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

7

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29 Highlights:

- 30 • *Equus* sp. enamel was sampled from Neumark-Nord 2 (find levels  
31 NN2/2b, 2/1c, 2/0)
- 32 •  $\delta^{18}\text{O}_{\text{PO}_4}$  data were generated in order to estimate mean annual air  
33 temperature (MAT)
- 34 • early Eemian ( $\sim 121 \pm 5$  ka) MAT estimates are  $\sim 9$  °C, correlating with  
35 other proxies
- 36 • early Weichselian ( $\sim 93 \pm 7$  ka) MAT was  $\sim 6$  °C, elevated compared to  
37 other proxies
- 38 • implications for archaeology and Neanderthal-environmental  
39 interactions are explored

40

41 Author contributions:

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

52 **Abstract**

53 Here we present phosphate oxygen isotope ( $\delta^{18}\text{O}_{\text{PO}_4}$ ) data from horse (*Equus*  
54 sp.) tooth enamel (bioapatite) from the early Eemian and early Weichselian find  
55 levels at the archaeological site of Neumark-Nord 2, Germany. Based on the  
56 relationship between  $\delta^{18}\text{O}_{\text{PO}_4}$  of bioapatite, body water, local precipitation and  
57 air temperature, these data are used to reconstruct palaeoclimatic conditions  
58 contemporary to the different phases of Neanderthal activity at the site. Bulk  
59 enamel samples representing one year of growth were taken from horse teeth  
60 from early Eemian (NN2/2b [ $\sim 121 \pm 5$  ka], and NN2/1c) and early Weichselian  
61 (NN2/0;  $\sim 93 \pm 7$  ka) find levels, and  $\delta^{18}\text{O}_{\text{PO}_4}$  values were then utilised to calculate  
62  $\delta^{18}\text{O}$  of local environmental water and mean annual air temperature (MATs)  
63 during these phases of MIS5. Results indicate that during the early Eemian  
64 MAT was  $\sim 9$  °C, with some evidence of variability through time. Although  $\sim 3$  °C  
65 lower, the calculated early Weichselian MAT exceeds that indicated by other  
66 local and regional climate proxy datasets, suggesting that Neanderthal activity  
67 may have been limited to more ameliorate phases of the early Weichselian in  
68 this area.

69

70 **Keywords:** Pleistocene; Paleoclimatology; Europe; Stable isotopes;  
71 Bioapatite; Phosphate; Neanderthal; Last Interglacial; Interstadial

72

73

74

75 **1. Introduction**

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

90

91 Ice core oxygen isotope data ( $\delta^{18}\text{O}$ ) provide a high-resolution record of Middle  
92 and Late Pleistocene climatic change, confirming and refining climatic  
93 information obtained from deep-sea marine sediment cores (Brook and Buizert,  
94 2018; Dahl-Jensen et al., 2013; Rasmussen et al., 2014; Seierstad et al., 2014).  
95 However, although these systems provide evidence of polar and global marine  
96 trends, the influence of these large-scale climatic and environmental changes  
97 in continental contexts varies geographically; this requires further  
98 characterisation in many regions and calls for the establishment of regional  
99 climatic records. Most notably, proxy or measurement-based studies on

100 geographical variation in  $\delta^{18}\text{O}$  of precipitation (directly related to local  
101 palaeotemperature) are rare. The gaining of inland, region-specific data is  
102 essential to the interpretation of human and animal responses to climatic  
103 variations, as well as to the construction of a palaeoclimatic record within a fully  
104 terrestrial framework. Such data are particularly important in understanding the  
105 broader climatic context of expansion and contraction of the Neanderthal  
106 geographic range (Hublin and Roebroeks, 2009) or that of early anatomically  
107 modern human expansions into central and more northerly Europe during the  
108 Late Pleistocene. The Neanderthal exploitation of semi-open or forested  
109 interglacial environments has been particularly contentious (see Pop and  
110 Bakels, 2015 and references therein), and thus environmental and temperature  
111 reconstructions at archaeological sites unambiguously dating to the Eemian  
112 interglacial (as well as at contrasting glacial sites) are particularly valuable.

113

114 Like today, the Last Interglacial, the Eemian (~121 to 109 ka in N-W Europe,  
115 see Sier et al., 2015; Sier et al., 2011), was characterised by reduced terrestrial  
116 ice volume relative to glacial periods and increased temperatures, recorded in  
117 ice core data (EPICA community members, 2004) and a minimum in benthic  
118  $\delta^{18}\text{O}$  values in marine sediment cores (Lisiecki and Raymo, 2005). However,  
119 the Eemian climate – both globally and locally – may have differed from the  
120 current interglacial. A compilation of terrestrial and marine records indicates  
121 global temperatures were ~1.5 °C warmer than in the mid- and late 20<sup>th</sup> century  
122 AD (AD 1961-1990, see Turney and Jones, 2010). The maximum annual mean  
123 warming is thought to have occurred in mid- and high- (Northern Hemisphere)  
124 latitudes (Turney and Jones, 2010), associated with changes in vegetation

125 patterns and characterised by warm summer temperatures. However, spatial  
126 (and temporal) variation was likely high, and competing proxies have resulted  
127 in varying estimations at similar locales (see review in Turney and Jones, 2010).

128

129 There are a number of geochemical methods that can be used to reconstruct  
130 continental palaeotemperatures based on the oxygen isotope analysis of  
131 incrementally growing minerals and biominerals. These approaches include the  
132 analysis of geological archives such as speleothems (e.g. Drysdale et al., 2005;  
133 McDermott et al., 1999; Vansteenberge et al., 2019), as well as biogenic hard  
134 tissues including shells of bivalves or other molluscs (e.g. Goodwin et al., 2003;  
135 Latal et al., 2006; Schöne et al., 2004), or mammal bone and tooth (see review  
136 in Pederzani and Britton, 2019). These methods are based on the relationship  
137 between the oxygen isotope composition ( $\delta^{18}\text{O}$ ) of these biominerals and the  
138  $\delta^{18}\text{O}$  of local environmental water (Iacumin et al., 1996; Kohn, 1996; Longinelli,  
139 1984; Luz et al., 1984), which is related to the  $\delta^{18}\text{O}$  of precipitation, reflecting  
140 local temperature and other factors (Clark and Fritz, 1997; Dansgaard, 1964;  
141 Gat, 1980; Yurtsever, 1975). The relationship between the  $\delta^{18}\text{O}$  of local  
142 environmental water and (bio)mineral  $\delta^{18}\text{O}$  values is mediated by the  $\delta^{18}\text{O}$  of  
143 percolating ground water in the case of speleothems and body water in the case  
144 of vertebrate mineralised hard tissues. As homeothermic mammals have a  
145 metabolically-controlled, relatively constant body temperature ( $\sim 37^\circ\text{C}$ ),  
146 bioapatite (a carbonated hydroxyapatite) precipitates in oxygen isotope  
147 equilibrium with body water at this temperature (Levinson et al., 1987;  
148 Longinelli, 1984; Luz et al., 1984). While there is a roughly linear relationship  
149 between ingested water and body water, this varies between different species.

150 However, fractionation factors have been established for a number of extant  
151 species, including horses (e.g. Delgado Huertas et al., 1995). Local processes  
152 such as water mixing, water movement, groundwater recharge and evaporation  
153 processes that occur in surface water bodies can all influence the oxygen  
154 isotope composition of environmental water (and, by inference, drinking water).  
155 However, broad correlations between groundwater, mean annual precipitation,  
156 and climate at specific locales are universally apparent (see review in  
157 Pederzani and Britton, 2019). Therefore, the oxygen isotope analysis of  
158 mammalian bioapatite can be useful in the reconstruction of past climatic  
159 conditions, specifically palaeotemperatures.

160

161 A number of recent studies have utilised oxygen isotope analysis of herbivore  
162 teeth in palaeoclimatological investigations, in order to reconstruct  $\delta^{18}\text{O}$  values  
163 of past precipitation, mean annual palaeotemperatures and seasonal  
164 temperature variations (palaeoseasonality). Studies have included analysis of  
165 both the carbonate ( $\text{CO}_3$ ) and phosphate ( $\text{PO}_4$ ) components of tooth enamel,  
166 using a range of different Pleistocene mammals (Arppe and Karhu, 2010;  
167 Bernard et al., 2009; Bryant et al., 1996; Bryant et al., 1994; Delgado Huertas  
168 et al., 1997; Fabre et al., 2011; Fricke et al., 1998a; Fricke et al., 1998b; Koch  
169 et al., 1989; Kovács et al., 2012; Skrzypek et al., 2011; Velivetskaya et al.,  
170 2016). The oxygen isotope analysis of small mammals has proven useful in  
171 palaeoecological terrestrial contexts, for example, in the Late Eocene (Grimes  
172 et al., 2004). However, the use of anthropogenically-derived (archaeofaunal)  
173 assemblages of larger mammals are particularly useful for reconstructing past  
174 climatic conditions at archaeological sites as these remains are normally the

175 direct product of human activity: thus, they can provide insights into that activity  
176 or the prevailing conditions, and can therefore generate terrestrial  
177 palaeoclimate proxy data near-synchronous to human site-use (see  
178 discussions in Britton, 2017; Pederzani and Britton, 2019). As obligate drinkers  
179 with significant daily water requirements, and taxa found in both glacial and  
180 interglacial faunal assemblages, equids may be particularly useful for mapping  
181 past  $\delta^{18}\text{O}$  precipitation patterns and palaeoclimate conditions.

182

183 Here, we present  $\delta^{18}\text{O}_{\text{PO4}}$  data of horse enamel (*Equus* sp.) from the Middle  
184 Palaeolithic site of Neumark-Nord 2, Germany, in order to investigate  
185 precipitation  $\delta^{18}\text{O}$  values and MAT in the early Eemian and Weichselian in this  
186 area of central Europe. Within the context of the rich archaeological and  
187 palaeoenvironmental record of Neumark-Nord 2, we seek to integrate these  
188 data with other archaeological data and palaeoclimatic proxies, and explore the  
189 potential and limitations of isotope zooarchaeological approaches in  
190 archaeological and palaeoclimatic studies.

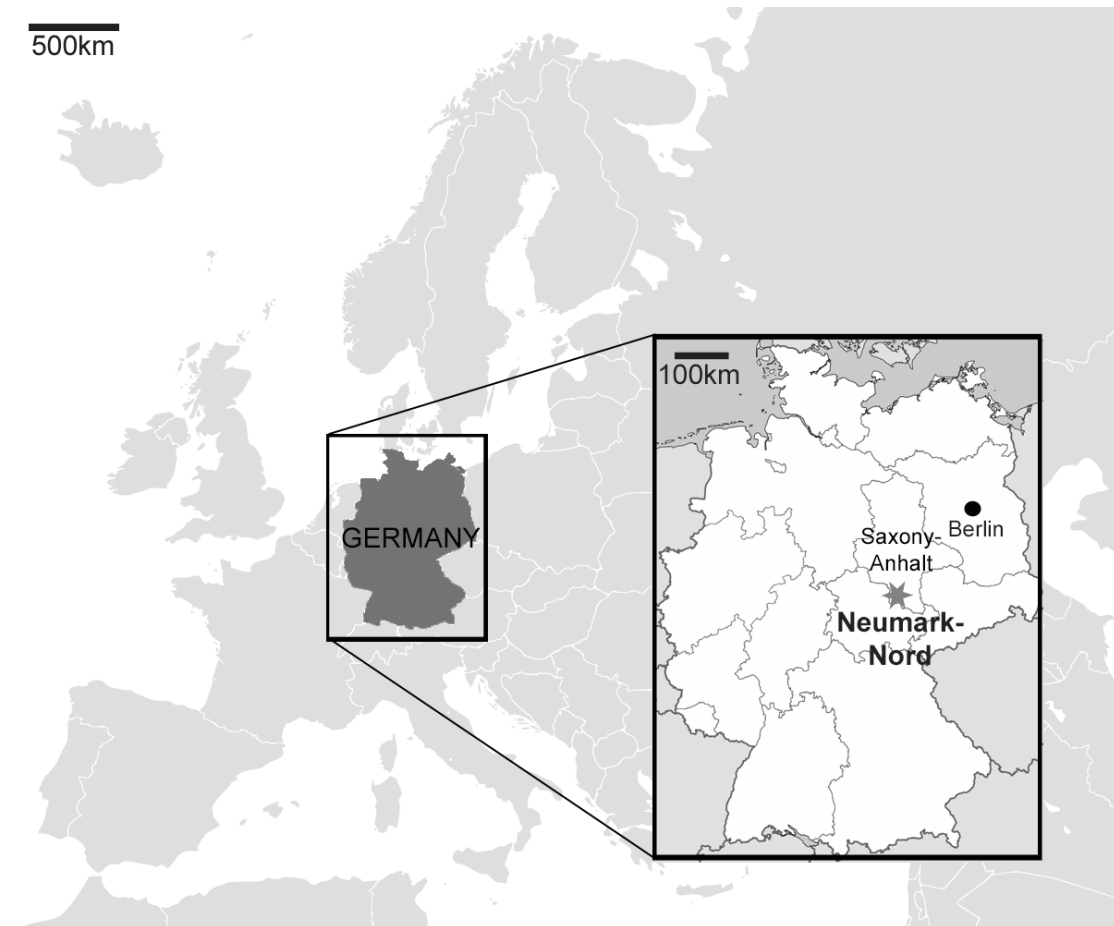
191

## 192 **2. The Site of Neumark-Nord 2, Germany**

193 The site of Neumark-Nord 2 is located approximately 35 km west of Leipzig in  
194 Saxony-Anhalt, Germany (51°19'28"N, 11°53'56"E; Figure 1).

195





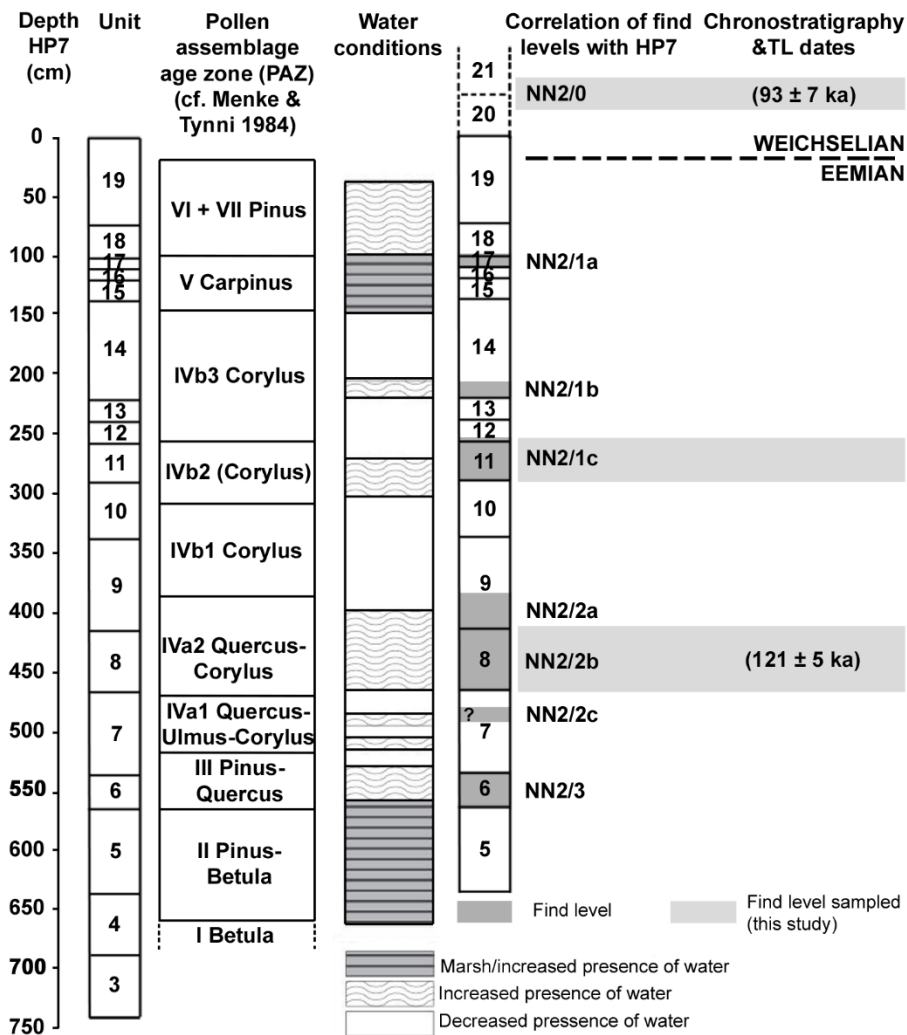
196

197 **Figure 1:** Geographical position of Neumark-Nord 2, Saxony-Anhalt, Germany.

198

199 First discovered in the 1980s, this area of the Geisel valley contains two Eemian  
200 basins, rich in archaeological, botanical and faunal remains, and which infills  
201 cover the complete last interglacial cycle. These basins include the large lake  
202 Neumark-Nord 1 (NN1; approximately 24 hectares) and the adjacent shallow  
203 pool Neumark-Nord 2 (NN2; ~1.6 hectares) (Gaudzinski-Windheuser et al.,  
204 2018; Gaudzinski-Windheuser and Roebroeks, 2014; Kindler et al., in press;  
205 Mania et al., 2010; Mania et al., 1990; Meller, 2010). In 2003, excavations  
206 commenced at Neumark-Nord 2, initially focusing on the early Weichselian  
207 levels (NN2/0) and then on the interglacial find horizon (NN2/2b). Extensive  
208 excavations were carried out at Neumark-Nord 2 between 2004 and 2008,

209 yielding around 20,000 Middle Palaeolithic flint artefacts and around 120,000  
210 faunal remains, dominated by warm-temperate species, specifically from the  
211 rich find level Neumark-Nord 2/2 (NN2/2, especially NN2/2b) (Gaudzinski-  
212 Windheuser et al., 2014; Kindler et al., 2014; Pop, 2014). Focusing on a profile  
213 section near the centre of the basin (HP7, Hauptprofil 7, or main profile 7), a  
214 recent multi-disciplinary study of Neumark-Nord 2 basin infill (Gaudzinski-  
215 Windheuser and Roebroeks, 2014) has produced detailed climatic and  
216 chronological proxy records (Figure 2). Results of these studies have shown  
217 that the archaeological find level NN2/2 (located to the north of HP7 and  
218 connected via an additional trench) dates to the early part of an interglacial (see  
219 Figure 2). The succession is constrained by the underlying diamicton, a glacial  
220 till of Late Saalian/Drenthe age (Eissman, 2002) and by the overlying  
221 Weichselian deposits, and attribution to the Eemian is clear from the pollen  
222 record and also from the positioning of the palaeomagnetic Blake Event in the  
223 Neumark-Nord 2 deposits (Bakels, 2014; Sier et al., 2015; Sier et al., 2011).  
224 Amino acid racemisation analysis of *Bithynia tentaculata* gastropod opercula at  
225 the site (Penkman in Sier et al., 2011) also suggest that the deposits are  
226 contemporaneous with those at the Amersfoort and Amsterdam basin in the  
227 Netherlands, the Eemian stratotype locality (e.g. Cleveringa et al., 2000; Van  
228 Leeuwen et al., 2000; Zagwijn, 1961). Thermoluminescence (TL) dating of  
229 heated flint artefacts from NN2/2b yielded a weighted mean age of  $121\pm 5$  ka.  
230 Optically Stimulated Luminescence (OSL) on the overlying sands which contain  
231 the (archaeologically less rich) Neumark-Nord 2/0 (NN2/0) deposits gave a date  
232 of  $93\pm 7$ ka, confirming likely Weichselian placing in the climatostratigraphic  
233 framework (Richter and Krbetschek, 2014).



234

235 **Figure 2:** Stratigraphical subdivision and assignment of archaeological find levels in basin NN2  
 236 and its Weichselian cover sequence, showing the find levels adapted in this study, adapted  
 237 from Pop and Bakels (2015: 77, Figure 5). Numbering of find layers and descriptive information  
 238 after Hesse and Kindler (2014). Eemian vegetation succession (pollen zones) and water  
 239 conditions from Pop and Bakels (2015). Thermoluminescence (TL) dates from Richter and  
 240 Krbetschek (2014).

241

242 Sedimentological and soil micromorphological studies of the NN2 sections  
 243 indicate a rapid infilling of the shallow basin with fine-grained calcareous silts,  
 244 a near continuous process with very little evidence of soil formation during  
 245 periods of non-deposition (Mücher, 2014). Malacological and botanical studies

246 demonstrate that the shallow basin contained water most of the time, and  
247 characteristic laminations in deeper parts of the sequence are consistent with  
248 repetitive seasonal rainfall (Gaudzinski-Windheuser et al., 2014: 35). Pollen are  
249 well preserved in the Eemian deposits, with the small basin (90m NE-SW by  
250 60m NW-SE at its largest extent, Hesse and Kindler, 2014) likely reflecting  
251 strictly local vegetation. Palynological data from HP7 demonstrate an  
252 interglacial succession that is typical for the Eemian interglacial in northern  
253 Europe (see Figure 2), the succession starting with Pollen Assemblage Zone  
254 (PAZ) I and ending with PAZ VI/VII, (cf. Menke and Tynni, 1984) at the top of  
255 the sections (Bakels, 2014; Pop and Bakels, 2015). Palynological analyses  
256 situate NN2/2 in the *Quercus-Corylus* phase of the Eemian, a vegetation phase  
257 that lasted ~1150 years (Bakels, 2014; Menke and Tynni, 1984), while the rich  
258 NN2/2b find material accumulated over a period of maximally 500 years. An  
259 additional archaeological find level NN2/1c overlies NN2/2 in the NN2 basin  
260 (see Figure 2), and can be positioned within the somewhat later *Corylus* phase  
261 of the Eemian interglacial, and is thus maximally 2,000 years younger than the  
262 NN2/2 assemblage (Bakels, 2014; Menke and Tynni, 1984).

263

264 Excavations in find complex NN2/2 (and especially of find-rich Level 2/2b)  
265 uncovered the remains of more than 154 large herbivores as well as ~18,000  
266 lithic artefacts and abundant traces of the presence of fire (Pop et al., 2016).  
267 The faunal record is dominated by large sized mammals and typical of Eemian  
268 fauna; aurochs (*Bos primigenius*) and horse (*Equus* sp.), as well as medium  
269 sized cervids such as red deer (*Cervus elaphus*) and fallow deer (*Dama dama*  
270 *geiselana*). The assemblage also includes straight-tusked elephant (*Elephas*

271 *antiquus*) and rhinoceros (*Stephanorhinus* sp.), giant deer (*Megaloceros*  
272 *giganteus*), bear (*Ursus* sp.), lion (*Panthera leo spelaea*) and wolf (*Canis lupus*)  
273 (Kindler et al., in press). Bones show abundant traces of butchery and marrow  
274 extraction, indications that they are the product of hominin (Neanderthal)  
275 activity (Gaudzinski-Windheuser et al., 2014; Kindler et al., 2014). The diverse  
276 faunal assemblage, particularly of NN2/2b, likely reflects a diverse or mosaic  
277 landscape, with both open, forested and lacustrine habitats. A previous study  
278 of carbon and nitrogen stable isotope data from well-preserved bone collagen  
279 extracted from horse and bovid bone from archaeological find Level 2/2  
280 suggests niche feeding differences between these species and further attest to  
281 the mosaic or semi-open environment at this time (Britton et al., 2012; Britton  
282 et al., 2014). Higher up in the sequence, in addition to lithic artefacts, a smaller  
283 amount (<5000 pieces) of highly fragmented, intensively weathered and  
284 abraded bone was uncovered from NN2/1c, with anthropogenic marks on some  
285 bone surfaces (Kindler et al., in press). Still higher up, at the base of the  
286 Weichselian loess sequence, the faunal assemblage from find complex NN2/0  
287 comprised approximately 8,000 fragments, including the remains of equids,  
288 bovids and cervids, and limited other mammalian species, such as bear,  
289 beaver, and fox, along with micromammals and mollusc species (Wijnand,  
290 2008). All three of the find levels discussed above (NN2/2b, NN2/1c and NN2/0)  
291 contained the remains of equids, including teeth.

292

293 The reconstruction of mean annual temperatures (MATs) at Neumark-Nord 2,  
294 making use of the abundant faunal record at the site, will provide valuable  
295 palaeoclimatic proxy data for this region and provide climatic context for the

296 Neanderthal exploitation of continental European interglacial (NN2/2b, NN2/1c)  
297 as well as early Weichselian (NN2/0) environments. Significantly, the bioapatite  
298  $\delta^{18}\text{O}_{\text{PO}_4}$  data from NN2/2b will be compared directly to other sources of site-  
299 specific palaeoclimate proxy evidence for the early Eemian, allowing the  
300 assessment of this approach. Given the sparsity of other palaeoclimatic  
301 evidence in find levels NN2/1c and NN2/0 (compared to NN2/2), data from  
302 these find levels will provide refined insights into prevailing MATs in the later  
303 early Eemian and in the early Weichselian, and thus a better context for the  
304 interpretation of hominin behaviours and Neanderthal adaptations in this  
305 region.

306

### 307 **3. Materials and Methods**

#### 308 *3.1 Sampling strategy*

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

321 wherever possible as they form/mineralise post-weaning (Hoppe et al., 2004).  
322 Furthermore, these teeth can be easily differentiated from other, earlier forming  
323 cheek teeth. In cases of poor physical preservation (i.e. where teeth were  
324 heavily fragmented), the tooth could not be identified but was also sampled in  
325 order to maximise sample size for each find level (see Table 1). While efforts  
326 were made to ensure duplicate samples were not taken (e.g. by maximising  
327 spatial distance between samples within levels), it is acknowledged that this  
328 sampling strategy could have resulted in multiple teeth originating from the  
329 same individuals.

330

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

339

340 In all teeth enamel was removed as powder using clean burrs, sampled to  
341 almost it's full depth (with care taken to avoid enamel directly at enamel-dentine  
342 junction and dentine itself), from an area of approximately ~1 cm (horizontal  
343 width) by ~3-3.5 cm (vertical height). This sampling area was selected to ensure  
344 that oxygen isotope data generated from each tooth were comparable and  
345 represented a full year of growth in each tooth and each individual selected

346 (Hoppe et al., 2004: 363). Horse teeth, like those of other hypsodont herbivores,  
347 form over an extended period, with tooth mineralization for individual teeth  
348 being between ~1.5 and ~2.8 years, depending on the tooth type (Hoppe et al.,  
349 2004: 362). While this can be advantageous during intra-tooth sampling (for the  
350 reconstruction of seasonality), this variability must be accounted for (and,  
351 ideally, removed) in 'bulk' sampling. A smaller sampling region would represent  
352 material formed over only a few months of the year introducing a seasonal bias  
353 in isotopic data and likewise would a sampling region spanning the full crown  
354 height (where it was considerably longer than 3.5 cm) and more than one year  
355 of growth. In the case of the M3 and P2, for example, ~3 cm and ~3-4 cm  
356 vertical height of enamel should be sampled respectively to ensure isotopic  
357 values roughly represent one year of isotopic inputs (Hoppe et al., 2004: 363).  
358 These estimates are consistent with empirical data from other oxygen isotope  
359 studies in equids (e.g. Bendrey et al., 2015; Sharp and Cerling, 1998; Traylor  
360 and Kohn, 2017).

361

### 362 *3.2 Analytical protocols*

363 Powdered enamel samples were prepared for phosphate oxygen isotope  
364 analysis following methods described in Britton et al. (2015), after Tütken et al.  
365 (2006) and based on O'Neil et al. (1994) and Dettmann et al. (2001: Appendix,  
366 GSA Data Repository item 20018). In brief, powdered samples (~10 mg) were  
367 pretreated with 30% hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>; 40 µl/1 mg of enamel powder)  
368 at room temperature for 24 hrs, before being rinsed in Milli-Q ultrapure water  
369 (x4) and dried (24 hrs, 50 °C). Dried samples were dissolved in 0.8 ml 2M HF  
370 and agitated in solution for 24 hrs at room temperature. In each instance, the



371 resultant phosphate solution was separated from the CaF<sub>2</sub> residue and the  
372 indicator Bromothymol Blue (1 drop), was added to each sample (yellow: acidic  
373 solution). Samples were then neutralized using 25 % ammonia solution  
374 (NH<sub>4</sub>OH) was added until a colour change (yellow to green) was observed  
375 (~180 µl). 0.8 ml of 2 M silver nitrate (AgNO<sub>3</sub>) was then added to each sample,  
376 forming the yellow silver phosphate precipitate (Ag<sub>3</sub>PO<sub>4</sub>). The precipitate was  
377 separated by centrifugation, the liquid fraction was discarded, and the  
378 precipitate was rinsed 4x with Milli-Q water, and dried for 24 hrs at 50 °C. The  
379 silver phosphate was then weighed into silver capsules for oxygen isotope  
380 analysis. Aliquots of NBS 120c were also prepared alongside the samples. NBS  
381 120c, although not certified for oxygen isotope values, is an international  
382 standard material commonly used in many laboratories as a reference material  
383 during phosphate oxygen isotope analysis as its composition and matrix is more  
384 similar to biogenic apatite than other reference materials (Chenery et al., 2010:  
385 159).

386

387 Phosphate  $\delta^{18}\text{O}$  values were determined by CF-IRMS, measured with a  
388 Thermo-Fisher TC-EA connected to a Finnigan Delta Plus XL mass  
389 spectrometer, at the Department of Geochemistry, University of Tübingen,  
390 Germany. Mean values and standard deviations (1 s.d.) were provided by the  
391 analysing laboratory, calculated from the analysis of each sample in triplicate  
392 (Table 1). In some instances, these values were provided from duplicate  
393 measurements, due to sample size, sample loss, loss of sample integrity or  
394 through internal data quality control checks in Tübingen (for exceptions, see  
395 Table 1). Long-term laboratory reproducibility was reported as  $\pm 0.3 \text{ ‰}$  (1 s.d.),

396 while mean reproducibility for the samples analysed in this study was  $\pm 0.2$  ‰  
397 (1 s.d.) or better. Samples were calibrated to  $\delta^{18}\text{O}_{\text{PO}_4}$  values using internal  
398 standards, including TU-1 ( $\delta^{18}\text{O}_{\text{PO}_4} = 21.11$  ‰ V-SMOW); TU-2 ( $\delta^{18}\text{O}_{\text{PO}_4} = 5.35$   
399 ‰ V-SMOW) and 130-0.5-1 ( $\delta^{18}\text{O}_{\text{PO}_4} = -1.13$  ‰ V-SMOW). Repeat analysis of  
400 NBS120c prepared alongside samples analysed here ( $n=4$ ) gave a mean  
401  $\delta^{18}\text{O}_{\text{PO}_4}$  value of  $21.40 \pm 0.52$  ‰ ( $1\sigma$ ), which is within error of the mean reported  
402 values from 19 previous publications (cited in Chenery et al. 2010: Table A3,  
403 161;  $21.7 \pm 0.5$  ‰ ( $1\sigma$ )) although slightly lower than weighted mean value  
404 reported in a recent inter-laboratory calibration ( $21.79 \pm 0.15$  ‰ ( $1\sigma$ ); Halas et  
405 al., 2011: 582).

406

### 407 *3.3 Conversion equations and air temperature estimates*

408 The generation of estimated air temperature values ( $^{\circ}\text{C}$ ) from mammalian  
409 skeletal bioapatite  $\delta^{18}\text{O}$  is underlain by a number of assumptions (primarily  
410 based on local environmental and landscape hydrology, and the drinking  
411 behaviour of the species in question), and is contingent on the use of  
412 conversion equations, initially to estimate drinking water  $\delta^{18}\text{O}$  (i.e. assumed  
413 local precipitation  $\delta^{18}\text{O}$ ) and then to estimate local temperature. For example,  
414 although there is a primary relationship between air temperature and  $\delta^{18}\text{O}$  of  
415 precipitation, there are also (temperature-related) variations with season, as  
416 well as variations with altitude and latitude, as well as amount effects (Clark  
417 and Fritz, 1997; Dansgaard, 1964; Gat, 1980; Rozanski et al., 1993; Yurtsever,  
418 1975). There may also be other local processes such as water mixing, water  
419 movement, groundwater recharge and evaporation processes that occur in

420 surface water bodies, which can influence the oxygen isotope composition of  
421 drinking water (making it distinct from local precipitation values). A water source  
422 (related to local precipitation values) and use of that water source by an obligate  
423 drinker is also an assumption in-built to use of faunal isotopic compositions as  
424 estimators of palaeoclimatic variables (see discussion in Pederzani and Britton,  
425 2019).

426

427 In order to convert bioapatite  $\delta^{18}\text{O}_{\text{PO}_4}$  values to  $\delta^{18}\text{O}$  values of that water source,  
428 various empirical regression equations have been proposed, including for  
429 horses (Bryant et al., 1994; Delgado Huertas et al., 1995; Sánchez Chillón et  
430 al., 1994). Such equations are required given that isotopic fractionation occurs  
431 in the body as water is metabolised, enriching the biomineral in the heavier  
432 isotope relative to drinking water. Species-specific conversion equations are  
433 necessary primarily due to inter-specific differences in water dependency, diet  
434 and physiology (Kohn, 1996; Kohn et al., 1996; Levin et al., 2006), although in-  
435 built within the application of these to archaeological materials is the  
436 assumption that fractionation factors established for extant animals are  
437 applicable to Pleistocene ones. Furthermore, error ranges in such conversion  
438 equations can be high, and it has been argued that, because of this, errors in  
439 the conversion of  $\delta^{18}\text{O}_{\text{bioapatite}} - \delta^{18}\text{O}_{\text{water}}$  could hamper their application to  
440 archaeological provenance studies in some circumstances. For example,  
441 where the total environmental variation of groundwater or meteoric water for a  
442 specific country is relatively small, such as in the United Kingdom, errors on  
443  $\delta^{18}\text{O}_{\text{water}}$  estimates must be substantially smaller than this range to permit  
444 meaningful regional allocations of place of origin (see Pollard et al., 2011).

445 Further calibration equations are then required to convert  $\delta^{18}\text{O}_{\text{water}}$  (‰) to air  
446 temperature estimates (°C). Multiple regression equations have been  
447 calculated and published based on data sets from modern water isotope  
448 monitoring stations, with each potentially generating slightly different predicted  
449 temperature values for any given  $\delta^{18}\text{O}_{\text{precipitation}}$  value. Furthermore, due to error  
450 estimates within these conversion equations, the  $\delta^{18}\text{O}_{\text{bioapatite}}$  to  $\delta^{18}\text{O}_{\text{precipitation}}$  to  
451 air temperature conversions required to infer palaeoclimate are prone to further  
452 error propagation (Pryor et al. 2014). It should be noted that the use of  
453 conversions that utilise modern water isotope data correlations with  
454 contemporary air temperature assume that atmospheric circulation and the  
455 factors that determine the distribution of rain in any particular region of study  
456 today were similar during the late Pleistocene, which may or may not be the  
457 case (Skrzypek et al., 2011: 484). It should be noted, however, that the study  
458 of old groundwaters appear to confirm the stability of the temperature-  
459  $\delta^{18}\text{O}_{\text{precipitation}}$  relationship overtime (e.g. Rozanski, 1985; Rozanski et al., 1992;  
460 Zuber et al., 2004). Furthermore, general circulation model-proxy comparison  
461 studies have indicated that the European atmospheric circulation patterns  
462 during the Eemian were broadly comparable to today (Kaspar et al., 2005).

463

464 In light of the above, the use of these methodologies is not without its caveats.  
465 However, given the potential of isotope zooarchaeological approaches as  
466 proxies for site-specific palaeoclimatic conditions from terrestrial contexts  
467 contemporary to human site use, their usefulness should not be disregarded.  
468 As part of this study, a number of sampling decisions and analytical steps were  
469 devised to maximise the quality of data generated and to characterise and

470 quantify potential errors. Firstly, the selection of an obligate drinker (horse)  
471 increases likelihood that isotopic inputs from those water sources are recorded  
472 with greater fidelity in mineralised tissue. Dental sampling strategies were  
473 employed incorporating the known formation and mineralisation process of  
474 extant horses, and in order to minimise the influence of seasonal bias in an  
475 incrementally-developed tissue when characterising MAT (see Section 3.1  
476 above). Furthermore, the sampling of multiple individuals from the same levels  
477 (see Table 1) was undertaken to reduce population-level uncertainty when  
478 using conversion equations (Pryor et al., 2014). It should be noted however that  
479 the diachronic nature of our study at a single site permits measured  $\delta^{18}\text{O}_{\text{bioapatite}}$   
480 values to be compared at the site without the use of conversion equations,  
481 providing temporal (albeit relative) insights into climatic change. However, in  
482 order to estimate palaeotemperatures, conversion equations must be  
483 employed. Here we use the most recently published conversion equation for  
484  $\delta^{18}\text{O}_{\text{PO4-}}$   $\delta^{18}\text{O}_{\text{drinking water}}$  for horses (Delgado Huertas et al., 1995, eq. 8: 4304,  
485 and following Pryor et al. 2014):

$$\delta^{18}\text{O}_{\text{PO4}} = 0.71(\delta^{18}\text{O}_{\text{drinking water}}) + 22.60$$

487 ( $R^2 = 0.77$ )

488 For temperature conversions, we utilise the recently published conversion  
489 dataset for Europe and an inverted forward fit regression (Pryor et al.,  
490 2014:100, and Appendix A. Supplementary data sheet Z2).

$$\delta^{18}\text{O}_{\text{precipitation}} = 0.53T_{\text{mean}} - 13.74$$

492 ( $R^2 = 0.60$ )

493 We calculate and report errors on the data conversion following Pryor et al.  
494 (2014: Appendix A. Supplementary data). We chose inverted forward fit

495 regression as it mirrors the causal dependencies inherent in the system  
 496 ( $\delta^{18}\text{O}_{\text{water}}$  is contingent on  $T$  °C, and not *vice versa*) but we acknowledge the  
 497 current debate regarding the calculation of palaeotemperatures using oxygen  
 498 isotope data from mammalian bioapatite (see Skrzypek et al., 2016) and that  
 499 alternative approaches have their own merits. For example, the transposed fit  
 500 approaches can introduce lower overall errors and can permit the incorporation  
 501 of data from multiple species (and their species-specific  $\delta^{18}\text{O}_{\text{PO}_4} - \delta^{18}\text{O}_{\text{water}}$   
 502 regression models) from the same site (Skrzypek et al., 2016; Skrzypek et al.,  
 503 2011).

504

## 505 4. Results and Discussion

### 506 4.1 'Bulk' oxygen isotope data and palaeotemperature estimations

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

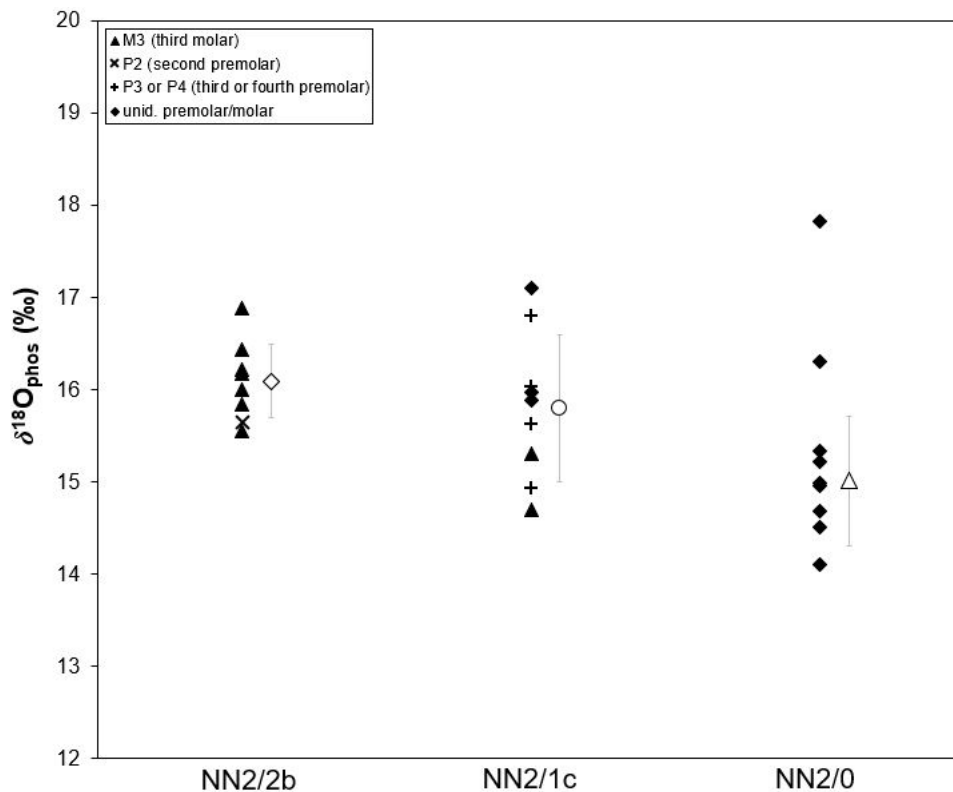
509 **Table 1:** Horse tooth enamel  $\delta^{18}\text{O}_{\text{PO}_4}$  data from early Eemian (NN2/2b, NN2/1c) and early  
 510 Weichselian (NN2/0) find levels at Neumark-Nord 2, Germany. † denotes where mean oxygen  
 511 isotope values and standard deviations are calculated from duplicate rather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

513

Sample number	Stratigraphic Level	Tooth sampled	Mean $\delta^{18}\text{O}_{\text{PO}_4}$ (‰)	stdev ( $\pm 1\sigma$ )	
14466.1	NN2/0	P/M sup.	14.1	0.4	
14467.1	NN2/0	P/M sup.	15.3	0.1	†
15339.1	NN2/0	P/M	15.0	0.2	
15340.1	NN2/0	P/M	16.3	0.0	†
15341.1	NN2/0	P/M	15.2	0.1	†
15342.1	NN2/0	P/M	14.5	0.3	
16755	NN2/0	P/M	17.8	0.0	†
16756	NN2/0	P/M	15.0	0.1	
16757	NN2/0	P/M	14.7	0.0	

14465.1	NN2/1c	M3 sup. sin.	14.7	0.1	
15233.1	NN2/1c	M3 sup. sin.	15.3	0.0	†
15335.1	NN2/1c	P3/P4 sup. sin.	16.0	0.2	
15336.1	NN2/1c	P3/P4 inf. dex.	16.8	0.1	†
15337.1	NN2/1c	P3/P4 sup. sin.	15.6	0.1	†
15338.1	NN2/1c	P3/P4 sup. sin.	14.9	0.1	†
16758	NN2/1c	P/M	16.0	0.0	†
16759	NN2/1c	P/M	17.1	0.1	†
16760	NN2/1c	P/M	15.9	0.3	†
14459.1	NN2/2b	M3 inf. dex.	16.9	0.0	†
14460.1	NN2/2b	M3 sup. sin.	16.2	0.2	
14461.1	NN2/2b	M3 sup. sin.	16.2	0.0	†
14462.1	NN2/2b	M3 sup. sin.	15.8	0.0	
14463.1	NN2/2b	M3 sup. sin.	16.4	0.1	
15332.1	NN2/2b	P2 sup. sin.	15.7	0.1	†
15333.1	NN2/2b	M3 sup. sin.	15.6	0.1	
15334.1	NN2/2b	M3 sup. sin.	16.0	0.2	

514



515

516 **Figure 3:** Horse tooth enamel  $\delta^{18}\text{O}_{\text{P04}}$  data from Eemian (NN2/2b, NN2/1c) and Weichselian

517 (NN2/0) find levels at Neumark-Nord 2, Germany. *Equus* sp. tooth types sampled and mean

518 values per find complex are depicted ( $\pm 1$  s.d.) (calculated excluding 16755, see text for

519 explanation).

520

521 The total range of enamel  $\delta^{18}\text{O}_{\text{PO}_4}$  values exhibited range from 14.1 to 17.8 ‰,  
522 with a mean of  $15.7 \pm 0.9$  ‰ (1 s.d.) for all data. Mean  $\delta^{18}\text{O}_{\text{PO}_4}$  values for each  
523 find level are:  $16.1 \pm 0.4$  ‰ (1 s.d.) for NN2/2b ( $n=8$ );  $15.8 \pm 0.8$  ‰ (1 s.d.) for  
524 NN2/1c ( $n=9$ ); and  $15.0 \pm 0.7$  ‰ (1 s.d.) for NN2/0 ( $n=8$ , excluding sample  
525 16755). It should be noted that, for NN2/0, one sample from an unidentified  
526 cheek tooth (16755) has a  $\delta^{18}\text{O}_{\text{PO}_4}$  value  $>17.5$  ‰, which is substantially  
527 elevated compared to the rest of the dataset and may suggest this tooth formed  
528 pre-weaning (Britton et al., 2015; Wright and Schwarcz, 1998). Other  
529 explanations could also account for values measured in this outlier (e.g.  
530 diagenetic alteration, physiology, a different drinking water source, etc). Given  
531 that modern feral foals can nurse for ~9 months, and substantial portions of  
532 both the permanent first and second molars form during this period (Hoppe et  
533 al., 2004: 362), the former explanation is favoured. Indeed, pairwise  
534 comparisons of  $\delta^{18}\text{O}_{\text{milk}} - \delta^{18}\text{O}_{\text{water}}$  of domestic cows have indicated milk values  
535 are ~4 ‰ elevated relative to those of water (Lin et al., 2003: 2191), suggesting  
536 offsets of a similar scale to those observed here. Whatever the underlying  
537 cause, we have chosen to exclude this data point from mean calculations and  
538 from palaeotemperature estimations in this paper.

539

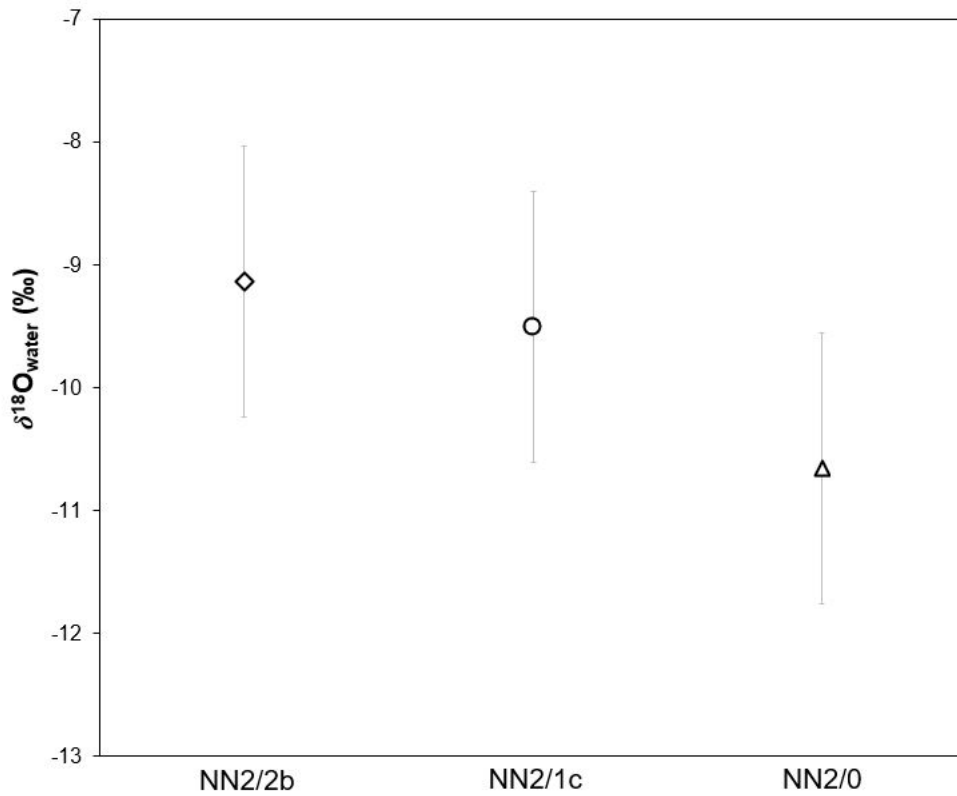
540 **Table 2:** Mean enamel  $\delta^{18}\text{O}_{\text{PO}_4}$  values, mean calibrated  $\delta^{18}\text{O}_{\text{water}}$  values and mean annual  
541 temperature (MAT) estimates for each of the find levels studied at Neumark-Nord 2, calculated  
542 excluding sample 16755 (after Delgado Huertas et al., 1995; Pryor et al., 2014). All standard  
543 errors are  $\pm 1$  s.d..



Stratigraphic Level	n	Mean enamel $\delta^{18}\text{O}_{\text{PO}_4}$ (‰)	stdev ( $\pm 1\sigma$ )	Mean calibrated $\delta^{18}\text{O}_{\text{water}}$ (‰)	Standard error ( $\delta^{18}\text{O}_{\text{PO}_4} - \delta^{18}\text{O}_{\text{water}}$ )	Calibrated MAT (°C)	Standard error ( $\delta^{18}\text{O}_{\text{water}} - \text{MAT}$ )
NN2/0	8	15.0	0.7	-10.7	1.1	5.8	2.2
NN2/1c	9	15.8	0.8	-9.5	1.0	8.0	1.9
NN2/2b	8	16.1	0.4	-9.1	1.1	8.8	2.1

544

545 Mean enamel  $\delta^{18}\text{O}_{\text{PO}_4}$  values for each find level studied at Neumark-Nord 2 are  
546 shown in Table 2 and, along with calibrated  $\delta^{18}\text{O}_{\text{water}}$  values and the calibrated  
547 temperature estimates, in Figures 4 and 5 (Delgado Huertas et al., 1995; Pryor  
548 et al., 2014: Appendix A. Supplementary data). The error in data conversion to  
549  $\delta^{18}\text{O}_{\text{water}}$ , and the compound error for the Mean Annual Temperature (MAT)  
550 conversions are also reported for the group means as an estimation of  
551 uncertainty (following Pryor et al., 2014: Appendix A. Supplementary data). The  
552 compound error of each temperature estimate gives an indication of the overall  
553 uncertainty of the temperature estimate which includes several different  
554 sources of uncertainty. This includes the uncertainty of regression lines, as well  
555 as the uncertainty of group means, which is also a function of sample size. The  
556 temperature reconstructions presented for the different find levels at Neumark-  
557 Nord 2 therefore vary slightly in their uncertainty due to differences both in  
558 sample size for each group, as well as the magnitude of uncertainty in the  
559 regression line around the value that is input into the regression.



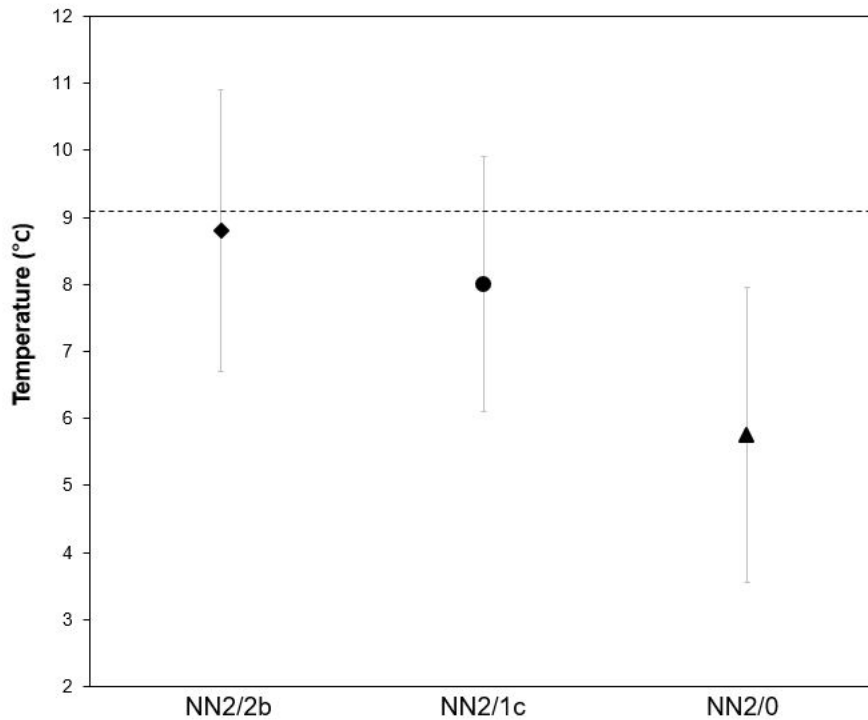
560

561 **Figure 4:** Mean calibrated  $\delta^{18}\text{O}_{\text{water}}$  values (based on  $\delta^{18}\text{O}_{\text{PO}_4}$  values of horse tooth enamel)

562 from find levels at Neumark-Nord 2. Data were calculated using the conversion equation in

563 Delgado Huertas et al. (1995), and following the recommendations detailed in Pryor et al.

564 (2014). Standard errors are  $\pm 1$  s.d..



565

566 **Figure 5:** Mean calibrated annual temperature estimations (based on  $\delta^{18}\text{O}_{\text{PO}_4}$  values of horse  
 567 tooth enamel) from find levels at Neumark-Nord 2. Data were converted from estimated mean  
 568  $\delta^{18}\text{O}_{\text{water}}$  values, utilising the dataset and following the recommendations of Pryor et al. (2014:  
 569 Appendix A. Supplementary data). Standard errors are  $\pm 1$  s.d.. Approximate modern MAT for  
 570 this region (AD 1961-1990) is depicted as a dashed line (Döring and Borg, 2008).

571

572 For NN2/2b (early Eemian;  $121 \pm 5$  ka) the mean annual temperature estimation  
 573 based on horse tooth enamel phosphate oxygen data is  $8.8 \pm 2.1$  °C. For NN2/1c  
 574 (also early Eemian) the mean annual temperature estimation is  $8.0 \pm 1.9$  °C. For  
 575 NN2/0 (early Weichselian;  $93 \pm 7$  ka) the mean annual temperature estimation is  
 576  $5.8 \pm 2.2$  °C.

577

578 The region surrounding Neumark-Nord 2 today has a mean annual temperature  
 579 of  $\sim 9$  °C (based on data from Halle, AD 1961-1990, from Döring and Borg,  
 580 2008), and data presented here indicate that a similar MAT may have

581 characterised the climate of the early Eemian in this area. These estimations  
582 are at the lower end of those based on other proxies, such as palaeobotanical  
583 and coleopteran data which suggest both summer and winter temperatures  
584 may have been several degrees warmer than today (Aalbersberg and Litt,  
585 1998; Zagwijn, 1996), but – given the relatively large standard deviations of the  
586 estimates – are well within the range anticipated MAT values. In contrast, MATs  
587 in early Weichselian find level NN2/0 at Neumark-Nord in this study are  
588 estimated to be substantially lower than those in the Eemian find levels at the  
589 same site, by between approximately 2 to 3 °C. However, the large error  
590 margins should be noted on these estimates, which are in part an artefact of  
591 the conversion equations and methodology employed (see above), with inverse  
592 forward fit employed here generating larger errors than some other approaches  
593 (Skrzypek et al., 2016).

594

#### 595 *4.2 Correlations with site-specific climate proxies and other datasets*

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

605 2015: 77, Fig. 7), the result of seasonal rainfalls (Gaudzinski-Windheuser et al.,  
606 2014).

607

608 The warm-temperate faunal assemblage is also consistent with the MATs  
609 estimated here. Horse, in particular, were an important species in Neanderthal  
610 subsistence strategies at the site and recent ontogenetic aging data of horse  
611 remains from the site suggest they were hunted all year round (Kindler et al.,  
612 2015; Smith et al., 2015). This may indicate that not only were MATs  
613 favourable, but also that seasonal temperature variations favoured year-round  
614 Neanderthal occupation of this area. This is supported by other proxy evidence  
615 for climate in the early Eemian in northern Germany, where the multivariate  
616 analysis of pollen and plant macrofossil data has indicated warm summer  
617 temperatures (>19 °C) (Kühl et al., 2007).

618

619 The variability in horse enamel  $\delta^{18}\text{O}_{\text{PO}_4}$  values and thus temperature estimates  
620 between NN2/2b and NN2/1c suggest, however, that climate conditions may  
621 have both been fluctuating and possibly in decline during the early Eemian at  
622 this location. The identification of the palaeomagnetic signal of the Blake-event  
623 in the Neumark-Nord 2 sequence allowed Sier et al. (2011) to correlate this  
624 high-resolution terrestrial record to the marine record. They suggest that the  
625 beginning of the Eemian interglacial as documented at NN2 occurred not simply  
626 after the major global ice sheets had melted, but considerably later, when sea  
627 levels had already begun to drop and substantial continental ice was once again  
628 accumulating. Our findings of a (slight) temperature decline during the early  
629 Eemian could be used in support of this interpretation. However, the relatively

630 small differences both in measured phosphate values and temperature  
631 estimates between NN2/2b and NN2/1c, coupled with the large (and  
632 overlapping) error ranges elicit caution.

633

634 While differences in MATs determined in Eemian and Weichselian find levels  
635 from Neumark-Nord 2 in this study are evident ( $\sim 3$  °C), the scale of these  
636 differences are at the lower end of those estimated from pollen/plant  
637 macrofossils in northern Germany ( $\sim 4$  °C, see Köhl et al., 2007) and not as vast  
638 as those differences estimated from  $\delta^{18}\text{O}$  measurements of bulk carbonates  
639 from lacustrine sediments at nearby Gröbern, 50 km north of Leipzig (6-11 °C,  
640 Eemian to early Weichselian) (Litt et al., 1996). However, the early Weichselian  
641 featured both stadials and interstadials, marked by strong climatic oscillations  
642 (Litt et al., 1996), and the oxygen isotope data from NN2/0 presented here may  
643 be consistent with milder intervals around that specific period of site-use ( $93 \pm 7$   
644 ka; Richter and Krbetschek, 2014, likely MIS 5c/Amersfoort/Brörup-  
645 Interstadial). This is consistent with the lack of strictly cold-adapted species at  
646 Neumark-Nord 2/0, such as reindeer. It can be noted that mean annual water  
647 isotope and temperature estimates from early Weichselian Neumark-Nord 2 are  
648 also consistent with those from the early Weichselian levels at the open-air site  
649 of Hallera Avenue near Wrocław, Poland (MIS 5d-a;  $\sim 115$ -74,000 yr BP). In the  
650 Hallera Avenue study tooth samples from multiple mid-sized and large  
651 herbivore species were targeted (bovids, horses, mammoths and rhinoceros),  
652 providing an estimated  $\delta^{18}\text{O}_{\text{water}}$  mean of  $-10.7 \pm 0.8$  ‰, identical to that  
653 calculated from NN2/0 in this study (Table 2). While Skrzypek et al (2011).  
654 calculate a MAT of  $6.8 \pm 1.5$  °C, 1 °C higher than that calculated for NN2/0 from

655 the same predicted water value (a product of the different regression  
656 methods/reference datasets used), both estimates are elevated relative to  
657 previous estimates based on pollen studies for the region. These observed  
658 differences – between temperature estimates from faunal oxygen isotope data  
659 and using local/regional climate archives – at both of these Central European  
660 sites (Neumark-Nord and Hallera Avenue) highlight the value of the isotope  
661 zooarchaeological approach in evidencing conditions contemporary to hominin  
662 activity, and in highlighting human ecological and climatic preferences and/or  
663 tolerances.

664

#### 665 *4.3 Implications and further studies*

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

680 palaeothermic conditions contemporary to human presence and activity at the  
681 location.

682

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

702

703 Ideally, isotope bioapatite studies should endeavour to maximise the number  
704 of 'bulk' samples in reconstructing MAT (Pryor et al., 2014), although the



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

720

721 While chronologically relating the data generated to long-term proxy datasets  
722 remains a challenge, comparisons with alternative datasets above, both on at  
723 Neumark-Nord 2 and on a broader level, emphasise the value of faunal  
724 bioapatite  $\delta^{18}\text{O}_{\text{PO}_4}$  analysis as a complementary methodology in  
725 palaeotemperature estimation, particularly within archaeological studies. While  
726 Neumark-Nord 2 boasts different palaeoclimate proxy datasets, useful here in  
727 corroborating the results of this isotope study, for the majority of archaeological  
728 sites this is not the case. It is in these contexts that archaeofaunal oxygen  
729 isotope datasets will prove particularly useful. As well as further applications to

730 late Pleistocene contexts, future studies could consider the application of these  
731 techniques to older (e.g. Lower Palaeolithic) sites in Europe, as this could help  
732 inform the climatic conditions surrounding the earliest human inhabitations of  
733 Europe, particularly at the more northerly extremes/mid- latitudes of occupation  
734 (Hosfield, 2016), illuminating pre-modern human adaptive strategies and  
735 palaeoecology. Finally, as well as acquiring data from anthropogenic faunal  
736 assemblages, undertaking such analyses in archaeologically-sterile levels (e.g.  
737 natural accumulations such as hyena dens) could also be significant in that it  
738 could inform the climatic contexts that limited or even prohibited human  
739 presence.

740

## 741 **5. Conclusions**

742 In this study, phosphate oxygen isotope ( $\delta^{18}\text{O}_{\text{PO}_4}$ ) data generated from horse  
743 (*Equus* sp.) tooth enamel at the Late Pleistocene archaeological site of  
744 Neumark-Nord 2 are used to reconstruct mean annual air temperatures (MATs)  
745 during the early Eemian and early Weichselian, contemporary to these different  
746 phases of Neanderthal activity at the site. Although the large compound errors  
747 and uncertainties inherent in the regressions utilised to ‘convert’  $\delta^{18}\text{O}_{\text{PO}_4}$  to MAT  
748 are acknowledged here and elsewhere (e.g. Pryor et al., 2014; Skrzypek et al.,  
749 2016), the estimates for early Eemian MAT (~9 °C) at Neumark-Nord 2 do  
750 correlate well with other site-specific climate proxies. Palynological evidence,  
751 for example, indicates a mild climate during the interglacial, semi-open  
752 environmental conditions, and an increased presence of water in the shallow  
753 lake (Bakels, 2014; Pop and Bakels, 2015). The warm-temperate faunal  
754 assemblage and year-round exploitation of horses emphasise the ameliorate

755 early Eemian conditions at the site (Kindler et al., 2015; Smith et al., 2015).  
756 While limited, the oxygen isotope data from NN2/1c (also early Eemian, but  
757 chronostratigraphically later than the NN2/2 deposits) may suggest climatic  
758 variability during this period and a possible decline in temperatures during the  
759 course of the early Eemian.

760

761 Enamel oxygen isotope data from later phases of the site indicate the local MAT  
762 was approximately 3 °C lower by the early Weichselian (~93±7 ka). These  
763 estimates, and those generated from faunal bioapatite at other early  
764 Weichselian sites in this broader region of Central Europe (e.g. Skrzypek et al.,  
765 2011), exceed those indicated by other local and regional climate proxy  
766 datasets. This may indicate that the hominin activity that was responsible for  
767 the accumulation of these faunal remains may have been limited to more  
768 ameliorate stages at this part of the Weichselian glaciation. The generation of  
769 further types of site-specific palaeoclimate proxy data from Neanderthal sites in  
770 Central Europe, particular that which illuminates seasonal conditions, will be  
771 helpful in better characterising this.

772

773 As demonstrated here, dental tissues from obligate drinking large mammal  
774 species can be a useful source of palaeoclimate proxy data. This does not just  
775 extend to incremental sampling of teeth for palaeoseasonality (e.g. Bernard et  
776 al., 2009), but also the bulk sampling of dental tissues in order to reconstruct  
777 past MATs. However, while studies should endeavour to maximise sample size,  
778 it is imperative that a consistent approach to sampling, incorporating a year of  
779 growth (~3 to 3.5 cm vertical crown height for most late forming horse teeth), is

780 employed to avoid introducing seasonal biases in 'bulk' samples. The  
781 similarities and differences between the new MAT data presented in this study  
782 and other regional palaeoclimatic archives highlights the complementary value  
783 of the isotope zooarchaeological approach. The analysis of archaeofaunal  
784 remains can not only provide evidence of contemporary climatic conditions, but,  
785 significantly, provides a link between those conditions and the past human  
786 presence. While these archives produce highly punctuated records compared  
787 to natural archives, and might be difficult to date across different sites, efforts  
788 should be made to incorporate such analyses into archaeological and  
789 palaeoanthropological studies, and to further integrate such data within other  
790 proxy datasets and frameworks.

791

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813

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