

1 **In front of the retreating ice-sheet: Fauna complex of Central Poland in MIS 3–2 (Krosinko**  
2 **site)**

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8 **Abstract**

9 A new locality in Central Europe (Krosinko, Poland) yields a rich fossil material of great  
10 taxonomical variety. Its location in the Warsaw–Berlin ice-marginal valley, where it forms a 1-  
11 m horizon at a the depth of 6–8 m, is suited to a taphonomic analysis aimed at reconstructing  
12 the paleoevents and depositional history of the late Pleistocene (MIS 3–2).

13 Our analysis revealed that the material accumulated as the result of high-energy fluvial  
14 transport. This transport disturbed the original bone associations, as indicated by the lack of  
15 articulation, low refitting, and bone surface modification. During water movement, the bones  
16 were polished, abraded, pitted, and fragmented. Prior to that, however, taphonomic  
17 signatures were left behind by predators, humans, and plant roots.

18 This is the first time that unquestionable burning marks have been found on woolly rhino  
19 remains from Poland. The secondary context of the faunal assemblage was confirmed by  
20 neodymium isotope studies of the faunal fragments and sediment. Given the results of  
21 sedimentological analysis from previous studies, these sediments can be associated with a  
22 high-energy braided river. The remains were moved along with paleobotanical material and  
23 flints in a westerly direction; this is suggested by the direction of water flows in the valley and  
24 the river waters supplying it. The deposition occurred within a single geologic event around  
25 26 ka BP, as indicated by the youngest radiocarbon date of the remains, or ca. 19 ka BP,  
26 considering the geochronological constraints for the local LGM ice margin position in central  
27 and eastern Poland ~22–18 ka, and the specified accumulation time of the sediments in which  
28 they were found. Secondary mineralization of manganese and iron on the bones was the final  
29 taphonomical process that impacted the remains. The combined taphonomic,  
30 palaeozoological, isotopic and geological results show for the first time for a Polish  
31 paleontological site how data integration improves interpretation and highlights the  
32 advantages of a multiproxy approach.

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34 **Keywords:** Mammals; Taphonomy; Isotopes; Late Pleistocene; MIS 3–2; Poland

## 35 1. Introduction

36 European ice sheets developed in a glacial–interglacial cycle, which is correlated with the  
37 climate and is reflected in the stratigraphy of the Quaternary, including for Poland (Table 1).  
38 This entailed changes in fluvial styles as response to combinations of periodic climate cooling  
39 and warming, ice sheet margin dynamics, fluctuations of the sea level, and neotectonic  
40 movements (Weckwerth, 2018). The climate was the main driving force of changes in  
41 terrestrial and aquatic ecosystems, and in the geomorphological processes (Wolfhagen et al.,  
42 2020), as shown by the example of the Eemian-Vistulian developmental history of the Ławy  
43 paleolake (Eastern Poland) (Hrynowiecka et al., 2018). During the last glaciation (Vistulian;  
44 Marine Isotope Stage 2 [MIS]), a significant warming of the climate in the Northern  
45 Hemisphere led to the retreat of the Scandinavian Ice Sheet (SIS). The southern margin of the  
46 SIS receded gradually to the north after the time of its maximum extensions, which in the  
47 northern continental Europe occurred between ~24 and ~18 ka (Last Glacial Maximum: LGM)  
48 (Tylman and Uścińowicz, 2022). At this time SIS formed the ice-marginal belts attributed to  
49 the three main phases of the last glaciation in Germany and Poland: Brandenburg (Leszno;  
50 ~24–23 ka), Frankfurt (Poznań; ~19 ka), and Pomeranian (18–17 ka or 17–16 ka) (Tylman and  
51 Uścińowicz, 2022 with further references) (Figure 1).

52 The functioning of ice-marginal valleys in Europe is associated with deglaciation (Figure  
53 2); the regime was so significant that these valleys transported various materials, including  
54 faunal remains. The direction of ice-marginal river flow was westward, which is consistent  
55 with the general slope of the European continent (Starkel et al., 2015; Zieliński, 2014).  
56 Hydrodynamic sorting based on internal features of the different faunal anatomical elements  
57 has been studied by several authors, with the conclusion that different assemblages can rise  
58 (Behrensmeyer, 1975; Blob et al., 2022; Dodson, 1973; Korth, 1979; Voorhies, 1969; Wolf,  
59 1973). Transport in fluvial environments also alters the completeness and surfaces of the  
60 elements being transported, thanks to two important factors: environmental energy and  
61 transport length. Vertebrate-bearing fluvial deposits have thus been the subject of numerous  
62 taphonomic investigations of bones, with implications for the interpretation of skeletal sorting  
63 in assemblages (Behrensmeyer, 1975; Blob, 1997; Boaz and Behrensmeyer, 1976; Coard and  
64 Dennell, 1995; Coard, 1999; Croitor et al., 2014; Dodson, 1973; Hanson, 1980; Pawłowska et  
65 al., 2014a, 2014b; Peterson and Bigalke, 2013; Schick, 1987; Stefaniak et al., 2014; Trapani,  
66 1998; Voorhies, 1969). As a result of these, methodological criteria that may be of use in  
67 exploring the role of water in the formation of the faunal record in fluvial environments were  
68 established (Blob et al., 2022; Gutierrez and Kaufmann, 2007).

### 69 1.1. Site: Geology and dating

70 In front of the retreating ice-sheet in the Vistulian Glaciation (MIS 2) was deposited a fauna  
71 complex within the Krosinko site in the sediments of the Warsaw–Berlin ice-marginal valley  
72 (Figures 1 and 2). Krosinko, is a gravel pit in Poland, and due to its location in the central-  
73 western part of Poland (52°13'05.9"N 16°49'16.5"E), is of great importance for Central Europe

74 not only for its faunistic implications but also for taphonomy (Figure 2). It was here that the  
75 largest latitudinal ice-marginal streamway functioned, including the Warsaw–Berlin ice-  
76 marginal valley, supplied by meltwater from the ice sheet and river water from the south  
77 (Figure 2).

78 This can be seen in the sedimentological record of Krosinko, where sediments of the  
79 Weichselian Glaciation dominated in the form of fluvioglacial sands and gravels (Figures 3 and  
80 4). Sedimentological analysis, including analysis of quartz grains and of quartz surface  
81 microtextures, revealed a change in the river regime (MIS 5e and MIS 2) under changing  
82 palaeoclimate conditions (Pawłowska et al., 2022). The basal part of the geological profile  
83 created sediments (silt, unit A) associated with a meandering river in a generally warm climate  
84 during the Eemian interglacial (MIS 5e) (Figure 4). These are records of a low-energy river, as  
85 are the overlying deposits of fine-grained sand (lower unit B). One result of the change of the  
86 river regime to a high-energy braided river in MIS 2 (around 19 ka BP; Poznań Phase) is the  
87 gravel-sand series (the upper part of unit B and unit C) with wood fragments, cones, and  
88 animal remains (Pawłowska, 2010, 2015, 2022; Pawłowska et al., 2022). The sediments of this  
89 unit were affected by chemical weathering (etching, crusting), mechanical weathering  
90 (crushing, abrasion), and frost weathering, as evidenced by the microtextural features of the  
91 grains (Pawłowska et al., 2022). Flints showed traces of water influence in the form of rounded  
92 edges, strongly shiny surfaces with a white or bluish patina (formed through exposure to water  
93 in the sediment (Stapert, 1976)), frost cracking, and various types of scratches, cracks, pitting,  
94 and the so-called pseudo-retouches that resulted from processes in the soil (e.g.,  
95 cryoturbation: Chambers, 2005; Chu et al., 2015; Pawłowska et al., 2022). All cones were  
96 incompletely preserved, slightly silicified, with very worn and smoothed surfaces. The  
97 Pleistocene sedimentary succession terminates with a sand series (unit D) that accumulated  
98 between 18 ka and 11.7 ka BP (MIS 2; LGI), marking a decrease in fluvial energy (Pawłowska  
99 et al., 2022). The sediments of unit D were overlain by Holocene peats. The numerous large  
100 mammal remains from Pleistocene fluvial deposits are dominated by woolly mammoth and  
101 woolly rhinoceros, as well as many other taxa, which reflects the structure of the  
102 *Mammuthus–Coelodonta* faunal complex (Pawłowska, 2022). This taxonomic diversity of  
103 material allowed us to reconstruct the biogeography of woolly mammoths, woolly rhinoceri,  
104 horses, giant deer, red deer, fallow deer, reindeer, steppe bison, aurochs, bears, and cave lions  
105 in Poland. Our research also illuminated the individual responses of taxa to changing  
106 environmental conditions in response to climatic ones (Pawłowska, 2020, 2022). Finally, the  
107 most prominent outcomes related to the discovery, for the first time, of the presence of  
108 woolly rhinoceri around 38ka BP in Central Europe, at a time that was though to represent a  
109 gap in the presence of this species (Pawłowska, 2022). The study of the evolution of Central  
110 European regional mammal assemblages between the Late Middle Pleistocene and the  
111 Holocene (MIS7–MIS1), using the Krosinko assemblages, shown a time/spatial invariance of  
112 species richness for the stationary states of fauna evolution (especially during MIS3)  
113 (Puzachenko et al., 2022). The faunal remains have been dated (48–9 ka BP) and revealed the  
114 presence of two subassemblages: one Late Pleistocene (at least MIS 3–2), corresponding to

115 the Vistulian Glaciation (Grudziądz Interglacial in the Polish chronostratigraphy), and one  
116 Holocene (MIS 1) (Pawłowska, 2022). The results are thus consistent with the geological  
117 outcomes. The wide range of dates that fall into Pleistocene (48.4 ka BP–26.4 ka BP)  
118 demonstrate that the assemblage does not represent a single biocenosis or even a single  
119 taphocenosis, but rather numerous variable original sources. Some open dates (>45,400 and  
120 > 48,300) do however suggest that some material is even older than MIS 3, but the depth of  
121 occurrence of the assemblage in the geological sequence (6–7 m), points to a single horizon  
122 of up to ~1 m thickness (Pawłowska, 2022). This was further interpreted as a quite compact  
123 assemblage that was possibly deposited as the effect of a geological event at c. 26,460 ± 240  
124 BP or later, as inferred from the latest available radiocarbon date, making use of the residual  
125 material approach (Ramsey, 2008; Pawłowska, 2022). This aim of this paper is to  
126 taphonomically evaluate the Krosinko faunal material, in order to reconstruct the depositional  
127 history in detail and to determine whether there are nonfluvial factors responsible for their  
128 shape and deposition. Taphonomy is an essential tool for the study of faunal remains, allowing  
129 definition of the factors of assemblage accumulation and determination of whether the  
130 assemblage is on the basis of a primary or secondary deposit (Pawłowska, 2010). This has to  
131 do with the factors that modify the individual components of the assemblage, leaving marks  
132 on their surfaces. The integration of taphonomic results with palaeozoological, isotopic, and  
133 geological results, which is here carried out for the first time in a study of a Polish  
134 paleontological site, is intended to improve the interpretation and highlight the advantages of  
135 a multiproxy approach. The term *contextual paleozoology* is proposed here for research into  
136 any kind of context in which Pleistocene animal remains were found, and term *social*  
137 *paleozoology* for research into any kind of hominin activity associated with animals and the  
138 use of their products which led to induced modifications of Pleistocene animal bones.

## 139 **2. Material and methods**

140 The study material consisted of Pleistocene fauna remains (n = 261) found at the Krosinko site,  
141 along with cones, wood fragments, and flints, at a depth of between 6 and 8 m. The  
142 assemblage was recovered during work at the gravel pit site using heavy equipment and a  
143 refiller, due to the high groundwater level. The spatial distribution of the bones could thus  
144 not be investigated.

145 The assemblage was taxonomically diverse, as shown by the distribution of species  
146 including woolly mammoths, woolly rhinoceri, horses, giant deer, red deer, fallow deer,  
147 reindeer, steppe bison, aurochs, bears, and cave lions (Pawłowska, 2022). Data on the  
148 abundance of taxa and elements in the assemblage are presented as the number of identified  
149 specimens (NISP).

150 We used various evaluative criteria that provide information essential to interpreting  
151 the accumulation factors and the taphonomic history of bone assemblages (Gutierrez and  
152 Kaufmann, 2007; Fernández-Jalvo and Andrews, 2003). In particular, there are: 1)  
153 representation of skeletal parts; 2) degree of association of the bone elements; and 3)

154 taphonomical analysis including natural bone and human-induced modifications. The data  
155 were also integrated and discussed, taking into account contextual information.

### 156 *2.1. Representation of skeletal parts*

157 Representation of skeletal parts was measured as a) frequency of bone elements, taking into  
158 account the fluvial transport potential groups (Fernández-Jalvo and Andrews, 2003; Voorhies,  
159 1969); b) tooth–vertebra ratio as a fluvial selection index (Behrensmeier, 1975); and c)  
160 unfused diaphysis/epiphysis proportion. Each element from the recognized anatomical  
161 distribution of the remains (Pawłowska, 2022) was divided into four Voorhies groups (I:  
162 immediately removed and transported by saltation and flotation; II: gradually removed and  
163 transported by traction; I/II: intermediate group; III: tending to resist transport and to remain  
164 behind as a lag deposit) that reflect different susceptibilities to fluvial transport (Voorhies,  
165 1969). The same was done with the classification of Fernández-Jalvo and Andrews (2003), who  
166 presented a general formula based on many studies dealing with the order in which elements  
167 are transported in a fluvial environment; such results supplemented Voorhies' work. The first  
168 (group 1) includes the lightest elements, such as vertebra, ribs and pelvises, which for this  
169 reason are transported first. The second group (group 2) consist of elements (scapula,  
170 phalanges, limb bones, calcanei, astragali, and other tarsals) that are transported when water  
171 energy increases. Yet higher water energies transport elements from group three (group 3),  
172 which include mandibles, teeth, and tibias (Fernández-Jalvo and Andrews, 2003).

### 173 *2.2. Degree of association of the bone elements*

174 The degree of association of bone elements was studied using evidence of articulation and  
175 bone refitting, both on taxonomical and anatomical levels. For this purpose, the articular  
176 surfaces of the bones were observed and interbone and intrabone anatomical refittings were  
177 performed.

### 178 *2.3. Taphonomical analysis*

179 Since a range of factors can contribute to material fragmentation, the degree of fragmentation  
180 of the material was recorded after separating out the classes of whole bone, predepositional,  
181 more predepositional than modern, modern, and more modern than predepositional.

182 A total of 261 remains were examined for the presence of natural and anthropogenic  
183 marks. The taphonomic analysis thus included a record of marks of burning, carnivora and  
184 rodent gnawing, digestion, weathering, trampling, abrasion of specimen surface and edges,  
185 including pitting (non-linear, edge bounded features), polishing, and human induced marks,  
186 such as butchery marks, those related to manufacturing, and anthropic fractures  
187 (Behrensmeier, 1978; Binford, 1981; Fiorillo, 1989; Fisher, 1995; Lyman, 1994; Lyman and Fox,  
188 1989; Pawłowska, 2017 with further references; Shipman and Rose, 1988). Specimens with  
189 compact bone removal and exposed spongy bones were classified as stage 3 according to the  
190 Gutierrez and Kaufmann (2007), which points to sedimentary abrasion of elements during  
191 fluvial transport, in contrast to stages 1 and 2, which can be linked to abrasion in situ. These

192 are associated with the biostratigraphic stage. The effect of the type of deposit and plant root  
193 was also inspected, as well as evidence of secondary mineralization, as all of them have an  
194 effect on faunal assemblages in the diagenetic stage (Efremov, 1940).

#### 195 *2.4. Isotopic analysis*

196 Isotopic studies involving neodymium (Nd) were performed at the AMU Isotope Laboratory in  
197 Poznań, Poland. An antler fragment and a sediment sample were collected for this study from  
198 a geological profile at a depth of 6–7 m, obtained during drilling (borehole: BH8).

199 The faunal material was not maintained and is stored in a private collection. Access to  
200 the specimens is available by request to the author. Each fragment received a general  
201 identification number (GID) composed of the site abbreviation (KR), unit number (111, 112,  
202 116 for Pleistocene context), the letter code for finds (F), and a unique ID number for each  
203 item.

### 204 **3. Results**

#### 205 **3.1. Representation of skeletal parts**

##### 206 *3.1.1. Fluvial transport potential groups*

207 Assigning bone elements to the Voorhies groups shows that group III dominated (41%),  
208 followed by group II (30%), group I (19%), and group I/II (Table 2).

209 In the separate allocation of bone elements to the general pattern of transported groups  
210 (Fernández-Jalvo and Andrews, 2003), group 3 dominated over groups 1 and 2 (Table 3).

##### 211 *3.1.2. Tooth/vertebra ratio*

212 There were 33 teeth and 23 vertebrae in the assembly, which means that the tooth:vertebra  
213 ratio is 1.4 (Table 4).

##### 214 *3.1.3. Unfused diaphysis/epiphysis proportion*

215 On the basis of the degree of epiphysis fusion, dentition, degree of obliteration of cranial  
216 sutures, and the development of horn cores and antlers, the Krosinko assemblage mainly  
217 contains elements of adult animals. Consequently, only six limb bones had unfused epiphyses  
218 (Table 4). The ratio of unfused long bone diaphyses to epiphyses was 2:4.

#### 219 **3.2. Degree of association of bone elements**

220 The vast majority of elements were found as separate units (98.5%; n = 257), with no evidence  
221 of the presence of articulated bones (Table 4). The degree of association of bone elements  
222 was low, as for no more than four cases (1.5% of assemblage; mandible and femur pieces) was  
223 anatomical refitting of the bone assemblage possible (Table 4).

### 224 3.3. Taphonomical analysis

#### 225 3.3.1. Fragmentation

226 Most elements were preserved incompletely (83.9%) (Table 4). The exceptions include teeth,  
227 vertebrae, phalanges, patellae, carpal and tarsals bones, and some long bones (radius,  
228 metacarpal, tibia, fibula, metatarsal), which were complete and represent 16.1% of the  
229 assemblage (Table 4). Among the incompletely preserved, the percentage of predepositional  
230 fractures was 47.1% (n = 123) and the percentage of modern fractures was 36.8% (n = 96).  
231 Bones were observed to usually be fractured perpendicular to the long axis.

#### 232 3.3.2. Natural surface modifications

233 Natural surface modifications found on the Krosinko specimens include burning, gnawing,  
234 surface and edge abrasion (including pitting), and polishing, as well as mineralization and  
235 evidence of plant root activity (Table 4).

236 Signs of burning are likely visible on two of the bones, one from a horse and one from  
237 a woolly rhino (0.8% of the assemblage; Figure 5A and B). Brown surface and black core were  
238 observed as features of deriving from high temperature.

239 This is the first time that unquestionable burning marks have been found on fossil rhino  
240 remains from Poland. Gnawing marks were present on eleven specimens (4.2%); these were  
241 generally light gnawing (n = 10) by predators (Figure 5C–E). The influence of predators  
242 manifests as uneven furrows, 3–5 mm in width, and slight crenulated edges, mainly on  
243 pelvises. Specimens with gnawing marks come from woolly mammoth, bovids, and horse.  
244 Signs of rodent gnawing were not found. None of the specimens displayed marks of digestion  
245 or trampling.

246 The surface of the specimens was usually dull (32.6%; n = 85) or glossy (38.7%; n = 101)  
247 but in 58 cases (22.2%) was both dull and glossy (Table 4). The latter was typical of some long  
248 bones, with a dull surface being found on the epiphyses or articular surfaces and a shiny  
249 surface on the shaft (Figure 6A–B). A dull-glossy surface was also observed on limb bone shafts  
250 as a result of selective abrasion with gravel (Figure 6C). The specimens show abrasion of stage  
251 1 and 2, but in extreme cases of abrasion, at the epiphyses of limb bones, the compact bone  
252 had been removed, consequently exposing spongy bone (stage 3 in the classification of  
253 Gutierrez and Kaufmann, 2007)(Figure 6D–F). There were also specimens in the assemblage  
254 that had clear signs of partially removed external flakes (Figure 6F–G) from the bone surface,  
255 and some displayed isolated polished and flattened patches on the bone (Figure 6H1 and H2).  
256 The surfaces of some specimens have sets of striations, and many specimens had pitting marks  
257 of varying diameter that were distributed irregularly (Figure 7A and B). Most elements had  
258 preserved quartz grains, a gravel fraction mostly in nutrient holes, and a sandy fraction in the  
259 sponge bone (Figure 7C–E). The edges of the specimens were mostly rounded (65.1%; n = 170;  
260 Figure 7F–G), although those that were acute (15.7%; n = 41) and acute along with rounded  
261 (3.4%) were also noted (Table 4). Many elements from group III (65.9%), which could resist

262 transport, where checked separately and showed evidence of rounded edges in 56 cases.  
263 Predepositional fractured specimens showed signs of abrasion.

264 Mineralization was also observed on some bone and teeth as black-colored manganese  
265 concentrations, and iron staining with a rusty color, but without adhered rust (Figure 8A–C).  
266 Iron staining formed irregular oval structures on some specimens, such as one mammoth tusk,  
267 with iron precipitation and localized corrosion also occurring on some (Figure 8B1 and B2).

268 The surfaces of several bones (n = 9; 3.4%) had traces of dendritic patterns left by plant  
269 roots (Table 4; Figure 8D1 and D2). These marks are the same color as the bone surface, ruling  
270 out the modern root systems as the cause.

### 271 3.3.3. Anthropogenic marks

272 No anthropic fractures were found. Within the study assemblage, several bones (n = 12; 4.6%)  
273 showed evidence of cuts and drilled holes, with potential cultural modification. Further  
274 studies have been designed for these—mainly taphonomical examination using electron  
275 microscopy; the results of this will be published separately. However, judging by preliminary  
276 results based on the nature of the cuts, they should be associated with the working of bone  
277 and antler as raw material.

### 278 3.4. Isotope analysis

279 The antler fragment certainly belonged to an individual of the family Cervidae, but its size as  
280 preserved did not allow the species to be identified. For the cervid antler fragment  
281 (KR/111.F180), a neodymium epsilon value of  $-13.0$  was obtained, while for the sediment  
282 sample (unit C of the sedimentary succession) it was found to be  $-15.7$  (Table 5).

## 283 4. Discussion

284 The Krosinko site yielded a faunal assemblage typical of the *Mammuthus–Coelodonta*  
285 faunal complex (Kahlke, 1999, 2014), dated to the MIS 3–2 (Pawłowska, 2022), occurring in  
286 the Warsaw–Berlin ice-marginal valley sediments. At the site location, sediments of the  
287 Warsaw–Berlin ice-marginal valley are represented by sand and gravel deposits (Chachaj,  
288 1996). Our taphonomic analysis of the remains of woolly mammoths, woolly rhinoceri, horses,  
289 giant deer, red deer, fallow deer, reindeer, steppe bison, aurochs, bears, and cave lions from  
290 Krosinko indicates that these were transported in an aquatic environment. In particular, they  
291 were associated with abrasion (including pitting), surface gloss, and rounded edges.

292 The abrasion of bone surface is one of the most widely recognized traits of bones that  
293 provides evidence of water transport (Gümrükçü and Pante, 2018). Abrasion can occur during  
294 transport (stage 3 in Gutierrez and Kaufmann's classification) or in situ by contact with  
295 sedimentary particles (stages 1 and 2 in Gutierrez and Kaufmann's classification). Abrasion in  
296 the Krosinko assemblage is significant on the epiphyses of long bones, as most of the study  
297 specimens show evidence of exposed spongy bone, due to the attrition of compact bone  
298 (stage 3). This results in a dull surface on the epiphyses and a shiny surface on the shafts

299 (22.2%). This has to do with the abrasion resistance of these parts of the limb bones, which  
300 are characterized by different densities (Lyman, 1984). In turn, the partial removal of the  
301 external flakes from the bone surface on some specimens that nevertheless survive in the  
302 fossil record is associated with a decrease in the abrasion rate, as the resistance to abrasion  
303 of the less affected inner surfaces of the bone increases, as observed by Fernández-Jalvo and  
304 Andrews (2003). In turn, those that display isolated polished and flattened patches on the  
305 bone underwent intense local abrasion. However, a glossy surface was recorded for most  
306 specimens (60.9%); this is related to the effect of water on the bones. Sedimentary abrasion  
307 is also responsible for producing sets of striations observed on the surface, which were  
308 distinguished from the scrape marks that they can resemble on the basis of the lack of  
309 chattermarks or of shavings between striations (Fisher, 1995; Olsen and Shipman, 1988). The  
310 action of water and sediment also resulted in the rounded edges observed for most specimens  
311 (65.1%). Rounding of bones is most commonly seen where there is long-term movement of  
312 water and sediment, particularly in rivers, and the circumstances involved in this need to  
313 include primarily the energy of the environment, rather than the actual transport of the bone  
314 (Fernández-Jalvo and Andrews, 2016). Considering the geological setting of the assemblage,  
315 this was more caused by the impact of gravel than of sands, since rounding develops more  
316 rapidly with gravel (Fernández-Jalvo and Andrews, 2003), the most abrasive sediment, than  
317 with other sediment types. Pitting of bones is also caused by sedimentary abrasion. The  
318 different diameter of the pits and their uneven distribution is associated with transport  
319 alongside sediment particles that strike the bone surfaces and leave structural changes. In  
320 addition, the diameter of the quartz grain impressions on the bone is consistent with the  
321 overall grain diameter for the gravelly-sandy sediments (coarser than 0.35 mm: Pawłowska et  
322 al., 2022) in which the assemblage was found, again confirming the sedimentary congruence  
323 between bone and the sediment. Some quartz and feldspar grains of the gravelly-sandy  
324 fraction have even been preserved within the bones, in both the natural holes of the remains  
325 and in exposed spongy bone.

326 Water transport is a frequent taphonomic agent in continental environments; it may  
327 not only affect surfaces of individual components, but also disturb original bone associations  
328 (Fernández-Jalvo and Andrews, 2003). This explains the anatomical and species diversity of  
329 the Krosinko assemblage and the very low degree of association of the skeletal elements,  
330 including the absence of any elements found in the articulation, namely anatomical order. This  
331 is confirmed by the low refitting percentage (1.5%), which additionally includes elements  
332 (such as mandibles and femurs) that could not have been displaced by flotation or saltation  
333 (according to how they are divided into fluvial groups) but were instead fragmented during  
334 transport.

335 The value of a fluvial selection index (1.4), expressed as the ratio of teeth to vertebrae,  
336 deviates from the value of 1.0 determined for mammalian skeletons (Behrensmeyer, 1975),  
337 indicating that less dense vertebrae may have been more easily transported from the bone  
338 deposit in this fluvial environment. By the same token, more teeth with lower fluvial potential  
339 but higher fossilization potential remained in the assemblage. This indicator of the degree of

340 hydrodynamic sorting based on differences in structural density between teeth and vertebrae  
341 thus points to high hydrodynamic sorting.

342 Generally the ration of unfused long bone diaphyses to epiphyses, with a  
343 predominance of epiphyses, can provide another line of evidence that a material represents  
344 a transported bone assemblage rather than a primarily deposited bone assemblage, pointing  
345 to low integrity (Gutierrez and Kaufmann, 2007). However, in Krosinko, the faunal complex  
346 with its balanced proportion (2:4), along with evidence of abrasion, suggests that both parts  
347 were transported, even though they do not have the same displacement predisposition due  
348 to their different density and size. The small number of epiphyses of limb bones is due to the  
349 dominant adult age of the animals from which the remains are derived, and thus the balanced  
350 proportion of bone diaphysis and epiphysis may be a function of sample size.

351 Further, since various factors can produce the same patterns of anatomical  
352 disproportion or destruction (so-called equifinality), modifying factors other than water were  
353 considered. Significant animal influence on assemblage shape was ruled out due to the  
354 negligible percentage of gnawing marks found (4.2%); these few were left by predators and  
355 none were due to rodents or omnivores. Evidence of carnivore gnawing—usually visible in  
356 assemblages as punctures, pits, scores, and furrows (Binford, 1981)— are visible in Krosinko  
357 assemblage as furrows and crenulated edges.

358 The Late Pleistocene spotted hyena (*Crocuta crocuta spelaea*) and steppe lion (*Panthera leo*  
359 *spelaea*), which were the main predators in Central Europe in the Late Pleistocene (Diedrich,  
360 2014), are well represented in fossil records in Poland; in particular, two cave lion individuals  
361 were found at Krosinko (Marciszak et al., 2021), which suggests that might be responsible for  
362 these marks. Of course, there are also predators of smaller mass, such as wolves and foxes,  
363 but they are ruled by the nature of the marks—shallow, 3–5 mm wide, irregularly shaped  
364 grooves. Some other examples of typical marks left by predators on Krosinko specimens  
365 (mainly pelvises), are the crenulated edges of bones, which result from gnawing. These  
366 irregular margins can be explained as caused by the premolar and molar teeth, as illustrated  
367 for modern hyenas (Diedrich, 2012). However, the attribution of gnaw marks to specific taxa  
368 is not straightforward, as they could have been left by juveniles or adults, they may have  
369 similar shapes and sizes, they can overlap, and they can undergo corrosion on their internal  
370 parts—not to mention many other issues (Diedrich, 2012; Sala and Arsuaga, 2018). Isotope  
371 evidence makes hyena involvement more feasible, as it points to an individualistic prey choice  
372 for cave lions, with some individuals being more oriented toward reindeer and others to young  
373 cave bears (significantly without competition from cave hyenas), which display different  
374 isotopic signatures (Bocherens et al., 2011). Cave hyenas are hypercarnivores—that is, animals  
375 with a diet consisting of 80–100% of vertebrate flesh (muscle, organs, and bones)—and there  
376 are some ontogenic differences between the adults, which exhibit a bone crushing behavior,  
377 and the juveniles which, besides bones, may have included a larger proportion of meat in their  
378 diet (Rivals et al., 2022). Hyena diets include whatever resources can be found, from termites,  
379 turtles, ungulates, and horses to other carnivores and elephants (Sala and Arsuaga, 2018). Red  
380 deer have also been confirmed by coprolite studies (Bon et al., 2012). Adult hyenas typically

381 modify bones of any size until the most advanced stages of consumption (Sala and Arsuaga,  
382 2018); this correlates with the distribution of marks in the collection from Krosinko, which  
383 come from woolly mammoth, bovids, and horses. Although hyenas do not have a significant  
384 impact at Krosinko, they are an important taphonomic agent in the formation of many bone  
385 assemblages in European and even African Plio–Pleistocene sites (Arribas and Palmqvist,  
386 1998; Brugal et al., 1997; Enloe et al., 2000; Fernández Rodríguez et al., 1995; Klein, 1975;  
387 Klein et al., 1991; Mangano, 2011; Marean et al., 2000).

388 Predators gnaw on bones when they are more interested in the fat and marrow than in  
389 extracting calcium and other minerals, as is the case with rodents (Klippel and Synstelien,  
390 2007). Their low incidence in the study may thus suggest a lack of access to fresh carcasses.  
391 The absence of digested bones, which result from the decay of feces, may however indicate  
392 that the predation activity took place in a different location to that of the faunal complex, or  
393 alternatively may indicate that these fragments were not preserved during redeposition.

394 Apart from surface modification, carnivores can also move bones from their original  
395 depositional loci (Kent, 1981; Marean and Bertino, 1994). This is, however, difficult to prove  
396 at Krosinko on account of the dominant influence of the aquatic environment.

397 Abrasion has a great effect on both gnawing and cut marks, proved on both qualitative and  
398 quantitative analyses, implying that especially the frequency of cut marks could be  
399 underestimated in assemblages preserved in fluvial environments (Gümrukçü and Pante,  
400 2018). However, the scarcity of anthropic marks and the lack of selective patterning in the  
401 anatomical distribution does not indicate that humans played a significant role in shaping this  
402 assemblage. One example of this is the presence of ribs—elements with a high economic value  
403 for humans (Binford, 1978). There is also no apparent anatomical skew, with the dominance  
404 of a few elements selected by humans for raw material or meat use. However, some human  
405 impact was found through the presence of several elements whose marks on the surface  
406 potentially represent a record of human influence. Their preliminary radiocarbon dating  
407 suggests that time at which the bone and antler were used as raw material for working lies  
408 between 47 and 26 ka BP (though research is ongoing). Although the analysis of these items,  
409 mainly traseological, will be the subject of a separate study, we can say now that they do not  
410 appear to have come from a Paleolithic site blur, given the lack of evidence of human  
411 settlement at the site and the absence of abundant culturally modified flints (Pawłowska et  
412 al., 2022) found with the fauna. That is, lithic artifacts were not found at the study site. The  
413 one horse bone and one rhinoceros bone with burning marks are not necessarily associated  
414 with human activity, and the nature of the temperature influence in the form of the browning  
415 that results from burning in a reducing atmosphere (Shipman et al., 1984), along with the black  
416 core, indicates that the bones were calcined.

417 However, their significance is immense. These burn marks from Krosinko are the first and  
418 unquestionable pieces of evidence to be found in Poland for woolly rhinoceroses in particular  
419 and for fossil rhinos in general. All taphonomic features of the individual specimens indicate  
420 water redeposition, which means that the material is allochthonous. Fossil allochthony can  
421 occur as a result of resedimentation (before burial) and/or of secondary deposition (after

422 initial burial) altering palaeoenvironmental and palaeoecological indications provided by  
423 fossils (Fernández-Jalvo and Andrews, 2003). Plant root marks (3.4%), are the result of the  
424 dissolution of the bone surface where dense roots covered it (Pei, 1938 in Binford, 1981), and  
425 which are consistent in color with bone, rule out the involvement of modern plants and also  
426 suggest that part of the assemblage was buried in the past. This cannot be extrapolated to the  
427 entire faunal complex, but the remains certainly occur in a secondary context, as shown by  
428 the multiple lines of taphonomic evidence, and as also indicated by the isotopic results of the  
429 different neodymium values of the cervid antlers and the sediments in which they were found.  
430 This is further corroborated by the presence of an antler of a fallow deer in the assemblage.  
431 Although this species is more flexible than other ungulates by inhabit a range of environments  
432 (Feldhamer et al. 1988), it prefers warmer environmental conditions than do woolly  
433 mammoths and woolly rhinoceri, which dominate in the Krosinko assemblage. Moreover,  
434 fallow deer are more sensitive to cold and habitat openness than are others cervids, such red  
435 deer (Pushkina et al., 2014). Given this and the taphonomic characteristics of the specimen,  
436 the presence of fallow deer remains in the assemblage is not an accurate reflection of the  
437 paleoenvironment, but does support the thesis of multisource material. Such material may  
438 even contain remains from periods preceding the assemblage itself, as evidence from other  
439 open sites such as the gravel pit shows (Baskin, 1991).

440 The implication of this is that an assemblage may incorporate bones of different  
441 taphonomic histories. The Krosinko site is no exception, and indeed palimpsests with diverse  
442 taphonomic histories are known from the Pleistocene. Barranco León (Orce, Granada, Spain)  
443 is an example of this, and Yravedra et al. (2022) distinguish co-occurring assemblages to  
444 demonstrate the complex taphonomic history of the site, which involved two depositional  
445 events. The initial depositional input was in a secondary position, with the materials being  
446 transported to the site by high-intensity hydraulic processes; the second depositional even  
447 was the subsequent accumulation in the primary position. The Thiongo Korongo site in  
448 Tanzania is also a cumulative palimpsest with faunal accumulation, similar to other Lower  
449 Pleistocene sites such as SHK at Olduvai or Ubeidiya in the Levant (Gaudzinski-Windheuser,  
450 2005, Domínguez-Rodrigo et al., 2014), which formed in riverine settings, with and without  
451 intervention by carnivores and with hominins playing an incidental role (Yravedra et al., 2016).  
452 The factors that affect the accumulation of material can be various and need not involve  
453 aquatic environments, as demonstrated in a study of the Cassenade site (France), where  
454 evidence has been presented on how activities of carnivores and humans can be mixed  
455 through natural processes (Discamps et al., 2019). The taphonomic results of the Krosinko  
456 remains are consistent with the results of our sedimentological study (Pawłowska et al., 2022)  
457 which showed the presence of a faunal assemblage in the fluvial sediments of the Pleistocene  
458 succession of the site that developed as gravelly sand (unit C) built up due to a high-energy  
459 braided river.

460 However, the environmental conditions under which the river operated (Pawłowska et al.,  
461 2022), in the form of strong freezing and aeolian weathering are not visible in the macroscopic  
462 taphonomic bone features. This certainly has to do with the effects of water on the remains,

463 which obliterated other earlier potential traces on their surfaces (Shipman and Rose, 1988).  
464 Pitting, which results from the impact of sand and gravel grains on the bone surfaces, and  
465 which is related to the intense sediment transport that characterized high-energy fluvial  
466 environments during the Weichselian period, hence dominates here. The river  
467 paleohydrological and pattern changes that occurred in Central Poland at that time were  
468 fluvial responses to the advances and retreats of the ice sheet, which took place 50, 28, and  
469 20 ka ago (Weckwerth, 2018). This is corroborated by the results of taphonomic studies of  
470 other organic materials found with the faunal remains, conifer cones (*Picea cf. abies*), and  
471 wood fragments (*Juniperus*), the edges of which have been found to be very rounded (see  
472 Figs. 13 and 14 in Pawłowska et al., 2022). Fluvial environments, especially river sands, are not  
473 conducive to pollen preservation, so only the macroremains of plants were recovered. The  
474 damaged and smoothed surface of the cones show various states of preservation, which  
475 implies that they may have been transported for various distances. Their occurrence in the  
476 secondary context cannot be the basis of a climatic reconstruction. This inconsistency in the  
477 taphonomic characteristics of the cones further suggests that the Krosinko assemblage was  
478 created through multiple depositional events.

479 Such rivers had high discharges and high energy (Zieliński, 2014), especially as we are  
480 dealing with the location of the study site in the Warsaw–Berlin ice-marginal valley. Taking  
481 into account the paleodirection of water flow from the melting ice sheet and the rivers that  
482 supplied the valley (Starkel et al., 2015), it can be concluded that the direction of transport  
483 was from east to west. This would be well documented by measurements of depositional  
484 structures which, however, cannot be studied in Krosinko due to the lack of exposure and the  
485 high groundwater levels. The rates of water flow can also be deduced from anatomical  
486 distributions in assemblage. The presence of mandibles, teeth, and tibiae in the Krosinko  
487 assemblage (group 3) is tied to high rates of water flow (Fernández-Jalvo and Andrews, 2003),  
488 which may otherwise remain as lag deposits (autochthonous) when the water energy is not  
489 strong enough to transport them. Evidence of the advanced polished and abraded surface are  
490 also indicators of movements under high-energy condition of flow (Fernández-Jalvo and  
491 Andrews, 2003, 2016; Gutierrez and Kaufmann, 2007). Separately looking at the distribution  
492 of elements assigned to the Voorhies groups revealed a slight prevalence of group III (41%)  
493 over the others (G II: 30% and G I:19%), which implies resistance to transport and may suggest  
494 lag deposit. Resistance to transport is however closely related to the current velocity  
495 (Voorhies, 1969), and evidence of the rounded edges of many elements in group III contradicts  
496 their absence of dispersal by movement. The slight differences between the values for all  
497 groups point rather to a balanced selective transport of elements.

498 Transport also results in fragmentation of material, and so most of the remains from  
499 Krosinko are fragmented (83.9%). Transverse breaks—that is, a break at right angles to the  
500 length of the bone, which occurs when bones are dry—have been observed as typical  
501 diagenetic or post-burial types of fracture (Lyman 1994, Reitz and Wing 2008; Villa and  
502 Mahieu, 1991). However, fragmentation is also a function of the manner in which the material  
503 was recovered using heavy equipment and a refuller, as indicated by the presence of modern

504 fractures (36.8%). In contrast, short bones, such as the carpal and tarsal bones, are generally  
505 completely preserved (16.1%).

506         Secondary mineralization of the remains is associated with the stage of deposition of  
507 faunal material, observed as manganese and iron staining and corrosion. In sedimentary rocks,  
508 especially sandy sediments, iron concentrations of various origins are common, and their  
509 contact with bone usually results in iron staining or even corrosion. The flow of pore waters  
510 containing various minerals, is also a factor responsible for iron and manganese staining. The  
511 example of the mammoth tusk from the assemblage shows that the presence of iron, and in  
512 some places even of corrosion, is related to pore water flow, the presence of which left  
513 irregular oval structures with precipitated iron. Manganese precipitates in the form of black  
514 staining, as evidence of a wet, oxidizing, and mildly alkaline environment (López-González et  
515 al., 2006), and this was also observed. Bones and teeth are stained by manganese dioxide, an  
516 insoluble inorganic compound, in an environment of newly oxygenated water (Fernández-  
517 Jalvo and Andrews, 2016), supported by the presence of clay minerals (Potter and Rossman,  
518 1979). However very sparse evidence of such mineralization suggests a sedimentary  
519 environment with low manganese concentration, unlike other Polish Pleistocene  
520 subenvironments, such as at Długopole (Hrynowiecka et al., 2022), where the local high  
521 manganese concentration was revealed through taphonomic investigation and geochemical  
522 analysis of sediments.

523         The time of deposition of the remains was determined using a series of radiocarbon  
524 datings of the faunal assemblage; these revealed a fairly wide range of dates, ranging from  
525 48.4 to 26.4 ka BP (Pawłowska, 2022). However, the bones were found at depths of 6–8 m,  
526 which suggest a fairly compact 1–2 m thick sediment horizon with bones. Integrating the data  
527 on the geological setting, the dating, and the taphonomy of the remains, it appears that the  
528 material underwent movement over some distance, to be deposited within a single geologic  
529 event as a faunal complex. This event occurred around 26 ka BP, as indicated by the youngest  
530 radiocarbon date of the remains (Pawłowska, 2022), or around 19 ka BP, considering the  
531 geochronological constraints for the local LGM ice margin position in central and eastern  
532 Poland around 22–18 ka (Tylmann et al., 2019) and the established time of sediment  
533 accumulation (Pawłowska et al., 2022).

534         Summarizing all the results, it seems that Krosinko is an intermediate site between the  
535 original location of the carcasses (which is more to the east), where they were subjected to  
536 selective transport, and a site where environmental energy slowed down considerably as  
537 expected (more to the west), and where the dominance of the transported groups (group I  
538 and group 1 in the two classifications) can be expected in the fossil record. The assemblage  
539 studied here thus reflects hydraulic sorting.

## 540 **5. Conclusions**

541 The Krosinko locality yielded an assemblage of a faunal complex from MIS 3-2 sediments. Its  
542 taphonomic analysis adds significantly to our knowledge of depositional processes in a fluvial

543 context that took place in the Warsaw–Berlin ice-marginal valley. The term *contextual*  
544 *paleozoology* is proposed here for research into any kind of context in which Pleistocene  
545 animal remains were found. The taphonomic signature allowed for the reconstruction of  
546 paleoevents in the late Pleistocene.

547 A possible paleo-event scenario includes the occurrence of faunal assemblage in the  
548 primary context in a land-based environment, where some elements were subjected to  
549 carnivore activity (Figure 9A). Some elements were used as raw materials by humans between  
550 47 and 26 ka BP (Figure 9A). Some remains were buried in a land-based environment, which  
551 left traces of plant roots (Figure 9B). Fluvial activity around 20 ka BP led to the redeposition of  
552 material, which was transported in a high-energy environment, as shown by taphonomical  
553 data and supported by already known geological data (Pawłowska et al., 2022). At that time,  
554 the surface of the remains were polished and damaged by abrasion both in situ (Figure 9C)  
555 and during transport (Figure 9D), as evidenced by the removal of compacted bone and the  
556 exposed spongy bone. The low degree of association of the bone elements, using refitting and  
557 articulation as lines of evidence, points to the natural factors responsible for the dispersal of  
558 the faunistic remains at the site, which led to low integrity. Approximately 26 ka BP (inferred  
559 by dating the remains) or approximately 19 ka BP (based on the extent of the ice-sheet in the  
560 LGM and sediment accumulation: Pawłowska et al., 2022), faunal remains were probably  
561 deposited within a single event at Krosinko, along with other water-carried materials in  
562 gravelly sand deposits (Figure 9E). At the depositional stage, water circulating in the sediments  
563 left manganese and iron on the surface of the remains as the last factor to affect the  
564 assemblage during the diagenetic stage of taphonomic processes (Figure 9E). Alternatively, it  
565 can be concluded that the Krosinko faunal assemblage, which was produced by fluvial  
566 transport, occurs in a secondary context, and for this reason may incorporate bones with  
567 different taphonomic histories; it is thus a depositional palimpsest.

568 In summary, an important conclusion from the geological, paleozoological,  
569 taphonomical, and isotopic studies is that the Krosinko bone accumulation is not the place  
570 where the animals died, nor is it the place where their carcasses were finally deposited. The  
571 predicted deposition site is further to the west, as can be deduced from the distribution of  
572 elements in the fluvial transport potential group and the direction of the water flow in the ice-  
573 marginal valley. Most of the assemblages are likely to represent a palimpsest of different  
574 events, leading to the weakened or destruction of the original taphonomic signature, as is the  
575 case in many such Pleistocene assemblages (Boschian and Saccà, 2010), especially in a fluvial  
576 context.

## 577 **Author contributions**

578 KP designed and performed the research, analyzed the results, wrote the manuscript, and  
579 responses for reviewers. KP is the author of the research hypothesis and the author of ideas  
580 for considering the scientific problem.

581 **Data availability**

582 The data presented in this manuscript are available on request.

583 **Declaration of competing interest**

584 The authors declare that they have no known competing financial interests or personal  
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591 author has applied a CC-BY public copyright licence to any Author Accepted Manuscript (AAM)  
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846 **Figure captions**

847 **Figure 1.** Extent of glaciation in Poland, with the location of the study site.

848 **Figure 2.** Proglacial stream valleys of the last glaciation in Europe with the location of the study  
849 site. 1: Wrocław–Magdeburg; 2: Głogów–Baruth; 3: Warsaw–Berlin; 4: Toruń–Eberswalde; 5:  
850 Pomeranian; 6: Reda–Łeba (Kashubian).

851 **Figure 3.** Geological cross-section of the vicinity of the Krosinko site (the Warsaw–Berlin ice-  
852 marginal valley). Stratigraphy: 1: Miocene and Pliocene; 2: Elsterian; 3: Holsteinian; 4: Eemian;  
853 5: Weichselian (including LGM); 6: Weichselian (including Poznań Phase); 7: Holocene. Based  
854 on Chachaj (1996), modified and reinterpreted.

855 **Figure 4.** Geological profile of the Krosinko site, in conjunction with paleoenvironmental  
856 outcomes. Explanation: sandy silt (A), sand (B), gravelly sand (C), and sand (D). The bone  
857 indicates the depth of the findings of mammals remains, along with botanical remains and  
858 flints. The radiocarbon dates given as 14 C years BP. Data from Pawłowska (2022); Pawłowska  
859 et al. (2022).

860 **Figure 5.** MIS 3–2, Krosinko site, Poland. Examples of natural surface modifications. A and B:  
861 evidence of burning on a horse metacarpal III and a woolly rhinoceros radius; C, D and E:  
862 carnivore gnawing marks on woolly mammoth pelvises and fourth carpal. Scale bar = 5 cm.

863 **Figure 6.** MIS 3–2, Krosinko site, Poland. Evidence of natural surface modifications: A–H:  
864 abrasion on a horse radius (A), woolly rhinoceros ulna (B), horse metacarpal III (C), aurochs  
865 radius (D), woolly mammoth femur (E), woolly mammoth pelvis (F), horse tibia (G), and woolly  
866 mammoth pelvis (H1 and H2). See main text for details. Scale bars = 5 cm.

867 **Figure 7.** MIS 3–2, Krosinko site, Poland. Evidence of natural surface modifications: (A1 and  
868 A2) striations, (B) pitting caused by sand (single arrow) and gravel (double arrow) on a bovid  
869 scapula, (C) gravel stuck in a woolly mammoth atlas, (D1 and D2) gravel stuck in a woolly  
870 rhinoceros cervical vertebra, (E) quartz grain stuck in a woolly rhinoceros phalanx III, (F)  
871 rounded edges of a woolly mammoth femur, (G) example of fragmentation, abrasion, and  
872 rounding edges. Scale bars = 5 cm.

873 **Figure 8.** MIS 3–2, Krosinko site, Poland. Evidence of natural surface modifications: (A) iron  
874 staining on a horse skull and (B) a reindeer antler, (C1) orange lines of iron staining on the  
875 inner surface of a tusk, (C2) iron corrosion effect on an previously abraded tusk surface, (D)  
876 manganese staining on a woolly mammoth tusk, (E1 and E2) root marks on woolly mammoth  
877 rib and evidence of abrasion. Scale bars = 5 cm.

878 **Figure 9.** A possible paleoevent scenario in the late Pleistocene (MIS 3–2), setting from land-  
879 based (A–B) to fluvial environments (C–D), based on taphonomic analysis of the faunal  
880 complex in Krosinko: (A) carnivore and human activity, (B) plant activity, (C) abrasion in situ,  
881 (D) abrasion during transport, (E) secondary mineralization during or after deposition.

## 882 **Table captions**

883 **Table 1.** Chronologic chart of the Pleistocene and Holocene succession in Poland, with  
884 references to Western Europe. MIS: Marine isotope stage; ka: thousand years ago; LGM: Last  
885 Glacial Maximum.

886 **Table 2.** The elements assigned to Voorhies groups. NISP: number of identified specimens;  
887 MP: *Mammuthus primigenius* (woolly mammoth); CA: *Coelodonta antiquitatis* (woolly  
888 rhinoceros); E: Equids; MG: *Megaloceros giganteus* (giant deer); CE: *Cervus elaphus* (red deer);  
889 DD: *Dama dama* (fallow deer); RT: *Rangifer tarandus* (reindeer); BPr: *Bison priscus* (steppe  
890 bison); BP: *Bos primigenius* (aurochs); B/B: *Bos/Bison*; U: *Ursus* sp. (bear); PSS: *Panthera  
891 spelaea* (cave lion); Ri: rib; At: atlas; Ax: axis; OV: other vertebrae; Sc: scapula; Ph: phalanges;  
892 Sc or Pe: scapula or pelvis; Fe: femur; Ti: tibia; Hu: humerus; Mc: metacarpal; Mt: metatarsal;  
893 Pe: pelvis; Ra: radius; Sk: skull; An: antler; Man: mandible; LT: loose tooth.

894 **Table 3.** The elements assigned to groups, according to Fernández-Jalvo and Andrews (2003).  
895 NISP: number of identified specimens; MP: *Mammuthus primigenius* (woolly mammoth); CA:  
896 *Coelodonta antiquitatis* (woolly rhinoceros); E: Equids; MG: *Megaloceros giganteus* (giant  
897 deer); CE: *Cervus elaphus* (red deer); DD: *Dama dama* (fallow deer); RT: *Rangifer tarandus*  
898 (reindeer); BPr: *Bison priscus* (steppe bison); BP: *Bos primigenius* (aurochs); B/B: *Bos/Bison*; U:  
899 *Ursus* sp. (bear); PSS: *Panthera spelaea* (cave lion); At: atlas; Ax: axis; OV: other vertebrae; Ri:  
900 rib; Pe: pelvis; Sc or Pe: scapula or pelvis; Sc: scapula; Ph: phalanges; Hu: humerus; Ra: radius;

901 Ul: ulna; Fe: femur; Mc: metacarpal; Mt: metatarsal; Ca: calcaneus; As: astragalus; OT: other  
902 tarsals; Ca: carpals; Pa: patella; Sk: skull; An: antler; Man: mandible; LT: loose tooth; Ti: tibia

903 **Table 4.** MIS 3–2, Krosinko site, Poland. The main taphonomic outcomes of the faunal  
904 complex. NISP: number of identified specimens.

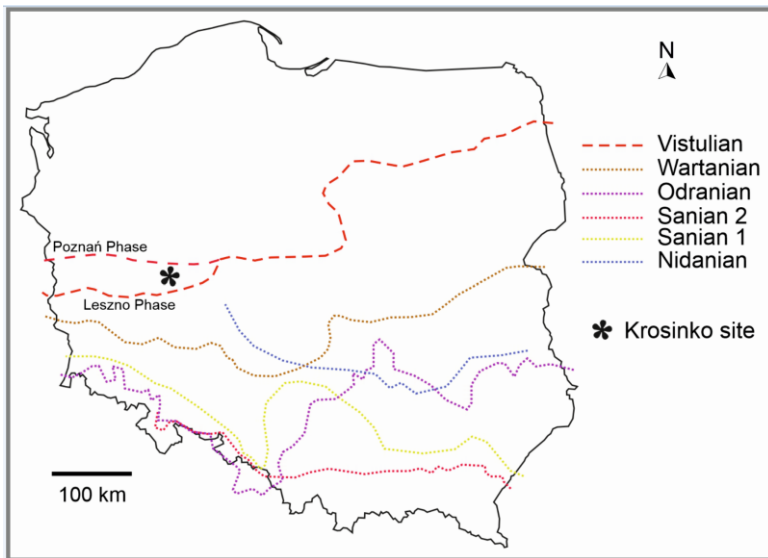
905 **Table 5.** MIS 3–2, Krosinko site, Poland. Neodymium isotopic results of cervid antler and  
906 sediment C-series.

907

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Preprint

909 Fig. 1



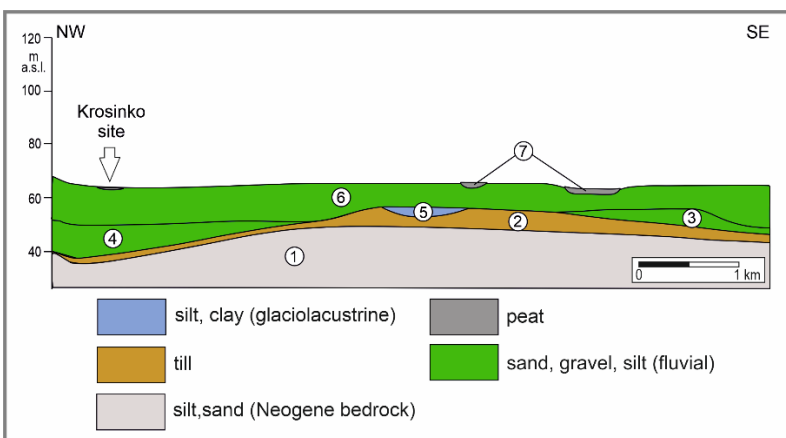
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911 Fig. 2



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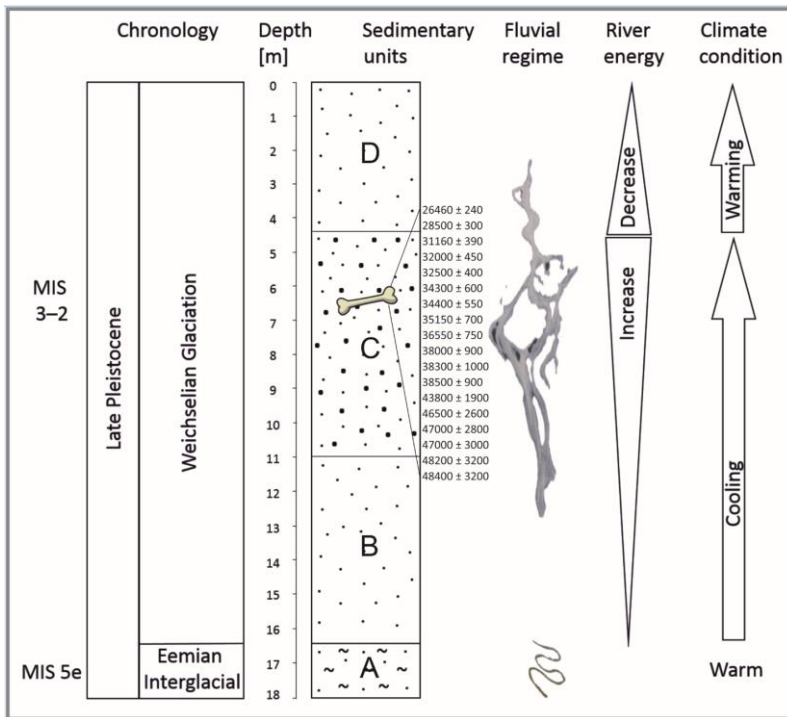
913 Fig. 3



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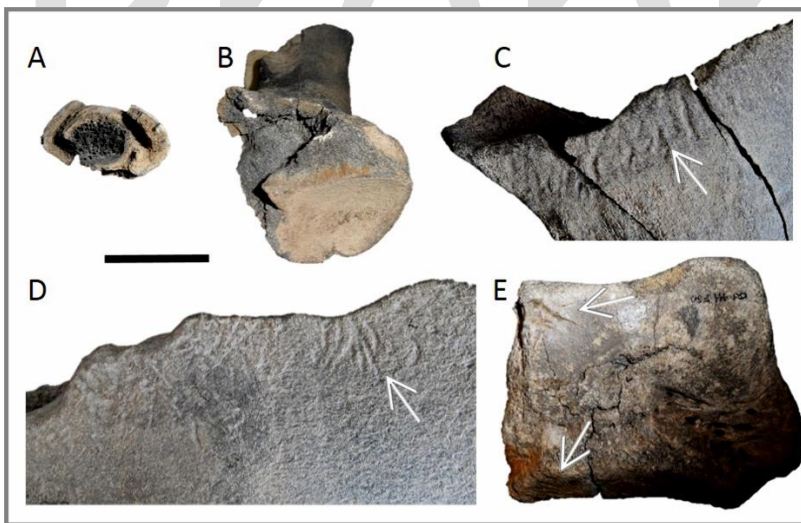
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916 Fig. 4



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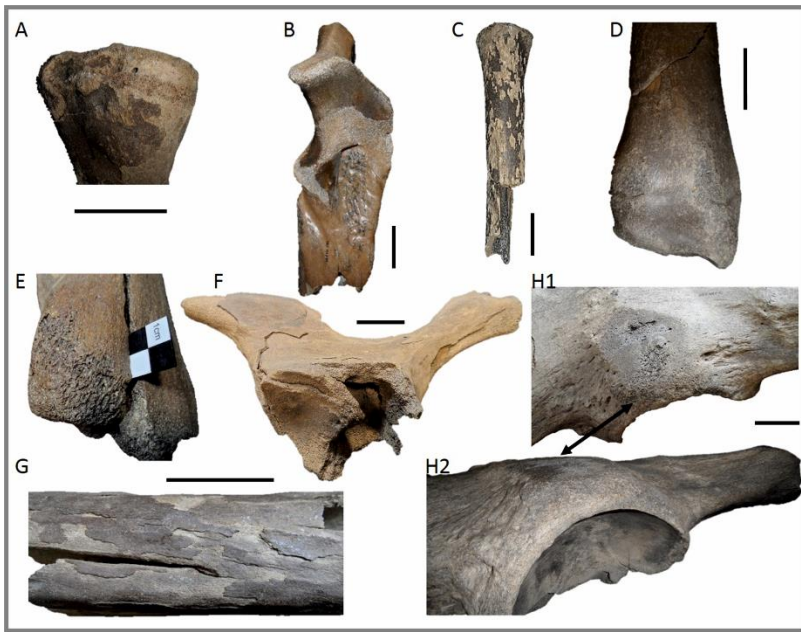
918 Fig.5



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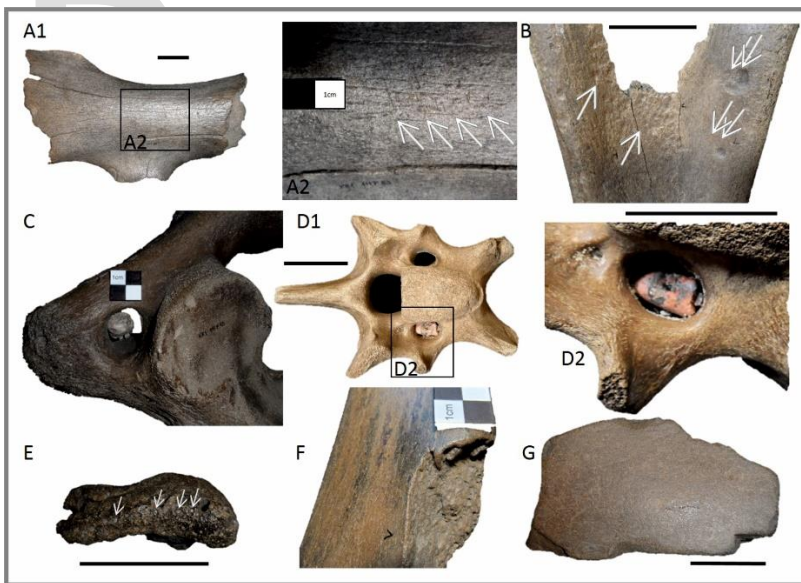
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921 Fig. 6



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923 Fig. 7



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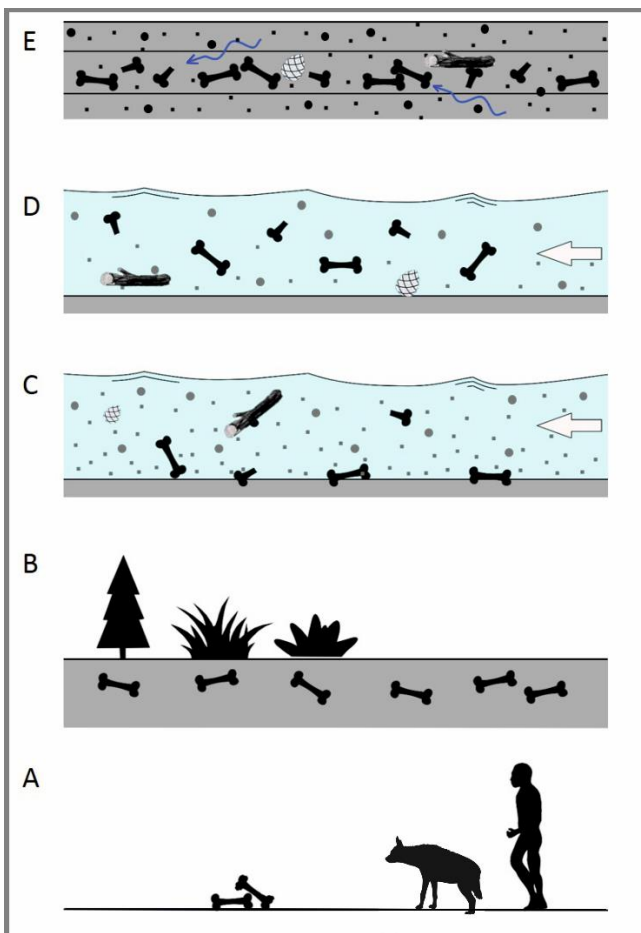
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926 Fig. 8



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928 Fig. 9



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930

931 **Table 1.**

Epoch	Poland	Western Europe (dates in ka)
<u>Holocene</u>	<u>Holocene</u>	<u>Holocene</u>
Late Pleistocene	Vistulian Glaciation (MIS 2)	Late Weichselian Glaciation, including LGM (29–11.7)
	Late Glacial Interstadial (LGI)	
	Gardno Phase	
	Pomeranian Phase	
	Poznań Phase	
Middle Pleistocene	Leszno Phase	Middle Weichselian Glaciation (57–29)
	Grudziądz Interstadial (MIS 3)	Early Weichselian Glaciation (123–57)
	Vistulian Glaciation (MIS 5d–4)	Early Weichselian Glaciation (123–57)
	Femian Interglacial (MIS 5e)	Femian Interglacial (130–123)
	Warthian Glaciations (MIS 6)	
	Odranian Glaciations (MIS 6)	
	Lublinian Interglacial (MIS 7)	Saalian Glaciation (347–128)
	Krznanian Glaciations (MIS 8)	
	Zbojnian Interglacial (MIS 9)	
	Liwecian Glaciations (MIS 10)	
Mazovian Interglacial (MIS 11)	Holsteinian Interglacial (424–374)	
Middle Pleistocene	Sanian 2 (MIS 12)	Elsterian (478–424)
	Ferdynandovian (MIS 15–13)	
	Sanian 1 (MIS 16)	Cromerian Complex (790–478)
	Kozi Grzbiet (MIS 21–17)	
	Nidanian (MIS 22)	

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933 **Table 2.**

Group Element	I Rj	I At	I Ax	I OV	I/II Sc	I/II Ph	I/II Ulna	I/II Sc gr	II Pe	II Fe	II Ti	II Hu	II Mc	II Mt	II Pe	II Ra	III Sk	III Au	III Man	III LT	III Total
MP	7	1		1	3				1	3		1	1		7		2			2	23
CA	1			6	1	1	2			4	2	2		2	3	3	5			1	3
E	2	2		4		4					3		2	3	1	2	1				5
Cervidae				1								1		1					3		
MG														1			1				
CE													1			1					
DD																			1		
RT																	2		11		
BPr																	1				
BP	2															1	1			1	1
B/B	1	2	1	2	3	2				1	2	1	2	2		1	2			1	1
Ruminantia										1		1				1				2	
Carnivora				1																	
U												1									
PSS							1														2
Mammals	4			2	2				1		1	3	1				13			1	1
Total NISP	17	5	1	17	9	7	3		2	9	8	10	7	9	11	9	28	15	10	33	
Total in group				40			21					63						86			210
% of group				19.0			10.0					30.0						41.0			

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935 **Table 3.**

Group Element	1 At	1 Ax	1 OV	1 Rj	1 Pe	1a Sc	1a Sc	1a Ph	2 Hu	2 Ra	2 Ul	2 Fe	2 Mc	2 Mt	2 Ca	2 As	2 OT	2 Ca	2 Pa	3 Sk	3 Au	3 Man	3 LT	3 Ti	Total
MP	1	1	1	7	7	1	3	1				3	1		1	1	2		2						23
CA		6	1	3		1	1	2	3	2	4		2					1	2	5			1	3	2
E	2	4	2	1			4	2				2	3	2						1			5	3	
Cervidae		1						1					1								3				
MG													1	1							1				
CE									1			1	1												
DD																						1			
RT																						2	11		
BPr																						1			
BP				2				1													1		1	1	
B/B	2	1	2	1			3	2	1	1	1	2	2	1						2		1	1	2	
Ruminantia								1	1			1											2		
Carnivora		1																							
U									1																
PSS																							2		
Mammals			2	4		1	2	3				1									13		1	1	
Total NISP	5	1	17	17	11	2	9	7	10	9	3	9	7	9	1	5	1	3	2	28	15	10	33	8	
Total in group				69								59										94			222
% of group				31,1								26,6										42,3			

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938 **Table 4.**

		NISP	%
Tooth/vertebra proportion	Tooth	33	
	Vertebra	23	
	Tooth/vertebra ratio	1.4	
Unfused diaphysis/epiphysis proportion	Unfused diaphysis	2	
	Unfused epiphysis	4	
	Unfused diaphysis/epiphysis ratio	1:2	
Degree of bone association	Separate	257	98.5
	Articulated bones	0	0
	Inter bone anatomical refittings	0	0
	Intra bone anatomical refittings	4	1.5
Fragmentation	Whole	42	16.1
	Predepositional	75	28.7
	Predepositional > modern	48	18.4
	modern	36	13.8
	modern > predepositional	60	23.0
Burning		2	0.8
Gnawing		11	4.2
Polish and surface abrasion	Glossy	101	38.7
	Matt	85	32.6
	Matt + gloss	58	22.2
	Unknown	17	6.5
	Pitting	present	
Bone edges abrasion	Acute	41	15.7
	Slightly rounded	118	45.2
	Greatly rounded	52	19.9
	Acute + rounded	9	3.4
	Unknown	41	15.7
Secondary mineralization	present		
Plant root		9	3.4
Cultural modification	Fractures	0	0
	Butchery marks	0	0
	Manufacturing marks	12	4.6

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940 **Table 5.**

Sample	<sup>143</sup> Nd/ <sup>144</sup> Nd	Error	<sup>143</sup> Nd/ <sup>144</sup> Nd <sub>(25 min)</sub>	Epsilon Nd <sub>(220 min)</sub>	<sup>147</sup> Sm/ <sup>144</sup> Nd	Nd (ppm)	Sm (ppm)	Sm/Nd
Antler	0,511958	± 0,000010	0,511938	-13,0	0,12266	139,49	28,30	0,20
Sand	0,511819	± 0,000016	0,511800	-15,7	0,11480	5,21	0,99	0,19

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