<td>0.0</td>
</tr>
<tr>
<td>14465.1</td>
<td>NN2/1c</td>
<td>M3 sup. sin.</td>
<td>14.7</td>
<td>0.1</td>
</tr>
<tr>
<td>15233.1</td>
<td>NN2/1c</td>
<td>M3 sup. sin.</td>
<td>15.3</td>
<td>0.0</td>
</tr>
<tr>
<td>15335.1</td>
<td>NN2/1c</td>
<td>P3/P4 sup. sin.</td>
<td>16.0</td>
<td>0.2</td>
</tr>
<tr>
<td>15336.1</td>
<td>NN2/1c</td>
<td>P3/P4 inf. dex.</td>
<td>16.8</td>
<td>0.1</td>
</tr>
<tr>
<td>15337.1</td>
<td>NN2/1c</td>
<td>P3/P4 sup. sin.</td>
<td>15.6</td>
<td>0.1</td>
</tr>
<tr>
<td>15338.1</td>
<td>NN2/1c</td>
<td>P3/P4 sup. sin.</td>
<td>14.9</td>
<td>0.1</td>
</tr>
<tr>
<td>16758</td>
<td>NN2/1c</td>
<td>P/M</td>
<td>16.0</td>
<td>0.0</td>
</tr>
<tr>
<td>16759</td>
<td>NN2/1c</td>
<td>P/M</td>
<td>17.1</td>
<td>0.1</td>
</tr>
<tr>
<td>16760</td>
<td>NN2/1c</td>
<td>P/M</td>
<td>15.9</td>
<td>0.3</td>
</tr>
<tr>
<td>14459.1</td>
<td>NN2/2b</td>
<td>M3 inf. dex.</td>
<td>16.9</td>
<td>0.0</td>
</tr>
<tr>
<td>14460.1</td>
<td>NN2/2b</td>
<td>M3 sup. sin.</td>
<td>16.2</td>
<td>0.2</td>
</tr>
<tr>
<td>14461.1</td>
<td>NN2/2b</td>
<td>M3 sup. sin.</td>
<td>16.2</td>
<td>0.0</td>
</tr>
<tr>
<td>14462.1</td>
<td>NN2/2b</td>
<td>M3 sup. sin.</td>
<td>15.8</td>
<td>0.0</td>
</tr>
<tr>
<td>14463.1</td>
<td>NN2/2b</td>
<td>M3 sup. sin.</td>
<td>16.4</td>
<td>0.1</td>
</tr>
<tr>
<td>15332.1</td>
<td>NN2/2b</td>
<td>P2 sup. sin.</td>
<td>15.7</td>
<td>0.1</td>
</tr>
<tr>
<td>15333.1</td>
<td>NN2/2b</td>
<td>M3 sup. sin.</td>
<td>15.6</td>
<td>0.1</td>
</tr>
<tr>
<td>15334.1</td>
<td>NN2/2b</td>
<td>M3 sup. sin.</td>
<td>16.0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Figure 3: Horse tooth enamel $\delta^{18}$O$_{\text{PO}_4}$ data from Eemian (NN2/2b, NN2/1c) and Weichselian (NN2/0) find levels at Neumark-Nord 2, Germany. Equus sp. tooth types sampled and mean values per find complex are depicted (±1 s.d.) (calculated excluding 16755, see text for explanation).
The total range of enamel $\delta^{18}O_{PO4}$ values exhibited range from 14.1 to 17.8 ‰, with a mean of 15.7±0.9 ‰ (1 s.d.) for all data. Mean $\delta^{18}O_{PO4}$ values for each find level are: 16.1±0.4 ‰ (1 s.d.) for NN2/2b ($n$=8); 15.8±0.8 ‰ (1 s.d.) for NN2/1c ($n$=9); and 15.0±0.7 ‰ (1 s.d.) for NN2/0 ($n$=8, excluding sample 16755). It should be noted that, for NN2/0, one sample from an unidentified cheek tooth (16755) has a $\delta^{18}O_{PO4}$ value >17.5 ‰, which is substantially elevated compared to the rest of the dataset and may suggest this tooth formed pre-weaning (Britton et al., 2015; Wright and Schwarcz, 1998). Other explanations could also account for values measured in this outlier (e.g. diagenetic alteration, physiology, a different drinking water source, etc). Given that modern feral foals can nurse for ~9 months, and substantial portions of both the permanent first and second molars form during this period (Hoppe et al., 2004: 362), the former explanation is favoured. Indeed, pairwise comparisons of $\delta^{18}O_{milk}$-$\delta^{18}O_{water}$ of domestic cows have indicated milk values are ~4 ‰ elevated relative to those of water (Lin et al., 2003: 2191), suggesting offsets of a similar scale to those observed here. Whatever the underlying cause, we have chosen to exclude this data point from mean calculations and from palaeotemperature estimations in this paper.

Table 2: Mean enamel $\delta^{18}O_{PO4}$ values, mean calibrated $\delta^{18}O_{water}$ values and mean annual temperature (MAT) estimates for each of the find levels studied at Neumark-Nord 2, calculated excluding sample 16755 (after Delgado Huertas et al., 1995; Pryor et al., 2014). All standard errors are ± 1 s.d..
<table>
<thead>
<tr>
<th>Stratigraphic Level</th>
<th>n</th>
<th>Mean enamel $\delta^{18}O_{PO4}$ (‰)</th>
<th>stdev ($\pm 1\sigma$)</th>
<th>Mean calibrated $\delta^{18}O_{water}$ (‰)</th>
<th>Standard error ($\delta^{18}O_{PO4} - \delta^{18}O_{water}$)</th>
<th>Calibrated MAT (°C)</th>
<th>Standard error ($\delta^{18}O_{water} -$ MAT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NN2/0</td>
<td>8</td>
<td>15.0</td>
<td>0.7</td>
<td>-10.7</td>
<td>1.1</td>
<td>5.8</td>
<td>2.2</td>
</tr>
<tr>
<td>NN2/1c</td>
<td>9</td>
<td>15.8</td>
<td>0.8</td>
<td>-9.5</td>
<td>1.0</td>
<td>8.0</td>
<td>1.9</td>
</tr>
<tr>
<td>NN2/2b</td>
<td>8</td>
<td>16.1</td>
<td>0.4</td>
<td>-9.1</td>
<td>1.1</td>
<td>8.8</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Mean enamel $\delta^{18}O_{PO4}$ values for each find level studied at Neumark-Nord 2 are shown in Table 2 and, along with calibrated $\delta^{18}O_{water}$ values and the calibrated temperature estimates, in Figures 4 and 5 (Delgado Huertas et al., 1995; Pryor et al., 2014: Appendix A. Supplementary data). The error in data conversion to $\delta^{18}O_{water}$, and the compound error for the Mean Annual Temperature (MAT) conversions are also reported for the group means as an estimation of uncertainty (following Pryor et al., 2014: Appendix A. Supplementary data). The compound error of each temperature estimate gives an indication of the overall uncertainty of the temperature estimate which includes several different sources of uncertainty. This includes the uncertainty of regression lines, as well as the uncertainty of group means, which is also a function of sample size. The temperature reconstructions presented for the different find levels at Neumark-Nord 2 therefore vary slightly in their uncertainty due to differences both in sample size for each group, as well as the magnitude of uncertainty in the regression line around the value that is input into the regression.
Figure 4: Mean calibrated $\delta^{18}O_{\text{water}}$ values (based on $\delta^{18}O_{\text{PO4}}$ values of horse tooth enamel) from find levels at Neumark-Nord 2. Data were calculated using the conversion equation in Delgado Huertas et al. (1995), and following the recommendations detailed in Pryor et al. (2014). Standard errors are ± 1 s.d.
Figure 5: Mean calibrated annual temperature estimations (based on δ18OPO4 values of horse tooth enamel) from find levels at Neumark-Nord 2. Data were converted from estimated mean δ18Owater values, utilising the dataset and following the recommendations of Pryor et al. (2014: Appendix A. Supplementary data). Standard errors are ± 1 s.d.. Approximate modern MAT for this region (AD 1961-1990) is depicted as a dashed line (Döring and Borg, 2008).

For NN2/2b (early Eemian; 121±5 ka) the mean annual temperature estimation based on horse tooth enamel phosphate oxygen data is 8.8±2.1 °C. For NN2/1c (also early Eemian) the mean annual temperature estimation is 8.0±1.9 °C. For NN2/0 (early Weichselian; 93±7ka) the mean annual temperature estimation is 5.8±2.2 °C.

The region surrounding Neumark-Nord 2 today has a mean annual temperature of ~9 °C (based on data from Halle, AD 1961-1990, from Döring and Borg, 2008), and data presented here indicate that a similar MAT may have
characterised the climate of the early Eemian in this area. These estimations are at the lower end of those based on other proxies, such as palaeobotanical and coleopteran data which suggest both summer and winter temperatures may have been several degrees warmer than today (Aalbersberg and Litt, 1998; Zagwijn, 1996), but – given the relatively large standard deviations of the estimates – are well within the range anticipated MAT values. In contrast, MATs in early Weichselian find level NN2/0 at Neumark-Nord in this study are estimated to be substantially lower than those in the Eemian find levels at the same site, by between approximately 2 to 3 °C. However, the large error margins should be noted on these estimates, which are in part an artefact of the conversion equations and methodology employed (see above), with inverse forward fit employed here generating larger errors than some other approaches (Skrzypek et al., 2016).

4.2 Correlations with site-specific climate proxies and other datasets

The milder climate during the early Eemian at Neumark-Nord 2 (NN2/2b and NN2/1c), indicated by the bulk oxygen isotope data presented here, correlates well with other site-specific climatic proxies. Palynological studies have designated find levels NN2/2b and NN2/1c as belonging to the IVa2 Quercus-Corylus and IVb2 Corylus phases of the Eemian vegetation sequence respectively (Pop and Bakels, 2015: 77), and the mild climate during the interglacial in particular is emphasised by the presence of Hedera (Ivy), Ilex (Holly) and Viscum (mistletoe) (Bakels, 2014). These phases also correlate with periods of increased presence of water at the shallow lake (Pop and Bakels,
2015: 77, Fig. 7), the result of seasonal rainfalls (Gaudzinski-Windheuser et al., 2014).

The warm-temperate faunal assemblage is also consistent with the MATs estimated here. Horse, in particularly, were an important species in Neanderthal subsistence strategies at the site and recent ontogenetic aging data of horse remains from the site suggest they were hunted all year round (Kindler et al., 2015; Smith et al., 2015). This may indicate that not only were MATs favourable, but also that seasonal temperature variations favoured year-round Neanderthal occupation of this area. This is supported by other proxy evidence for climate in the early Eemian in northern Germany, where the multivariate analysis of pollen and plant macrofossil data has indicated warm summer temperatures (>19 °C) (Kühl et al., 2007).

The variability in horse enamel $\delta^{18}$O$_{PO4}$ values and thus temperature estimates between NN2/2b and NN2/1c suggest, however, that climate conditions may have both been fluctuating and possibly in decline during the early Eemian at this location. The identification of the palaeomagnetic signal of the Blake-event in the Neumark-Nord 2 sequence allowed Sier et al. (2011) to correlate this high-resolution terrestrial record to the marine record. They suggest that the beginning of the Eemian interglacial as documented at NN2 occurred not simply after the major global ice sheets had melted, but considerably later, when sea levels had already begun to drop and substantial continental ice was once again accumulating. Our findings of a (slight) temperature decline during the early Eemian could be used in support of this interpretation. However, the relatively
small differences both in measured phosphate values and temperature estimates between NN2/2b and NN2/1c, coupled with the large (and overlapping) error ranges elicit caution.

While differences in MATs determined in Eemian and Weichselian find levels from Neumark-Nord 2 in this study are evident (~3 °C), the scale of these differences are at the lower end of those estimated from pollen/plant macrofossils in northern Germany (~4 °C, see Kühl et al., 2007) and not as vast as those differences estimated from $\delta^{18}$O measurements of bulk carbonates from lacustrine sediments at nearby Gröbern, 50 km north of Leipzig (6-11 °C, Eemian to early Weichselian) (Litt et al., 1996). However, the early Weichselian featured both stadial and interstadial, marked by strong climatic oscillations (Litt et al., 1996), and the oxygen isotope data from NN2/0 presented here may be consistent with milder intervals around that specific period of site-use (93±7 ka; Richter and Krbetschek, 2014, likely MIS 5c/Amersfoort/Brörup-Interstadiial). This is consistent with the lack of strictly cold-adapted species at Neumark-Nord 2/0, such as reindeer. It can be noted that mean annual water isotope and temperature estimates from early Weichselian Neumark-Nord 2 are also consistent with those from the early Weichselian levels at the open-air site of Hallera Avenue near Wroclaw, Poland (MIS 5d-a; ~115-74,000 yr BP). In the Hallera Avenue study tooth samples from multiple mid-sized and large herbivore species were targeted (bovids, horses, mammoths and rhinoceros), providing an estimated $\delta^{18}$O<sub>water</sub> mean of -10.7 ± 0.8 ‰, identical to that calculated from NN2/0 in this study (Table 2). While Skrzypek et al (2011) calculate a MAT of 6.8 ± 1.5 °C, 1 °C higher than that calculated for NN2/0 from
the same predicted water value (a product of the different regression methods/reference datasets used), both estimates are elevated relative to previous estimates based on pollen studies for the region. These observed differences – between temperature estimates from faunal oxygen isotope data and using local/regional climate archives – at both of these Central European sites (Neumark-Nord and Hallera Avenue) highlight the value of the isotope zooarchaeological approach in evidencing conditions contemporary to hominin activity, and in highlighting human ecological and climatic preferences and/or tolerances.

4.3 Implications and further studies

For archaeologists, the limitations of the most commonly used global palaeoclimatic and palaeoenvironmental proxies lie with relating them to human activity at what are most often lower latitude terrestrial sites. The Greenland ice cores, for example, are a valuable, robust and continuous record of precipitation $\delta^{18}O$ at the site of ice accumulation (e.g. Dansgaard et al., 1993), but are neither temporally nor spatially directly relatable to activities at archaeological sites. Additional records that make use of natural incremental deposits more proximal to sites, such as lake varves, pollen cores, or speleothems provide complementary and valuable proxy datasets, however, relating any of these records to the timing of human activity at any given Pleistocene site is again challenging – not least given the uncertainties related to the most useful direct and indirect dating methods currently employed (see discussions in Skrzypek et al., 2011). However, the analysis of skeletal bioapatite from humanly modified animal bones at archaeological sites allows the reconstruction of
palaeothermic conditions contemporary to human presence and activity at the
location.

The analysis of horses or other obligate drinkers, such as bison, from other
sites could better inform about the climatic conditions surrounding Neanderthal
and early modern human presence in Europe. While intra-tooth analysis may
be useful for inferring seasonal conditions, for the estimation of MATs from
tooth enamel, sampling strategies must be employed that are sufficient to limit
potential seasonal bias. The potential of these approaches to reveal diachronic
changes in climate across individual archaeological sites is now becoming
clear, particularly when combined with other isotope approaches (e.g. Richards
et al., 2017), and spatial studies (utilising the same species across multiple sites
across a broader geographical area, and employing consistent sampling
strategies) should be undertaken to further explore the potential of these
techniques to characterise different contemporaneous climatic zones. Such an
approach could allow the testing and refining of recently proposed models of
Eemian climatic zones and their relationship to Neanderthal landscape-use
(Nicholson, 2017) by providing palaeotemperature estimates concurrent with
site-use. Site-specific proxy data that is concurrent to hominin activity, such as
that produced here, can provide more nuanced insights to the conditions
surrounding what may only have been short-lived and/or intensive occupations
of certain regions during these periods.

Ideally, isotope bioapatite studies should endeavour to maximise the number
of ‘bulk’ samples in reconstructing MAT (Pryor et al., 2014), although the
integration of limited intra-tooth sampling on some specimens would enhance such studies through providing valuable information about seasonal climatic variability (e.g. Bernard et al., 2009). At Neumark-Nord 2, for example, seasonal palaeotemperature estimations generated using such an approach could further help characterise the climatic conditions that may have favoured hominin activity at this site, and could be used to corroborate seasonal temperature amplitude differences between the Eemian and Weichselian in this region evidenced by other proxies (e.g. Hoffmann et al., 1998; Kühl et al., 2007; Walkling and Coope, 1996). Whole bone phosphate, which reflects averaged isotopic inputs over a number of years prior to death, also has great potential to provide estimates of ambient temperatures (Delgado Huertas et al., 1997; Stephan, 2000). However, further studies on bone, particularly on diachronic sites, are needed (Hedges et al., 2004), along with further considerations of appropriate pre-treatment methodologies (which may differ from tooth enamel) and the issue of diagenetic alteration.

While chronologically relating the data generated to long-term proxy datasets remains a challenge, comparisons with alternative datasets above, both on at Neumark-Nord 2 and on a broader level, emphasise the value of faunal bioapatite $\delta^{18}$O$_{PO_4}$ analysis as a complementary methodology in palaeotemperature estimation, particularly within archaeological studies. While Neumark-Nord 2 boasts different palaeoclimate proxy datasets, useful here in corroborating the results of this isotope study, for the majority of archaeological sites this is not the case. It is in these contexts that archaeofaunal oxygen isotope datasets will prove particularly useful. As well as further applications to
late Pleistocene contexts, future studies could consider the application of these techniques to older (e.g. Lower Palaeolithic) sites in Europe, as this could help inform the climatic conditions surrounding the earliest human inhabitations of Europe, particularly at the more northerly extremes/mid-latitudes of occupation (Hosfield, 2016), illuminating pre-modern human adaptive strategies and palaeoecology. Finally, as well as acquiring data from anthropogenic faunal assemblages, undertaking such analyses in archaeologically-sterile levels (e.g. natural accumulations such as hyena dens) could also be significant in that it could inform the climatic contexts that limited or even prohibited human presence.

5. Conclusions

In this study, phosphate oxygen isotope ($\delta^{18}$O$_{PO4}$) data generated from horse ($Equus$ sp.) tooth enamel at the Late Pleistocene archaeological site of Neumark-Nord 2 are used to reconstruct mean annual air temperatures (MATs) during the early Eemian and early Weichselian, contemporary to these different phases of Neanderthal activity at the site. Although the large compound errors and uncertainties inherent in the regressions utilised to ‘convert’ $\delta^{18}$O$_{PO4}$ to MAT are acknowledged here and elsewhere (e.g. Pryor et al., 2014; Skrzypek et al., 2016), the estimates for early Eemian MAT (~9 °C) at Neumark-Nord 2 do correlate well with other site-specific climate proxies. Palynological evidence, for example, indicates a mild climate during the interglacial, semi-open environmental conditions, and an increased presence of water in the shallow lake (Bakels, 2014; Pop and Bakels, 2015). The warm-temperate faunal assemblage and year-round exploitation of horses emphasise the ameliorate
early Eemian conditions at the site (Kindler et al., 2015; Smith et al., 2015). While limited, the oxygen isotope data from NN2/1c (also early Eemian, but chronostratigraphically later than the NN2/2 deposits) may suggest climatic variability during this period and a possible decline in temperatures during the course of the early Eemian.

Enamel oxygen isotope data from later phases of the site indicate the local MAT was approximately 3 °C lower by the early Weichselian (~93±7 ka). These estimates, and those generated from faunal bioapatite at other early Weichselian sites in this broader region of Central Europe (e.g. Skrzypek et al., 2011), exceed those indicated by other local and regional climate proxy datasets. This may indicate that the hominin activity that was responsible for the accumulation of these faunal remains may have been limited to more ameliorate stages at this part of the Weichselian glaciation. The generation of further types of site-specific palaeoclimate proxy data from Neanderthal sites in Central Europe, particular that which illuminates seasonal conditions, will be helpful in better characterising this.

As demonstrated here, dental tissues from obligate drinking large mammal species can be a useful source of palaeoclimate proxy data. This does not just extend to incremental sampling of teeth for palaeoseasonality (e.g. Bernard et al., 2009), but also the bulk sampling of dental tissues in order to reconstruct past MATs. However, while studies should endeavour to maximise sample size, it is imperative that a consistent approach to sampling, incorporating a year of growth (~3 to 3.5 cm vertical crown height for most late forming horse teeth), is
employed to avoid introducing seasonal biases in ‘bulk’ samples. The
similarities and differences between the new MAT data presented in this study
and other regional palaeoclimatic archives highlights the complementary value
of the isotope zooarchaeological approach. The analysis of archaeofaunal
remains can not only provide evidence of contemporary climatic conditions, but,
significantly, provides a link between those conditions and the past human
presence. While these archives produce highly punctuated records compared
to natural archives, and might be difficult to date across different sites, efforts
should be made to incorporate such analyses into archaeological and
palaeoanthropological studies, and to further integrate such data within other
proxy datasets and frameworks.

Acknowledgements

We thank Annabell Reiner (MPI-EVA) for technical and practical support with
preparation of samples and Bernd Steinhilber for the oxygen isotope
measurements of the silver phosphate samples at the Institut für
Geowissenschaften (Universität Tübingen); Thanks to the Landesamt für
Denkmalpflege und Archäologie, Sachsen-Anhalt, and Landesmuseum
Sachsen-Anhalt in Halle for providing samples; and to Geoff Smith (RGZM
Monrepos and MPI-EVA) for comments on earlier versions of this manuscript.
Financial support for the Neumark-Nord 2 excavations was provided by the
Lausitzer Mitteldeutsche Braunkohlengesellschaft mbH, the Landesamt für
Denkmalpflege und Archäologie Sachsen-Anhalt (Harald Meller, Susanne
Friederich), the Römisch-Germanisches Zentrummuseum Mainz, the Leids
Universiteits Fonds “Campagne voor Leiden” program and the
Netherlands Organization for Scientific Research (N.W.O.). The isotope research was funded by the Max Planck Institute and a Deutscher Akademischer Austausch Dienst Junior Research Grant to KB (ref: A0970923). Thanks also to the University of Aberdeen, and The Leverhulme Trust (RPG-2017-410) for financial and professional support during this project and preparation of the manuscript. TT acknowledges funding by the German National Science foundation in the framework of the Emmy Noether Program (DFG grant TU 148/2-1 “Bone Geochemistry”).
References


Cleveringa, P., Meijer, T., Van Leeuwen, R.J.W., De Wolf, H., Pouwer, R.,
Lissenberg, T., Burger, A.W., 2000. The Eemian type locality at Amersfoort in
the central Netherlands: redeployment of old and new data, in: Van
Kolfschoten, T., Gibbard, P.L. (Eds.), The Eemian – local sequences, global
perspectives, pp. 197-216.
Dahl-Jensen, D., Albert, M.R., Aldahan, A., Azuma, N., Balslev-Clausen, D.,
Baumgartner, M., Berggren, A.M., Bigler, M., Binder, T., Blunier, T.,
Bourgeois, J.C., Brook, E.J., Buchardt, S.L., Buizert, C., Capron, E.,
Chappellaz, J., Chung, J., Clausen, H.B., Cvijanovic, I., Davies, S.M.,
Ditlevsen, P., Eicher, O., Fischer, H., Fisher, D.A., Fleet, L.G., Gfeller, G.,
Gkinis, V., Gogineni, S., Goto-Azuma, K., Grinsted, A., Gudlaugsdottir, H.,
Guillevic, M., Hansen, S.B., Hansson, M., Hirabayashi, M., Hong, S., Hur,
S.D., Huybrechts, P., Hvidberg, C.S., Iizuka, Y., Jenk, T., Johnsen, S.J.,
Jones, T.R., Jouzel, J., Karlsson, N.B., Kawamura, K., Keegan, K., Kettner,
E., Kipfstuhl, S., Kjær, H.A., Koutnik, M., Kuramoto, T., Köhler, P., Laepple,
T., Landais, A., Langen, P.L., Larsen, L.B., Leuenberger, D., Leuenberger, M.,
Leuschen, C., Li, J., Lipenkov, V., Martinerie, P., Maselli, O.J., Masson-
Delmotte, V., McConnell, J.R., Miller, H., Mini, O., Miyamoto, A., Montagnat-
Rentier, M., Mulvaney, R., Muscheler, R., Orsi, A.J., Paden, J., Panton, C.,
Pattyn, F., Petit, J.R., Pol, K., Popp, T., Possnert, G., Prié, F., Prokopiou, M.,
Quinet, A., Rasmussen, S.O., Raynaud, D., Ren, J., Reutenauer, C., Ritz,
C., Röckmann, T., Rosen, J.L., Rubino, M., Rybak, O., Samyn, D., Sapart,
C.J., Schilt, A., Schmidt, A.M.Z., Schwander, J., Schüpbach, S., Seierstad, I.,
Severinghaus, J.P., Sheldon, S., Simonsen, S.B., Sjolte, J., Solgaard, A.M.,
Sowers, T., Sperlich, P., Steen-Larsen, H.C., Steffen, K., Steffensen, J.P.,
Steinhage, D., Stocker, T.F., Stowasser, C., Sturevik, A.S., Sturges, W.T.,
de Wal, R.S.W., van der Wel, G., Vaughn, B.H., Vinther, B., Waddington, E.,
Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup,
N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjörnsdottir, A.E.,
Jouzel, J., Bond, G., 1993. Evidence for general instability of past climate
of fossil mammal remains from the Paglicci cave, southern Italy, 13 to 33 ka
Delgado Huertas, A., Iacumin, P., Stenni, B., Sánchez Chillón, B.S.,
Dettman, D.L., Kohn, M.J., Quade, J., Ryerson, F.J., Ojha, T.P., Hamindullah,
S., 2001. Seasonal stable isotope evidence for a strong Asian monsoon
throughout the past 10.7 m.y. Geology 29, 31-34.
Döring, J., Borg, H., 2008. Ist das Klima von Halle (Saale) noch „normal“?
Betrachtungen anhand der Temperatur- und Niederschlagsreihe von 1851 bis
heute. Hercynia-Ökologie und Umwelt in Mitteleuropa 41 3 –21.


Velivetskaya, T.A., Smirnov, N.G., Kiyashko, S.I., Ignatiev, A.V., Ulitko, A.I., 2016. Resolution-enhanced stable isotope profiles within the complete tooth rows of Late Pleistocene bison (Middle Urals, Russia) as a record of their individual development and environmental changes. Quat. Int. 400, 212-226.


Tertiary sands derived from combined isotope, noble gas and chemical data.

J. Hydrol 286, 87-112.